UDC 621.391.6:621.395.4

WDM Optical Fiber Transmission Systems

●Daisuke Maruhashi ●Kazuo Yamane ●Hiroyasu Sumiya
●Yasuo Nagai

(Manuscript received March 15, 1999)

This paper introduces Fujitsu's wavelength division multiplexing (WDM) systems and the technologies they incorporate. Two types of systems have been developed; one is for a long-haul network and other is for a metro network. These systems have a high-capacity (maximum 320 Gb/s) and good performance (transmission up to 600 km) and are very compact. They can easily be modified to meet customers' needs because a common platform is used for all configurations.

1. Introduction

The traffic volume of telecommunication networks is rapidly increasing, and this trend will clearly continue into the next century. Therefore, it is important to build network systems which can be easily upgraded to cope with increases in traffic volume. Because the wavelength division multiplexing (WDM) system has the merits of high-capacity, high-speed, low-cost, and good upgradability, it will be a fundamental system in future networks. The WDM system also provides traffic transparency, therefore it can be operated with various interfaces, for example, the interfaces of SONET/SDH, ATM switches, and IP routers.

We have developed two types of WDM systems; one is for a long-haul network and the other is for a metro network. These systems can have up to 32 wavelengths and operate at 2.4 Gb/s or 10 Gb/s using single mode fiber (SMF) and non-zero-dispersion shifted fiber (NZ-DSF).

2. WDM systems

2.1 Features

The overall specifications of the Fujitsu WDM systems are shown in **Table 1**.

There are two systems. One is the FLASHWAVE 320G, which is a very-high-capacity system mainly for long-haul networks, the other is the FLASHWAVE Metro, which is a middle-capacity, economical system mainly for metro networks.

Table 1
System specifications.

Item	FLASHWAVE 320 G	FLASHWAVE Metro
Multiplexed wavelength	1 to 32	1 to 16
Wavelength range	1535.82 to 1560.61 nm (0.8 nm spacing)	1536.61 to 1560.61 nm (1.6 nm spacing)
Fiber	SMF / NZDSF	←
Signal rate	9.95328 Gb/s or 2.48832 Gb/s	2.48832 Gb/s
Signal format	Scrambled NRZ	←
Maximum distance	320 km (80 km × 4) 600 km (100 km × 6)	60 km
System gain	23 dB × 4 / 25 dB × 6	15 dB
Dispersion compensation	Dispersion Compensator (DC)	No need
BER	< 1E − 15	←
Supervisory	Optical supervisory channel (OSC)	←

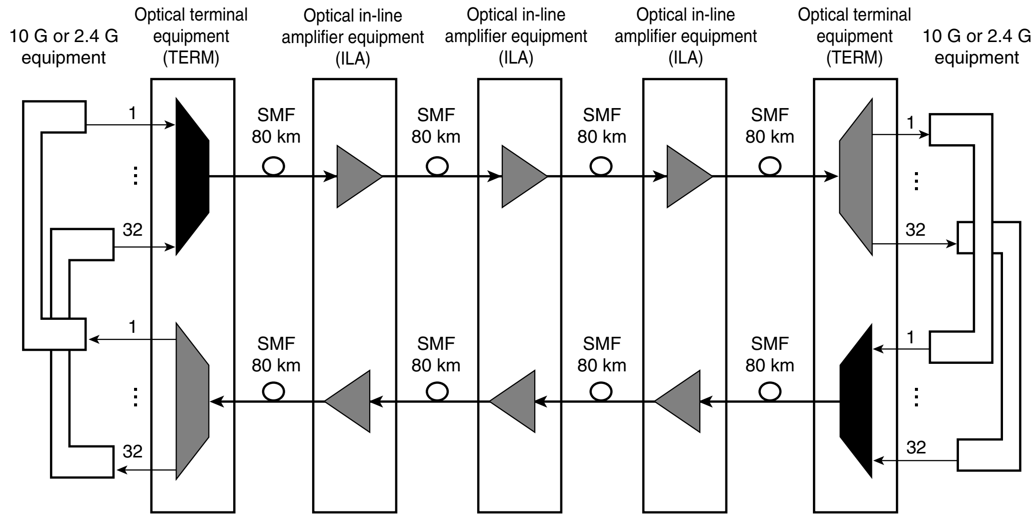


Figure 1
FLASHWAVE 320G network configuration.

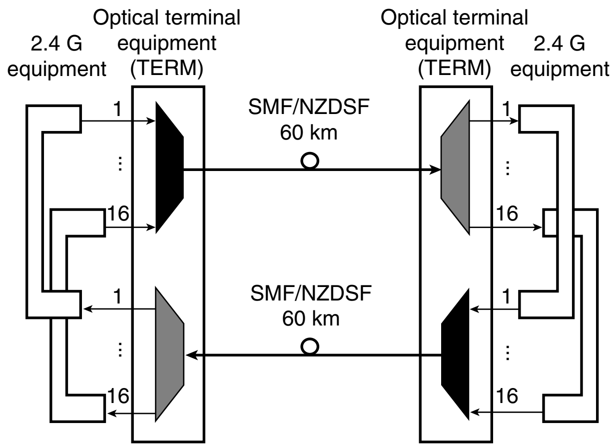


Figure 2
FLASHWAVE Metro network configuration.

The network configurations of FLASHWAVE 320G and FLASHWAVE Metro are shown in **Figures 1** and **2**.

2.2 System configuration

FLASHWAVE consists of Optical Terminal Equipment (TERM) and Optical In-Line Amplifier Equipment (ILA). A TERM is located at each terminal site and accommodates functional units such as a WDM Multiplexer/Demultiplexer and WDM amplifiers (Post-amp and Pre-amp). ILAs are located between TERMs and support WDM in-line amplifier functionality.

Figures 3 and **4** show the block diagrams of the TERM and ILA of FLASHWAVE 320G.

3. Technology

3.1 Optical network system design

3.1.1 SNR design

In a WDM system such as the one shown in Figure 1, the 2.4 Gb/s or 10 Gb/s modulated optical signals for other equipment are input to the TERM on the transmitter side. These signals are multiplexed and transmitted into the line optical fiber and optically amplified at the appropriate position in the TERM if necessary. At the ILA sites, the optical signals, which have been attenuated due to optical fiber loss, are optically amplified to their initial levels. Then, at the TERM on the receiving side, the optical signals are amplified, demultiplexed, and output to 2.4 Gb/s or 10 Gb/s equipment.

The optical signals experience SNR degradation during transmission, even though the WDM crosstalk is suppressed to a negligible level. One of the reasons for this degradation is the optical SNR degradation, which is mainly due to noise accumulation in the optical amplifier. Another source is waveform degradation, which is mainly due to dispersion or non-linearity in the

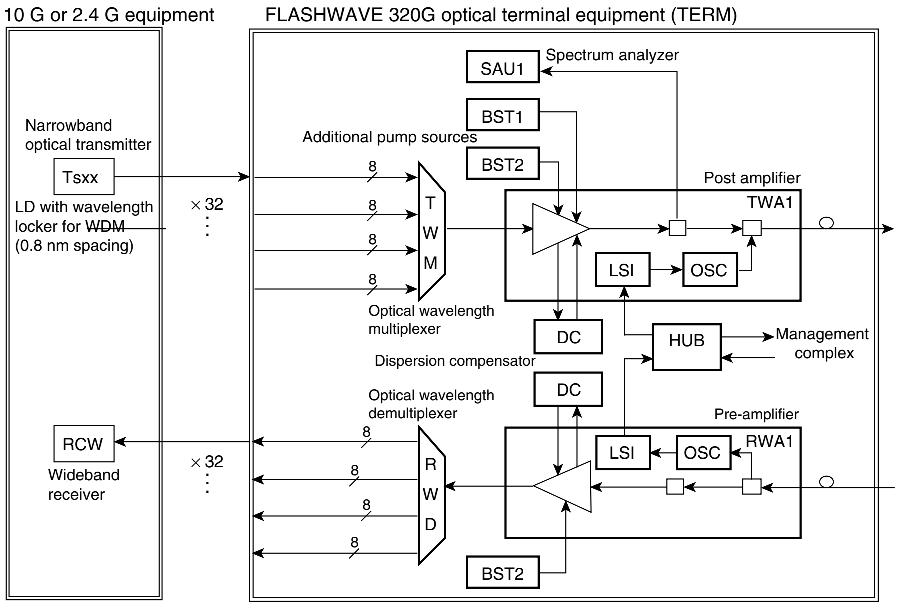


Figure 3
TERM block diagram.

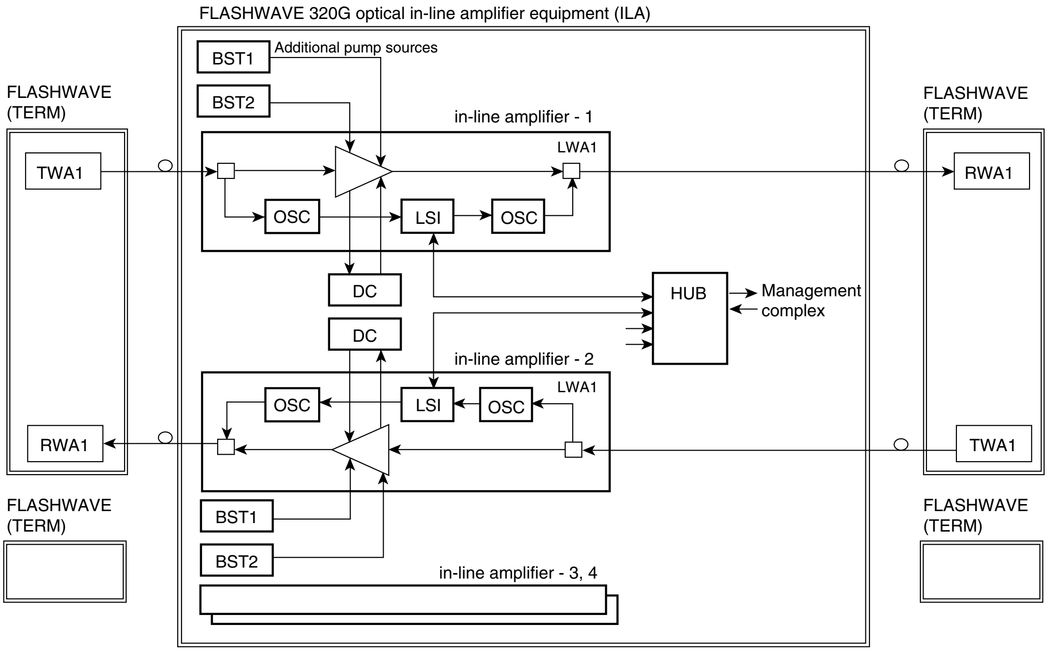


Figure 4
ILA block diagram.

transmission line.

Therefore, we optimize each parameter of optical devices in our equipment to obtain the maximum system gain for each type of fiber so that this degradation is minimized or eliminated.

3.1.2 Pre-chirping and dispersion compensation

One of the most important issues in the transmission of a 10 Gb/s optical signal is providing countermeasures for the waveform degradation caused by fiber dispersion and optical non-linearity. For this purpose, we use a pre-chirping technology and a dispersion compensator in our system.

Pre-chirping[1)] is a technique for varying the carrier frequency or wavelength of a transmitter using a Mach-Zender type $LiNbO_3$ external modulator[2)] in order to improve the received waveform after fiber transmission. The sign of pre-chirping is selected according to the combination of optical fiber type, length, and the power launched into the optical fiber. **Table 2** shows the suitable pre-chirpings for these combinations. In Table 2, it is assumed that the minimal and optimized dispersion compensator are used together if required.

Generally speaking, in high-power optical fiber transmission, positive pre-chirping is useful for compensating for the waveform degradation caused by self phase modulation (SPM). SPM is a negative chirping in the optical fiber due to the optical Kerr effect, which is an effect of optical fiber non-linearity.

On the other hand, in a low-power optical fiber transmission, pre-chirping having the opposite sign to that of the chromatic dispersion of the optical fiber being used is effective because pulse compression is done to cancel the pulse broadening caused by the chromatic dispersion. If a dispersion compensator is used in a low-power optical fiber transmission system, the sign of chromatic dispersion could be considered to be the sign of the total dispersion of the fiber and the dispersion compensator.

In the design of a 10 Gb/s transmission, we usually optimize the value of both the pre-chirping and dispersion compensator by numerical non-linear simulations. As a result, we can obtain an almost non-degraded waveform, even, for example, after transmission over several hundred kilometers of conventional single mode fiber (SMF).[3)]

3.1.3 Bit error rate (BER)

The BER versus span loss in an optical transmission system that has a 320 Gb/s (10 Gb/s, 32-channel) capacity over 320 km (4 spans of 80 km) of conventional SMF is shown in **Figure 5**. An almost 29 dB system gain for each of the spans was obtained at a BER of 1.0E−15.

There is almost no power penalty due to fiber transmission in Figure 5. This is also indicated in **Figure 6**, which shows the good eye-opening at the input of the O/E receiver. In this system,

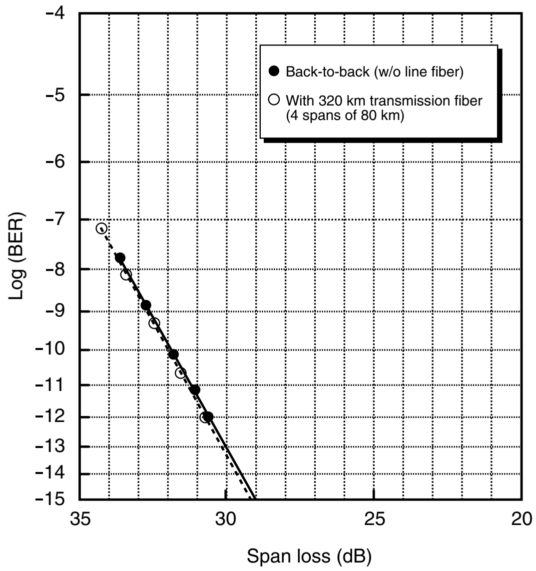


Figure 5
Bit error rate of 10 Gb/s 32-channel transmission over 320 km of SMF.

Table 2
Suitable combinations of pre-chirping and fiber type & power.

Pre-chirping \ Fiber/power	Short haul & low power		Long haul & low power		Long haul & high power	
	Positive dispersion	Negative dispersion	Positive dispersion	Negative dispersion	Positive dispersion	Negative dispersion
Positive	—	good	—	good	good	good
Negative	good	—	good	—	—	—

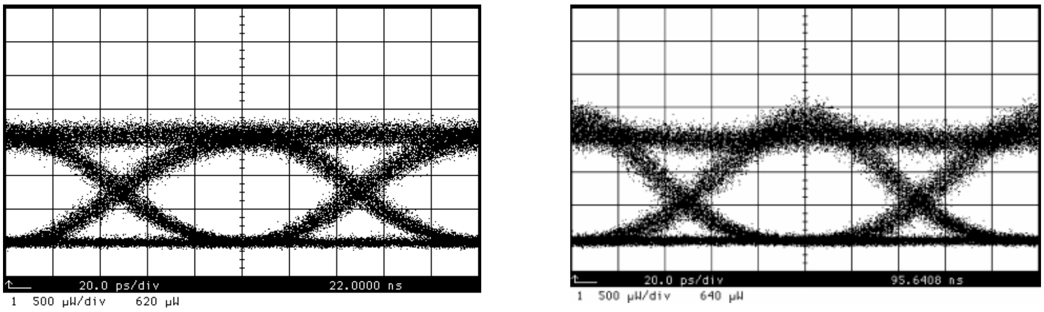
positive pre-chirping is used in the transmitter and dispersion compensators (DCs) are used in the TERMs at the transmitting and receiving sides and in the ILAs to compensate for the large chromatic fiber dispersion.

Other examples of the BER characteristics and received waveform are shown in **Figures 7** and **8**, respectively. These examples are from a 32-channel transmission modulated at 10 Gb/s along 600 km (6 spans of 100 km) of NZ-DSF. A 27 dB system gain for all six spans was obtained at a BER of 1.0E−15. However, the use of in-band forward error correction (FEC) enhances the system gain, as shown in Figure 7. Also, because the FEC improves the BER (for example, from 2.2E−10 to 1.0E−15), a system gain of as much as 29.5 dB was obtained for each span at a BER of 1.0E−15. Optimized pre-chirping and the DCs are also used in this transmission.

3.2 Optical device technology

3.2.1 Optical transmitter

The wavelength of a semiconductor laser can be stabilized by controlling the laser temperature



(a) Back-to-back (w/o line fiber)
(H: 20 ps/div., V: arbitrary unit)

(b) After 320 km SMF transmission
(H: 20 ps/div., V: arbitrary unit)

Figure 6
Received optical waveform with equalizing filter.

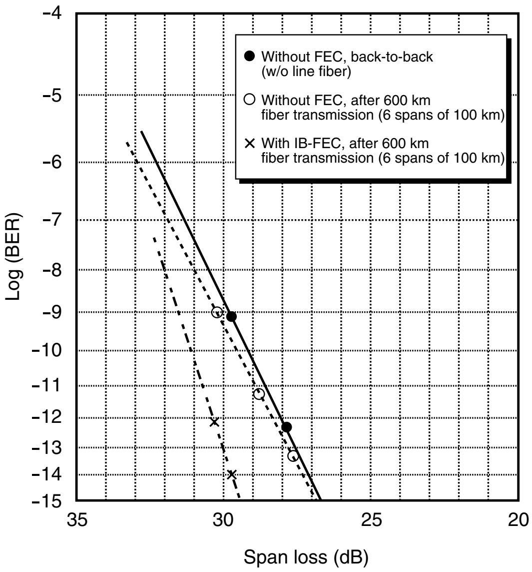
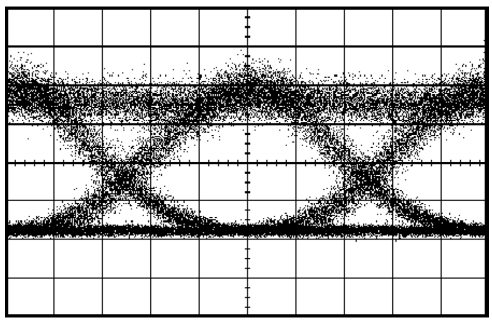


Figure 7
Bit error rate of 10 Gb/s 32-channel transmission over 600 km of NZ-DSF.



After 600 km NZ-DSF transmission
(H: 20 ps/div., V: arbitrary unit)

Figure 8
Received optical waveform with equalizing filter.

and current; however, the wavelength is liable to drift from 0.2 to 0.3 nm due to environmental factors and aging. In the case of a 0.8 nm wavelength interval, the wavelength stability almost has to be better than 0.08 nm. Therefore, we have used a "wavelength locker." A wavelength locker accurately detects the wavelength difference with two optical filters having stable temperature characteristics and then feeds the difference signal back to the peltier controller of the laser diode to stabilize the wavelength. Using a wavelength locker, we can reduce the wavelength drift to less than 0.05 nm.

3.2.2 WDM optical fiber amplifier

The WDM optical fiber amplifier has the following features.

1) A flat-gain over a bandwidth of 25 nm for 32 wavelengths with an ITU-T 100 GHz grid.
2) Per carrier grid-to-grid automatic level control (ALC) operation over a 7 dB input power range.
3) Field-installation of DC by automatic loss compensation.
4) A flexible configuration that allows field-installation of additional pump sources.
5) Scalability of the number of wavelengths using the ALC/AGC switching scheme as described in Subsection 3.3.2.

The amplifier consists of a pre-amplifier for low noise, a mid-attenuator for ALC operation, and a post-amplifier for a high output power. The automatic gain control (AGC) scheme is employed in the pre-amplifier and post-amplifier sections in order to maintain a fixed spectral-gain over input power variations. Two gain equalizers, GEQ1 and GEQ2, are used to flatten the gain over the entire signal band of 32 wavelengths (1535.8 to 1560.6 nm) for the pre-amplifier and post-amplifier, respectively. The configuration of two separated and gain-flattened blocks supports easy fabrication and testing. The variable attenuator (VAT), which operates on the Farady effect, absorbs both the span-loss and DC loss variation to realize ALC operation. When the number of wavelengths increases, the amplifier can accommodate additional pump source units in the post-amplifier during operation. The optical supervisory channel (OSC) section is attached to the amplifier section, which demultiplexes the supervisory channel (1510 nm) at the input and mutiplexes at the output.

Figure 9 shows a typical output spectrum of 32-wavelength amplification.

3.2.3 MUX/DMUX

We have adopted an arrayed waveguide grating (AWG) to multiplex and demultiplex 32 wavelengths. Characteristically, the insertion loss of an AWG does not depend on the number of wavelengths. **Figure 10** shows the insertion loss of the AWG.

3.2.4 Optical attenuator

In WDM optical fiber amplifiers, a non-mechanical optical attenuator is used, the atten-

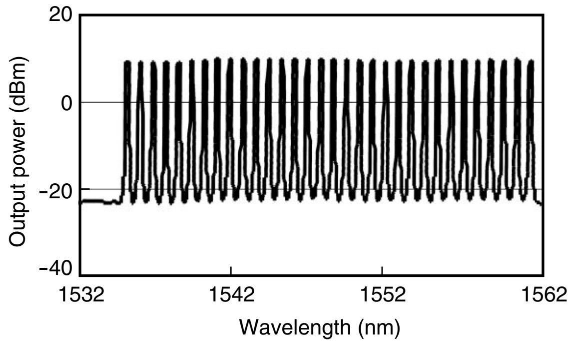


Figure 9
Output spectrum of 32-channel amplification.

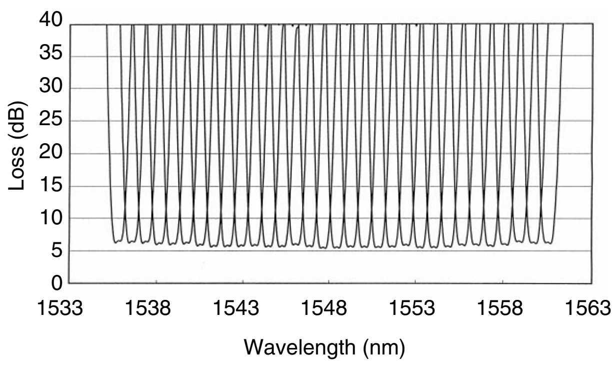


Figure 10
AWG loss spectra (P1-P32).

uation of which can be adjusted electronically to a high accuracy. The applied control signal depends on the number and amplitude of the optical signals. The attenuator consists of two polarizers and a Farady rotator which adjusts the angle of polarization according to a current applied to an electromagnet. The attenuator provides a range of attenuation from 1.6 to 25 dB for an input current from 0 to 40 mA.

3.3 System key technology

3.3.1 Optical supervisory channel (OSC)

The OSC is an optical interface placed between TERMs and ILAs for alarm surveillance, overhead information transmission, and remote amplifier control. The OSC data is transmitted along the fiber used for the main signal. **Table 3** shows the overall specification of the OSC, and **Figure 11** shows its signal format.

WCF, WCR, and WCS are the bytes which indicate the status of each wavelength; they are used for remote amplifier control. WCF is the Failure indication byte of each wavelength. WCR is the Bit-Rate indication byte of each wavelength. WCS is the Status indication byte of each wavelength; it posts the IS/OOS (in-service/out-of-service) condition.

3.3.2 Overhead interface

The OSC provides an equivalent interface to those of SONET Overhead, for example, E1, F1, and DCC (D1-D3).

Figure12 shows the configuration of OSC control.

Amplifier control

1) Automatic turn-up

Each amplifier (Post, Pre, In-line) can be set up automatically. The WCx bytes are transported from the transmitter TERM to the downstream ILAs/TERM, and each downstream amplifier operates according to the WCx information. It is not necessary to provision at each ILA. This architecture enables a very quick installation.

2) In-service wavelength increase/decrease

When the traffic capacity or the network configuration changes, the number of wavelengths has to be adjusted. This adjustment should be done without affecting the other wavelengths in the fiber. The number is increased by provisioning WCS from OOS to IS at the transmitter TERM. Then, the change is relayed downstream by the OSC automatically.

3) Wavelength failure management

During operation, one or more wavelengths may fail, for example, because of a low optical signal level. When the system detects such a failure,

Table 3
Optical supervisory channel specification.

Wavelength	1510 nm	Signal format	DS1 ESF
Signal rate	1.544 Mb/s	Line code	CMI

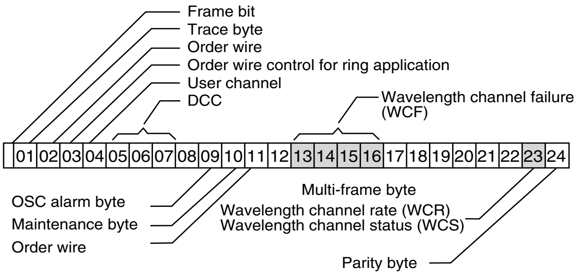


Figure 11
Optical supervisory channel signal format.

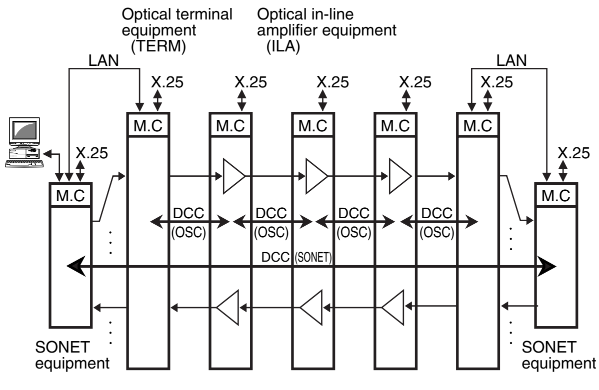


Figure 12
Configuration of OSC control.

it generates the appropriate WCF bytes and transports them downstream on the OSC. At each ILA site, the amplifier operating mode is rapidly changed from ALC mode to AGC mode when the WCF byte is received. The remaining wavelengths are not affected (not degraded) by the failed wavelength.

Figure 13 shows the amplifier automatic control path through the OSC.

4. Future enhancements

To provide a more flexible and cost-effective network in the near future, the following should be achieved.

1) Increased capacity: One approach is to narrow the channel (wavelength) spacing. Currently, the spacing is 100 GHz, and we will realize spacings of 50 GHz, 25 GHz, and lower in the next step. Another approach is to use additional bandwidth. Current amplifiers work at 1535 to 1560 nm, i.e, in the C-band (Conventional wavelength band). We will develop both an L-band (Longer wavelength band) and C-band system and add them to the current system.
2) Higher bit-rate: The next step is 40 Gb/s.
3) More flexibility: Currently, the SONET/SDH interface is popular; however, various interfaces should be considered for connection with WDM systems, for example, ATM and IP. Some of the functionality accomplished at the electrical layer, for example, protection switching, should also be supported on the photonic layer.

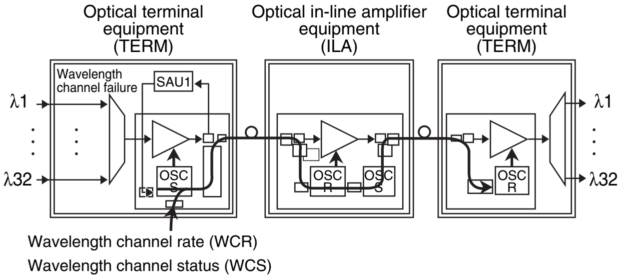


Figure 13
Automated remote gain control for optical amplifier.

5. Conclusion

This paper introduced Fujitsu's WDM systems and described some of the advanced technologies they incorporate. These systems can accommodate a wide range of bit-rates, capacities, span lengths, span numbers, fiber types, and so on. They also realize superb performance with fully worked-out technologies.

We believe that these are the fundamental systems for future networks. We will continue to use the newest technology and architecture to create a convenient and flexible photonic network.

References

1) G. Ishikawa, M. Sekiya, H. Onaka, T. Chikama, and H. Nishimoto: 10-Gb/s repeaterless transmission using standard single-mode fiber with pre-chirping and dispersion compensation techniques. *IEICE Transactions on Electronincs,* **E78-C**, 1, pp.43-49 (Jan. 1995).
2) M. Seino, N. Mekada, T. Namiki, and H. Nakajima: 33 GHz *cm broadband Ti: $LiNbO_3$ Mach-Zehnder modulator. ECOC '89 (Gothenburg, Sweden) Proc., **1**, ThB22-5, pp.433-436 (Sep. 1989).
3) A. Ehrhardt, A. Gladisch, N. Hanic, F. Kueppers, R.Leppla , W. Weiershausen, L.Olofsson, A. Beka, T. Tsuda, Y. Yamane, and T. Tsurumi : 10 Gbit/s 750 km regenerator-free WDM field trial – upgrading an operated 2.5 Gbit/s based system without changing the installed infrastructure. OFC'99 (San Diego), Technical Digest, TuQ2, pp.237-239, Feb., 1999.
4) H. Miyata, H. Isono, and S. Kinoshita: Wavelength division multiplexing technology. (In Japanese), *FUJITSU*, **48**, 5, pp.424-435 (Sep. 1997).
5) H. Isono, K. Moriya, and M. Yano: Optical device core technology for optical fiber transmission systems. (In Japanese), *FUJITSU*, **48**, 5, pp.457-462 (Sep. 1997).
6) S. Kinoshita, C. Ohshima, H. Itoh, M. Takeda, T. Kobayashi, Y. Sugaya, T. Okiyama, and T. Chikama: Wide-dynamic-range WDM optical

fiber amplifiers for 32 × 10 Gb/s, SMF transmission systems. OAA98, WA2, pp.173-176, Jul., 1998.

7) N. Fukushima, H. Onaka, M. Shirasaki, Y. Suzuki, and T. Tokumasu: Non-mechanical variable attenuator module using Faraday effect. OAA96, FD9-1, pp.154-157, Jul., 1996.

Daisuke Maruhashi received the B. S. degree in Electronics Engineering from Waseda University, Tokyo, Japan in 1982. He joined Fujitsu Ltd., Kawasaki, Japan in 1982 and has been engaged in development of optical fiber transmission systems.

Kazuo Yamane received the B. S. degree in Electronics Engineering from the University of Tokyo, Tokyo, Japan in 1980. He joined Fujitsu Ltd., Kawasaki, Japan in 1980 and has been engaged in development of optical fiber transmission systems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Hiroyasu Sumiya received the B.S. degree in Electrical Engineering from Kyoto University, Kyoto, Japan in1978. He joined Fujitsu Ltd., Kawasaki, Japan in 1978 and has been engaged in development of transmission systems.

Yasuo Nagai received the B. E. degree in Electronics Engineering from Shizuoka University, Shizuoka, Japan in 1969. He joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1969, where he engaged in research and development of millimeter-wave transmission systems until 1973. Since 1974 he has been engaged in development of optical fiber communication systems (FLM series, etc.)