UDC 621.383:621.391.6

Photonic Networking Using Optical Add Drop Multiplexers and Optical Cross-Connects

●Terumi Chikama ●Hiroshi Onaka ●Satoshi Kuroyanagi

(Manuscript received May 8, 1999)

The photonic network will enable the construction of high-capacity and flexible optical communication systems for the future data-centric era. Optical add drop multiplexers (OADMs) and optical cross connects (OXCs) along with already mature DWDM systems are key technologies for photonic networking. Prototype systems of OADMs based on the acousto-optic tunable filter (AOTF) and OXCs based on PLC optical switches have been demonstrated.

This paper provides a perspective of the latest optical path layer technologies.

1. Introduction

In the 21st century, there will be an explosive growth in the amount of information being transmitted by digital services such as electronic commerce, software distribution, and digital video/music distribution services. The capacity required to handle all this information will be provided using new communication technologies. IP/ATM and photonic networking are key-enablers for realizing terabit capacities and effective and reliable use of networks. Current transport technologies based on the SONET/SDH format are already in wide use in today's networks. The transport network has a layered structure as defined by the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). It consists of a circuit, transmission media, and path layer. The maturity of OC48, OC192, and extremely dense WDM forces us to rethink the strategy for cost-efficient bandwidth management using these layers. The introduction of an optical path layer with high bit rate TDM pipes multiplexed by DWDM which can be managed by OADM and OXC will be effective for overall network efficiency.1) In the ring architecture, an OADM can be introduced to make efficient use of network capacity, network protection, wavelength routing, and many more features. In the mesh architecture, an OXC could provide the scalability, modularity, and transparency required in the network. In addition, photonic networks based on OADMs and OXCs will provide openness and transparency in future networks to accommodate various client signals with different bit rates and formats (e.g., SONET, SDH, ATM, and IP) efficiently and to forward the client signals transparently to end users.

This paper provides a perspective of the latest optical path layer technologies. Some key advancements in the OADM architectures using acousto-optic tunable filters (AOTF) will be described along with the concept of optical path protection. Also, optical path cross connect architectures will be discussed along with the key features required for practical use of this technology.

2. Optical Add Drop Multiplexer (OADM)

OADM technology is used to cost effectively access part of the bandwidth in the optical domain being passed through the in-line amplifiers with the minimum amount of electronics. OADM can be used in the static as well as dynamic mode. **Table 1** shows the migration scenarios of OADM. In passive OADM, the add and drop wavelengths are fixed beforehand. In dynamic mode, the OADM can be set to any wavelength after installation. Passive OADM is currently being used in networks with WDM systems. The technologies used to accomplish passive OADM are thin-film interference filters, fiber gratings, and planar waveguides. The optical characteristics such as the insertion loss and the inter-band and intra-band crosstalk are well understood for each of these technologies when used in a passive OADM application. Dynamic OADM has the advantages of better cost-effectiveness and flexibility than passive OADM because it can select any wavelength by provisioning on demand without changing its physical configuration. A smooth migration from passive to totally reconfigurable and dynamic OADM will be necessary. Dynamic OADM is classified into two generations. The second generation is mainly applied in a linear configuration without an optical path protection function. The path protection function is supported by electrical ADMs. Finally, the third generation will be applied in a ring configuration to provide optical layer path protection based on the 4-fiber Bi-directional Line Switched Ring (BLSR) and other protection schemes.[2]

Table 1
Migration of OADM.

Generation	I	II	III
Configuration	Passive OADM	Dynamic reconfigurable OADM	
Add/Drop wavelength Number of wavelengths	Fixed	Settable by provisioning	
Connection to electrical nodes (client)	Manual change of fiber connections	Automatic change of connections by optical SW with provisioning	
Network protection	SONET/SDH APS		Optical layer APS
Network architecture	Linear	Linear	Linear, ring OBLSR/OBPSR
Key devices	Fiber grating Dielectric filter	Optical SW, AOTF Tunable wavelength LD	

Regarding the architecture of dynamic OADM configurations, there are two types. One is the SW type with a back-to-back multiplexer/demultiplexer, and the other is the AOTF type. **Figure 1** shows these configurations. One of the technical difficulties in using the SW type for OADM is that for n channels in a WDM system, an $n \times n$ optical switch will be required on the drop and add sides to accomplish a dynamic capability. This can be extremely expensive and cumbersome. Other problems such as channel passband narrowing due to concatenation of multiplexers/demultiplexers for a channel spacing of 0.8 nm or less can also create major problems in a long-distance network.[3] The AOTF type holds a lot of promise for providing a cost-effective solution for a static as well as dynamic OADM and presents no passband narrowing problem. We have therefore been developing dynamic OADM systems using AOTF.

2.1 Acousto optic tunable filter (AOTF) configuration

Figure 2 shows the device configuration of an AOTF developed by Fujitsu.[4] The device is fabricated on lithium niobate ($LiNbO_3$) and is composed of an inter-digital transducer (IDT), optical waveguide, thin-film surface acoustic wave (SAW)

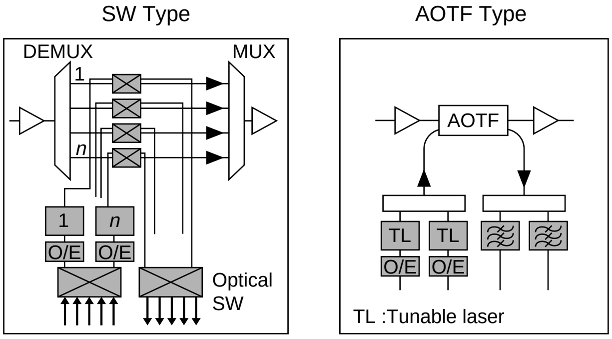


Figure 1
SW and AOTF types of OADM architectures.

guide, and polarization beam splitters (PBSs). The incident light is propagated over the optical waveguide and divided into perpendicular components (TE/TM) by the first PBS. An acoustic wave is generated by applying an RF signal to the IDT. This acoustic wave travels through the SAW guide and causes a periodic modulation of the refractive index of the optical waveguide. This change of refractive index induces TE-TM or TM-TE conversion for only the drop wavelength. The drop wavelength corresponds to the applied RF frequency and becomes perpendicular to the incident light. The second PBS is then used to separate the drop wavelength from the incident light. An AOTF can not only drop a single wavelength but also multiple wavelengths simultaneously. By changing the number of RF signals and their frequencies, we can control the number and frequencies of the drop wavelengths. There are no moving parts in the AOTF, and it offers high-speed wavelength tuning that can be done sequentially or randomly based on the applied RF frequency. Although the insertion loss of AOTFs has been relatively high and the sidelobe suppression has been poor, recent advancements have significantly improved both of these characteristics and allow optimal network efficiencies in the photonic layer unit (SAU).

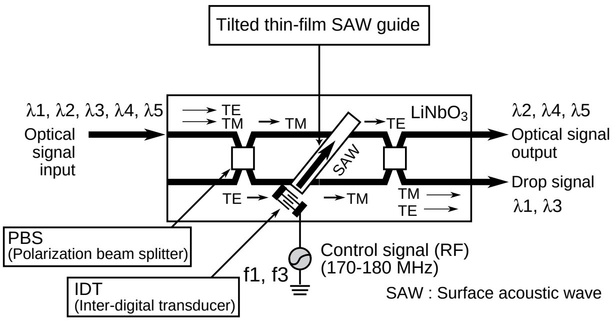


Figure 2
Configuration of AOTF.

Figure 3 shows WDM signal separation using an AOTF. By using two AOTFs, we were able

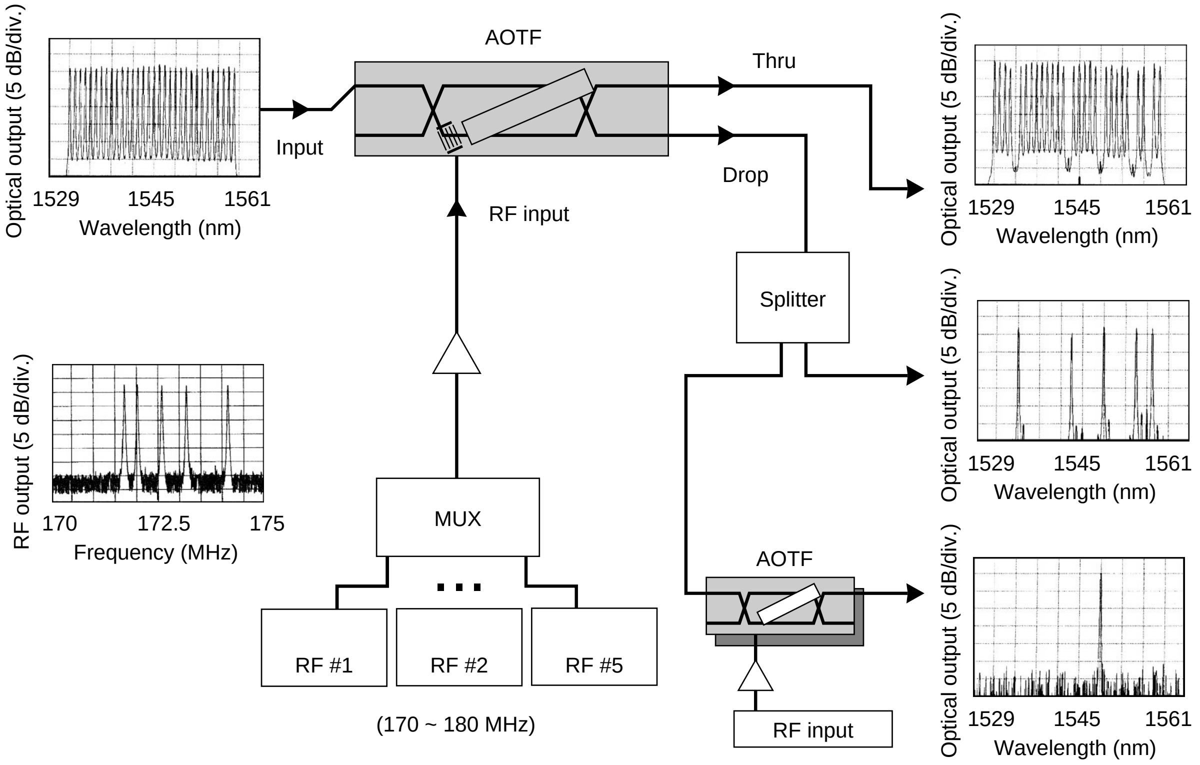


Figure 3
Wavelength selection by AOTF.

to extract any wavelength among 32 wavelengths separated with a 0.8 nm channel spacing. The first AOTF dropped five wavelengths simultaneously and passed the remaining 27 to the through port. Then, the second AOTF extracted the desired wavelength from the five dropped ones. This method provides sufficient adjacent channel crosstalk suppression.

2.2 OADM design considerations

To maximize the effectiveness of an OADM, the functions listed in **Table 2** have to be considered. Our system was designed according to the following five main considerations:

1) In the case of an OADM node with AOTFs, an AOTF can be used instead of an $n \times n$ switch to retrieve individual or multiple channels. Also, transponders (O/E, E/O, optical modulators) with tunable lasers can be used on the add side to provide the dynamic capability. In this case, the OADM can support random selection of wavelengths.
2) Our system can support a drop-and-continue or broadcast feature by using a signal tap component within the OADM node. This function will be useful for the configuration of dual-hubbing in a multiple ring connection.
3) Our system can support a function of optical layer protection such as the 4-fiber Bi-directional Line Switched Ring (BLSR). **Figure 4** shows the OADM node configuration of an optical self-healing ring. This configuration consists of four fibers for two bi-directional lines, dual nodes (work and protection node) for each direction, optical span SWs, and optical ring SWs. Protection line and optical span SWs are used during OADM equipment failures and fiber breaks on the work side. Optical ring SWs are prepared to loop back during fiber breaks on both the work line and the protection line. In addition, this system can monitor parameters of optical signals such as the optical power, wavelength, number of wavelengths, and optical SNR using a built-in optical spectrum analyzer unit (SAU).5)
4) It is clear that by using AOTF-based OADM, multi-channel access can be easily and cost effectively accomplished. Multi-channel drops can be fed into a simple splitter/coupler, after which multi-channel tributary interfaces can be used to feed the signals into a subtending ring.

Table 2
Functions of OADM.

Functions	Issues
Wavelength MUX/DMUX	•Maximum number of wavelengths: 16, 32, 64, 128... •Number of add/drop wavelengths
Wavelength cross-connect (λ SA: λ slot assignment)	•Add wavelength: Fixed/Settable •Drop wavelength: Fixed/Settable •Through wavelength: Fixed/Settable (λ SI: λ Slot interchange) •Broadcast (Drop and Continue)
Inter-office IF	•Transmission fiber: SMF/DSF/NZ-DSF, span, number of spans •Inter-working for maintaining survivability: SONET/SDH APS, optical SNR
Intra-office IF	•OC192/c, OC48/c, Asynchronous signal, G-Ethernet, 100 BaseF •Inter-working for maintaining survivability
Management and control	•Wavelength control, Performance monitoring, Output level control, wavelength path trace •Transferring supervisory channel: OSC (optical supervisory channel)

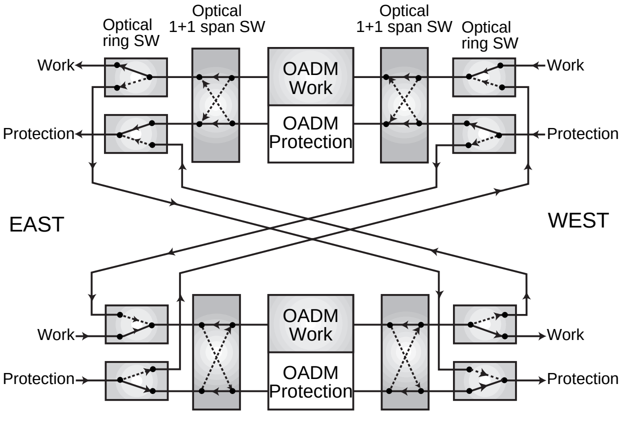


Figure 4
OADM node configuration for optical self-healing ring.

5) Our system can support a Bellcore standard 1510 nm OSC channel for retrieval of alarms and other supervisory information. These OADM nodes can support express pass-through of the OSC channel.

2.3 Prototype OADM system

Figure 5 shows the configuration of a prototype OADM system using an AOTF, and **Table 3** lists its specifications. The OADM system consists of an OADM shelf, Tributary shelf, and Wavelength bank shelf. This system can accommodate 32 wavelengths at 10 Gb/s with a 0.8 nm channel spacing (line capacity: 320 Gb/s) and add/drop any four wavelengths. The AOTF in the OADM shelf divides input WDM signals into drop and through signals. The drop signals are passed through the AOTFs in the Tributary shelf to extract the desired wavelengths, which are then received by each electrical node. In the add process, the wavelength bank is used instead of tunable LDs. In the Wavelength bank shelf, LDs having the same wavelengths as the wavelengths used in the line are prepared in advance. These wavelengths are combined and provided to each optical external modulator. The modulators are driven by the add signal received from the O/E. The desired wavelength is selected after modulation by an AOTF and launched out of the line as the add signal. As a result, the wavelength of the add signal is converted to the desired wavelength in the OADM.

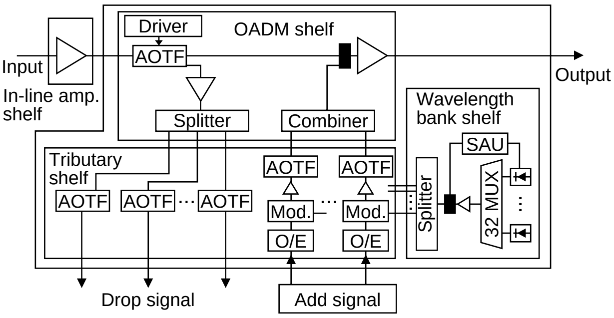


Figure 5
OADM configuration using AOTFs.

Table 3
OADM system specifications.

Items	Features	Remarks
Architecture	AOTF-based free wavelength add/drop	Wavelength conversion
Line capacity and wavelength	320 Gb/s 10 G × 32 w	Compatible with FLASHWAVE320G
Add/drop capacity wavelength	40 Gb/s 10 G × 4 w	8 w (max.) 32 w (in future)
Channel spacing	100 GHz	ITU-T grid
Optical path rates	10 Gb/s, 2.5 Gb/s	Transparent
Protection	—	Upgrade to optical BLSR

The prototype OADM system is shown in **Figure 6**. This system was demonstrated at Supercomm'98 in Atlanta as the world's first totally reconfigurable, dynamic OADM.

3. Optical Cross-connect System

To realize efficiency and transparency in the optical network, wavelength grooming and routing functions for each client signal and optical path supervising functions such as performance monitoring and path tracking must be provided. The key element for providing these functions is the optical cross-connect (OXC) system.[6)]

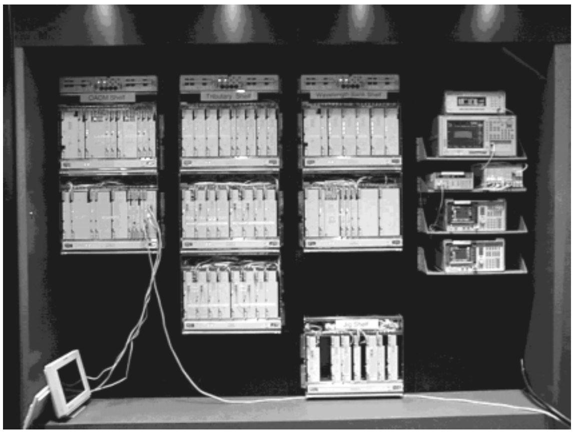


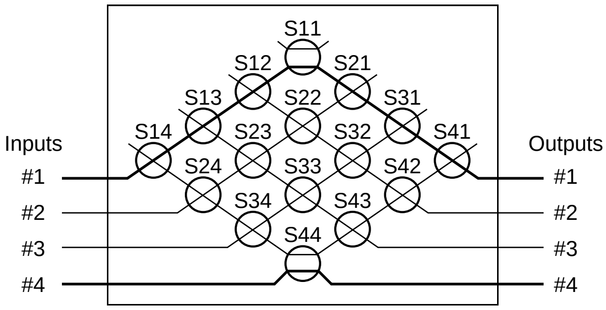
Figure 6
Prototype OADM system at Supercomm'98 in Atlanta.

3.1 Key technologies

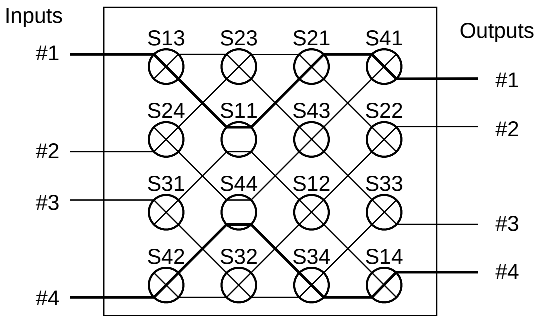
Some technical issues have to be considered in connection with the development of the OXC. We investigated these issues from the viewpoint of the optical switch architecture and the supervision of the optical path (especially, path tracking).

3.1.1 Optical switch architecture

The optical switch is a key element for realizing an OXC node. If the insertion loss of the optical switch is large, optical amplifiers (OAs) must compensate for the loss inside the node. If the loss variation at each switch port is too large, the optical receivers (ORs) at the termination and regenerating nodes cannot receive the optical signals because the dynamic range of the ORs is exceeded. The extinction ratio of the optical switch depends on switch-specific characteristics (the device that is used and the configuration of the switch element). On the other hand, the crosstalk in the optical matrix switch depends mainly on the architecture of the switch. If the crosstalk of the optical switch is large, optical signals will be disturbed by other optical signals. For these reasons, the optical switch requires an architecture which can suppress the degradation of transmission quality (insertion loss, loss variation, and crosstalk).



(a) Conventional structure (Crossbar switch)



(b) Proposed structure (PI-LOSS switch)

⊗ : Cross ⊖ : Bar

S*ij* : Control point for connecting input #*i* to output #*j*
PI-LOSS : Path-independent insertion loss

Figure 7
Optical switch architecture (4 × 4).

In the case of a conventional crossbar switch,[7] the number of switch elements in each optical path is different. In the 4 × 4 switch, the best path passes through only one switch element (from input #4 to output #4), while the worst path passes through seven switch elements (from input #1 to output #1) (**Figure 7(a)**). As a result, the insertion loss, its variation, and crosstalk become larger as the switch capacity increases. Therefore, we have proposed a PI-LOSS (path-independent insertion loss) optical switch as a solution for these problems (**Figure 7(b)**).[8] In the PI-LOSS switch architecture, all optical signals pass through the same number of switch elements, which means that the insertion loss is constant and is about half of the maximum loss of the conventional crossbar switch.

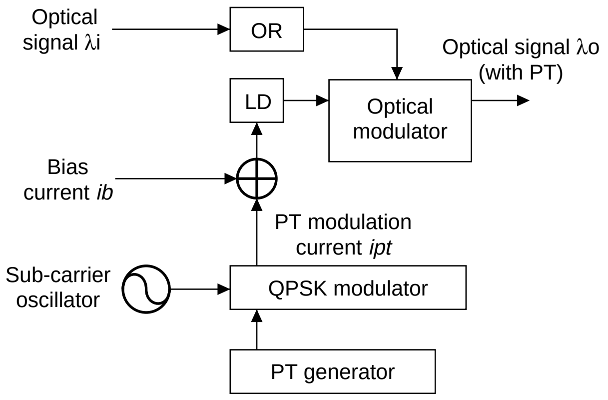
We developed the 8 × 8 optical switch using the PI-LOSS topology for the OXC node. The 8 × 8 PI-LOSS switches are silica-based, thermo-optic matrix switches. Each switch element for the PI-LOSS switch is constructed from double Mach-Zehnder Interferometers (MZIs). The insertion loss and insertion loss variation of the PI-LOSS switch were less than 6 dB and 1 dB, respectively. The loss variation of 1 dB includes not only the variation between path routes, but also the wavelength and polarization dependency loss. The total crosstalk from other channels was less than –37 dB.

3.1.2 Optical path tracking

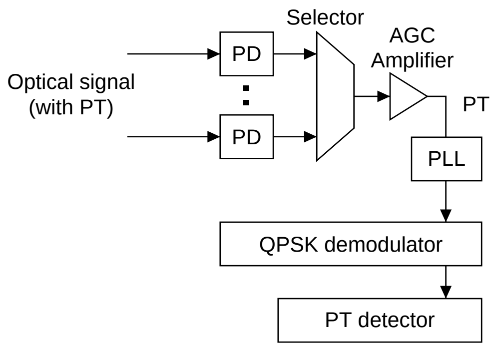
An optical path tracking method which is independent of the client signals is also required for maintaining the transparency of the optical network. Optical path tracking using a pilot tone

(PT) is an effective tracking method and is currently being discussed in the ITU-T.9)-11) In this method, the PT signals modulate a sub-carrier that is superimposed onto an optical signal that acts as a main carrier. The PT signals that modulate this sub-carrier are monitored at each node, which enables the identification (ID) of the optical paths to be established, which in turn makes it possible to check the optical path connection.

A block diagram for a PT circuit we manufactured for trials is shown in **Figure 8**. The PT signal is a 4 kb/s base-band signal with 142 bits per frame. This frame contains the ID of an optical path, the ID of the OXC, and the status information. The PT signal is modulated using quadrature phase shift keying (QPSK), since QPSK has good transmission characteristics and a good performance with respect to frequency availability. The sub-carrier frequency used in this experiment was 150 kHz.



(a) PT sender (with λ CNV)



(b) Pt receiver

Figure 8
Block diagram of PT sender and receiver.

The PT sender was mounted on a board including an OR module and an optical sender (OS) module with a laser diode (LD) and an optical external modulator. The LD was directly driven by the QPSK modulated PT signal current superimposed on a bias current. The output power of the LD was modulated in the optical modulator by the main signal. The sender can adjust the sub-carrier amplitude. We varied the sub-carrier amplitude modulation index, m, which is the ratio of the main optical signal to the sub-carrier amplitude.

The PT receiver was mounted on a board which had four receiving ports. The phase lock loop (PLL) technique was used in the receiver, which was useful for keeping the bandwidth of the electric receiver very narrow. Consequently, the receiver delivered a good performance with respect to the signal-to-noise ratio (SNR).

3.2 Prototype system

Figure 9 shows the configuration of the prototype OXC node, and **Table 4** lists its specifications. The prototype system mainly consists of optical switches (OSWs), wavelength multiplexers (WMUXs) and demultiplexers (WDMXs), and optical pre-amplifiers (Pre-OAs) and post-ampli-

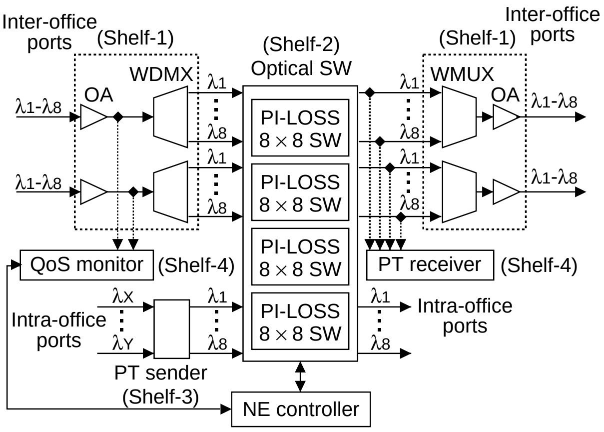


Figure 9
Configuration of prototype OXC system.

fiers (Post-OAs). In this system, we used our proposed PI-LOSS switches for the OSWs. The PT senders were connected to the input intra-office ports, and the PT receivers were arranged at the output of the OSWs. The optical signals from each input port were routed by the OSWs to the appropriate output ports according to the control signal from the network element (NE) controller. We also monitored quality of service (QoS) factors such as the optical power, wavelengths, and optical SNR for each optical path at the input inter-office ports by using an optical spectrum analyzer. The performance information was sent to the NE controller.

Eight wavelengths can be multiplexed in a single fiber, which leads to a wavelength spacing of 1.6 nm. The OXC node accommodates three input ports and three output ports plus one intra-office port. This means that the OXC node switches 24 optical paths (three ports × eight wavelengths). The bit transmission rates per optical path are 10 and 2.5 Gb/s. The WMUXs and WDMXs are array waveguide grating (AWG) multiplexers and demultiplexers.

The prototype OXC node was constructed using various kinds of boards mounted in a single cabinet. The cabinet contained an inter-office port interface shelf (shelf-1), an OSW shelf (shelf-2), an intra-office port interface shelf (shelf-3), and an optical path supervision shelf (shelf-4). By using eight OSW boards and another cabinet having two inter-office port interface shelves and one intra-office port interface shelf, the OXC can accommodate 64 optical paths.

3.3 Evaluation results

We measured the bit error rate (BER) of the system using the evaluation setup shown in **Figure 10**. For the performance test, four 10 Gb/s and four 2.5 Gb/s optical signals were input to the intra-office ports of OXC-X, relayed to OXC-Y, and then received at the output intra-office ports of OXC-Z. **Figure 11(a)** shows the BER versus the received power for the case of the 10 Gb/s optical signals. The tests showed a power penalty of less than 1.2 dB at a BER of 10^{-11}. The BER penalty is caused by the amplified spontaneous emission (ASE) noise of the OAs and coherent crosstalk in the OSWs.

The quality of the PT signal and main optical signal are in a trade-off relationship. The

Table 4
OXC system specifications.

Items	Specifications
Optical path	Wavelength path (WP)
Multiplexed λs	8 (@1.6 nm, ITU-T grid)
Input/Output ports	3 (Inter-and intra-office ports: 2 and 1) @Upgradeable to eight ports
Signal speed	10 G (OC-192) and 2.5 G (OC-48)
Operation and supervision	• NE based control and management • Path trace using pilot tone signal • Quality monitor using OSA
Optical devices	• 8 × 8 PI-LOSS optical switch (Silica-based TOSW) • WDMX and WMUX: AWG
Equipment size	1 bay (6.5-foot rack)

AWG: Arrayed-waveguide grating
OSA : Optical spectrum analyzer

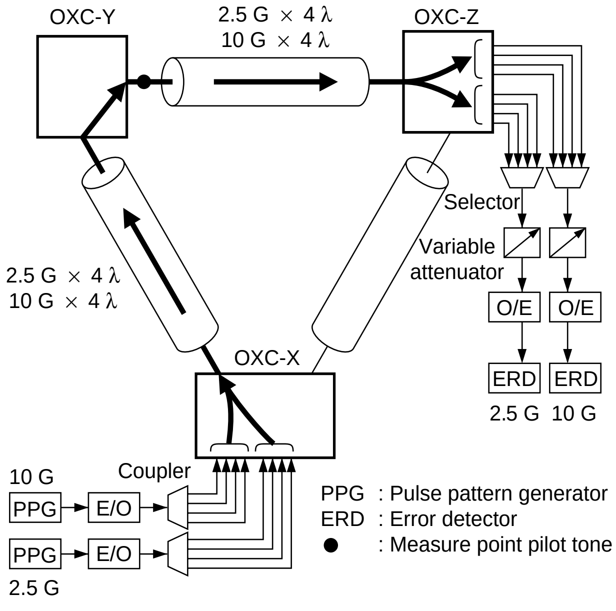
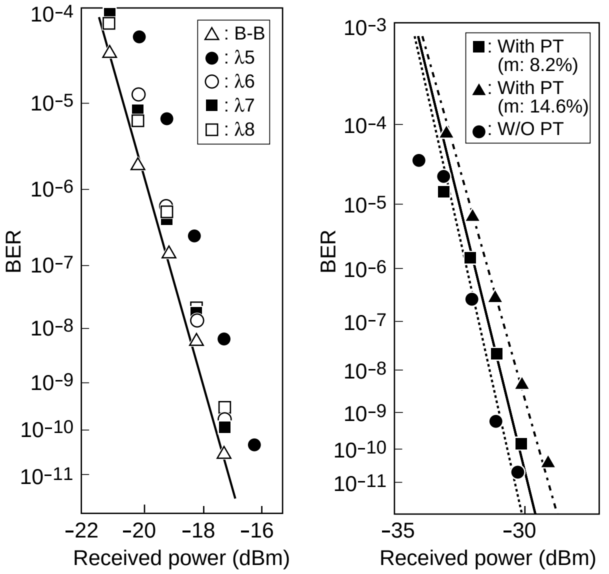


Figure 10
Evaluation setup for OXC.



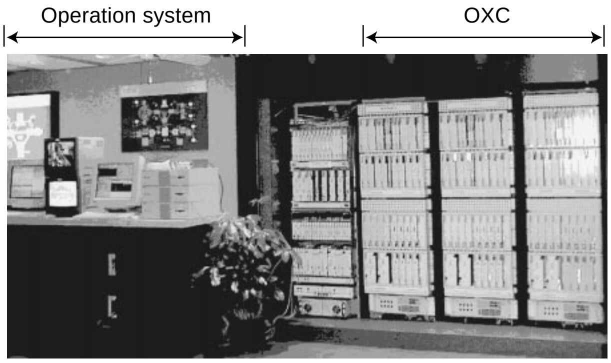
(a) 10 G signals

(b) 2.5 G signals with PT

Figure 11
BER characteristics.

larger the modulation index, *m*, the more the BER of the main signal is degraded, but the more the BER of the PT signal is improved. We therefore examined the relationship between *m* and the BER of the main optical signal. PT signals were superimposed on the 2.5 Gb/s optical signals in OXC-X. Then, the BERs of the main optical signal were measured for the non-overmodulated signal and the overmodulated signal with an *m* of 8.2% and 14.6%, respectively. Measurements showed that the power penalty at a BER of 10^{-11} was 0.5 dB for an *m* of 8.2%, and 1.5 dB for an *m* of 14.6% (**Figure 11(b)**). The PT signals were correctly detected by the PT receiver in OXC-Y. We suppose that a PT with an *m* of 10% will not interfere with the main signal very much, and we confirmed the optical path connection by using the PT scheme.

The prototype system was successfully demonstrated with an operation system in Supercomm'98. **Figure 12** shows a photograph of the prototype system at the event.



(June 9 -11, 1998)

Figure 12
Prototype OXC system at Supercomm'98 in Atlanta.

4. Summary

We are just at the beginning of photonic networking, which will enable the transfer of extremely large amounts of traffic over optical fiber and provide the foundation for efficiency, flexibility, and reliability in the next-generation backbone networks. The key network elements of OADM and OXC using advanced optical devices such as the AOTF and PI-LOSS SW are now being made available to provide efficient management of the optical path layer.

References

1) K. Sato, S. Okamoto, and H. Hadama: Network Performance and Integrity Enhancement with Optical Path Layer Technologies. *IEEE J-SAC*, **SAC-12**, 1, pp.159-170 (Jan. 1994).

2) GR-2979-CORE: Common Generic Requirements for Optical Add-Drop Multiplexers (OADMs) and Optical Terminal Multiplexers (OTMs). Issue 1, Bellcore, Apr. 1998.

3) H. Miyata, H. Onaka, K. Otsuka, and T. Chikama: Bandwidth and ripple requirements for cascaded optical (de)multiplexers in multiwavelength optical networks. Proc. OFC'97, TuE3, Feb. 1997.

4) T. Nakazawa, M. Doi, S. Taniguchi, Y. Takasu, and M. Seino: Ti: $LiNbO_3$ AOTF for 0.8 nm channel-spaced WDM systems.

OFC'98, PD1, Feb. 1998.
5) K. Otsuka, T. Maki, Y. Sampei, Y. Tachikawa, N. Fukushima, and T. Chikama: A high-performance optical spectrum monitor with high-speed measuring time for WDM optical networks. Proc. ECOC'97, pp.147-150, Sep. 1997.
6) M. Koga, A. Watanabe, S. Okamoto, K. Sato, H. Takahashi, and M. Okuno: Optical Path Cross-connect Demonstrator Designed to Achieve 320 Gbit/s. Proc. ECOC'96, ThC.3.1, Sep. 1996.
7) P. Granestrand, L. Thylen, B. Stoltz, K. Bergvall, W. Doldissen, H. Heidrich, and D. Hoffmann: Strictly nonblocking 8 × 8 integrated optic switch matrix in Ti: $LiNbO_3$. Proc. OFC'86, WAA3, Feb. 1986.
8) T. Simoe, K. Hajikano, and K. Murakami: A path-independent insertion loss optical space switching network. *Tech. Dig. ISS*'87, **4**, C12.2, pp.999-1003 (1987).
9) Y. Hamazumi and M. Koga: Transmission Capacity of Optical Path Overhead Transfer Scheme Using Pilot Tone for Optical Path Network. *IEEE J. Lightwave Technol.*, **15**, 12, pp.2197-2205 (Dec. 1997).
10) Proposed Overhead Channel Realization for Optical Layers: ITU-T SG15, Delayed Contribution, D. 68, NTT, Geneva, April 1997.
11) F. Heismann, M. T. Fatehi, S. K. Korotky, and J. J. Veselka: Signal Tracking and Performance Monitoring in Multi-Wavelength Optical Networks. Proc. ECOC'96, WeB.2.2, Sep. 1996.

Terumi Chikama received the B.S., M.S., and Ph.D degrees in Physics from the University of Tokyo, Tokyo, Japan in 1977, 1979, and 1982, respectively. Since 1982 he has been with Fujitsu Laboratories Ltd., Kawasaki, Japan, where he has been engaged in research and development of high-speed optical transmission systems, wavelength division multiplexing systems, and photonic networking. He is a member of the IEEE and the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

E-mail : chikama@flab.fujitsu.co.jp

Hiroshi Onaka received the B.S. degree in Electrical Engineering from KANAGAWA INSTITUTE OF TECHNOLOGY, Kanagawa, Japan in 1982. From 1982 to 1984 he was with the same university as a research associate. Since 1985 he has been with Fujitsu Laboratories Ltd., Kawasaki, Japan, where he has been engaged in research and development of coherent lightwave transmission and optical wavelength division multiplexing transmission systems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan and the Japan Society of Applied Physics (JSAP).

E-mail : onaka@flab.fujitsu.co.jp

Satoshi Kuroyanagi received the B.E. degree in Electrical Engineering from Nagoya Institute of Technology, Nagoya, Japan in 1986. He joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1986 and has been engaged in research of photonic switching systems and optical cross-connect systems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

E-mail : kuroya@flab.fujitsu.co.jp