3-3 EA Modulator Based OTDM Technique for 160 Gb/s Optical Signal Transmission

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Ultra high-speed signal transmission at a bit rate of 160 Gb/s is one of key technologies to construct next generation ultra high-capacity optical network. In the “Research and Development on Ultrahigh-speed Backbone Photonic Network Technologies” project, promoted by NICT, we have developed 160 Gb/s optical multiplexing/demultiplexing techniques with a capability for practical use. In this report, we describe the overview of the 160 Gb/s OTDM technologies based on EA modulators, and we also discuss the applicability of the OTDM techniques to real system, reviewing 160 Gb/s field transmission experiment on JGNⅡ optical testbed.

Keywords
OTDM, Ultra high-speed optical transmission, EA modulator, JGNⅡ optical testbed, Field transmission experiment

1 Introduction

As a result of the growth of broadband communications through the spread of ADSL (Asymmetric Digital Subscriber Line) and FTTH (Fiber to the Home) technologies, we can expect to see a rapid increase in the communication capacities of backbone optical networks. Meanwhile, many researchers have been conducting studies on DWDM (Dense Wavelength Division Multiplexing), which expands communication capacity by accommodating more wavelength channels densely in a single fiber. Today, 40-Gb/s-based DWDM optical transmission technology has entered the stage of practical application and is gaining attention as a next-generation ultra-high-capacity optical transmission system to replace current commercial 10-Gb/s optical transmission systems. At the same time, research and development of 160-Gb/s optical transmission systems is gradually spreading, mainly in Japan and Europe, on the view that these systems will allow implementation of high-capacity DWDM with a small amount of wavelength multiplexing and easy wavelength management. In particular, we have seen the recent introduction of the DPSK (Differential-Phase-Shift-Keying) modulation format, which offers better receiver sensitivity than the conventional IM/DD (Intensity-Modulation/Direct-Detection) modulation format. Such techniques have significantly improved the transmission performance of ultra-high-speed transmission. Following upon these developments, many field experiments for 160-Gb/s transmission have been conducted in laboratory facilities using installed optical fiber cables[1]-[4]. One widely used method for transmitting and receiving ultra-high-speed signals at a transmission rate of 160 Gb/s (regardless of the modulation format) is seen in the OTDM (Optical Time Division Multiplexing) technique. The OTDM technique performs time-domain multiplexing and demultiplexing of two or more optical data sequences that have the same wavelength. In principle, this method does not depend on the processing speeds (normally approximately 100 Gb/s) of electronic devices and can generate ultra-high-speed signals at a single wavelength, the speed depending on the extent of multiplexing. Important elemental techniques for OTDM signal generation include ultra-short optical pulse generation, which prevents interference between multiplexed optical data; and optical time division multiplexing, which bit-interleaves individually data-modulated optical signals. For signal reception, OTDM also requires a clock extraction technique, which extracts the system clock synchronized to the OTDM signal; and optical demultiplexing, which extracts multiplexed channels without crosstalk. In the "Research and Development on Ultrahigh-speed Backbone Photonic Network Technologies" project underway at NICT (National Institute of Information and Communications Technology), we have conducted studies to develop a high-performance, practical OTDM transmitter-receiver. In the course of this project we have been working on the development of 40-GHz ultra-short optical pulse generation technique and 4 × 40-Gb/s optical multiplexing/demultiplexing technique using EA (electroabsorption) modulators offering superior operability and stability. As a result of these efforts we have succeeded in producing a high-quality, highly stable prototype 160-Gb/s OTDM transmitter-receiver[5].

In this report, we present an overview of 160-Gb/s optical time division multiplexing and demultiplexing techniques based on the use of EA (electroabsorption) modulators. To demonstrate the practicability of the developed 160-Gb/s OTDM transmitter-receiver, we have also conducted a field transmission experiments using the JGNⅡ (Japan Gigabit Network Ⅱ) optical testbed. Based on the results of the field experiment, we were able to identify problems in implementation of the 160-Gb/s transmission system.

2 160-Gb/s Optical Time Division Multiplexing technique[5]

Figure 1 shows the configuration of the 160-Gb/s OTDM transmitter-receiver. The equipment consists of an ultra-short optical pulse source and a time division multiplexer, which encodes optical pulse-trains according to input electrical data signals and converts these into the OTDM signal. The optical pulse source is required to stably generate uniform optical pulses at a constant rate of repetition (i.e., with low jitter performance). In order to conduct time division multiplexing without causing inter-symbol-interference, the optical pulses must be ultra-short, at <3 ps, and a high pulse extinction ratio (>35 dB) is also required. The mode-locked laser diode (MLLD) is a representative optical pulse

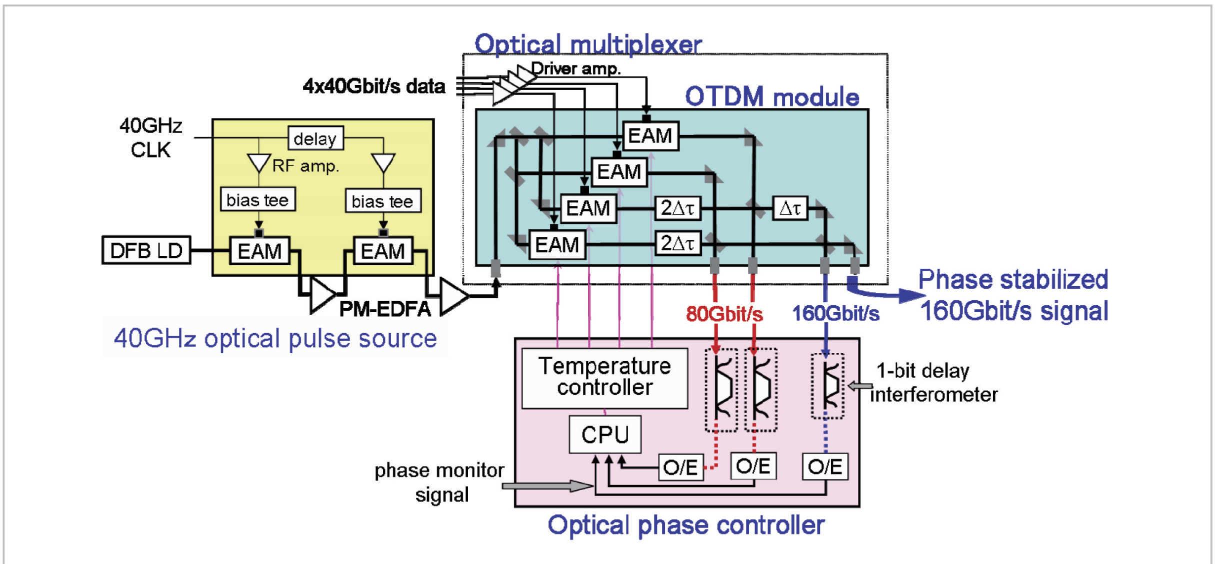

Fig.1 *Configuration of 160-Gb/s OTDM transmitter*

source known to satisfy these conditions[6][7]. However, as the repetition rate depends on the laser cavity length, the MLLD needs to be designed taking system clock frequency into account. Meanwhile, we have been investigating the external modulation optical pulse source using EA (electroabsorption) modulators, with particular attention to flexibility in operation. The optical pulse generation with the external modulation supports arbitrary clock frequencies in principle and can generate extremely stable optical pulses using low-jitter modulation signals. Here, the system uses two EA modulators connected in series to generate optical pulses that can be applied to the 160-Gb/s OTDM signal. The two EA modulators are driven by the 40-GHz clock signals with adjusted timing and convert the input CW (Continuous Wave) beam into Gaussian pulses with a FWHM (Full-Width-Half-Maximum) of approximately 3 ps. The 40-GHz optical pulse train is sent to the optical time division multiplexing circuit and is converted into 160-Gb/s OTDM signal. The OTDM circuit performs data modulation for each multiplexed channel individually, thus requiring multiple optical modulators. A 160-Gb/s OTDM circuit with a basic rate of 40 Gb/s requires four optical modulators. It is important that these modulators be efficiently installed within a compact package. Accordingly, we have developed an OTDM circuit based on a free-space integration technology, which we determined would accommodate the optical modulators relatively easily. Figure 2 shows a general view of the OTDM circuit. The optical modulators adopted are EA modulators, which are small and offer high-speed modulation. The four EA modulators are individually encapsulated in airtight packages to secure stability and reliability in modulation and are placed in four deferent spatial paths composed of half mirrors and prisms. The modulators each convert the 40-GHz optical pulse-trains into 40-Gb/s optical signals. Each of the four 40-Gb/s optical signals is sequentially bit-interleaved to 80 Gb/s and then to 160 Gb/s, and two sets of 80-Gb/s signals and 160-Gb/s signals are then output. The OTDM module offers delay time accuracy of 6.28 ps ±0.01 ps and insertion loss of 18 dB. This OTDM module is unique in that the optical phase difference between adjacent bits (i.e., the carrier-phase difference) is variable. The optical phase difference is an important parameter that influences the degree of fiber non-linear effects, which are among the factors leading to degradation of transmitted signals. Generally, an OTDM method that multiplexes four or more optical signals has difficulty stabilizing optical phase between multiplexed signals propagating different paths. This module adopts a free-space integration technology and has suppressed variation in the optical phase difference between adjacent bits within 5°/°C (environmental temperature). By changing the driving temperature of the EA modulators, which exhibit the thermo-optic effect, it is also possible to set an arbitrary optical phase difference between adjacent bits. In this way, it is now possible to apply a superior modulation format even to 160-Gb/s signals, including CS-RZ (Carrier Suppressed Return to Zero)[8], which is effective in reducing signal degradation due to fiber non-linearity. Figure 3 shows the optical spectrum (a) and optical sampling (b) of 160-Gb/s CS-RZ signals generated using the developed transmitter. Each of the four multiplexed 40-Gb/s signals is a PRBS (Pseudo-Random-Bit-Sequence) signal with a data length of $2^{15}-1$. The optical phase difference between adjacent bits of the CS-RZ signals rotates 180° every bit, so that

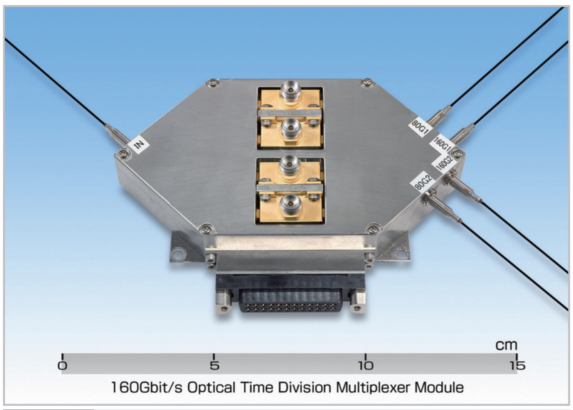

Fig.2 160-Gb/s OTDM module

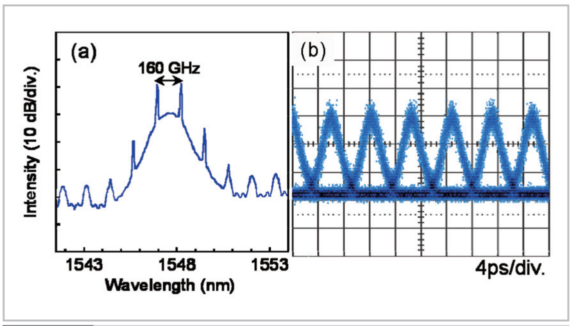

Fig.3 *Optical signal spectrum (a) and optical sampling waveform (b) of 160-Gb/s OTDM CS-RZ signals*

the optical spectrum exhibits a characteristic shape, with suppression of the center carrier components. From the shape of the optical sampling waveform, the uniformity and well-defined eye-opening of the generated 160-Gb/s signals are clear.

This transmitter features an automatic optical phase control function to generate stable phase control signals even in environments of wide shifts in temperature[9]. To detect the phase difference between adjacent bits of the OTDM signals, a 1-bit-delay interferometer is used. This system makes use of the characteristic change in the output level of the 1-bit-delay interferometer according to the phase difference. Here the phase differences between adjacent bits of the 80-Gb/s and 160-Gb/s OTDM module output signals are quantified separately and the driving temperature of the EA modulators in the OTDM module is controlled to obtain the desired phase difference. Figure 4 shows the optical signal spectrum of the 160-Gb/s CS-RZ signals measured continuously for 12 hours. The environmental temperature (i.e., the laboratory temperature) changed between 22˚C and 30˚C during the period of the experiment. Nevertheless, the spectral form showed very little change, thanks to the automatic phase control. Here, the fluctuation of the optical phase is 180˚±5˚, which demonstrates the stability of the generated 160-Gb/s CS-RZ signals.

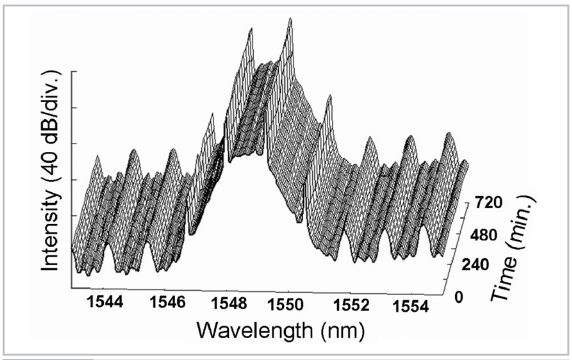

Fig.4 *Results of 12-hour continuous measurement of CS-RZ signal spectrum*

Figure 5 (a) shows the configuration of the 1:4-time division demultiplexer. After the 160-Gb/s signals are demultiplexed by the demultiplexing gate with the EA modulators driven at 40 GHz, they are sent to the 40-Gb/s receiver and detected. The time width of the demultiplexing gate is approximately 4 ps. The suppression ratio of the adjacent channels in the 40-Gb/s demultiplexing signal is 15 dB or greater. The 40-GHz clock synchronized to the input 160-Gb/s signals is extracted using the opt-electronic hybrid phase-locked loop circuit, as shown in Fig. 5 (b)[10]. The input 160-Gb/s signals are sampled at a frequency of 40−Δf GHz by the EA modulators installed in the front of the device. The phase difference of the local oscillator signal (LO, Δf = 250 MHz) is detected using the beat signal at the frequency of 4×Δf (= 1 GHz) contained in the output signal as the reference signal. The result of the phase comparison is sent to the 40-GHz VCO (Voltage Controlled Oscillator)

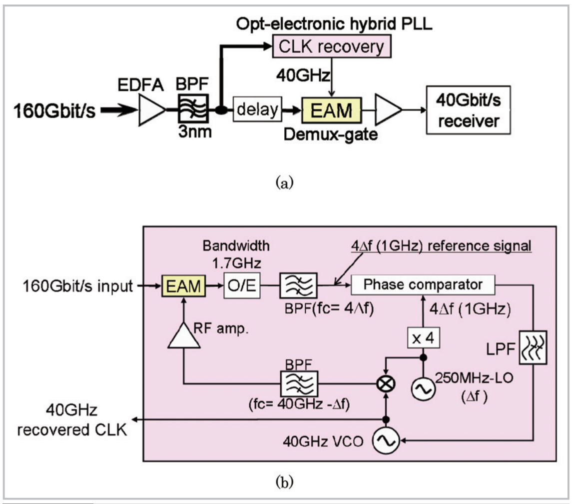

Fig.5 *(a) Configuration of 1:4-optical time division demultiplexer and (b) configuration of 40-GHz clock extraction unit*

as the control signal. By controlling the VCO output frequency such that the reference signal and the local oscillator signal have the same phase, the 40-GHz clock synchronized to the input 160-Gb/s signal is extracted. The RMS time jitter of the recovered 40-GHz clock is approximately 60 fs. The synchronization capture range is 12 MHz, and the locking range is 1.2 MHz. The EA modulators used in clock extraction and the demultiplexing gate are designed to respond to the input optical signals in an arbitrary polarization state, so that they are polarization-insensitive as receivers. There is a concern that the clock extraction function may degenerate due to the way the unit is designed when the signal waveform is distorted by chromatic dispersion or PMD (Polarization Mode Dispersion). However, laboratory experiments and the field transmission experiment described later have demonstrated that the system operates stably within a range of chromatic dispersion between −5 Ps/nm and 5 Ps/nm and within a range of DGD (differential group delay) by PMD between 0 Ps and 3 Ps. Thus in practice the system does not present a problem in terms of this concern.

The back-to-back performance of the developed equipment was evaluated in terms of the Q-factor estimated based on the measurement of BER (Bit Error Rate) for each of the four 40-Gb/s demultiplexing signals. We confirmed that the equipment provides a Q-factor of 27 dB or more for all demultiplexing channels. This value corresponds to a BER value of 10^{-100} or less, attesting to excellent back-to-back performance. Favorable results were also obtained in terms of system stability, an essential factor in practical applications. Figure 6 illustrates stability in back-to-back performance evaluated based on over four hours of continuous Q-factor measurement for the 40-Gb/s demultiplexing signals. Although fluctuations in the Q-factor of approximately 1.3 dB were noted, due mainly to measurement error, the figure reveals an extremely stable Q-factor of 27 dB on average. A similar evaluation in the wavelength range of

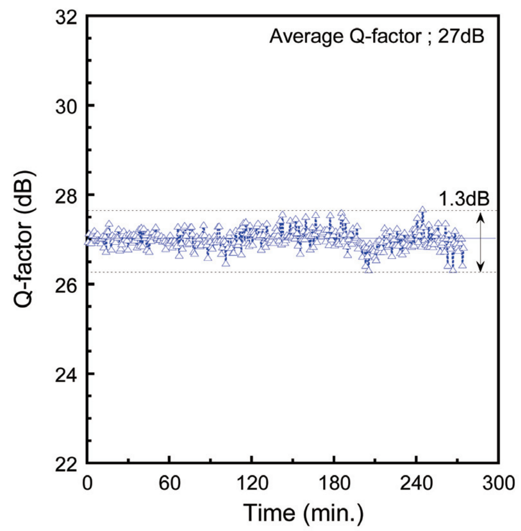

Fig.6 Results of evaluation of stability in 160-Gb/s back-to-back performance

1,540 nm to 1,560 nm also shows equivalent back-to-back performance. The device is designed to meet the requirements of WDM transmission flexibly, with a basic rate of 160 Gb/s.

3 160-Gb/s field trial on JGNⅡ (Japan Gigabit Network Ⅱ) optical testbed

Due to its wide signal band, (at or over 1 nm in a 3-dB band), 160-Gb/s transmission responds sensitively even to slight residual dispersion in the optical transmission line, leading to degradation in transmission characteristics. Waveform degradation due to non-linear effects also become conspicuous, which restricts the input level into the optical fibers and makes it more difficult to maintain a sufficient SNR (Signal to Noise Ratio) over a long distance. We have already experimentally confirmed that applying the CS-RZ modulation format to 160-Gb/s signals can reduce degradation of transmission performance caused by residual dispersion and the non-linear optical effects of the optical fibers. We conducted a re-circulating loop transmission experiment in the laboratory demonstrating error-free

(BER<10^{-9}) transmission over 640 km (8 × 80 km) without the use of FEC (forward-error-correction)[5]. On the other hand, for ultra-high-speed transmission of up to 160 Gb/s, the degradation in transmission characteristics due to PMD of the optical fiber transmission line represents a serious problem. Among other experiments, a field transmission experiment using installed optical fiber cables has demonstrated the necessity of applying the PMD compensation technique[1]-[4]. Unlike in relatively stable laboratory environments, for installed optical fibers in actual use, PMD and chromatic dispersion varies according to external factors such as weather conditions[1]. For practical applications, the desired transmission characteristics must be maintained under circumstances in which the optical fiber characteristics are subject to continuous change. As the final achievement of the “Research and Development on Ultrahigh-speed Backbone Photonic Network Technologies” project, which ended in 2005, we performed a field transmission experiment using the JGNⅡ optical testbed and verified the practicability of the developed 160-Gb/s transmission technique. Figure 7 shows the network configuration of the optical testbed and the experimental transmission system. The optical testbed consists of 10 standard SMFs (Single Mode Fibers) installed between the Keihanna Human Info-Communication Research Center (Seika Town, Kyoto) and the Dojima Base Station (Dojima, Osaka). Each transmission line is 63.5 km long, offering a maximum total connected length of 635 km, with five loop-back paths. Five sets of optical amplifiers (EDFAs, or Erbium Doped Fiber Amplifiers) are installed at Keihanna and Dojima to form a 10-span link structure with a repeater spacing of 63.5 km. The transmission loss per span is approximately 15 dB. The optical amplifier has a two-stage configuration with a DCF (Dispersion Compensating Fiber) between the stages. Management of settings such as output signal level is integrated at the Keihanna facility. Here, the signal input levels into the SMF and the DCF are set at 4.5 dBm and 1 dBm, respectively. The residual dispersion per span is typically +10 Ps/nm, and compensation for dispersion slope is nearly 100%-compensated. Chromatic dispersion over the entire transmission line is adjusted at 0 Ps/nm, with the additional DCFs installed at input-end and output-end of the transmission line. Slight pre-compensation of the dispersion (performed by installing a DCF prior to transmission) also helps reduce signal degradation attributable to fiber non-linearity. A PMD compensator (PMDC) is placed directly in front of the receiver. The PMDC features the first-order PMD compensation scheme consisting of a polarization controller, a tunable DGD generator, and a monitor to detect the degree of polarization (DOP). The PMDC compensates for PMD by adjusting the polarization of the

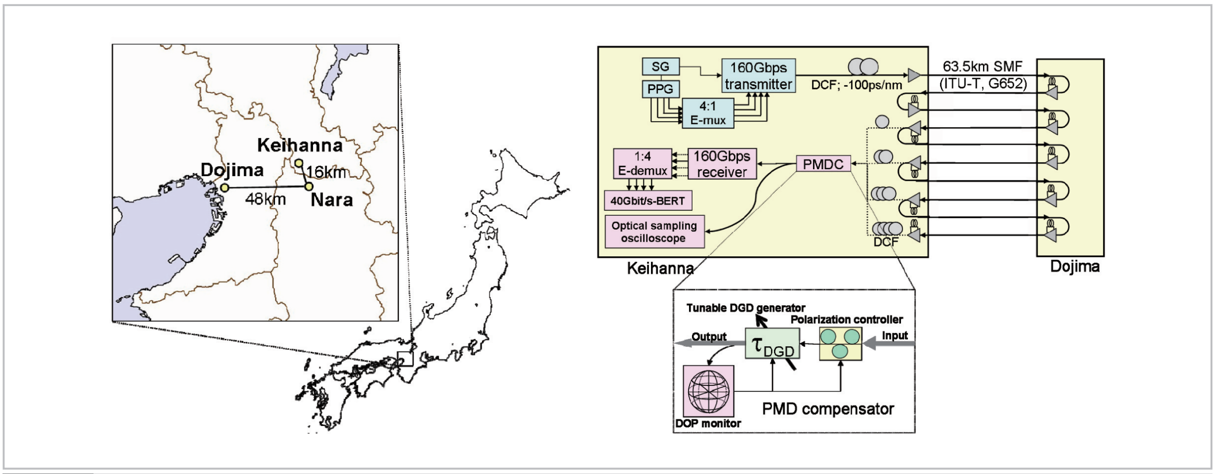

Fig.7 Configuration of JGNⅡ (Japan Gigabit Network Ⅱ) optical testbed and the experimental system

input signals and the extent of DGD generation, maximizing the DOP of the output signals. In the experiment, the PMDC was controlled manually.

Figure 8 shows the results of Q-factor measurement performed every 127 km from 254 km to 635 km. The Q-factor was evaluated for all tributary channels demultiplexed to 40 Gb/s from 160 Gb/s. We obtained good transmission characteristics with a Q-factor of 16.2 dB (BER<10^{-10}) on average over a transmission distance of 508 km, which corresponds to the distance between Tokyo and Osaka. The Q-factor was estimated at 15.7 dB (BER approximately 10^{-9}) on average even after transmitting over 635 km. Figure 9 shows the optical sampling waveforms after transmitting the signals over 508 km and over 635 km, as observed by an optical sampling oscilloscope following PMD compensation.

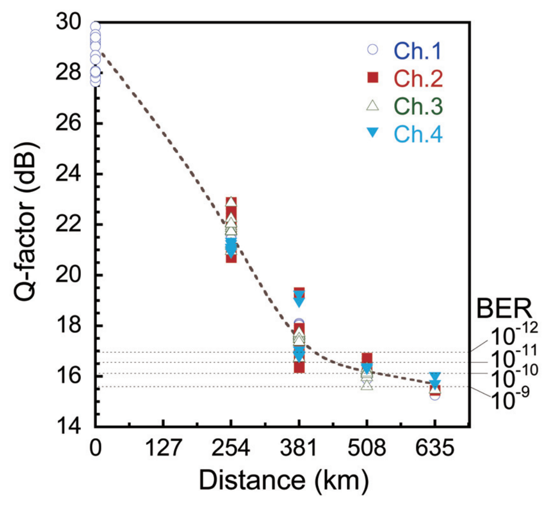

Fig.8 *Results of Q-factor measurement at each transmission distance*

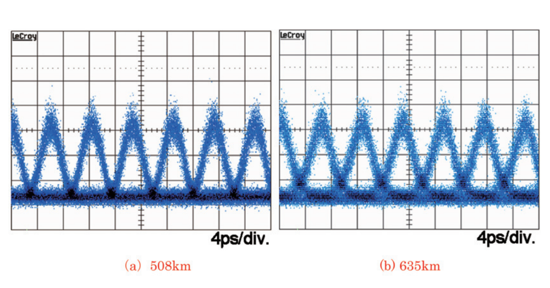

Fig.9 *Optical sampling waveforms of 160-Gb/s transmission signals*

Both waveforms indicate clear eye-opening. On the other hand, the transmission characteristics varied with time even at the same transmission distance, causing fluctuations in the Q-factor. This is mainly due to the fact that the effects of PMD on transmission characteristics change according to the external environment. It has been confirmed that the amount of DGD generation due to PMD changes from 3 Ps to 7 Ps at maximum at a transmission distance of 635 km. Figure 10 shows the results of continuous Q-factor measurement at transmission distances of 381 km and 508 km. The arrows indicate the time at which the PMD compensator was readjusted in response to Q-factor degradation. In both cases, the PMD compensator required readjustment after 10 to 20 minutes in order to maintain satisfactory transmission characteristics. Nevertheless, the results indicate that introducing the automatic PMD compensation technique will secure the long-term stability required for practical applications. In terms of the accuracy of PMD compensation, experiments and simulations have indicated that the degradation of signal quality is slight with a DGD of 1 Ps or less. For these reasons, we have concluded that the adaptive PMD compensation technique, which is technically mature as a 40-Gb/s transmission technology, can meet the necessary requirements. In the same vein, although this experiment did not lead to the detection of any distinct effects, it has been reported that the effects of higher-

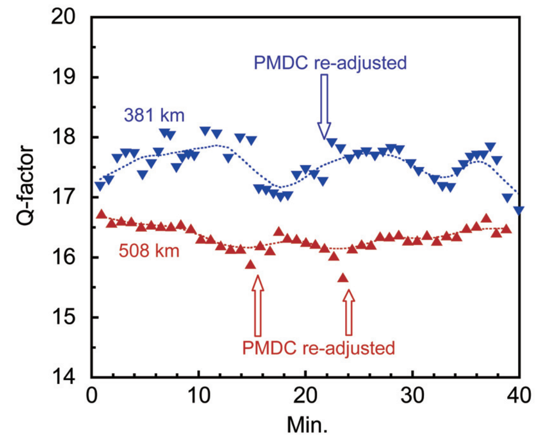

Fig.10 *Stability of transmission characteristics*

order PMD are also serious in 160-Gb/s long-distance transmission[3]. We believe that design of the transmission system must take these possible effects into consideration as well.

At the same time, in addition to the evaluation of the transmission characteristics with PRBS signal, we believe that comprehensive system evaluation is required, including an assessment of signal processing for accommodating real data in 160-Gb/s optical signals. Accordingly, we have also performed a transmission experiment, as part of a comprehensive field transmission experiment, for 160-Gb/s optical signals incorporating high-definition image data, as part of a collaborative project with the University of Electro-Communications. This experiment demonstrated stable demodulation of images after 254 km of transmission with quality equivalent to that of the transmitted images[11]. This represents the first field transmission experiment anywhere for 160-Gb/s optical signals carrying actual data and is a significant first step toward practical applications.

4 Conclusions

160-Gb/s ultra-high-speed optical transmission is expected to become an important fundamental technology in the construction of next-generation high-capacity optical networks. Accordingly, we have been developing 160-Gb/s optical time division multiplexing/demultiplexing techniques based on EA (electroabsorption) modulators, focusing on practicality and operability. In the course of our activities, we have developed a free-space integrated OTDM module that supports individual data modulation for all multiplexed signals and have established a technique for generating stable and high-quality 160-Gb/s OTDM signals while maintaining practicability. These are regarded as core technologies for generating ultra-high-speed OTDM exceeding the processing speeds of electronic devices. CS-RZ is an example of a superior modulation format suitable for ultra-high-speed transmission. We have also enabled the introduction of such formats into 160-Gb/s signals, taking advantage of the stable carrier phase, a characteristic of a space-integrated OTDM module. In a field transmission experiment using the JGNII optical testbed connecting the Keihanna Human Info-Communication Research Center (Seika Town, Kyoto) and the Dojima Base Station, we have demonstrated satisfactory 160-Gb/s ultra-high-speed long-distance transmission over 635 km and succeeded for the first time anywhere in a 254-km transmission experiment with 160-Gb/s signals containing high-definition image data.

Minor problems remain, such as the long-term stability of transmission performance. However, along with rapidly progressing optical signal processing techniques—involving modulation format, adaptive chromatic dispersion, PMD compensation, and 3R signal regeneration—we are optimistic that efforts toward practical application of our ultra-high-speed transmission system will soon yield results.

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