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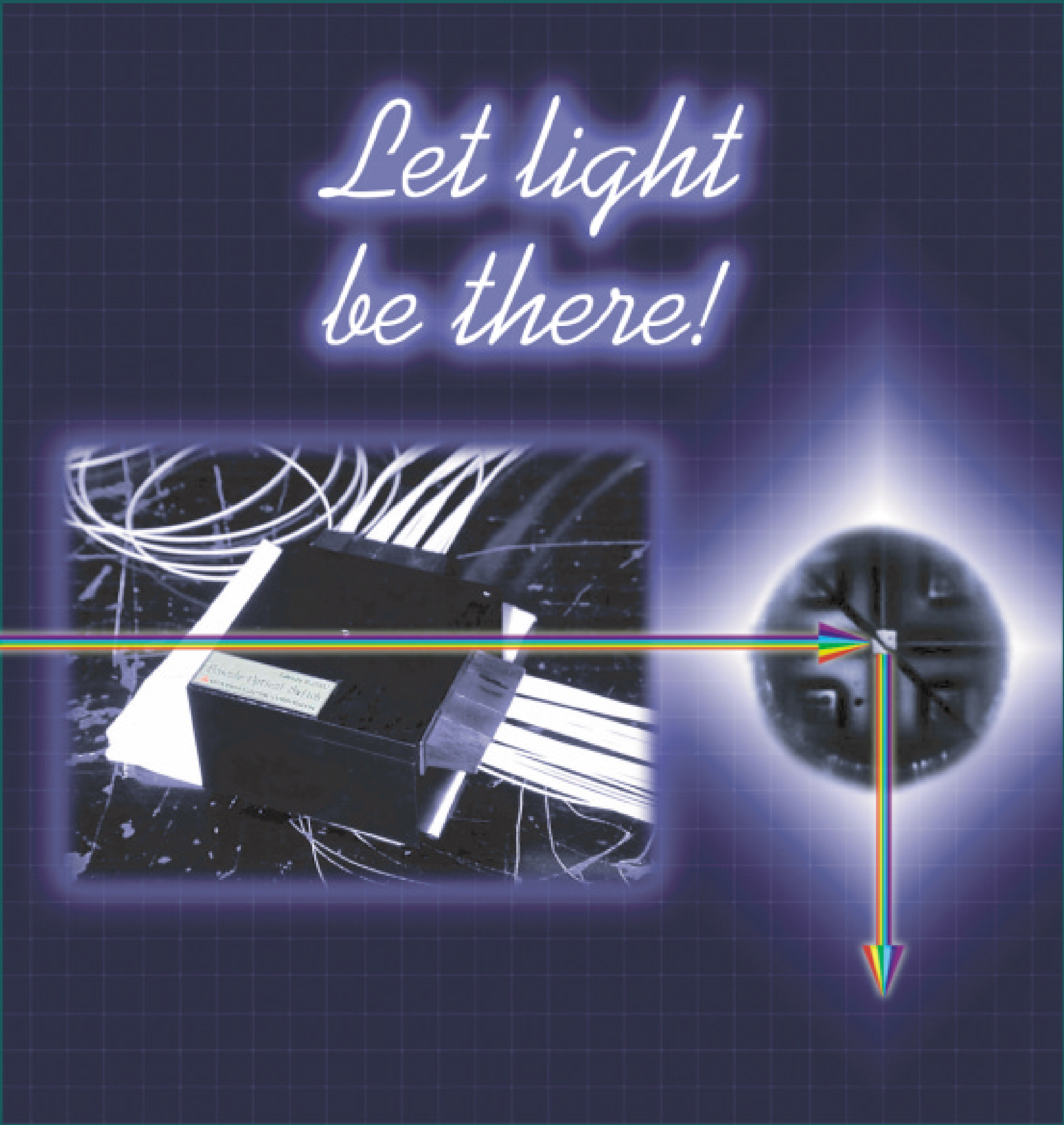
Optical Communication & Device Technologies Edition



MITSUBISHI ELECTRIC
Changes for the Better

●Vol. 101/March 2003 Mitsubishi Electric **ADVANCE**

Optical Communication & Device Technologies Edition

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Cover Story

Our front cover shows a prototype of the 32 x 32 "Bascule" optical switch (lower left) and an individual optical switch unit (on the right). Their optical switch technology is central to next-generation optical networks. "Let light be there," a slight reordering of a much more famous phrase, implies that the newly-developed Bascule optical switch can route the incoming optical signal to any of the output fibers. something that our graphic attempts to illustrate.

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Overview

Optical Communications in the Broadband IT Renaissance

*by Professor Kazuroh Kikuchi**

I visited Copenhagen in early September, 2002, to attend the European Conference on Optical Communication (ECOC), a conference that ranks with America's Optical Fiber Communication Conference (OFC) in this field. The frenetic pace of research and development in optical communications continues unabated, but in sharp contrast, the booths of equipment vendors at the associated exhibition were incomparably more subdued than those that marked the peak of the IT "bubble" in 1999 at the ECOC conference held in Nice. Equipment vendors all over the world are facing difficult conditions, as evidenced by the withdrawal of the former leading US optical component manufacturer, Agere.

One major cause of the IT bubble was the optimistic prediction of growing demand for communication capacity without any basis in real needs. The 1996 Telecommunications Act in the United States, while it allowed the local monopoly telephone companies to participate in long-distance communications, also forced them to give up their monopoly of subscriber communications equipment. This liberalization had the unintended consequence of limiting investment in subscriber systems, and invited higher pricing of broadband services such as ADSL. We cannot expect the optical communication market to recover its health without much more widespread adoption of optical technologies in subscriber systems and the real demand that this will create.

The prosperity of the US communication sector in the 1990s began in 1992, with an OFC keynote speech identifying the "catalysis of the government" as an important element in the sector's growth. This was followed by the well-known initiatives of the multiwavelength optical network (MONET) consortium and other joint projects involving government, private industry and academia. This research and development is responsible for the high level of current US optical communication technology. In Europe, similarly decisive influences were exerted by all-European projects such as RACE/ACTS. In Japan, the e-Japan strategy was decided on by the IT Strategic Headquarters in January 2001, with the declared aim of using fiber to the home (FTTH) to secure ten million subscribers for ultrahigh-speed Internet services within five years, providing the necessary legal framework and cooperation between industry and government as a national project. This marks the start of a national commitment to an IT renaissance driven by broadband communication using optical technology. Recently, such national projects are expected to form the nucleus of a new industry within five years. This means even greater pressure on corporate R&D than before. I take the occasion of this special issue of *Advance* to express my desire to see Japanese optical technology, and the industry as a whole, make healthy progress. ❑

**Professor Kikuchi is at the Research Center for Advanced Science and Technology, the University of Tokyo.*

Submarine Optical Transmission Technology for Multi-Terabit Capacity

*by Junichi Nakagawa and Masatoshi Kato**

In order to handle the increased capacity of international telecommunications due to growing demand for international telephony and the rapid expansion of the Internet, 10Gb/s wavelength-division multiplexing (WDM) optical submarine repeaters for optical submarine-cable systems have been developed, along with 10Gb/s line-terminal equipment. Fig. 1 shows the system configuration for a 10Gb/s WDM optical submarine-cable system. The system comprises a 10Gb/s line-terminal equipment and optical submarine-repeater, where wavelength division multiplexing in the line-terminal equipment is performed with multiple 10Gb/s optical signals of different wavelengths. The WDM optical signals are all amplified simultaneously by a highly reliable optical undersea repeater, making transmission distances in excess of 9,000km possible. The optical undersea repeaters developed in the current project hold the promise for increased capacity in the future, with broadband characteristics capable of WDM for up to 96 different wavelengths of 10Gb/s optical signals through the application of high-power 980nm pump-laser diodes, and through the development of large casings capable of housing up to 12 subsystems. Additionally, the line-terminal equipment improves transmission quality through the use of second-generation forward error correction (FEC) technology with vastly improved error-correction capabilities, while saving space using a high-density packaging technology able to house eight wavelengths in each bay.

Broadband optical submarine repeaters

CONFIGURATION OF OPTICAL SUBMARINE REPEATERS. Fig. 2 shows an external view of the optical submarine repeater developed in this project.[1,2] The larger pressure housing makes it possible to increase the housing structure from the conventional four-fiber pair (4FP) structure to a structure with a maximum of 12FPs, making it possible to increase the maximum transmission capacity for a single repeater up to 11.52Tb/s (for each fiber

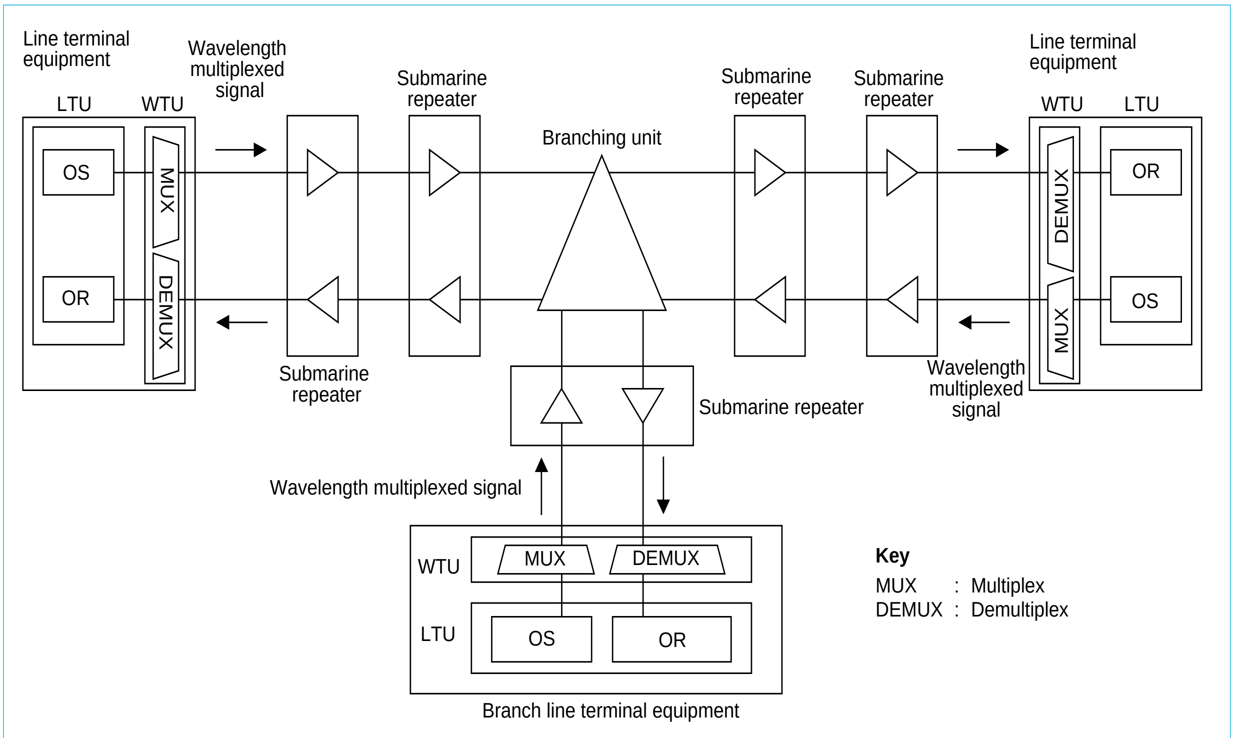

Fig. 1 Line terminal equipment

**Junichi Nakagawa and Masatoshi Kato are with the Communication Networks Center.*

Fig. 2 Photograph of optical submarine repeater

pair: 0.96Tb/s = 10Gb/s x 96 wavelengths). (The photograph shows an 8FP configuration.)

Fig. 3 shows the subsystem configuration of optical submarine repeaters. The optical submarine repeater can house a maximum of 12 subsystems, where each subsystem is structured to amplify the optical signals for an upstream/downstream fiber pair. The optical submarine repeater comprises EDFs, pump-laser diode modules, pump-laser diode-drive circuits, WDM couplers, optical isolaters, gain equalizers, and supervisory-control circuits. The power supplied to the optical submarine repeaters is a direct-current power supply from the shore-end station, and is supplied to each subsystem through power-supply circuitry within the optical submarine repeater units.

Four 980nm pump-laser diodes are used, in order to reduce noise relative to the 1,480 nm pump-laser modules so as to make 10Gb/s transmission possible over long spans. Four 980nm pump-laser diode modules provide redundancy across the entire optical output in a highly reliable design; there will be no adverse effects on the system transmission performance even if three of the four pump-laser diodes in a subsystem were to fail. Supervisory functions (SV functions) capable of monitoring the status of the repeater in real time during system operation are provided in the supervisory-control circuits. These SV functions can be used to monitor the optical input and output power in the repeater, the electric current in the pump-laser diode modules, and their optical output power. The power consumption per subsystem has been reduced successfully to less than 9.8 watts by circuit integration.

OPTICAL PERFORMANCE. In order to implement a WDM transmission system for 96 wavelengths, it was necessary to increase the bandwidth and the output power, and to reduce the noise in the optical submarine repeater. In the optical submarine repeaters in this project, the use of newly-developed high power 980nm pump-laser diode modules, combined with the use of etalon filters as the gain-equalizer elements (GEQ elements), made it possible to achieve broadband characteristics in a range of about 30nm. An output power of more than +15 dBm with a noise factor of less than 5.0dB was also achieved. Fig. 4 shows the optical output spectrum when the input signal into the repeater

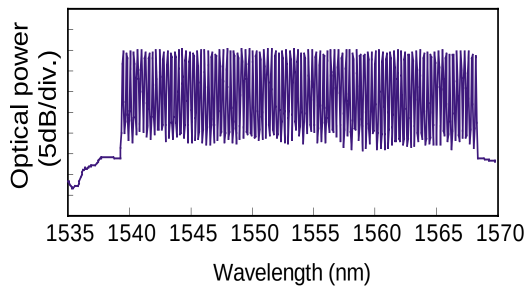

Fig. 4 Optical output spectrum of optical submarine repeater.

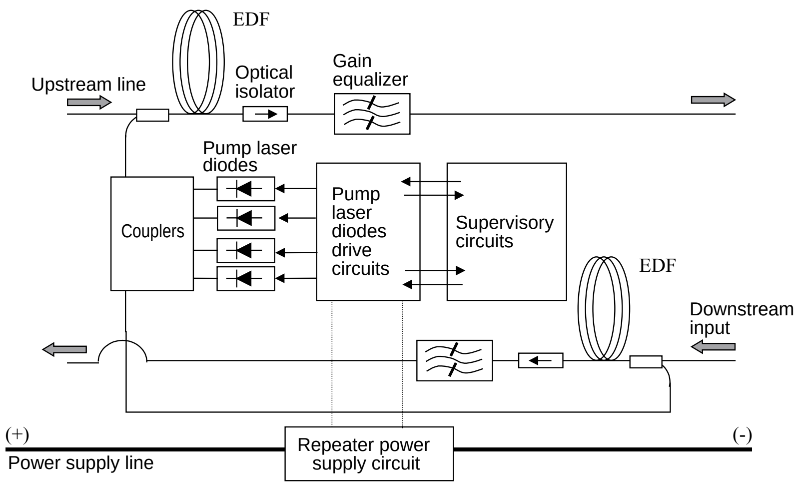

Fig. 3 Configuration of optical submarine repeater

is 96 wavelengths of 10Gb/s signals. A flat gain profile was obtained for the amplification characteristics across the entire wavelength band.

MECHANICAL DESIGN. The pressure housing for the optical submarine repeaters, to be deployed on the ocean floor to a maximum depth of 8,000 meters, are structured from a high-pressure cylinder (made from a copper-beryllium alloy because of its excellent ability to withstand corrosion from sea water), end plates, and joint rings for connecting to the submarine-cable joints. The optical fibers and power-supply lines are connected into the pressure housing using a feedthrough structure fitted to the end plates in order to maintain a tight seal. The repeater circuitry was mounted in the pressure cylinder using a heat-dissipating/shock-absorbing structure.

In developing a pressure housing capable of containing the maximum 12 subsystems of this project, the outer diameter of the housing was set at 320mm, allowing for the possibility of future increases in the number of subsystems. Consideration was also given to the limitations of the deployment facilities, such as the cable ships. The structural design ensures that the stresses produced when the housing is subject to water pressure at a depth of 8,000 meters (78.5MPa) do not exceed the elastic limits of the beryllium-copper material (588MPa). For the end plates, in particular, the development of the 24-core fiber feedthrough for high-density packaging and the use of three-dimensional FEM analysis to decrease the wall thickness around the location of the feedthrough by performing optimizations made it possible to increase the internal packaging capacity while reducing the weight of the repeater.

The cylindrical shapes of the subsystems were optimized to hold the optical components. The repeater circuit units were produced by bolting the cylindrical subsystems to each other, increasing the flexibility in system configuration. The thermal dissipation characteristics, which become an issue given the increased power consumption, were optimized in the component layout and in the frame structure using simulations.

High-Density Submarine-Line Terminal Equipment

An external view and the system configuration of the submarine-line terminal equipment are shown in Fig. 5 and Fig. 6, respectively.

EQUIPMENT CONFIGURATION. The line-terminal equipment comprises the line terminating unit (LTU) that converts electrical signals into optical signals of corresponding wavelengths, the

Fig. 5 10Gb/s WDM submarine line terminal equipment

wavelength-terminating unit (WTU) that multiplexes and demultiplexes the optical signals and sends and receives the signals over the submarine cable, and the maintenance controller (MC) that monitors for faults in the transmission path, monitors the quality of the transmission path, and monitors for faults in the equipment. This line-terminal equipment can be connected to a maintenance terminal that monitors transmission quality and equipment status.

10GB/S OPTICAL LINE-TERMINATING UNIT (LTU). The LTU comprises an STM interface unit that houses the client interface, an FEC unit that adds error-correction codes and performs error-correction on received signals, and a line OS/OR unit that performs wavelength conversion for theWDM and that also has an RZ conversion function and a phase-modulation function to make ultra-long span transmission possible. In the line OS/OR unit, an RZ modulation method is employed using an electro-absorption external modulator in order to make ultra-long span transmission of 10Gb/s signals possible, and transmission quality has been improved by using second-generation FECs in the FEC unit, thus improving error-correction capabilities. In addition, the level of device integration has been raised and power consumption has been reduced to produce packaging with eight wavelengths (i.e., 80Gb/s) per bay, which is twice the previous capacity. Furthermore, the use of tunable laser diodes wherein multiple wavelengths can be selected reduced the maintenance components, and all of the connectors can be accessed from the front panels.

WAVELENGTH TERMINATING UNIT (WTU). The WTU comprises the optical demultiplexer unit that multiplexes and demultiplexes the WDM signals, an optical amplifier unit that amplifies

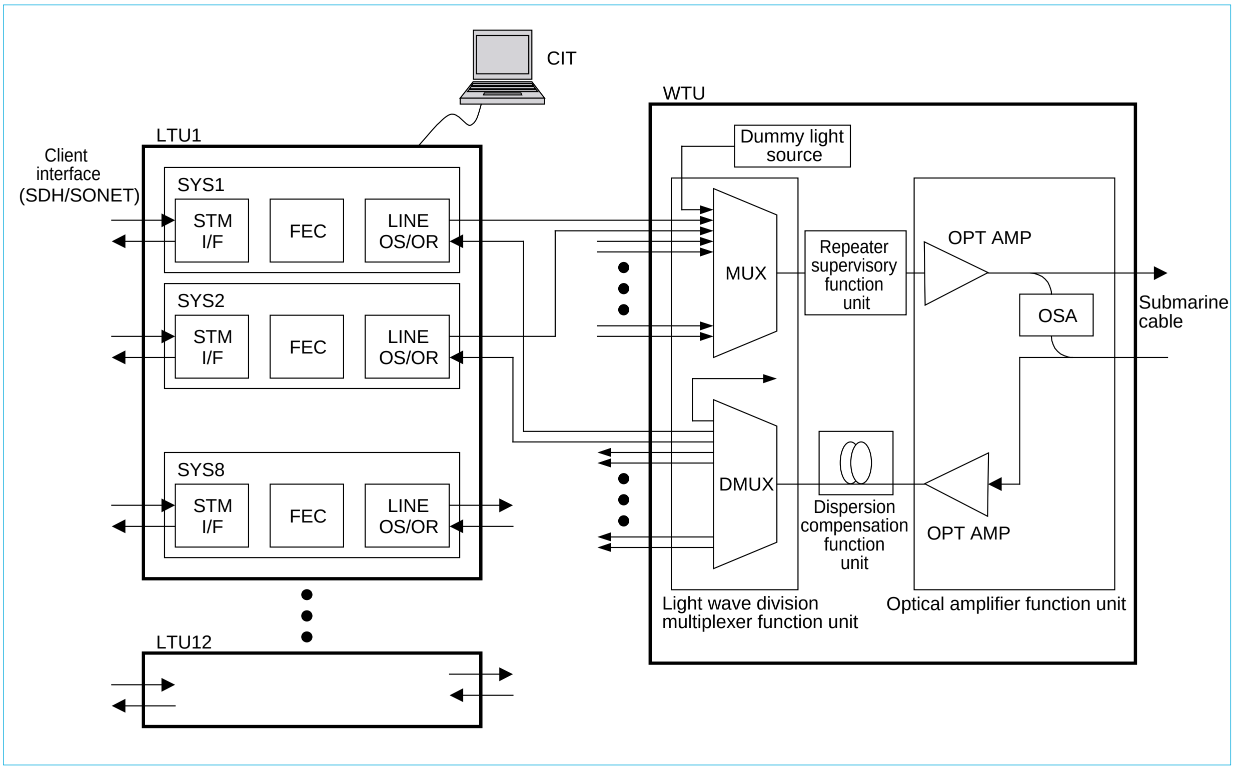

Fig. 6 System configuration of submarine line-terminal equipment

the entire WDM signal, a dispersion-compensation unit that compensate the cumulative dispersion over the long-distance transmission, a dummy optical output unit that stabilizes the spectral profile of the WDM signal, and the repeater supervisory function unit that forms the interface unit with the line-monitoring equipment (LME) that monitors the repeaters. The optical amplifier has been successful in expanding to 30nm the bandwidth by using a gain equalizer to smooth the wavelength-dependent-gain properties inherent in the EDF. A wavelength spacing of 0.3nm has been achieved by suppressing crosstalk between adjacent channels through adopting a series of cascaded low-insertion-loss arrayed wave guides (AWGs) and optical filters.

SUPERVISORY CONTROL FUNCTIONS. These include craft interface terminals (CITs) and a number of other interfaces.

1. Craft Interface Terminal (CIT)
   The CIT is a PC-based supervisory control terminal that monitors and controls the status of the various items of equipment via a LAN. The CIT is used to monitor the transmission-path faults, transmission-path quality and equipment faults that are critical in operations, and also makes it possible to control transmission parameters such as wavelength and optical output power, etc., thereby improving the ease of maintenance in the monitoring station.
   The CIT is not only positioned as a supplementary supervisory terminal for use when the MC cannot be used (i.e., when making local adjustments or when there are faults), but can also be used as a calibration- and adjustment-support terminal when cards are changed and during upgrade operations, thus making it possible to decrease substantially the time taken in these operations.
2. Other interfaces
   The LTUs/WTUs and MCs are connected through a LAN interface, where communications use a Q3 interface based on the OSI protocol stack. The equipment also provides a loop/earth contact interface.

MAJOR TECHNOLOGIES. The major technologies applied in the line terminal equipment developed in this project include the following:

1. Optical Interface Technology
   High-performance optical send/optical receive (OS/OR) units are essential for 10Gb/s ultra-long-span optical transmission. In the current project, electro-absorption modulators used successfully at 2.5Gb/s were used in order to simultaneously reduce the size and reduce the power consumption of the equipment.

Fig. 7 shows the RZ optical signal waveform. Excellent OS/OR back-to-back Q factors in excess of 22.5dB were achieved. Furthermore, the use of laser-diode modules equipped with wavelength lockers capable of five-

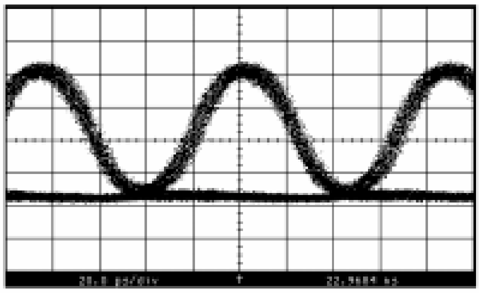

Fig. 7 Optical transmitted waveform.

wavelength coverage in the OS/OR unit has made it possible to achieve high stability levels at less than ±15pm wavelength drift and far fewer wavelength-dependent cards.

2. Error-Correction Technologies

The increased capacities and increased transmission distances in recent years have pushed Q factor budgets to the limit, requiring improvements in the FEC performance in order to obtain an additional margin. A second-generation FEC integrated circuit using error-correction encoding with a 14% redundancy, linking to Reed-Solomon encoding with RS(239,223) and RS(255,239) was developed for this equipment.[3] Fig. 8 shows an external view of the second-generation FEC LSI, and Fig. 9 shows its error-correction performance. An improvement of approximately 2dB in error-correction performance when compared to the G.975 FEC was obtained, enabling long-distance transmission at a rate of 960Gb/s per fiber.

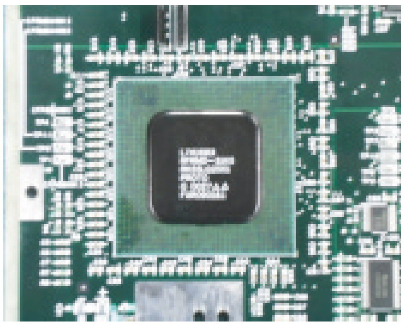

Fig. 8 Second-generation FEC LSI

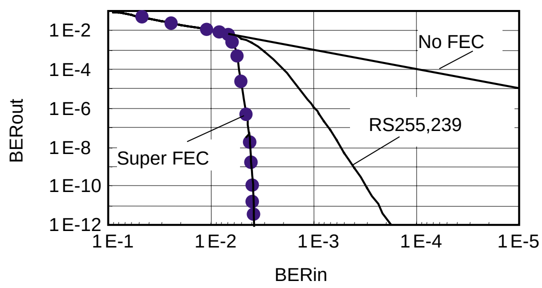

Fig. 9 FEC performance

3. Intelligent Technologies

In order to expedite and simplify the calibration and adjustment (C&A) operations at initial installation and when increasing the number of wavelengths in use, a system has been developed that provides for automatic remote control of parameters such as the optical output power, the phase modulation, the threshold value, etc. This uses an external computer and provides more advanced electronic control of adjustments. These functions have made it possible to reduce the amount of work involved in C&A by automating the transmission-quality calibration. For example, a preemphasis adjustment function is provided that sets the optical SNRs for the various wavelengths at the receiving terminal, a reception-threshold adjustment function that sets the reception-threshold value as appropriate depending on the waveform of the received signal, etc.

This article has described the device structures and key technologies in the optical submarine repeaters and line terminal equipment used in the 10Gb/s WDM optical submarine cable system in the current development project. Based on the individual technologies accumulated in this development project, future developments of optical submarine repeaters and line terminal equipment with even higher levels of WDM are planned. ❑

We wish to express our thanks to KDDI Submarine Cable Systems, Ltd., for their extensive input during this development project.

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[1] T. Asakawa, et al., SubOptics 2001, P4.1.4, 2001.
[2] Y. Kurosawa, et al., SubOptics 2001, T4.2.1, 2001.
[3] T. Mizuochi, et al., SubOptics 2001, P4.2.3, 2001.

Terrestrial WDM Technology for Long-Haul and Metro Networks

*by Kiyoshi Shimokasa and Aritomo Uemura**

Mitsubishi Electric Corp. has developed a wavedivision multiplexer (WDM) capable of handling transmission capacities up to 400Gbps for terrestrial trunk networks and metro networks. The device efficiently provides not only a variety of interfaces but also high carrier-level quality with improved ease-of-network maintenance using the various automatic adjustment and calibration functions provided.

With the rapid rise in internet-data traffic in recent years, the need has arisen for increased capacity, lower cost, improved compatibility with a variety of interfaces and improved maintainability in transmission equipment used in metro and backbone networks. In particular, WDM technology, where multiple channels share common transmission paths, is critical for economical network configuration.

This article describes the MF-80GWL WDM developed by the corporation for terrestrial backbone networks and metro networks.

Fig. 1 WDM transmission equipment

System Configuration and Specifications

SYSTEM CONFIGURATION. The WDM system has a transmission capacity of 2.5Gbps/10Gbps x 40 wavelengths and consists of a WDM device, see Fig. 1, linear repeater units (1R-REP) and network-management equipment (OpS: Operation Systems), providing point-to-point and ring-topology networks, see Fig. 2.

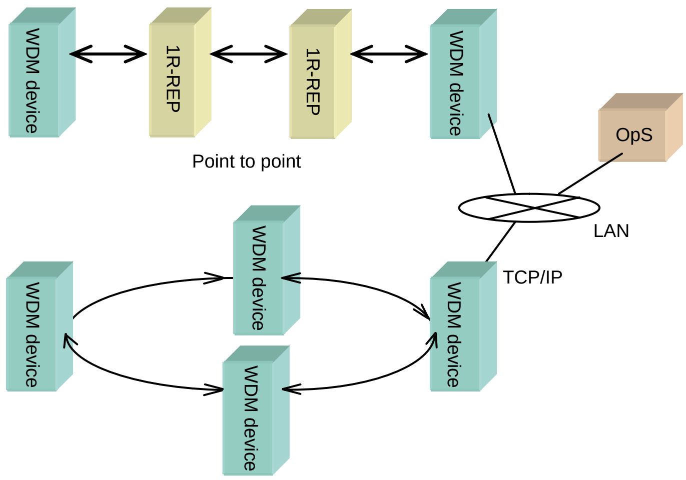


Fig. 2 WDM transmission equipment network topologies

Kiyoshi Shimokasa and Aritomo Uemura are with the Communication Networks Center.

SYSTEM SPECIFICATIONS. Various system specifications are shown in Table 1. In addition to the SONET/SDH signals used in conventional backbone networks, the system carries GbE and 10GbE Ethernet signals, making it compatible with increased data traffic.

Optical Communications Technologies.
In order to hold the costs of the optical communications equipment to a minimum, a direct modulation system is used for 2.5Gbps transmissions, and an external modulation system is used for transmissions at 10Gbps. Preemphasis technology (which minimizes transmission penalties), receiver threshold control technologies, and high-gain forward error correction (FEC) technology are used in order to provide high-performance transmission at low cost. The use of these technologies has enabled eight-repeater/nine-span (720km) SMF transmission paths and five-repeater/six-span (480km) DSF transmission paths, without the use of a 3R repeater (estimated assuming a loss of 25dB per span).

WAVELENGTH BANDS USED. In order to be able to handle different fiber types and different traffic loads flexibly, the system uses 40 different wavelengths in a 100GHz grid in the C band or the L band. To reduce the construction and operation costs for the fiber in the transmission paths, 20 wavelengths each can be assigned to transmission and reception, in a structure using bidirectional transmissions on individual fibers.

PREEMPHASIS. In linear multi-repeater transmission, the wavelength characteristics in the optical amplifiers and optical components will accumulate to cause differences in levels from wavelength to wavelength, and in poorly-conditioned channels the transmission distance will be limited by non-linear penalties and degraded signal-to-noise ratios. Preemphasis technology is used in this system to optimize the optical transmission levels for each wavelength. Based on the system parameters, such as line losses, system configuration, and the wavelength-dependent gain profiles of every repeater, software processes calculate the optimal values for the optical transmission levels automatically and control the output power of each of the transmission components.

RECEIVER-THRESHOLD CONTROL TECHNOLOGY. The receiver-threshold values in this system are optimized while monitoring the corrected-error bit count using an FEC IC to maintain the best receiver performance. With this automatic control function, the maintenance procedures become very simple when the network is constructed or when nodes are added or removed.

FEC TECHNOLOGY. FEC encoding is used in this system to enable transmission distances up to 720km for SMF transmission paths and 480km for DSF transmission paths. A high-gain FEC used in 10Gbps channels has 2dB better encoding gain than the FEC used in 2.5Gbps channels, and it enables a highly flexible system wherein the system design does not depend on the transmission speeds of the various wavelength channels.

PROTECTION FUNCTIONS. The system has a unidirectional path-switched ring (UPSR) protec-

Table 1 System Specifications

Item	Detail	Comments
Transmission Capacity	2.5Gbps/10Gbps x 40 wavelengths	With FEC
Wavelength Bands Used	DSF: 1570.42-1607.47nm	L Band
	SMF: 1529.55-1564.68nm	C Band
Wavelength Spacing	100GHz	ITU-T Grid
Client interface	OC-3/STM-1 (contains four channels/wavelengths)	ITU-T Compliant
	OC-12/STM-4 (contains four channels/wavelengths)	
	OC-48/STM-16 (contains one channel/wavelength)	
	OC-192/STM-64 (contains one channel/wavelength)	
	GbE (contains two channels/wavelengths)	IEEE Compliant
	10GbE (contains one channel/wavelength)	
Operating Environment	48VDC, 0~50°C	

tion switching function for each wavelength unit to select the signal from the proper path at the receiver terminal. Each wavelength channel can be set to either "redundant" or "non-redundant," making it possible to configure a highly reliable network matching the service level to be provided.

Maintenance and Operability Technologies

CONTROL NETWORK STRUCTURE. Fig. 3 shows the structure of the control network for maintenance operations. The OpS comprises servers and human-machine interface (HMI) terminals, and can monitor multiple networks for a maximum of 256 devices. A regular PC can be used for the HMI terminal, with up to 20 units connected per server, providing distributed control of the network. The system provides high levels of reliability by having up to four servers operating in parallel as a redundant structure.

One equipment function connects to the OpS server using a proprietary interface that provides detailed performance monitoring, and another function connects to the user's standard SNMP manager via a standard SNMP interface that provides simple monitoring functions. The connections between the higher-level OpS and the OpS server utilize the SNMP interface.

This equipment also has a function that sends and receives optical supervisory channel (OSC) signals for supervisory control, transmitting supervisory control information between devices. Because of this, connecting even a single WDM device in the system to the OpS through a data communications network makes it possible to monitor and control all of the equipment in the system from the OpS, thereby reducing the costs of the data transmission network.

MAINTENANCE OPERATIONS. Table 2 summarizes the operations performed at construction or when nodes are added or removed. Care was taken to make it possible for even inexperienced maintenance operators, who lack technical skills, to operate the system flawlessly through the application of automated software technologies.

Table 2 Streamlined Maintenance Operations

Network construction/modification	
Equipment-fiber connections	On-site operations
System Data download	NE-OpS/CIT
Level adjustments according to transmission path losses	Automatic
Repeater amplification gain adjustment	Automatic
Preemphasis/receiver-threshold control	NE-OpS/CIT
Transmission quality verification	NE-OpS/CIT
Station equipment connection tests	On-site work
During maintenance operations	
Adjustment for changes in transmission path losses over time	Automatic
Adjustment for changes in transmission path losses when there is a fault	

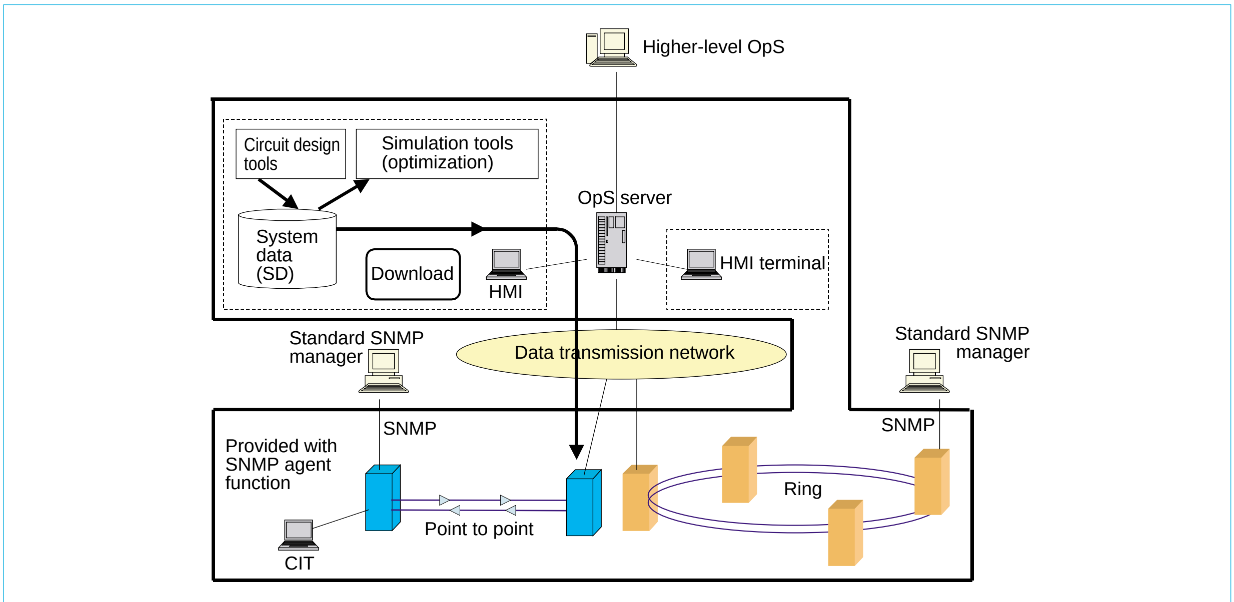


Fig. 3 Supervisory network structure

TRANSMISSION PATH LOSS EQUALIZATION AND ADJUSTMENT. In conventional systems, the addition or removal of nodes or characteristics drift in transmission lines cause change in the number of wavelength channels or in transmission-path losses, and adjustments of the input level for each of the linear repeaters, or complex and burdensome maintenance operations are required. In contrast, this equipment has a function that compensates automatically for changes in transmission path losses by controlling variable optical attenuators in the linear repeaters, thus reducing maintenance costs when nodes are added or removed or when other maintenance is performed. In addition, high-speed control of these variable optical attenuators ensures stable transmission quality even when there is a sudden change in loss over a transmission path due to, for example, stress on a fiber, see Fig. 4.

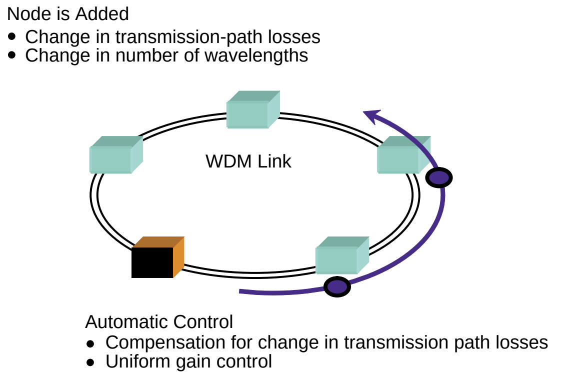


Fig. 4 Transmission path-loss adjustments when a node is added

PROVISIONING TOOLS. To facilitate quick and flexible network design, the system provides circuit design tools and simulation tools for designing optimal circuits based on network information such as transmission distances. The circuit design tools enable the easy compilation of system data such as various information on structures and settings required when constructing a system or when adding or removing nodes, doing so using a simple GUI. The structural changes are implemented easily by downloading the data to the equipment. Simulation tools simulate optical transmission characteristics based on the system data.

There are plans to use the individual technologies developed during this project to increase capacity and transmission distances, and to provide even more complete client interfaces, doing so even more economically. ❑

Passive Optical Network Technologies for Subscriber Systems

*by Shinya Makino and Tetsuya Yokotani**

There is an urgent need for improved economy and functionality in fiber-access systems if fiber to the home (FTTH) is to become popular. Mitsubishi Electric Corp. has developed an Ethernet passive optical network (EPON) system based on a 100M fast Ethernet optimized for economy and for Internet protocols, and an asynchronous-transfer mode (ATM)-based passive optical network (APON) system suited for providing multiple services.

APON Systems

Fig. 1 shows the system architecture for the APON system. The optical access scheme is based on the International Telecommunications Union-Telecommunications (ITU-T) Recommendation G.983 series. A multiservice platform that multiplexes transmissions such as POTS (Plain Old Telephone Service), leased-line services, Internet services, analog video services, and the like, over a single fiber is provided to a combination of ATM technologies and wavelength-division multiplexing (WDM) technologies.

ATM DISTRIBUTION SWITCH (ADS2000). In a one-unit/one-system architecture, three units can be housed in a standard North American 23-inch rack. The unit comprises an interface unit, a dual power-supply unit, and ATM-switch unit, a supervisory unit, and a clock unit. The switch conforms to the North American Standard Network Equipment Building Systems (NEBS) level 3. The specification are given in Table 1, and the switch is shown in Fig. 2.

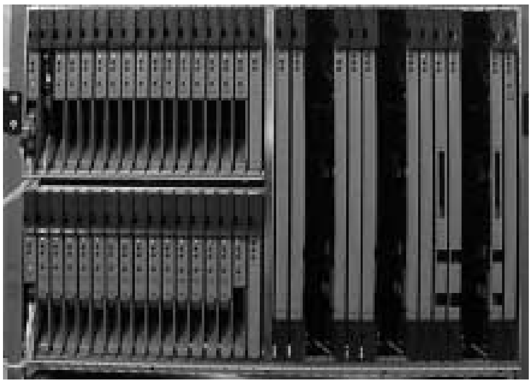


Fig. 2 External appearance of the ADS2000

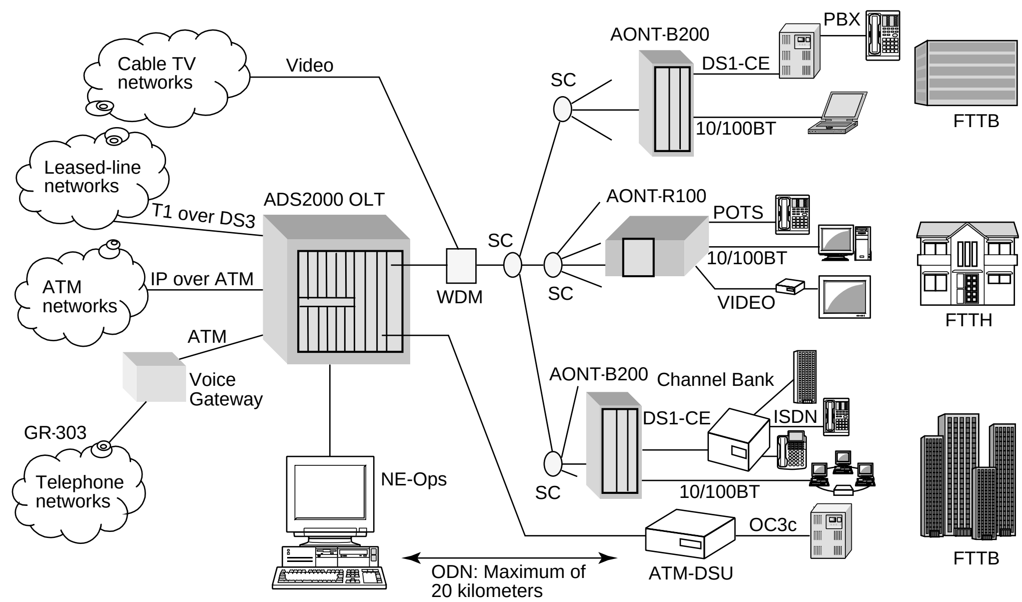


Fig. 1 The network configuration using an ATM passive optical network system

**Shinya Makino is with the Communication Networks Center and Tetsuya Yokotani is with the Information Technology R&D Center*

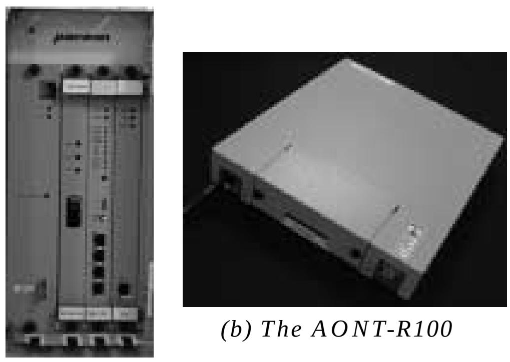
Table 1 Specifications of the ADS2000 ATM Distribution Switch

Item	Specification		
		Access line	Transmission line
Interface unit	Type	156 Mbps ATM-PON (ITU-T G983-series compliant) OC-3C (156 Mbps)	DS3 (45 Mbps) OC-3C (156 Mbps)
	Redundancy	None	DS3: n:1 redundancy architecture OC-3C : 1+1 redundancy architecture
	No. of interfaces	32 (max)	DS3: 16 (max) OC-3C: 32 (max)
		Total of the above: 32 (max)	
Class-of-service ATM switching unit	Switching spec.	20 Gbps	
	Traffic control	CBR, UBR and UBR with guaranteed bandwidth by the PVC. Class-of-service control mechanism.	
Supervisory unit	OAM functions	Various warnings issued and sent, quality monitor, loopback	
	EMS interfaces	CMIP over TCP/IP	
Operating environment	Temperature/humidity	0~50°C, 5% to 90% humidity	
	Cooling method	Forced-air cooling using fans.	
Power-supply	Voltage	-40.5V DC to -57.0V DC	
	Consumption	607 watts (typical), 1,024 watts (max)	
Dimensions (mm)	H x W x D	445 x 544 x 305 (Can be housed in a 23-inch rack)	

Table 2 Specifications of ATM-ONTs (AONT-B200 and -R100)

Item		Specification	
		AONT-B200	AONT-R100
User-network interface	Type (No. of ports/cards)	DS1-CE (4 ports/pkg) 10/100 Ethernet (1 port per package)	POTS (4 ports) 10/100 Ethernet (1 port) Video RF output (1 port)
	No. of cards	Two cards per ONT	One card, integrated
Access line interface	Type	156Mbps ATM-PON (ITU-T G983-series compliant)	
	Number of ports	1	
Power supply	Voltage	120V AC (60Hz) (with battery backup)	120V AC (60Hz)
	Consumption	41W (max)	20W (max)
Operating environment	Temperature	0 ~ 50°C	
	Cooling method	Passive air cooling (no fan)	
Dimensions (mm)	H x W x D	312 x 130 x 320	58 x 290 x 330

ATM-ONT (AONT-B200/R100). The ATM-optical network terminal (ONT) user-network interface supports two different types of interfaces, the AONT-B200 for business users, providing DS1-CE (digital signal level 1-circuit emulation, 1.5Mbps) and 10/100Base-T, and the AONT-R100, providing telephone services, 10/100Base-T, and an analog video interface. These interfaces comply with the North American Standard NEBS level 3, and to UL1950. The specifications are summarized in Table 2, and an overview of the unit is shown in Fig. 3.



(a) The AONT-B200

(b) The AONT-R100

Fig. 3 External appearance of AONT-B200 and AONT-R100

SUPERVISORY EQUIPMENT (NE-OPS, LCT). The supervisory equipment comprises the NE-Ops (network element-operations systems) server and the human interface (HMI) terminal, where multiple ADS2000 units and the ATM-ONT units under it are monitored and controlled remotely through an Internet network. Although normal maintenance is controlled using the NE-Ops, maintenance personnel provide maintenance functions such as installation, and, if necessary, when performing the maintenance operations, a local craft terminal (LCT) can be used.

EPON Systems

Fig. 4 shows the EPON system architecture. The optical access scheme uses a proprietary variable-length media access control method that directly encapsulates the Ethernet frame and follows the LAN access control method. The system performs both the fair-share and the best-effort transmissions, and can provide an economical system optimized to IP-type data communications.

OPTICAL LINE TERMINALS (AS-100EL, AS-100ELG). The optical line terminal units are small enough that four units can be housed in a standard 19-inch rack, and each unit can house a maximum of eight access-line interface cards, one supervisory-unit/switch-unit card, and two redundant power-supply cards. The core network interface is equipped with two ports in the supervisory-unit/switch-unit card, and the optical line terminals come in two types, the AS-100EL (compatible with 100Base-FX) and the AS-100ELG (with 10/100/1000BaseTX and 1000BaseSX/LX interfaces selectable). The primary specifications are given in Table 3.

OPTICAL NETWORK TERMINALS (AS-100EN). The AS-100EN has an access-line interface function, a bridge function, a user/network-interface function, supervisory functions, and a power supply, equipped in a small plastic case, providing world-class miniaturization. The functions are achieved without the use of a processor, resulting in lower costs. The primary specifications are given in Table 4, and the unit is shown in Fig. 5.

Fig. 5 External appearance of an ONT (AS-100EN)

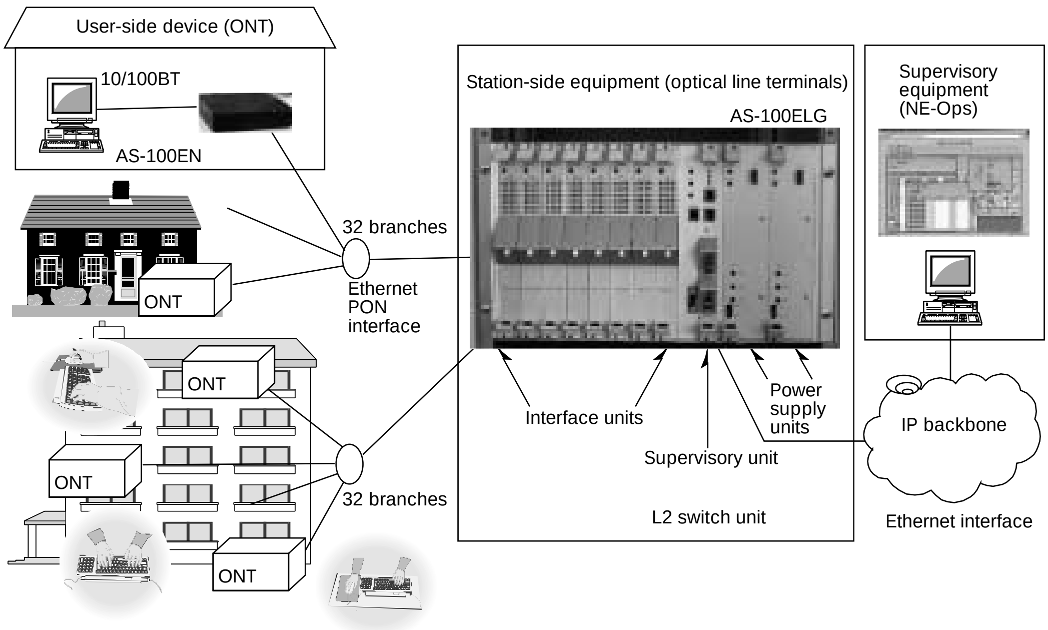


Fig. 4 The network configuration using an Ethernet passive optical network system

Table 3 Specifications of OLTs (AS-100EL and -100ELG)

Item		Specification
Access line interface	Communications method	EPON interface (125Mbps: variable-length media-access control)
	No. of subscribers	1 to 256 subscribers per unit
	Transmission distance	Max. 20km (G983.1 class B equivalent)
	Wavelengths	Up: 1.3µm Down: 1.5µm
	No. of ports	8 max. (max. of 8 interface packages per unit)
Transmission line interface	Communications method	AS-100EL: 100 Base FXAS-100G: 10/100/1000 Base TX, 1000 Base SX/LX, selectable
	No. of ports	2
Monitoring & control	Items monitored	User interface link status, equipment failures, power outage notifications, etc.
	Items controlled	Loopback test control, status notification requests
Connection control functions		VLAN, link-aggregation functions, spanning-tree functions
Quality of service control		Priority control based on IEEE802.1p
SNMP agents functions		Present ((MIB I, MIB II)
Dimensions (mm)	H x W x D	266 x 483 x 181
Operating environment	Temperature	0 ~ 50°C
	Cooling method	Forced-air cooling using fans
Power supply	Voltage	-40.5V DC ~ -57.0V DC
	Consumption	200W (max)

Table 4 Specifications of the AS-100EN ONT

Item		Specification
Access line interface	Communications method	EPON interface (125 Mbps: variable-length media-access control)
	No. of ports	1
User-network interface	Communications method	10/100 BaseT Ethernet (full duplex/half duplex, automatic detection, fixed settings)
	No. of ports	1
Connection control functions		Bridge functions
Quality of service control		Priority control based on IEEE802.1p
Dimensions (mm)	H x W x D	40 x 150 x 135
Operating environment	Temperature	0 ~ 50°C
	Cooling method	Passive air cooling (no fan)
Power supply	Voltage	100V ©10V AC (50Hz and 60Hz), using an AC adapter
	Consumption	6W (max)

SUPERVISORY EQUIPMENT (NE-OPS). The optical line terminals and the optical network terminals are monitored and controlled using SNMP through an IP network. The management database supports standard and extended management information bases.

Mitsubishi Electric is currently developing a 1.25Gbps gigabit Ethernet-PON (GE-PON) system, currently undergoing the standardization process, using IEEE 802.3ahEFM, in order to increase the speed of services in the future. ❑

Next-Generation Optical Transmission Technologies

*by Takashi Mizuochi and Kuniaki Motoshima**

This articles summarizes the state of research and development of next-generation optical transmission technologies for increasing transmission distances and capacities. After discussing transmission lines, Raman amplification, new modulation formats, forward-error correction, and compensation technologies, it goes on to discuss the results of tests in which 20Gbps signals were transmitted for 9,180km over 85 wavelength channels, and of bidirectional 43Gbps signals transmitted using a single fiber for 200km over 32 wavelength channels.

Dramatic advances in optical transmission technologies were seen in the late 1990s, spurred by advances in wavelength division multiplexing (WDM). The product of the total transmission bit rate times the transmission distance, which is a measure of performance in optical transmission, increased at a rate of an order of magnitude every three years, reaching 20Tbps-Mm in the laboratory in 2001. At this point, the record-breaking pace slowed down, perhaps as an effect of the collapse of the optical communications market, but the march by research institutions throughout the world towards increased capacity proceeds relentlessly.

This article describes individual technologies for next-generation optical transmission currently being researched at Mitsubishi Electric Corp. for longer transmission distances and increased transmission capacity. It describes the results of optical transmission tests in excess of 2Tbps performed using the technologies developed.

Transmission Lines

Dispersion management, periodically combining various parameters of the optical fibers such as the group-velocity dispersion (GVD), dispersion slope, and effective area (Aeff) in the transmission direction, is important in order to achieve long-distance optical transmissions. They provide control of self-phase modulation (SPM) and cross-phase modulation (XPM), factors that degrade transmission performance. On the other hand, when Raman amplification is used, it is useful to manage Aeff. Making use of the fact that the Raman gain is inversely proportional to the Aeff, the insertion of fibers with a small Aeff between repeater intervals averages out the level diagram during transmission, improving the signal-to-noise ratio. Transmission of 40Gbps signals across 32 wavelength channels for a distance of 202km without using repeaters was demonstrated.[1]

Raman Amplification

Raman amplifiers are used to obtain an amplification band of over 40nm, which is difficult using EDFA. The effect of the improved optical signal-to-noise ratio due to the uniform distribution of optical power along the optical fiber in the transmission path, and the small polarization-mode dispersion (PMD) due to the reduced number of components, makes it possible to transmit 40Gbps signals over long distances. Because Raman amplifiers produce a polarization-dependent gain (PDG), it is important that the pump light be depolarized. We have discovered a method of minimzing the degree of polarization (simultaneously minimizing the PDG) with a minimal amount of birefringence if a longitudinal-mode spacing and a single longitudinal-mode line width is selected. [2]

Modulation Formats

Active research is proceeding into ways to use innovative modulation methods to increase the efficiency with which frequencies are used. When a comparison was made between conventional return-to-zero (RZ) modulation and three modulation methods that can be applied to long-haul optical transmission–vestigial side-band (VSB) RZ and carrier-suppressed (CS) RZ–using 20Gbps signals at 50 wavelengths in 4,000km transmissions, it was discovered that CS-RZ exhibited vastly superior transmission performance.[3] As bit rates increase, so does the SNR signal-to-noise ratio (SNR) required to obtain a given bit-error rate (BER). For example, 40Gbps requires an SNR 6dB higher than that required for 10Gbps. Coherent modulation/demodulation methods are being reexamined as a way to compensate for this. Of these, the differential phase-shift keying (DPSK) method is attracting interest as a means of improving the SNR by 3dB over conventional amplitude modulation. The viability of 9,000km transmission of 100

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wavelengths of 10Gbps RZ-DPSK signals has been confirmed.[4] Fig. 1 shows the waveforms for RZ-DPSK before and after transmission. When transmitting over a distance of 9,180km, the Q factor dropped to a level at or below that of RZ-ASK through, primarily, SPM; however, at shorter distances, the RZ-DPSK method exhibited superior transmission performance.

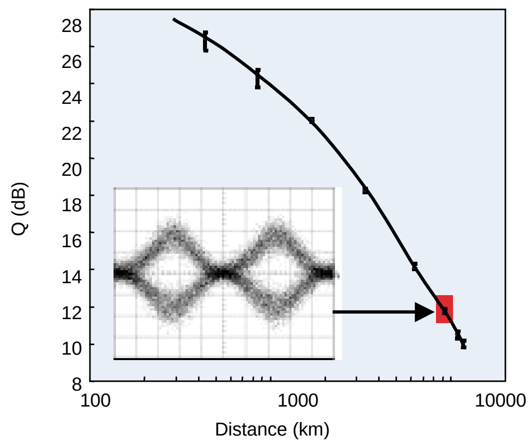

Fig. 1 Transmission performance of 10Gbps RZ-DPSK

Forward Error Correction (FEC)

The concatenated Reed-Solomon code was developed to suppress fluctuations in the BER over time due to changes in polarization, etc., in addition to the degradation of the SNR because of cumulative noise from the optical amplifiers. The net encoding gain for RS(255,239) increased by about 2dB to reach 7.7dB.[5] The development of a new FEC using soft decisions/turbo code squeezed out another 1dB at the Shannon limit, which is another 2dB higher.[6] A promising candidate for the encoding is the product code of Bose-Chaudhuri-Hocquenghem (BCH), which is a form of cyclical coding. The "soft decision" method plays an important role in performing turbo decoding. The signal received is judged by deciders that have multiple different decision thresholds, where the certainty is indicated by an additional bit called the "confidence bit." Fig. 2 shows a 3-bit soft decision integrated circuit that has been developed. Because this was prototyped using an SiGe BiCMOS process for 40Gbps, excellent decision sensitivity was obtained at less than 20mV, operating at 12.5Gbps.

Compensation Technologies

Increasing transmission bit rates are putting

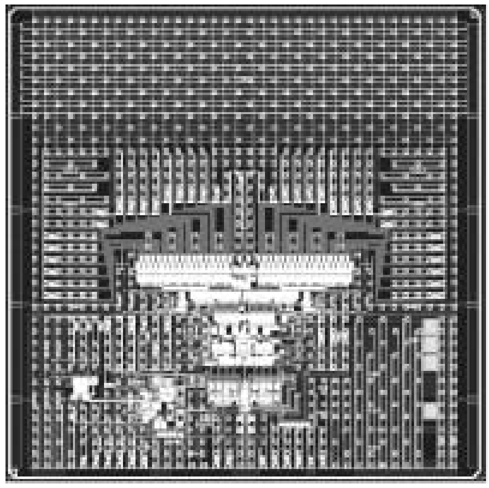

Fig. 2 Soft decision LSI

pressure on the tolerances for polarization mode dispersion, making it vital to find a way to perform dynamic compensation for PMD. In order to minimize the bit-error rate on the receiver side, the incident polarization is controlled on the transmitter side to have a stabilizing effect, even if the changes in signal quality due to PMD are incomplete. Fig. 3 shows the case where incident polarized-light compensa-

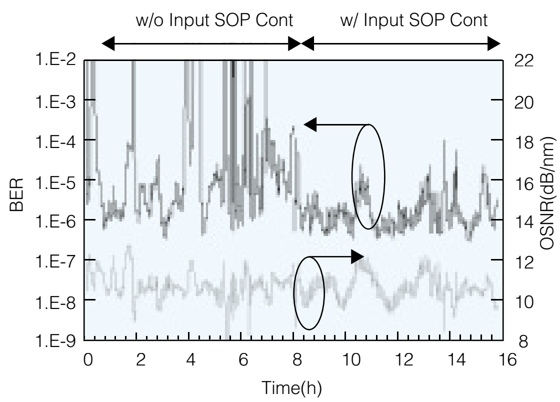

Fig. 3 Test result of PMD mitigation

tion control was performed for the measurement wavelength for one wavelength of the 42-wavelength 20Gbps signal in a recirculating transmission path 2,540km long, where each loop was 3,504km. Although there was a remarkable drop in quality, to the degree that frame synchronization was lost without compensation, PMD compensation was able to suppress changes in the BER by about two orders of magnitude.[7]

20Gbps x 85λ - 9180km Transmission Experiment

A Raman/EDF hybrid amplifier repeater, which uses hybrid Raman amplification in an EDFA repeater, was used. By optimizing the repeater and the transmission path parameters, a transmission test of a 1.7Tbps (85 wavelengths x 20Gbps each) signal was transmitted the distance it takes to cross the Pacific Ocean (9,180km). The test system is shown in Fig. 4, and the received Q factor for all channels is shown in Fig. 5. The average Q value and the worst case Q value were 9.6dB and 9.0dB, respectively, with a result 0.5dB above the required Q factor.[8]

43Gbps x 32λ - 200km Bidirectional Transmission Experiment

The transmission distance was extended using Raman amplification technology in a system that performs bidirectional transmission of C band and L band signals over a single fiber, without the use of a repeater. The transmission test results are shown in Fig. 6. In both the C band and the L band, 32 channels (for a total of 64 channels) of 43Gbps CS-RZ signals were provided with 100GHz spacing. With bidirectional transmissions of non-zero dispersion-shifted fiber, 200km long, Q values of at least 11dB were obtained for every channel.[9]

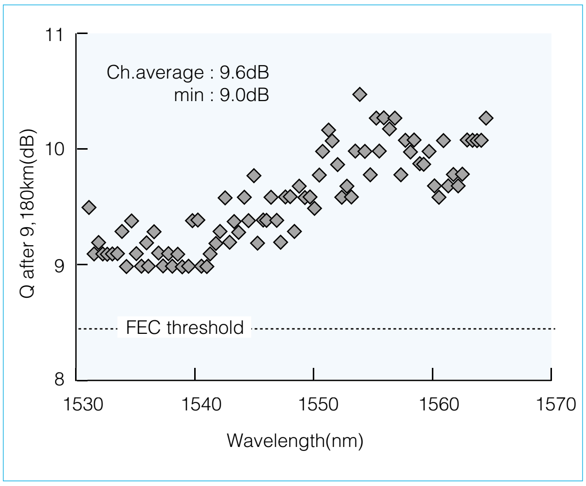

Fig. 5 Measured Q of 85 x 20Gbps signals after 9180km transmission

We expect optical communications in the future to produce the coherent technologies established in wireless and microwave communications, the forward-error correction that is enabled by high-speed integrated circuit technologies, the Raman-amplification technologies that use non-

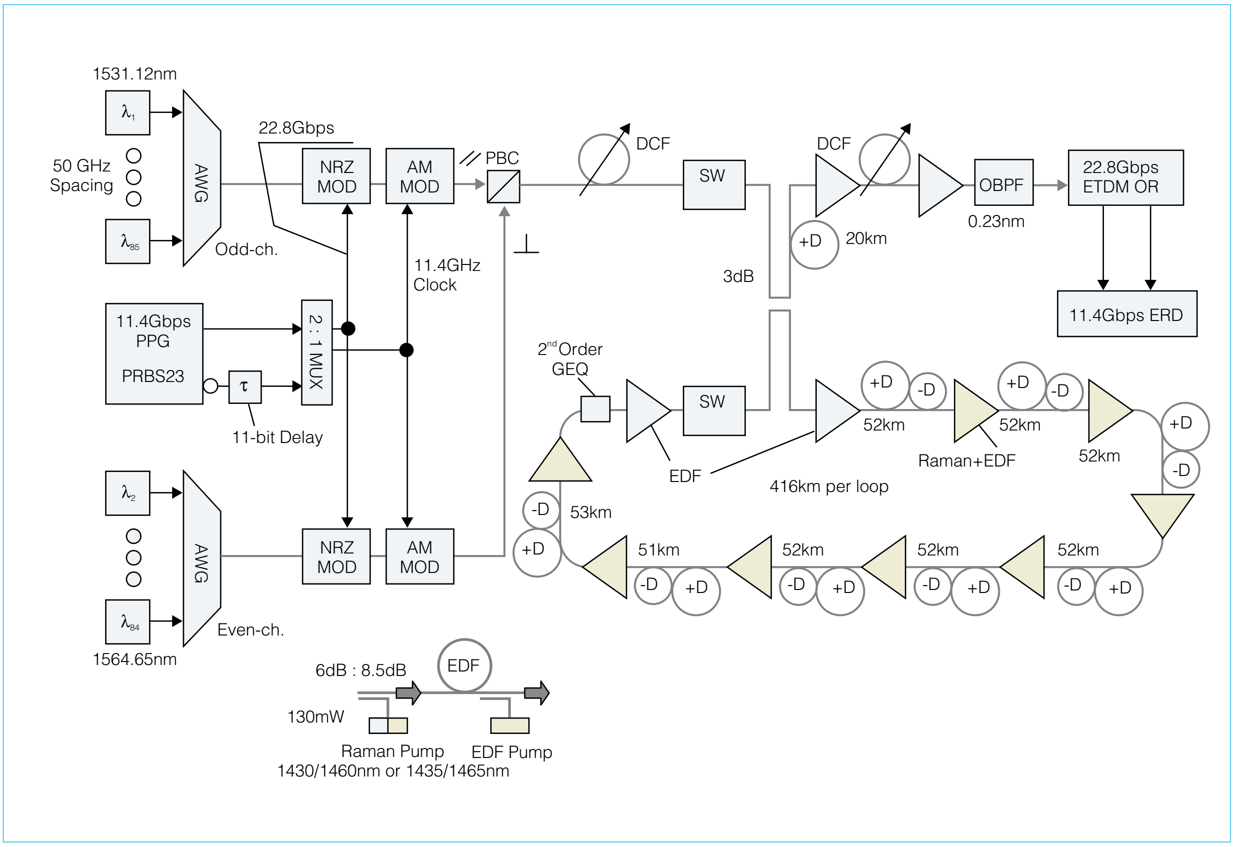

Fig. 4 Setup for 20Gbps x 85channels transmission experiment

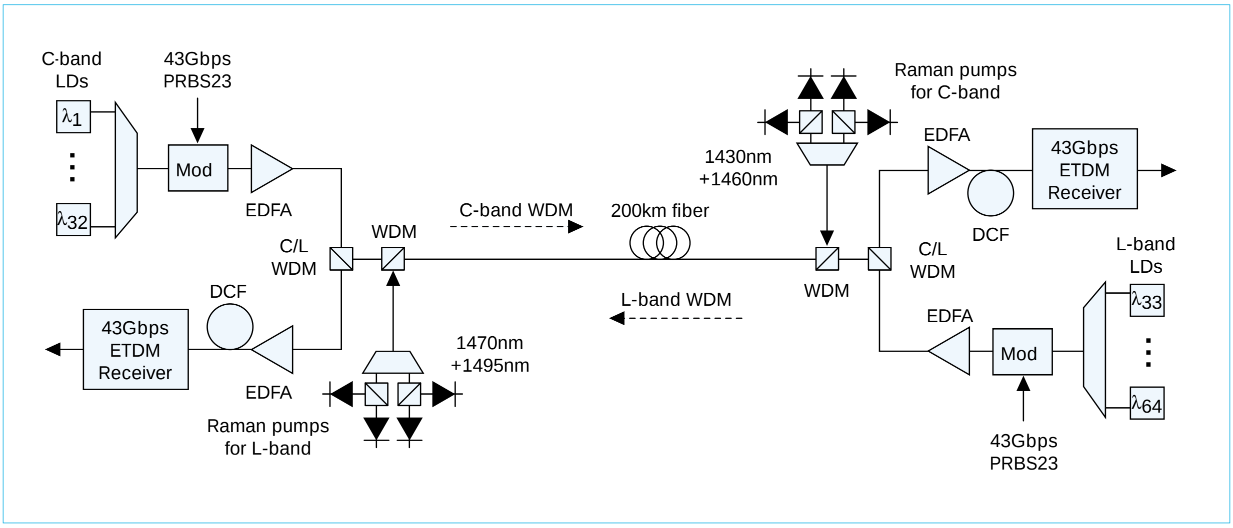

Fig. 6 Setup for 43Gps x 32 channels over 200km bidirectional

linear fibers effectively, and various types of compensation technologies for movements in waveforms will experience a resurgence. ❑

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Optical Cross-Connect Technologies

*by Shoichiro Seno and Masashi Akita**

Optical cross connects (OXCs) are node devices for optical transport networks that form the next-generation network infrastructure, making it possible to establish optical paths flexibly and to switch optical signals. Mitsubishi Electric Corp. has researched and developed OXCs for all-optical networks, providing low-cost solutions that are independent of transmission protocols and transmission speeds, and that do not require opto-electrical/electro-optical conversions. The corporation announced prototype units in February 2002, and is currentnly engaged in interoperability verifications.

Structure of Optical Networks

There is a need for high-capacity network infrastructures well suited to Internet protocols (IPs) to handle the explosive growth in Internet traffic and the broad scope of IP applications. In the optical networks of today, ring networks using optical add-drop multiplexers (OADM) are being introduced in addition to the point-to-point networks wherein two locations are linked together using wavelength-division multiplexing (WDM). OADM is able to transport high-capacity signals by performing add/drop operations for individual wavelengths in WDM optical signals. The development of mesh networks using OXC, capable of switching individual wavelengths, is under consideration as a way to structure easily expandable, highly flexible networks. Mesh networks can be used to structure efficient networks where recovery paths for failure recovery are shared.

There are two types of OXC: optical-electrical-optical (OEO) and optical-optical-optical (OOO). OEO-type OXCs are based on high capacity electrical switches combined with transponders, making it possible to perform signal switching by individual wavelengths. While this requires opto-electrical/electro-optical conversions, the flexibility in the electrical processes provides multiplexing and monitoring functions. The OOO-type is based on optical switches, which, in principle are format free, bit-rate free, and can accommodate increases in transmission speeds. The OOO-type is thought to be more useful than the OEO-type from the perspective of future increases in speed and capacity, and in terms of power consumption and size. Leading-edge users have already begun implementing them in combination with WDM equipment or optical transponders.

Optical Switching Technologies

OPTICAL SWITCHES. At transmission speeds over 10Gbps, electrical switches are expected to be two to three times larger than optical switches, with at least three-fold power consumption. Optical switches also have the advantage that the switching is done with the signal still in an optical state, not needing to convert the optical signal into an electrical signal.

There are various forms of optical switches, including mechanical optical switches, micro electro-mechanical (MEMS) optical switches, and other drive-type optical switches, along with non-drive-type optical switches, using, for example, varying indices of refraction in optical wave-guides. From the perspective of reliability, the non-drive-type optical switches provide benefits not found in the drive-type optical switches, but the MEMS optical switches have advantages in terms of insertion loss, cross talk, and the ability to handle large numbers of ports. The MEMS optical switches currently under development include two-dimensional (2D) optical switches and three-dimensional (3D) optical switches, where the 3D type is promising in terms of expandability for the number of ports. However, the difficulty of MEMS control has become a major impediment to practical application. Fig. 1 shows an overview of bascule optical switches[1] currently in development within the corporation. These switches have 32 I/O ports, and have achieved excellent performance with insertion of losses of less than 6.0 dB and cross-talk characteristics better than 35 dB. The switches fully comply with Telcordia Standard GR-1073-CORE, because a loss variance of less than 0.3dB over ten-million switching operations was achieved by a single switch of this kind.

OPTICAL SWITCH PLANE. The optical signal-transmission function in the OOO-type OXCs is provided by an optical switch plane, that is a

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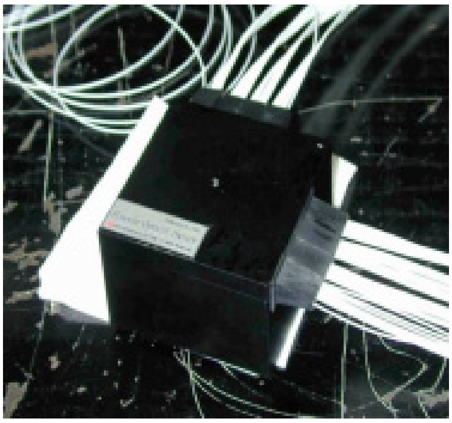

Fig. 1 Bascule optical switch

data plane that uses optical switching. The objectives for researching its structure include improved device reliability, improved packaging density, the provision of test functions, and compatibility with connectivity-discovery operations. Fig. 2 shows an optical switch plane fulfilling these objectives. The benefits of this optical switch plane are:

1. Compact multiport connectivity for the optical switching, using multichannel optical components such as multifiber connectors and multiple-connection PD arrays.
2. Board-level maintenance operations using connectors between redundant components and shared components, with A-system and B-system optical switches mounted on separate circuit boards for redundant systems.
3. Link-path test functions are provided through the use of redundant-branching couplers, and optical signal test ports are provided by which discovery functions can be performed.

The optical switch devices are still in the research and development phase, and increased performance (such as more ports, lower insertion losses and less cross talk) is anticipated. The OXC optical switch plane prototyped by the corporation is designed to be capable of increasing the number of ports by means of an interface with a control plane, making it possible to migrate smoothly to systems using optical switches with improved performance in the future.

The GMPLS Optical Network-Control Protocol

Generalized MPLS (GMPLS) has become the standard optical path-control protocol between OXCs (including OEO-type OXCs) and between OXCs and optical transport-network clients[2]. GMPLS is an enhancement to the multiprotocol label switching (MPLS) protocol that provides the IP with an underlying layer path that does not depend on the Layer 2 technology, making it possible to apply MPLS to optical paths for wavelengths or fibers. Here, the GMPLS signaling protocol can be used to set and release optical paths between OXCs dynamically and in real time, and the GMPLS routing protocol makes it possible to share resource-use information between OXCs in the independent and distributed way.

Although the basic aspects of GMPLS have already been standardized, functions such as optical-path protection (discussed below) are still incomplete, so the OXC prototypes produced by the corporation use the hierarchical modularized software structure shown in Fig. 3, as well as to avoid dependence on specific hardware in the optical switch plane. The architecture in Fig.

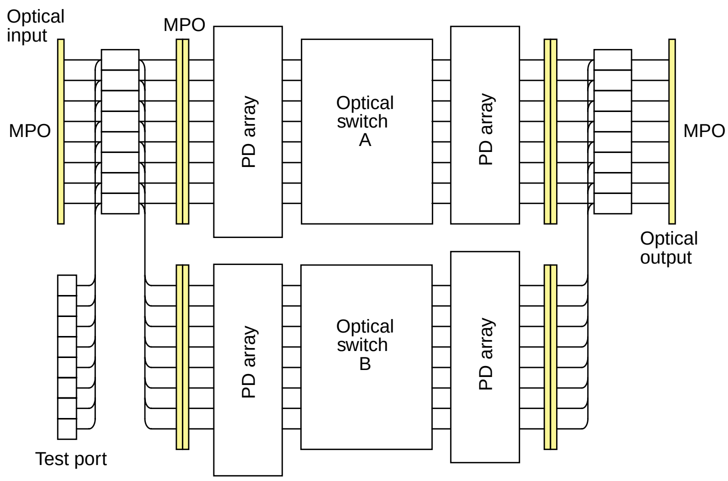

Fig. 2 Optical switching-plane architecture

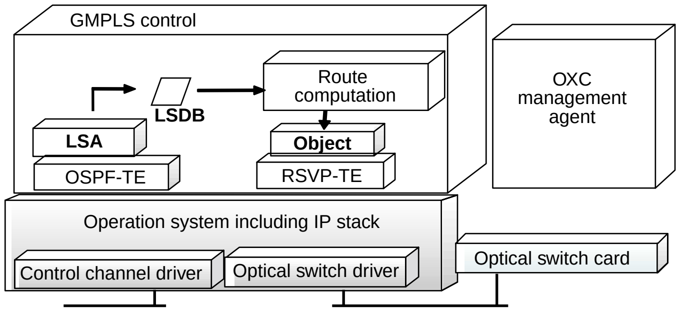

Fig. 3 OXC software architecture

3 is based upon the approach of first; separating the OXC management agent (which handles the management interface and the optical path-setup information) and the GMPLS control unit (which provides the GMPLS protocol processes), and second; hardware transparency by controlling the hardware in the optical switch plane using switch drivers.

Optical Path High Reliability Technologies

PROTECTION. Protection, restoration, and rerouting are means by which the optical path is restored immediately when there is a fault. The fastest of these is path protection, where a backup path for the working path is established in advance and the user traffic is switched to the backup path when a fault occurs.

Standardization of optical path protection methods is underway with ITU-T, IETF, and OIF. The methods envision a general topology (mesh) network, and are categorized by the path protection units and by the backup path use methods, see Fig. 4.

Path protection (1+1) establishes a working path and a backup path in advance, copies the user traffic at the ingress node to both the working path and the backup path, and, at the egress node, selects and outputs the traffic from the working path. If an interruption to the optical input from the working path is detected at the egress node, the traffic from the backup path is selected immediately. The switching can be done rapidly in the hardware, without the need for any signaling when a fault occurs, and in our prototypes, switch-over times of approximately 2ms have been demonstrated.

Path protection (m:n) is similar to 1+1 path protection in the fact that working paths and backup paths are established in advance; however, the user traffic is transmitted on the working paths only. When an interruption to the optical input from a working path is detected at the egress node, notification is sent to the ingress node, and transmission of the user traffic is switched over to a backup path. In m:n path protection n working paths are protected by m backup paths (where m is usually less than n). Although more time is required for restoration in m:n path protection than in 1+1 path protection, the backup paths can be used for the transmission of low-priority extra traffic, and multiple working paths can use a shared pool of backup paths, so m:n has an advantage over 1+1 in terms of the efficiency of network resource utilization.

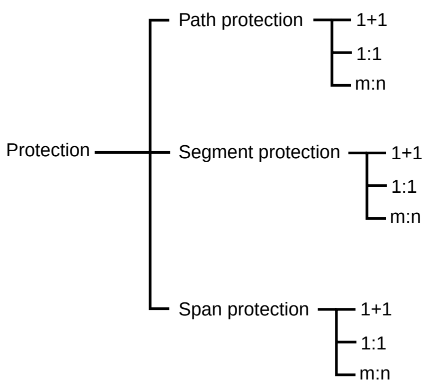

Fig. 4 Classification of protection schemes

ROUTE SELECTION. For the protection scheme to work effectively, the routing for the backup path must be selected for high independence of the working path so that the backup path does not become unusable at the same time as the working path. The concepts of disjunction of links, nodes, etc., and of a shared-risk link group (SRLG) have been introduced in performing this type of routing selection. SRLG is an abstraction of wavelengths or ranges that will fail as a unit, such as fiber bundles or conduits shared by multiple optical paths. Generally a single link between OXCs comprises multiple SRLGs. Although insuring fault protection from a single fault requires the working path and the backup path to comprise disjoint SRLGs, this raises the issues of an increased load in routing computations and in securing correct SRLG information. The information upon which the routing computations are based includes the topology information and the unused bandwidths in SRLGs, or the like, and is advertized by the routing protocol. The routing of the protection paths is calculated using a routing computation algorithm based on this information and on the specific protection method used, and reflects operating policies reflecting the weighting of routes in the process and the sharing of backup path bandwidths.

OPTICAL PATH QUALITY VERIFICATION. Because, throughout all the optical network, end-to-end optical paths are set through passive devices, there have been suggestions that the quality of the paths should be verified using continuity testing when paths requiring high levels of reliability are established[3]. This continuity testing requires a test signal on the optical path, and control-plane messages providing notification of transmission and reception of the test signals. An example of a message sequence is given in Fig. 5.

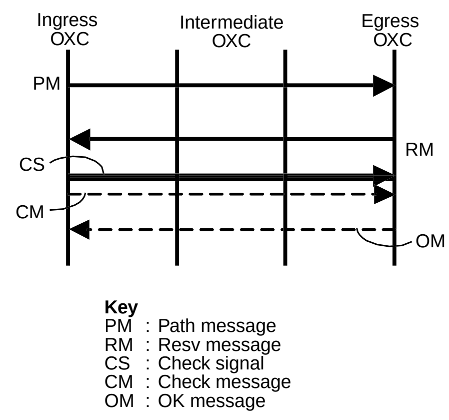

Fig. 5 Message sequence for optical path-continuity test

The article has discussed switching technologies, GMPLS protocol technologies, optical path reliability-assurance technologies, and the combinations of these at Mitsubishi Electric to give OXCs for use in creating all-optical networks. Fig. 6 shows an OXC prototype incorporating these technologies. The all-optical network-compatible OXCs will first be implemented in metro networks, where the shift to all-optical networks

Fig. 6 External appearance of the OXC prototype

will increase the capacity of the networks and reduce communications costs. ❑

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Next-Generation Optical Devices

*by Toshiro Isu and Tetsuya Nishimura**

Both widely wavelength-tunable light sources and ultra-short-pulse light sources are needed in next-generation optical devices for wavelength-division multiplexing (WDM) ultra-high speed optical communication systems. This article describes the multiple-electrode distributed Bragg reflector (DBR) laser and mode-locked semiconductor laser currently under development, and their basic performance as established thus far.

Introduction

WDM transmission optical communications systems require light sources whose wavelengths can be varied over a broad band, where they are used for signal sources, for backups, and for wavelength routing. Multiple electrode DBR lasers[1], [2] have been proposed for use as broad-band variable-wavelength lasers. These lasers are composed of a single wave guide, have a broad tunable wavelength range, and allow for rapid switching between wavelengths. However, adjustment of several parameters is necessary to control the wavelength, and a simple and reliable method of controlling wavelength is needed, along with long-term wavelength stability. In this development we have prototyped with a sampled grating (SG)-DBR as the front unit and a superstructure grating (SSG)-DBR as the rear unit. This SG-SSG-DBR laser is equipped with a phase control region that tunes the phase of the resonant light, and has demonstrated variable wavelength characteristics over a bandwidth greater than 30nm, confirming that stable wavelength control is possible.

On the other hand, there is the need for a laser light source capable of producing pulsed waveforms appropriate for high-speed transmissions in order to further increase the speed of transmissions to 40Gbit/sec or faster. Semiconductor mode-locked lasers (ML-LDs) are capable of producing high-speed repetitive pulses of several dozen GHz or more, and are expected to be useful devices because their pulse waveforms have close to the Fourier-transform limited values applicable to high-speed communications. There have already been reports of passive mode-locked laser diodes with the saturable absorber region operating at repeat frequencies between 40GHz and 480GHz[3].

We have proposed and prototyped a mode-locked semiconductor laser using a novel structure that has non-uniform excitation of a laser cavity without a saturable absorber region. The results have confirmed that it is possible to produce pulses of 40GHz with a waveform that is essentially at the Fourier transform limit, and are promising in terms of the next-generation semiconductor optical device for ultra-high speed optical communications systems. The article goes on to describe the results obtained so far with these two lasers.

The SG-SSG-DBR Laser Structure

SG and SSG are non-uniform diffraction gratings that have periodic superstructures, where SG has a regularly repeating structure apart from some parts that have been removed, and SSG has a periodic superstructure of a chirped diffraction grating. Diffraction gratings having these repeating superstructures have multiple Bragg-reflection wavelengths. SG-DBR lasers and SSG-DBR lasers have DBR regions on the front and the rear sides of the active region, and generate laser radiation at wavelengths where the front and rear DBR reflectance peaks are coincident. Because the refractive index is reduced when an electric current is injected into the semiconductor, such current injection into the DBR region makes it possible to shift the Bragg-reflection wavelength towards the short wavelength side. When the gap between the reflectance peaks of the front and rear DBRs is designed to be slightly different, the Vernier effect causes the adjacent reflectance peaks to be coincident when the wavelength of the reflectance peak has been shifted. This makes it possible to effect a large change in the wavelength produced.

The structure we used placed an SG region on the front side and an SSG region on the rear side, thereby making it far easier to obtain an output. A phase-shift region was added to adjust the phase of reflection lights on both sides. Fig. 1 shows a schematic diagram of the SG-SSG-DBR laser prototype. The active regions consist of strained multi-quantum wells (MQW), the transparent waveguide outside of the gain region is grown with a butt-joint structure, and the

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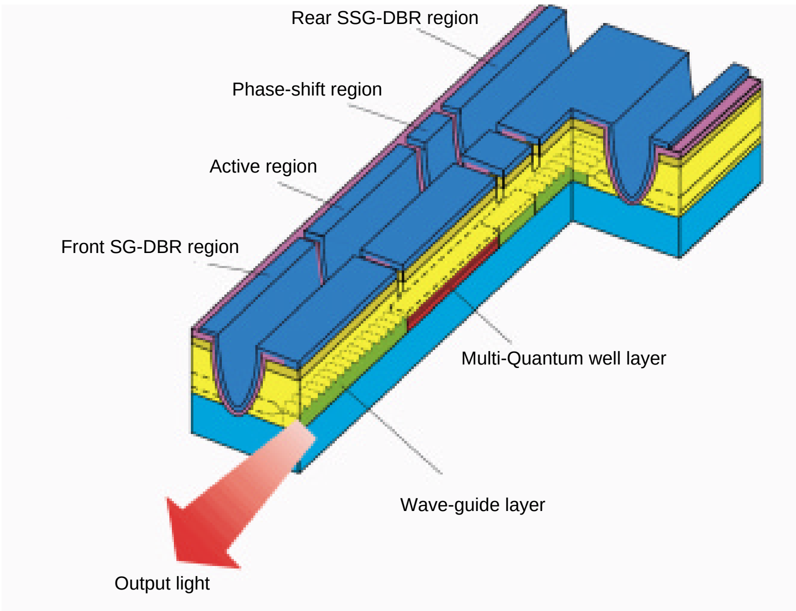

Fig. 1 Schematic of the SG-SSG-DBR laser

DBRs are formed by an embedded grating layer. Anti-reflective coatings are formed on both ends in order to prevent reflections from the cleavage edge.

Characteristics of the SG-SSG-DBR Laser

The laser prototype had a typical output of about 13mW when a current of 100mA was injected, with a threshold value at about 14mA. The oscillated wavelength control was done by adjusting the currents injected into the DBR regions at both front and rear. When moving to different combinations of reflection peaks in the front and rear DBRs based on the Vernier effect, a small variation in the electric current can cause a large shift in the wavelength. Thus, wavelength control avoiding the conditions close to these hoping areas is important. Fig. 2

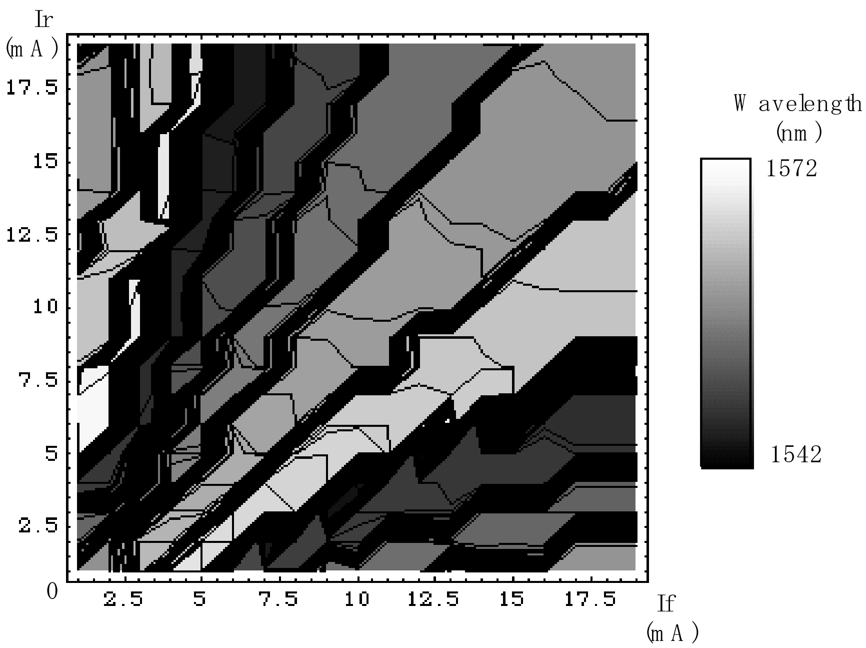

Fig. 2 Contour map of wavelength for DBR currents If *and* Ir

shows a contour map of the wavelength for combinations of front DBR electric currents (*If*) and rear DFB electric currents (*Ir*) when the electric current in the active region is held constant. It is clear that the overall range of variation in wavelengths spanned 30nm. After aging at 60°C for between 18 and 770 hours in order to ensure wavelength stability, the wavelengths were measured. The overall range of wavelength variation remained constant, regardless of the aging time. However, the small change in refractive index due to the aging shifts the regions wherein the contour lines converge, or in other words, changes the boundaries between lasing modes, and thus changes of the oscillated wavelength occurred under these operating conditions. In view of this, it is important to control the wavelengths under electric-current conditions that avoid the mode boundaries in order to obtain wavelength stability over extended periods of time. In order to obtain stabilized wavelength control, a table of electric currents must be generated carefully focusing on the wavelength contour map for *If* and *Ir*; however, a new algorithm is under development in order to reduce the time required for detailed mapping in performing wavelength control.

Fig. 3 shows the results of spectral measurements performed for the modules in butterfly packages with isolators. For 65 wavelengths in a wavelength grid based on the ITU-T recommendation for 50GHz intervals, stabilized outputs were verified at 1mW, and a stable side-mode suppression ratio of 40dB was confirmed. A 50km transmission test was performed also, using 2.5Gb/s direct modulation at the appropriate electric current conditions, where a power penalty of 0.7dB relative to a bit-error rate of 10^{-9} was obtained.

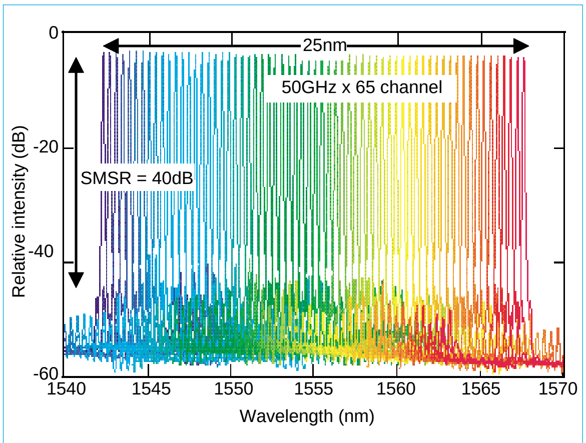

Fig. 3 Stabilized lasing wavelengths of the SG-SSG DBR laser

40GHz Mode-lock DBR Laser Structure

As is well known, there are many longitudinal modes in a Fabry-Perot(FP)-type semiconductor laser and passive-mode locking occurs when the phases of adjacent modes coincide at a given carrier density. We have demonstrated the emission of mode-locked pulses at a repeat frequency of over 60GHz, and performed a theoretical analysis of the relationship between the phase differences and carrier density for a model assuming three longitudinal modes.[4] The mode-lock frequency is determined by the length of the resonator, so a long cavity of approximately 1100µm is required in order to produce a repeat frequency of 40GHz. We performed theoretical analyses of structures that would produce mode locking with a stable amplitude even with long cavities such as these. We designed and fabricated a novel-structure, mode-locked semiconductor laser that does not have a saturable absorption region.[5] Fig. 4 shows a schematic diagram of the structure. The wave guide comprises transparent regions in front and rear of a central gain region, with the lengths of each designed to produce stable mode locking. The rear transparent region is equipped with a DBR to limit the spectral width, with an antireflective facet coating on its surfaces, and the front side, without a DBR, uses the cleavage edge as a mirror.

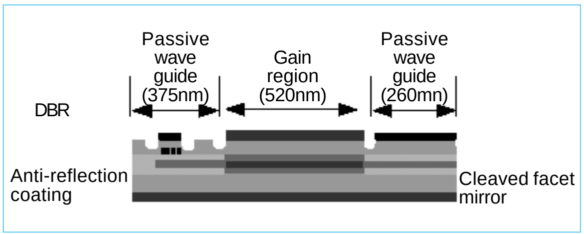

Fig. 4 Schematic of the mode-locked semiconductor laser structure

Characteristics of the Mode-Lock Operations

The lasing threshold value of the prototyped laser was 13mA, and the output was 10mW with a 130mA injection current at 25°C. Fig. 5 shows the lasing spectrum with a gain-region current of 130mA, and a DBR-region current of 3.66mA. It was confirmed that the DBR narrowed the spectral width, and that three cavity longitudinal modes were selected at less than -20dB. Fig. 6 shows the output waveform observed using an autocorrelator after amplification using an optical fiber amplifier. The repeat frequency was 40.4GHz (from the pulse spacing), and it was calculated that the pulse was 8.8ps wide and had a waveform of a $sech^2$ function. This value for the pulse width is nearly the same as the

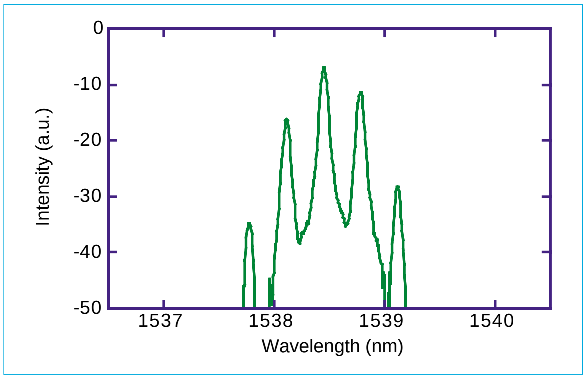

Fig. 5 Spectrum of the mode-locked laser

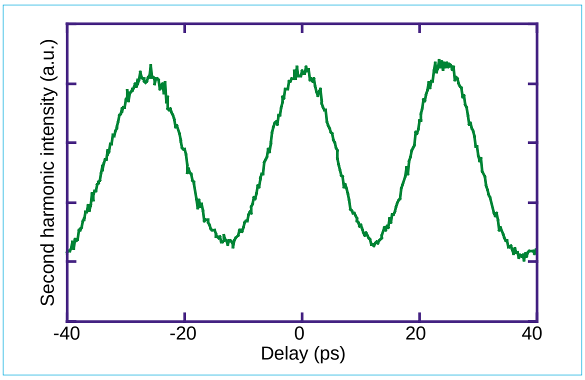

Fig. 6 Autocorrelation trace of the lasing pulses

waveform for the Fourier transform limit calculated from the spectral width, where the time-bandwidth product was 1.14 times the conversion limit. It was also confirmed that it was possible to change the mode-lock central wavelength by about 5nm by a plasma effect in the DBR region by increasing the electric current in that region.

Topics for the Future

The SG-SSG-DBR lasers have been shown to be promising devices as broadly tunable lasers. However, they suffer the disadvantage of a complex wavelength-control procedure. In future commercial development (such as increasing the output power), not only is it necessary to optimize the structure of the semiconductor elements such as the DBR design and the active region but it will also be necessary to further improve the wavelength control algorithms.

Laser oscillating at a repeat frequency of 40GHz was demonstrated in a non-uniform excitation semiconductor mode-locked laser that does not have a saturable absorption region, as proposed in this development project. The observation shows that this laser has a pulsed waveform suited to ultra high-speed optical communications. In the future, it will be necessary to demonstrate clearly not only the optical properties but also the characteristics of the frequency synchronization with the external signal. Further, it will be necessary to confirm the usefulness in optical communications systems above 40Gbps. These semiconductor lasers can produce functions such as wavelength switching and optical 3R through integration with wave-guide devices and through combinations with optical switches, and can be expected to be developed as next-generation devices used in photonic network nodes. ❑

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A Tunable Dispersion Compensator

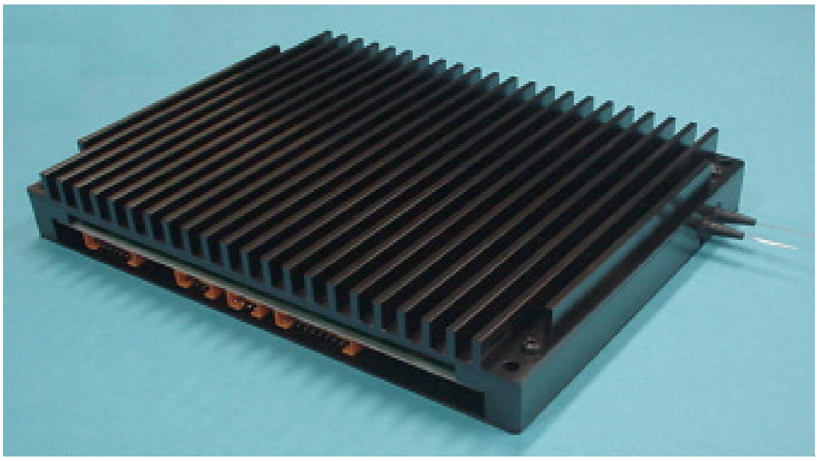

Fig. 1 Tunable dispersion compensator

The explosive growth of the Internet and demand for the transmission of higher quality video images are among factors driving the growing demand for communications. Optical-fiber communication systems are the optimum solution for such expanding demand.

Currently, the signal modulation speed of such optical-fiber communication systems is 10Gb/s with practical wave-division multiplexing (WDM) methods, although vigorous research and development work is taking place on faster, 40Gb/s WDM methods.

The inherent chromatic dispersion of optical fibers distorts the pulse width of light as it is transmitted over longer distances, and the overlapping of adjacent pulses gives rise to bit errors, limiting the distances over which signals can be transmitted. Chromatic dispersion also varies with time under the influence of the fiber environment (temperature and pressure), and these effects cannot be ignored at higher signal modulation speeds above 40Gb/s.

This makes it essential to develop accurate chromatic dispersion compensation technology if the next-generation optical-fiber communication systems are to be used for long-distance, high-speed communications.

Mitsubishi Electric's tunable dispersion compensators use a combination of optical-fiber Bragg gratings with precise temperature control to achieve accurate compensation of dispersion with 40Gb/s signals.

The optical insertion-loss characteristic has a bandwidth better than 0.6nm at -1dB, giving insertion losses under 5dB, with a dispersion tuning range of at least 350ps/nm and a group-delay ripple of ±2ps/nm, figures that put them in the very first rank worldwide. In carrier-suppressed return-to-zero tests at 43Gb/s, excellent results were attained: when compensating for 374ps/nm, more than 0.4nm of signal-transmission pass bandwidth was achieved. ❑

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