

Needs and Prospects for Ultrahigh-speed Optical Communication Systems

—Toward realization of 100 Gb/s or faster systems—

June 2005

New Energy and Industrial Technology Development
Organization (NEDO)
Incorporated Administrative Agency

Preface

Last year, we undertook an exhaustive investigation of the needs and prospects for ultrahigh speed photonic technology by organizing a special working group (WG) that consisted of a variety of eminent Japanese researchers. This WG was established by NEDO and had more than 40 members. The Ultrahigh-Speed Photonic Network WG studied several interesting fields, namely, backplane technology (SWG1), LAN/SAN (SWG2), grid computing (SWG3), and the public optical network (SWG4), and focused particularly on their high-speed properties. After a year of many discussions, we have now summarized our activities in one book that we have published in the form of a report entitled *“Requirements and attractive prospects for ultrahigh speed optical communication systems- Towards the realization of optical systems above 100 Gbit/s”*.

At the last meeting of the WG, we decided to have this report translated into English as we wanted the US and Europe to know the way in which Japanese researchers and company people are thinking as regards the future of high-speed communication. Japan is working hard on activities ranging from basic research to the commercialization of high-speed optical communication technology, and we want to become even more active in the near future. We will be very happy if this report encourages consideration of the future of ultrahigh speed communication throughout the world.

June 2, 2006

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Preface

The New Energy and Industrial Technology Development Organization (NEDO), an incorporated administrative agency, is expected to play the following roles as a central national organization for promoting industrial technology policy.

- For commercializing new technology, to carry out research and development projects through an advanced management capability with the concerted efforts of business enterprises, universities and public organizations and aim at the commercialization of new technologies such as the discovery of technological seeds as cores for future industries, mid-term and long-term projects as a foundation for industrial competitiveness, and research and development of each step toward development of practical applications, with regard to industrial technologies that will become the sources of Japan's international industrial competitiveness.
- For responding to such expectations, to perform its activities in a dynamic, effective and efficient manner by surveying and studying the needs and the movements of technological innovation of the industrial circles on the basis of the government policies of industrial technology and by implementing research and development assessment and activity appraisal.

In the electronics and information technology areas, it is necessary to promote technological development in a strategic manner considering the status of technical variability, speed of technological innovation and increased energy demands for information technology applications in order to realize an advanced information communication (IT) society and strengthen industrial competitiveness as driving forces of the Japanese economy. In this regard, optical communication and device technology supporting high-speed transmission of data for advanced information communication has been an area of technology where Japan has been ahead of the world, and it is imperative to continue to develop new areas of technology in this field to retain a competitive edge in the future.

Under this background, the Ultrafast Optical Communication System Working Group (WG) was organized under the Electronic Information Technology Strategic Survey Committee by the Electronic and Information Technology Development Department of the New Energy and Industrial Technology Development Organization (NEDO) in order to focus on themes related to ultrafast optical communication systems and to intensely study the future outlook for such

technology. While recognizing the importance to the need for ultrafast communication, this WG selected and then studied backplane technology, LAN/SAN technology, grid technology, and public communication network technology as main themes.

This report has been developed by Committee Chairperson Nakazawa and committee members, including leaders of sub-working-groups and participants from industry, academia and governmental organizations, through their dedicated research and discussion activities. With deep appreciation of the efforts of committee members and those engaged in drafting this report, we hope that its content will be used not only in the area of optical communication technology but also in the whole arena of information and communication as well as various interdisciplinary circles of business enterprises, universities and government organizations.

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Introduction

Introduction

Recently, the capacity of Internet Protocol (IP) traffic has expanded greatly and the low cost Asymmetric Digital Subscriber Line (ADSL) system has boosted the number of subscribers to 17 million. In addition, the use of Fiber to the Home (FTTH) has been growing rapidly, and a true broadband environment based on an optical fiber network is becoming a reality. One of the key issues in the “Second Phase Basic Plan for Science and Technology” initiated in 2001 by the Japanese government was “Information and Communication Technology (ICT)”, and indeed the IP broadband era is making rapid progress.

With this as the foundation, there are great expectations with respect to constructing a backbone network with lower electricity consumption, smaller space requirements, and wider availability. A high-speed optical communication system exactly meets these needs because of its lower power consumption associated with all-optical high-speed signal processing and simplified signal processing at Wavelength Division Multiplexing (WDM) nodes. The trend towards ultrahigh speed is evident not only in the field of public optical communication networks, but also in relation to computer/router backplanes and Local Area Networks (LAN)/ Storage Area Networks (SAN). In addition, there is a large demand for the development of high-speed networks for broadcasting media and medical field applications such as the real-time on-line transmission of very high-resolution images or news without data compression and high-quality TV telephony using mobile phones.

Here, let us consider the benefits of “high-speed communication” by providing some examples. For instance, the real-time transmission of super high definition (SHD) images, as mentioned above, provides an extremely realistic sensation that will bring about significant changes in telemedicine and telesurgery. In addition, a household storage device (DVD) with a capacity of several hundred Gbytes has been marketed recently, and the digital content industry is attracting the public’s attention by producing killer software applications. These applications can be easily combined by using ultrafast optical networks. For example, a 100 Gb/s Time Division Multiplexing (TDM) system will be able to transmit a one-hour 300-Mb/s High Definition Television (HDTV) program in just 10 seconds.

An “earth simulator” (parallel-processing ultrafast computer), which employs ultrafast electronic devices, is able to produce a result instantaneously against an extremely complicated calculation. For example, the latest earth simulator was applied to a combined atmosphere/ocean model to analyze both atmospheric and oceanographic interactions, and it soon predicted that there will be 120 tropical days per year and a 20% increase in rainfall in Japan 100 years from

now. Such fast computation has been made possible solely through the use of ultrafast supercomputers. The speed of electronic devices is being rapidly increased and the gate width of a Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) is now much less than 100 nm. If a computer clock can operate at a speed of several hundred GHz by using such ultrafast electronic/optical devices, it will be possible to compute much more complicated phenomena in a shorter time.

When electricity is used, the speed of router backplanes and computers is limited to less than 10 Gb/s due to their electric power consumption and dispersion, however if ultrafast optical technology is used a speed of over 100 Gb/s is feasible. It is predicted that a capacity of 1 Tb/s will be required for the backplane line rate after 2010, and therefore, electronic device speeds of more than 100 Gb/s will be essential.

Now, we turn to the current status of ultrafast optical technology. At recent international conferences, a number of reports have been presented on 160-Gb/s Optical Time Division Multiplexing (OTDM) transmission experiments, and various types of research and development are under way on 320 Gb/s~1 Tb/s OTDM transmission with ultra-short pulses in the pico ~ femtosecond regime with the goal of achieving ultrafast transmission and connection between high-speed computers. There is every possibility of realizing such a system because electronic devices and an optical modulator operating at 100 Gb/s have already been demonstrated. A 160-Gb/s Electrical Time Division Multiplexing (ETDM) transmission system will not be achieved immediately, but ETDM transmission of over 100 Gb/s is likely to be realized within a few years.

The Femtosecond Technology Research Association (FESTA) Project (1995~2004), which successfully linked femtosecond science and technology to the industrial arena, made great technological progress in the field of ultrafast optical device/short-pulse technology and realized a large number of groundbreaking achievements. This project was particularly influential in Europe, and triggered the launch of many projects on ultrafast optical communication including UPC, FASHION and TOPRATE. As for recent examples, Eindhoven University is proceeding with the COBRA Project, and an HHI (Heinrich Hertz Institute) research group is working on the commercialization of ultrafast transmission technology. At the same time, the Europe-U.S.-Japan Symposium on Ultrafast Photonic Technology was established, and there is growing motivation for a discussion of R&D results and the future prospects for ultrafast technologies. This symposium is a very important event in terms of Japan taking the initiative in future ultrafast technology, and we hope for great progress both in the optical industry and the academic world.

It is often said that Japan, with its limited natural resources, must achieve the practical use of advanced technology ahead of the rest of the world to support the country's growth through its

industrial capabilities. Now, there is a strong need for Japan to offer cutting-edge optical industries to the world. The creation of an ultrafast optical system of over 100 Gb/s will provide a very suitable driving force for energizing the currently stagnant economy. It will also play a positive role over the next few years in creating an advanced communication industry and generating many social benefits as mentioned above. To achieve these goals, we must construct an optical industry with a broad range of technologies including new transmission systems such as Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK), related optical measurement technology, and ultrafast optical and electronic devices. In addition, we would like to accelerate the creation of new technologies and assist the realization of technological breakthroughs to support the sustainable prosperity of the country.

With the above situation in mind, we formed the Ultrafast Optical Communication System Study Working Group in 2004 to create new optical industries and drive advanced technologies, and we have pursued discussions from various directions. This report was developed based on discussions related to such themes as the technological potential and future direction of Japan, where we took particular account of system developments that can be achieved through collaborations between industry, academia, and government, based on the urgent need for high-speed systems.

This report constitutes an intense discussion of the application of optics to ultrafast backplane technology, LAN/SAN, grid computing technology and public communication networks as these are regarded as the areas with the greatest need for ultrafast optical communication. Readers will find an exchange of in-depth arguments with an eye to the future, which I believe makes this report noteworthy as an indication of Japan's strengths with respect to high-speed communication. I wish to express my sincere gratitude to all the committee members who contributed considerable time and effort to the discussion and writing of this report, which I hope will assist the future development of Japan's optoelectronic industry.

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Purpose and Scope of Study

Purpose and Scope of Study

Part 1 Introduction

The Ultrafast Optical Communication System Study Working Group is positioned under the Electronic Information Technology Strategic Survey Committee formed by the Electronic and Information Technology Development Department of the New Energy and Industrial Technology Development Organization (NEDO). The Electronic Information Technology Strategic Survey Committee mainly aims at creating road maps and technology maps and includes the Semiconductor WG, Usability WG, Computer WG, Storage and Memory WG, Network WG and Interfield and Regulation WG. At the same time, the Ultrafast Optical Communication System Study Working Group was not necessarily intended to create roadmaps and technology maps as its main purpose. The accomplishments of the Ultrafast Optical Communication System Study Working Group are reflected in the roadmaps of the Network WG, Computer WG, etc. as needed through reports and the secretariat and by means of committee members participating in multiple WGs. The goal of the Ultrafast Optical Communication System Study Working Group is to develop and consider in-depth arguments relating to the theme of ultrafast optical communication systems.

Part 2 Purpose

The purpose of the Ultrafast Optical Communication System Study Working Group is to study next-generation ultrafast optical communication systems, and to clarify the feasibility of ultrafast optical communication technology over 100 Gb/s. It is expected that the future image of ultrafast optical communication systems having a focus on potential for commercialization will be used for the following purposes:

- A. Creation of research and development strategies and proposal/management systems for new and existing projects of NEDO and the Ministry of Economy, Trade and Industry (METI), etc.
- B. Determination of directions for research and development of optical device/systems, etc. in business corporations and research laboratories.
- C. Early commercialization of research results in the research laboratories of the Femtosecond Technology Research Association, the National Institute of Advanced Industrial Science and Technology (AIST) as well as private sector companies participating in the Femtosecond Technology Project (which was completed in FY2004) promoted by NEDO and METI.
- D. Determination of directions for continued joint study of the Femtosecond Technology Project in which AIST is playing the major role.
- E. Development of road maps and technology maps for the Electronic Information Technology

Strategic Survey Committee, Network WG, Computer WG, etc.

Ultrafast optical communication technology of over 100 Gb/s represents the leading-edge of basic technology. Technology development in this area will continue to be needed with an eye to industrialization and commercialization. We hope the reports of this WG will be used for such purposes.

Part 3 Contents of Study

Discussions about ultrafast optical communication systems have mostly centered on public trunk network communication systems. Progress in this area, however, was affected by the collapse of the bubble economy, and an applicable system of 40 Gb/s is belatedly coming to market. Therefore, we have decided to broaden the scope to other fields and examine several systems, without limiting the application area of ultrafast optical communication technology to only public trunk network communication. In this study, we have taken up system themes for which high-speed/high-capacity communication is used at present and there are needs for ultrafast optical communication with an increased communication volume requirement in the future.

The first theme adopted was the backplane that takes charge of communication within the router, server, etc. Because the existing backplane that transmits information by parallel processing of an electric signal of about 2.5 Gb/s is reaching the limit of communication capacity, the introduction of new optical technology is required. In NEDO's Super-High Density Electronic System Integration project that was completed in FY2003, the study of optical backplane was carried out, and this work was followed by the Optical/Electronic SI Research Partnership (Hyper-SI Project) of AIST. In this theme, the potential for an increase in speed of the optical interconnection in the backplane is being explored.

The second theme selected was local area network (LAN) and storage area network (SAN) technology. At present, 10 Gb/s Ethernet is in commercial use, and 100 Gb/s Ethernet is the next milestone. For ultrafast LAN/SAN in the future, however, Ethernet does not necessarily serve as a solid basis for planning. In the case of short distance communication such as communication between devices and in a local area network, parallel fiber transmission or space division multiplexing and wavelength division multiplexing can compete with ultrafast optical technology. In this connection, we have made an attempt to clarify the need for ultrafast communication from the viewpoints of applications and content.

The third theme is grid technology. Grid technology and ultrafast optical communication technology are not necessarily related directly to each other, but it is apparent that ultrahigh

volume communication is needed in the development of grid technology. Grid computing provides services by combining multiple resources of different domains on networks. Since grid technology is anticipated to cover the communication route and communication wavelengths as part of the resources to be managed, it is necessary to study the impact of ultrafast communication and large-capacity communication on grid technology.

Finally, public communication networks make it necessary to renew the study of ultrafast optical communication systems and their elemental technology. Device technology and elemental technology have much in common with the above three above themes. Thus, elemental technology and device technology that have been previously studied can provide important lessons for implementation of the other study themes.

After the WG selected the four themes mentioned above, a sub-working group (SWG) for each theme was established as follows to proceed with the study.

- SWG 1 (Backplane)
- SWG 2 (LAN/SAN)
- SWG 3 (Grid technology)
- SWG 4 (Public communication network)

Before starting the discussions within each SWG, the following items were proposed as study tasks in order to proceed based on needs rather than technology seeds.

- A. Where and how will ultrafast optical communication technology over 100 Gb/s be used?
- B. What are the benefits of using the technology?
- C. What will the system structures, necessary device functions and specifications be like?
- D. What system changes will be needed for 100 Gb/s communication technology?

It was assumed that it would be difficult to obtain clear answers to all the above questions, but we requested answers to the extent possible.

Part 4 Committee Members and Schedule

The chairperson of the Ultrafast Optical Communication System Study WG is Professor Masataka NAKAZAWA of the Research Institute of Electrical Communication of Tohoku University. The WG consists of researchers from a number of disciplines ranging from systems to devices, and WG and SWG committee members include representatives from AIST, the National Institute of Information and Communications Technology (NICT), Nippon Telegraph and Telephone

Corporation (NTT), KDDI, Japan Broadcasting Corporation (NHK), universities and business corporations, etc. The role of the secretariat was played by the Electronic and Information Technology Development Department of NEDO. (Please refer to pgs. i to vii for a list of committee members.)

This report was completed after serious discussions by the participating researchers held within a short period of time of just six months from October 2004 to March 2005. The WG and SWG meetings were held according to the following schedule.

WG and SWG Meetings

WG

- September 29, 2004 1st WG meeting held
- December 17, 2004 2nd WG meeting held
- March 16, 2005 3rd WG meeting held

SWG-1 (Backplane)

- December 3, 2004 1st SWG meeting held
- February 3, 2005 2nd SWG meeting held

SWG-2 (LAN/SAN)

- November 11, 2004 1st SWG meeting held
- January 26, 2005 2nd SWG meeting held
- February 21, 2005 3rd SWG meeting held

SWG-3 (Grid technology)

- December 5, 2004 1st SWG meeting held
- January 13, 2005 2nd SWG meeting held
- February 23, 2005 3rd SWG meeting held

SWG-4 (Public communication network)

- November 26, 2004 1st SWG meeting held
- December 15, 2004 2nd SWG meeting held
- January 27, 2005 3rd SWG meeting held
- February 23, 2005 4th SWG meeting held

Part 5 Future Activities

Although this report has been completed, the WG will continue its activities in FY2005 to carry out

the following activities:

- A. To hold a meeting (scheduled for June 6, 2005) for the general public to publicize the content of this report for common use.
- B. To study extraction of technology and specifications commonly necessary for the four themes.
- C. To continue activities and further studies by the SWGs requiring a broader and more in-depth examination.
- D. To establish a new SWG to continue the study if it is required for a new field other than that covered by the four SWGs established thus far.
- E. To extract more detailed tasks and select study themes to identify research projects for realizing ultrafast optical communication systems.

I. Backplane

I. Backplane

Part 1 Introduction

Backplane transmission technology is essential technology required for equipment such as routers and cross connects having an architecture that implements a high speed signal termination function and a switching function using different cards. For example, in a router containing multiple numbers of 10 Gb/s line interfaces, a 10 Gb/s signal is deployed in parallel at 10 Gb/s x 4, and a switch card and a line card are connected by electrical wire. As greater speed and more capacity are required, the serial transmission speed of the backplane needs to be increase from the current 2.5 Gb/s to 10 Gb/s and then to 40 Gb/s. Although, the backplane transmission requires high speed circuit technology with complex functions such as delay equalization function, and deskew function between parallel signals, 10 Gb/s is expected to be the maximum limit due to power consumption restriction. Optical backplane transmission technology is a promising new technology that will avoid the above mentioned bottleneck in electrical input/output (I/O) technology.

This report first discusses the necessity of optical backplane technology based on advances in the processing speed of the electrical router, and clarifies the potential functions and performance of optical backplane technology. In addition, it discusses the status and future techniques which will become the core of optical backplane technology, including optical interconnection, OE/EO conversion LSI circuits, and optical connectors. Further, it also discusses optical backplane implementation technology such as optical boards and multi-channel optical connectors for parallel optical fiber links, which were developed in the Super-High Density Electronic System Integration Project as core optical backplane technology. Finally, it discusses three-dimensional LSI chip technology, wavelength division multiplexing (WDM) technology, and optical time division multiplexing (OTDM) as future technologies for ultrafast and large-capacity optical backplane technology, and summarizes related technological issues.

Part 2 Technical Trends and Needs

2-1 Trends

2-1-1 Equipment trends (server/router)

In information processing, equipment represented by the server/router, demand for utility is expanding and components are becoming commodities at a far greater speed than in the past. In this environment, high performance information processing equipment is not based on a central processing unit (CPU) or a single piece of equipment such as a hard disk. Rather, the trend to realize high overall system performance by connecting function blocks called a blade system in parallel at the backplane is becoming noticeable.

Because of this trend, a blade structure is beginning to be used in many types of information processing equipment, especially high-end servers and routers. The blade structure has three advantages: (1) it provides the flexibility of adding functions at will, (2) it has scalability to realize a large capacity by parallel arrangement, (3) and it has high reliability due to switching functions among the blades at the time of a failure. Because of this, a blade structure will be used not only across a wide area from high-end to mid-range equipment, but the need and demand for higher backplane performance (communication capacity, size, etc.) will increase.

2-1-2 Processor trend

Improvement of slow processor performance using finer design rules is one of the factors that will serve to more rapidly disseminate use of a blade structure. Processor performance is an offshoot of the performance improvement called Moore's Law, where packing density is improved twice every 1.5 years and high performance is achieved by clock speed accompanied by integration improvement.

However, from 2002 or so when semiconductor fine patterning technology reached close to the 100 nm level, an increase in current leakage and power-related problems surfaced, and there has since been slow improvement in the clock speed of processors. Given this situation, the trend to realize improved equipment performance not by improvement in the performance of a single processor but by using a blade structure with parallel drive of multiple equipment is becoming obvious.

2-2 Backplane performance index

The blade structure of a backplane consists of a processor installed on a card called a line card, a network interface, a card called a switching card that interconnects line cards using a star shaped connection, and a backplane that connects both cards (Fig. I-2-1).

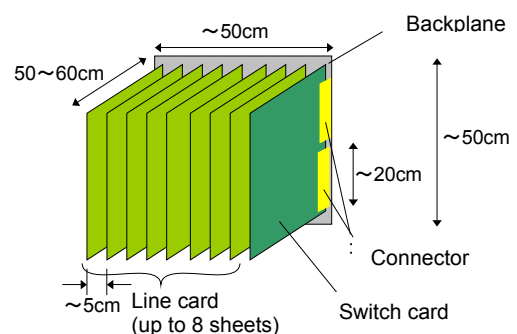


Fig. I-2-1 Example of blade structure

Fig. I-2-2 shows the expected performance regarding processing capacity for a line card and a switch LSI mounted on a switch card.

Based on technology demand relating to the equipment trend, the information processing capacity of equipment backplanes used for servers and routers is expected to double annually.

As of 2004, backplanes utilizing an electric signal and wiring attained an average processing capacity of approximately 160 Gb/s with a switching LSI, and that the need for additional capacity will grow to nearly 1.2 Tb/s by around 2007.

It is considered that it will be hard to realize 1 Tb/s, which is ten times the processing capacity of that in 2004 without a technological breakthrough.

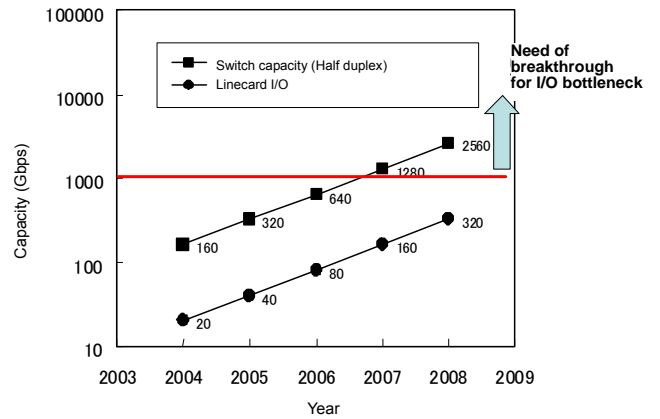


Fig. I-2-2 Processing capacity trend of components inside equipment [1]

Part 3 Electric Backplane Limitations and the Potential of Optical Technology

The most important technological advantage of the blade structure is found in the compact connection among multiple functional cards. For such a purpose, backplane performance is determined based on the following three considerations.

- (1) Transmission performance (speed x distance): It is essential to realize long distance (1 m or more) communication without losing high speed signals.
- (2) Transmission density: It is imperative to have high density to realize large capacity processing with compact equipment.
- (3) Power consumption: In order to facilitate cooling and reduce operating cost, lower power consumption is indispensable.

The discussion below covers the status of the electric backplane and the potential of optical technology in accordance with the three above considerations.

3-1 Transmission performance (speed x distance)

The conventional backplane was realized by means of a method that communicates through electric signals. In the past, when the backplane requirement was 10 Gb/s or less in signal speed and 1 m or less in transmission distance, there was very little motivation to apply optical technology which requires an increase in the number of components related to the backplane (the signal process itself is realized in the form of electric signals).

However, with 2007 in mind, a backplane link capacity of 100 Gb/s or more (backplane capacity could be 1 Tb/s or more by using multiple units) will become necessary. In order to make a link capacity of 100 Gb/s transmission (1 m) compatible, as electric signal attenuation is large in an electric backplane, a technological breakthrough is required both for the required link capacity and transmission distance. For this reason, it is expected that a link capacity of 100 Gb/s and transmission distance of 1 m will be realized by applying optical technology capable of low-loss signal transmission.

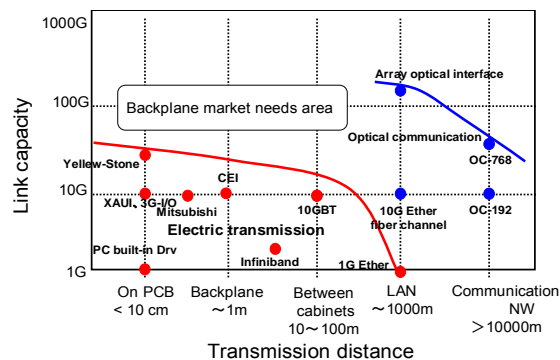


Fig. 1-3-1 Transmission performance [2]

3-2 Transmission density (speed/volume)

A blade structure aims at realization of a high level of system performance through the integrated installation of multiple functions in a small amount of space. Thus, the key performance index for a backplane is how to realize high capacity communication in a minimum amount of space.

In order to achieve a high speed and high density backplane, it is imperative for transmission density, which is realized by LSI-I/O, LSI packaging, and printed wiring boards and connectors, to improve in parallel. The status of each of these components and issues and expectations related to optical technology are described below.

3-2-1 LSI-I/O

In order to improve backplane transmission density, it is essential to first know how much signal capacity can be obtained from the silicon die of an LSI (switching LSI to which signal wiring concentrate especially).

For transmission density improvement, there are two options: improvement in clock speed and improvement in the number of wirings. Scaling up silicon die size in order to increase the number of wirings will cause a sharp increase in manufacturing cost associated with a decline in manufacturing yield. (Regarding the narrower pitch of wire derived from a silicon die in view of manufacturing engineering, it is difficult to achieve a narrower pitch than the current 100 μm or so.) Due to this fact, technical emphasis on clock speed improvement will now be needed. While an effective clock speed increase for electric signal transmission can be realized by pre-emphasis or multilevel signaling, realization of high density LSI-I/O with less circuit scale is expected with optical technology that does not need pre-emphasis as it is estimated that a circuit scale increase may become a bottleneck.

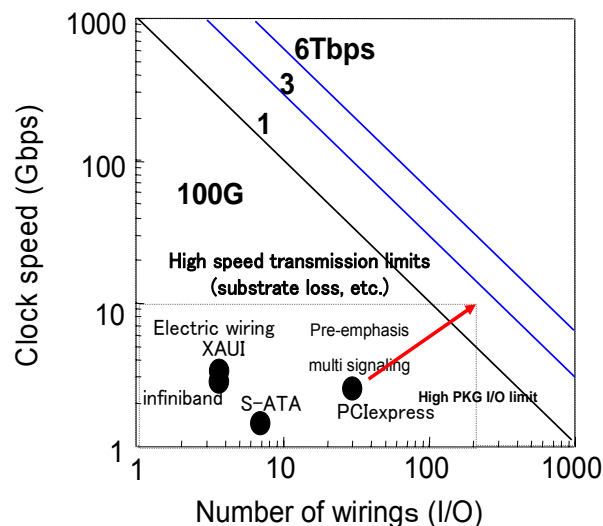


Fig. I-3-2 Status of LSI-I/O [1]

3-2-2 LSI packaging

In realizing backplane capacity, an increase in LSI package capacity will become an issue. When 1 Tb/s of backplane signal is stored in a LSI package for signal processing, 250 pins (differential signal line for independently sending and receiving) are necessary (the LSI package as a whole will be at the 1000 pin level, see Fig. I-3-3) in case high signal pins for 10 Gb/s are used. If electric signal lines of 10 Gb/s are integrated at a high density with 250 pins, the impact of noise may be significant. Therefore, a breakthrough in optical technology which enables signal input and output with low noise and low loss is needed.

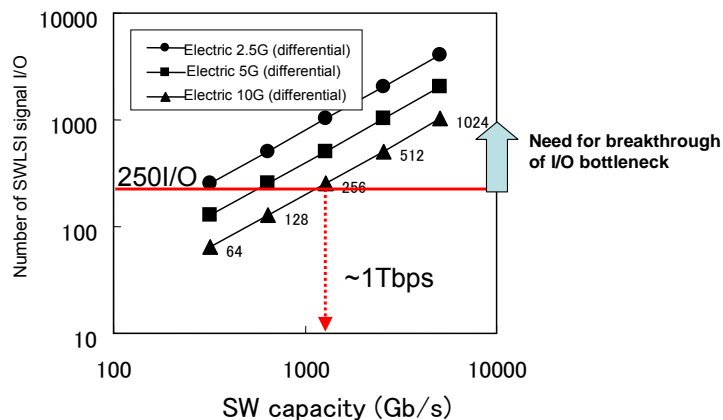


Fig. I-3-3 Status of LSI package [1]

3-2-3 Printed wiring boards and connectors

Printed wiring boards (PWB) that connect packages requires high density wiring for high speed signals. Considering signal input and output, even when a ball grid array (BGA) package that is suitable for high speed input and output is used, the distance between ball grids needs 1000 μm to reduce crosstalk. (Therefore, PWB wiring connected to the BGA requires a basic structure of 1000 μm pitch.) On the other hand, when an optical interconnection is used, a signal interval as short as 125 μm (it can be further reduced to around 50 μm by using waveguides) (Fig. I-3-4) can be achieved with a ribbon fiber. Therefore, optical interconnection technology is necessary to improve PWB transmission density.

A guideline for the length of connectors used for a backplane is a width of 100 mm or so for a 19 inch rack, but a connector with a 100 mm width may not attain the required transmission capacity of 1 Tb/s in connections between backplanes using electric signals. Thus, use of an optical interconnection is expected to reduce the distance between wirings.

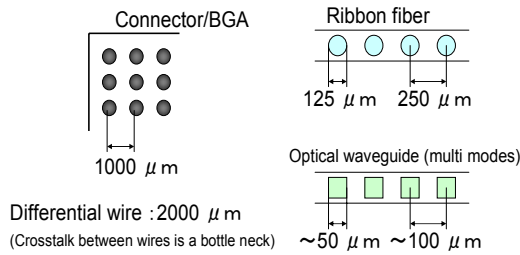


Fig. I-3-4 High density of PWB [1]

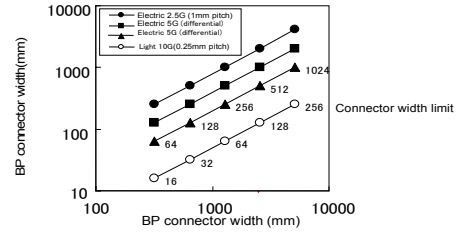


Fig. I-3-5 High density of connectors [1]

3-3 Power consumption (speed/power)

In order to pursue the achievement of a large capacity backplane for use inside equipment, a reduction in power consumption is essential. Power consumption for servers and routers is limited at present to several kW taking cooling conditions and running cost into account. Further, in light of the Kyoto Protocol, further expansion is difficult.

Therefore, in a situation where transmission speed per wire is increasing, power consumption which tends to increase has to be reduced to 10 mW/Gb/s or less. So, it is expected that transmission effectiveness with optical interconnection technology may enable signal transmission with high power effectiveness. Optical devices enabling transmission with low power consumption centered on the vertical cavity surface emitting laser (VCSEL) have a greater potential capability than a local area network (LAN) to realize power savings and miniaturization by limiting transmission speed as required by a backplane.

3-4 Cost

A cost reduction for electric signal wiring to be used for a backplane is easy to achieve as the component count is small due to interface commonality with the LSI circuit that processes electric signals. As a result, when optical technology is used for a backplane, a lower cost is possible due to full integration with the electric signal LSI and also a reduced number of components needed for assembly.

Table I-3-1 Power consumption trend per unit speed [1]

Capacity per line (Gbps)	Power consumption per 1Gbps (mW/Gbps)		
	Electric transmission (present)	Electric transmission (Development)	Optical transmission (present)
2.5	20 to 30 ↓ Preemphasis/ equalize	10 to 12	To 70 ↓ Conversion to CMOS
10	30 to 50 → Low bit/multi valuation	10 to	To 30 (10) Expectation
40	(50 to 70)		

Part 4 Realization Form and Future Image of the Optical Backplane

Optical interconnection represents a breakthrough over conventional backplane technology using an electric interconnection in terms of transmission performance (speed x distance), transmission density, and power consumption. When an optical interconnection is used for a backplane, two architectures for a switching system can be considered, one with an electric switch and the other with an optical switch.

The architecture with an electric switch consists of an optical interconnection for only input/output and switching itself uses a conventional electric switch. A large capacity can be realized, thereby easing bottlenecks such as the aforementioned transmission density by using optical interconnection. However, optical-to-electrical conversion at the switching system, compared with that of the optical switch, will create further overhead. On the other hand, by using an electric switch conventional technology can be used for complex processes such as avoidance of data collision inside the switching system and communication protocol between line cards/switch cards. The structure with an optical switch can realize total input/output and switching in the form of an optical signal. By using an optical switch, dramatic miniaturization of the switching system can also be realized. However, only msec order micro electro mechanical system (MEMS) technology can be used for a multi port optical switch at today's technology level, and switches with a nsec order required by communication protocol to be used in routers have not yet been developed. Also, an optical switch without memory is not able to handle complex process such as avoidance of data collision, and it will be necessary to develop a new system architecture centered on the collision avoidance process. As a precondition of the above two backplane forms, two potential directions for the evolution of optical back plane technology (parallel high density and ultrafast) will be examined below.

4-1 Parallel high density

Through use of optical interconnection technology, high speed, high density and low power consumption LSI input/output is expected to be realized. By miniaturization of VCSEL/PD arrays and drive circuits, it is possible that a switch capacity exceeding 1 Tb/s, which is the maximum limit for electric interconnection, can also be achieved.

Fig. I-4-1 shows an example of a system architecture which realized a large capacity using optical interconnection (switch capacity of 2.5 Tb/s). By arranging 32 signal transmitter/receiver sets on each side of an LSI consisting of four sides, a 2.4 Tb/s capacity can be realized (around 0.5 mm per transmitter/receiver set).

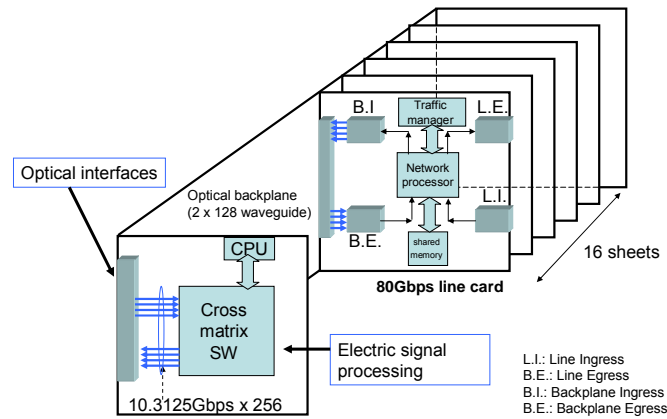


Fig.I-4-1 Example of system structure using compact/high density connection
(Switch capacity 2.5 Tb/s) [1]

4-2 Ultrafast systems

By means of optical transmission technology advancement, when a 40 Gb/s or more ultrafast optical transmitter/receiver is realized with a compact size and low power consumption device, as the structure in Fig. I-4-2 shows, a further increase in capacity to 2.5 Tb/s will become feasible. However, normal circuit miniaturization of input/output for the 40 Gb/s level is considered to be difficult as it requires an arrangement of eight signal transmitter/receiver sets per side with around a 2 mm width per transmitter/receiver set. So, in combination with a high speed compact size optical switch with nsec level switching speed which is expected to be realized in the future (32 by 32), an ideal architecture to eliminate integration of the optical conversion circuit at the switching system where input and output of signals concentrate. However, when an optical switch without memory is used, a new control switching mechanism will need to be developed in order to avoid signal collision. (A potential procedure will be to send out after setting up store and pass at the card side without having a collision avoidance buffer inside the switch.)

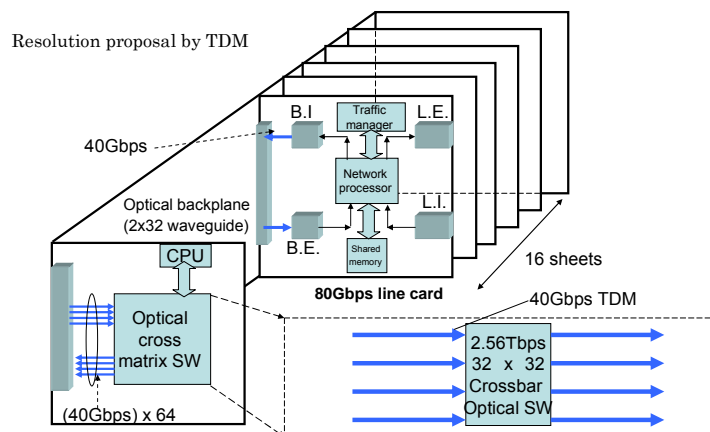


Fig. I-4-2 Ultrafast optical interconnection/Example of system structure using light
(switch capacity 2.5 Tb/s) [1]

Reference Literature

- [1] Shinji Nishimura, Implementation issues for router/server improvement and OEIC expectations, Optoelectronic Industry and Technology Development Association, Optical Integration Technology Feasibility Investigation Committee (Sep 2004)
- [2] Optoelectronic Industry and Technology Development Association, Optical Circuit Implementation Technology Roadmap (Sep 2003)

Part 5 Optical Backplane Development and Technical Issues

5-1 Basic architecture constituent of optical backplanes

In servers and routers, multiple process boards called a processor or line card are connected. With serialization of the electric interface, the architecture is such that each card is connected through a switch card. Normally, each card is connected through a wiring board that is located in the back section of each piece of equipment. This wiring board is called a backplane. Connection between the boards of an optical backplane is made by an optical transmission channel consisting of an optical interface which converts between an electric signal and an optical signal on the process board, and an optical connector which connects the optical transmission channel and optical transmission channels as basic constituents. The key issues are low power consumption, size and cost.

Current architecture design practice arranges multiple channels mounted in a block to reduce cost per port. In the beginning, the optical interface was individually modularized and placed at the edge of the board, but a high speed electric transmission section to which system LSI and optical interface are connected on the card remained and space for modules was still needed. Therefore, this was not user-friendly compared to the electric type. An architecture where system LSI has optical ports at the package level through integration of system LSI and the optical interface is now the mainstream approach. With a super miniature optical interface and electric transmission enclosed in a package, the issue of optical technology application in equipment is expected to be resolved.

In the optical transmission channel, a multi-core multi-mode optical fiber is applied because of its low loss and ease of optical connection. In the beginning, this architecture will be put to practical use, although in recent years development of an optical print board in which a polymer optical waveguide is placed on the print board has intensified. The eventual issue will be a practical optical coupling structure, and this will take several more years to achieve practical use. However, when optical channels increase in the future, a mounting structure where electric connections and optical connections will be implemented together at the same time is expected in terms of cost and high density ^{[1][2]}. Fig. I-5-1 shows the basic structure of an optical backplane and its mounting form trend. Major points regarding these structures will be described below.

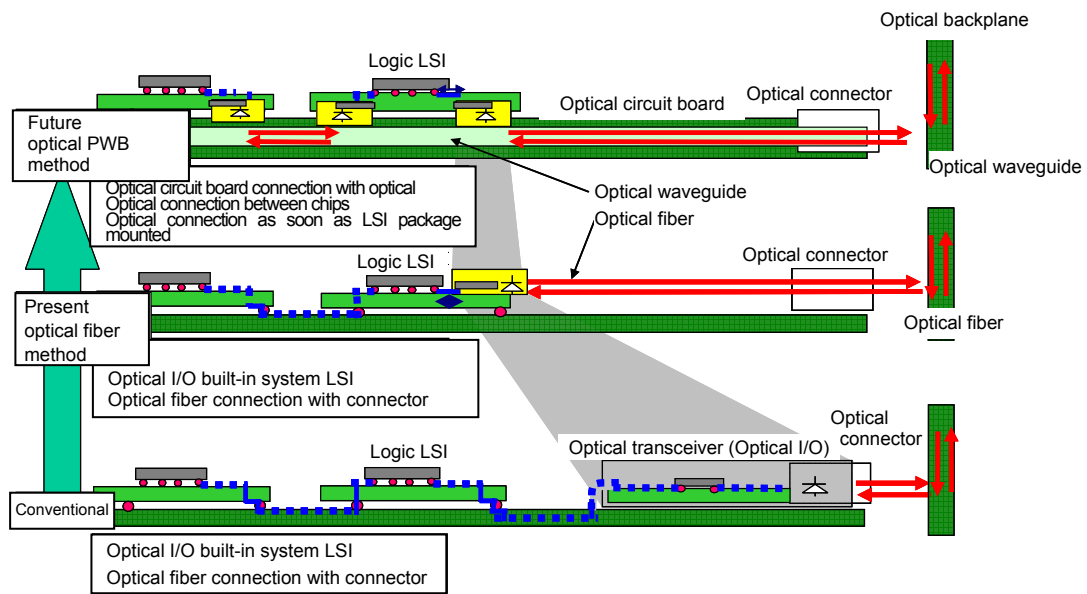


Fig. I-5-1 Basic structure trend of optical backplane

5-2 Power consumption

In an optical backplane system which replaces only a part of the conventional electric transmission with optical transmission, power consumption caused by the conversion between light and electricity will increase. A study that includes the electric transmission section between system LSI and the optical interface is thus necessary. Fig. I-5-2 shows a simulation result of electric transmission speed and distance. In electric transmission, the transmission channel is frequency dependent and the faster the greater the loss. Normally, transmission distance is 20 to 30 cm with 10 Gb/s against a distance of 1 m required by a backplane. Due to this fact, during transmissions exceeding several Gb/s, the transmission distance is being stretched by two methods, a pre-emphasis where some amount of wave form is deformed inversely in advance in proportion to that of anticipated wave form degradation at the transmitting section, and an equalizer in the transmission channel where the deformed wave due to frequency dependency at the receiving section is inversely compensated. Recently, a method to improve effective transmission speed by multi-level has been studied. Because of this, around 1 m of transmission distance with 10 Gb/s is now possible. However, these methods require an additional circuit in the electric I/O section and power consumption in the I/O section increases. Enough amplitude is required to protect against any loss in the transmission channel, thus, the power consumption increases as the speed becomes faster. On the other hand, with the structure described in Part 5-1 where an optical interface is installed in the LSI package, the transmission distance is quite short as the electric transmission section is enclosed in the LSI package, and amplitude may be small without the additional circuit for pre-emphasis^[3]. Due to this, power consumption at the I/O between system LSI and the optical interface may be lower than at the I/O of normal electric transmission. Power

consumption at the optical interface section has been designed to be low by using a vertical surface emitting laser (VCSEL) as the light source^[4], and applying CMOS for a driver LSI and a receiver LSI resulting in around several 10 mW/channel with transmitter/receiver which is almost the same power consumption with that of the I/O between the LSI's. Toward larger capacity transmission, there are measures such as increased channel numbers and channel speed. With direct modulation using VCSEL, 20~25 Gb/s may be the limit, and it is considered to be better in terms of total power consumption to improve channel speed up to that. For speeds that exceed this level, an external modulator is required. While it may take several more years to develop, a modulator using Si photonics technology is being studied, and when low drive voltage is realized it will have greater potential to become a low power consumption modulator than with electric transmission. At this time, optical application is expected for not only connection between optical backplanes but also between board LSI.

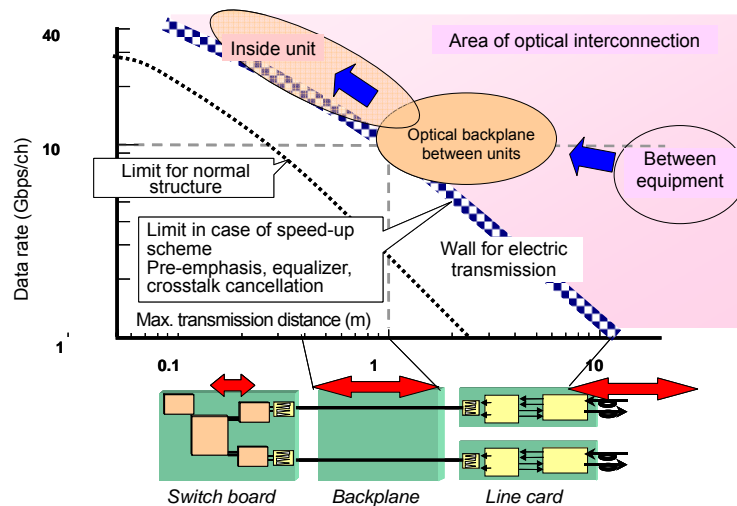


Fig. I-5-2 Electric transmission speed and transmission distance

5-3 Size (density)

Compared to an electric backplane, an optical backplane can easily facilitate high density interconnection over a wide band. In order to utilize this attractive capability, miniaturization of the optical interface and connectors (high density) is an important factor.

Optical interface

Normally, a ball grid array (BGA) board used for a LSI package is defined by the connection pad count and size of heat sinks. Because of this, while LSI size is around several mm square, the BGA is several 10 mm square, which leaves dead space on the BGA package. When an optical I/O is included in the dead space, space for optical I/O installation is not needed on the print board. The amount of dead space is about 10 cm². Unless innovative low power consumption or heat sink technology for system LSI is developed, the difference in LSI package and BGA size may stay

the same. At present, a mounted optical interface having a size of about 1 cm² and an optical-to-electrical converter of four channels and transmitter/receiver LSI has been realized. Given the current technology level, optical ports for a maximum of around 100 channels can be installed per LSI package, which is equal to 1 Tb/s assuming a 10 Gb/s/signal. Fig. I-5-3 shows a development example. Up to one-fourth of the present size is possible, and there is potential to realize up to 4 Tb/s assuming the same transmission speed. However, as the number of optical channels has increased to 100, the issue of optical interconnection now needs to be considered. With miniaturization of the optical interface, the ease of optical interconnection with the aforementioned optical print board will also be an issue. Moreover, an idea for dissipating heat due to increased power consumption is necessary.

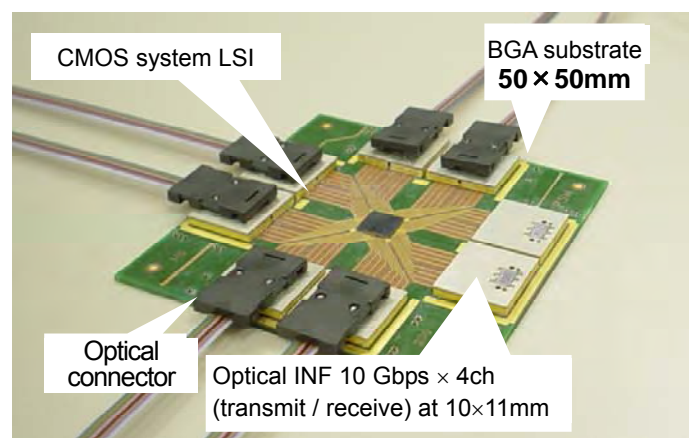


Fig. 1-5-3 Development example of system LSI package installment type interface

Optical connector ^[5]

With current optical interconnection technology, 250 μm-pitch wiring is possible and optical fiber of 125 μm-pitch is under development. By using an optical waveguide, an even narrower pitch interconnection is possible. Considering a 1 mm width with differential-mode electric signal wiring in the print board, which is required due to loss and impedance limits, the competitive edge for wiring density is clear. In order to make full use of this advantage, optical connectors need a similar high density increase. There are two kinds of optical connectors, an optical connector which connects optical fiber to the above mentioned optical interface, and an optical backplane connector which connects optical fiber on the function card to an optical backplane. The basic structure of connectors is arranged with an array shaped optical fiber fixed at the terminal to form a precise alignment and by precisely putting optical fiber and optical devices or optical fiber into position. The connector size is determined by the terminal for which the positioning mechanism (normally guide pins) was formed, and the connectable capacity per connector is determined by the number of optical fibers used in the terminal and their transmission speed. Connectors for an optical backplane are being developed by the Association of Super-Advanced Electronics

Technologies, and a signal density of several Gb/s/mm has been made possible based on calculations that assume a signal strength of 10 Gb/s per fiber.

In the case of electric connectors, size is determined by the number of terminals and pitch, and 2 mm spacing is needed due to wiring restrictions. Signal wire density is around 0.5 Gb/s/mm by differential with 10 Gb/s/core, and with the above optical connector a higher density is possible than with an electric connector. One issue concerning the optical connector is that the number of units required needs to be reduced for cost reduction as the cost per unit is high. The need to lower cost by reducing utilization count will thus become important in optical connector high density.

5-4 Cost

Unlike with an electric backplane, an optical backplane can realize a high rate of transmission and a high density. On the other hand, there is a corresponding cost increase due to a higher optical component count. Cost performance, which can be obtained from performance divided by cost, thus needs to be examined. When optical backplane cost is being considered, the following three points need to be kept in mind. First is the component cost of the transmission section itself. With an optical backplane, an electric transmission line on the backplane and a low-layer print board can be used, thus the cost of the print board and electric connector can be reduced. On the other hand, the cost of an optical interface, optical connector and optical interconnection is new. Second is the cost reduction effectiveness in simplifying the structure of equipment by utilizing the competitive edge of light. Other cost reduction includes board quantity reduction through high density mounting and peripheral material reduction by simplifying measures against electromagnetic Interference (EMI). Third, through maximum utilization of high speed transmission which cannot be realized in electric transmission, there is a lower cost due to component count reduction by means of equipment architecture modification. Fig. I-5-4 shows the cost structure of common sections in equipment such as a router and server. The cost of the transmission section itself is not significant compared with the equipment as a whole. In the past, the cost of this section experienced more than double-digit growth as soon as the use of light was applied. In recent years, there has been cost reduction due to improvement in manufacturing engineering and production volume growth driven by greater demand, thus it can not be said that it is expensive because of light.

A close examination of each piece of equipment is necessary, but considering such things as board quantity, the cost reduction gap is becoming smaller. In order to confirm the absolute competitive edge of the optical backplane, component count reduction and cost performance improvement of equipment as a whole by modification of the architecture itself as mentioned in the third point above are key factors. While such ideas as memory reduction through load reduction on the buffer utilizing advantages of high speed large transmission are being proposed, it has not yet been proven with an actual commercial product as optical backplane technology development

itself has a short history. In the future, it is expected that various architectures which are excellent in terms of cost performance will be proposed after optical backplane technology is recognized as a general technology for equipment architects.

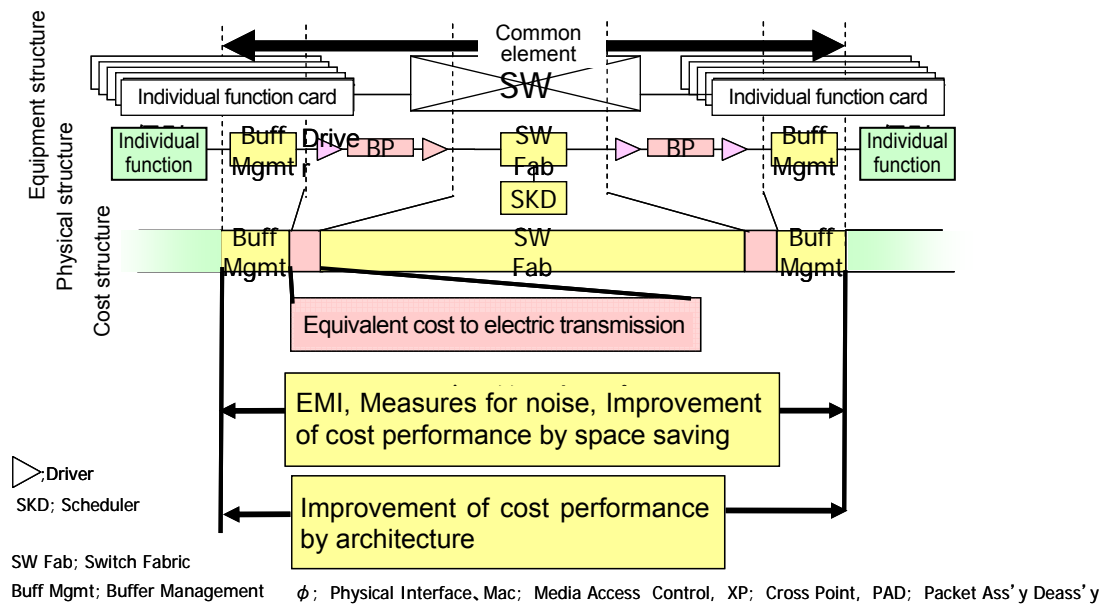


Fig. I-5-4 Structure of equipment common section and cost structure

5-5 Toward high speed and enhanced functions

In the area of optical backplane technology, efforts to replace electric transmission channels with optical channels and realize high speed large capacity which can not be achieved by the electric method is currently mainstream. The band width of optical transmission channels still has enough room and research on high speed is now being pursued. On the other hand, for the optical method, realizing sophisticated features utilizing functions such as wavelength can be expected. While the optical backplane was introduced to the market only a short time ago, development towards more speed and sophisticated features will accelerate once it is recognized as a generic technology. High speed and sophisticated features are briefly discussed below.

For the moment, a throughput of 40 to 80 Gb/s per line card is sufficient. In case the transmission speed is 40 Gb/s or more, it should be assumed that the same line card structure throughput of 320 Gb/s to 800 Gb/s per line card is required. CMOS technology development and optical modulation and demodulation methods have to be considered regarding how to realize such a throughput. It is expected that CMOS with 45 nm technology will be possible by 2010, and in that case 40 Gb/s per port will become realistic. In the case of more than 100 Gb/s, taking the process limits of CMOS, the process speed of internal core circuits and the load of parallel/serial conversion section into account, other LSI technology may be involved and a close examination of power consumption and cost advantages is necessary. With optical modulation, there is a realization issue for VCSEL direct drive at 20 to 25 Gb/s or more and an external modulator is required. While

it may take more than several years for realization, modulators using Si photonics technology are also under study and practical application may not be far away when high speed and low voltage can be verified. Development of a low power consumption receiver together with an external modulator is also needed. For low power consumption, optimization of the receiver amplifier circuit, including serializer/deserializer (SER/DES) hardware is required, and photodetector build up on amplifier built-in CMOS-LSI becomes necessary. With this technology development, optical transmission in equipment is expected to be applied for connection not only between optical backplanes but also LSI in a board.

Multiplexing on one transmission channel with light is easy using wavelength multiplex transmission. In case a signal is electrically multiplexed power is always consumed, but there is no power consumption with wavelength multiplexing. Also, a multiplexed optical signal is free from skew within a short distance. There is an idea of processing a signal as light by means of sophisticated features, an approach which considers that improvement of throughput per transmission channel as mentioned above, low power consumption and low cost may become important. At present, the passive optical device is handicapped in terms of its size and cost compared with electric circuits. However, when the prospect of achieving a similar size and cost are in sight by utilizing studies on such subjects as Si photonics, research is expected to accelerate.

Fig. I-5-5 shows the evolution of the optical backplane technology discussed so far. [1]

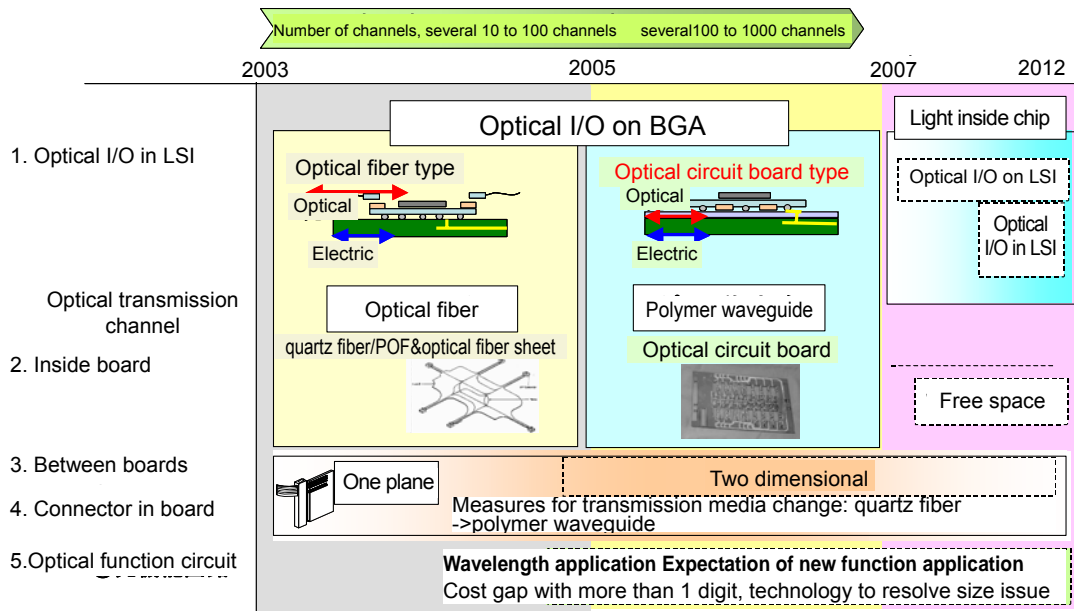


Fig. I-5-5 Development of optical backplane technology

5-6 Standardization

An optical circuit packaging standardization committee has been established by the Japan Printed Circuit Association and standardization activities for connectors and optical interfaces for a backplane have been started [6]. In electric and electronics technologies, the supply chain has been established over many years. On the other hand, in various components to be used for an optical backplane, the supply chain among within industry has not yet been established. Components and devices are being developed independently based on the views of each manufacturer and organization. In conventional development, improvement has been achieved and technology has been completed by manufacturers in their own handling loop. However, with the optical backplane, the technological area to cover is large and individual improvement among manufacturers has its limits. In recent global competition, a system in which speedy organization of overall optimization, including peripheral technologies, is implemented to complete technologies may become important. Regarding standardization activities, various manufacturers relating to areas and layers are participating and close examination of technologies is possible. When the optical backplane is taken as integrated technology of various technologies and made into a field where standardization activities can function to integrate advantageous technologies into products, fostering a systematically competitive product line is considered to be effective and a good result is expected in the future.

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Part 6 Optical Backplane Packaging Technology R&D

6-1 Requirements for optical backplanes

Regarding the development of a roadmap for optical technology, a report by the Optoelectronic Industry and Technology Development Association noted that to realize optical packaging technology, it was necessary to develop technology centered on the optical backplane as shown in Fig. I-6-1. As shown in Fig. I-6-2, at first the area above 1 Gb/s was estimated to be the area for optical backplane application. However, electric transmission technology for high speed utilization has been actively developed. Thus, the area for optical backplane application is shifting upwards toward a higher speed area. However, further advances in electric transmission now face a limit regarding the large scale of equalizer circuits and power increase potential, and the area above 10 Gb/s is considered to be the optical backplane application area. It is estimated that after 2010, node related equipment of 100~160 Gb/s and over 1000 waves of wavelength multiplexing technology will be required. Also, while the optical backplane is expected to become the backbone of ultrafast optical communication systems, speed and non-inductiveness of light are expected to be key requirements. Thus, given the performance level of the conventional electric backplane, it will be necessary to improve the performance and cost of each item as shown in Table. I-6-1.

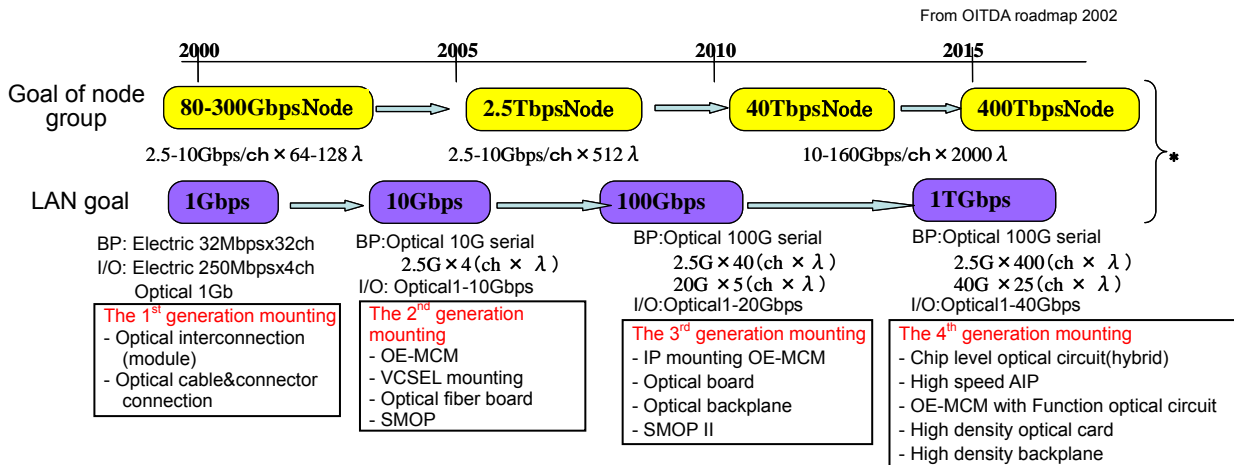


Fig. I-6-1 Development road map for optical mounting technology

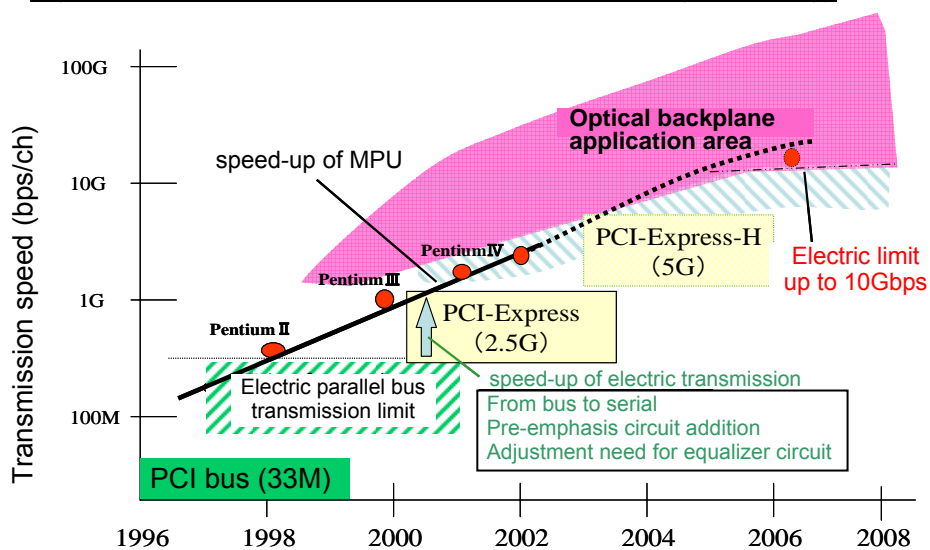


Fig. I-6-2 Backplane speed trend

Table I-6-1 Requirements for an optical backplane [1]

Item	Required specifications	Reference: In case Electric BP
Transmission capacity (half duplex)	>2 Tb/s	<1 Tb/s
Clock speed	10~40 Gb/s	<3~10 Gb/s
Transmission distance	>150cm	~15cm
Optical connector terminal pitch	<250 μ m	~2mm
OE Module density	<0.02mm ² /Gb/s	~0.05 mm ² /Gb/s
Process delay time(excluding transmission channel)	<~100ns	~100ns
Power consumption	<10mW/Gb/s	~50mW/Gb/s
Reliability	Telcordia complied	The same on the left
Temperature resistance	Storage : -40~+80°C Operation : 0~50°C	The same on the left
Cost	¥2k/40 Gb/s	¥1~10k/10 Gb/s

6-2 Development status of the optical backplane

The usefulness of the optical backplane has been recognized for some time, and R&D has been undertaken around the world aiming at realization of the specifications shown in Table I-6-1. In this section, major development examples and the current level of technology is discussed.

Optical backplanes are classified according to (1) the use of optical fiberboard, (2) the use of a channel type polymer optical waveguide, and (3) the use of a planer type polymer optical waveguide. Technology level will be described later, however at present the closest realization of the requirements in Table I-6-1 is found with optical fiberboard. Low loss with a polymer optical waveguide and development for cost reduction are being actively pursued, and in the future optical backplanes utilizing a channel type polymer optical waveguide and a planar type polymer optical waveguide are expected to be developed.

(1) Optical backplane using a fiber bend right angle optical connector

In the Super-high Density Electronic System Integration project (1999-2004), an optical backplane combined with optical fiberboard and a fiber bend right angle optical connector was developed as shown in Fig. I-6-3 [2]. The advantages of low loss and high speed transmission in the optical fiber can be utilized and the transmission channel loss is almost negligible. Also, the connecting section of the board adopts a structure in which it can self-lock the connector housing to float. This allows control of the bend radius to reduce loss by bending fiber to 0.1dB or less and make a multi-core bundle connection using multiple MT ferrules. In case boards are connected through the backplane, transmission loss as low as 0.8dB or less with multimode transmission and 1.4dB or less with single mode and stable connecting characteristics can be obtained.

An optical backplane similar to the above fiber bend right angle connector is being developed by 3M [3]. Shown in Fig. I-6-5, its structure consists of a backplane using fine wire GGP fiber (high strength circuit fiber) and a fiber bend right angle connector using a ball and socket ferrule. The connection loss of the ball and socket ferrule with multimode is said to be within 0.7 and 1.1dB.

In addition, the Opto-electronic System Integration Collaborative Research Team (Hyper SI project) is pursuing higher density and cost reduction for the optical backplane of the Super-high Density Electronic System Integration project as well as research and development on a high

speed version of the Advanced Telecommunications Computing Architecture (ATCA), which is the standard backplane for electric high speed transmission being promoted [4]. As shown in Fig. I-6-5, in order to realize 20 mm of board mounting pitch for the optical backplane, compact housing, fine wiring high Δ fiber board (Δ : refractive index differential proportion), and MTPIPE (MT ferrules with Pre-Installed, Pre-polished both Ends fibers) are under development. While fine wiring high Δ fiber board has a similar structure to the GGP fiber of 3M with a core diameter 50 μm , a silica glass diameter 80 μm and a resin layer diameter of 125 μm , an outer diameter of 125 μm has been realized with high precision. It can be assembled directly into a MT ferrule which supports 125 μm without peeling resin layers off, and loss can be made 0.1dB or less when Δ increases to 1.9% to bend up to the bend radius of 3 mm. In addition, an MTPIPE for ferrule assembly with a board mounting pitch of 20 mm was made by dividing a MT ferrule into a block with polishing fiber, and a fiber board terminal end with a wiring adhesive block is also under development.

In this project, the current application for the optical backplane is a development plan with a throughput of 5.6 Tb/s per backplane in 2005 by quickly completing a throughput of 2 Tb/s with 10 Gb/s/ch and making a board mounting pitch and optical connector high density. Further in the future, single mode optical backplane development will be carried out in order to improve module speed and wavelength multiplexing performance will also be further clarified. For example, using a module of 100 Gb/s /ch may lead to technology capable of supporting up to around 40 Tb/s.

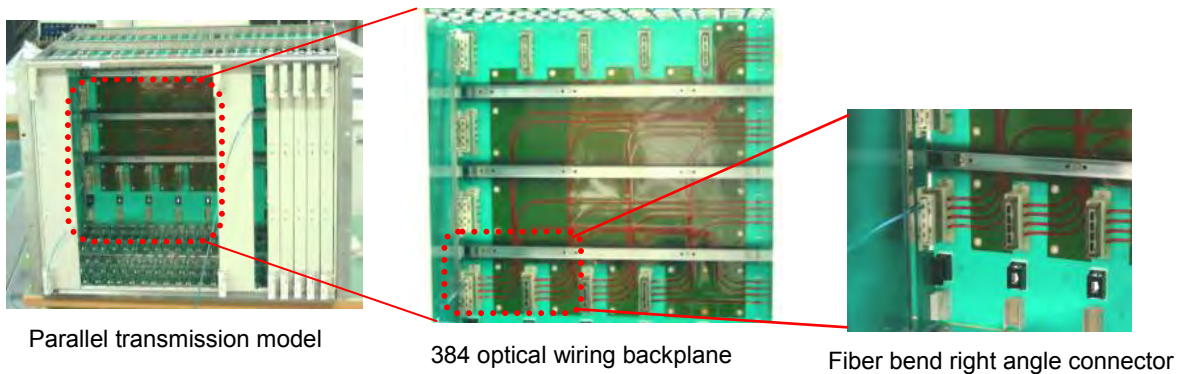


Fig. I-6-3 Super-high Density Electronic System Integration project development optical backplane

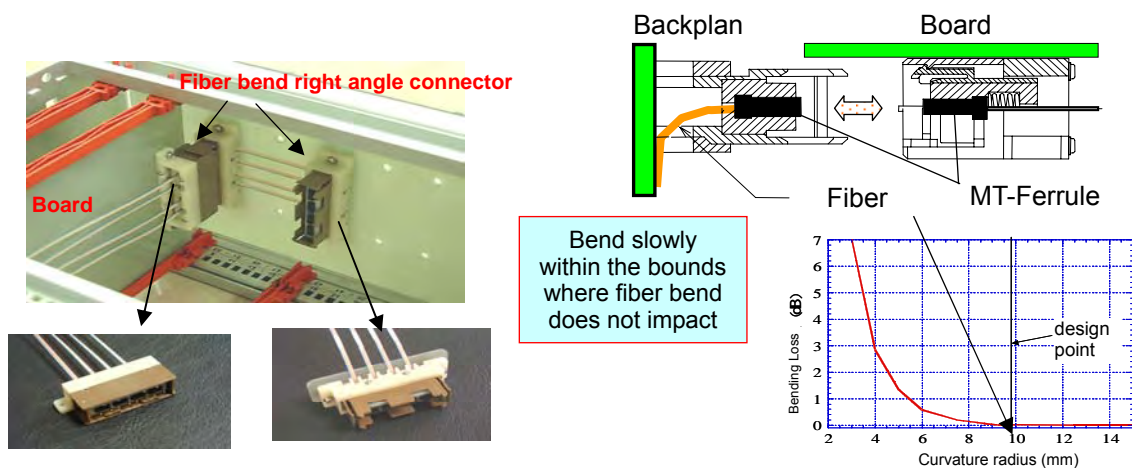


Fig. I-6-4 Fiber bend right angle connector

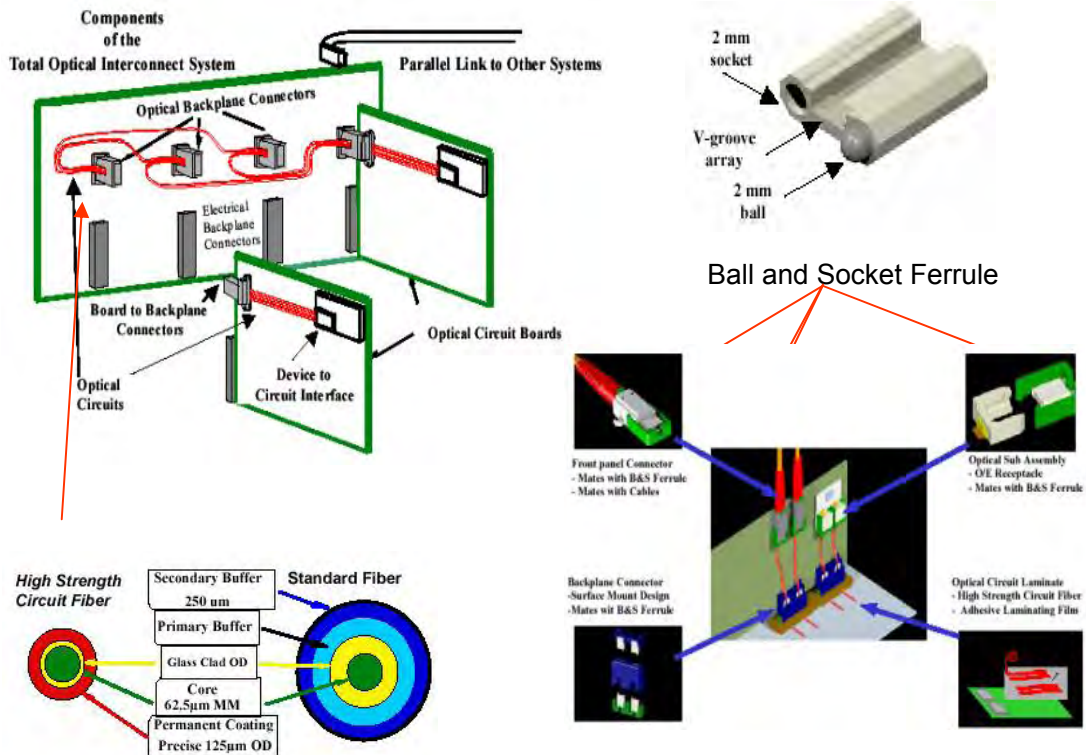


Fig. I-6-5 Optical backplane developed by 3M [3]

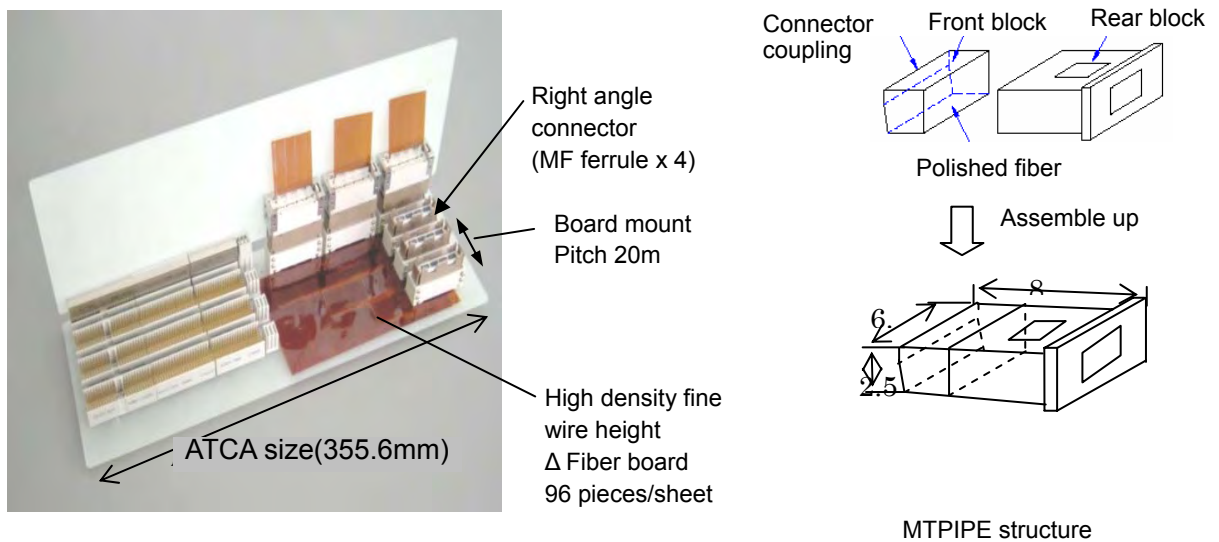


Fig. I-6-5 Hyper SI optical backplane

(2) Optical backplane using a polymer optical waveguide

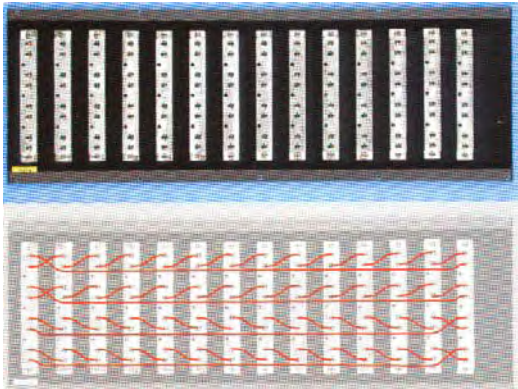
An optical backplane structure using a polymer optical waveguide was reported in the U.S. in 1998 as a result of the Polymer Optical Interconnect Technology (POINT) project [5]. In this case, a PMMA optical waveguide (50 μm square core, 0.1dB/cm@850 nm) was used with a right angle

connection section in which a board-like optical fiber polymer optical waveguide having a large radius of curvature was bent to a right angle to be connected by an optical connector. It was reported that an insertion loss of 16.3dB of the total transmission distance of 50 cm, including the two right angle connections, was realized. 3 Gb/s operation with a 20 cm wave path was confirmed, and there has been no report yet that an optical backplane structure has been applied to specific equipment.

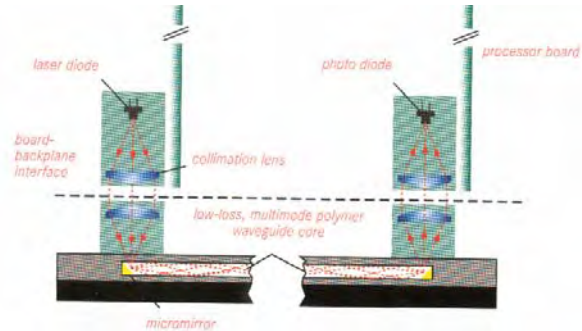
DaimlerChrysler has reportedly used a low loss polymer waveguide (0.04dB/cm@840 nm) to develop the optical backplane shown in Fig. I-6-6 for an aircraft computer. The core of the polymer optical waveguide is as large as 200 x 250 μm, and it uses a micro mirror with a 45° optical pass that is bent at a right angle to connect perpendicular to the board connector (it has a built-in optical transceiver). Further, in order to increase optical coupling effectiveness, a lens is used for each optical backplane and board connector. The loss between the optical transceivers is assumed to be 14dB, and a transmission speed of 2.5 Gb/s/ch has been realized.



Optical backplane mounted in 19-inch rack



Optical backplane unit (up)
Bus connection explanation (down)
14 slots



Right angle coupling of optical backplane and board
(45° mirror and lens are used)

Fig. I-6-6 Example [6] of optical backplane using a polymer waveguide

(3) Optical backplane using optical bus sheet

An optical backplane using a planer optical waveguide (slab type waveguide) called an optical sheet is being developed by Fuji Xerox, Aica Kogyo Co., Ltd. and Honda Communication Industries. Utilizing features where an optical bus sheet with a planer optical waveguide having a polymer (poly olefin) inner spread optical signals to propagate, it is the optical backplane structure characterized by connection with an optical bus of N:N. An architecture where an optical signal is transmitted from the input edge face which cut to a 45° angle perpendicular to the sheet plane, after a 90° optical path conversion, is made to propagate through the slab type optical waveguide and turn back and spread optical signals in a mixing area, then propagate to many output edges, convert the optical path by 90° at the mirror plane cut to a 45° angle and received from the sheet plane. Light input and output to the optical bus sheet is implemented by a photo transceiver which was included in the board connector in the same way as the optical backplane of DaimlerChrysler. The so-called "optical bus" is realized in this way, and while it still has a slow optical transmission speed, it has been sufficiently commercialized for application to a SCSI bus (160 Mb/s x 6 bit). The insertion loss of the optical sheet is a maximum 12.5dB (in the case of 8 ch branches), the board connector has a built-in transceiver with a lens, and as the optical input and output edge sections are as large as 1 mm square, connection with a waveguide is relatively easy and connection effectiveness is as high as 1.5dB. Light is spread with this structure, and loss is larger than that with a 1:1 connection, as there seems to be many issues. However, when transmission distance is limited to around 2.5 Gb/s, the potential has been verified through simulation. Also, an optical bus connection can be made with a simple structure, and as an inexpensive optical backplane can be structured various applications are expected to emerge.

6-3 Technical issues toward ultrafast optical communication systems

The current optical backplane speed is between the Gb/s and 10 Gb/s level. Together with IT broadband network progress, a transmission speed of 40 Gb/s is now required, and a speed exceeding 100 Gb/s will be needed in the future. There is no problem regarding high speed transmission for a polymer waveguide of a optical backplane or fiber optics. As the transmission distance is around 1 m, no concern for distributed loss over a long distance is needed up to several hundred Gb/s.

In parallel with increased transmission speed, as the light receiving/emitting area of a laser diode (LD) and photo diode (PD) for optical-electrical conversion devices is being shrinking and minimization of the core section is also required for the optical waveguide of the optical backplane, there still is a transmittable range with both multimode and single mode. Also, optical to electrical conversion efficiency of PD in the high frequency region decreases, and loss minimization is required for the entire transmission system, including backplane optical connectors. Regarding the insertion loss of the entire transmission group, 20dB or so at Gb/s is acceptable, but less than 15dB or so is required with 10 Gb/s. Therefore, it can be said that a structure using a fiber board

has an advantage as a backplane at present.

In an ultrafast optical communications system, it is effective for high speed processing to use labeling and switching with wavelengths, which is one of the optical features. In the equipment, coarse-wavelength division multiplexing (CWDM) rather than dense-wavelength division multiplexing (DWDM) is believed to be useful in view of cost performance and miniaturization. For such a wavelength multiplexing process, a single mode transmission channel will be used for the backplane.

In applying an optical backplane to optical communications systems, ease of maintenance operation is one of the issues to be resolved. In particular, cleaning is a unique problem associated with light and as it is difficult to clean the connector section of an optical backplane in equipment. For this reason, the development of a special cleaning device is needed.

Further, in order to promote dissemination of the optical backplane, standardization of optical mounted components will be effective and also contribute to cost reduction. For this purpose, standardization development for a fiber bend right angle connector for an optical backplane, an MCM connector, and a right angle optical channel conversion waveguide for AIP is underway in the ASET "Optical Mounted Components Standardization Project." In addition, a JPCA Photo Electronic Circuit Packaging Standardization Committee was established to issue standards for domestic corporations and propose international standards to IEC/TC91[7].

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Part 7 Toward Ultrafast and High Density Backplanes

7-1 Development status of high speed and high density packaging technology and deployment for ultrafast optical systems

- Development status of three-dimensional LSI chip stacking technology

Technology for high density mounting of semiconductor LSI chips using three-dimensional stacking is classified into package level stacking, chip level stacking and wafer level stacking. Regarding package level stacking, stacking technology development of a compact LDI package very close to a low-profile chip size is underway, and some products have already been commercialized. For chip level stacking, three-dimensional LSI chip stacking technology is now at the most advanced level in the world as a result of ASET efforts in NEDO's Super-high Density Electronic System Integration Project from FY1999 to FY2003. However, in terms of technology performance, basic elemental technology has just been established. Regarding basic elemental technologies, they include 10 μm diameter LSI chip Cu penetration electrode forming technology, 50 μm thickness LSI chip low-profile processing technology, back side insulation wiring technology, 20 μm pitch low-profile flip chip connecting technology, and 50 μm pitch multi-pin inspection technology, etc. (refer to Fig. I-7-1). In the area of wafer level stacking, research and development is underway in the laboratory of Professor Koyanagi at Tohoku University, and three-dimensional LSI basic technology to simply realize a parallel process architecture for image processing and image recognition is being established. Additionally, three private companies are carrying forward the development of DRAM chip three-dimensional stacking technology in a three-year theme under NEDO's Stacked Memory Chip Technology Development Project. Establishment of volume production of three-dimensional mounting technology is also expected to be realized. Regarding three-dimensional stacking technology for a logic LSI chip, current efforts are not enough sufficient and approach involving industry, academia and government will be imperative in the future.

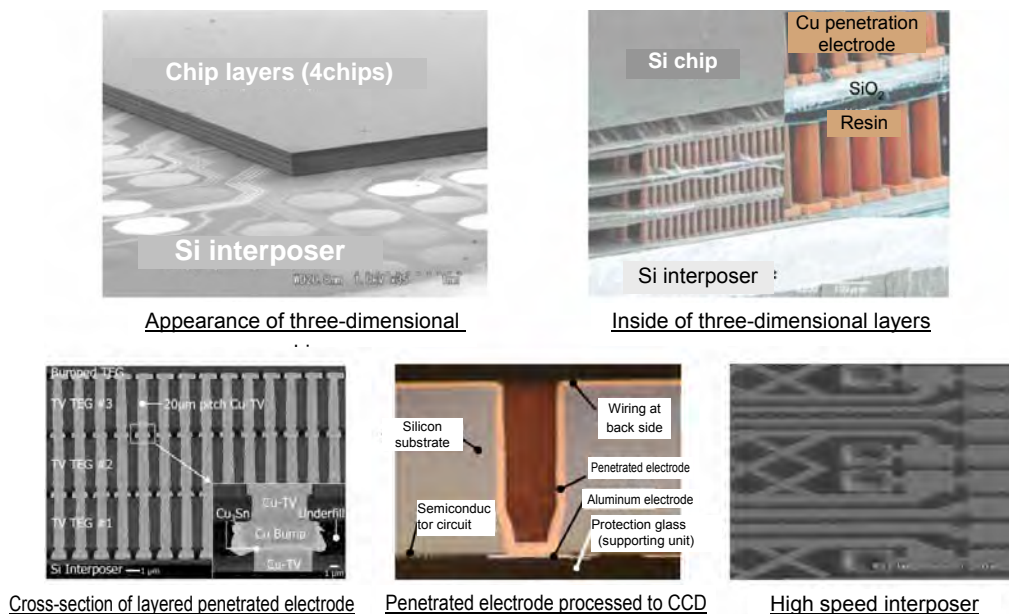


Fig. I-7-1 Major achievements in three-dimensional LSI chip stacking technology in the Super-High Density Electronic System Integration Project

- Development status of high density mounting technology supporting high speed transmission

As an example of high density mounting technology supporting high speed transmission, research and development is being pursued by a research association, aiming at applications for high density package wiring and LSI global wiring, of a fine wiring structure appropriate for high speed transmission exceeding 10 Gb/s using a low dielectric constant photosensitive polyimide insulation layer. With the cooperation of ASET, a 20 μm pitch transmission channel structure has been developed toward high speed digital signal transmission of 10 Gb/s, and a transmission experiment using 10 Gb/s high speed signals has succeeded.

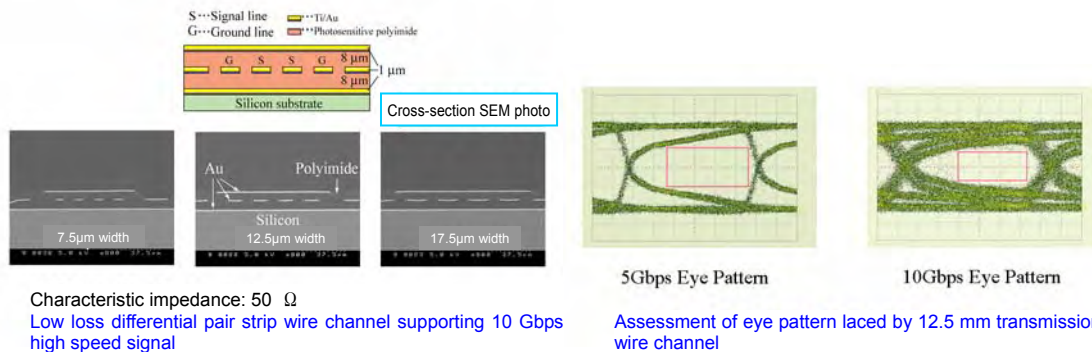


Fig. I-7-2 Trial model and transmission experiment of 20 μm pitch transmission wire channel structure

- Deployment to ultrafast optical systems

When three-dimensional LSI chip stacking mounting technology is applied to an ultrafast optical communications system, as long distance transmission of high speed electric signals of a 10 Gb/s level is limited to use for transmission in an interposer which is set up adjoining to the inside of three dimensional chip stacks. Fig. I-7-3 shows an outline of an optical-electric compound module in which the transmission range of high speed electric signals is limited to a square cm using an optical fiber for signal input and output with the outside. It may be possible to utilize such a design in a network router for a switch module.

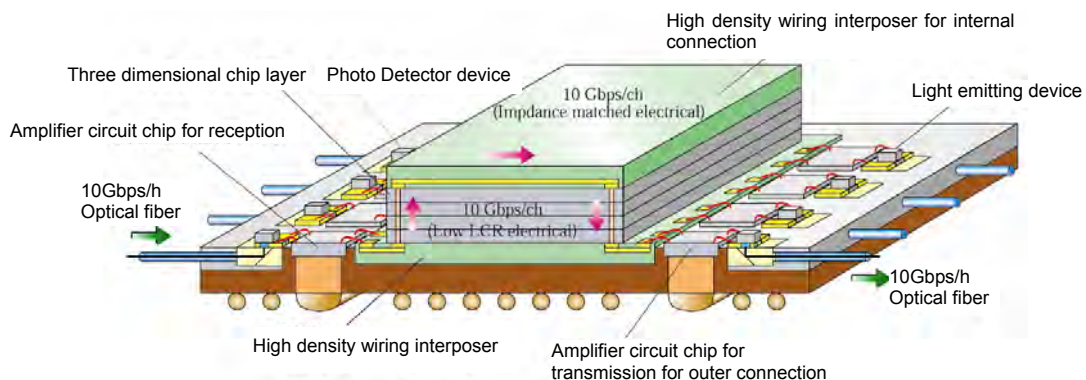


Fig. 1-7-3 Outline of optical-electric compound module using three-dimensional stacking technology

While technology development supporting a high speed of 10 Gb/s per signal line in a LSI chip and LSI package is underway, an innovative wiring technology breakthrough supporting extra-high density and ultrafast speed inside the chip and package is required in order to advance next-generation ultrafast transmission technology from 40 Gb/s to 100 Gb/s. Towards this, a fundamental reexamination of insulation materials, line channel structure, multilayer wiring, device mounting methods, etc. is imperative.

7-2 Deployment of ultrafast network technology

• Status and issues related to WDM/OTDM network device technology

With the start of digital broadcasting, diffusion of information home appliances, and dissemination and expansion of TV telephone use including mobile phones, a sharp demand increase is expected for real time high image quality transmission of motion pictures using optical fiber networks. In addition to this, the movement for high definition video by dissemination of large screen display is steadily making progress. Further, a plan to encourage around half of current subscribers (30 million) to switch to the Fiber to the Home (FTTH) program is underway. The spread of asymmetric digital subscriber line (ADSL) service, which started in the latter half of 2001, has encouraged a shift from conventional character information to image information, and the growth rate of Internet traffic has jumped 20-fold. The shift to motion picture information by diffusion of FTTH is expected to show a dramatic increase rate trend in a similar way.

Such a sharp traffic increase considers starting from a metro-network system, but in case an information volume of several Tb/s or more at network nodes is processed by only electronic technology, problems such as backplane interconnection, power consumption, and electric switches may surface. Therefore, there is concern over limits in process capability. In proportion to information processing volume, backplane high density and transmission speed are required. Along with this, countermeasures will become necessary as crosstalk, signal distortion and heat generation become noticeable. Up to now, various measures have been taken along with large capacity information processing and faster system speeds, and it has been reported that optical utilization will become necessary with 40 Gb/s or more per channel and Tb/s or more of throughput.

After 2010, ultra large capacity close to 1 Tb/s will be required as a backplane line rate and device speed of more than 100 Gb/s is utilized. An effective method for this will be OTDM. Optical wiring, conventional parallel wiring and WDM wiring have been subjected to examination, and trial models have been made. However, each of these has issues, and as a means to resolve these issues OTDM wiring is worth examining in the future. Also, as the electric crossbar switch that processes a large volume of information electrically is said to be near its performance limit, the development of an optical crossbar switch utilizing an ultrafast optical switch has to be considered. In order to mount such an optical crossbar, development of an optical buffer memory (optical RAM) to avoid collision with packets will be required at the same time.

The National Institute of Advanced Industrial Science and Technology (AIST) and the Femtosecond Technology Association (FESTA) have been developing various devices required for OTDM technology, as shown in Table I-7-1, during NEDO's "Femtosecond Technology" project. This project will end in FY2004, and the transition optical switch and photonic crystal technology developed by AIST and FESTA will be further deepened and fused, and advanced new mountable devices in areas beyond the limits of electronics technology are going to be developed. In particular, research and development on an ultra low energy motion switch and an ultra low light bi-stable logic device with an optical buffer memory that utilizes it will be carried out. In the future, it is expected that such devices can be used for OTDM wiring and an optical crossbar switch.

Table I-7-1 Devices developed in the Femtosecond Technology project

	Device name	Function	Operation principle
Light source	Mode-locked laser ¹⁾	Generate high repeated short pulse row	Collision mode locking Injection mode locking
Dispersion compensation device	Pulse compression device ²⁾	Control wave form by pulse compression	mode distribution in coupled waveguide
	Dispersion compensation device ³⁾	Compensation of chromatic dispersion	Temperature control of charped fiber Bragg grating
Time switch	Inter subband transition optical switch ^{4, 5)}	DEMUX Ultrafast gate	Absorption relaxation between sub-bands of quantum well
	Symmetric Mach-Zehnder interferometer ⁶⁾	DEMUX Logic operation	Compensation for slow component of semiconductor amplifier by SMZ interferometer
	Multi-layer 2 photon resonance switch ⁷⁾	Ultrafast gate	Light confinement and 2 photons absorption
Time – space conversion switch	Femtosecond Large Area Parallel Processor ⁸⁾	Serial/parallel bundle conversion of high speed signal	Absorption saturation of organic material
Wavelength switch	Wavelength conversion switch ⁹⁾	Wavelength conversion of ultrafast signal at full band	four wave mixing at quantum dot optical amplifier

Source: "Future Vision of Optical Industries" (Light Association 2004)

Research and development of an ultrafast optical switch utilizing inter sub-band transition (ISBT) has been pursued by AIST and FESTA independently using different compound systems. The II-IV AIST group realized an ultrafast response time at 1.55r μm ⁴⁾, while III-V low energy operation

and DEMUX operation of a pulse row equivalent to 1 Tb/s was verified by FESTA. In order to make ISBT optical switch mounting level, the switching energy has to drop to 100 fJ or so. Research and development can be accelerated by shifting the research to a parallel effort on response time characteristics, switching energy characteristics, and the two types of ISBT switches mentioned above, each of which has features of a semiconductor superlattice structure. Also, in this project, many accomplishments regarding photonic crystal technology have been obtained, such as verification of the principle of Photonic Crystal-Symmetric Mach Zehnder (PC-SMZ) with a world record low propagation loss photonic crystal waveguide^{10, 11}). Photonic crystal makes strong light confinement possible. By using it, low energy operation of an optical switch by reinforcing of optical nonlinearity and operation of RAM which can read and write at will leading to buffer memory can be expected. Further research on important elemental technology is required.

On the other hand, by accelerating the dissemination of FTTH, communication traffic in metro network systems will sharply increase and the large capacity requirements of communication networking are going to be handled by dense wavelength division multiplexing. By introducing OTDM technology to increase transmission capacity per channel, a necessary reduction in wavelength as well as wavelength management will subsequently become easier.

With ultrafast transmission systems utilizing OTDM technology, optical 3R (Re-shaping, Re-generating, Re-timing) technology will be imperative and at AIST, optical 3R technology is being developed. Research on optical clock extraction technology has been completed, and development of all optical 3R technology for 40 Gb/s using clock extraction technology has also been completed. At present, development of all optical 3R technology for 160 Gb/s utilizing ISBT ultrafast optical switch is underway.

A proposal for the structure of a 160 Gb/s-OTDM/WDM time slot type network system node incorporating the above technology is presented in Fig. I-7-4.

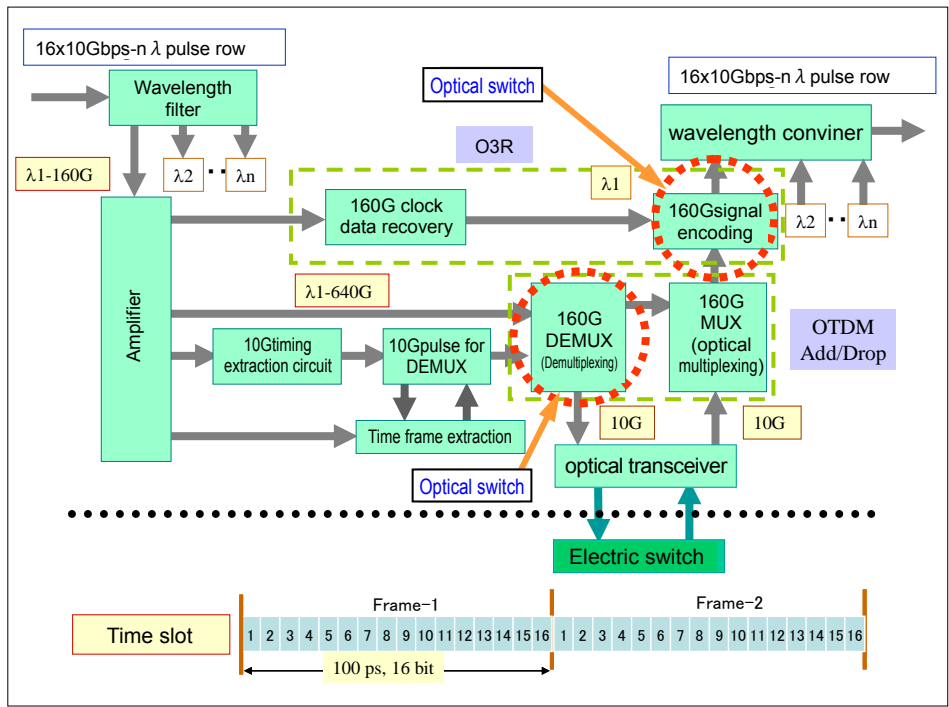


Fig. I-7-4 160 Gb/s-OTDM/WDM node example

When the above extra-large capacity optical signal processing technology based on OTDM technology matures, a relatively short distance ultrafast connection field is expected to be used with backplanes, storage area networks (SAN), local area networks (LAN) and optical interconnection between CPUs or between PFLOPS computers before public communication networks provide this service. Fig. I-7-5 shows an outline of a backplane incorporating OTDM technology.

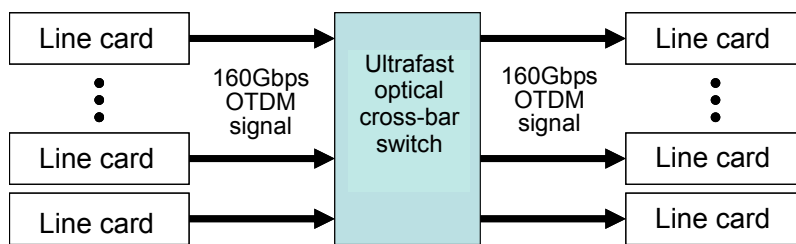


Fig. 1-7-5 Introduction of 160 Gb/s-OTDM to backplane

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Part 8 Summary

This report summarized the needs for optical backplane technology and present and future issues related to optical devices LSI circuits as well as optical packaging techniques to realize optical backplane technology. The following is the conclusion given in a discussion by the SWG, and is described by separating technologies to be urgently completed by 2010 from future technologies to be completed between 2010 and 2015.

• Technical Issues to be addressed by 2010

The structure of the server/router to be put into practical use will utilize the current architecture, having an electrical switch as a core. For the backplane in such server/router, improvement is required in transmission characteristics (speed x distance), transmission density (speed/volume), and power consumption (speed/electric power), and realization of 100 Gb/s x 1 m class performance is expected by incorporating optical technology. On the other hand, in the area of transmission systems for server/router input/output, systems with 160 Gb/s per channel will be introduced.

Therefore, from this viewpoint, backplane transmission technology of 100 Gb/s or above is required between line cards and switch cards. The following technology is required for such systems.

- (1) The most important points to be considered regarding optical backplane technology are size and cost. The current method where a 10 Gb/s line rate signal is time-demultiplexed into four 2.5 Gb/s for backplane transmission will be followed in the future. Similarly, even when the line rate becomes 160 Gb/s or more, parallel signal transmission methods with more mature 10 Gb/s or 40 Gb/s or so will be attempted for maximum utilization by considering the power consumption and cost of optical and electrical devices,.
- (2) A bottleneck for the transmission rate of an optical backplane is, like in a backplane using electrical signals and an electrical switch, optical interconnection technology, including OE/EO conversion. While in view of the current restriction for power consumption and packaging density, the upper limit will be 10 Gb/s or so, commercial viability of 40 Gb/s will not be far off when ultrafast and low power consumption vertical cavity surface emitting laser (VCSEL) array and 45-nm CMOS LSI technology are put into practice. From the fact that an OE/EO conversion section including an optical device has been already incorporated (optical I/O on BGA substrate) in an electrical switch LSI package, the viability of a low power consumption OE/EO conversion section has been demonstrated and in future technology, reduction of pin density, power consumption and cost will be achieved.
- (3) Regarding optical board technology as a core packaging technology for an optical backplane, optical technology ranging from the backplane to wiring inside the card using photonic circuit technology, including fibers and planer optical waveguides, is just one step away for practical

application as shown in the research and development by the Opto-electronic System Integration Collaborative Research Team at the National Institute of Advanced Industrial Science and Technology.

• **Technical issues to be addressed during 2010 to 2015**

For practical application after 2010, two technical directions are expected. The first is conventional architecture using an electrical switch that has been speeded up, and the second is to convert the switch so that it has an optical function. Each method may involve the following technical issues.

- (4) In order to realize further high performance by combining an architecture using electrical switch and optical backplane transmission technology with 100 Gb/s or more, innovative technologies are required in compact, super low power consumption optical devices, external modulation, and extra-high density integration and packaging techniques. In order to realize miniaturization and low cost, optical I/O in LSI to integrate opto-electric devices by applying Si photonics technology, further to integrate monolithically optical I/O on LSI, and three-dimensional stacking technology to implement those elements with extra-high density will become critical technologies.
- (5) In architecture using an optical switch, if a packet switch is realized by optical time division multiplexing (OTDM) technology, OE/EO conversion for electrical switching can be eliminated and a bottleneck of the above I/O LSI circuit can be overcome. A promising means for substantial performance improvement will thus be found in future. However, for realization, optical memory and an optical switch having a switching speed at the nsec level is essential. While recent progress in the ultrafast switch field has been noticeable, as seen in the results of the FESTA project, further effort is necessary to realize new functions for optical memory. On the other hand, while extra-high performance can be achieved with architecture using an optical switch with a msec level of switching speed through current micro electro mechanical systems (MEMS) technology, this may require special consideration due to the necessity of rebuilding router architecture from the bottom up. In order to realize extra-high capacity systems in the future, research on both optical devices and router architecture are prerequisite.

As mentioned above, miniaturization, low power consumption and low cost are essential for an optical backplane. The application of ultrafast optical devices may be difficult judging from the present maturity of technology that is in contrast with long distance transmission systems. However, I/O LSI circuit technology needs the most advanced technology. Internal interfaces such as the system packet interface (SPI) and Serdes Framer Interface (SFI) are leading development of optical electronics circuit technology, as is seen in the Optical Internetworking Forum (OIF), etc. In this sense, optical backplane technology will have an impact on the development of the optical communications equipment family, and extra-high speed and ultralarge capacity is expected to be

achieved in the future through the application of the most advanced optical devices, LSI process/circuit technology and high-density integration and packaging technology.

II. LAN/SAN

- Digital Content Group Network -

II. LAN/SAN

- Digital Content Group Network -

Part 1 Introduction

Local area network and storage area network (LAN/SAN) systems have a strong relationship with storage technology and continue to expand synergistically along with expansion in communications and storage capacity. Storage for home use has already been commercialized up to several hundred GB and is moving to the terabyte stage. At the same time, communication is becoming to be such that it utilizes ever increasing storage capacity required by video on demand and server type broadcasting. In this section, digital LAN/SAN systems for such content, which is expected to continue growing is considered.

Digital content for entertainment such as games, animation, movies, etc. is subject to strengthening the creation of new industry and international competitiveness as core industries. On the other hand, in view of communications technology, they consist of LAN technology which converts digital content in the production area into networked environment and SAN technology which distributes data. Digital audio visual (AV) content focusing on entertainment requires different information characteristics compared with conventional data as it appeals to sensitivity and a realistic sensation. At the same time, the requirement for information quality is severe in terms of equality and simultaneity in the broadcast industry, and information quality itself has an aspect of direct impact on our society. Along with this, the demand for quality is high in the communications area.

In this way, communications for digital AV content including broadcasting requires upgrading of communication quality compared with conventional communications. For example, from the position of content users, production without concern for delay due to compression and decompression, and appreciation of imaging entertainment are required. In order to satisfy them, communication methods such as data compression and extraction which cause deterioration of content should be avoided and an environment in which content is transmitted and used without manipulation is desirable. From such a point of view, realization of a system to transmit without compression processes and utilize digital content is expected. The information volume of content itself is tending to increase due to high definition TV and high level digital processing. An ultrafast time multiplexing system is highly expected as a communication technology for such an environment. As a time multiplexing system for a single frequency does not divide content by wave channel, etc., deterioration of the content can be avoided by a frame process at the time of reception, and development of this field will be stimulated if sufficient capacity able to be responsive to non-compression content can be realized.

Taking next-generation high definition TV and digital cinema as examples concerning the current status and future, the impact on technology and society brought by ultrafast optical communications technology was examined. Both are fields in which Japan is promoting development ahead of the world and attracting keen international attention. The prospect that progress can be made by utilizing ultrafast optical communication in fields where Japan has competitive strength will be verified.

Part 2 LAN/SAN Systems for Broadcasting

2-1 Introduction

Terrestrial digital broadcasting started in December 2003, and an era of full-scale digital multichannels arrived. Progress in the diversification of broadcasting services such as data broadcasting got underway by means of digitalization together with multimedia and multichannels. In order to respond to such a variety of services, storage and networks within broadcast stations are being required to provide a one-source multi-access environment where program content can be utilized efficiently.

Also, the current broadcast station system consists of elements such as news coverage, compilation, delivery and archives based on the work flow based on a video tape recorder (VTR) used as the recording media for program content. For efficient compilation and delivery, environment build-up is desirable where these are linked together by networking and picked up freely at any time for quick utilization.

On the other hand, within a broadcast station the information volume of program content in the market continues to increase due to high quality imaging such as high-vision. In order to realize a broadcast station system where one-source multi-access and wideband video can be handled at any time and in any place without stress, ultrafast and large capacity networks are essential.

Here, the current status of storage and network systems as elements of LAN/SAN technology for broadcasting and system requirements within a broadcast station toward realization of a future desirable environment will be outlined.

2-2 Status of technology and trend

2-2-1 Broadcast station systems

During broadcast station program production to delivery, and in archives where programs are kept, productivity improvement, reduction of operation cost, labor saving, and stable system operation are needed. In order to satisfy these requirements, it is necessary to fully review the work flow and then upgrade the network system of the broadcast station. Within the broadcast station, in order to meet a variety of broadcast services for clients to search and immediately obtain and use through the network by adding data (metadata) to describe the data to video and sound content and establish a filing system and storage system, a one-source multi-access environment is required.

Fig. II-2-1 shows the current broadcast station outlined by function. An example of a system within the broadcast station which satisfies requirements such as a one-source multi-access environment is shown in the figure. The broadcast system consists of multiple basic cells that are linked through a high speed network.

One of the basic broadcast cells is for news compilation. The metadata in which motion

picture, sound content and news materials are described is filed and stored in a content server. The content is compiled in a one-source multi-access environment and input to the program server. The content in the program server is input to a delivery cache according to an organization protocol and then broadcasted. The content to be stored is retained in the archives.

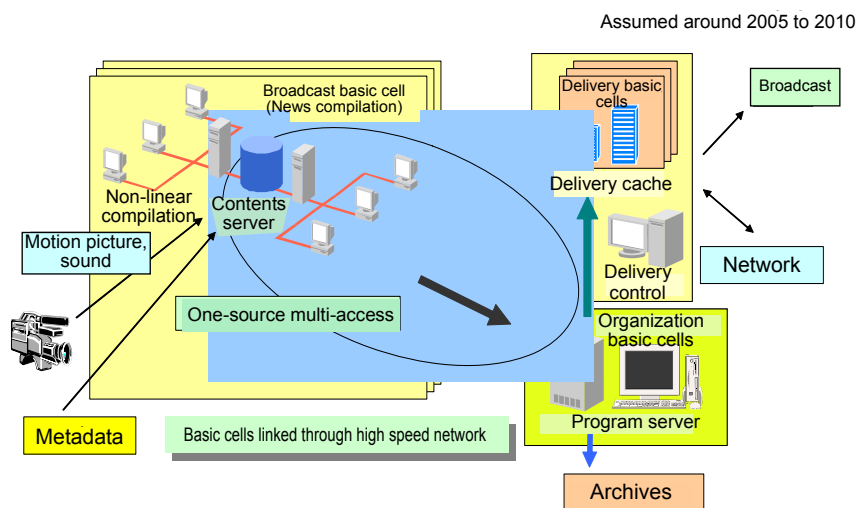


Fig. II-2-1 Example of a future broadcast station system

2-2-1-1 Storage capacity and transfer rate

In a news compilation system which makes up a production system, for example, a week's worth of high vision program materials for 24 hours a day must be stored. In consideration of future video picture compression technology progress, assuming a system where the material transfer rate is 60 Mb/s and 30 compilers can access at the same time to compile needed program material, memory capacity will be 45 TB with a transfer rate of 2 Gb/s.

In a server type broadcast Internet delivery system which makes up the delivery system, it is envisioned to accumulate a month's worth of three channel HDTV content with a confirmed broadcast quality transfer rate of 25 Mb/s. When a day's worth of content accumulated in the server type broadcast receiver is played back, assuming that use of 1000 accesses at the same time is allowed, targeting services after a second day with less play back demand, the memory capacity will be 25 TB with a transfer rate of 25 Gb/s.

- Archive systems

Japan Broadcasting Corporation (NHK) started to operate archives in February 2003. Fig. II-2-2 shows an outline of the archives of NHK. The archives consist of the main function of searching and delivering of accumulated content and an expansion function to publicize programs.

The software kept in NHK archives was 800,000 at the beginning, and an annual increase of

60,000 is expected. The area shown with an oval shape at the center of the figure is the storage area. Initially, mainly VTR cassettes are stored, and it is imperative to introduce a high resolution content server in the future. The content can be searched and previewed from standard personal computers through an Internet Protocol (IP) network. The content for a search is encoded by MPEG-4 and accumulated. It is accessible by 300 users at the same time. HDTV content which has been archived can be delivered to the broadcast center through a 4 Gb/s optical IP network at 60 Mb/s. Some of the programs in the archives are open to the public. The programs in the archives can be watched through an IP network. One hundred users can access high vision programs at 20 Mb/s and standard programs at 6 Mb/s in high resolution. Assuming 30 minutes to accumulate one unit of content, the accumulation time will be 30,000 hours a year. Assuming the transfer rate is 60 Mb/s, the accumulation time will be 1 PB a year and will be 30 PB in 2018, which is the storage limit for VTR cassettes. Here, the combined use of a hard disk drive (HDD) as an accumulator, which makes high speed access possible, and removable media which can be kept in a stable condition for a long time, is assumed.

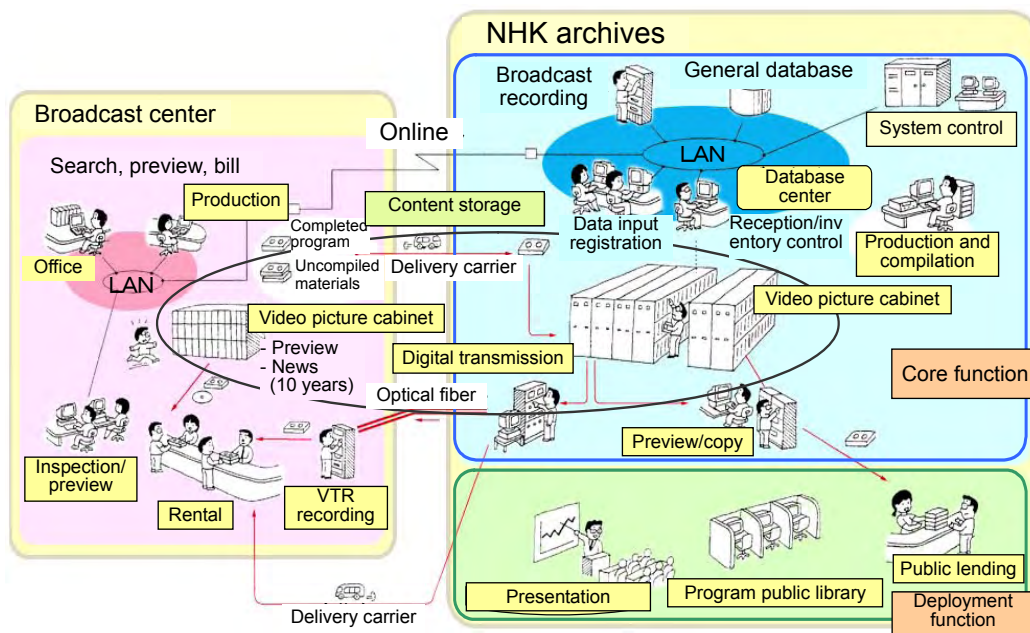


Fig. II-2-2 Outline of NHK archives

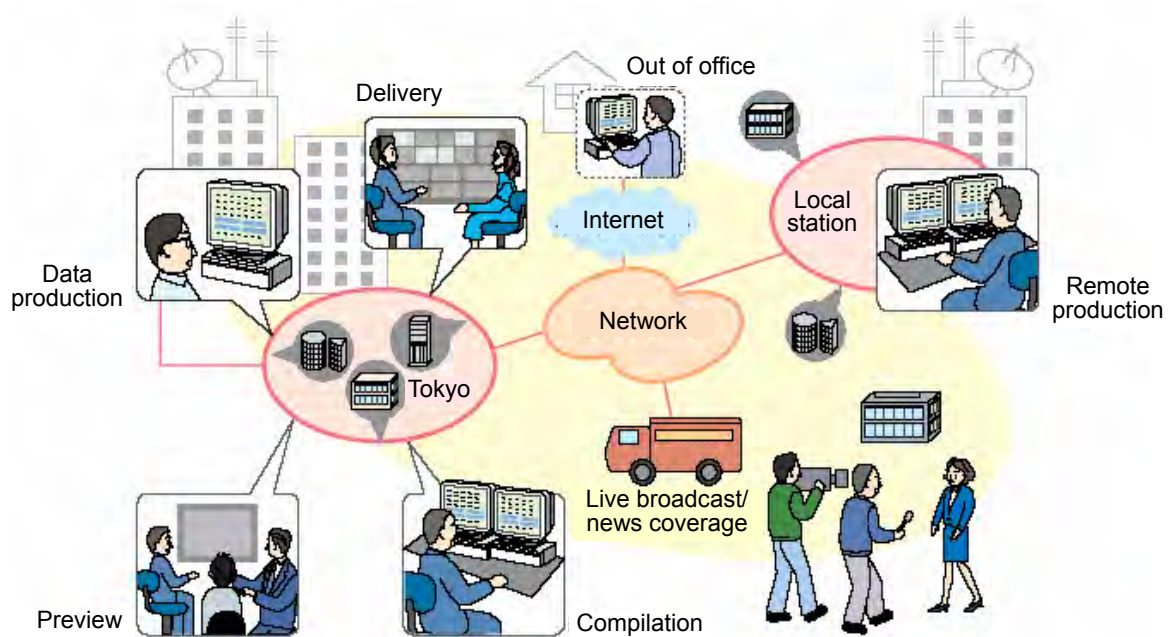


Fig. II-2-3 Image of networked broadcast station

2-2-1-2 Network systems

In the past, broadcast station systems were built mainly for VTR, and a broadcast system (Fig. II-2-3) actively utilizing a network is now being studied and experiments regarding use are being introduced. As shown in Fig. II-2-3, the major advantages expected by introducing such a network to a broadcast station and integrating content and broadcast equipment, and issues toward their realization were summarized.

Advantages

- (1) Convenience of use from anywhere by sharing content and equipment
- (2) Organize broadcast services and flexibility of delivery
- (3) Parallel operation or unification from conventional phased operation (Offline compilation to online compilation)
- (4) Efficient operation linked with related information such as contents rights information
- (5) Integrated production of multimedia content for data broadcast or Internet services

Issues

- (1) Securing equipment interoperability or between methods
- (2) Expandable architecture considering technology progress
- (3) Securing of system reliability
- (4) Smooth shift from current system
- (5) Securing security, etc.

Along with the realization of the above advantages, an object oriented methodology will be applied as a means to resolve some of the known issues. The content and equipment for using it will be treated as the object in the methodology, and studies on methods to realize various broadcasting station functions are already underway.

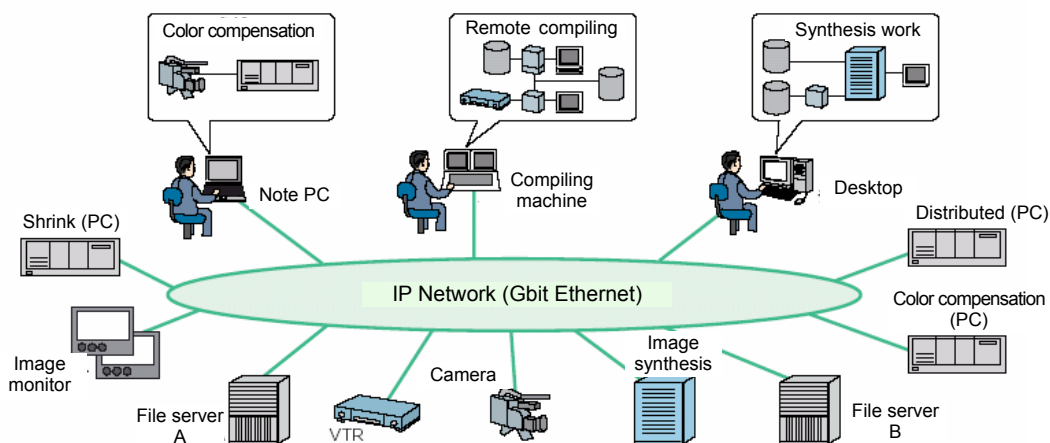


Fig. II-2-4 Video compilation system using a network

2-2-1-3 High resolution improvement of broadcast group content

Broadcast group content and network speed are being improved through large storage capacity increases for high resolution. In terrestrial digital broadcasting, many high vision programs are on the air. Around five times of the data volume is required compared with conventional standard television. Further, an NHK study on a super-high definition motion picture system exceeding 70 mm film and super high vision is underway. Table 1 shows the present specifications and Fig. II-2-5 gives a system outline. The number of pixels is four times that of HDTV, and the angle of field of 100° is three times that of HDTV. The super-high definition motion picture scan transfer rate is about 40 Gb/s, which is 32 times that of HDTV. In the future, assuming compression of a super-high definition motion picture from 1 Gb/s to 2 Gb/s or so to record 100 hours, a storage system can be realized in one rack space using a HDD with recording capacity of 1 TB to 2 TB and a surface recording density of 500 G to 1 Tbit/in².

Image signal	Number of pixels	Aspect ratio	Frame frequency	Required transmission rate
Standard TV	720 x 480	4:3	59.94 Hz 2:1 interlace	270 Mbps
High vision	1920 x 1080	16:9	60.00,59.94 Hz 2:1 interlace	Around 1.5 Gbps
Super high vision (G skew pixels displacement)	7680 x 4320	16:9	60 Hz Progressive	<u>Around 24 Gbps</u>
Super high vision (full)	7680 x 4320	16:9	60 Hz Progressive	<u>Around 48 Gbps</u>

Fig. II-2-5 Required super high vision video transmission rate

2-3 Expected communications technology

Current issues and technology trends, and examples of system requirements for expected communications technology, are discussed below.

2-3-1 Production and delivery systems and server requirements for archives

Fig. II-2-6 shows the storage capacity in a broadcast system by application field, and the relationship with data transmission speed is assumed up to 2010. It is estimated that a storage capacity of several TB to 100 TB with a transfer rate of 1 Gb/s to 100 Gb/s for production and delivery system will be required. Also, for the archive system, storage capacity will be several 10 PB to several 100 PB, and the transfer rate will be 10 Gb/s or so. Fig. II-2-7 shows requirements for a content server used for production and delivery, and Fig. II-2-8 shows requirements for broadcasting archives.

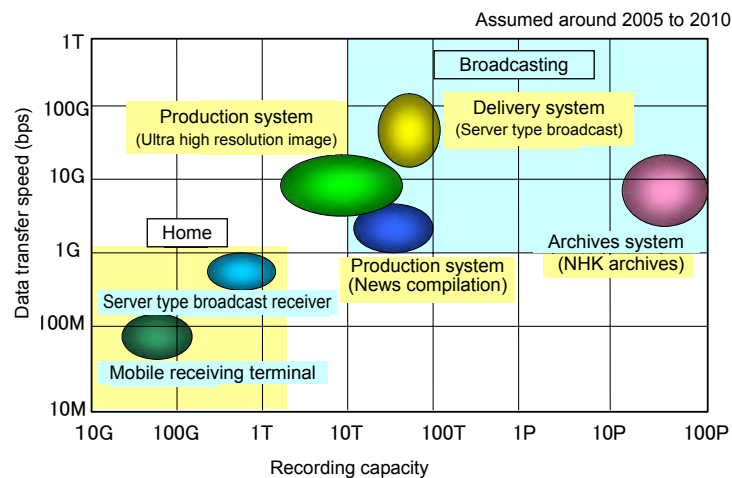


Fig. II-2-6 Future broadcast system data transfer speed and recording capacity

- Realize efficient program production and delivery by ultrafast transfer
- Introduction of ultrahigh capacity HDD and 100 Gbps network

Application	Specifications ¹⁾
Program compilation	<ul style="list-style-type: none"> ▪ HDTV material (300Mbps) 100 hours accumulation (Accumulation capacity : 50 TB) ▪ Transfer 1 hour program in 10 sec.
News compilation	<ul style="list-style-type: none"> ▪ HDTV material (100 Mbps) 24 hours a day, accumulation a week(Accumulation capacity : 75 TB) ▪ Supports 1000 accesses at the same time
Server type broadcast	<ul style="list-style-type: none"> ▪ HDTV material (24 Mbps) Accumulate 3 channels for a month (Accumulation capacity : 100 TB) ▪ Supports 4000 accesses at the same time

1) Storage capacity was estimated considering back up and system margin.
Transfer time and number of accesses at the same time was estimated by transfer bit rate of network only.

Fig. II-2-7 Requirements for production and delivery content server

- Realize efficient program utilization by ultrafast transfer
- Introduction of ultrahigh capacity HDD and 100 Gbps network

Application	Specifications ¹⁾
Search, utilization	<ul style="list-style-type: none"> ▪ HDTV materials (60 Mbps²⁾ Accumulate 30,000 hours over a year (Storage capacity : 2PB) ▪ Supports real time transfer up to 1600 accesses at the same time When occupied transfer 30 min. program in 1 sec.

1) Accumulation capacity was estimated considering system margin.
Transfer time and number of access at the same time was estimated by transfer bit rate of network only.

2) Set up considering future progress of compression technology

Fig. II-2-8 Example of requirements for archives

2-3-2 Requirements for network performance in production and delivery systems

Fig. II-2-9 shows the technology development trend for networks and a future development forecast. From the requirements in the previous chapter, realization of 100 G Ethernet as a transfer speed is expected to occur. In addition to the viewpoint of storage, the following are considered as requirements for a typical broadcast system.

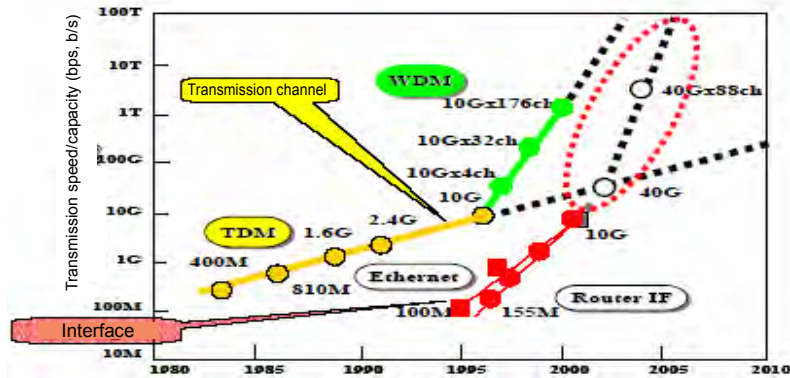


Fig. II-2-9 Technology development trend for networks

- Transmission within a broadcast station
 - Requires exchange capacity of 500 x 500 between studio and compilation office
 - Thirty units of content resources of high vision resolution in each studio and compilation office
 - Program content transmission must be at least real time (programs can be watched in real time)
 - Requires at least one-tenth of the real time for the program content copy
 - Requires 20 Tb/s or more as the total capacity
- Transmission between broadcast stations
 - Large capacity is required as control between stations is difficult compared with band securement (quality of service: QoS) of one switch step within a broadcast station
 - As QoS control (shaping) of ultrafast signals such as super high vision becomes loaded, ultrafast operation using time division multiplexing (TDM) is required.
 - Broadcast content is rarely split and no intricate elements will change the routes.

2-3-3 Summary

Regarding LAN/SAN technology for broadcasting, an outline of the status of storage and networks and requirements of the system within a broadcast station for around the year 2010 were reviewed. In a broadcast application, considering efficient compilation and delivery operation along with high resolution of content programs, at least 100 Gb/s of Ethernet is required. Further, taking super high vision content and conditions such as reduction of copying operation time in compilation operation into account, realization of an

even faster ultrafast network is expected. From real time and QoS control, which are typical conditions in broadcasting, rather than the speed increase approach of wavelength division multiplexing (WDM), which requires shaping at a parallel serial conversion buffer, faster operation using TDM is considered to be desirable.

Part 3 LAN/SAN in Digital Cinema

3-1 Introduction

In 2002, "Star Wars Episode II: Attack of the Clones," which was shot completely in the digital format, was released to the public. This innovative process that does not use film represents a dramatic technological innovation in the movie industry and has attracted a great deal of attention.

By digitalizing everything from shooting, compiling to delivery, everyone involved in movie production, cinema operators and viewers will enjoy benefits. For example, digitalization of the shooting process allows a smooth synthesis of live action with computer graphics and results in substantial efficiency improvement during compilation. By using large capacity hard disk systems, efficiency improvement and cost reduction at shooting locations is possible for long continuous shooting without film changes. Also, by realizing digital delivery of movie content, in addition to a reduction in film printing and transportation cost, it is expected that it will become possible to show programs flexibly and show popular movies selectively. Further, due to the dissemination of broadband, full-scale home theater at home may be realized.

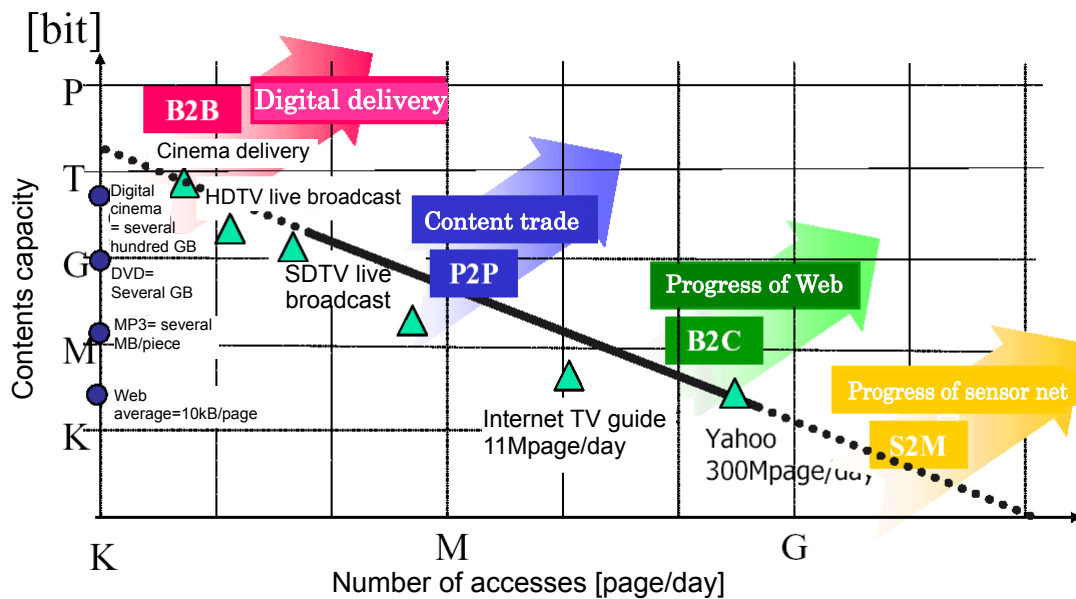


Fig. II-3-1 Trend of content distribution using IP networks

Dissemination of digital cinema delivery will have a large impact on the communications industry. Fig. II-3-1 shows the trend of content distribution using IP networks. While the access number for digital cinema delivery is small, a very large amount of data has to be transferred compared with Web site browsing, which is the mainstream of current content

distribution and peer to peer file exchange. Further, depending on the case, there are needs to transmit contents by streaming, and it may be necessary to branch out large capacity connections end to end. In this way, digital cinema is content with a new traffic form, and it is expected that new demand for IP network systems will be generated. Also, services such as digital cinema may be provided and a ripple effect to create new markets is expected. This section will cover an effort related to digital cinema at the Network Innovation Laboratories of Nippon Telegraph and Telephone Corporation (NTT) and comment on current technology flow around digital cinema distribution.

3-2 Status of current technology and technology trend

- Digital cinema specifications, production sites

In April 2003, the Digital Cinema Initiative (DCI), a group made up of seven large Hollywood studios, initiated a digital cinema format called 4K. The screen size is 8 million pixels with 4000 pixels horizontal by 2000 pixels vertical, and the number of frames is the same as film at 24 frames per second, and color display is RGB 10 bit. Regarding screen size, digital cinema is equal to four times that of HDTV at 2 million pixels with 2000 pixels horizontal by 1000 pixels vertical. In order to circulate digitalized movie data into a network as is, bandwidth of 6 Gb/s or more is required and this is not practical. Thus, in order to do so, motion picture data is compressed on the sender side and the receiving party has to decompress it so that the required channel bandwidth can be under control.

In digital cinema, data compression by JPEG2000 is becoming the mainstream. This method allows lossless reversible compression different from conventional JPEG. Also, as further compressed data can internally be extracted, any resolution according to need can be selected. With this compression, the data rate will be 1/10 to 1/15, and digital cinema can be delivered in a channel bandwidth of several hundred Mb/s.

- Delivery method

At present, movie delivery is realized by mailing the 35 mm film that is used. When digital cinema becomes prevalent, storage media of content may be converted from film to hard disk and digital versatile disk (DVD), etc. By achieving only this there is much merit of easy delivery as the media size becomes smaller physically. However, in order to fully utilize the advantages of content being digitalized, delivery through networks is desirable.

Fig. II-3-2 shows digital cinema delivery pattern diagrams for systems envisioned in the future. The delivery flow of produced digital cinema content to movie theaters according to this figure is as follows.

Digital cinema content produced by movie production companies is compressed by JPEG2000 and transferred and stored in digital archives through a network. On the other hand, a control center situated at each movie theater requests the digital archives to transfer

content. Given security of the communication network, it can be assumed that delivery will be implemented by an exclusive line or virtual private network (VPN). The control center will deliver the content to the screen according to the program sequence through a LAN system.

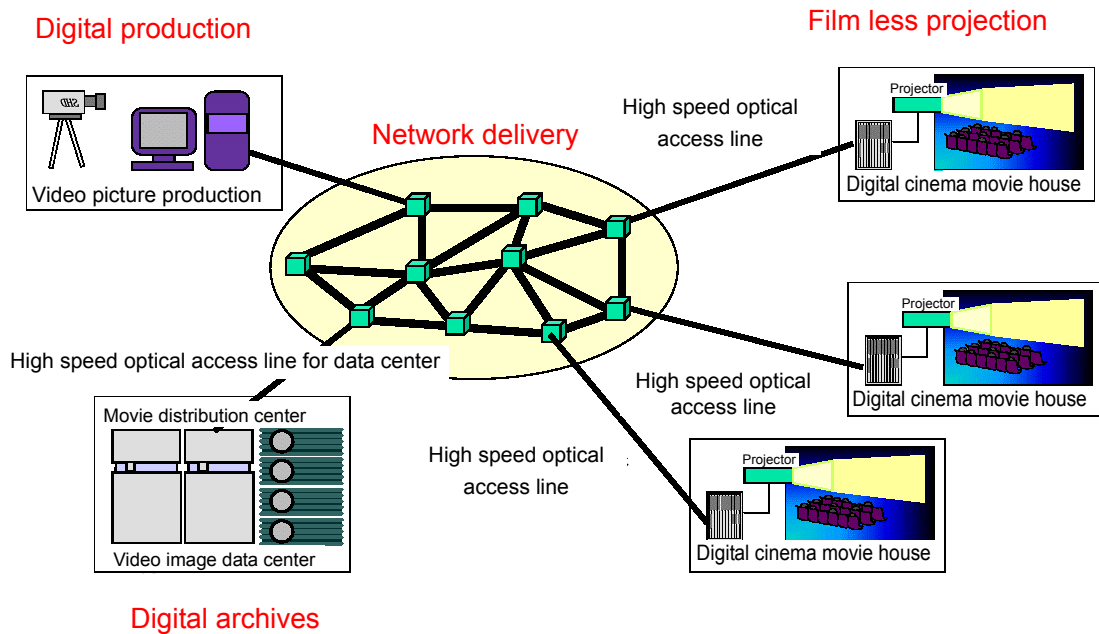
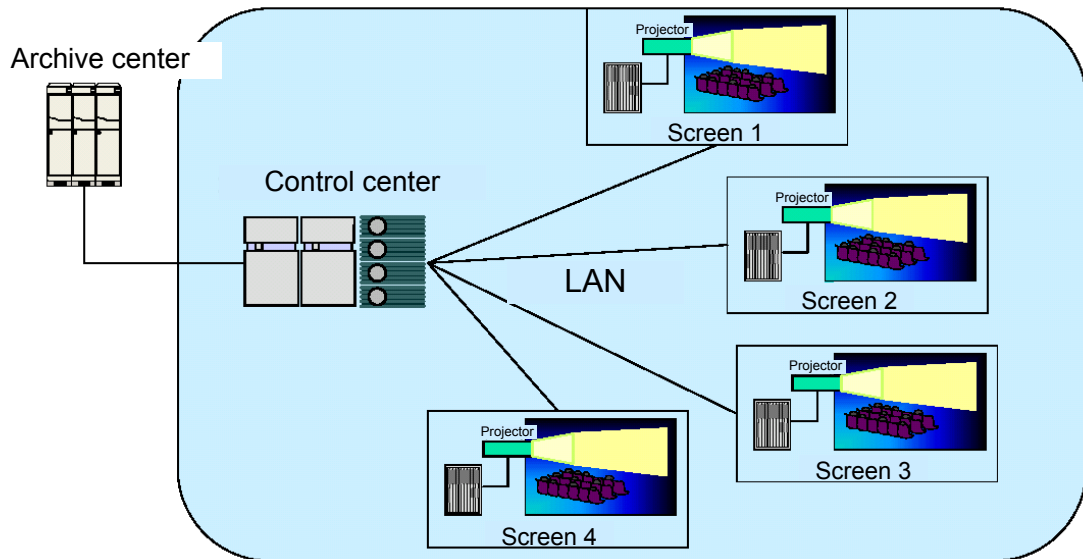


Fig. II-3-2 Digital cinema delivery

The content delivered to the screen will be projected onto a screen after being decoded by a

JPEG2000 decoder in real time. By streamlining the delivery system, the showing of can become flexible, and for example, it will become easy to selectively show popular movies. As a result, movie theater owners can operate a business which is profitable.

3-3 Commercialization efforts

Field tests are being carried out on digital cinema delivery both in and out of Japan, and such activities have drawn keen attention. The following are two examples¹.

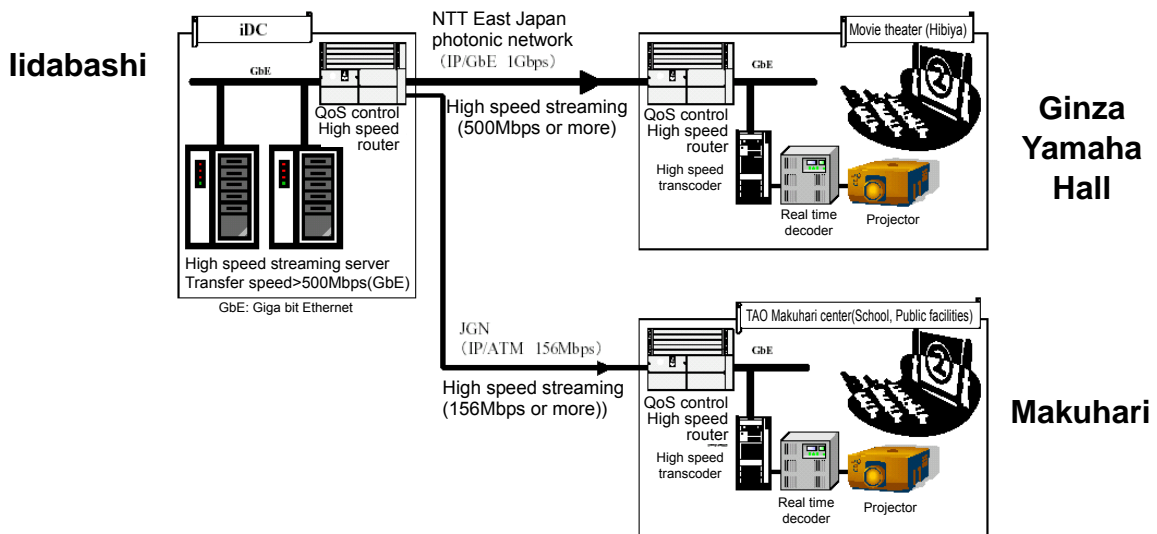


Fig. II-3-3 IP stream delivery experiment for digital cinema

NTT conducted the world's first 8 million pixel IP stream delivery experiment in March 2002 (Fig. II-3-3). A two hour western movie was delivered by connecting to a network (Metro ether) using gigabit Ethernet from a content server installed at the center (Iidabashi) of East NTT using an IP stream at 300 Mb/s to Ginza Yamaha Hall, which was the location for showing the movie. It received a great response.

In October 2002, an experiment to deliver large capacity IP stream content at 300 Mb/s using the US's Internet2 environment between Chicago and Los Angeles, a distance of around 3000 km, was successful. With a delay, 59 msec (round) was achieved by multiplexing the transmission control p (TCP) protocol) with streams (64 units), realizing 300 Mb/s. At the time, delivery of large capacity content over a distance of 3000 km at 300 Mb/s was a world first. In this way, digital cinema delivery technology is now at the commercialization test stage, and it will not be too long before a large amount of content will be carried over broadband networks in the future.

3-4 Expected communications technology

Given the above examples of current issues, technology trends and further system requirements, expected communications technology in the future will be discussed.

¹ <http://www.ntt.co.jp/news/>

- Local area networks

At content production sites, due to the exchange of data (6 Gb/s and more) without compression within a studio, demand for high speed LAN of more than 10 Gb/s is expected to increase. As the required specifications of LAN/SAN are almost the same as that for broadcasting, details are not discussed here.

On the other hand, one of the options for a video interface that connects a digital cinema decoder to a projector is optical fiber. Other than networking, optical communications can be utilized as a high speed interface.

- Access and wide area networks

The data rate of digital cinema is a minimum 300 Mb/s or so, and optical transmission is essential. In the US, optical fiber has not yet been disseminated to access lines, and it is difficult to deliver digital cinema through networks to all movie theaters. On the other hand, the potential realization for network delivery is high in Japan.

A higher data rate, with a higher influence on transmission round delay time (RTT: Round Trip Time) will be possible. With a standard TCP parameter, when RTT becomes only 2 msec, the theoretical throughput value will drop to 250 Mb/s. In contrast to this, there are solutions such as an expansion of window size and parallel transmission using multiple TCP connections. However, it is not easy to improve effective throughput.

When the User Datagram Protocol (UDP) is used for the transmission protocol, a decrease of throughput due to RTT can be avoided, but necessary controls such as data transmission control, re-transmission control at packet disposal and packet sequence control has to be installed individually. In such a case, user level action is involved and performance may drop more than by TCP process overhead. An error correction technique can be used, but when the data rate reaches the Gb/s order it is hard to put into practical use.

From the above reason, it can be said that even if the network bandwidth improves, the bandwidth improvement per data flow unit has a limit. The solution for this needs approaches from two sides, the application side and the network side.

- Security

Encoding is imperative in order to avoid the drain of content over the Internet. It is questionable if movie production companies can be convinced by the use of the public cryptography key method which is now being widely used today. Encryption for high level security, such as digital watermarking, is thus essential. In order to avoid compilation on the movie theater side, streaming delivery without the need for storage is desirable.

Security is the most critical factor for network use of digital media content. If you look at this from the other side, if this problem is solved the data volume of digital media content carried over networks will dramatically increase.

Part 4 Technical Issues to Be Solved and Approaches

As described above, ultrafast optical communication systems are essential for the development of next-generation high definition TV and digital cinema. In order to realize these technologies, the following recommendations and approaches were proposed by expert committee members.

4-1 Ultrafast OTDM devices from the development perspective

When various types of equipment are connected for HDTV in a broadcast station office, it is estimated that a total capacity of 20 Tb/s will be required. As a single channel transmission rate of 48 Gb/s is required for super high vision transmission, a large capacity transmission line will also be required for short time transfer of large capacity content files in a broadcast station office. Also, if cinema content is delivered through networks, an extremely large transmission capacity will be required. Further, from the viewpoint of simultaneity and security, uncompressed real time delivery, not file transfer, is necessary. In view of this, a larger transmission channel is essential; however, the achievable capacity depends on the status of technology development and cost.

A realistic approach to Tb/s class capacity is bundling 100 GbE with multiple fibers or wavelengths. Even in this case there are many technological issues, such as development of electronic circuits and light sources (direct modulation or external modulation) for supporting 100 Gb/s. Also, with 100 Gb/s as a base, synchronization issue between fibers or wavelengths needs to be resolved. The other approach is to increase the single channel bit rate as high as 160 Gb/s - 1 Tb/s by developing OTDM technology. By bundling a small number of channels, huge capacity can be realized. In the area of ultrafast optical time division multiplexing (OTDM), ultrafast light sources and switching devices have been developed in NEDO's Femtosecond Technology project. Through full optical signal processing ranging from 100 Gb/s to 1 Tb/s, the transmission of signals of 320 Gb/s for 40 km has been demonstrated. However, it should be understood that only an initial possibility has been indicated. It will be necessary to climb over another hurdle to realize an actual system.

Looking from the viewpoint of cost, it is said that the cost has doubled against each four times of bit rate increase in conventional intermediate and long range systems. Therefore, a three times or less cost increase for 10 GbE to 100 GbE and four times or less cost increase of the current 10 Gb/s system to 160 Gb/s OTDM must be realized. In a broadcast station office, specifications have priority. The requirement for construction may be more moderate than transmission systems, and the cost standard varies according to application. For 100 Gb/s Ethernet or OTDM, the immediate goal for a cost increase should be a maximum of 10 times compared to 10 Gb/s. The development of new technologies will lead

to substantial cost reduction thereafter.

There are demands for huge capacity systems. It is necessary to develop more practical devices for OTDM on the basis of achievements thus far. What is important is to understand that cost is one of the most critical issues in order to put devices and systems into practical use. Realizing high performance and high level functions with a simple device structure is a key.

In ultrafast system over 100 Gb/s, there are many issues concerning long range transmission due to fiber dispersion, as discussed in this report. A strategy to put systems over 100 Gb/s in short distance applications, such as short distance LAN and SAN system for broadcast station offices, should thus be developed. Success in this field should lead to expansion of application field such as metro network.

4-2 Approaches to low cost and low power consumption modules

Technical issues and approaches to realize LAN/SAN systems exceeding the 100 Gb/s class will be described. LAN/SAN equipment such as Ethernet and fiber channel networks are one-tenth the cost compared with transmission equipment such as synchronous digital hierarchy (SDH) for communications carriers. Though SDH equipment is better in terms of reliability and monitoring functions, greater cost reduction is required even taking these into account.

Other than cost there are severe requirements in terms of size and power consumption. When 100 Gb/s is realized at ten times the cost, size and power consumption of 10 Gb/s, commercialization will be slow. At least cost and size should be limited to four to five times and just parallel transmission without a power consumption reduction may have a risk in operation due to a temperature increase. From these points of view, the progress of electrical time division multiplexing (ETDM) technology is important. OTDM is acceptable if low cost can be realized; however, in order to achieve low cost OTDM, the integration of multiple modulators and their drivers into one small chip is needed. In the same way as parallel transmission, unless power consumption is improved, the problem of a temperature increase is generated. These technical issues are hard to resolve. If one small integrated chip cannot be realized, the cost will continue to be high. Therefore, it is not beneficial to use OTDM from a low speed such as 10 Gb/s.

Ideally, modulation at 100 Gb/s is desirable, but initially modulation at 25 Gb/s or 50 Gb/s would be acceptable. With these speeds, parallel transmission, WDM or OTDM will be performed, and what is important is that users can use it without concern about multiplex transmission. Namely, use must be expanded without concern about bit phase adjustment or fiber dispersion, not to mention frequency management. For that, a buffer needs to be installed inside it or link types must be increased. Eventually, it is desirable to modulate and demodulate at 100 Gb/s. In order to do so, ultrafast mounting technology as well as ultrafast

electronics device technology and modulation and demodulation technology are important. In order to facilitate mounting, an optoelectronic integrated circuit (OEIC) which integrates an optical semiconductor and electronics circuit will become very important technology. Also, with the intention of reducing electric mounting as much as possible, utilization of optical devices is a possible method. For example, it could be a structure where an optical amplifier is placed before a photodiode (PD) so as not to place a preamplifier after the PD. Thus, development of a low noise semiconductor optical amplifier monolithically integrated PD with a high speed high level input is desirable and further integration of the electronics circuits described in a later section is much better.

In order to achieve inexpensive and small devices, a direct modulated laser diode (LD) is desirable. In view of electroabsorption (EA) modulators with issues such as reduced optical loss, decreased drive voltage and temperature dependency, an EA modulator integrated LD is the next best solution. A breakthrough in a very large direct modulated LD is an advance that would have a considerable impact. Of course, there is another direction for the development of an EA modulator where optical loss is reduced, drive voltage is lowered and temperature dependency is eliminated. In any event, direct modulation of 100 Gb/s is considered to be the key point leading to low cost, miniaturization and low power consumption.

4-3 Fusion with LSI technology: Using opto-electronics to reestablish Japan's LSI technology

With volume production of short wavelength LD, demand expansion for hard disks for not only business use such as servers and digital archives but also home appliances such as long play digital video is expected. Instant transfer technology of large volume storage data is considered to be a technical issue that needs to be resolved in order to for backing up important data, server mirroring and remote compile processing efficiently in a short time.

Relevant technology development issues and approaches can be listed as follows.

- (1) Realization of ultrafast parallel and serial conversion devices.
- (2) Proposal of a method appropriate for large volume storage data transfer compatible with the existing data transmission format (fiber channel, GbE etc.) and standardization based on market size.
- (3) Exploitation of delivery and compilation of high resolution video picture, development of applications such as GRID between supercomputers (such as the earth simulator) and review of mounting fit for application.
- (4) Opto-electronics integrated circuit technology which is an element device needed to realize the above.

From a long-term point of view according to Moore's rule, in 2020 the estimated integration will be a 10 nm rule CMOS transistor, 100 million transistor/ mm² with a 400 GHz response

frequency and an IO bus speed of 80 Gb/s and a central processing unit (CPU) and memory throughput of 640 Gb/s between caches (Fig. II-4-1). Accordingly, regarding issue (4) above, the fusion of LSI electronics circuit technology and optical wiring technology including the backplane is considered to be especially important. In LSI technology, which is essential for the encoding and decoding of image signals, Japan should aim to reestablish its development status and take up the issue as a national project. In order to do so, in addition to mounting technology to make things compact, the design policy which is the base for mounting should be most important. Also, it is expected that ultrafast optical switches will be adopted as a low power consumption high density integration solution as FESTA and AIST have already developed a cross-bar switch that can handle ultrafast bus data signal exchange.

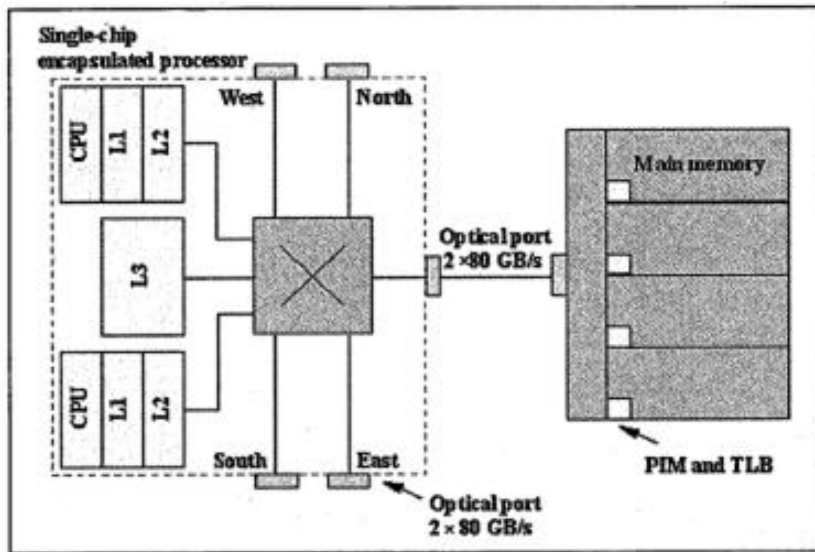


Fig. 1. The encapsulated processor is a single CMOS chip with optical ports as the only means of external high-speed data communication. The processor consists of two CPUs with L1 and L2 cache connected by a crossbar switch. The crossbar connects to shared on-chip L3 cache and multiple high-speed fiber-optic ports. Each optical port is capable of sustaining 80 GB/s (640 Gbit/s) data throughput in each direction and one such port is dedicated to local main memory. Main memory could be configured to have its own processors and TLB. The remaining optical ports are available for IO and scalable SAN interconnect.

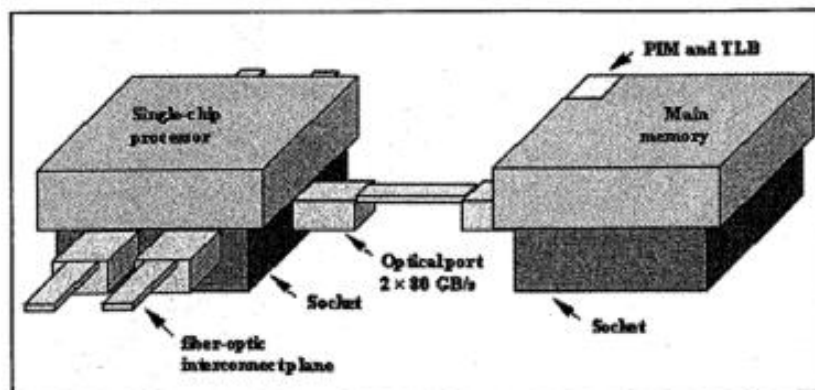


Fig. 2. The encapsulated processor includes a socket that supplies DC current and ground. Incorporated into the socket are the physical optical ports, each of which provide 2×80 GB/s = 1.28 Tb/s data bandwidth external to the encapsulated processor. One optical port is dedicated to local main memory

Fig. II-4-1 CMOS processor with optical port assumed in 2020 [1]

Reference Literature

[1] A. F. J Levi, "Challenges for Photonics in Future Systems," IEEE LEOS Vol.18, No.5, p10, October 2004.

4-4 Optical-optical control ultrafast switching

<Issue recognition>

LAN or SAN networks for relatively short distances show an increasing exchange of relatively large capacity information, for example, as their purpose is to link groups of information within corporations or offices. Especially in recent years, business information is handled via multimedia, and in order to smoothly exchange files an increase in traffic speed is required. Compared with long distance together with low recognition of bottlenecks, a large capacity increase almost moves ahead than basic group. The issue of when 100G Ethernet will be standardized will also be in the background in the near future.

On the other hand, for LAN systems used in broadcasting or for delivery of image content between two points, high resolution requirements such as more than a 1 Gbit capacity increase per one frame of video picture is being intensified. Depending on the image type and end use, there are cases where compression is possible and compression is not desirable. If compression is possible delivery can be made later without hurry, but in case real time is required or in an application that can not accept a quality delay, traffic from several 10 Gb/s to 100 Gb/s in one channel can be generated. Current network systems can not handle this, thus it seems a measure in which the content is stored in the media before delivery is needed.

As mentioned, in a LAN area including a broadcast group, some areas and scene present traffic shortage is already noticeable as an issue.

<Technological approach>

In a normal LAN when 100 Gb/s or more traffic is going to be secured, considering whether the possibility of utilizing ultrafast devices exists is very difficult. For LAN systems in offices, cost is the most important consideration and at the same time high system reliability is also needed. Advanced ultrafast technology such as the optical to optical switch developed by FESTA has benefited considerably from technology extension, and the initial investment must be fairly large, including streamlining of peripheral technology. In terms of cost, it cannot compete with the achievement of 100 Gb/s by utilizing simple wavelength multiplexing or multiple lines. Also, even 100 Gb/s in one frequency is required, and a prioritized effort to confirm electrical processing will be needed.

Next, in the case where image content is delivered under the condition where compression is possible, the network itself needs to be changed as there is a problem where a load on a network is extremely large because current network packets become too small and large in volume when the content is large. For example, technology such as optical burst switch technology which was recently proposed by Professor Aoyama of The University of Tokyo may solve this problem. At least, changing the existing networks in use may be easier than introducing ultrafast technology.

On the other hand, as far as high resolution motion picture delivery, which demands real time, or when compression is not possible, high bit rate traffic will inevitably be required. Further, basic packet division is impossible and since time-series accuracy between signals is required, good matching with even wavelength division multiplexing technology cannot be expected due to concern regarding time displacement between individual frequencies. Time division multiplexing technology by one optical clock with a single frequency can be the most appropriate application area. In addition, that packetization is not done means simple information leak condition, high level ultrafast information processing technology such as optical routing which has not been resolved yet in ultrafast technology will become not essential. What is required is MUX technology that multiplexes the signals of multiple channels into one channel, transmission technology which transmits high bit rate signals without degradation, clock generation, control technology, DEMUX technology which combines time division multiplexed optical signals or divides by channel, etc. Naturally, the possibility of utilizing optical-optical control technology developed by FESTA is considered to be high as a high definition picture requires traffic of over 100 Gb/s. However, co-existing of sending out signals of time division multiplexing high bit rate and occupying more than one frequency (a little more bandwidth is required) with untreated output not with packet form is quite difficult. After thorough study, if parallel use with the current system is possible, if an exclusive line is required, and if the cost is large, it should be investigated if there is comparable merit.

<Suggestion>

In order that the most advanced technology which enables optical communications with over 100 Gb/s configured by FESTA will reach the stage where it can actually be utilized, the application area for which optical-optical control is essential must be addressed. A case where femtosecond technology is required may be generated, and technology does not progress in such a situation and differentiation is difficult. Also, even if there is a so-called "killer application," in order for it to be completed and put into practical use, it is essential to share enough funds to overcome the hurdle, devices and strong enthusiasm and sense of value of the system engineers. It is considered that differentiation of ultrafast technology by Japan can be possible only with support which assumes such risk. At least, the proposal of a killer application by which effectiveness of achievement can be strongly empathized together is a major premise.

4-5 From the standpoint of networking

While in a core network where a large volume of concentrated traffic is controlled by a large bundle, granularity of switching can be at minimum a frequency channel or so, in LAN/SAN switching of random capacity data which is generated with random timing from each end

terminal (user) as needed is necessary. Especially, LAN has been directed to relatively simple conventional network systems, major examples are such as carrier sense multiple access with collision detection (CSMA/CD), which has been used initially and token ring. The direction of such a simplification of control is considered to be the same even when the line rate is enhanced to increase the speed up to 100 Gb/s or more. However, the difficulty level for components and devices increases as a trade off for reducing system complexity. Fig. II-4-2 shows an image of this trade off. From the viewpoint of complexity reduction the time division multiplexing method is more appropriate than wavelength division multiplexing, and in LAN/SAN it will become a motivation to apply ultrafast transmission of 100 Gb/s or more.

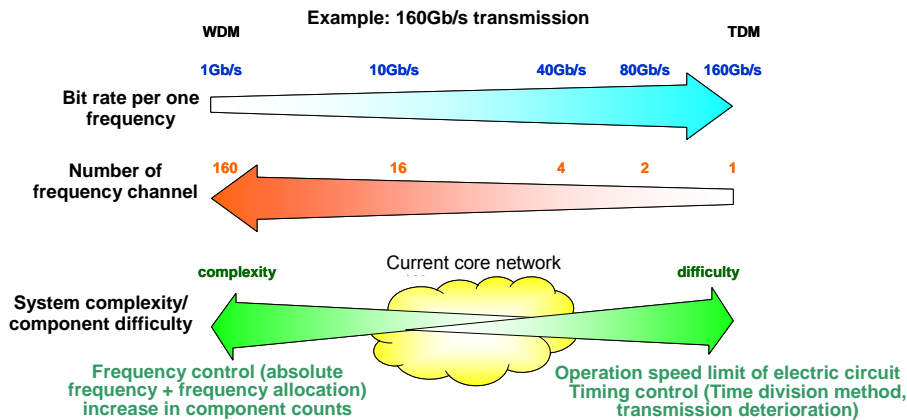


Fig. II-4-2 System complexity and trade off of component difficulty

On the other hand, component difficulty will increase at each device level. Especially because there is no electronics circuit to operate with a base rate, it is necessary that it is converted to the bit rate which can be handled by the electronics circuit with signal processing in the optical area by performing time channel multiplex and separation. Also, from the standpoint of the aforementioned switching of small granularity, the ultrafast optical matrix switch now under development seems to hold great promise. While realization of ultrafast LAN/SAN systems depends on the development progress for individual devices, since the base technology of each element device has already been developed, from now on elemental development of an completely integrated network is considered to be essential.

Part 5 Social Impact

In Japan, the fostering of a content industry is being tackled on the basis of a new creative industry strategy together with a new advanced industry by both the business and government sectors together with fuel cells, home information appliances and robotics. It is expected that an expansion of Japanese content will disseminate into culture and markets around the world and the impact of communications relating to both content production and delivery with ultrafast optical communication systems as the infrastructure supporting it especially the industrial impact will be large. On the other hand, from the standpoint of dissemination of ultrafast optical communication systems, cost reduction can be promoted by developing a large-scale market for digital content delivery in the consumer area, and application areas will be expanded much more than now. In this way, it should be viewed as progress of communication technology linking up with a new service industry. From this viewpoint, LAN/SAN systems related to digital content is expected to have a wide range of spin-off effects.

Part 6 Summary

Progress of a large capacity increase in communications technology has been made in the area of storage technology. Storage capacity in terminal equipment has reached several 100 GB, and in the near future the terabyte level will come. At the same time, in addition to conventional characters a media to be served for communications large capacity increase is seen together with images, video pictures and diversity expansion. Today, not only increased capacity but relating to media quality an era of improvement of quality, so-called QoS enhancement, is going to arrive. This will lead to a requirement for uncompressed content delivery. Here, regarding digital content production and delivery, next-generation high definition TV and digital cinema have been taken up as examples to consider the impact relative to ultrafast optical communications systems.

While a fusion of communications and broadcasting is a topic that has been discussed for a long time, it has become evident that progress in large capacity ultrafast optical communication will enable the delivery of high quality broadcasts and at the same time will become a big factor to be able to provide new services such as interactive communications. It became clear that such public services will bring about new progress to content production sites. It was also indicated that there exists ultrafast LAN needs to support it. It can be said that there is high expectation as a technology which conveys sensitivity taking a step out of a concept of conventional data communications in the application of ultrafast optical communications to this field. On the other hand, a fusion of movie with video picture media was reviewed. Large capacity communications has a possibility to prompt new movie delivery and production which will change the delivery system to movie theaters using conventional film media. This is expected to lead to a new type of movie business that eliminates differences in distance and simultaneousness brought by communications.

For digital content production and related delivery services, ultrafast optical communications will have a wide-ranging impact not only in terms of hardware such as production effectiveness and flexibility of delivery but that high level quality, simultaneousness and immediacy will influence sensitivity as well, and is expected to contribute extensively for progress of related business areas.

Regarding digital content, it has become evident that LAN and SAN systems based on ultrafast optical communication can be an effective solution based on the review results obtained at this time. However, the technology issues to realize this have also been raised in detail. There are many issues, such as how will large capacity increases be achieved without reducing content quality or cost reduction technology enabling dissemination. While ultrafast optical communication, especially single channel communication of the 160 Gb/s class, has been verified in the field utilizing a special fiber environment, the current status is not sufficient for dissemination. Also, technical issues regarding content production and delivery environments became obvious in this review. In the future, it will be important to conduct another review to overcome technical issues that hinder conforming to needs.

III. Vision for Broadband Networks Based on Grid Technology

III. Vision for Broadband Networks Based on Grid Technology

Part 1 Introduction

Grid technology is a computer network technology to make a variety of resources connected with a communication network, such as computers and storage, usable without being aware of their locations and management styles. In the era that private networks with relatively broad bandwidths and safety and wide area networks with relatively narrow bandwidths were managed and operated separately, grid technology was regarded as a special technology for advanced calculation and so on. Nowadays, however, the communication bandwidths of wide area networks are sharply being broadened, for example, gigabit Ethernet has been introduced into quite ordinary personal computers and PtoP service is spreading. Hence, it is becoming required to uniformly handle private networks and wide area networks which were managed quite differently in the past to manage and operate resources. In other words, grid technology is being expected to be a platform to provide users with an easy-to-use way even with networks themselves, which connect a resource with another resource, as grid resources as well as the resources dispersed over networks to ensure more steady and efficient services.

On the other hand, as wide area networks are rapidly improving into broadband networks, best effort services and so on which provide slower response as traffic increases does not work well and creates a bottleneck, no effective network service of a large capacity has spread sufficiently. In fact, traffic from users to the backbone network is restricted to around 10% of the maximum when congested, so that communication becomes impossible in the case of ticket sales of popular events, new year greeting e-mail, and serious disasters. Even now it is impossible to overlook insufficient communication capacity. In addition to this, there are some demands on the business side, such as keeping storage dispersed over a wide area, application to large-scale science and technology calculations, or content distribution. On the other hand, users are not satisfied with the drop of effective throughput due to the increase in broadband subscribers. However, potential demand does not increase well due to the restriction of communication volume.

One of the bottleneck factors is an inflexible network structure which is unable to ensure bandwidth as needed and also network cost. In other words, this means that some hard-to-fix difficulties suddenly occur because of the problems of power consumption, I/O and so on over the existing network infrastructure depending on the packet switching of electrical signals. To fix such difficulties substantially, it is necessary to develop various technologies to use a large capacity ultrafast network flexibly. This will allow the construction of a communication network on which users can use bandwidth as needed. To do so, it will be necessary not only to introduce optical communications as much as possible but also to develop technology to use communication bandwidth efficiently and easily. Through these efforts, it will be possible to suppress the increase of power consumption of communications as well as reduce communication costs and improve

usability. Moreover, if such a network is provided to users at an appropriate cost, bidirectional large capacity communications will spread like an explosion, for example in the field of content distribution, high-quality TV phones, or unification of large-scale data centers. So, it is promising that the communication industry, which has not had much invested in it, will be boosted.

Expectations for grid technology are being raised as a platform to use such large-scale data communications easily without any distinction between wide area networks and private networks. Consequently, it is expected that development to connect IP networks with optical networks seamlessly will be an important theme influencing the future of information communication networks. For the construction of such large capacity ultrafast optical communication networks, this report considers the status quo and future ideals of the development of each network layer, including optical devices, optical network architecture and grid technology which unifies optical communication networks with IP networks. In the consideration, this report covers the form in which ultrafast optical technology of 160 Gb/s or more may be introduced into real networks based on the trends of current technologies.

Part 2 describes the status quo of transmission/interface technologies by reviewing the progress of optical networks in recent years. Part 3 outlines that large capacity communication is usable in a secure and useful manner by using grid technology, and describes the problems of the applications which occupy networks, such as a storage using a wide area network, demand prediction in the field of science and technology calculation, or content distribution. Part 4 describes methods to realize 16 Tb/s transmission, which is the expected target level to be reached around the year 2010, based on the transition of average communication volume over the Internet so far, and considers the meaning of high-speed channels for load sharing and other purposes. Part 5 covers the technological trend to the ultra broadband network, and describes the status quo and future development goals of the current electrical switching interface, generalized multi-protocol label switching (GMPLS) technology, optical circuit switching (OCS), optical burst switching (OBS), and optical packet switching (OPS), respectively. Part 6 describes required technologies for networks, in other words, wavelength conversion technology, signal reproduction/degrading protection technology, and signal quality monitoring technology. Part 7 describes the advantages and disadvantages of the methods of service architecture from the viewpoint of the usage of future broadband networks, and considers the service architecture for grid technology using the OCS method as an example. Finally, Part 8 summarizes the arguments. We hope that this report helps clarify the technological problems for providing ultra broadband communication networks from upper layers to lower layers of the networks throughout.

Part 2 Status Quo of Optical Transmission/Interface Technology

Fig. III-2-1 shows the progress of the backbone optical transmission system and the progress of the interface speed of data devices such as routers. In the 1980s, transmission speed was smoothly increased to 2.5 Gb/s because of ongoing development of new technologies. Such technologies included low-loss single mode fiber fabricated by the vapor phase axial deposition (VAD) method, which is the core technology for large capacity backbone optical transmission, laser diode (LD) lasing at 1.3 μm , distributed feedback (DFB) laser lasing at 1.5 μm without modal noise allowing dynamic single wavelength emission, and dispersion shifted fiber. Furthermore, time division multiplexing (TDM) of 10 Gb/s was put into practical use with erbium doped fiber amplifier (EDFA) technology and a lithium nitride (LiNbO_3) external modulator, which were put into practical use in the 1990s, so that an economic backbone system of a large capacity could be constructed.

In and after 1995, WDM transmission technology advanced rapidly mainly in North America. In North America, practical use of a 16-wavelength WDM of 2.5 Gb/s was launched prior to any other countries. However, this was because the number of fibers was small and many transmission lines were manufactured by the modified chemical vapor deposition (MCVD) method of an early date with poor polarization mode dispersion (PMD), so that the transmission line was not good enough to bear a transmission of 10 Gb/s. However, after that, transmission capacity with WDM technology increased sharply as a trend because new communication carriers entered in the competition one by one based on the deregulation of the communication industry by the Federal Communications Commission (FCC) and the construction of optical fiber networks was initiated.

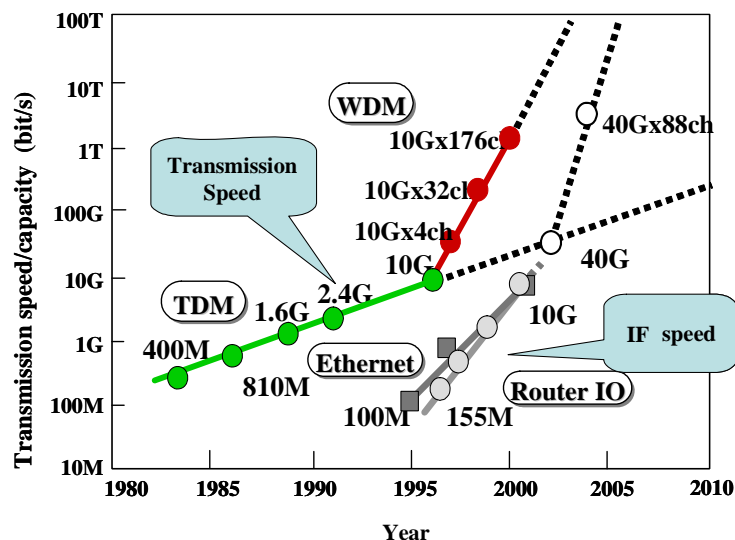


Fig. III-2-1 Progress in interface speeds of backbone optical transmission systems and data devices

Because of the influence of this communication boom, the WDM transmission system's good

background and other reasons, a WDM system of the terabit class which transmits 160 wavelengths or more at a bit rate of 10 Gb/s was put into practical use a few years after WDM technology was put into practical use. Fig. III-2-2 shows the outline and major specifications of a WDM transmission system with a total transmission capacity of 1.76 Tb/s (10 Gb/s x 176 waves). The trend of the development of the WDM transmission system is detailed from the two viewpoints of academy papers and product commercialization. The technologies supporting WDM transmission, such as L-band EDFA, Raman amplification technology, non zero-dispersion shifted fiber (NZ-DSF), and broadband dispersion compensation fiber, were developed from 1995 to around 2000. In this period, development progressed at such a high pace that state-of-the-art transmission technology announced as a post-deadline paper at a major international conference was applied to products just one to two years later. In 2001, NEC and Alcatel reported experiments of transmission with an ultra large capacity over 10 Tb/s, so that development competition of WDM transmission technologies reached a peak.

Fig. III-2-3 shows the configuration of NEC's 10 Tb/s WDM transmission and part of the results. By utilizing a concentrated optical amplifier with three bandwidths of S, C, and L, a distributed Raman amplifier, and polarization multiplexing technology, 273 signals with a capacity of 40 Gb/s were multiplexed, and a transmission experiment of a total capacity of 10.9 Tb/s was achieved. [1]

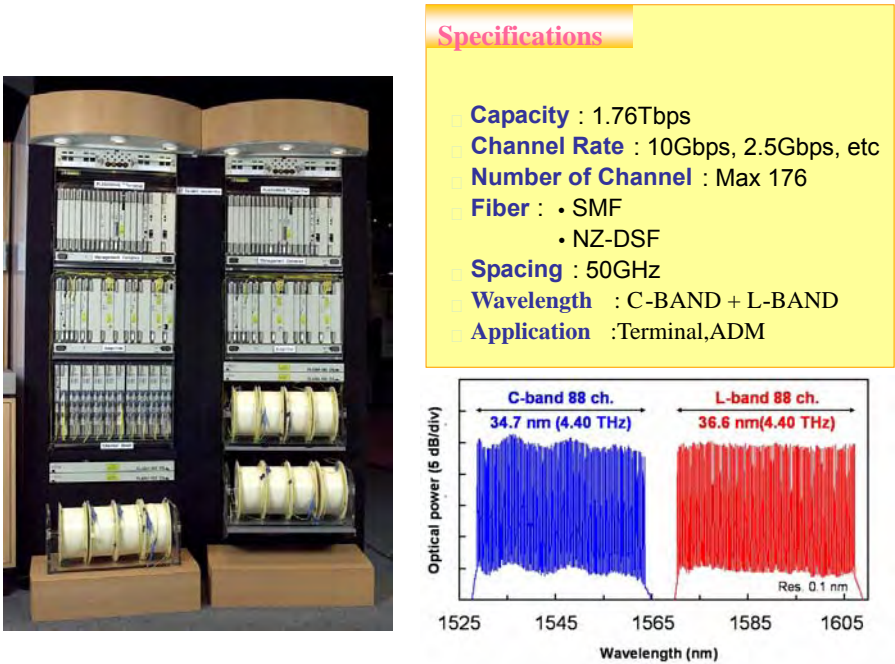


Fig. III-2-2 Appearance and major specifications of WDM transmission system with total transmission capacity of 1.76Tb/s (10 Gb/s x 176 waves)

However, the competition of technology development of total transmission capacity came to an end after transmission experiments of 10 Tb/s. While communication carriers invest excessively in equipment, the theme of research and development is shifting to the development of economic

long-haul transmission technology which can reduce electric reproductive relay devices and the development of an optical switching node technology which improves network flexibility.

The interface speeds of data devices used for Ethernet or router I/O, shown in Fig. III-2-1, are rising at a rapid pace by utilizing the properties developed by the transmission technologies of the backbone system. So, an interface speed of 10 Gb/s, which is as high as the transmission speed of the trunk line system, has already become popular on high-end data devices.

Cisco announced a large-scale core router (CRS-1) in May 2004. This router has an I/O speed of 40 Gb/s, so that the interface speed of the router has become higher than that of the transmission speed of the trunk line system. Since router scale is determined by the number of I/O ports, it is strongly required to raise the interface speed of each I/O port. It is expected in the future that the transmission speed of the trunk line system will be increased due to the need to raise the interface speeds of router I/O ports.

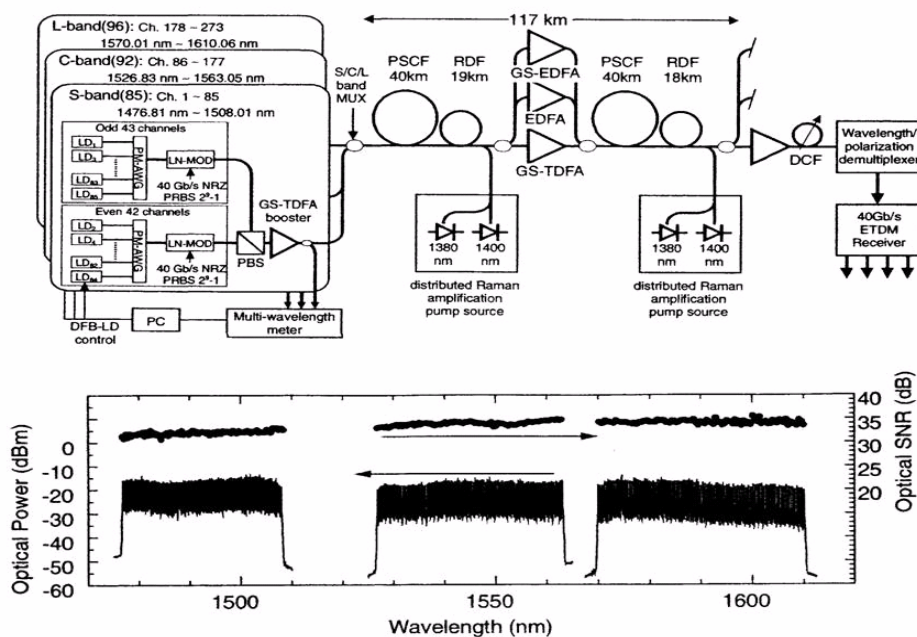


Fig. III-2-3 40 Gb/s, 273 waves, 10.9Tb/s, WDM transmission experiment (Document [1])

Reference Literature

[1] K. Fukuchi et al, "10.92-Tb/s(273 × 40-Gb/s) triple-bandwidth/ultra-dense WDM optical-repeated transmission experiment," OFC2001, PD24 (2001)

Part 3 Requests for Grid and Broadband-width Communications

There was a big difference between private networks and wide area networks in the style of their use in the past. Private networks were broadly used for applications requiring a broad bandwidth and close network component mutual dependency, while wide area networks were used for communication applications with relatively dispersed devices, such as e-mail, the Web, and file transfer. This is due to the following two major reasons. The first is that conventional wide area networks have relatively narrow usable bandwidths compared with those of private networks, and the second is that wide area networks, which are accessed by a unspecified number of users, have problems regarding authentication and security, so that it was difficult to use wide area networks easily like private networks. The former problem will be fixed by optical communication technology. Delay does not matter so much in many applications if a sufficient bandwidth is ensured. Consequently, wide area networks and private networks will be able to use this without being conscious of a distinction once the latter problem is fixed.

Grid technology is technology to fix the latter problem above to make it possible to use resources on a network easily and safely. The grid is originally the term meaning a power feeding network. This network connects power facilities such as power plants and transfer substations via a power feeding network to provide power for homes and offices. In our daily lives, electric appliances are usable only by plugging into a socket, so we are not aware of where and how electricity was generated and fed. Based on this technology, a (virtualization) technology to make various resources connected with a network (the Internet) usable without being aware of what resource is connected, where the resource is located, and how the resource is managed, is called grid technology. One of the merits of grid technology is that it can provide services by making multiple resources belonging to different management domains on a network collaborate with each other. For this purpose, this technology is configured with some technologies, such as a technology to detect and reserve the resources and services required for providing services, a technology to authenticate users and services, and a technology to make it possible for a service to access resources over a network with the authority of a user delegated by the user. In addition, some technologies such as management of accounting information across multiple management domains are also included in grid technology. With such technologies, users will be able to use the services on a wide area network, which they were not able to use easily or with sufficient confidence, in the past. By constructing such a framework, the use of wide area networks will spread as much as or more than the use of conventional private networks, so that the use of broad bandwidths will spread.

New applications have appeared one by one and demand for bandwidth has also increased so far as Internet's usable bandwidth increases. If grid technology makes it possible to use a broad bandwidth inexpensively as well as securely and conveniently, applications will additionally expand. It is difficult to predict such new applications. Some examples of concrete applications

currently under consideration are keeping storage dispersed over a wide area, science and technology calculations, content distribution, and bidirectional communications of high-definition images.

First of all for storage, a style of use without memory at individual terminals is becoming popular because of the establishment of so-called personal information protection law. If a wide area network with a sufficient bandwidth becomes usable, it will be possible to use all storage facilities online via a wide area network. Suppose, for example, an organization with 5000 workers makes all storage usable online. Currently, ordinary hard disks have an access bandwidth of around 300 Mb/s. If access frequency is around 1/10, a bandwidth of $300 \text{ Mb/s} \times 0.1 \times 5000 = 150 \text{ Gb/s}$ will be required in total.

For science and technology calculations, since no wide area network with a sufficient broad bandwidth is usable so far, it was not realistic to distribute a large parallel processing program over a wide area to execute it. However, only if a sufficient bandwidth is obtained, it will be able to execute a single parallel calculation which was executed using clustered computers in an organization using cluster groups distributed on a wide area network. Fig. III-3-1 shows performance levels when parallel processing programs were executed over a broad bandwidth network. This figure shows the performances of seven types of application programs executed by two clusters of eight nodes connected to each other via a wide area network (WAN) emulator of 1 Gb/s, compared with the performance of an environment without delay. When the round-trip delay was 4 msecond, a performance of around 80% was obtained compared with the case of no delay. A round-trip delay of 4 msecond is equivalent to that of a wide area network with a scale of around 100 km. This shows that high performance can be realized if sufficient bandwidth is usable. Currently, InfiniBand with a bandwidth of around 10 Gb/s per link is used as an interconnect in a cluster. It is necessary for such interconnect to have a sufficient bisection bandwidth. For example, suppose a cluster computer with 1000 nodes has a full bisection bandwidth, if the cluster is separated into two sub-clusters with 500 nodes, respectively, the bandwidth between the separated sub-clusters will be 5000 Gb/s (5 Tb/s). When applying this assumption, a bandwidth of up to around 5 Tb/s will be needed between a cluster and another cluster which have widely dispersed 500 nodes, respectively.

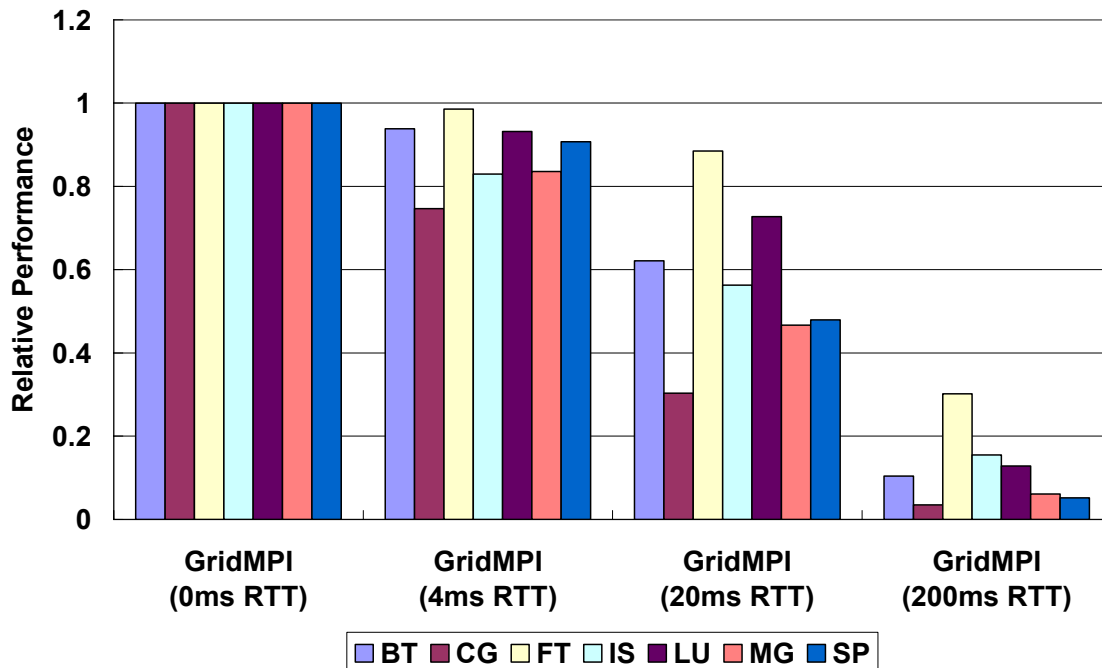


Fig. III-3-1 Relation between delays and parallel processing program effective performance

Next, content distribution is considered. The number of users of content distribution is far more than that of science and technology calculations because general consumers are the target users. Digital high vision requires a non-compressed bandwidth of around 1.5 Gb/s, and animation of the 4K standard, which is a digital movie of a ultra high-definition, requires a non-compressed bandwidth of around 8 Gb/s. To distribute such high-definition content into ordinary homes, a very broad bandwidth will be necessary. Many subscribers share a line of an upper layer over the current Internet. For example, in the case of an asymmetric digital subscriber line (ADSL), it is common for thousands of subscribers to share a line of an upper layer of 1 Gb/s. Even such a configuration can be put into practical use because each subscriber uses only a narrow bandwidth on average even if a broad bandwidth is temporarily used. Such an effect, however, will not be promising if any applications require a very broad bandwidth for a long time, such as contentf distribution. Hence, the requirement for bandwidth of a line of an upper layer will remarkably increase.

Since there is great potential demand for broad bandwidth networks as mentioned above, broad bandwidth wide area networks of the Gb/s or higher class will greatly spread, as inexpensive wide area networks are supplied and grid technology allowing secure and easy use of a broad bandwidth is disseminated.

Part 4 Requests and Problems regarding High-speed Channels

It was noted earlier that demand for a broader bandwidth of core networks is now increasing, and bandwidths and uses are in a relation similar to the question of “Which came first, the chicken or the egg?,” so new usage will spread if a broader bandwidth is provided. This part assumes 16 Tb/s as a bandwidth per fiber which will be really usable within five to ten years, and considers the advantages and disadvantages of bandwidth per channel and the number of channels per fiber.

4-1 Realistic scenario and technological problems from the viewpoint of optical communication technologies

To transfer a large volume of data with a short delay time, it is desirable to ensure a path with a guaranteed bandwidth. The following considers what network is desirable when a request for reserving a path of 160 Gb/s is issued at a user’s initiative in the future. The link of the network is assumed as 16 Tb/s, and comparative consideration is performed between the case of configuring the network as 160 Gb/s x 100 channels and the case of configuring the network as 10 Gb/s x 1600 channels. Only for the link, it will be more desirable to support a path of 160 Gb/s with 16 wavelength channels of a bit rate of 10 Gb/s, while it will be desirable to support a path of 160 Gb/s with a single wavelength channel of a bit rate of 160 Gb/s, as shown below. Although a desirable network style will change ultimately depending on the relation of cost between the link portions and node portions, the importance of the node portions will definitely increase more and more in the future.

Hereafter, as shown in Fig. III-4-1, the following two types of networks configuring a link of 16 Tb/s will be considered.

(a) 160 Gb/s x 10 wavelengths (400 GHz or 3.2 nm interval, 30 nm max. bandwidth) x 10 fibers

(b) 10 Gb/s x 160 wavelengths (25 GHz or 0.2 nm interval, 30 nm max. bandwidth) x 10 fibers

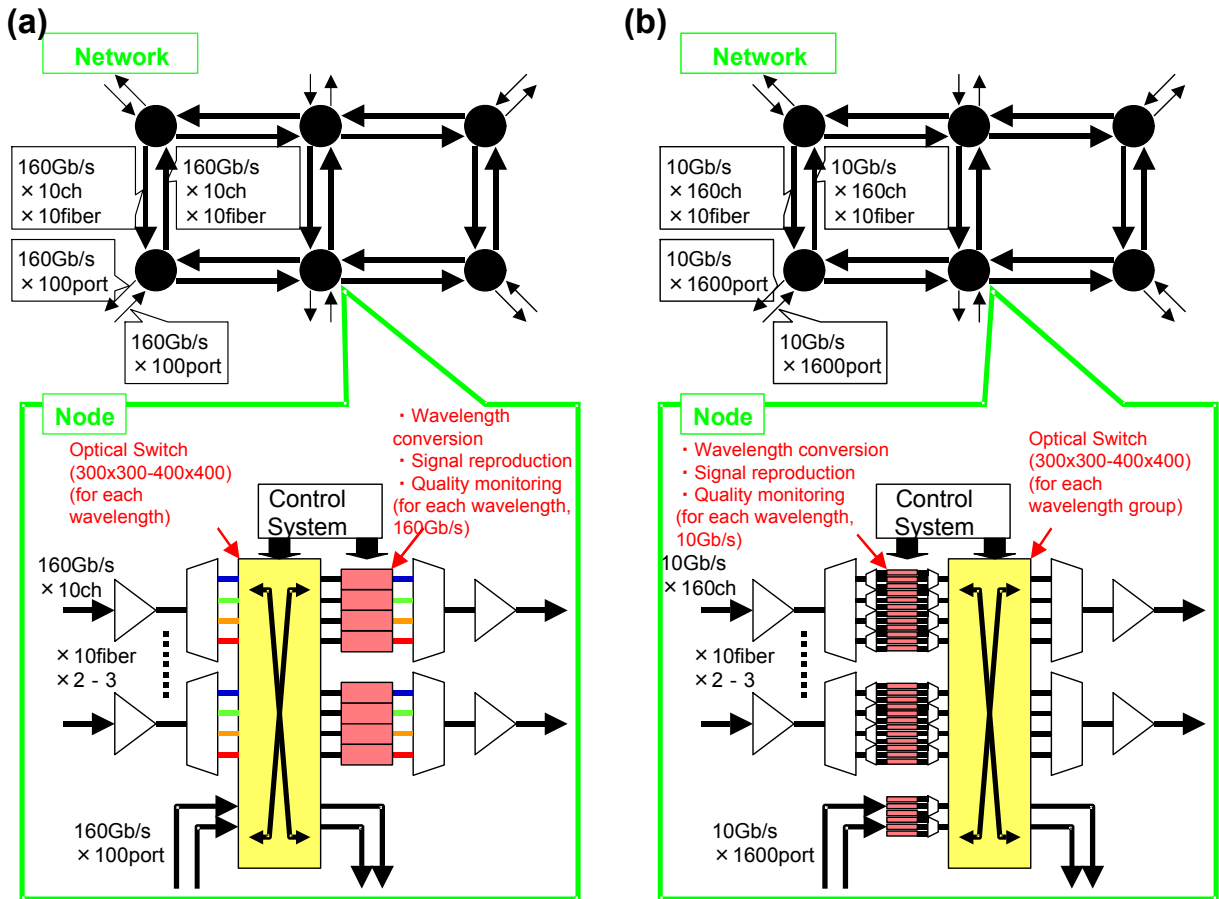
In case (a), a path of 160 Gb/s is supported by a single wavelength channel of a bit rate of 160 Gb/s. In case (b), a path of 160 Gb/s is supported with 16 wavelength channels of a bit rate of 10 Gb/s. In either case, two or three links are connected with a node, and part of the traffic which is input or output via these links is added or dropped. The traffic to be added or dropped is assumed as 16 Tb/s.

Paths of 160 Gb/s are switched at nodes. This switching will be performed in the optical domain. This switching must be performed between a fiber and another fiber or between a wavelength and another wavelength, so that spatial switching and wavelength conversion will be needed. How to conduct signal reproduction and quality monitoring must be considered to make optical signals go through nodes without change as they are.

In case (a), spatial switching will have a scale of 300 x 300 or 400 x 400. Such a scale seems to be feasible using spatial switching with a micro-electro mechanical system (MEMS) mirror. Wavelength conversion may be performed for each wavelength channel before unifying

wavelengths. As for the technology [1] which uses the non-linear optical effect to perform wavelength conversion of the all optical type at 160 Gb/s, some methods using a semiconductor [2-3], LiNbO₃ [4], fiber [5-6] and so on have been reported. For all optical wavelength conversion performed for each wavelength channel, non-linearity between the intensity of an input optical signal and the strength of an output optical signal is used in many cases, and this characteristic is also usable for signal reproduction in many cases. Although the method of quality monitoring is an important theme when optical signals go through a node without photoelectric conversion, such quality monitoring will be performed for each wavelength channel no matter what optical signal monitoring technology is adopted. Using the method of supporting a path of 160 Gb/s with one wavelength, it will be possible to perform wavelength conversion, signal reproduction, and quality monitoring in a reasonable way at a node.

In case (b), it will be necessary to devise a way of minimizing the number of ports for the spatial switch. If switching is performed not for each separated wavelength but for each separated wavelength group of 10 Gb/s x 16 wavelengths, it will be able to minimize the number of ports for spatial switching to around 300 x 300 or 400 x 400. However, wavelength conversion, signal reproduction, and quality monitoring must be performed for each separated wavelength. Although a method to perform wavelength conversion for an optical signal of multiple wavelengths in block using the non-linear optical effect of LiNbO₃ [7] or fiber [8] has been reported as a technology for all optical wavelength conversion, it is very difficult to realize this method. In addition, to convert multiple wavelengths in block, it is necessary to eliminate non-linearity between the intensity of input optical signal and the intensity of output optical signal. This conversely means that signal reproduction is not promising. On the other hand, to perform wavelength conversion, signal reproduction, and quality monitoring for each separated wavelength, a large number of devices will be necessary. In addition, even at a demultiplexing or multiplexing component, if a wavelength is demultiplexed, converted, and then multiplexed again, it will be necessary to devise a way to use the multiplexer's wavelength go-around characteristic, so that a more complicated configuration will be adopted. When a path of 160 Gb/s is supported by 16 wavelength channels of a bit rate of 10 Gb/s, it is inevitable that a more complicated configuration will be adopted for wavelength conversion, signal reproduction, and quality monitoring at nodes.



(a) Configuring 16 Tb/s using 160 Gb/s x 100 channels (b) Configuring 16 Tb/s using 10 Gb/s x 1600 channels

Fig. III-4-1 Network configured with inks of 16 Tb/s

So, if a user wishes to ensure a path of 160 Gb/s, it is desirable for a network to support a path of 160 Gb/s by a single wavelength channel of a bit rate of 160 Gb/s, taking node configuration into consideration. How to implement wavelength conversion, signal reproduction, and quality monitoring is an important technological theme.

To realize a function like wavelength conversion and signal reproduction, which inputs optical signals and outputs optical signals, it is promising to utilize an all optical device which uses the non-linear optical effect without performing high-speed optic-electric conversion. Some methods of wavelength conversion and signal reproduction at 160 Gb/s have been reported, and these methods use a semiconductor optical amplifier (SOA) [2-3], LiNbO₃ [4], and fiber [5-6]. It will be necessary in the future to accumulate as much data as possible for making a basic prospect of power consumption and sizes. However, it is expected that a device usable for system demonstration will come on the scene around 2008. In addition, for the signal reproduction function, it is necessary to clarify the correspondence between the characteristic of input noises and that of output noises to make it possible to design the specifications of real optical signals. While 2R type (Re-shaping and Re-generating) and 3R type (Re-shaping, Re-generating, and Re-timing) functions are usable, the 3R type is necessary to obtain a sufficient signal reproduction effect, whether wavelength conversion or signal reproduction is used. However, the 2R type has some advantages such as a simple configuration and independence on bit rate, moreover, noise (jitters) can be minimized in the direction of the time axis if the response speed is adequately high. It is necessary to clarify the scope of applications of the 2R type and 3R type, respectively.

Also for quality monitoring, it is promising to use a method without high-speed optic-electric conversion. Many methods to monitor the quality of optical signals have been suggested since optical networks were proposed. However, further verification is still necessary to determine whether or not electronic circuit quality monitoring based on digital operations can be replaced with these methods. The quality monitoring technology of optical signals is roughly classified into a method based on time-division measurement data and a method based on time-mean measurement data from the viewpoint of what is used as measurement data. For performing time-division measurement, it is ordinarily necessary to synchronize with optical signals. However, there have been many reports in recent years of a method to estimate the noise characteristic of optical signals from the data obtained without synchronization. In the case of time-mean measurement, one of the simplest methods is average power measurement and optical signal noise ratio (OSNR) measurement, which decomposes signals in the direction of frequency axis, is also usable. In addition, it is also important not only to adopt one of the measurement methods above but to also establish an adequate correspondence to determine a factor (insufficient optical intensity, influence of wavelength dispersion, influence of polarization mode dispersion, influence of non-linearity and so on) based on measured data. Moreover, such monitoring technologies of optical signal quality must measure part of the optical signal by tapping so that the original optical signal transmission is not disturbed, that is, high sensitivity is needed. To perform a time-division

measurement which can support 160 Gb/s, an optical sampling gate with a high time resolution and a high sensitivity is needed. Although many reports on high time resolution have been issued so far, it is necessary to consider raising sensitivity in the future, and it is promising that a usable device for system demonstration will be introduced around 2008. For the methods of time-mean measurement, it is expected that the method considered a technology to support an optical network of the 10 Gb/s or 40 Gb/s class will be adopted for 160 Gb/s as well, and it is also very likely that the technology will be established earlier than expected. The technologies mentioned above measure some parameters of optical waveforms. On the other hand, efforts towards a technology to enable digital operation of the all optical type are also required. This technology is, in short, a technology to enable performance of the digital operations required for the quality monitoring of optical signals of a high bit rate. Some studies on AND operation, EXOR operation [9-10], and flip-flop operation [11] using an all-optical device have already been reported. However, there is no example of performing such operations at a bit rate of the 160 Gb/s class, so this is a future theme.

4-2 The significance of ultrafast channels from the viewpoint of users

Ultrafast transmission through a single channel is more advantageous than parallel transmission in the following cases: 1) Network terminals such as computers use ultrafast channels independently, and 2) Multiple communication streams can distribute a load by sharing a channel by packet multiplexing.

If the transmission capacity of a channel is larger than the independently usable capacity of a network terminal, it is necessary for efficiency improvement to transfer traffic from multiple terminals on a channel. The methods for this purpose are roughly classified into time division multiplexing (TDM) and packet multiplexing. TDM is a method to set slots on the time axis and traffic from each terminal uses pre-determined slots only. On the other hand, packet multiplexing is a method to send packets which arrive from terminals to a transmission line one by one.

For example, if a channel of 160 Gb/s is divided into 16 slots of 10 Gb/s by TDM, each terminal can use 10 Gb/s at most, and it is impossible to use any other vacant slots. For users, such a status is equivalent to that of 16 channels of 10 Gb/s being usable, so that using a channel of 160 Gb/s is not advantageous.

On the other hand, packet multiplexing allows a terminal to use up to 160 Gb/s unless another terminal is performing communications. Therefore, this method allows efficient load distribution. However, a buffer is indispensable for packet multiplexing. Fig. III-4-2 shows a block diagram of a packet switching method using electric signals. Although the buffer's position varies depending on the switch actually, this example uses a model with a buffer on the input (ingress) side. If the packets to be output to the same output port arrive at multiple input ports, it is unable to output these packets simultaneously, and some packets are stored in a buffer and kept waiting until the output port becomes usable. If no buffer is usable, it is unable to store the packets which cannot

be output, so that the packets will be discarded (or will be output to another output port as described in section 5-3). As will be discussed later, technologies for optical packet switching are under development. However, the development of an optical buffer memory which provides adequate performance is not yet in sight. Hence, packet multiplexing is subject to use switching by electric signals. At present, switching by electric signals supports a link speed of 40 Gb/s maximum. To use a method of a higher transmission speed per channel, such as 160 Gb/s, faster switching technology for electric signals will be required.

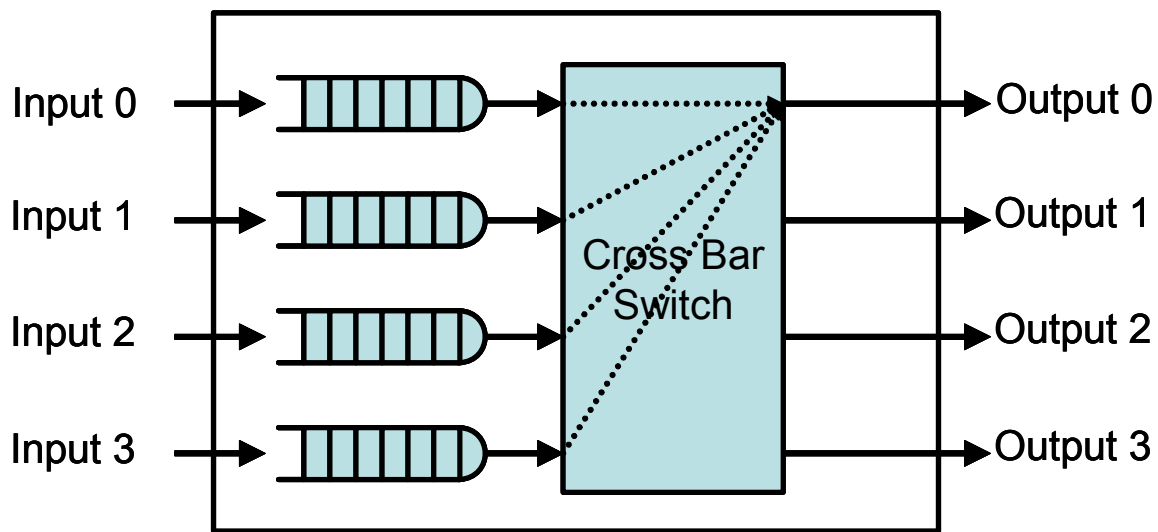


Fig. III-4-2 Block diagram of switching using electric signals

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Part 5 Ultra Broadband Network Application Technologies

5-1 Technological trend for electrical signal switching

This section describes the current trend of switching (IP routers). Fig. III-5-1 shows the transition of router interface speed and switching capacity using a Cisco router as an example.

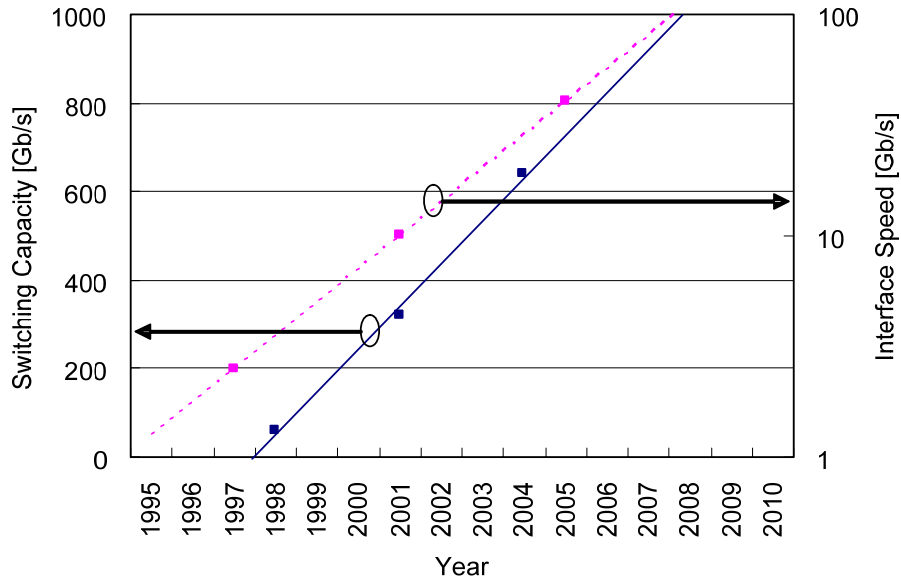


Fig. III-5-1 Transition of router interface speed and switching capacity

Currently, 10 Gb/s is the performance standard for router backplanes or cards, although some routers supporting up to 40 Gb/s have been released. So, most routers currently have an interface speed of 10 Gb/s (STM-64/OC-192 or 10 GbE) or 2.5 Gb/s (STM-16/OC-48), and 40 Gb/s routers (STM-256/OC-768) will appear in the future. However, since router interface speed has quadrupled at intervals of approximately four years, faster speed (100 GbE or 160 Gb/s) may be required after a period of nearly four years (around the year 2010) if such a speed increase is to continue along this time scale, so consideration will be necessary.

As for switching capacity, some vendors have released routers with a switching capacity of several hundred Gb/s to over 1 Tb/s. In addition, as shown in Fig. III-5-1, the latest Cisco router is able to have a switching capacity of 92 Tb/s. In this case, if an interface of 40 Gb/s is adopted, 2300 units of a 40 Gb/s interface will be required. Hence, it is also an effective method to introduce a high-speed interface (100 GbE, 160 Gb/s and so on).

In addition, if a large-capacity link (100 Gb/s) is established between two routers, and an interface of 10 Gb/s is adopted, ten pairs of interface cards will be necessary. However, since such a link is regarded as the same cost by routers, packets will be collected to only a pair of interface cards if a route control method such as the open shortest path first (OSPF) method is adopted, so that a problem will be caused. In order to avoid this problem, a method to assign usable links of the same

cost for each packet destination will be adopted. However, since traffic volume is different for each destination, it will be difficult to assign traffic evenly, and throughput will inevitably become lower than the total throughput of those links. Therefore, from the viewpoint of resource it is not effective to configure a large-capacity link by putting multiple low-speed interfaces together in combination. Conversely, it is desirable to connect routers to each other using a pair of high-speed links, and it may be necessary to develop a high-speed interface (100 GbE or 160 Gb/s and so on).

As mentioned above, this section has reviewed the transition of router interface speed and switching speed, and then come to the conclusion that the next goal of research and development should be 100 GbE or 160 Gb/s because an interface of 40 Gb/s has already been released.

5-2 Research and development on optical packet switching technology

Technologies for realizing IP traffic transmission using an optical network are now being actively studied in order to realize faster or broader-band communications. In particular, because of the potential benefits in processing speed, density implementation, electronic circuit power consumption and so on, research and development on optical packet switching technology, which realizes packet transfer by means of an optical method, is becoming more important [1, 2]. Although an optical packet switching component has a configuration similar to that of a conventional electric router, the switching minimizes the load of electronic circuits by introducing optical signal processing. This is a feature of optical packet switching. By introducing optical signal processing, which is faster than the method using electronic circuits, it is promising that the efficiency of packet transfer will be improved and bandwidth will be better utilized. On the other hand, optical header identification circuits for header analysis and optical buffers for conflict control will be important technological themes.

Optical packet switching converts electric IP packets (μsec to msec) into optical IP packets at the entrance of an edge node, and then transfers these packets through an optical network as they are. Optical packet switching allocates a wavelength for each optical packet to perform routing on a per optical packet basis. Optical packet switching devices are configured with a header processor which processes a packet's address information in the optical domain, an optical buffer to avoid conflict, an optical switch to switch optical routes on a per optical packet basis based on the output information obtained by referring to an address table, and a wavelength converter. This method identifies the headers included in optical packets to control the optical switch. Headers include address information corresponding to packet destinations, so optical packet switching devices collaborate with each other to create/update routing tables autonomously based on the address information. The time interval of switching is 10^{-6} second or less, so an order of 10^{-9} second is required as the switching speed of optical switching. Fig. III-5-2 is a block diagram of the configuration of an optical packet switching device.

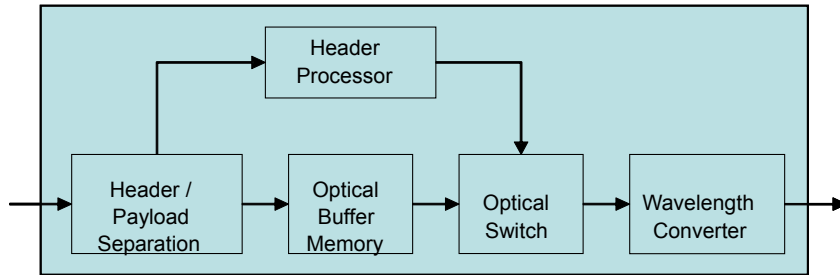


Fig. III-5-2 Configuration of optical packet switching device

The key components of optical packet switching can summarized as follows.

(1) Optical Header Identifier

It is important to develop an optical header identification circuit which operates at a high speed and can be implemented in a small size. In addition, since electric processing will still be necessary in the immediate future to manage address tables and exchange routing information among optical packet switching devices, it is necessary to clarify the distinction between electric processing and optical processing to stipulate the interfaces between the optical circuit and electric circuit.

(2) Optical Buffer

An optical buffer to buffer optical packets as they are is an indispensable element device for implementing optical packet switching. In particular, it is expected that a small-sized optical buffer which can select any delay time and maintain signal quality will soon be realized.

(3) Optical Switch

An optical switch used for optical packet switching requires a switching speed on the order of 10^{-9} second. In addition, this component must satisfy requirements such as low insertion loss, small size, and low crosstalk. Moreover, it is important to undertake research and develop on advanced integration technology for optical switching to support the input/output volume of optical packet switching.

(4) Wavelength Converter

For optical packet switching, an all-optical wavelength conversion process which can avoid conflicts and effectively use wavelength channels is a highly prospective technology area. This is particularly the case for a wavelength converter which can convert the wavelengths of input optical signals into any wavelength and does not depend on signal speeds or signal formats. In addition, for future optical networks, wide-range wavelength tunable lasers and multi-wavelength lasers capable of simultaneous oscillation at multiple wavelengths are also important device technologies.

Of the devices outlined above, the optical buffer seems to be the one that will be the most difficult to realize. Using an optical fiber delay line is the only way to accumulate optical signals at present,

so realization of an optical random access memory (RAM) equipped with a random accessing function is a long-awaited theme. Although optical fiber delay lines are able to delay optical signals by the time of the fiber's transmission delay, it is not possible to stop optical signals themselves. Consequently, the cable must be as long as the value of the light speed multiplied by the buffering time, so it will be difficult to reduce size, and delay time will be limited and become discrete. On the other hand, research on elements and phenomena based on substance properties (for example, bistable elements and electromagnetic wave induction clearing phenomena), which are regarded as promising for realizing optical RAM, is also going on. However, such research is still at the basic study stage, so great progress will be necessary in the fields of materials and substance properties.

As described above, optical buffer technology, which is regarded as indispensable to realize optical packet switching, has not been fully developed yet. So, the scenario for putting optical packet switching into practical use has not been clarified yet. Some companies and research institutes are now developing an optical packet switching device of the optical fiber delay line type on a trial basis. However, most are still at the stage of principle confirmation, so that the realization of a commercial product usable for system application is not in sight yet. The typical components of an optical packet switching system of the optical fiber delay line type at present are a bit rate of 10 to 40 Gb/s per channel, a fixed packet size of some ten to some thousand bytes (a packet 64 bytes long and a packet 1500 bytes long last for 51.2 nsec and 1.2 μ sec at a transmission speed of 10 Gb/s respectively, and 12.8 nsec and 300 nsec at a transmission speed of 40 Gb/s, respectively), and a total throughput of 1 to 10 Tb/s. It is desired that a system with a bit rate of over 100 Gb/s per channel and a total throughput of the Pb/s class be realized in the future. On the other hand, since a breakthrough in optical buffer technology to realize an optical packet switching device of the optical RAM type will be required, full-scale research and development will begin in and after the year 2010. So, this will be another future study theme.

For realization of an optical packet switching network, optical synchronization technology, optical signal modulation-demodulation technology, optical signal reproduction technology, optical packet routing control, and optical traffic engineering are also important element technologies in addition to the key technologies mentioned above.

5-3 Outline of GMPLS technology and dynamic wavelength path set-up management technology

Backbone line capacity is increasing due to the spread of the Internet and the progress of broadband services. Currently, routing control and trouble recovery of (backbone) networks are performed using electric switching and IP routers, TDM devices and so on. However, it is becoming obvious as traffic is increasing that reliability has deteriorated. With increases in equipment footprint and power consumption, operation and maintenance become more complicated, so a next-generation network architecture capable of accommodating future

large-capacity traffic is an important theme to be considered. Because migration with existing networks is indispensable, it is desirable to fix the various problems caused by the increase of capacity by performing unified control and management on the capacity of the backbone network using new optical switching technology and leaving existing signal switching at IP routers and so on as it is. In particular, attention should be focused on optical cross-connect technology which can switch optical signals without converting them into electric signals and generalized multi-protocol label switching (GMPLS) technology which can control and manage service nodes such as IP routers and add/drop multiplexer (ADM) and optical cross-connect devices together. Various research institutes are now actively performing research and development in these areas (Fig. III-5-3).

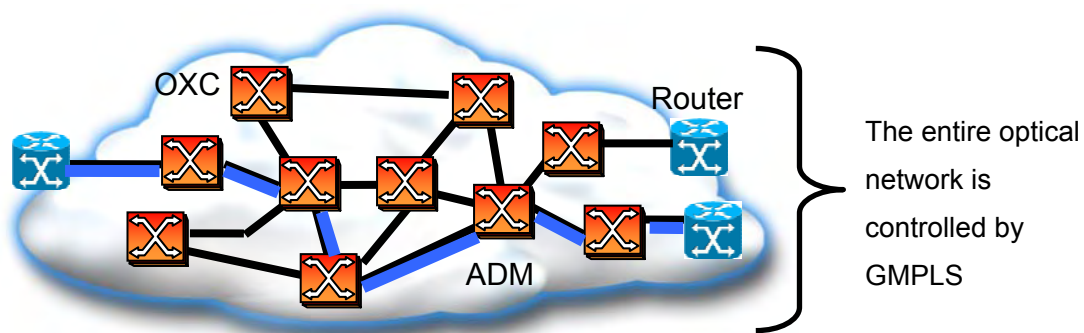


Fig. III-5-3 GMPLS block diagram

GMPLS is, as the name implies, a generalized method of multi-protocol label switching (MPLS). MPLS is currently broadly used over IP networks for services such as an IP virtual private network (IP-VPN) and Ethernet-VPN and optional functions such as traffic engineering, which specifies a source and a destination for a packet not by an IP address but by a label to perform route control (switching) based on the label. GMPLS provides a function to control optical paths by optical switching instead of switching packets based on labels. However, since this technology has been enhanced so that it can be applied to other switching methods, it is applicable not only to optical paths but also time slot switching of TDM devices and fiber switching and so on. Before GMPLS came on the scene, IP routers were not able to know which route an optical cross-connect device set up as well as optical cross-connect devices were not able to know which route an IP router wished to set up. Consequently, it was difficult to improve the usability of resources and the reliability of paths among IP routers. Resource usability and network reliability will be improved because the introduction of GMPLS provides two advantages: One is that IP routers will be able to set up the most appropriate routes by themselves automatically by exchanging resource information between IP routers and optical cross-connect devices with each other, and the other is

that the devices which have been operated independently so far can be managed together. In addition, it is also expected that paths among IP routers can be set up immediately over an optical IP integrated network although currently the schedule must be coordinated on a weekly or monthly basis for design, set-up, operation and so on to open up paths among routers. Moreover, it is also possible to search for an alternate route immediately to detour around a route when trouble occurs.

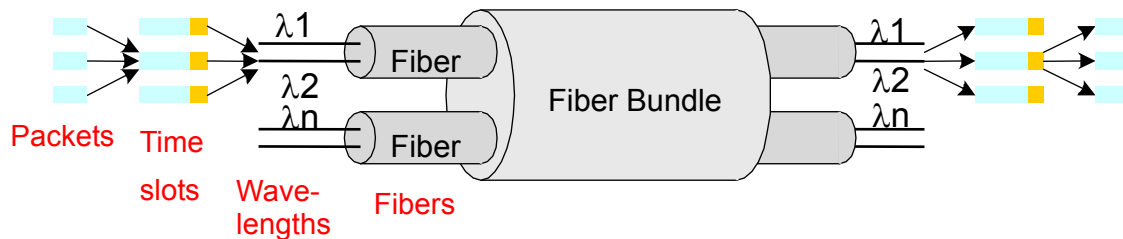


Fig. III-5-4 Block diagram of GMPLS switching

In a GMPLS network, the links of optical wavelengths are connected as if with a mesh using an optical cross-connect device. Since it is possible to set up optical wavelength paths more flexibly at a higher speed by GMPLS in a GMPLS network (set up an optical wavelength via the shortest route or set up an optical wavelength to avoid a particular route in case of cable maintenance), it will be able to provide new services such as VPN service which directly provides users with wavelength paths and dynamic wavelength service (pay-by-the-hour service).

Electric switching has been primarily used thus far for devices for switching the route control of optical signals transmitted by WDM devices. Consequently, it was necessary to convert optical signals into electric signals, and again convert these signals into optical signals. A signal speed around 2.5 Gb/s has been realized at a low cost. However, 10 Gb/s is spreading as the main speed of optical signals flowing via IP routers, and 40 Gb/s will become more common in the future. For such speed/capacity increases, it is a concern that existing electric switches are not usable because of their heating, device footprint, and processing speed. So, the transparency of light switching is attracting attention, and an optical cross-connect device to switch optical signals as they are without converting into them electric signals is under research and development. The heart of an optical cross-connect device is an optical switching component, and several different methods are usable. However, an optical switching component applying micromachine technology called three-dimensional micro-electro-mechanical systems (3D-MEMS) is promising. 3D-MEMS is configured with multiple small mirrors which can be controlled in a three-dimensional manner, and the optical routes over the optical fiber arrays among the input/output ports of an optical switching component are controlled by adjusting the positions (angles) of the mirrors. Since this component can be configured with very small mirrors, it is excellent in expandability (for example,

switching at 1000 ports), high-speed switching, power saving, and device footprint saving. In addition, because this component is able to set up and switch paths flexibly regardless of format, bit rate, wavelength type and so on, it will be suitable for constructing a large-scale optical/IP network efficiently. At present, configurations on a 10 Gb/s basis have been adopted and commercialization has partially started. However, research and development on a 40 Gb/s basis is going on, so it is expected that this method will be put into practical use around the year 2008. Furthermore, since bit rate is basically transparent when an optical cross-connect method is used, it is advantageous that such a method can be applied even when a bit rate of 100 GbE or 160 Gb/s is adopted in the future. However, such a method will not be introduced until around the year 2014.

5-4 Outline and advantages of optical burst switching technology

Optical burst switching (OBS) may be positioned as a technology which can more quickly evolve the functionality and flexibility of optical circuit switching. This technology sets up an optical path in a short time on the order of a msec or less according to a request to transfer IP data, and transfers burst data, which is a block of IP data. The optical path will be released soon after the transfer finishes. Because it can assign a wavelength to different optical paths continuously at short time intervals over a network, it will be possible to improve the time-efficiency for accommodating payload data per wavelength.

5-4-1 Outline of optical burst switching (OBS)

The basic principle of OBS is separating a control channel (wavelength) to keep routing information and so on from multiple data channels (wavelengths) to be used for transmission of payload data. It will be able to construct a network utilizing the advantages of electricity and light by processing the control signals which require information processing in the electric domain as needed but transferring payload data (optical burst) in the light domain as it is [3, 4].

Fig. III-5-5 is a conceptual diagram of OBS. Electric IP packets bound for the same node are collected at the entrance edge node, generated to an optical burst, and then sent. Here, a wavelength is assigned for each optical burst, and switching is performed. Control signals with information on an optical burst are sent prior to the optical burst, and then the optical burst is sent after a time interval called an offset time. At relay nodes, optical switching is set up based on control signals. OBS grasps an optical burst as a connection between an edge node and another one in an OBS network, and reserves or releases wavelengths at a high speed to this connection for each IP packet block generated. The reservation method of a wavelength is roughly classified into the unidirectional reservation (one-way) focusing on high speed, and the bidirectional reservation (two-way) focusing on reliability. The one-way method starts sending a burst without confirming if a reservation was made successfully after sending a request for reservation. Because it takes a short time to start sending a burst, wavelengths can be reserved and released based on a short time scale as if on a per burst basis. However, since a burst is sent even if a

wavelength is not reserved successfully, it is not guaranteed that sent data actually reaches the destination node. On the other hand, the two-way method does not start sending a burst before waiting for ACK (confirmation response), which indicates the success of reservation, after sending a request for reservation. A certain bandwidth is guaranteed once a wavelength is reserved successfully, however, since much time is required for making a reservation, it is difficult to reserve and release a wavelength at a high frequency. A request for reserving/releasing a wavelength is issued at time intervals on the order of a msec to a second. An optical path is reserved and released in a short time on the order of a msec or less as requested. Although control signals are converted into electric signals for processing as needed, optical burst signals are processed entirely in the optical domain without conversion between electricity and light.

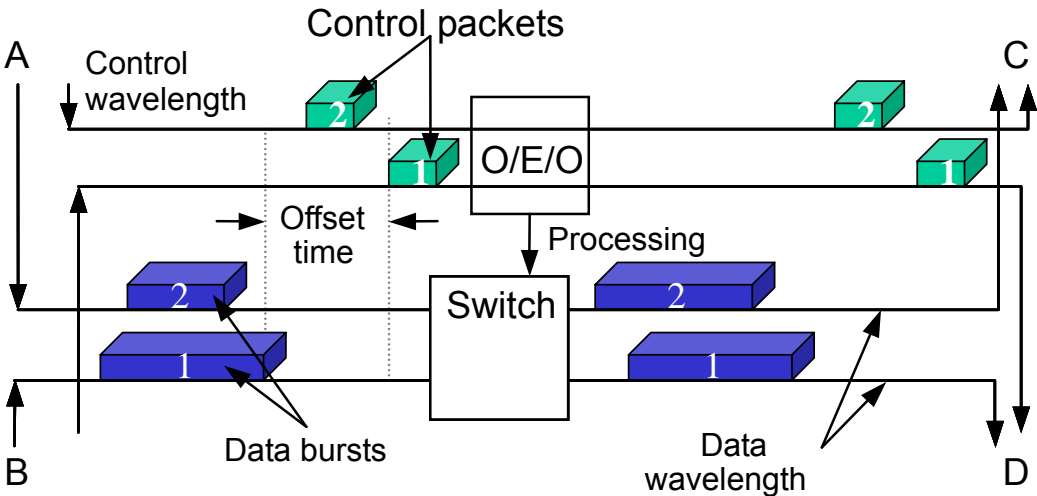


Fig. III-5-5 Optical burst switching

5-4-2 Advantages of optical burst switching (OBS)

For OBS, control signals are transferred using a special wavelength, but bursts can be transferred using all of the wavelength bandwidth of a transmission link. Therefore, wavelengths can be reserved easier than with other methods. OBS in particular is advantageous if the number of wavelengths is great. Because the offset time is very short in most cases, reservation takes a shorter time than a bidirectional wavelength reservation such as circuit switching. On the other hand, since OBS collects multiple electric IP packets to perform switching on a per burst basis, the overhead of control and processing is smaller than that of a method to relay data on a per packet basis. In addition, by transferring control signals and optical bursts on different channels as inserting a time difference called an offset time, the processing delay of control signals is not regarded as an immediate problem. Moreover, using a wavelength assigned to a burst signal as a label makes it possible to utilize the class of service (CoS) or quality of service (QoS) index to classify transmission quality. As a result, it will be possible to realize a more economic and

well-functioning photonic network. Currently, OBS is actively being researched and developed by domestic/overseas universities, companies and national institutes, and an OBS testbed network is under construction. The system which is mainly used at present is composed of a data channel of 4 to 16 wavelengths, a link speed of 1 to 10 Gb/s, a switching time on the order of a μ sec to msec, and a burst length of some hundreds to some thousand bytes (a set of a few to some tens of IP packets). In the future, it is expected that an OBS node of 100 or more data channel wavelengths, a link speed of 40 Gb/s or more, and a switching speed of 1 μ sec or less will be developed. Recently, there is a trend to standardize OBS node architectures and network control planes, so research and development of OBS will reach the stage of commercialization sometime between 2007 to 2009.

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Part 6 Technical Themes Common to Optical Packet Switching (OPS), Optical Burst Switching (OBS) and Optical Circuit Switching (OCS)

6-1 Wavelength conversion technology

The role of the optical network from the viewpoint of grid technology is to provide an optical path of a particular quality within a particular period for the resources to be connected. On the other hand, there are a variety of optical path requests, such as an on-demand request, a wait request according to a schedule, and a reservation request based on a specified time. So, it is necessary that resources for optical paths can be ensured in a sufficiently flexible manner to provide optical paths for such complicated requests. Although the problem of optimization of wavelength assignment on an optical path route is a NP-complete problem [1], this problem can be mitigated and flexibility in ensuring optical path resources is also improved by adopting a wavelength conversion function at optical cross-connect (OXC) nodes [2].

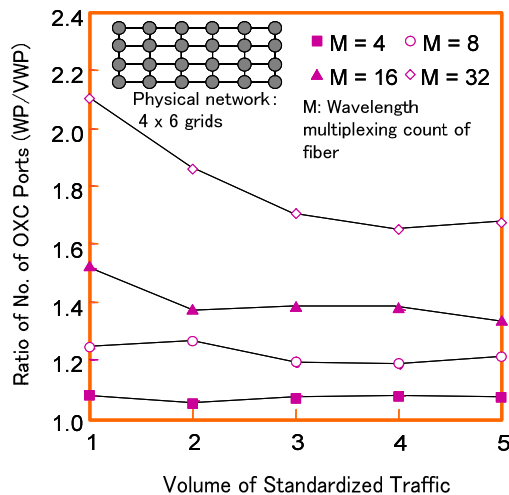


Fig. III-6-1 Difference of OXC scale due to existence of wavelength conversion function

Fig. III-6-1 shows a comparison of the average OXC scale required when random traffic is accommodated in a physical network whose wavelength multiplexing count per fiber is limited to 4, 8, 16, and 32 between the case that wavelength conversion is not performed by OXC (WP method [3]) and the case that any wavelength can be converted into any wavelength by OXC (VWP method [3]). (In this example, spatial multiplexing using multiple fibers was also used as needed among nodes, and the average OXC scale was equivalent to the total number of input/output fibers.) This example shows that OXC scale is decreased by the wavelength conversion function. This example also shows that the effect of wavelength conversion increases as the number of wavelength multiplexed signals per fiber increases. This mechanism can be described as follows:

When the number of wavelength multiplexed signals is small, the probability of assigning the same wavelength to an optical path on an end-to-end basis is relatively high. On the other hand, when the number of wavelength multiplexed signals is high, this probability is low.

A DWDM transmission system with more than 100 wavelengths per fiber has already been put into practical use. Since it is currently assumed that each node edits synchronous digital hierarchy (SDH) and IP electric paths, optical paths are only used for point-to-point connection between a node and its neighboring node. On the other hand, if optical path networking is implemented via multiple OXC nodes by implementing OXC at nodes, wavelength conversion will be an indispensable function.

As for the implementation method of the wavelength conversion function, a method to use the cross phase modulation, cross gain modulation, and four-wave mixing of a semiconductor optical amplifier, and a method to use a quasi-phase matched LiNbO₃ (QPM-LN) waveguide is used. For realizing all such optical wavelength conversion functions at a low cost, it must be considered to what extent the degree of freedom should be given to wavelength conversion. For example, if a transmission system of 100 waves is connected to OXC nodes, flexibility will be maximized by converting any wavelength into any wavelength (a degree of freedom of 100%). On the other hand, it may become difficult to realize the wavelength conversion function at a low cost. Conversely, there is a report on the effectiveness for networking of the so-called partial wavelength conversion method, which separates wavelengths into multiple groups and permits wavelength conversion only in each group [4]. Fig. III-6-2 shows the results of an evaluation of the number of wavelength multiplexed signals which will be necessary when grouping wavelengths into the three groups of two, four, and eight wavelengths and accommodating optical paths in a network.

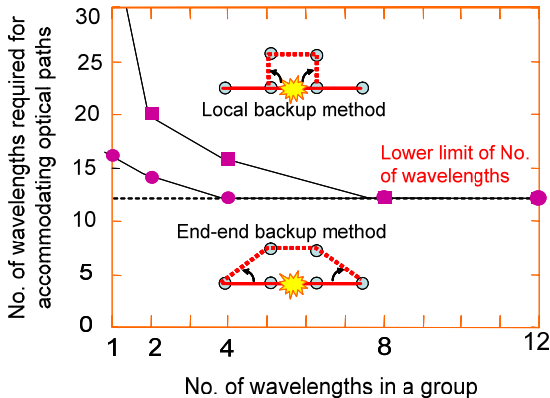


Fig. III-6-2 Effect of partial wavelength conversion

(For example, if grouping wavelengths on a per four wavelength basis, λ_1 to λ_4 can be converted into any wavelength out of λ_1 to λ_4 . However, they cannot be converted into λ_5 , λ_6 , λ_7 ,...) In this example, the lower limit of required number of wavelengths is 12, so 12 wavelengths in a group is

equivalent to the wavelength conversion function of a degree of freedom of 100%. Although Fig. III-6-2 considers accommodating backup optical paths in the event of trouble on the transmission route, the number of wavelengths in a group reached a lower limit of 12 when it is eight (equivalent to a degree of freedom of 67%), independently on the backup method. Since the wavelength conversion function with a degree of freedom of 100% is not indispensable for networking using optical paths, consideration including partial wavelength conversion will be necessary for research and development on all-optical wavelength conversion in the future.

As methods for wavelength conversion and signal reproduction at 160 Gb/s, a method to use a semiconductor optical amplifier (SOA) [5, 6], a method to use QPM-LN (simulated phase matching LiNbO₃) waveguide [7], and a method to use fibers [8, 9] have been reported. It will be necessary in the future to collect adequate data to estimate basic factors such as power consumption and size. It is expected that a device which is sufficiently completed to use for system demonstration will be available around the year 2008.

6-2 Technologies for signal reproduction and maintaining quality

There are two scenarios for realizing a grid computing environment at a bit rate of 160 Gb/s as follows: The first is a scenario to utilize a photonic network based on wavelength paths, and the introduction of this scenario is currently under consideration. The second scenario is to construct a new exclusive optical fiber network which can easily provide ultrafast transmission of 160 Gb/s or more.

For the first scenario, it is necessary to realize transmission of 160 Gb/s on a photonic network designed for a transmission speed of 10 to 40 Gb/s. A technical theme to realize this is to make a signal of 160 Gb/s flow via an optical ADM or a wavelength multiplexer-demultiplexer in an optical cross-connect device designed for 40 Gb/s. To do so, it is necessary to develop a highly effective modulation method with a narrow spectrum occupying bandwidth by a 40 Gb/s signal. More specifically, multi-level modulation-demodulation technology which can transfer data at a bit rate of 160 Gb/s on WDM signals with a frequency of 50-100 GHz and support a rate of over 1.0 b/s/Hz will be indispensable. On the other hand, if high-efficiency modulation technology can be established, the technology which is currently applied at a bit rate of 40 Gb/s may be utilized as it is to the compensation technology of wavelength dispersion and polarization dispersion which will matter for ultrafast signals.

The second scenario, which covers the construction of an exclusive fiber network suitable for ultrafast signals at a bite rate of 160 Gb/s or more, can be applied when 160 Gb/s transfer is difficult due to the characteristics of optical fiber and the restrictions of node performance, or when the construction of a new optical fiber network is required because the existing network's capacity has become full. Since a network can be designed based on this scenario assuming the transmission of ultrafast signals of a bit rate of 160 Gb/s or more as a characteristic of transmission routes and optical nodes, the scale of a transparent network of 160 Gb/s may be

upgraded. In addition, it is also expected that network costs may be minimized more than the first scenario after several years have passed and a signal of 160 Gb/s has become popular.

A common theme to the first and second scenarios is that an OSNR 6dB higher than that of 40 Gb/s is required for 160 Gb/s transfer in principle, and this is an inevitable technological theme to realize 160 Gb/s transmission. For OSNR improvement, there are such methods such as 1) increase transmission power, 2) reduce the noise level of optical amplifiers, 3) shorten the intervals for installing optical amplifiers or signal reproduction devices, and 4) introduce technologies for optical signal reproduction and quality maintenance. However, since the influence of a non-linear effect such as self-phase modulation (SPM) becomes more prominent at 160 Gb/s, it will be difficult to adopt the method mentioned in 1) to increase transmission power. In addition, since the technology of optical amplifiers has matured, it is also difficult to adopt the method mentioned in 2) to improve the characteristics of optical amplifiers. Method 3) for reducing relay intervals is a real solution, although network costs will rise. Consequently, to construct an economic 160 Gb/s transmission network, it will be indispensable to realize optical signal reproduction technology to keep the quality of transmission waveforms and optical SNR to avoid deterioration.

As technologies for signal reproduction and quality maintenance, two technologies have been proposed. The first is the optical 2R technology which implements a reproduction function of signal levels and a function of waveform forming, and the second is optical 3R technology which has a function to restore waveform timings in addition to the 2R technology. These technologies must be based on non-linear operation which having a threshold characteristic, and various configurations are usable, such as a configuration to use the non-linear optical effect in optical fiber and the non-linear operation of semiconductor devices.

Table III-6-1 Sample configuration of optical 2R/3R using optical fiber

Name	Self phase modulation (SPM) + optical filtering type optical 2R	NOLM type optical 2R	Soliton type optical 2R	Optical Kerr effect switch + Wavelength shift type optical 3R
Bit rate	10 Gb/s	40 Gb/s	40 Gb/s-4 waves	160 Gb/s
SN improvement	Improvement of space part	Q-value > 10 after going through 12 steps of NOLM	Improvement of 2dB receiving sensitivity	Realization of 160Gb/s - 186km transmission (Transmission is impossible without optical 3R)
Wavelength characteristic	Wavelength may be shifted by SPM	Wavelength variation may be accumulated	Predicted to be good	Good (adjustable)
Power of operation	Average: 90 mW	Peak: 90 mW	A large value is needed.	CLK light for re-timing (average value) + 21 dBm
Problem	High dependency on input waveform	Dependency on polarization, susceptible to vibration	Too much operation power needed?	Dependency on polarization, complicated configuration

Table III-6-2 Sample configuration of optical 2R/3R using semiconductor elements

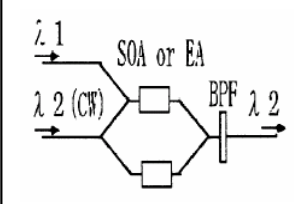
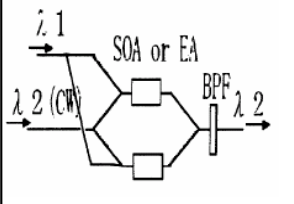
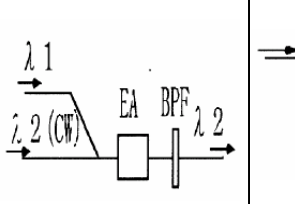
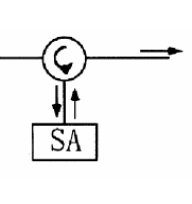
Name	Cross phase modulation (XPM) - Interference type	XPM - Time difference (τ) - Interference type	XPM type using an optical modulator of electric field absorption type	Saturable absorber (SA) type (multiplexed quantum well structure)
Bit rate	40 Gb/s (3R)	84 Gb/s (3R) (operable even at 168Gb/s for wavelength conversion)	40 Gb/s (3R)	20 Gb/s (2R)
SN improvement	A round transmission of 50km x 300 times at 10 Gb/s	A round transmission of 40km x 100 times at 40 Gb/s	A transmission of 40Gb/s and 6,500km	A round transmission of 160km x 49 times at 20 Gb/s
Wavelength characteristic	Wavelength variation may be controlled.	Wavelength variation may be controlled.	Wavelength variation may occur. (Hard to control?)	Wavelength variation may occur. (Hard to control?)
Power of operation	Around -10dBm at several Gb/s	SOA: -5 dBm (average) EA: +15 dBm (average)	Average +18 dBm	Average +7.5 dBm
Problem	Complicated device	Complicated device, difficult timing adjustment	Great power of operation	Great power of operation
Configuration diagram				

Table III-6-1 is a summary of the configurations using optical fiber, and Table III-6-2 is a summary of those using semiconductor elements. Operation demonstration at the basic configuration and device levels has been realized for both proposals. For example, an experiment of the transmission of 40 Gb/s and 10,000 km has been performed in a configuration of optical 3R using a LD of the mode lock type and an optical gate of the SOA type. In addition, for the optical fiber type, a demonstration of the optical 3R function at 160 Gb/s succeeded by polarization switching using the optical Kerr effect. However, many technological problems must be overcome to put the 2R/3R technologies into practical use, such as the realization of long-term stable operation, reduction of operation power, and elimination of polarization dependency, so various matters must be considered to put the technologies into practical use. Conversely, if a very simple high-performance 2R/3R function is realized, for example, introduction of the ultrafast transmission technology at a bit rate of 160 Gb/s or more will progress quickly. This will be as impressive as when EDFA technology emerged from the viewpoint of technologies. This is a technological theme which is very challenging but also one that should be realized by all means.

6-3 Signal quality monitoring technology

Individual devices configuring an optical network (OXC devices and linear relays) are configured with different functional blocks, respectively. For OXC devices, the signal unit handled by major functions is not uniform. For example, wavelength multiplexing signal lights are input, demultiplexed into some wavelengths, switched by optical switching devices on a single wavelength basis or on a multiple wavelengths (wavelength group) basis, multiplexed with other wavelengths (wavelength group), and then sent to the fibers on the output side. On the other hand, it is not enough to realize multiple functional blocks for each device to configure a highly reliable optical network system, so it is important to implement functions which can be commonly and cross-sectionally managed without discrepancy for each targeted optical signal unit.

ITU-T standardized architecture to manage optical networks which makes it possible to design such a system [10] based on Recommendation G.872, and an optical network divided into the following three functional layers, is shown in Fig. III-6-3.

(1) Optical Channel (OCh)

A layer corresponding to optical paths. This layer realizes end-to-end networking functions

(2) Optical Multiplex Section (OMS)

A layer to multiplex multiple optical channels as well as divide a wavelength multiplexing signal light into individual optical channels.

(3) Optical Transmission Section (OTS)

A layer to regard OMS as a function to provide signals suitable for transmission through optical fiber, and support the transmission function of optical signals.

In an optical network system realized based on a layered management system, an operator can easily identify the cause or location of a fault which has occurred on the network by monitoring optical signals for each layer. It is very important from the viewpoint of network operation that not only disconnection of optical signals caused by a laser degradation, fiber disconnection and so on but also the deterioration of signal quality can be detected.

Signal quality is stipulated by a bit error rate (BER). However, since the signal quality must currently be monitored in the electric domain by optical-electrical conversion, it will be indispensable to do optical-electrical conversion for each node over a wide-area optical network. However, since the interface for such optical-electrical conversion must be implemented on a per wavelength basis, power consumption and interface costs will increase. (It is known that over half of the total cost of the OXC system is occupied by interface costs.) So it will be necessary, in particular in an area where a transmission speed per wavelength exceeds 100 Gb/s, to realize signal quality management by all optical processing.

There are various efforts to manage signal quality using all optical processing, and there are many methods to implement it. For example, some methods use statistical techniques and other methods use an optical power monitor, OSNR monitor and so on. As statistical methods, a method to use synchronous sampling [11,12], a method to use asynchronous sampling [13,14], and a method to use an asynchronous eye monitor [15] are usable. On the other hand, as methods using an optical power monitor or OSNR monitor there is a method to use gratings and PD arrays [16], a method to use an arrayed waveguide grating (AWG) filter [17], and a method to use an acousto-optical tunable filter [18]. These technologies cannot fully replace direct monitoring using BER. However, if a technology to monitor signal quality by all optical processing which is reliable as well as BER is realized at a low cost, the operation of optical networks may also be influenced. For example, different quality monitoring technologies are used according to the service classes of different quality assurance classes. So, research and development in the future is expected.

In addition, it will also be necessary to address technology to perform the digital operations of the all optical type. In short, this is technology to make it possible to perform the digital operations required for monitoring the quality of optical signals at a high bit rate using light as it is. There are reports on AND operation, EXOR operation [19, 20], and flip-flop operation [21] using all optical devices. However, no case of executing such operations at a speed of the 160 Gb/s class has been reported, so this is a future theme.

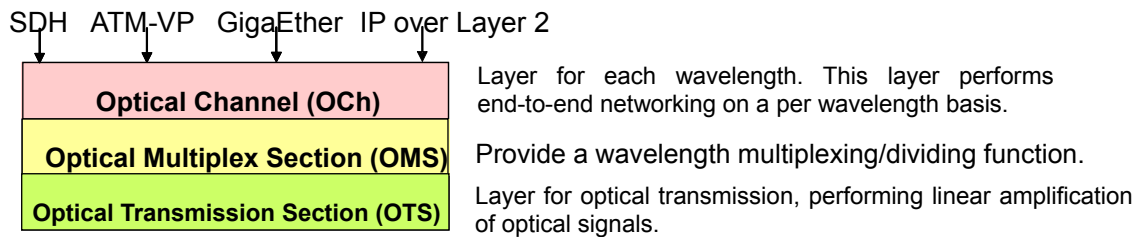


Fig. III-6-3 Optical network architecture (G.872)

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Part 7 Service Architecture for Grid Technology

As mentioned above, the service architecture used will be an important factor in the future use of wide area networks. Switching by electric signals is seriously problematic when used broadly due to its power consumption, implementation density, costs and so on. Hence, a method to control routes using light will be used. However, since it is difficult to use OPS to realize the same function as the conventional method which uses electric signals, communication methods including communication protocols, must be completely changed.

Optical circuit switching (OCS) reserves optical paths during a period of some seconds to some days using control technologies such as GMPLS. It is able to perform communications using a protocol such as TCP/IP (Transmission Control Protocol/Internet Protocol) in the same way as conventionally used when a path is reserved. However, it is difficult when and by what trigger a path should be switched.

The one-way type of OBS is a method to use a packet greater than an OPS packet in size. Since signals are switched together on a per burst basis, switching as fast as OPS is not necessary and is not required. In addition, since data in a burst arrives according to transmission sequence, data are handled in an easier way than OPS. However, when channels are being used frequently, data may be lost due to a conflict at the exit links of switching as well as the case of OPS. On the other hand, the two-way type is a method to use a shorter time to ensure optical paths than the optical path ensuring method. Since communications never start before a path is ensured, data is never lost due to a conflict at the exit links of switching. However, because ensuring a path takes a longer time than the round-trip delay, this method is not as flexible as the one-way type. In addition, because ensuring a path takes a short time, two-way is not suitable for protocols such as TCP/IP, which takes a long time from the start of communications to the establishment of an effective transmission bandwidth which is sufficiently wide.

As mentioned above, the candidate service architectures for using wide area networks have merits and demerits, so it is not clear which method will be broadly adopted in the future.

7-1 Service architecture for optical circuit switching (OCS)

To implement the broadband optical network mentioned above in a more user-friendly manner, a method to provide networks as resources for users through resource management by grid technology will be usable. OCS, which ensures optical paths, is suitable for this method. Grid technology will provide users with the resources distributed over networks in an easy-to-use manner. In this case, by providing users networks that connect resources with each other as grid resources, more secure and highly efficient services can be provided. The framework of network resource management using grid technology will be as shown in Fig. III-7-1.

When a user requests a service from a service provider, the service provider will construct a framework to schedule resources, including the networks necessary for providing the service, and

then provide the service. For example, if a user requests a service provider to distribute high-resolution content needing a broadband for distribution, a server capable of providing the content and a path from the server to the user will be simultaneously ensured, and then the content will be distributed. The model assumed here may not be only a model for distribution by a concentrated server but also a model for dispersed servers capable of distributing content, such as the peer to peer (P2P) type.

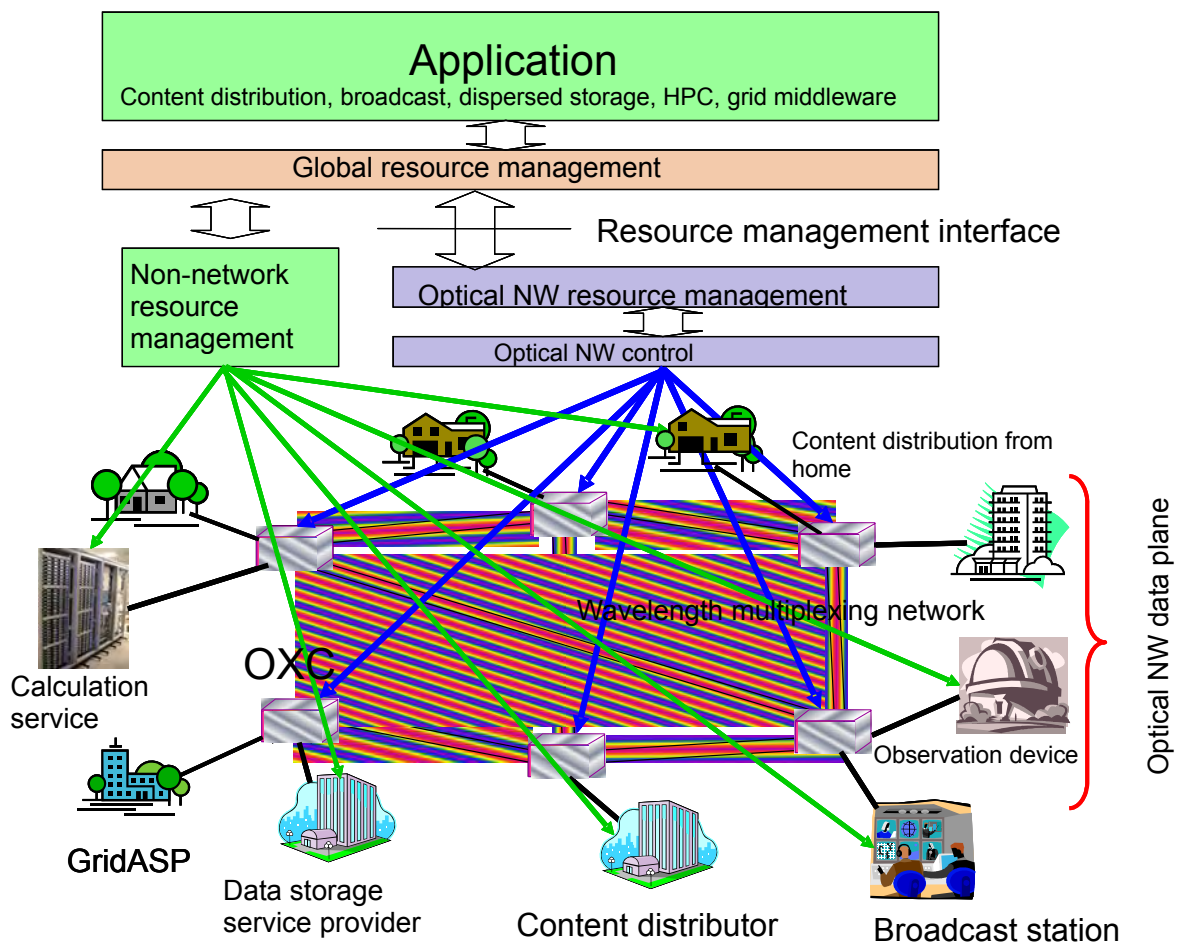


Fig. III-7-1 Resource management and networks by grid technology

A user directly, or an application service provider who receives a service request from a user, requests a global resource management organization to ensure network resources and other resources (such as a content distribution server) simultaneously. Here, requests from users must be able to include, for example, payment of a high price to enjoy content immediately or enjoy content at a low price without specifying any particular time. By introducing such an economic model, resources, including networks, will be able to be used effectively. Not only a model to establish pricing for each time zone, but also more flexible economic models such as bidding will be introduced.

To realize such a style of use, it is necessary to stipulate the resource management interface between network providers and grid services. Hereafter, this section describes each layer regarding networks.

- Application layer:
Applications and middleware. For example, a user request for content distribution is applicable to this layer.
- Global resource management layer:
Configured with a global resource management component for performing distributed management over grid resources. This layer manages resources, including computers and optical networks (NW), based on requests from the application layer to perform necessary operations such as scheduling.
- Optical NW resource management layer:
Configured with the optical NW resource management component for controlling the status of use of optical NW resources (wavelengths, switching ports and so on) and controlling requests to use such resources.
- Optical NW control layer:
Configured with the GMPLS control function of each communication device, which automatically collects optical NW topological information and sets up (or removes) an optical path of 160 Gb/s, which is a logical communication route, between two points using GMPLS control based on topological information.
- Optical NW data plane:
In Fig. III-7-1, the network portion which actually sends data, shown at the bottom of the figure, is applicable to this portion. This component is configured with wavelength routing devices for switching signals on a basis of 160 Gb/s wavelength, such as OXC and reconfigurable optical add/drop multiplexer (ROADM), IP routers and layer-2 switches for transferring bulk data of 160 Gb/s sent from a cluster or storage to a wavelength routing device, and connection groups (optical fiber and optical paths) for connecting such communication devices to each other physically or logically.

A logical interface to control collaboration is stipulated between the global resource management layer and the optical NW resource management layer. The former layer is generally connected with the latter layer on a many-to-many basis. In addition, on a mature grid-light unified network which needs to set up an optical path of 160 Gb/s, mutual collaboration of multiple global resource management layers and mutual collaboration of multiple optical NW resource management layers will also be needed. In particular, the latter collaboration will be necessary when an optical NW is configured by multiple network carriers.

The network carriers of optical networks provide optical paths as services for users on the grid side in exchange for a usage fee. In other words, a user network interface (UNI) is stipulated between the network carriers and users of optical networks in the same way as applied to the

conventional communication services. If the optical network data plane has user communication devices, the control of such user devices will be separated from the control of the communication devices of network carriers at UNI.

When grid networks are unified with optical networks for commercialization purposes, a so-called overlay model (Fig. III-7-2) is adopted to the optical NW control layer to separate control between users and network carriers (separation of routing and signaling). For the collaboration of the control layers between users and network carriers, for example, GMPLS UNI, which was standardized by the Internet Engineering Task Force (IETF), is used. In particular, if network carriers provide only wavelength routing devices as grid technology, optical UNI (OUNI), which has been standardized by the Optical Internetworking Forum (OIF), is also usable.

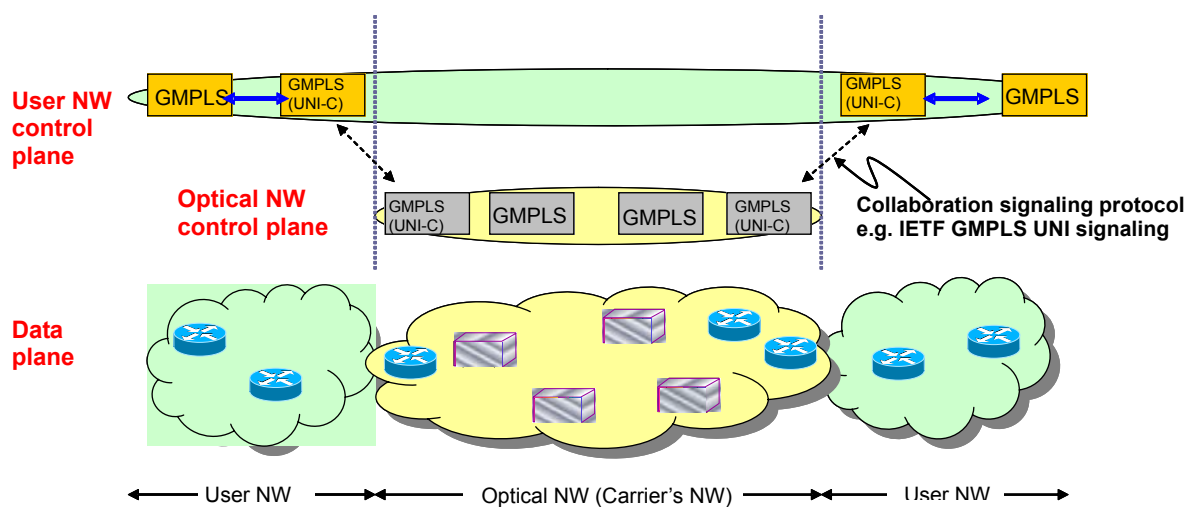


Fig. III-7-2 Separation of control plane using an overlay model

The optical NW resource management layer assigns wavelength resources so that the resources specified by the global resource management layer (computers and so on) are connected to each other by optical paths (160 Gb/s). The optical NW resource management layer has a table of the nodes accommodating the resources specified by the global resource management layer and determines if the specified resource is accommodated in any node (admission control).

An optical path set-up request message includes an event type, start node, end node, optical path type, optical path bandwidth (160 Gb/s, 40 Gb/s and so on), optical path opening time, optical path removal time, quality request and so on. The event type above indicates what processing the global resource management layer requests to the optical network resource management layer, by which an event such as optical path set-up, optical path removal, reservation change, reservation cancellation, and reservation status inquiry and so on is specified. Optical path type is an identifier for a set-up form of an optical path, identifying a case of requesting immediate set-up and a case of reserving set-up at a time in the future. In other words, the optical NW resource management

layer can handle two forms of optical path set-up: on-demand set-up and advance reservation. In particular, on-demand set-up performs queuing (scheduling) as needed.

The optical NW resource management layer has management information such as the status of resource use (wavelengths) and reservation status of optical networks at any time. It is judged if advance reservation or on-demand set-up can be made by comparing a new optical path set-up request with the management information, and then the results are provided to the global resource management layer.

When an optical path set-up request is normally received, the optical NW resource management layer sends a signaling start-up message to the GMPLS control component of a start-up node (ingress) at a predetermined time (or immediately) based on the content of the received request. This start-up message includes the name of a predetermined end node (egress), and an optical path (route and wavelength) to the egress is automatically ensured (loose specification) by a signaling message sent by the ingress, such as by Resource Reservation Protocol/Traffic Extension (RSVP-TE). When a normal optical path has been set up, the GMPLS control component of the ingress will notify the results of the set-up to the optical NW resource management layer, and then update the management information of the optical NW resource management layer.

Some applications may require an optical path of preferred quality (delay, fluctuation of delay and so on). In such a case, an optical path route satisfying the quality is calculated by the optical NW resource management layer, and then the results are explicitly notified to the GMPLS control component of the ingress (explicit specification).

To manage optical network resources, the series of functions mentioned above are indispensable. By making these functions collaborate with the global resource management layer, it will be possible to unify resource management between grid networks and optical networks. Such resource management unification will make it possible to use optical networks at the initiative of users, and optical networks will be used as an infrastructure capable of ultra broadband connections potentially possessed by computer grids and data grids.

Part 8 Summary

This SWG3 report was organized by commission members covering each layer of the optical network, except for the top layer related to content and so on (optical devices, optical network architecture, and IP networks). This is because it was a goal that engineers of each layer understand what is requested by end users (for optical devices, from the users of optical networks, and for optical networks, from the users of grid IP networks). With this framework, it will be possible to understand the problems on the user side, and make an argument to put needed technology into practical use.

The following is a summary of SWG3 tasks.

It will become necessary in the future to ensure the availability of a large-capacity communication route at any time for the style of use which occupies a network for a long time, such as content distribution, and storage connected online based on the so-called personal information protection law. Moreover, as large-scale science and technology calculations are adapted to the field of the environment and fully applied to some industries such as finance, it will become necessary to use wide area networks safely and easily and provide services at a low price. So, using networks effectively through collaboration between the upper layer management function and optical network management function, such as grid technology, will become necessary.

For nodes, the problems to address are protection against lower network use effectiveness and implementation of an ultra broadband network. To avoid a decrease in network use effectiveness, it will be important to raise the speed of the WDM node and its interface in addition to the methods of increasing the number of ports and multiplexing packets. Technologies related to 160 Gb/s will become important from this viewpoint as well. On the other hand, for the configuration of an ultra broadband network, it will be effective to develop a method to provide circuit switches using optical paths (OCS) and optical burst switches (OBS) in a easy-to-use way in the case of using current element technologies, so a method to connect GMPLS technology, which is the network control layer, with IP networks is under consideration. On the other hand, for the implementation of optical packet switching (OPS) which replaces the architecture of current electric packet switching as it is to use networks in the most effective way, since the key optical buffer memory is still at the stage of principle demonstration, it is necessary to address future research and development in a strategic manner.

In addition, as for the development themes to realize ultra broadband networks, required technologies common to OCS, OBS and OPS were considered. To be specific, wavelength conversion technology, signal reproduction and quality maintenance (deterioration protection) technology, and signal quality monitoring technology and so on are important themes, so it will be necessary in the future to sufficiently verify the development of such technologies and their effectiveness. To do so, it is necessary to carry out research and development broadly to include

devices, optical networks, and even IP networks by mutual collaboration, so this will be a theme deserving a national program.

In addition, technologies for GMPLS, optical circuits, optical bursts, optical packets and future themes were also considered. To meet user needs in each network layer which uses these technologies, it is necessary to fix not only problems such as MEMS for optical switching, which can be resolved by research and development within a relatively short time period, but also risky problems requiring extensive verification and important problems related to optical buffer memory and so on, which must be fixed in principle. For high risk technology development such as the latter, it will be necessary to address issues effectively and strategically from a mid- to long-term viewpoint, so it will be an ideal way for Japan's research and development to address the latter in addition to the former in a well-balanced manner.

IV. Public Network

IV. Public Network

Part 1 Introduction

In addition to ADSL (Asymmetric Digital Subscriber Line) and CATV (Community Antenna Television), access to optical broadband by the use of FTTH (fiber to the home) is finally beginning. The year 2005 will welcome the second phase of broadband and be seen as the first year of the true broadband age, which will continue to grow for the next five to ten years. Data traffic is almost doubling every year, and this is anticipated to continue for some time. In order to support such traffic volume, public networks such as the backbone network and the METRO system will need transport technology and networking technology that are highly reliable and stable with ultrahigh capacity/high throughput transmission.

With regard to “photonic networks” in the next generation and following generations, they may be required to provide features such as “Bandwidth on Demand (BOD)” that can easily provide tunable bandwidth depending on the needs of user applications, where bandwidth would quickly be allocated to a serial mode or a parallel mode. In this case, the necessary signal rate will be far over 100 Gb/s and could reach the order of Tb/s, and high speed and ultrahigh capacity will be required for digital multiplexing ETDM (Electrical Time Division Multiplexing), analog parallel multiplexing such as OTDM (Optical Time Division Multiplexing) and WDM (Wavelength Division Multiplexing). In particular, with ETDM and OTDM that are based on time division multiplexing technology, the signal of each TDM channel is in the same bandwidth and does not have a skew, therefore ETDM and OTDM are inevitable technologies for the need of high speed and low delay transmission.

Here, we have divided ultrafast technology constituting the public network in 2010-2015 into the three categories of node technology, link technology and key technology, and summarized each of them in consideration of the current status and issues, and necessary technology. Part 2 describes the outline of node functions, the benefits of ultrafast communication as well as various areas of technology required for the ultrafast optical node. Part 3 summarizes link (CORE, METRO) technology, including its outline and application areas of ultrafast transmission, and necessary technology, including an ultra long-haul transmission system, a long-haul transmission system, and a short-reach transmission system. Part 4 explains the key technologies indispensable for realizing ultrafast node technology and ultrafast link technology.

Part 2 Node Technology

2-1 Outline of node functions: status and issues

The area of the optical communication system is expanding from simple point-to-point transmission technology to a network technology made up of multiple nodes. Here, the role of the node in the network and the issues to be solved by the ultrafast optical technology are described.

2-1-1 Switching

Switching (exchange) can be divided into two categories, that is, direction switching by the unit of optical fibers and switching by the unit of optical path multiplexing the circuits or flow into a certain bundle. An optical path is a logical concept and does not necessarily correspond to a transmission network. To construct a large-scale network economically, it is necessary to provide functions for transmitting signal efficiently by multiplexing the paths and enable add/drop and cross-connect functions at the optical path level at intermediate nodes.

Based on recent development of wavelength multiplexing technology, a study is underway on a method to manage wavelengths as optical paths and switching using wavelength cross-connect switching. Assuming a network consisting of 25 nodes with a full-mesh path setting for domestic use, it is calculated that a node for switching 512 optical paths (16 wavelengths x 32 directions) will be needed. [2.1.1.1]

Because of the rapid increase in traffic and the diversification of transmitted data, switching at a smaller size than wavelengths is required to make more efficient use of network resources. While current switching technology is based on electronics, it is necessary to develop optical switching technology without optical-to-electrical conversion in order to speed up processing and reduce power consumption.

2-1-2 Gateway

The gateway function at a node is an important technology to connect mid- to-low speed METRO and ACCESS networks with a high-speed backbone network. This requires technologies to combine optical signals of various bit rates and modulation formats transmitted from lower layer nodes and terminals, and to convert them into the bit rate and modulation format signal suitable for a backbone network. Technology in the backward direction is also required. Specifically, technologies for bit rate conversion, NRZ/RZ (Non-Return to Zero/Return to Zero) conversion, WDM/OTDM (Wavelength Division Multiplexing/Optical Time Division Multiplexing) conversion, etc. will be required. At present, such gateway functions are processed electrically, but development of all-optical technology is desirable to speed up node processing and reduce power consumption.

2-1-3 Signal monitoring

In a transparent network without optical/electrical conversion, transmission distances and transmission lines may change due to dynamic switching of optical paths, which may also change signal quality. Therefore, it will be necessary to monitor the quality of optical signals passing through the nodes, and to protect and recover optical paths as needed. For this purpose, the development of on-line monitoring technology during services for various parameters such as signal-to-noise (SN) ratio, eye diagram, Q-factor, etc. will be required regardless of modulation formats or bit rates. At present, the prevailing method is to convert optical signals into electric signals for monitoring, but monitoring technology without complicated clock extraction is required for ultrafast optical signals over 100 Gb/s.

2-1-4 Network control/management

To realize optimization of network resources depending on traffic variations and quality assurance responding to the characteristics of transmitted data, control/management functions at the nodes are required such as setting/switching of optical paths, recovery from failure, and scheduling. These functions will be carried out by electronic or software processing at the control plane. Information on network control/management must be transmitted through a separate network from that of user data from the standpoint of reliability. In a network that handles ultrafast optical signals over 100 Gb/s, network control/management responding to service status and monitoring technology for ultrafast optical signals is important.

2-2 Benefit of ultrafast transmission – Comparison with electric processing and WDM

The characteristics of each device constituting the nodes depends strongly on the switching methods in the nodes that consist of four basic functions, switching, gateway, signal monitoring, and network control/management, as mentioned in Section 2-1. Data traffic is continuously increasing due to the rapid growth of the number of Internet users and content diversification. The ultrahigh capacity of optical transmission technology making use of signal speed increases and wavelength division multiplexing (WDM) is becoming available. While ultrahigh capacity long haul transmission technology is steadily improving, essential tasks for development to establish an ultrafast transmission infrastructure are realization of faster speed and greater capacity of transmission. [2.2.0.1]

In this section, we compare, from the viewpoint of the device, transmission capacity enhancement via WDM and transmission capacity enhancement via over 100 Gb/s ultrafast signal processing technology that is currently being developed as a method for realizing larger volume processing at a node.

2-2-1 Wavelength management

With regard to larger capacity transmission technology via WDM, the interval of wavelength channel was initially considered to be 100 GHz by ITU-T (International Telecommunication Union-Telecommunication Sector). The spectral efficiency, however, has increased dramatically since wavelength multiplexing at higher density has become possible through research on modulation formats such as DPSK (Differential Phase Shift Keying), CS (Carrier Suppress), etc. At the same time, a larger capacity transmission technology using the ultrahigh density WDM method with 12.5 GHz wavelength division is being examined since a narrower bandwidth of wavelength multiplexing/demultiplexing was realized through a wavelength multiplexing/demultiplexing circuit like AWG (Arrayed Waveguide Grating). realize such an ultrahigh density WDM method, technology is required for precisely controlling and managing the wavelength of output signal sources. The wavelength grid of wavelength multiplexing/de/multiplexing like AWG, and the wavelengths of control light sources such as a wavelength converter, optical switch, and optical 3R by using a high accuracy frequency standard, a narrow-band filter, etc. to control signal degradation due to crosstalk between adjacent channels.

Ultrafast transmission more than 100 Gb/s that sets up a wider wavelength space between adjacent channels as compared with the ultrahigh-density WDM method alleviates measurement/management accuracy by about 1/2 to 1/10 as compared with 10 Gb/s or 40 Gb/s wavelength management, assuming the same level of spectral efficiency as the ultrahigh-density WDM method. Alleviation of wavelength measurement and management systems for wavelength channels will directly mean accuracy alleviation in manufacturing and control of devices constituting the node. Furthermore, with the next-generation node requiring a larger capacity throughput of about 100 Tb/s in the future, the number of ports needed will be huge like 1000 x 1000, and therefore it is preferable that the channels be fewer and easier to manage.

2-2-2 Mass processing

In a WDM network that handles an increase in capacity by increasing the number of wavelength channels, if the number of channels increases, it is anticipated that the number of wavelength paths from one node to the same target node will increase. Moreover, the wavelength channel of the switched output port will be occupied by signals from other input channels, causing a collision of signals, and setting up and managing a wavelength channel to avoid such collisions will possibly become complicated.

The WDM method network converts wavelength at the time of switching in order to avoid a collision of signals. The conventional network uses optical/electrical/optical signal processing. Considering device cost, electric power consumption and the fact that about 70% of signals passing through the node are cut-through transmission, optical/electrical/optical signal processing will not be efficient. With regard to a wavelength conversion device, therefore, an all-optical wavelength conversion device that converts light of a certain wavelength directly into wavelengths

without electric signal processing will have a great advantage.

To simplify system management/control and devices, there is a method called optical cross-connct (OXC) that routes wavelength multiplexing as it is by using light switching through demultiplexing/multiplexing of multiple wavelength paths as a group. In this connection, with regard to the optical burst switching method currently underway for applicability that establishes a path dynamically, it may also be possible to use a method for controlling the wavelength paths as a group as traffic increases. As for these switching methods, an all-optical wavelength conversion device is suitable if it uses nonlinear effects in a medium such as four wave mixing and difference frequency generation, etc. which can convert multiple wavelengths at the same time. It is expected that the number of devices within a node may be reduced by means of wavelength group conversion and switching using these devices. [2.2.2.1]

In addition, by speeding up signal transmission to over 100 Gb/s and using Time Division multiplexing (OTDM), mass processing of 10 channels of the 10 Gb/s WDM method will be possible by using one wavelength of 100 Gb/s signals.

2-2-3 Scalability

When the same level of traffic volume at 10 Gb/s or 40 Gb/s is replaced with 100 Gb/s ultrafast transmission, the number of wavelength channels will be reduced to 2/5 to 1/10. A reduction of the number of wavelength channels will lead to a reduction in the number of light switches and paths within a node, which will make it easier to reduce the number of component parts of a device and make their control easier as well. If the traffic volume increases and the number of paths is also increased (in the WDM method), an over 100 Gb/s bit rate will increase its traffic volume per unit wavelength channel or unit time by 2.5 times to 10 times, as compared with 10 Gb/s or 40 Gb/s speed. Therefore, the number of parts and number of control points can be fewer to cope with the same increase in traffic. As a result, there can be effects of controlling the increase of electric power consumption and costs. Since the number of channels is smaller, the number of switches within a node can be reduced, thereby decreasing quality degradation of signals and improving scalability.

2-2-4 Electric power consumption

It has been pointed out that the conventional node with electric signal processing was not able to respond to ever-increasing traffic. There are issues like the limit of signal processing capacity in a semiconductor integrated circuit for processing signals, electric power consumption due to a larger scale, and a limit of unit dimensions.

Since the optical/electrical/optical conversion device in an electric signal processing node becomes a main factor for increased electric power consumption and costs, it is a better policy to use all-optical that switches light directly for signals with possible cut-through. This will reduce electric power consumption to 1/3 ~ 1/10. As for an all-optical device, the increase of electric

power consumption is smaller in the case of speeding-up than in the case of increasing the number of channels, and is smaller than an electric device. Therefore, the use of an ultrafast optical signal processing device is better from the viewpoint of electric power consumption reduction.

2-3 Technology necessary for an ultrafast optical node

2-3-1 Add-drop, time slot exchange

A drop function at the level of the time slot of ultrafast optical signals can be realized with DEMUX (Demultiplexing). An add function can be passively realized by using a directional coupler. There are reports on experiments using optical switches utilizing a semiconductor optical amplifier [2.3.1.1, 2] and an electro-absorption optical modulator [2.3.1.3] for 160 Gb/s OTDM signals. Turkiwicz, et al. [2.3.1.2] constructed an add-drop node for 160 Gb/s OTDM signals by using an optical switch based on cross-phase modulation effects in a semiconductor optical amplifier, and reported a network experiment using installed 137 km and 275 km optical fibers (Fig. IV-2-1). This experiment showed that the OTDM add-drop function can be used in a current network. However, downsizing and higher reliance of sub-systems such as a transmitter, clock extraction, and an add-drop multiplexer are needed.

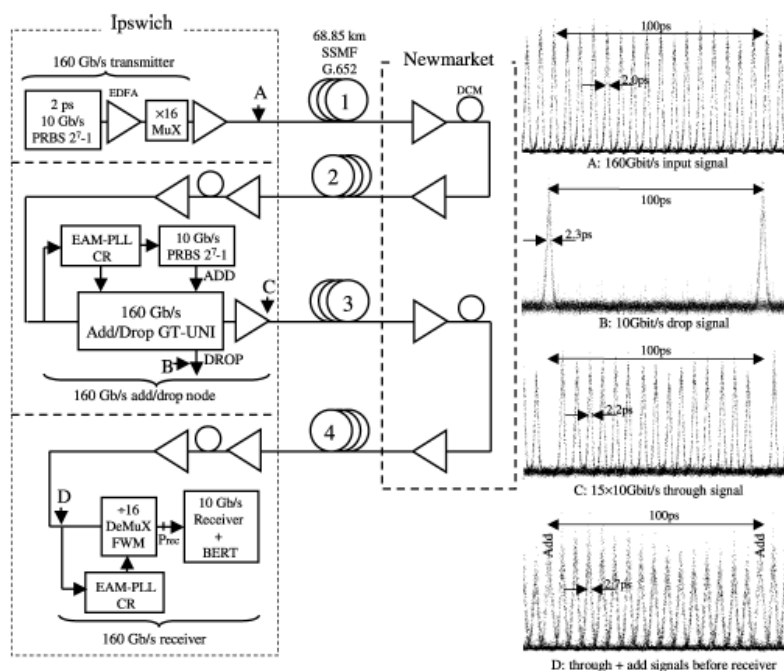


Fig. IV-2-1 OTDM add-drop node [2.3.1.2]

An extension of the add-drop function is a time slot exchange, which is realized by dropping multiple slot data, controlling the delay of each datum, and adding these data into appropriate time slots. In particular, delay control of dropped data is technically difficult, and timing accuracy and tunability is required. So far, methods of using fixed optical fiber delay line [2.3.1.4], combination of wavelength conversion and fiber Bragg grating [2.3.1.5] have been proposed. While an experiment was reported for 2.5 Gb/s signals [2.3.1.5], a penalty arising from crosstalk between time slots was observed. Development of tunable delay control technology is essential for higher performance and speed.

2-3-2 Modulation format conversion

Conversion from NRZ (Non-Return to Zero) signals to RZ (Return to Zero) signals can be realized by the combination of clock extraction and optical switching. In other words, RZ signals are obtained by switching the optical clock signals extracted from the NRZ signals by the NRZ signals as control signals (Fig. IV-2-2). Methods using four wave mixing in a semiconductor amplifier [2.3.2.1], cross phase modulation in a semiconductor optical amplifier [2.3.2.2], and an electroabsorption modulator [2.3.2.3] have been proposed thus far, but the bit rate of the signals is limited to 2.5~10 Gb/s. Technology for converting multiple WDM-NRZ signals to a single OTDM-RZ signal is required in the near future. Technology for timing control and buffering to convert multiple asynchronous signals into OTDM signals is essential.

Conversion from an RZ signal to an NRZ signal can be realized by combination of the duplicating of an RZ signal pulse and an optical switch. As shown in Fig. IV-2-2, an NRZ signal is obtained by duplicating an RZ signal and lining up the signals so as to occupy a one bit interval, and by using them as control light for wavelength conversion [2.3.2.2]. Operation at 2.5 Gb/s has been confirmed by using a Mach-Zehnder interferometric optical switch. To apply it to a higher bit rate signal, it is necessary to reduce crosstalk from adjacent time slots arising from the pulse width and timing jitter of RZ signals.

WDM to OTDM signal conversion was proposed by using wavelength conversion [2.3.2.4]. To generate OTDM-RZ signals, multiple WDM-NRZ signals are converted to RZ signals with an appropriate pulse width, which are then multiplexed to form an OTDM signal with different wavelength in each tributary and are used as a control signal for wavelength conversion. As shown in Fig. IV-2-3, there is a report about conversion from 4-channel 10 Gb/s WDM signals to 40 Gb/s OTDM signals [2.3.2.4], and it is regarded possible to expand it to 160 Gb/s. OTDM to WDM signal conversion can be realized by four wave mixing of chirped supercontinuum light and OTDM signals. There is also a report about conversion from 80 Gb/s OTDM signals to 8-channel 10 Gb/s WDM signals using 100 m long highly nonlinear optical fiber [2.3.2.5]. Expansion to 160 Gb/s can be considered but the wavelength after conversion will be restricted by chirp characteristics.

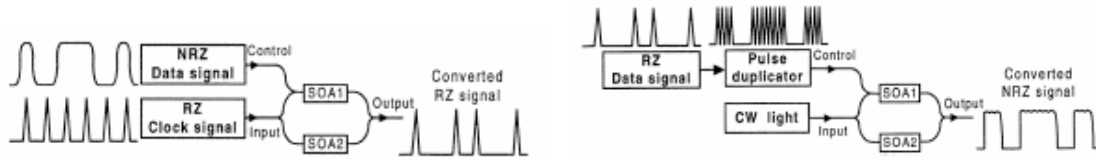


Fig. IV-2-2 NRZ/RZ conversion [2.3.2.2]

With regard to optical bit rate conversion, there is a report on principle experiments of compression and decompression of packet signals of less than 10 bit length [2.3.2.6.7]. Development of optical buffer memory is inevitable to realize compression and decompression of burst signals and longer packet signals [2.3.2.8].

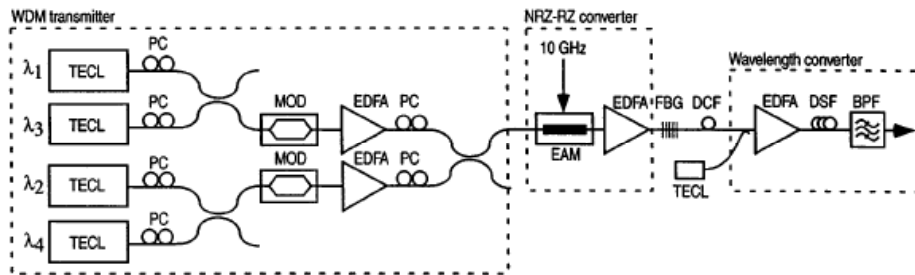


Fig. IV-2-3 WDM/OTDM conversion [2.3.2.4]

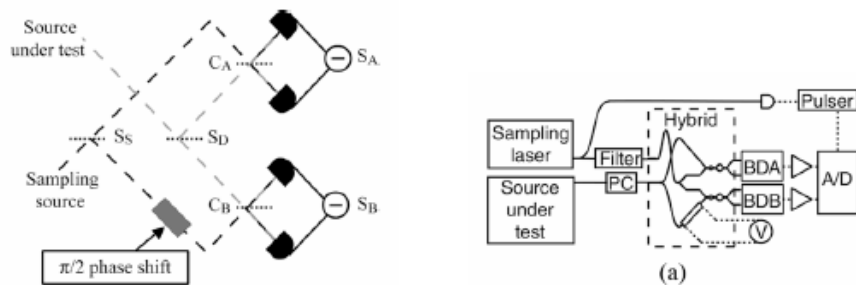


Fig. IV-2-4 Principle of linear optical sampling and measurement device [2.3.3.4]

2-3-3 Ultrafast optical signal monitoring

There is a report about asynchronous sampling as a technique for optical signal monitoring without clock extraction. Asynchronous sampling does not depend on the bit rate of signals, and it is comparatively easy to get an SN ratio and an average Q-factor [2.3.2.4]. A technique using electro-optic sampling with an electro-absorption modulator is proposed to monitor Q value at fixed timing, from which bit digital error rate can be estimated.

These methods assume conversion to electrical signals with a photodetector that is applicable to optical signals with a bit rate below 40 Gb/s. To monitor an optical signal beyond 100 Gb/s, an ultrafast sampling technique is necessary. Optical sampling is a technique to measure eye patterns of ultrafast optical signals by using sum frequency generation with nonlinear optical crystal or parametric effects in optical fiber. Measurement equipment based on this principle has

been commercialized and there is a report on observation of 640 Gb/s using sampling pulses of a 210 fs time duration [2.3.3.3]. It is difficult, however, to apply this technique directly to optical signal monitoring at a network node since it requires a sampling light source of ultrashort pulses and complicated clock recovery, and detection sensitivity is low. It is necessary to develop a compact and low power consumption measurement system with high sensitivity by using a semiconductor laser-based sampling light source and an asynchronous sampling technique without clock extraction. A linear optical sampling technique has been proposed to improve detection sensitivity and to measure the amplitude and phase of light, and 1000 times improvement in sensitivity has been reported as compared with nonlinear sampling [2.3.3.4].

2-3-4 New nonlinear material

Nonlinear optical phenomena in a material will be used for many optical switches and optical 3R devices that will become key devices of next-generation nodes. Since nonlinear optical phenomena are very weak, efficiency improvement is necessary for their application to signal processing.

The development of new materials will include various methods such as (1) using optical confinement by a waveguide structure like highly nonlinear optical fiber, photonic crystal, photonic crystal fiber, (2) using quantum-confined effects in semiconductor super-lattice, semiconductor quantum wire, semiconductor quantum dot, carbon-nanotube, organo-mineral complex quantum well, etc., and (3) quasi-phase matching using a polarization inversion structure like PPLN (Periodically Poled LiNbO₃), PPKTP (Periodically Poled KTiOPO₄), PPRTA (Periodically Poled RbTiOAsO₄), PPSLN (Periodically Poled Stoichiometric LiNbO₃), and PPSLT (Periodically Poled Stoichiometric LiTaO₃), (4) using high nonlinearity materials, bismuth optical fiber, organic molecules and high polymer compounds such as KTa_{1-x}Nb_xO₃, possibly enabling optimum nonlinear effects and intentional design of materials by means of design technology for large molecule material, etc. [2.3.4.1] A summary is shown in Table IV-2-1.

Table IV-2-1 Nonlinear effect increase method of nonlinear material and materials

Nonlinear effect increase method	Materials
Optical confinement by waveguide structure	Highly nonlinear optical fiber, photonic crystal fiber, micro-structure fiber, holey fiber, photonic crystal
Quantum-confined effects	Semiconductor super-lattice, semiconductor quantum wire, semiconductor quantum dot, carbon nanotube

Quasi-phase matching	PPLN, PPKTP, PPRTA, PPSLN, PPSLT
New materials	Highly nonlinear bismuth optical fiber, K _{1-x} Ta _x NbO ₃ Organic molecule, Polymer compound

Together with ultrafast signal processing, high-speed optical characteristics or a speed increase are required. With regard to the application of ultrafast optical devices, the efficiency of nonlinear optical effects must be enhanced and it will be needed to develop nonlinear materials compatible with a waveguide structure and having an ultrafast response (<1 psec) wide bandwidth (over 100 nm), non-centralized operation, stability and ease of integration.

2-3-5 Others (optical 3R, wavelength conversion, implementation technology)

To realize ultrafast optical node technology, it is important to commercialize a wavelength conversion device indispensable for optical switching and an optical 3R device that prevents signal quality degradation due to path dependency of signal quality and internal switching. These devices require specifications for downsizing and reduction of electric power consumption to prevent transparency not dependent on signal speed/modulation formats/multiplexing method, and to prevent upsizing of equipment, cost increases and increased electric power consumption related to an increase in the number of ports. To promote downsizing, it is indispensable to develop technology for implementing the integration of node functions. Promising technology for implementing a microminiature device and a new function device is silicon photonics technology using semiconductor optical processing technology such as optical switching and wavelength conversion functions within OADM, integration and microprocessing technology for a wavelength division demultiplexing/multiplexing device, nanophotonics technology, OADM using a ring resonator, AWG with a silicon waveguide, etc. [2.3.5.1]. (Table IV-2-2)

Table IV-2-2 Technology necessary for ultrafast node (others)

Item	Requirement for specifications
Optical 3R	Signal speed, modulation formats, non-dependency on multiplexing method (transparency), high extinction ratio, high SN ratio, downsizing, low electric power consumption
Wavelength conversion	
Implementation technology	Optical switch, wavelength conversion, integration of wavelength division/multiplexing device

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Part 3 Link (CORE, METRO) Technology

3-1 Outline of link technology - current status and issues

3-1-1 Current status of link technology

A terrestrial trunk network system requires a transmission distance of several hundred km to 1000 km (up to 3000 km in the case of North America). At present, the WDM (Wavelength Division Multiplexing) transmission technology of up to 10 Gb/s is available, and the number of wavelengths used is mostly about 40. Such systems use WDM transmission technology with a channel spacing of 50 GHz~100 GHz, an NRZ (Non Return to Zero) modulation format, optical amplification repeater technology of about a 30 nm bandwidth, and a standard error correction code (FEC : Forward Error Correction). The utilized optical transmission fibers are SMF (Single Mode Fiber), DSF (Dispersion Sifted Fiber) and NZDSF (Non-Zero Dispersion Shifted Fiber), and dispersion compensation is usually done with a dispersion-compensating fiber installed in a repeater station. There are some systems compatible with WDM transmission of about 160 wavelengths by using multiple amplification bandwidths (C band and L band).

In an optical transoceanic submarine cable system, transmission of an ultra long distance is required, such as about 6,000 km for the trans-Atlantic system and about 9,000 km for the trans-Pacific system. In the case of an optical submarine cable system, the most up-to-date technologies were introduced for each system to increase system capacity. With 10 Gb/s-based WDM transmission technology, the CRZ (Chirped Return to Zero) modulation format, distributed management transmission line technology, low-noise optical amplification repeater technology, high-performance FEC, etc., the transmission capacity per fiber in the latest systems reaches about 1 Tb/s [3.1.1.1].

The METRO system is a ring-structured network for a large city or connecting multiple cities, and the distance between nodes is generally about 50 km. At present, WDM systems up to 10 Gb/s are in place, and a mainstream network has about 40 wavelengths of 100 GHz spacing. The traffic, however, is continuing to grow rapidly. Recently, a system using multiple amplification bandwidths (C band and L band) compatible with WDM transmission of about 80 wavelengths for a 400 km ring distance was developed. There is a tendency that makes the borderline between a metro system and a terrestrial trunk system look ambiguous.

3-1-2 Issues for ultrafast systems (limiting factors)

Various issues as shown below must be solved in order to realize ultrafast systems of the 160 Gb/s class and long-distance transmission applicable to CORE/METRO systems, etc.

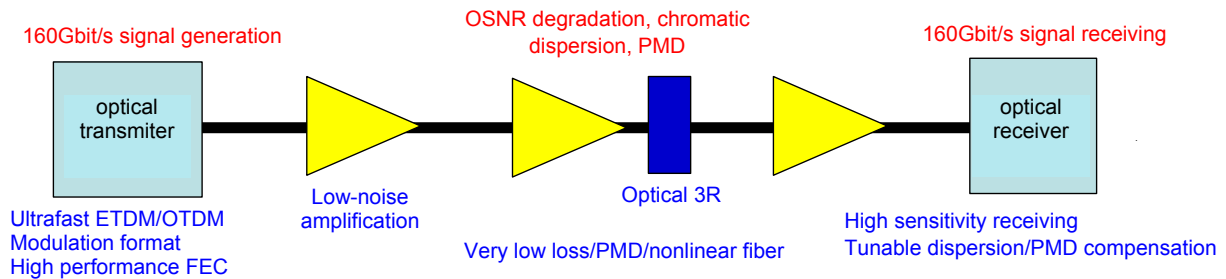


Fig. 3.1.2.1 Issues for realizing very high speed transmission systems

A. Transmitter/receiver technology

Realization of ultrafast electrical/optical devices used in the transmitter and receiver is an important task for generating and receiving ultrafast optical signals. In particular, time division multiplexing (ETDM: Electrical Time Division Multiplexing) is important since it is expected to reduce the necessary circuit size and cost drastically. The development of electronic/optical devices compatible with 40 Gb/s is progressing, and there are many reports about WDM transmission experiments of 40 Gb/s using such devices in papers and at conferences. Accelerating the bit rate by ETDM will be used up to 40 Gb/s, and OTDM (Optical Time Division Multiplexing) technology using an optical circuit will be important to attain further acceleration to a 160 Gb/s level with time division technology. There are a number of academic reports about transmission experiments at over 160 Gb/s bit rates, but research and development efforts are still required to attain commercialization of space saving, stability, low electric power consumption, etc. On the other hand, acceleration of bit rate by TDM will significantly affect the tolerance against various degradation factors in transmission as discussed later. Therefore, as a means of avoiding this, research and development efforts on multiple-level optical modulation/demodulation technology like the DQPSK (Differential Quadrature Phase-shift Keying) format [3.1.2.1] that can increase the bit rate without increasing a symbol rate are regarded to be important.

B. Transmission technology

To transmit ultrafast optical signals in a stable manner, it is inevitable to take measures against various degradation factors during transmission.

First, it is necessary to enhance the Optical Signal-to-Noise Ratio (OSNR) by four times (6dB) in order to increase bit rate by four times from 40 Gb/s to 160 Gb/s while keeping the signal quality. In this case, if it is possible to increase the optical signal power four times, sufficient OSNR will possibly be obtained. As the bit rate goes up, however, optical nonlinear effects in the optical fiber give a significant influence and limitation on the power of optical signals to be input into the optical fiber. This makes it difficult to increase the power of the optical signals and obtain necessary OSNR.

In order to reduce the degradation of transmission characteristics due to insufficient OSNR, there can be two solution alternatives, a method to decrease the OSNR requirement and a method to lessen OSNR degradation during transmission. Improvement of transmitter/receiver technology is essential to reduce the OSNR requirement, and development of a high sensitivity modulation /demodulation format and high performance FEC technology is needed. On the other hand, to reduce OSNR degradation during transmission, it is necessary to lower loss and nonlinearity of optical fiber and to reduce the noise of an optical amplifier. For example, assuming an optical amplification repeater system with a repeater spacing of 100 km, improvement of 1dB (about 20%) of transmission characteristics (Q factor) is obtained if 0.01dB/km of optical fiber transmission loss is reduced. If the permissible input power increases by reducing nonlinearity of optical fiber, improvement of transmission characteristics consistent with the increase of the permissible input power will be gained, and also with the reduction of noise of an optical amplifier, improvement of transmission characteristics consistent with the improvement of the noise figure will be obtained. (Improvement of 0.5dB of permissible input power/noise figure corresponds to improvement of 0.5dB transmission characteristics.) Assuming an upgrading of the optical transmission system up to a very large capacity of the 100 T/s class, it will be necessary to increase the input signal power into optical fiber up to over the watt class. In such an area, there is the potential occurrence of an input power limitation due to not only optical nonlinear effects but also physical damage of optical fiber (fiber fuse), and examination in this regard is needed.

In addition to OSNR, there are limitation factors degrading signal quality, such as chromatic dispersion and polarization mode dispersion (PMD). Tolerance of cumulative chromatic dispersion to a transmission line diminishes in proportion to the power of 2 of the bit rate, and the dispersion tolerance of a 160 Gb/s optical signal significantly shrinks to plus/minus 2 ps/nm (in the case of RZ signal). Therefore, dispersion compensation in a transmission line is essential, and assuming the applicability to an actual system, tunable dispersion compensation technology that can enable optimal dispersion compensation in detail regardless of the condition of the transmission line is imperative. Since a high-speed optical signal has a wide spectral breadth, reduction of dispersion slope will also be required.

It is known that PMD characteristics of optical fiber show a statistical behavior, and its tolerance is regarded to be about 1/10 of the time slot corresponding to the bit rate. If this value is used, the tolerance of a 160 Gb/s optical signal will be about 0.6 ps. Assuming the PMD coefficient of an existing optical fiber transmission line at $0.1 \text{ ps/km}^{1/2}$, the transmission distance will be limited to about 40 km. Therefore, research and development of technology to mitigate the PMD effect is very important. Reduction of the PMD coefficient of optical fiber is one of the solutions. For example, it is necessary to reduce the PMD coefficient down to $0.02 \text{ ps/km}^{1/2}$ to achieve 1000 km transmission. Since other components, such as an optical amplifier, etc., are also included in a transmission line, it is also necessary to reduce the PMD of such components. However, since

there is a limitation to lowering the PMD of optical fiber and an optical amplifier, the introduction of PMD compensation technology will also be essential

3-2 Benefits of ultrafast systems

With regard to the progress of optical transmission systems thus far, the cost per bit of a transmitter/receiver unit has been reduced by an increased bit rate, and the bit rate has been increased by an increment of four times every time. At present, commercial introduction of 40 Gb/s transmission is becoming realistic as a next generation successor to 10 Gb/s transmission. When the bit rate is upgraded to 160 Gb/s, the cost of a 160 Gb/s transmitter/receiver unit will be about four times the cost of a 10 Gb/s system if the relationship of bit rate and cost is maintained as in the past, and the transmission cost per bit will be significantly reduced.

Furthermore, in the case of an optical transmission system with a very large aggregate capacity, there will be a great benefit in reducing the number of required channels with acceleration of bit rate per channel. For example, 100 channels are needed to attain 1 Tb/s transmission capacity with a 10 Gb/s-based system, but if a 160 Gb/s based system is realized, only six channels would be able to obtain the same level of transmission capacity. Such a significant reduction in the number of channels will largely reduce the number of transmitter/receiver units, and an overall system space saving, lower electric power consumption, and cost reduction will be expected. In addition, there will be benefits of simplified operation management from the viewpoint of network operating management since an increased number of wavelengths will cause an increase in operating load.

Acceleration of bit rate also has benefits from the viewpoint of effective use of bandwidth (enhancement of spectral efficiency). When the bit rate per channel is increased with spectral efficiency unchanged, the channel spacing can be enlarged. For example, the spectral efficiency in the case of wavelength multiplexing of a 10 Gb/s signal at 50 GHz division will be 0.2 b/s/Hz (= 10 Gb/s / 50 GHz), and the channel spacing will be increased to 800 GHz to obtain the same spectral efficiency with a 160 Gb/s-based system. If such a large expansion of channel spacing is realized, enhancement of spectral efficiency with a very high density will be relatively easy since it will largely increase the ease of manufacturing optical components like arrayed waveguide grating (AWG). The increase in spectral efficiency will be able to reduce bandwidth required to obtain a certain transmission capacity, and cost reduction can be expected due to a reduction of bandwidth handling the dispersion/loss management of optical fiber for transmission and gain bandwidth (including gain flattening) to be secured by an optical amplifier.

In addition, it is anticipated that standardization of 100 GbE will be realized as the next generation Ethernet standard subsequent to 10 GbE, and ultrafast optical transmission over 100 Gb/s will be first applied to a LAN (Local Area Network) with a short transmission distance ahead of other applications. When 100 GbE is used for LAN and other applications, the necessity will increase for

accelerating the bit rate of CORE and METRO networks from the viewpoint of the interface with such networks.

3-3 Applicability of ultrafast transmission and necessary technology

The following summarizes matters relating to technology for applying ultrafast transmission of the 160 Gb/s class to a trans-Pacific optical submarine cable system, terrestrial trunk network system and the METRO system. The following will focus on the description of transmission technology since the necessity of transmitter/receiver technology for generating and receiving ultrafast optical signals will be common to systems in all areas.

3-3-1 Ultra long haul transmission system (submarine cable system)

In the case of a transoceanic optical submarine cable system requiring long distance transmission over several thousand kilometers, any factor degrading the transmission characteristics will severely restrict the transmission characteristics. Regarding cumulative dispersion and the cumulative dispersion slope of a transmission line, ultrafast transmission will be possible by using a dispersion managed transmission line (controlling the dispersion and dispersion slope by constituting a transmission line combining two or more types of optic fiber) more precisely compared with a 10 Gb/s-based WDM system at present. Since the dispersion tolerance is only about plus/minus 2 ps/nm, however, some kind of tunable dispersion compensation method will be needed. In addition, OSNR and PMD are considered to restrict transmission characteristics to a large extent. As for OSNR restrictions, various types of OSNR improved technologies have been introduced, and a 40 Gb/s transmission has been barely achieved in the past several years. Improvement of OSNR by a further 6dB will be extremely difficult, and optical 3R (Retiming, Reshaping, Regenerating) technology that regenerates (waveform-shapes) optical signals without converting them to electric signals will be essential. In the case of an optical submarine cable system, however, there are serious restrictions to repeater unit sizing and electric power consumption, and technology must fulfill such requirements. Besides, due to a large volume of point-to-point traffic, simultaneous processing for all WDM channels is desirable.

Since it is necessary to keep the PMD coefficient below $0.006 \text{ ps/km}^{1/2}$ in a 10,000 km 160 Gb/s system, conventional technologies to reduce optical fiber PMD will not be able to solve the problem. Therefore, the introduction of new technologies such as PMD compensation technology, single-polarization optical transmission fiber, etc. will be essential. In addition, optical multiple level modulation/demodulation technology compatible with enhancing the bit rate without increasing the symbol speed is expected as a method to improve PMD tolerance.

3-3-2 Long haul transmission system (terrestrial trunk system)

The transmission distance of a terrestrial trunk system is about several hundred kilometers to several thousand kilometers in Japan and up to about 3,000 km in North America. Since repeater

spacings are long, OSNR limitations will be similar to those for an optical submarine cable, and the introduction of various OSNR tolerance improvement technologies and the optical 3R method will be necessary. A transmission line will consist of one type of optical fiber, but dispersion compensation with a repeater unit is needed. Since it tends to be influenced by environmental changes like temperature changes as compared with an optical submarine cable, the need for a tunable compensation method will increase. As for PMD, to realize 1,000 km transmission, it is required to make the PMD coefficient needed for optical fiber below $0.02 \text{ ps/km}^{1/2}$, and PMD reduction technology for optical transmission fiber and PMD compensation technology will become important. A remedy for PMD by combined use of FEC and polarization scramblers distributed on a transmission line is also proposed [3.3.2.1], and there is a possibility of reducing the influence of PMD of multi-wavelength en masse.

In a terrestrial transmission system, the path change in the unit of wavelength by OADM (Optical Add/Drop Multiplexer) can be considered, and corresponding chromatic dispersion/PMD compensation technologies will be required. The compensation unit in such a case will possibly be in the unit of wavelength.

3-3-3 Short distance transmission system (METRO System)

In the METRO System, OSNR limitations are smaller. Therefore, the main factors for transmission limitations will be chromatic dispersion and PMD. In particular, the METRO System is often required to make effective use of installed optical fiber, and transmission technology for various types of optical fiber with different characteristics will be required. The METRO System also needs flexible networks compatible with various services, and it is assumed that path changes per wavelength will frequently be done. For this reason, a tunable dispersion compensation technology compatible with dispersion changes in wide ranges will become important.

If advanced optical fiber with lower PMD can be used, the influences of PMD will be limited in the METRO System over a short distance. However, since there can be optical fiber with a very high PMD coefficient among the existing types of optical fiber, some kind of PMD compensation technology may be necessary.

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Part 4 Key Technologies for Realizing Ultrafast Optical Communication Systems

This part mainly discusses the current status and issues of the key technologies that are regarded to be necessary for realizing an ultrafast optical communication system (over 160 Gb/s).

Table IV-4-1 shows the devices or elemental technologies discussed by SWG4. This table shows the relationship of functions and characteristics regarded necessary for each device/elemental technology and an ultrafast optical communication system. Some of these devices/elemental technologies will be selected and discussed later.

Table IV-4-1: Device/elemental technologies for realizing ultrafast optical communication systems

No.	Elemental technology		Transmitter/receiver			Transmission line				Node				Security
			Faster speed	Higher output/ higher sensitivity	Downsizing/ stabilization	Loss compensation	CD measures	PMD measures	Nonlinearity measures/ thermal measures	Optical ADM	Optical XC	WDM/ OTDM conversion	Optical signal monitor	
1	OTDM (Optical time division multiplexing)	Ultra-short pulse light source	○	○						○	○	○	○	
2		Optical time division multiplexing/ demultiplexing technology	○	○						○	○	○		
3	ETDM (electrical time division multiplexing)	Electronic circuit	○		○		○	○	○					
4		Optical modulator	○	○	○				○					
5		Direct modulated laser	○	○	○									
6		Photodiode	○	○	○								○	
7	Modularization/ integration technology				○					○	○	○		
8	Modulation/ demodulation format (CS-RZ、 DPSK、 multiple level, etc.)		○				○	○	○			○		
9	Soft judgment receive, maximum likelihood receive			○		○	○	○	○					
10	FEC(Error correction code)			○		○	○	○	○					
11	Phase conjugation						○	○	○					
12	Chromatic dispersion (CD) compensation technology						○							
13	Soliton transmission						○	○	○					
14	Fourier conversion transmission						○							
15	Polarization mode dispersion (PMD) compensation technology							○						
16	Absolute single-polarization fiber							○						
17	Low PMD fiber technology							○						
18	Low nonlinearity fiber								○					
19	High-power fiber								○					
20	Parametric optical amplification					○								
21	Raman amplification			○		○			○					
22	Optical 3R					○	○	○	○	○	○	○		
23	Optical memory									○	○	○		
24	Bit rate conversion									○	○	○		
25	Optical logic element									○	○		○	
26	Optical clock data recovery technology			○	○					○	○	○	○	
27	Wavelength conversion									○	○	○		
28	Optical switch									○	○			
29	CDM (Code division multiplexing) technology													○
30	Quantum cryptography													○

ADM: Add-drop multiplexer, XC: Cross-connect

4-1 Transmitter/receiver technology

4-1-1 Ultrashort pulse light source

The OTDM transmission system is a transmission method to control optical pulses with optical pulses, and a short pulse light source is a necessary key device not only as a signal pulse source but also as a control signal pulse light source. A short pulse light source based on a semiconductor laser is preferable since the light source for transmission is required to be small, stable and highly reliable. In addition, the pulse width must be below 3 psec and timing jitter below 0.5 psec since the time slot is about 6.3 psec in a 160 Gb/s OTDM system.

Table IV-4-2 shows short pulse light sources reported so far for communication use.

Table IV-4-2 Ultrashort pulse light source

	Repetition Frequency	Pulse duration	Optical output	Jitter
Gain switching	~20GHz	~20ps	Several mW	Large
EA modulator	~40GHz	~10ps	Tens of μ W	Small
Mode-locked semiconductor laser	10GHz~1THz	Several ps	Several mW	Small
Mode-locked fiber laser	~40GHz	Several ps	Several mW	Small

Gain switching is the simplest method to excite a DFB (Distributed Feedback) laser with an electric current pulse. As for pulse duration and chirp, the pulse duration can be compressed to about 5 psec with chirp compensation by optical fiber, etc., but further nonlinear compression is needed to make it below 3 psec because nonlinear chirp remains. As for jitter, a seeding method is under study to output light itself or external light. Ultra-short pulse generation using an EA (electro-absorption) modulator is a method to obtain optical pulses by driving large amplitude sinusoidal waves by utilizing nonlinearity of optical extinction characteristics. It has small jitters and excellent frequency variability. However, the problem is that loss is large, thus output intensity is small and pulse duration is long. A pulse duration of 3 psec has been realized by connecting two sets of 40 GHz EA modulators in cascade, the problem is that the loss is large and phase adjustment between sine waves for driving the two modulators is difficult [4.1.1.1]. The mode-locked fiber laser consists of excellent optical components developed for optical communication and satisfies most of the performance requirements as a light source for 160 Gb/s OTDM. However, it is large in size, expensive, and unstable due to a long cavity, so that it needs downsizing and stability improvement.

With the development of frequency control technology and stability technology, the mode-locked semiconductor laser can generate stable optical pulses with pulse rates up to 10 GHz~1 THz [4.1.1.2]. It is the only pulse light source that can generate optical pulses at frequencies beyond

100 GHz for a clock pulse light source of 160 Gb/s optical 3R. The problem with the mode-locked semiconductor laser is that the repetition rate is fixed because of being determined by the cavity length so that it is difficult to adjust to the system clock frequency. The pulse duration is currently about 0.8 psec at the shortest, and far shorter pulses are required in order to widen the application areas to include over 160 Gb/s systems and measurement systems.

4-1-2 Optical time division multiplexing [4.1.2.1]

Regarding methods for multiplexing/demultiplexing signals from the client (tributary signal) on a time axis in an ultrafast optical communication system, there are two methods or a method during a step of electric signals and a method during a step of optical signals. Here, the technology for multiplexing/demultiplexing at the state of optical signals (OTDM) is described.

A. Applicable area

The functions achieved by applying OTDM technology are (i) transmitter/receiver at an end office and (ii) optical ADM (Add Drop Multiplexer) and optical XC (Cross Connect).

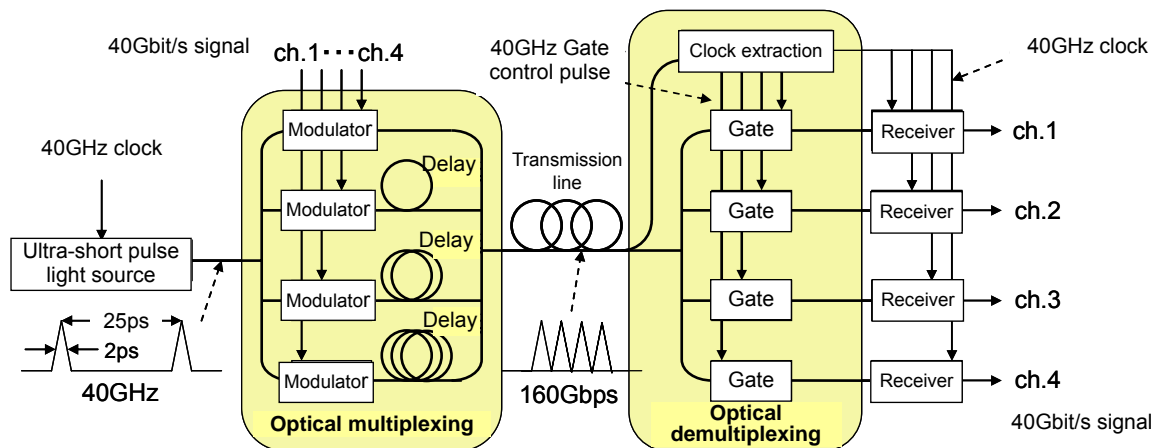


Fig. IV-4-1 Example configuration of an optical communication system using optical time Division multiplexing (OTDM) technology

Fig. IV-4-1 shows an end office configuration for an optical communication system using optical time division multiplexing technology. The sender side transmits a tributary signal of four signals of 40 Gb/s by optical time division multiplexing into 160 Gb/s. The receiver side generates control pulses from the transmitted optical signals, demultiplexes them into four optical signals with an optical demultiplexing circuit and then receives them. An optical pulse used as a signal is an optical pulse of 2~3 psec duration.

B. Main technology at present

Current means of achieving optical multiplexing are (i) an individual connection of optical modulator, optical fiber used as a delay line and an optical coupler, (ii) integrating an optical delay circuit on the PLC, (iii) a bulk optical system like an optical prism, and (iv) integrating a modulator, etc. on LiNbO₃. Demultiplexing technologies used for gate experiments are (i) cross-phase modulation effect (XPM) in NOLM (Nonlinear Optical Loop Mirror), (ii) XPM in a semiconductor optical amplifier (SOA) installed in a Mach Zehnder interferometer, (iii) four wave mixing (FWM) inside optical fiber and SOA, (iv) an electro-absorption (EA) modulator, and a (v) Kerr switch.

C. Research subjects

Research subjects of optical multiplexing/demultiplexing methods are to achieve (i) ease of delay time adjustment, (ii) stability, (iii) low insertion loss, (iv) small size/low electric power consumption, (v) frame synchronous function, (vi) high quality of optical pulse, and (vii) low cost.

The following describes each of these items in brief:

(i) In view of the configuration of a multiplexing circuit, it is necessary to multiplex the optical pulses at a correct timing. To adjust the delay time in optical fiber, a deviation of 1 mm means a deviation of 5 psec, which is equivalent to 0.8 bits in the case of 160 Gb/s, and cannot achieve optical multiplexing. Therefore, a mechanism for setting up a tunable delay time is needed.

(ii) A mechanism for stabilizing the pulse interval is also required so that multiplexed pulse intervals will not change due to surrounding environment changes.

(iii) With regard to insertion loss in the item (iii) above, if an optical coupler is used at the exit of the multiplexing circuit or at the entrance of the demultiplexing circuit, a loss of $10\log N$ (dB) will take place (where N is the multiplexing number), and this needs careful consideration. Since there are four multiplexing signals in Fig. IV-4-1, the loss will be 6dB, but if the number of signals is 16, the total loss in the multiplexing circuit and the demultiplexing circuit will be 24dB. This will pose a problem from the viewpoint of SN.

(iv) As the number of multiplexing signals increases, the scale of an optical circuit grows, which requires specific ideas for implementation. It is also a research issue to lower electric power consumption by reducing light power necessary for gating at the optical demultiplexing circuit, for example. In view of the above items or (ii) stability, (iii) low insertion loss and (iv) small size/low electric power consumption, integration of multiplexing/demultiplexing circuits (including modulation/gate) will become an essential research theme.

(v) A description of the frame synchronous function follows. In time division multiplexing, a function is needed to relate each time slot and tributary signal, one to one. (This is called a TSA function or time slot assignment function.) This one-to-one relation must be kept between a transmitter and a receiver. Frame synchronicity is an essential function to realize optical ADM and Optical XC enabling concentration of traffic on an optical level (Optical XC needs a TSI (Time Slot Interchange) function to interchange the time slot.). Therefore, it is necessary to study frame

architecture and frame synchronous function in an OTDM (Optical Time Division Multiplexing) system.

(vi) A brief explanation of high quality in terms of an optical pulse follows. In the transmission design of WDM (Wavelength Division Multiplexing), it was necessary to consider nonlinear interaction between different wavelengths, but in the case of OTDM with the same wavelengths, nonlinear interaction between adjacent optical pulses (or different tributary signals) on a time axis will become a problem. Specifically, it is a problem with intra-channel XPM and intra-channel FWM (hereinafter called IXPM and IFWM, respectively). IXPM appears as an optical pulse jitter, and IFWM appears as degradation of an optical pulse amplitude change or extinction ratio. (As a method to suppress these, there is a proposal for a technique to multiplex polarization of adjacent optical pulses by orthogonalization, although the effectiveness of this approach is reduced if there is polarization dispersion). The quality of optical pulses after multiplexing must be studied in connection with optical multiplexing systems. It is also necessary to study a system in terms of optical demultiplexing circuits for controlling crosstalk from adjacent channel (tributary signal) light and gate control pulse light and for obtaining useful signal light with high quality.

(vii) Concerning cost reduction, assuming the multiplexing number of the tributary signal as n , pricing of about $n^{0.5}$ times must be achieved. In other words, in the case of a multiplexing number of four for 40 Gb/s, pricing of 160 Gb/s must preferably be 2 to 2.5 times that of 40 Gb/s. This will be a target for cost reduction through research.

4-1-3 Direct modulated laser

This is a method to obtain direct modulation optical output by modulating the injection current of a semiconductor laser. It requires no modulator, thus it is simple and has a low cost structure and low electric power consumption. Therefore, this approach has been used as a transmission light source in optical communication systems, but since its chirp is so large the external modulation system has been adopted for long haul transmission. In recent years, however, the bit rate has become higher in short distance transmission, and demand for a direct modulated laser is increasing as a low cost high-speed transmission light source.

The response speed of the semiconductor laser is determined by a CR time constant and relaxation oscillation frequency. Fig. IV-4-2 shows an example of a semiconductor laser achieving chip capacity reduction and differential gain increase.

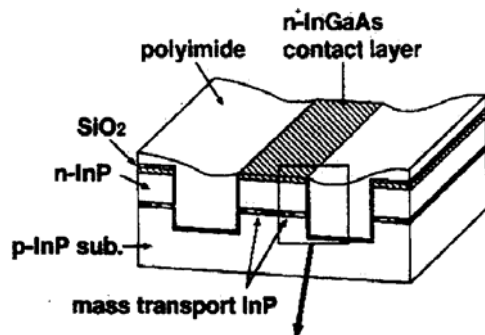


Fig. IV-4-2 Chip configuration of high speed semiconductor laser [4.1.3.1]

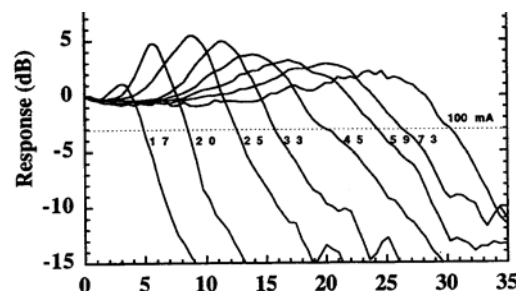


Fig. IV-4-3 Small signal response characteristics [4.1.3.1]

An active layer is composed of an InGaAsP/InGaAlAs strain-compensated multiple quantum well structure for increasing the number of wells and enabling uniform injection. A mushroom structure reduces the parasitic capacitance and obtains 30 GHz of CR frequency. Fig. IV-4-3 shows the small signal response characteristics. It has achieved 30 GHz for a 3dB bandwidth at a bias current of 100 mA [4.1.3.1]. There are some reports on 40 Gb/s optical transmission experiments with direct modulation by using a high speed semiconductor laser. It seems that 40 Gb/s to 50 Gb/s operations will be achieved with current technologies. Concerning modulation beyond 100 Gb/s, however, development of a new material will be required. There have been breakthroughs in direct modulation such as quantum well structure and strained quantum well structure. It is expected that the differential gain will largely increase by going from quantum wells to quantum wire to quantum dot, but high speed operations have not been achieved so far due to difficulty in manufacturing. Further progress in high speed semiconductor lasers is expected.

4-1-4 Electronic circuits for ETDM

There is a possibility of attaining high speed with the current ETDM as a means to achieve the optical transmitter/receiver in 160 Gb/s systems instead of OTDM. Here, we will discuss feasibility and issues of 160 Gb/s ETDM and a comparison with OTDM.

The basic configuration of ETDM is shown in Fig. IV-4-4. The configuration consists of a MUX (Multiplexer), a CMU (Clock Multiple Unit), a Retimer (D-F/F = D-Flip-Flop), an optical modulator driver, a PD (Photodiode), a Pre-Amp (Pre-amplifier), a DEC (Decoder), a CDR (Clock Data Recovery), and a DEMUX (Demultiplexer).

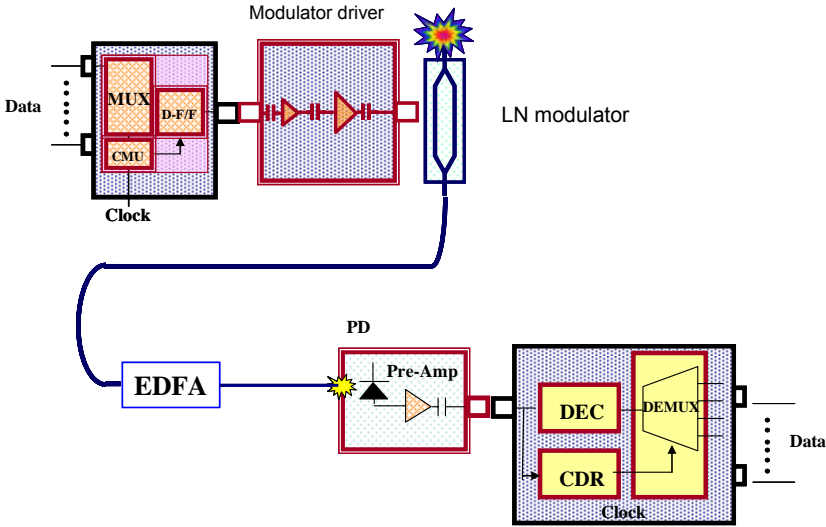


Fig. IV-4-4 Configuration of ETDM

High-speed transistor technology is required for such electric circuits to go to 160 Gb/s. At present, the transistor technology most likely to be realized is HEMT (high electron mobility transistor) on

the basis of InP [4.1.4.1]. In addition to high mobility of electrons in the InGaAs channel layer, the gate capacitance has been greatly reduced, and the cut-off frequency has been largely improved. As for a single transistor, there is a report on 560 GHz at 25 nm gate length. About 400 GHz has been attained with a gate length of 100 nm including successful integration. In view of the feasibility of 160 Gb/s, SiGe HBT (Hetero Bipolar Transistor) is short of the maximum oscillation frequency and CMOS will barely be able to achieve 40 Gb/s.

Concerning MUXs in the transmitter, there is a report on 144 Gb/s with a selector, and the achievement of 160 Gb/s is within reach. With the driver circuit for the optical modulator, bandwidth of up to 80 GHz and 2Vpp has been developed, and the possibility is high for 120 GHz. The greatest problem will be the reduction of operating voltage in the optical modulator.

PDs in the receiver have attained the bandwidth of 100 GHz. The bandwidth of a pre-amplifier is limited to under about 80 GHz, and it will be difficult to increase the bandwidth since the improvement of transistor speed will usually cause a greater increase of noise than the increase of the bandwidth. To avoid the use of a pre-amplifier, there is technology to make a higher input and a higher output of a PD and amplify optical signals up to the level that a DEC can directly work with an EDFA (Er³⁺ dope optical fiber amplifier). A DEMUX for a 160 Gb/s system is within reach since it is realized in the same digital circuit as a MUX.

As for overall tasks related to ETDM, there are stable oscillation of a 160 GHz clock for a CDR, a CMU, etc., stabilization of ground, the interface between each electronic circuit, and common issues of ultrafast electronic circuits. The current InP-HEMT circuit has a limitation to integration at several W of power due to thermal problems, and is, therefore, with a multiple chip structure. If lower electric power consumption is achieved, a one chip structure will become possible, and problems of ground and interface will be solved. There is a possibility of attaining a fraction of electric power consumption.

Here is a brief comparison with OTDM. At the transmitter, ETDM has difficulty in realizing a driver or an optical modulator with low voltage operation. On the other hand, in the case of OTDM, operations are already successful, and electric power consumption will be reduced by simply bundling the signals optically on the MUX section. Thus, if optical integration and downsizing of OTDM are achieved, OTDM will successfully work. As for the receiver, ETDM will be feasible without a pre-amplifier by making use of EDFA. On the other hand, OTDM could be replaced by ETDM if the reduction of power consumption in an optical switch (several 10 mW per step or less) and integration are not developed. Furthermore, adjustment of a DEMUX is difficult for OTDM.

Depending on the situation, a mixed system of OTDM/ETDM, in which MUX with OTDM is used in the transmitter and ETDM is used in the receiver, may likely be adopted as a scheme achieving the lowest electric power consumption and downsizing. Beyond 160 Gb/s, there is little hope for ETDM, and OTDM will be unrivaled.

4-2 Node technology

4-2-1 Optical clock extraction

Clock extraction is a basic function in an optical communication system for time division multiplexing/demultiplexing and signal regeneration. Currently, an optical signal is converted into an electric signal, and a clock signal is electrically extracted. An electrical clock extraction circuit below 40 Gb/s is commercially available at present, but a bit rate of over 100 Gb/s will need all-optical clock extraction. Since there can be benefits of lower electric power consumption and costs at the bit rate where electrical clock extraction is possible, active research on optical clock extraction is ongoing.

Fig. IV-4-5 show a report on an optical clock extraction experiment using the mode-locked semiconductor laser [4.2.1.1]. By injecting 160 Gb/s OTDM signals into a 160 GHz mode-locked semiconductor laser, 160 GHz optical clock pulses synchronous with the input signals are output. In this case, while input signals are distorted, obtained clock pulses are in a uniform waveform and equal time intervals, thus proving the function of re-shaping and re-timing. In addition, there is a report of using a self-pulsation semiconductor laser as a clock extraction device.

Optical clock extraction with injection locking with a mode-locked semiconductor laser and a self-pulsation semiconductor laser offers the advantage of generating clock pulses with one chip. On the other hand, an active study is continuing with an optical PLL (Phase Locked Loop) compatible with phase synchronization [4.2.1.2]. The optical PLL reported so far is a hybrid type, and phase comparison is handled electrically. Input optical signals and clock optical signals are input into nonlinear media to generate correlated signals. The electric signals and clock signals are phase-compared, the compared signals are converted to voltage as feedback to VCO (Voltage Controlled Oscillator), and the semiconductor laser is driven by VCO to generate optical clock signals. To create an all optical PLL, it is necessary to develop an optical VCO such as a device to control the repetition frequency with light.

4-2-2 Optical memory

When packet processing is realized in an all-optical node, development of an optical buffer memory will be indispensable to avoid packet collision. In addition, if an optical memory is developed, ultrafast optical signal processing will possibly be applied to various areas. At present, it is a realistic approach to convert optical signals to electric signals via optical-electrical conversion, store them in an electronic circuit memory, and read them out as optical signals via

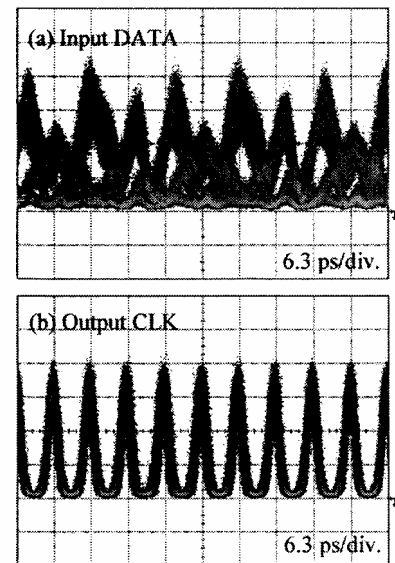


Fig. IV-4-5 Clock extraction experiment using mode-locked semiconductor lasers

electrical-optical conversion as needed. This method has a delay problem in reading and writing. A technical breakthrough of this technology is expected among optical signal processing issues. The optical memory approaches currently proposed are largely divided into two types, the optical logic type and the delay type. For the optical logic type, proposals are formulated such as optical bi-stable devices that have two optical output values for an optical input and bi-stable lasers that have two oscillatory states for an identical injection current. As for bi-stable lasers, there are a number of various approaches such as a method to use two states of oscillation/non-oscillation, one to use two oscillation modes in combining ring resonators, and another to use two polarization states of a surface emitting laser. Since the transition speed of two-modes in a semiconductor laser is determined by photon life time in the optical resonator of a laser and intra-band relaxation time of a carrier, high speed compatible with 160 Gb/s can be expected. But, a breakthrough in integration technology for achieving a memory of several Mbits is required as any element must be several 10 μm to several 100 μm in size. Again, read/write interfaces and protocols are still to be examined.

Proposals on the delay type have been offered, such as an approach to transmit optical signals to optical fiber temporarily by using low loss characteristics of optical fiber, and one to lower group velocity of light by using photonic crystal or electromagnetically induced transparency (EIT) [4.2.2.1].

Optical fiber has the merit of storing a number of bits on one device, and its length can be shorter if the speed is increased (about 1 km for storing 1 Mbit at 160 Gb/s). But, if one line of optical fiber is used, about several μsec of delay will take place, which requires technical ideas about configuration. EIT uses an acute transparent line an absorption spectrum to generate a large plus chromatic dispersion, which reduces group velocity significantly. The principle of reducing light velocity by one ten-thousandth at the low temperature of 10 K by using a quantum dot has been proven, but there is still no way to know about the possibility of behavior at a normal temperature to apply it to an actual system. Photonic crystal has a task to be solved about how to materialize dynamic changes.

The delay type using slow light is still at the stage of principle verification. It is pending for future discussion of input/output. As compared with the logic type, the delay type has potential for a transparent node since it can keep both intensity and phase information of light, and the potential impact can be significant if realized. Long-term research is thus desired.

4-2-3 Optical switch

An optical logic device for controlling an optical signal with a different optical signal will be required in order to process an optical signal at a node in the domain of 160 Gb/s to 1Tb/s. Every logic device can be constructed if logic of AND, NOT and OR is developed. But, as the size and electric power consumption of an optical logic device are superior to those of an electronic device, the development of essential functions for DEMUX and node configuration like an ON-OFF switch,

optical path switch and so forth was started at the beginning. A high-speed optical switch is indispensable for optical 3R regeneration, and a response speed below a peco-second is needed in the case of regeneration over 160 Gb/s.

Proposals related to an optical switch are formulated mainly for the use of optical nonlinearity of optical fiber or semiconductor.

The optical Kerr effect of optical fiber has sufficient response speed for Tb/s. While its third-order nonlinear susceptibility is low, a very long interaction of tens of meters can be used due to its low dispersion/low loss characteristics, and therefore a sufficient level of speed and extinction ratio has been realized. Proposals have been formulated for the use of Kerr rotation or XPM (Cross Phase Modulation) of NOLM (Nonlinear Optical Loop Mirror) etc. As for optical fiber used for such a purpose, highly optical-nonlinear fiber has been developed with a one digit higher order of optical confinement into the core.

Various proposals using semiconductors have been made such as a device like a Mach-Zehnder interferometer (MZI) type using XPM of a semiconductor optical amplifier, one using saturated absorption of Inter Sub-Band Transition (ISBT), one using four-wave mixing, two photon absorption, etc.

It has been verified that MZI can attain movement of over 160 Gb/s by a push/pull action of inputting control light with a time difference into both arms of the Symmetric Mach-Zehnder interferometer (SMZ). Since it has a function of optical path switching and input/output characteristics are sinusoidal and nonlinear, a proposal has been made as a waveform shaping device. As for its shortcomings, conditions for operating the interferometer are severe, and how to control the operating conditions is a problem to solve. Its electric power consumption is still significant at present in view of the electric current put into SOA (Semiconductor Optical Amplifier). The structure of ISBT is simple, but reduction of power (currently tens of pJ) and improvement of extinction ratio over 20dB are required. When application to DEMUX in the area of 160 Gb/s is considered, more than a single-digit of power reduction is demanded in order to get an advantage over an electronic circuit consuming only tens of mW per step of logic.

Summing up the above, there is a device available with a sufficient performance using optical fiber so far as a single-logic device is concerned. But, for downsizing a system in the future, integration at the similar level of a semiconductor array will be desirable although large integration like LSI may not be necessary. For this purpose, it is further required to speed up a semiconductor type optical switch (less than 1 psec response time) and reduce electric power consumption (below several pJ).

4-2-4 Wavelength conversion

Wavelength conversion is essential even for a system over 160 Gb/s. It is indispensable not only for wavelength routing in a mixed system of WDM and ultrafast TDM systems but also for connection of different ultrafast transmission systems, since it is needed to adapt the signal optical

wavelength to a value with a suitable chromatic dispersion of optical fiber, which seriously influences transmission characteristics in ultrafast TDM systems. As an example of special application of wavelength conversion, phase conjugate optical light transformation by coherent type wavelength conversion can compensate for even-order dispersions among high-order dispersions causing a problem in an ultrafast optical fiber transmission system. From such a viewpoint, it is necessary to discuss wavelength conversion in ultrafast transmission systems.

There are various methods of wavelength conversion in addition to the method of modulation of different wavelength light sources after O/E conversion. These include a method of modulation on different wavelength light sources by an optical switch, and coherent wavelength conversion by difference frequency generation using second-order nonlinear effects or four wave mixing using third-order nonlinear effects. Table IV-4-3 shows a brief categorization.

With regard to an optical switch type, it has characteristics equivalent to those of the optical switch discussed in Section 4-2-3. Generally, the linearity of intensity of output conversion light from input signal light is bad and has a narrow dynamic range. On the other hand, this characteristic gives 2R effects and waveform shaping at the same time with wavelength conversion.

Table IV-4-3 Comparison of various wavelength conversion methods

	Principle	Device	Speed	Modulation format	Input/output ratio	Extinction ratio	Linearity	Input level	Wave dependence	Output wavelength variability	Integration	Remarks
OE-EO type	Opto-electric conversion	PD+Electric+LD	40Gb/s	format fixed	by amplification ratio of electric amplifier	○	○	○	per light source	OK	Difficult	
Optical switch type	Cross gain modulation (XGM)	SOA	~20Gb/s	1M	3dB	18dB	×	-10~0dBm	medium	OK	Easy	ON/OFF Reversal Optical fiber unneeded
	Cross phase modulation (XPM)	Optical fiber	~1Tb/s	format fixed	8dB	>40dB	×	+10dBm	None	OK	Difficult	Waveform shaping Optical fiber needed
		SOA-MZI	~160Gb/s	format fixed	10dB	20dB Dependent on operating point	×	-15~-5dBm	Weak	OK	Integration device	Waveform shaping Negative chirp operation Optical fiber unneeded
Coherent type	Difference Frequency Generation (DFG)	PPLN	>1Tb/s	format non-dependent	-20dB	>40dB		-30~10dBm	None	Two times tunable wavelength laser	Difficult	Optical filter needed Conjugate light generation
	Non-degenerate four-wave mixing (NDFWM)	Optical fiber	>1Tb/s	format non-dependent	-10dB	>40dB	○	-20~0dBm	None	Two times tunable wavelength laser	Difficult	Optical filter needed Conjugate light generation
		SOA-LD	~1Tb/s	format non-dependent	+5dB	+30dB	○	-25~0dBm	Strong	Two times tunable wavelength laser	Easy	Optical filter needed Conjugate light generation

Unlike the coherent type to be discussed later, there can be a structure requiring no wavelength filter to separate input signal light and output conversion light.

The coherent type, unlike the optical switch type, can cause conversion with every optical modulation format and bit rate. In high-speed systems, in particular, there is a possibility of using signals other than conventional NRZ (Non-Return to Zero) format. This characteristic may turn out to be a strong point. In addition, linearity of output conversion light from input signal light is good. Wavelength conversion en masse of a WDM signal is also possible and has been verified. Its

shortcoming is the need for an optical filter to separate output conversion light and input signal light at the end. In the case of changing the target wavelength freely, it will be necessary to change not only the excitation light wavelength but also the center wavelength of a wavelength filter.

As a device for different frequency generation, an optical waveguide made of LiNbO₂ with a periodically poled domain for phase matching among the pump signal, and a converted wave is used. A pump wave is supplied through virtual generation of the wave by injecting light of 1.55 μm wavelength, not light of 0.78 μm wavelength.

As for four-wave mixing, there are several reports of experiments with optical fiber using its low dispersion and low loss characteristics. The device has sufficient characteristics.

As for a semiconductor device, there are a number of publicized reports on four-wave mixing by using an active layer of a semiconductor optical amplifier or a semiconductor laser [4.2.4.1]. It is a method for obtaining larger conversion efficiency among semiconductor devices of several hundred-μm length using large optical-nonlinear susceptibility and large optical gain, the later of which solves the problem of larger absorption at the trade-off relation with larger optical-nonlinear susceptibility in usual optical-nonlinear materials. Monolithic integration with a pump light source is regarded to be feasible. Since degradation of NF (Noise Figure) arises due to the influence of ASE (Amplified Spontaneous Emission), improvement of intrinsic conversion efficiency without optical gain is required. In addition, higher efficiency conversion of the whole C-band is a problem to solve.

Concerning the optical switch type and coherent type, power consumption (below tens of mW) and downsizing (below several mm x several mm) are required for a device up to 160 Gb/s, as compared with the O/E-E/O conversion type that has more potential for feasibility. Furthermore, integration with a wavelength-tunable light source and an array structure for wavelength cross-connect of a WDM signal is considered to be necessary in order to achieve downsizing. If the semiconductor coherent type reaches a practicable level, its impact will be considerable.

The task for wavelength conversion technology overall is to develop a wavelength-tunable light source with high quality in order to freely change a target wavelength.

4-3 Link technology

4-3-1 Optical 2R/3R regeneration technology

Fig. IV-4-6 shows the basic configuration of an optical 3R regenerator [4.3.1.1]. Optical 3R consists of the three functions of Reamplification, Retiming, and Reshaping. It recovers signal light with degraded quality to the original quality. Eliminating “Retiming” out of optical 3R, optical 2R consists of Reamplification and Reshaping only, and is called optical 2R regeneration.

It is indispensable that an optical device used for optical 3R (2R) regeneration have transparency characteristics that can operate regardless of signal speed or pulse shape. In particular, reshaping is performed with the use of nonlinear optical effects, and high transparency is needed for the nonlinear optical effects used. Especially, when applied to 160 Gb/s systems, excellent high-speed

processing performance below a picosecond is essential and the working speed of the waveform reshaper must be sufficiently fast compared with the signal speed.

With regard to optical 3R regeneration of 160 Gb/s, there is a report on an optical 3R regeneration experiment with an optical gate switch using optical fiber [4.3.1.2]. In the optical 3R regeneration of signals consisting of short pulses of 1~2 psec like 160 Gb/s signals, the switching time interval (called the "window") must be narrow enough as compared with the pulse interval (6.25 psec). For this reason, there can be a problem that, if signal light contains jitter noise, the jitter noise is converted into amplitude noise by optical gate switching. To avoid this trouble, optical gate switching after converting the peak of input signal pulse into a planar shape with a pulse shaper has been adopted. By using these approaches, elemental functions and their effects that are necessary for an optical 3R regenerator of 160 Gb/s signals have also been proven by re-circulating loop transmission experiments.

Optical 3R regeneration is an important elemental technology for future photonic networks. For a photonic network that will be able to freely exchange a large volume of information over Tb/s, enhancement of functions at an optical node between each network will become important, and achievement of optical 3R regeneration at an ultrafast is expected. As mentioned above, the study of special devices and systems will be needed for achieving optical 3R regeneration at such a high-speed as 160 Gb/s. In the case of an optical semiconductor device, it is necessary to develop devices to remove signal-pattern dependence and realize transparent waveform shaping. Development of a new device like an optical device with quantum dots is hoped for. With regard to optical fiber, development of optical fiber with improved nonlinear optical effects will be needed. It is anticipated that a new optical fiber will be invented on the basis of combining such studies for enhancing nonlinear optical effects as carried out for highly optical-nonlinearity fiber, photonic crystal fiber, holey fiber, and the like.

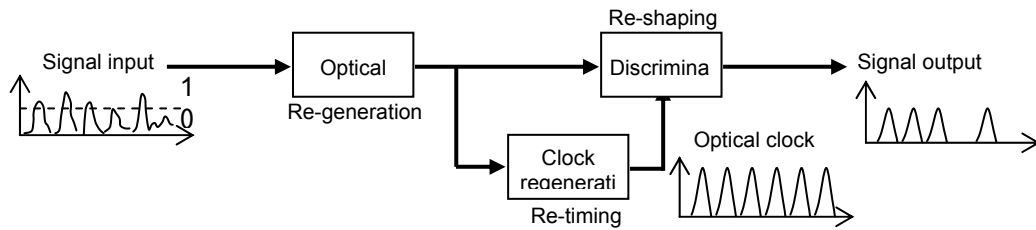


Fig. IV-4-6 Basic configuration of all-light 3R generator

4-3-2 Modulation and demodulation system [4.3.2.1, 4.3.2.2]

This section describes the current status and issues of a modulation and demodulation system that are essential for developing an ultrafast optical communication system.

A. Necessity of study on modulation and demodulation format

To achieve economical development of an ultrafast communication system over 160 Gb/s, it is necessary to study a new modulation and demodulation format from the viewpoints of (i) transmission volume and (ii) transmission distance.

A-1. Viewpoint of transmission volume

The NRZ waveform has been mainly used up to 10 Gb/s. The optical spectral bandwidth of the NRZ waveform $2R_b$ (R_b : modulation speed) when the zero-point interval of the main lobe is defined as spectral width. Therefore, when WDM (Wavelength Division Multiplexing) is considered, the wavelength interval from the adjacent signal is at the limit of $2R_b$. In other words, when the NRZ waveform is used, the limit of spectral efficiency is 0.5 b/s/Hz. As shown in Table IV-4-4, if the NRZ waveform continues to be used, the merit of increasing the spectral efficiency will be lost, so study of a new modulation format is in progress including research of a 40 Gb/s system.

Table IV-4-4 Spectral efficiency in using NRZ waveform

Modulation speed (Gb/s)	Wavelength interval (GHz)	Spectral efficiency (b/s/Hz)
2.5	100/50/25	0.025/0.05/0.1
10	200/100/50	0.05/0.1/0.2
40	200/100	0.2/0.4
160	400	0.4

A-2. Viewpoint of transmission distance

It is necessary to maintain S/N and control the influence of chromatic dispersion and nonlinear optical effects in optical fiber as much as possible in order to secure the transmission distance of an existing optical communication system (~10 Gb/s) in a next-generation ultrafast optical

communication system. While dispersion compensation technology is important from the viewpoint of controlling the influence of chromatic dispersion, a modulation system to make the modulation spectrum narrower is needed, which comes to the same conclusion that a modulation format is desired from the viewpoint of transmission capacity as described in A-1 above. On the other hand, concerning a modulation format with large nonlinear tolerance, research is ongoing from the viewpoints of (i) receiver sensitivity (nonlinear tolerance increases since average power of the path can be decreased) and (ii) narrowing of optical pulse range (nonlinear tolerance increases by reduction of interaction time between pulses).

B. Main technology at present

Modulation and demodulation systems currently under study are: (i) CS-RZ (Carrier Suppressed RZ), (ii) optical duo-binary, (iii) optical pre-filtering (post-filtering), (iv) RZ-DPSK (RZ-Differential Phase Shift Keying), (v) multiple level modulation such as RZ-DQPSK (RZ-Differential Quadrature Phase Shift Keying) and 16 APSK (16-Ary Amplitude Phase Shift Keying) and (vi) FSK (Frequency Shift Keying).

(i) The CS-RZ system is a modulation format where the phase difference of adjacent RZ pulses is π . The characteristics of this format are (1) with the RZ waveform, it is possible to improve sensitivity, increase nonlinear tolerance and narrow the spectrum by using an optical filter, (2) a $3R_b$ of spectral width (ordinary RZ waveform is $4R_b$) and (3) an increase in tolerance of SBS (Stimulated Brillouin Scattering).

(ii) The optical duo-binary format is an optical modulation format where a ternary signal (Duo-binary signal) obtained through addition (subtraction in the case of modified duo-binary) to a 1-bit delay pulse is converted so that the phase difference of adjacent optical pulses becomes π through an MZ modulator and optical light intensity becomes binary (refer to Fig. IV-4-7).

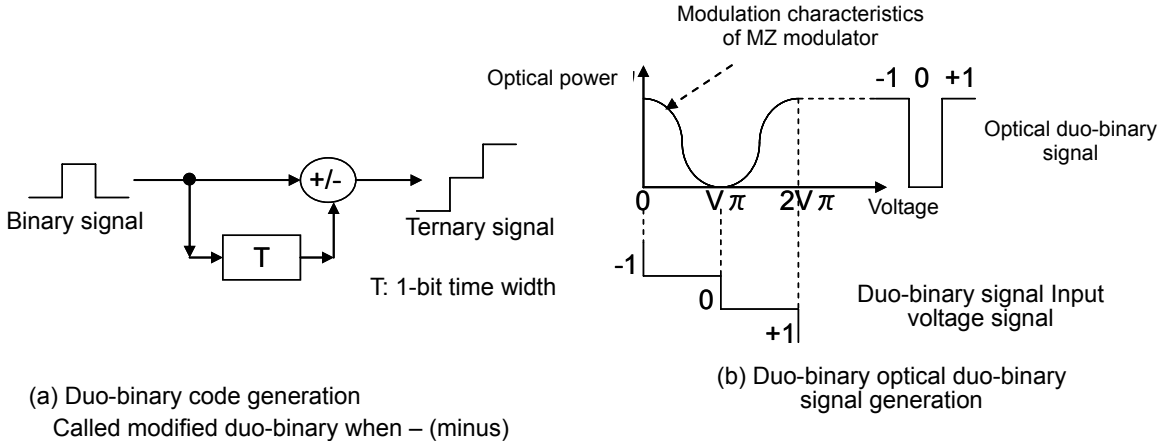


Fig. IV-4-7 Duo-binary signal

This method is a kind of partial response code, and its characteristics are (1) spectral width is as

compact as Rb and (2) SBS tolerance increases since there is no carrier component. Since the spectrum is compact, there is a successful experiment of SMF 225 km at 10 Gb/s, and a 3.75 times dispersion tolerance as compared with NRZ has been obtained in an experiment. In a system with large nonlinearity of optical fiber, however, a report says that this does not suit an ultra long haul transmission system since the phase difference between bits is deviated by π due to the nonlinearity.

(iii) The optical pre-filtering (or post-filtering) system is a modulation format that tries to make the signal obtained through ordinary modulation much closer to the spectrum obtained from SSB (Single Side Band) modulation with a narrow-band optical filter. In this connection, optical SSB modulation is also being experimented, and the enhancement of dispersion tolerance with its narrow-band characteristics has been demonstrated. However, an ultra-wide-band Hilbert conversion circuit is necessary to apply it to ultrafast communication over 160 Gb/s. Therefore, its implementation will be very difficult.

(iv) RZ-DPSK above is a modulation format to move information with an optical phase difference by using the RZ waveform as an intensity waveform. (For example, if the optical phase difference of adjacent bits is 0 (zero), it means "1", and if the phase difference is π , it means "0 (zero)".) The receiver lags a signal delayed by one bit (delayed detection) and receives with a balance type receiver the phase difference information as converted to intensity signal. The characteristics are: (1) the effects of the RZ waveform are excellent sensitivity, tolerance to nonlinearity, and tolerance to spectral deformation, (2) the effects of adopting DPSK are improved sensitivity of 3dB in receiving DPSK with the balanced receiver as compared with the intensity modulation/direct detection method, there are nonlinear optical effects with intensity changes, self phase modulation effects and cross phase modulation effects are not produced, and there is high tolerance to spectral deformation with an optical filter.

On the other hand, it is necessary to take it into account that the optical delay detector needs to be stabilized and signal amplitude fluctuates due to noise applied by an optical amplifier, and the noise is converted to its own phase noise or to the phase noise of other adjacent wavelength signals due to nonlinearity of optical fiber, which causes sensitivity degradation (Gordon-Mollenauer Effect). In this connection, the modulation spectral bandwidth is $3R_b$, nearly identical to that of CS-RZ mentioned above.

(v) Multi-level modulation above is a modulation format (2^n -level modulation) to transmit n bits, not conventional 1 bit, within the 1 time slot, and it is the modulation format traditionally used for wireless system technology as applied to optical modulation. Fig. IV-4-8 shows signal space arrangement. In the chart, part (a) shown below for reference is a signal space arrangement of PSK that is a kind of binary modulation. Part (b) is QPSK with 2-bit modulation worked over the phase, and part (c) shows phase space arrangement of 16APSK with 2-bit modulation worked over the oscillation and the phase.

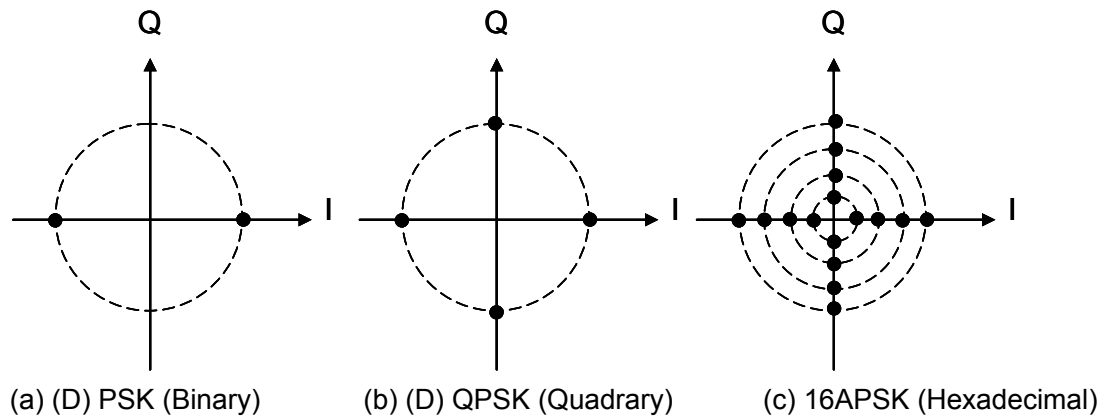


Fig. IV-4-8 Signal space arrangement

Multi-level modulation has a modulation spectral width of $1/n$ since one timeslot is $1/n$ as compared with the conventional binary modulation. Therefore, there are these characteristics:

- (1) Chromatic dispersion tolerance theoretically increases to n^2 times,
- (2) polarization also increases theoretically to n times,
- (3) an electronic circuit with $1/n$ bandwidth can be used.

On the other hand, there are shortcomings:

- (1) As demonstrated in Fig. IV-4-8, multi-level modulation has an unacceptable S/N and is sensitive to oscillation and phase noise, and receiver sensitivity deteriorates as the number of multiple levels increases,
- (2) thus, path mean power increases to secure receiving S/N and the influence of nonlinearity expands,
- (3) a control circuit is needed to stabilize a modulator and a demodulator,
- (4) the structure of the modulator and the receiver (demodulator) will be complicated.
- (vi) FSK is a format to modulate optical frequency by digital signal and receive it by using an optical heterodyne or optical delay detector at the receiving side. The technology was extensively studied as coherent optical communication technology 15 years ago. During the past year, FSK technology has been widely researched. It has been reexamined for such reasons as (1) spectral efficiency can be enhanced by the use of narrow bandwidth FSK like MSK (Minimum Shift Keying) and by the combined use of a wide bandwidth FSK and narrow bandwidth optical filter and (2) the structure of a transmitter can be simplified (FSK through direct modulation of semiconductor laser).

C. Research themes

Based on the discussions above, the following shows research themes for modulation and demodulation formats to develop an ultrafast optical communication system over 160 Gb/s. Firstly, the spectrum obtained through modulation must be compact. This is needed to realize

enhancement of spectral efficiency via faster communication that is a strong point of TDM. Specifically, the first step of achievement should be a target of almost 100% spectral efficiency. Secondly, the other task should be technology with high a receiving sensitivity and high nonlinear tolerance. Since receiving sensitivity generally deteriorates in proportion to the acceleration of the bit rate, the path mean power must be increased to secure repeater spacing. As a result, nonlinear optical effects appear significantly. Therefore, a modulation format with high receiving sensitivity and great nonlinear tolerance is required. Finally, from the viewpoint of economics, the structure of a modulator and a receiver (demodulator) should be as simple as possible.

4-3-3 Chromatic dispersion compensation technology

The following describes the current status and issues of chromatic dispersion compensation technology that is essential for developing an ultrafast optical communication system.

A. Necessity of chromatic dispersion compensation technology

In an optical communication system over 160 Gb/s, the tolerance for chromatic dispersion is about 4 ps/nm (in the case of RZ), which corresponds to 0.23 km in the case of ordinary dispersion fiber (at 17 ps/km/nm of chromatic dispersion). (In other words, it is necessary to consider chromatic dispersion of optical fiber and optical amplifiers installed in communication stations as well as optical fiber in a transmission line.) Thus, chromatic dispersion compensation is essential. A chromatic dispersion compensation system can be classified into the fixed compensation type and the tunable compensation type. Considering a 160 Gb/s system, a tunable compensator is essential for reasons such as:

- (i) The dispersion value of optical fiber changes depending on changes in the environment such as temperature;
- (ii) Measurement errors arise when wavelength is measured at the time of installation;
- (iii) The optimum dispersion compensation quantity changes (especially, compensation quantity at the receiving end) if the network structure changes (such as in the case of a reconfigurable optical network in the future);
- (iv) Fluctuations in characteristics of wavelength and optical filter at the light source take place;
- (v) Light power changes (such as changes in the number of wavelengths and in the power of a transmitter) may change the optimum dispersion compensation quantity (due to a change in the influence of nonlinear optical effects in optical fiber), and
- (vi) Inventory control of a fixed dispersion compensator.

For example, let us look at the temperature change of (i). Assuming that the temperature of a 300 km transmission line changes by 25°C, temperature dependency of a zero dispersion wavelength of optical fiber is 0.03 nm/°C. In the case of dispersion slope of 0.08 ps/nm/nm/km (SMF value), the 25°C change in temperature changes the dispersion value of optical fiber by 18 ps/nm. This will largely exceed the chromatic dispersion tolerance as mentioned above, so the fixed dispersion

compensation examined at the time of installation cannot permit this change of temperature. In short, a tunable dispersion compensator is essential for a 160 Gb/s system.

B. Current status of main technologies

There are fixed dispersion compensation systems using technologies such as

- (i) dispersion compensating fiber that has dispersion of the opposite sign of the transmission line,
- (ii) chirped fiber Bragg grating (CFBG),
- (iii) dispersion compensating fiber using a higher-order propagation mode (LP_{11}), and
- (iv) phase conjugation.

There are several types of tunable dispersion compensation devices such as (i) a method to apply non-uniform distortion or a non-uniform heat gradient to uniform fiber grating, (ii) a method to apply uniform stress or heat to nonlinear CFBG (WDM compatible), (iii) a method to apply uniform stress to sample-type nonlinear CFBG (FBG writing nonlinear CFBG cyclically in the longitudinal direction of optical fiber), and (iv) a VIPA (Virtually Imaged Phased Array) device (WDM compatible). In addition, there are dispersion compensation systems such as GT etalon, tunable ring resonator, AWG (Arrayed Waveguide Grating), phase-tunable MZ (Mach Zehnder) interferometer, a device using MEMS (Micro-Electro-Mechanical Systems) (these devices are WDM-compatible), Fourier conversion transmission, and an electronic circuit combining FFE (Feed Forward Equalizer: linear filter) and DFE (Decision Feedback Equalizer: quantizing feedback). Here, the systems described as "WDM compatible" are those systems which can compensate for dispersion of multiple signals with different wavelengths en masse (sometimes called slope compensation, not necessarily consistent with higher order dispersion compensation). In the meantime, to realize a tunable dispersion compensation system, a control circuit and a dispersion detection system are required for controlling the tunable dispersion compensation device mentioned above depending on the dispersion of a transmission line. Research is in progress on methods to detect changes due to dispersion and what can be detected by a receiver, such as

- (i) pulse duration (pulse duty ratio),
- (ii) peak power of pulse,
- (iii) high frequency component of signal spectrum,
- (iv) clock signal component. In addition, there is ongoing research with regard to
- (v) a method to detect phase distortion of two signals of different wavelengths, and
- (vi) a method to detect dispersion from the quantity of change in oscillation modulation of modulation components (or quantity of changing frequency phase) via chromatic dispersion from activated phase (or frequency) modulation.

C. Research themes

The following summarizes the themes of chromatic dispersion compensation systems based on

the above discussion.

Compensation quantity is determined by system parameters (bit rate, modulation format, transmission distance, path mean power, transmission fiber) as a matter of course. The characteristics required for the chromatic dispersion compensation method are: (i) low insertion loss, (ii) small size, (iii) low electric power consumption, (iv) multi-channel compatibility, (v) high-order dispersion compensation (no ripple within signal bandwidth), and (vi) high-speed variability. Here, (iv) high-order dispersion compensation and (vi) high-speed variability, which have not been described so far, are briefly referred to. In 160 Gb/s ultrafast optical communication, waveform distortion arises if dispersion is different within the signal spectrum. The task of item (iv) is to compensate for high-order dispersion (third-order dispersion, fourth-order dispersion).

The speed at which a wavelength changes can be on the order of several hours if the cause is temperature or residual stress. In this case, the conventional tunable dispersion compensation system has no problem, but in the case of future optical network applications, a chromatic dispersion change will occur in the order of 10 msec if network topology is reconstructed (if path length changes). Task (vi) assumes a case of compensating for a high-speed wavelength change.

4-3-4 Polarization mode dispersion compensation technology [4.3.4.1]

The current status and issues concerning polarization mode dispersion compensation technology essential for development of an ultrafast optical communication system are described here.

A. Necessity of polarization mode dispersion compensation technology

Polarization mode dispersion tolerance, if it is assumed to be 10% of a time slot, is 0.64 psec in a 160 Gb/s system. This will be equivalent to 40 km in terms of current optical fiber cable (polarization mode dispersion: $0.1 \text{ ps}/(\text{km})^{0.5}$). Thus, study of polarization mode dispersion technology is necessary for development of a long haul optical communication system. (A study of fiber having a polarization mode dispersion as close to zero as possible and a study on an absolute single polarization mode transmission system are certainly necessary as well.) Since polarization mode dispersion changes over time, the compensation method must, in principle, be a tunable compensation system.

B. Current status of main technologies

To compensate for polarization mode dispersion, it is necessary to detect and cancel the Principal State of Polarization (PSP) and Differential Group Delay (DGD). Optical compensation systems include the following:

- (i) a method to combine a polarization mode control unit and a fixed DGD (PMF: Polarization Maintaining Fiber, for example) to cancel DGD of the transmission line,
- (ii) a method to combine a polarization mode control unit and a tunable DGD (e.g., nonlinear chirp type FBG, PMF + polarization controller + PMF, etc.) and cancel DGD of the transmission line,

(iii) a method for pulse compression (a combination of asynchronous phase modulation and a chromatic dispersion device) at the receiver end (advantage of no feedback system needed), and (iv) a method to detect PSP in the transmission line at the receiver and transmit the signal along this axis (control speed is determined by signal round-trip time between transmitter and receiver). With regard to high-order polarization mode dispersion compensation systems, there are studies in progress on a method to connect a combination of a polarization control unit and a PMF in series of two steps (compensation bandwidth is limited) and a so-called distributed polarization mode dispersion compensation method to connect a polarization control unit and a small DGD in multiple steps. However, they have shortcomings in that insertion loss of a compensation unit gets larger and that the number of polarization mode control parameters increases.

In the meantime, polarization mode compensation using an electronic circuit is also under study. In principle, it is a method to detect intersymbol interference and compensate for it, and is similar to a compensation circuit for chromatic dispersion. A compensation method using an electronic circuit has advantages such as low cost, small size, compensation for a wide range of intersymbol interference, and no loss of optical power. As for specific structures, a study is under way on the combination of a transversal filter (linear filter, also called a feed forward equalizer, whose weakness is inability of compensation if cross polarization power is 1 to 1 or DGD exceeds 1 time slot) and quantum feedback (a nonlinear filter whose weakness is occasional error cascading). Another study currently under way is on a method to achieve a high-speed polarization scrambler with a transmitter for rotating sufficient polarized waves in a frame of FEC (Forward Error Correction) and cancel the influence of polarization mode dispersion by combining a transversal filter in a receiver and FEC unit.

To develop the optical compensation system mentioned above for polarization mode dispersion compensation, there must be a means to monitor a quantity that is sensitive to polarization dispersion and its change and is eventually correlated to bit error. The monitoring systems currently under study are a method to extract with a filter a part of RF spectra of received signals, for example, a frequency component of $1/2$, $1/4$, and $1/8$ of a bit rate (this method is compatible with DGD over 1 bit); a method to measure the whole RF power of received signals (weakness is low sensitivity); a method to measure error rate of the received signals by using a decision gate circuit capable of setting a tunable discrimination level; and a method to measure the degree of polarization (DOP) degraded by polarization dispersion (measurable regardless of a bit rate).

C. Research themes

The issues of polarization mode dispersion compensation systems are summarized here based on the above discussion.

The polarization dispersion mode compensation systems necessary for an ultrafast optical communication system pose requirements such as a method to detect DGD and PSP and compensate primary and secondary PMD, small size, low insertion loss, low cost, and high-speed

compensation.

The topics of low cost and high-speed compensation are briefly discussed as follows. Since it is difficult to compensate a volume of polarization mode dispersion over a wide wavelength bandwidth in the case of WDM transmission, a polarization mode dispersion compensator will be needed for each wavelength channel. Therefore, a low cost compensator is desirable. To develop a low cost compensator, it will be necessary to study a method such as DOP detection regardless of the bit rate..

The speed of the change of polarization dispersion is determined by changes in the environment, for example, temperature changes and the speed of the change of distortion added to optical fiber. A temperature change takes place on the order of an hour or several months, but the distortion added to optical fiber changes rapidly. For example, there is a report on the observation that PSP runs on a Poincare sphere at 50 rotations per second. Therefore, to follow the fast polarization movement, high-speed polarization mode dispersion that operates on the order of a msec will be necessary.

4-3-5 Next-generation optical fiber

This section describes issues for fiber characteristics required, previous efforts and problems related to high-speed transmission over 160 Gb/s, and issues concerning high-speed transmission over 160 Gb/s, with regard to optical fiber used for a transmission line as key technologies for developing a 160 Gb/s next-generation ultrafast optical communication system.

A. Fiber characteristics

With regard to the characteristics and issues required for a fiber transmission line during high-speed transmission, a description of the following three items is given below: chromatic dispersion control, polarization mode dispersion suppression, and signal power increase.

i) Chromatic dispersion control

- High accuracy second-order and third-order dispersion compensation limit
- Higher-order (fourth-order) dispersion compensation

The current technology uses a dispersion management fiber to avoid signal degradation by chromatic dispersion and nonlinearity. Chromatic dispersion (second-order dispersion) and dispersion slope (third-order dispersion) are compensated by the dispersion and slope compensating fiber at the same time. Second-order dispersion becomes a limiting factor of speeding up of transmission in proportion to the square of the bit rate. In addition to third-order dispersion compensation, fourth-order dispersion compensation will be needed for over 100 Gb/s transmission.

ii) Polarization mode dispersion (PMD) suppression

- PMD suppression technology (improvement of fiber manufacturing technology and cable structure optimization)

- Single polarization transmission (high-birefringent fiber)

PMD limit on transmission quality diminishes in reverse proportion to bit rate. The limit assumed for 40 Gb/s is 1/4 at 160 Gb/s. Since PMD with the current fiber cable for long haul transmission is about 0.1 ps/ $\sqrt{\text{km}}$, a value approximately equivalent to 1/4 of this value should be the target for manufacturing fiber and cable products.

iii) Measures against transmission signal intensity increase (nonlinearity control, high power tolerance, lower loss)

- Low-power density fiber structure
- Loss reduction

To maintain signal quality (SNR: Signal to Noise Ratio) for high-speed transmission at the conventional level, it is necessary to increase mean signal intensity in proportion to the bit rate, and signal peak intensity will increase by a square. As its influence, there are concerns about signal quality degradation due to nonlinear effects and fiber damage due to heat. Nonlinear effects increase in proportion to signal peak intensity and are major factors in transmission quality deterioration. The effects are mainly waveform distortion (proportionate to the third power of bit rate) due to self-phase modulation (SPM) and chromatic dispersion, inter-channel cross-phase modulation (XPM), four wave mixing (FWM), stimulated Raman scattering (SRS), etc. Another thing to consider would be the influence of fiber fusion from heat given to the optical fiber by a high power signal.

B. Conventional approaches to high-speed transmission and problems with communication speeds over 160 Gb/s

The following explains conventional approaches to transmission up to 40 Gb/s.

i) Chromatic dispersion management

A dispersion management transmission line is established to optimize chromatic dispersion in a span between repeater stations. In line with the broadening of the wavelength band used, optical fiber with a reduced dispersion slope (third-order dispersion) has been developed. Thus, the structure (refractive index profile) to control the desired chromatic dispersion has been optimized and a more complex profile with multi layers is created. There are many cases where it is a matter of trade-off between chromatic dispersion control in the structural design of fiber and other characteristics (such as a core diameter increase for low nonlinearity), and it is necessary to examine the structure based on the required characteristics. In addition, there is a problem in that fiber with a complex structure is difficult to control and reproduce in manufacturing.

ii) Polarization mode dispersion (PMD) suppression (polarization stabilization)

As for the manufacturing technology to reduce the PMD of fiber, oscillatory twisting during fiber drawing and high temperature control has been adopted. Since the cause of PMD deterioration during cable manufacturing is not clear, investigation of the cause of PMD occurrence in each

manufacturing process, such as fiber ribbon manufacturing and cabling as well as optimization of manufacturing conditions, are being tested. PMD is largely influenced by external disturbances (temperature, lateral pressure, etc.) and has a number of uncertainties. Therefore, it is necessary to control polarization and aim to make transmission by single polarization possible. The methods are available from the use of polarization maintaining fiber with high double fraction by stress imparted and core deformation as well as single polarization mode fiber removing radiation mode from ever transmitting polarization mode.

iii) Non-linearity control

The general solution is to enlarge the core diameter (A_{eff} : effective area) to reduce the power density of signal in the fiber. However, changes in the core diameter influence structure dispersion characteristics. In particular, a dispersion slope reduction and core diameter increase are in the relationship trade-off and their compatibility is a problem. An optical fiber using new materials with a nonlinear refractive index (n_2) is under consideration.

iv) Loss reduction

While transmission loss reduction is an overall problem for optical fibers, it is a very important issue from the standpoint of high-speed transmission since it will contribute to nonlinearity reduction and avoidance of fiber damage by high power, both as the results of heat generation control by energy dissipation reduction in transmission lines and the reduction of transmission signal intensity. With regard to silica glass optical fiber, reduction of structural inconsistency loss is under way by removal of impurities (transition metals, OH^-), reduction of Rayleigh scattering by optimization of base material composition, and optimized heat treatment in fiber drawing. In addition, research is being undertaken on new materials (pure silica, P-doped silica, multi-component fibers).

v) High power tolerance

Reduction of optical power (fiber structure with core diameter increase) in the optical fiber is carried out like the nonlinearity reduction.

Table IV-4-5 Conventional approaches to high-speed transmission

Subject		Approach	Objective/specific measures	Problem
(i)	Chromatic dispersion control	Structure (Refractive index profile) Optimization	Multilayer core	Manufacturing controllability and reproducibility, High-dimensional dispersion compensation is a problem. Complication
		Dispersion management design	Bandwidth broadening by reduction of dispersion/dispersion slope	Splice loss reduction
(ii)	Polarization mode Dispersion suppression (polarization stabilization)	Fiber PMD reduction technology	Twisting during fiber drawing and accurate control of refractive index Fiber drawing control (temperature control: high temperature), optimization of coating materials	Dependence on manufacturing
		PMD reduction during cable manufacturing (Measures for factor in each manufacturing process)	Fiber ribbon: Manufacturing condition optimization (material improvement)	Deterioration factor during cable manufacturing is not clear. (Too many uncertain factors to control)
			During cabling: reduction of tension	

		Polarization maintaining fiber	Stress imparted, Refractive index profile Deformation, core deformation	Crosstalk deterioration during long-distance transmission (Present cross talk -20dB/1km)
		Single polarization mode transmission fiber	Removing polarization mode at the other end as radiation mode Structure induction type (axial asymmetry refractive index profile) Stress induction type (axial asymmetry internal stress distribution)	Mode coupling control is a problem. Transmission loss is great.
(iii)	Nonlinearity control	Low non-linearity due to A_{eff} enlargement	Ring type refractive index profile, etc. Compatibility with dispersion slope control	Dispersion slope and trade-off
		Reduction of nonlinear refractive index (n_2) with new materials	Pure silica, P-doped silica etc.	Manufacturing technology improvement
(iv)	Loss reduction	Absorption control (impurity removal)	Reduction of transition metals and OH^-	Dependence on manufacturing technology
		Reduction of Rayleigh scattering	Optimization of base material composition	
		Reduction of structural inconsistency loss (viscosity consistency between core clads)	Heating treatment method (low temperature, slow fiber drawing → reduction of density deviation)	
		New material research	Pure silica, P-doped silica, Multi-ingredient type fiber, Fluoride fiber	Manufacturing technology improvement
(v)	High power tolerance	Structure for transmission power reduction	A_{eff} , MFD expansion	Bending loss (deterioration during fiber and cable manufacturing)

Table IV-4-6 Photonic crystal fiber (PCF) technology

Type	Guide wave principle	Structure	Characteristics	Characteristics for high-speed transmission line				Subject
				Chromatic dispersion control	Non-linearity, high power tolerance	Low loss	Polarization mode dispersion	
Hole assisted fiber (HAF)	Index guiding (waveguide by refractive index difference (entire reflection))	Core: SMF core (Ge/Si)	Ultra-low bending loss	—	Compatibility between MFD and bending loss control	—	Double refraction can be obtained in asymmetric structure due to large differences in refractive index of glass and air. Beat length smaller by one digit than conventional polarization maintaining fiber has been developed.	Transmission loss is high: Structural inaccuracy loss increases due to scattering and absorption occurring in the longitudinal direction, depending on hole accuracy and irregularities of the inner surface of the hole. Improvement of fiber splicing technology The range of low loss operation band is limited (PBGF). Fiber length obtained is short (currently about 1km).
Holey fiber		Core: Silica glass	Wide bandwidth single mode, MFD diameter enlargement	Control variation is large. (since effective refractive index difference is up to 10 times larger and waveguide dispersion greatly contributed to chromatic dispersion.)	MFD diameter enlargement is possible.	Reduction of Rayleigh scattering and low loss due to pure silica core		
Photonic band gap fiber (PBGF)	Core: Hole	Low loss, low nonlinearity, high power tolerance is high.	Low nonlinearity high power is high due to the hole.		Ultra-low loss potential due to the hole (<0.001dB/km)			

vi) Approach to transmission line using photonic crystal fiber (PCF) technology

In examining fiber designs for a transmission line satisfying the above characteristics, problems arise relating to various conditions such as the relation trade-off between dispersion slope control and A_{eff} increase, deterioration of basic characteristics (such as bending loss) due to core diameter increase, and PMD deterioration for lateral pressure. Therefore, in order to satisfy all the conditions, there is a need for a structure that is not available in conventional fibers. Photonic crystal fiber (PCF) is a fiber with cyclic holes in the clad portion and has different characteristics from conventional fiber structures. Therefore, PCF has great potential for high-speed transmission lines. PCF is mainly classified by its structure into three types (hole assisted fiber (HAF), Holey fiber, and photonic bandgap fiber (PBGF)). General characteristics of PCF are wide single mode transmission wavelength range, zero dispersion wavelength, nonlinearity variation, large MFD (mode field diameter), single mode compatibility (power tolerance), and large core-clad index differences. Holey fiber and PBGF can be compatible with chromatic dispersion control and A_{eff} expansion, and have potential for loss reduction. With regard to polarization mode control, it is also possible to use a double fraction arising from large refractive index differences between glass and air in an asymmetric structure. Despite these revolutionary characteristics, there are a number

of problems in designing and manufacturing due to complex structures. In particular, transmission loss remains greater as compared to that of ordinary silica fibers, since scattering and absorption change depending on accuracy of holes and irregularities of the inner surface of holes.

C. Issues for high-speed transmission over 160 Gb/s

In order to deal with the above issues, the technical issues to solve are proposed for consideration. Measures for fiber and cable technology are presented for a transmission line.

Table IV-4-7 Direction of high-speed transmission over 160 Gb/s

Technical issues		Target	Fiber			Cable
			Technical improvement of silica fiber	Development of new material fiber	Development of photonic crystal fiber (PCF)	Cable manufacturing technology
(i)	Chromatic dispersion control	High stability dispersion control High-order (third and fourth order) dispersion compensation	○ High-order dispersion compensation waveguide structure design	⊙ Material dispersion control	⊙ High-order dispersion compensation waveguide structure design	—
(ii)	Polarization mode dispersion suppression	Reduction to 1/4 or less of the existing, High birefringent fiber development, Low PMD cable manufacturing technology	○ Polarization maintaining fiber, Improvement of polarization cross talk	—	⊙ Development of high birefringent fiber	Development of low PMD cable manufacturing structure
(iii)	Loss reduction	New material/structure development, Improvement of manufacturing technology,	○ Impurity removal technology	⊙ Low-loss base material development (used for PCF as well)	⊙ Use low loss base material, Use hole assisted fiber, Improve manufacturing technology, Inter-fiber connection technology	Inter-cable (tape) connection method in development of cable manufacturing technology
(iv)	Low nonlinearity	Inter-fiber connection technology	○ Aeff increase	○ Development of low nonlinearity material	○ Aeff expansion, Use hole fiber	
(v)	High power tolerance					

○: Effective technology ⊙: More effective technology in spite of many technical issues

i) Fiber development

As a direction of research, we take up three issues, or technology enhancement for silica fiber, development of new material fiber, and application of photonic crystal fiber (PCF). An approach to silica fiber is the extension of past efforts, but the present requirements are waveguide structural

design for achieving expansion and compatibility with high-order dispersion compensation, improvement of polarization crosstalk in polarization maintaining fiber, and impurity removal technology for development of low loss material.

In addition, it is possible to control material dispersion by development of new materials regardless of waveguide dispersion control and to attain low nonlinearity. Much can be expected from optimization with the combination of structural design by conventional technologies. Low-loss and low nonlinear materials can be applied to PCF. PCF is a very promising area, together with structural design optimized for a high-speed transmission line, high-birefringent fiber, low loss by using low-loss new base materials and electron holey fiber. To achieve these matters, there are a number of issues concerning manufacturing technology. In particular, a manufacturing method with high structural accuracy, specifically stability of fiber drawing, accuracy improvement of hole positioning, and radial uniformity are important requirements for improvement. Stable manufacturing and high productivity for long fiber are also essential. Also wanted is the development of inter-fiber connection technology considering the control of hole positioning.

ii) Cable manufacturing technology

One of the technical issues of cable manufacturing is polarization mode dispersion suppression, and cable manufacturing structures need to be optimised for this purpose. Reduction of splice loss between cables (ribbons) will be an issue to solve for fiber with a complicated structure such as PCF.

4-3-6 Next-generation optical amplification technology

Upgrading of optical amplification technology aiming at optical transparency is further needed in the next-generation photonic network for transmitting a very large amount of data end to end stably and without stress. The requirements for next-generation optical amplification technology are substantial expansion of bandwidth (400 nm or more including SCL band, U band, O band, and E band), reduction of noise characteristics (NF) (clearing NF 3dB), and provision of a signal processing function like optical 3R and 2R. Various research studies are being conducted on these requirements so that interdisciplinary technology development efforts may complement each other in technology development.

A. Rare-earth doped fiber type optical amplification technology

Development of optical communication is supported by commercialization of a rare-earth doped fiber amplifier, particularly an erbium-doped fiber amplifier, which amplifies light as is. Thus far, transmission capacity has increased with the WDM system, and as a result broadbanding of EDFA is wanted. Broadbanding of 85 nm between 1530 nm and 1615 nm has been demonstrated. Next, we will touch on the approach and the problem of erbium-doped fiber amplifier technology for next-generation information communication at a 160 Gb/s bit rate.

i) EDF absorption value upgrading

Shortening of the length of fiber will become possible by increasing amplification efficiency through

upgrading of the EDF absorption value. Subsequently, reduction nonlinearity and dispersion control will be feasible. Available approaches are concentration of erbium with additive processing, optimization of refractive index, and (3) new host glass (trade-off with dispersion and nonlinearity).

ii) Higher output capacity

An ultrafast speed of 160 Gb/s will reduce the power per bit. Therefore, higher output capacity of optical amplifiers is needed. Possible solutions are an expansion of the core cross-sectional area and an increase in power conversion efficiency by lower loss, and high power multi-mode LD excitation by a double-cladding architecture.

iii) Dispersion control

Higher dispersion control is required in a transmission line due to a faster bit rate, and is necessary to control dispersion in an optical amplifier under an ultrafast transmission of 160 Gb/s. Its approach requires technology that will optimize the refractive index profile and increase the degree of freedom in designing the dispersion value and dispersion slope.

iv) Nonlinearity suppression

With ultrafast transmission and a faster optical amplifier, the peak-to-peak value of a signal will go up. As a result, nonlinear effects will tend to take place in a fiber for amplification, and nonlinearity of optical fiber for amplification must also be controlled to prevent deterioration of signals. As a solution, it will be necessary to shorten the length of fiber by increasing the absorption value of EDF and to develop technology for reducing optical power density by expansion of A_{eff} .

v) PMD suppression

Dispersion control as well as PMD control will be necessary. Possible solutions are (1) improvement of manufacturing conditions such as oscillatory twist during fiber drawing and high temperature control and (2) fixed polarization maintaining fiber of EFM, and development of single-polarization fiber. These issues are common to a rare-earth doped type optical amplifier, for example, a thulium-doped fiber type, erbium-doped optical waveguide amplifier.

B. Fiber Raman amplification technology

A fiber Raman amplifier makes use of molecular vibration and Raman scattering phenomenon of optical fiber materials, and generally, silica fiber has a bandwidth of about 100 nm, which is the frequency of scattering shift molecular vibration (Stokes shift). If tellurite fiber is used, the bandwidth will increase up to 170 nm (Raman gain coefficient is 16 times that of silica fiber) [4.3.6.1]. Raman amplification technology has characteristics capable of amplifying an arbitrary waveband by changing excitation light wavelength, and is a promising technology for further transparency of a photonic network. There is a possibility of development for very large capacity optical amplifier technology beyond 200 nm bandwidth by searching for new glass materials and improving excitation conditions in the future.

C. Parametric optical amplification technology

Fiber parametric amplification that uses four-wave mixing effects or third-order nonlinear optical effects of optical fiber is already at the stage of application with an amplification bandwidth of about 40 nm and about 30dB gain [4.3.6.2]. If fiber dispersion control technology is enhanced, 100 nm or more bandwidth may be feasible in the future. The so-called “phase non-sensitive type” will be able to attain NF close to a theoretical limit value and high gain of 50dB or more by using other fiber materials and by adopting new excitation conditions. At the same time, development of an optical signal processing function (high-speed wavelength conversion etc.) is also awaited.

D. Coherent optical amplification technology [4.3.6.3]

With “phase non-sensitive type” amplification such as a laser amplifier that provides the equal gain to two optical components with an orthogonal phase, the signal-to-noise ratio (SN ratio) is degraded by 3dB theoretically even under ideal conditions. To expand regenerative repeater spacing (optical transparent domain), it is imperative to reduce the Noise Figure (NF), which is a degradation amount of SN ratio. In recent years, an experimental study of “phase sensitive type” amplification was started as a special case of parametric optical amplification, and it has been theoretically proven that noiseless amplification is possible without degrading the SN ratio between input and output. Also, signal processing functions such as for optical waveform shaping effects and jitter reduction effects have been practically verified. To commercialize these technologies, however, remaining research issues are measures for increased bandwidth, gain, WDM signal and polarization dependency, etc.

E. Quantum dot semiconductor optical amplifier technology [4.3.6.4]

Development of a semiconductor optical amplifier (SOA) using semiconductor quantum dots (semiconductor particles with a size of several tens of nm) in the active region is in progress [4.3.6.4]. The performance characteristics beyond those of SOA with a quantum well or bulk in an active region have been demonstrated, such as high output power of more than 20dBm using a small part of active region volume and wide bandwidth gains over 100 nm making use of variances of quantum dot size. Low noise like EDFA is expected theoretically, because the population inversion parameter can take a value very close to one. In addition, lower electric power consumption is also expected. It is effective as a small-sized energy-saving optical amplifier, not only as a replacement for a conventional EDFA but to be used for optical power compensation at various places of optical nodes. Application studies for various optical-nonlinear devices such as wavelength conversion devices and optical switching are in the process of being studied.

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Part 5 Summary

This part divides the areas of ultrafast technology that will constitute the public network in 2010 ~ 2015 into the three categories of node technology, link technology and key technology, and summarized each item from the viewpoints of the current status, issues and necessary technology.

Chapter 2

Various benefits such as ease of wavelength management, multi-channel lump processing, scalability improvement, reduction of electric power consumption, etc. are expected by introducing ultrafast optical technology into network nodes, which play roles of switching, gateway, signal monitoring and network control/management. For this purpose, development of various types of technology such as add/drop, time slot interchange, modulation format conversion, ultrafast optical signal monitoring, new nonlinear materials and so forth is needed.

Chapter 3

In the CORE/METRO systems that are expected to demand transmission capacity of the tera-bit class or more in the near future, ultrafast transmission that can significantly reduce the necessary number of wavelengths for securing such a large capacity is expected to provide benefits such as space saving, low electric power consumption, lower costs, and the like. However, as the bit rate gets faster, various factors related to transmission quality deterioration will impose a significant limitation, and it will be difficult to maintain stable transmission for a long distance. Therefore, research and development of technologies for improving transmission characteristics, such as transmitter/receiver technology for generating and receiving ultrafast optical signals in a stable manner as well as optical 3R and polarized mode dispersion (PMD) compensation technology, is needed.

Chapter 4

Devices and fundamental technology regarded as being essential for developing ultrafast (over 160 Gb/s) optical communication systems was studied. As a result, we have pointed out that research and development will be essential in terms of ultrafast optical signal generation technology in transmitter/receiver technology, functional devices like clock extraction and an optical switch in node technology, and an optical modulation and demodulation format, dispersion compensation technology or high performance optical fiber in link technology.

Conclusion

Conclusion

The growth of optical technology is one of the very great engineering revolutions of the 20th century. In particular, the progress of technology for high-speed large-capacity optical communications has played an important role in the social infrastructure to support the sharp growth of the Internet. On the other hand, in terms of the prospect for Japan's industrial technologies in the 21st century, research and development of information communications and electronics is indispensable as one of the major strategies in Japan. The technology of optical communications and devices is, in particular, one of Japan's world-leading technological fields. So, it will be important to bring this field into fruition as an industrial technology effectively while retaining its superiority.

Ultrafast optical device technology in particular has grown greatly in Japan over the past ten years, and it has become a world-leading technology due to NEDO's "Femtosecond Technology" project carried out from 1995 to 2004. However, since it will still take a long time to put the technology into practical use, it will be necessary for the market to pull up the technology (pull) as well as devise additional technological ideas (push).

This report presented outlines of the themes and feasibilities of research and development from the viewpoint of technologies for following and conforming to such a social trend. In particular, from the aspect of technological seeds, it is expected in the future to realize various improvements, and various technological themes to be overcome have been discussed. These improvements are to develop a smaller, faster, larger capacity, lower cost, and lower power consumption products by utilizing the excellent characteristics of light in various scales from micro to macro. Examples of applications include optical interconnection inside an LSI-chip, optical interconnection between LSI-chips, optical interconnection between boards, and LAN/SAN and optical communications over a short to long distance.

For backplane transmission technology which is necessary for improving the information processing function of servers and routers, optical transmission technology is expected more than ever to be a technology to overcome the bottleneck of electric IO technology as it is necessary to develop faster and larger-capacity products. The technologies for realizing this, including optical device technology, conversion LSI circuit technology, optical implementation technology and so on, must be small-sized, have low power consumption, and be low in cost. The implementation of optical switching and its architecture will be future themes.

In addition, for LAN/SAN technology which is necessary for introducing networks into the production sites of the digital content industry and for other purposes, large-capacity optical communications have potential for creating content or enjoying video entertainment titles without suffering from delays due to compression and decompression, and ultrafast optical communication systems are necessary as an infrastructure.

On the other hand, for grid technology which uses various resources connected with

communication networks, such as computers and storage systems, technological development of various themes will be necessary in the future to flexibly utilize large-capacity high-speed networks. So, it is important to control increased power consumption by communications as well as reduce communication costs and improve usability by utilizing optical communications.

Furthermore, in the field of large-capacity optical communications, it will be necessary in the future to implement a function to make bandwidths variable in accordance with the needs of users and applications. So, a signal data rate of nearly Tb/s will be necessary, and TDM technology of over 100Gb/s will be indispensable for high-speed low-delay transmission. Hence, it is necessary to deploy node technologies, link technologies, and key technologies in the field of ultrafast communication technology for configuring future public networks.

Japan's themes in the 21st century are harmonization with the global environment, ensuring safety and freedom, intellectual flexible social life and so on. It is promising that ultrafast optical communication device technology which has overcome the technological themes mentioned above contributes greatly to the realization of such themes. Some examples of such contributions are improvement of energy-saving using optical communication technology, ensuring of security by network technologies, increased business opportunities, and enrichment of personal social life by sending/receiving large-capacity motion pictures.

However, there still remain the following problems:

- (1) The need to create more innovative optical devices
- (2) Difficulty in grasping the market trend for optical communications and device technologies
- (3) A decrease in large-scale needs which have a favorable impact on society and pull the market
- (4) Issues concerning market size and cost competition
- (5) Responses to world trends (especially the technological boom in Asian countries).

To deploy optical technologies to contribute to Japan's industry in the future under such circumstances, it will be important to adopt a well-thought-out strategy of research and development that is different from conventional strategy. In particular, regarding the devices mentioned in (1), it will be necessary to greatly improve performance and create a brand-new excellent function. As DFB lasers and EDFA brought about a big turning point and a big jump in optical communication technology in the past, ultrafast optical technology will be a key technology to create innovative devices. In addition, considering that the market trend is currently not correctly understood as mentioned in (2) and the necessity of arranging the infrastructures for Japan's security, it is also an important element to pull the market by means of national public institutes. Technological development is a new challenge, and a breakthrough is always expected to achieve a goal which has not been achieved by conventional technologies. To do so, it will be necessary in the future to draw a clear scenario towards the future and support technological progress by strategic efforts.

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