3-4 Research and Development of High-Capacity Optical Link Technologies

FUKUCHI Kiyoshi, HATAKEYAMA Ichiro, ITO Toshiharu, and KURATA Kazuhiko

In order to accommodate the explosively increasing Internet traffic into trunk optical fiber network, there are several issues to be solved, such as effective transmission over long distance with high capacity data stream, and small-sized / low-power LSI interface for high capacity traffic routing chip. In this paper we demonstrate our developed ultra-dense WDM technology and transmission line design to enable 10 Tbps and/or thousand-wavelength WDM long-haul transmission system. Result of switch LSI module development with very small optical interfaces is also summarized that will enable very high capacity optical interconnection.

Keywords
Optical fiber communication, Wavelength division multiplexing, Terabit transmission, Photonic module technology, Optical interconnection

1 Introduction

In order to accommodate the explosive increase in data-communication demands emerging from the Internet, backbone and access networks are beginning to offer rapidly increasing speeds and bandwidths. Backbone networks are expected to provide for reduced transmission costs and flexible reconfiguration to variations in traffic through efficient multiplexing of high-volume traffic for long-haul transmission. Such transmission technology will ideally be based on an existing or highly feasible method. Yet in metropolitan-area networks connecting backbone and access networks, the processing speeds of the routers lead to a bottleneck, limiting any potential increase in network bandwidth. Processing speeds within the LSI switches constituting the routers may increase with the production process refinement of CMOS LSIs; however, the connection between the LSI and the external circuit and the interfaces between boards continues to pose problems in terms of increasing speed, reducing power consumption, and reducing the number of signal lines. High-speed optical interconnection technology is expected to resolve these problems.

This paper discusses the techniques that we have developed with regard to two technologies toward realization of broadband networks: a high-capacity trunk network transmission technology and an intra-module optical link technology. Discussing research and development of ultra-high-capacity wavelength division multiplexing transmission technology, we will describe experimental studies of ultra-high-capacity 10.9-Tbps transmission, thousand-wavelength wavelength division multiplexing (WDM) transmission, ultra-long-haul 40-Gbps 9,000-km transmission, and 5-Tbps optical link design featuring a simple transmission line structure. These represent our achievements to date in the implementation of ultra-high-capacity ultra-long-haul transmission and our progress toward technical deployment with a focus on practical applications. We have also conducted studies on a switch LSI module with built-in optical I/O as low-cost optical links, developing one such module offering a speed of 10 Gbps per channel. Here we will discuss the relevant elementary techniques: extremely small, low-cost optical I/O, 10-Gbps full-channel operation, and switching behavior in the CMOS switch LSI. We also discuss the optical interconnection when working with speeds on the order of 10 Gbps per channel.

2 Research and development of ultra-high capacity wavelength division multiplexing technology

2.1 Development of ultra-dense WDM transmission technology

To increase capacity in a trunk transmission system, it is necessary to increase the number of signals multiplexed within a single fiber. An effective method of doing so involves simultaneously increasing the signal speed—which increases the degree of time-division multiplexing—and the number of WDM wavelengths. However, high-capacity signal transmission requires a wide bandwidth, so we need to either extend the optical transmission bandwidth or to use higher density format such as the narrowband modulation technique. In the current study, we developed two technologies that will be required to reach the goal of 10-Tbps transmission using 40-Gbps signals.

The first consists of a dense multiplexing technique implemented by polarization division multi- and demultiplexing technology. When the channel separation of 40-Gbps signals in NRZ format, which is a simple modulation format, is reduced to 50 GHz, crosstalk between adjacent channels becomes a serious problem. Polarization division multiplexing technology multiplexes signals at the transmitter by setting the polarization states of adjacent channels orthogonal to each other; at the receiver, the polarization demultiplexing technique removes the crosstalk that remains after wavelength demultiplexing. An experimental evaluation confirmed that no degradation was observed after demultiplexing of multiplexed 40-Gbps signals with 50-GHz spacing.

The second involves optical bandwidth extension by the newly developed thulium doped fiber amplifier (TDFA)[1], which is an S-band optical amplifier for use near the wavelength of 1490 nm. The TDFA includes a thulium (Tm^{3+}) doped optical fiber medium pumped by semiconductor lasers. The TDFA provides an optical power conversion efficiency of more than 40 percent, which is equivalent in practicality to an erbium doped fiber amplifier (EDFA). We obtained an optical bandwidth of 107 nm with the TDFA, a C-band EDFA, and an L-band EDFA. Combining these technologies, we succeeded in a 100-km transmission of 10.9-Tbps (40 Gbps × 273 ch) capacity signals[2], as shown in Fig. 1.

On the other hand, high-capacity WDM transmission technology using large numbers of wavelengths will also be required in a net-

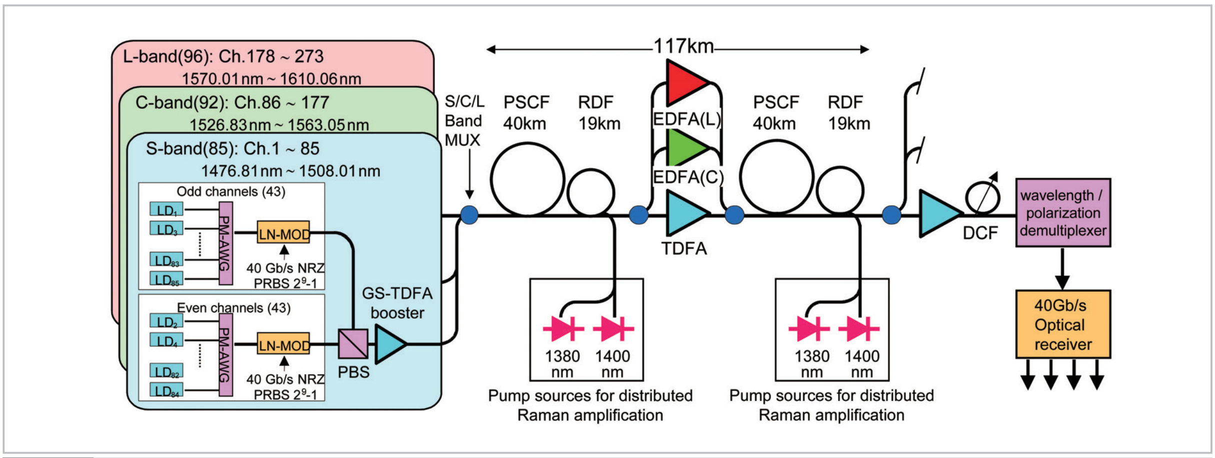

Fig. 1 *System configuration of 10-Tbps WDM transmission experiment*

work that takes full advantage of wavelength resources. Recent studies on thousand-wavelength WDM transmission are now making progress, as seen in the error-free transmission of 2.7-Gbps, 1,044-wavelength WDM signals over the JGN-Ⅱ optical testbed[3]. To employ the high-channel count WDM system in trunk transmission lines, not only the capacity extension but also a long-haul transmission will likely be required. For this reason, the current study aimed to realize a 10-Gbps-per-channel thousand-wavelength WDM long-haul transmission. To accommodate one thousand wavelengths seamlessly in the low-loss region of the optical fiber, we used an ultra-wideband lumped Raman amplifier that provides 100 nm bandwidth (approximately 125 THz) as a repeater amplifier[4].

Because in this case the channel spacing needs to be extremely narrow (12.5 GHz), the crosstalk between adjacent channels becomes the most severe problem, as in the case of the 10.9 Tbps WDM. In this study, we determined not to use polarization multiplexing. To demultiplex signals by only wavelength demultiplexing, a rectangular optical filter having an 11 GHz bandwidth and a 35-dB suppression ratio, consisting of multi-stage interleavers, was developed. We also optimized the modulation format and the multiplexing method to minimize the crosstalk penalty. We evaluated the NRZ and the duo-binary as modulation formats, and two multiplexing methods, polarization-aligned and polarization-interleaved multiplexing methods. Figure 2 shows the measured bit error rates after demultiplexing for different combinations of two modulation formats and two multiplexing methods. The combination of duo-binary and polarization-interleaved multiplexing minimized the degradation to approximately 1 dB, demonstrating the usefulness of this combination for long-haul transmission. Using these techniques, we conducted a 10-Gbps, 12.5-GHz-spaced, transmission experiment using the 100-nm-bandwidth lumped Raman amplifier repeater, and experimentally confirmed the feasibility of transmission in the 1,000-km range[5].

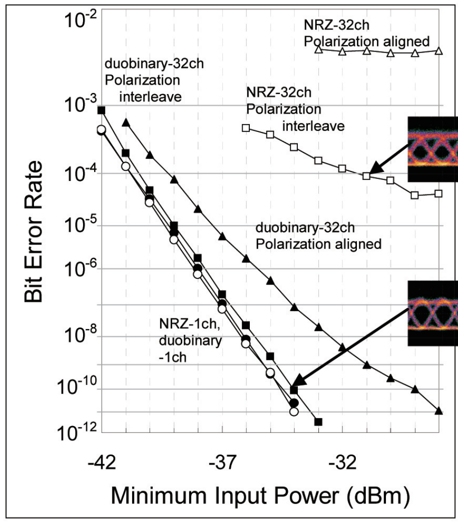

Fig.2 *Bit error rate characteristics of various high-density multiplexing methods for 10-Gbps, 12.5-GHz-interval transmission*

2.2 Ultra-long-haul optical fiber transmission technology

40-Gbps high-capacity transmission demands high launch power for the signal light, and because of the high signal power and higher signal speed, the signal suffers larger degradation due to distortion by the nonlinear effects of the optical fibers. To address these problems, in the current study we developed a large-core-diameter pure silica core fiber with an effective core area (Aeff) extended to 195 μm^2 (abbreviated below as the "195-μm^2-Aeff PSCF")[6]. In combination with the distributed Raman amplification technology, we successfully constructed a transmission line featuring an extremely small degree of nonlinearity. Figure 3 (a) shows the configuration of the transmission line, which we called the "inverse double alternating connection" configuration: a 195-μm^2-Aeff PSCF with low loss and small Raman gain, placed at a position in the second half of the line and a DCF placed at a position in the first half of the line. With this configuration, the loss and the gain thus became approximately equivalent, as shown in Fig. 3 (b). This configuration

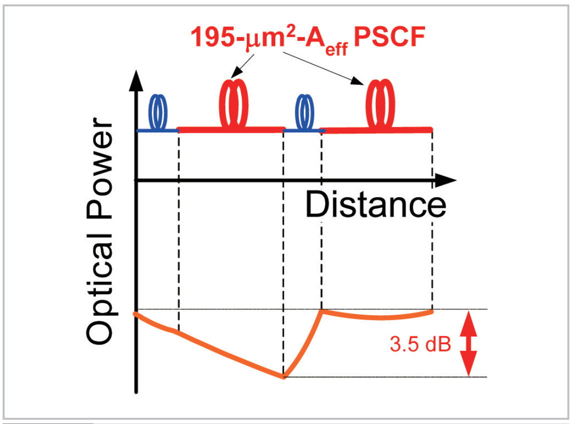

Fig.3 Configuration of transmission line with low nonlinearity

reduces power variation in the span to as low as 3.5 dB, which in turn significantly reduces the power input to the transmission line.

We evaluated the transmission characteristics of the inverse double alternating connection transmission line constructed with a 195-μm^2-Aeff PSCF to verify its ability to reduce nonlinear effects. The wavelength of the 32 DFB-LD light sources ranged between 1539 nm and 1563 nm with 100 GHz spacing, and they were modulated by the CS-RZ modulation format at 42.7 Gbps and then multiplexed to be the polarization-interleaved multiplexing. For distributed Raman amplification in the 50-km transmission line, we used a four-wavelength WDM pumping light source with wavelengths of 1424 nm, 1437 nm, 1449 nm, and 1465 nm. The total power was 650 mW. Figure 4 shows the optical spectrum of the signal after 9,000-km transmission. The signal-to-noise ratio of the optical signal is uniform and the signal spectrum is not very broad. These features indicate the effective suppression of nonlinear effects. When decoded by the error correction IC, all 32 wavelength signals were confirmed to be error-free. This represented the first demonstration of 40-Gbps WDM transmission over a distance equivalent to the trans-Pacific distance.

Although the transmission line described above offers high performance with extremely low nonlinearity, it also presents problems in practical application in that it is constructed with four fibers per span and features a relatively short actual span length of 50 km. To address these problems, we set as a goal the establishment of both a simpler transmission line and a longer span length; these efforts led to the development of a medium-distribution distribution management fiber (MD-DMF)[7]. The MD-DMF consists of a positive fiber and a negative fiber, each featuring medium local dispersion of around 14 ps. The length of the positive dispersion fiber is approximately 51 km, and the negative dispersion about 29 km. The Aeff of the positive distribution fiber is 120 μm^2; this large value enabled a smaller nonlinear effect, reduced loss, and produced a flat dispersion characteristic. Figure 5 shows the results of measured loss for all five spans of the developed 80-km MD-DMF. The loss value obtained is 19 dB over the C- and the L-band. We evaluated the performance of 40-Gbps, 100-GHz-spaced, 32-channel transmission over the C-band. The RZ-DPSK format was employed as a modulation format. We obtained the Q-factor shown in Fig. 6 with optimized signal output power of 0 dBm/ch. The evaluation confirms that the MD-DMF transmission line can enable transmission in

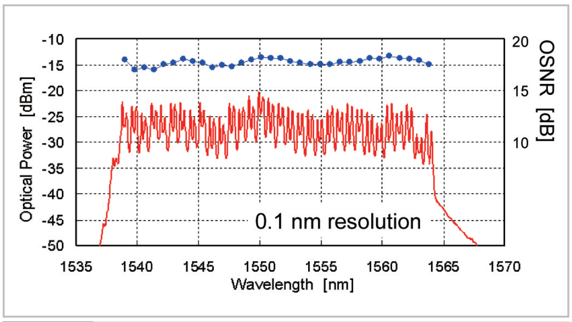

Fig.4 Optical spectrum after transmission over 9,000 km

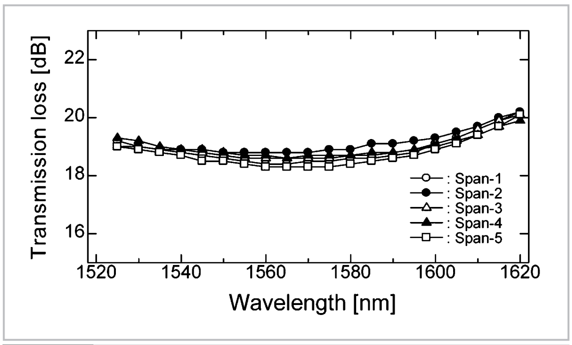

Fig.5 Loss characteristics of MD-DMF

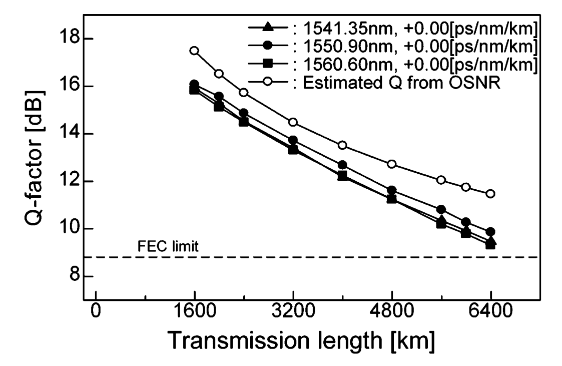

Fig.6 Transmission characteristics of MD-DMF

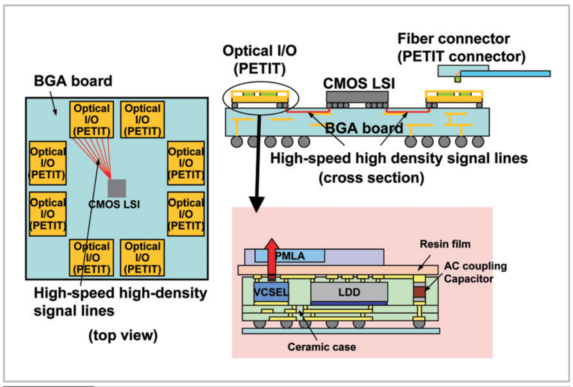

Fig.7 Conceptual illustration of switch LSI module with built-in optical I/O

the range of 6,000 km even with an 80 km span length. These results attest to the effectiveness of our transmission line design technology.

3 Research and development of switch LSI module with built-in optical I/O

In order to improve the processing speed of routers, which are at the heart of the bottlenecks preventing application of broadband technology to the entire network, it is not enough to increase the processing speed within the LSI switch. It is also important to avoid an increase in the number of signal lines and to lower power consumption by increasing the speed of the interfaces linking the LSI, the board, and the cabinet. To address these problems, we attempted to develop a switch LSI module with built-in optical I/O—specifically, a switch LSI module containing optical input/output interfaces (referred to below as "optical I/O") within the package, with a port speed of 10 Gbps per channel.

Figure 7 shows the concept of the switch LSI module with built-in optical I/O. The BGA board is equipped with a CMOS switch LSI and an extremely small optical I/O (or PETIT, for "photonic/electric tied interface"), which performs optical-to-electrical conversion. The optical I/O integrates four channels each for transmission and receiving. For its optical devices, the PETIT contains a VCSEL (vertical-cavity surface-emitting laser) for a wavelength of 850 nm and a PIN-PD (PIN-Photodiode). The VCSEL and the PIN-PD are connected by a fiber connector which has been specially developed for the PETIT. This module uses optical fibers for the high-speed input and output signals, such that the system can be constructed on an inexpensive printed-wiring board. As the optical I/O is small, the distance of electrical transmission to the LSI on the BGA board is short, and the module does not require waveform degradation correction circuits. This in turn reduces power consumption.

We carried out detailed design of this switch LSI module featuring built-in optical I/O. For the platform of the optical I/O (PETIT), we selected a low-cost, low-dielectric constant, low-loss resin film[8]. We used an optical coupling system with the resin film as the reference, for simplicity and efficiency. The highly precise flip-chip bonding technique[9] is applied to mount the optical devices. To decrease crosstalk between the transmitter side and receiver side, we constructed a complete box structure for electromagnetic shielding. To decrease crosstalk between the channels in the transmitter side or the receiver side, we used coupled lines as electrical transmission lines. We used PETIT connectors[10] to connect the optical I/O (PETIT) and the fibers. Figure 8 shows the configuration of the developed ultra-small optical I/O. The volume of the entire PETIT is only 294 mm^3 (14 mm × 14 mm × 1.5 mm).

To evaluate the minimum receiver sensitivity and the amount of crosstalk, we measured the bit error rate of the developed low-cost optical I/O for three different cases: transmitter only, receiver only, and simultaneous transmitter and receiver. For the test signal, we used a 10.3125-Gbps, (2^7-1)-PRBS signal. Figure 9 shows the transmitter optical output waveform and receiver electric output waveform. We confirmed clear eye patterns for all channels. Figure 10 shows the receiving characteristics of the optical I/O. When a single channel was operated, we obtained minimum receiver sensitivity of −9 dBm, which yields an error rate of 10^{-12}. The crosstalk penalty when all four channels were operated was small: 1.0 dB at the transmitter, 1.0 dB at the receiver, and 0.6 dB between the transmitter and the receiver.

We developed a prototype switch LSI module with built-in optical I/O using ultra-small 10-Gbps optical I/O and a 20 × 20 cross-point switch LSI. We operated a prototype module using 10.3125-Gbps, (2^7-1)-PRBS optical signals (extinction ratio of 3 dB) and checked the waveforms by switching the output signals. We obtained clear output waveforms from all four channels. Using the Advanced TCA (or "ATCA") standard rack and a fiber sheet compatible with this rack in the backplane, we also developed a simplified prototype switching system using a switch card installed in the developed module and vertical optical connectors for connecting the card (Fig. 11). We evaluated the device and confirmed backplane optical interconnection. This experiment demonstrates the effectiveness of the low-cost, small optical link.

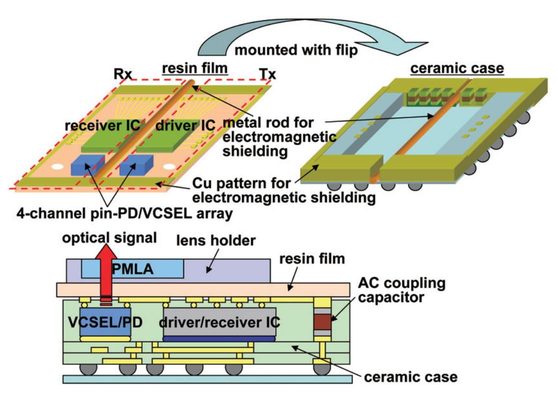

Fig.8 Configuration of ultra-small optical I/O

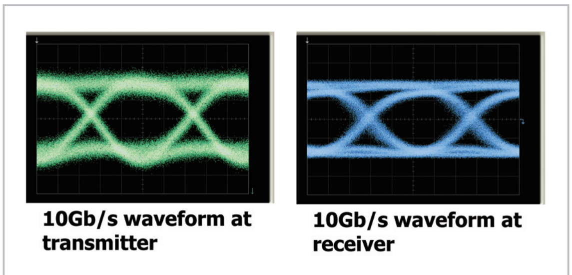

Fig.9 Transmitter and receiver waveform of optical I/O

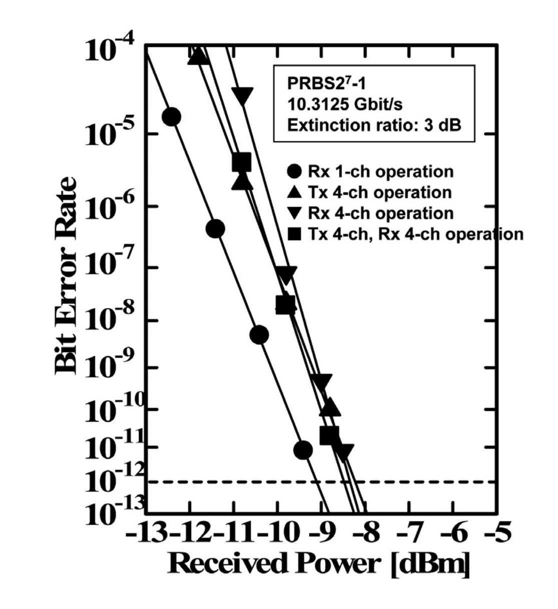

Fig.10 Receiving characteristics of optical I/O

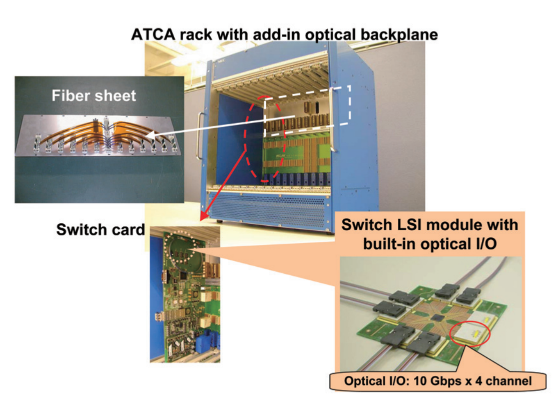

Fig.11 Simplified switching system using ATCA standard rack

4 Conclusions

This paper discussed achievements in research and development of high-capacity transmission technology and the low-cost optical link technology, which will be required in the implementation of wideband optical networks. We developed ultimate technologies in 10.9-Tbps transmission, as well as 40-Gbps, 9,000-km, thousand-wavelength WDM transmission, at the same time developing technologies for practical applications in the establishment of a 5-Tbps optical link transmission line. We implemented low-cost small optical technologies in the development of the switch LSI module equipped with built-in optical I/O. We anticipate advancing these technologies even further, with the aim of helping to bring about the highly reliable, flexible optical network expected in the future.

Acknowledgments

This work was supported by National institute of Information and Communications Technology (NICT).

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FUKUCHI Kiyoshi

System Platforms Research Laboratories, NEC Corporation

High-Capacity Optical Fiber Communication

HATAKEYAMA Ichiro

System Platforms Research Laboratories, NEC Corporation

High-speed Optical Sub-System

ITO Toshiharu

System Platforms Research Laboratories, NEC Corporation

High-Capacity Optical Fiber Communication

KURATA Kazuhiko

System Platforms Research Laboratories, NEC Corporation

High-speed Optical Sub-System