3 Photonic Network Technology

3-1 Ultrafast 160 Gb/s-based Transmission Experiment on JGNⅡ

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We have been investigating basic technology to establish a Peta-bit/s class photonic network, such as ultrafast photonic processing, novel modulation/demodulation format and ultrafast transmission technology. We would like to report our recent research works including collaborative work with private company using JGNⅡ optical test bed to curve the expansion of the foot print and electrical consumption power in network nodes and to release network management by lowering required the wavelength number against endlessly growing demand of internet traffic.

Keywords
Ultrafast optical communication, Highly efficient modulation/demodulation formats, Peta-bit/s-class photonic networks

1 Introduction

Internet traffic continues to increase despite the current difficult economic conditions; these circumstances demand optical transmission technology that can efficiently accommodate this growing traffic. When constructing photonic networks for the near future and beyond, technology to increase data-transmission capacity per wavelength will be essential, in addition to conventional technology relating to Wavelength Division Multiplexing (WDM). The 160-Gb/s ultrafast optical communication system[1][2], with a bit rate per wavelength exceeding the maximum processing speeds of current electronic circuits (approximately 100 Gb/s), will be able to carry the same traffic in far fewer wavelengths than the 10-Gb/s systems now commercially available (and still fewer than in the 40-Gb/s WDM systems soon to enter the market). Ultrafast communication is thus expected to simplify future network operations and management to a significant extent, such as establishing wavelength path and signal quality monitoring for switching in the event of failure. Recent progress in optical device technology has enabled indoor and field transmission experiments with 160-Gb/s optical transmission systems using installed fiber optic equipment. These experiments, conducted mainly by research institutions involved in national projects within Europe, have been the subject of a steady stream of recent reports[3][4].

Installed fiber optic equipment differs from corresponding laboratory equipment designed with ideal characteristics for 160-Gb/s transmission, in that the former is installed in severe outdoor environments involving significant temperature variation and environmental vibration. In a particular challenge to actual implementation, 160-Gb/s optical pulse signals feature small repetition intervals; as a result, Polarization Mode Dispersion (PMD) is the main cause of degradation in transmitted signal quality[1]-[4]. Nevertheless, we succeeded in stable 160-Gb/s field transmission for the first time in Japan in July, 2004, using the fiber optic testbed established for the JGNII project[5], by implementing a simple system based on an automatic PMD compensator. This experiment was performed in collaboration with KDDI R&D Laboratories[6]. We also evaluated the suppression of PMD signal degradation, adopting a multi-level format for a data capacity of 160 Gb/s per wavelength. The obtained data indicated satisfactory results[7]. Further, in March 2005, we performed the world's first stable inter-city WDM optical transmission, spanning 200 km at a total capacity of 1.28 terabits per second, applying 160-Gb/s 8-wavelength WDM; success in this case relied heavily on the strength of the simple automatic PMD compensator[8].

2 Characteristics of fiber optic line[6]

Figure 1 shows the network configuration of the optical testbed. Optical repeaters, including Dispersion Compensating Fibers (DCFs), are installed at the Ootemachi and Tsukuba JGNII Research Center stations and at the relay station (Kashiwa); these stations are connected with Single-Mode Fibers (SMFs; compatible with ITU-T G.652) approximately 50 km in length. In the current configuration, the optical signals from Ootemachi are rerouted at Tsukuba, in a 4-span transmission-line structure featuring a total length of 200 km (50 km × 4 spans). As aerial cable routes were already present in Spans 2 and 3, a practical optical testbed is thus formed. Each station is equipped with optical amplifiers featuring gain deviation of ± 0.5 dB or less for wavelengths from 1,535 nm to 1,565 nm. Dispersion Compensating Fibers (DCFs) are installed between the stages of each optical amplifier. In the optical amplifiers at Kashiwa, Dynamic Gain Equalizers (DGEs) are installed to adjust link gain flatness. The optical amplifiers and DGEs within the system can be remotely controlled from other stations. For the 200-km transmission link, the accumulated dispersion is plus or minus 5 ps/nm or less over a bandwidth of 30-nm (1,535 nm to 1,565 nm) in the C band.

As shown in Fig.2, signal quality degrades if PMD causes Differential Group Delay (DGD)— i.e., optical pulses splitting to cause differences in speed of the optical pulses in the direction of polarization. Figure 3 shows the wavelength dependence of DGD measured every 30 minutes over 8 hours from day into evening, with the 30-minute segments overlaid. Within the optical signal wavelength indicated with the dotted line (1,558 nm), a maximum of approximately 3 ps of DGD is observed. This indicates an extremely severe transmission environment for 160-Gb/s optical signals at 6.25-ps pulse intervals.

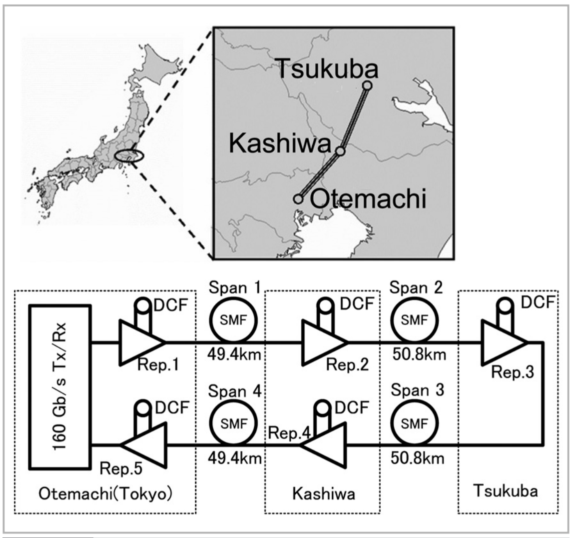

Fig.1 JGNII optical testbed network

Tx: transmitter system, Rx: receiver system, DCF: Dispersion Compensating Fiber, SMF: Single-Mode Fiber, Rep: optical repeater

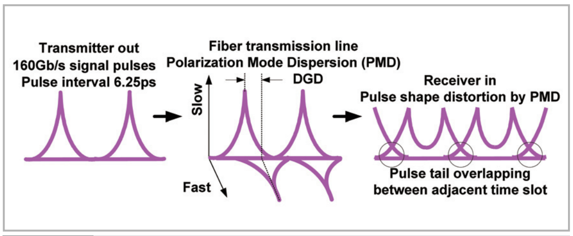

Fig.2 Polarization Mode Dispersion (PMD)

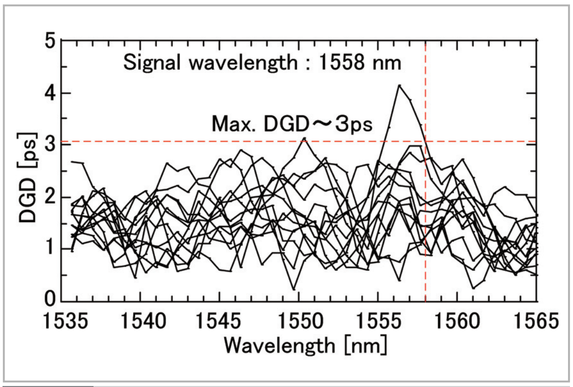

Fig.3 *Time variation in wavelength dependence of DGD characteristics*

3 Field transmission experiments

3.1 160-Gb/s single-wavelength DPSK transmission[6]

We applied DPSK modulation with high receiver sensitivity to achieve stable 160-Gb/s transmission, introduced a polarization stabilizer in the receiver as a simple PMD compensator, and evaluated the suppression of PMD variation.

Figure 4 shows the 160-Gb/s DPSK transmitter and receiver systems.

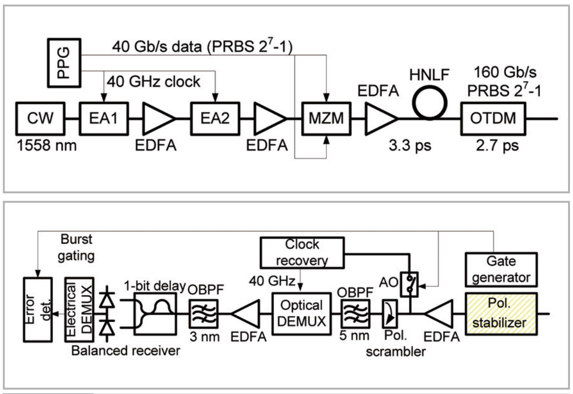

Fig.4 *160-Gb/s DPSK transmitter and receiver systems*

The transmitter (Tx) generates 40-GHz optical pulse trains using a set of 2-stage Electro-Absorption Modulators (EAMs), applies Differential Phase Shift Keying (DPSK) at 40 Gb/s, compresses the pulses using highly nonlinear fiber (2.7 ps), and transmits single-polarization 160-Gb/s-DPSK signals (PN 7 stages) using polarization-maintaining Optical Time Domain Multiplexing (OTDM) equipment. The receiver (Rx) contains an automatic PMD compensator consisting of an automatic tracking polarization stabilizer and a polarizer. The Demultiplexer (DEMUX) uses a 2-stage EAM operating at a clock rate of 40 GHz generated by the hybrid Phase-Locked Loop (PLL) clock extraction circuit. After the DEMUX, the 160-Gb/s DPSK signals were demultiplexed into 40-Gb/s signals, and then, the 40-Gb/s signals into 10-Gb/s signals by electrical time division, and the Bit Error Rate (BER) is measured.

Figure 5 shows the correlation characteristics between the Q-factor (higher values indicating fewer errors) calculated from the average error rate of the received sixteen 10-Gb/s signals demultiplexed from the 160-Gb/s signals and the DGD near the signal wavelength. When the polarization is adjusted on the transmitter side, (the black circle indicating the best value and the white circle indicating the worst value), stable transmission characteristics are obtained following 200-km transmission (18 dB<Q) even with DGD of over 2 ps (which occurred during over 32 percent of the transmission time-slot). The results indicate that signal quality is also maintained for PMD (DGD) larger than that obtained without the use of the stabilizer (indicated by the black triangle in the figure).

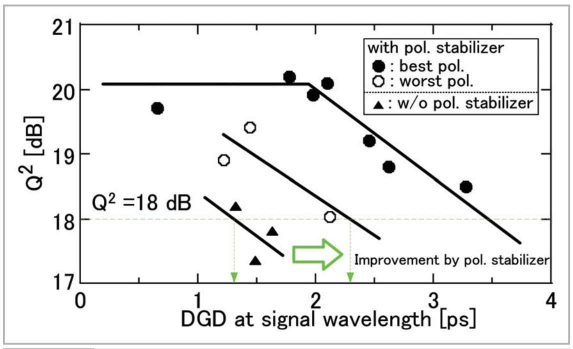

Fig.5 *DGD dependence of signal quality (Q-factor)*

3.2 160 Gb/s APSK transmission[7]

Simultaneous Amplitude and Phase-Shift Keying modulation (APSK, or ASK-DPSK) allows us to obtain 2-bit/symbol multilevel modulation by the superposition of Differential Phase-Shift keying (DPSK) modulation onto Amplitude Shift Keying (ASK) modulation. As shown in Fig.6, the ASK and DPSK components, each featuring a bit rate of 80 Gb/s, produce 160-Gb/s APSK modulation signals. In this case, the pulse interval is 12.5 ps, which is twice the value of normal 160-Gb/s optical pulses and equivalent to that of the 80-Gb/s pulses; resistance to PMD fluctuation is therefore expected to be higher. Thus, using the JGNⅡ optical testbed (between Ootemachi and Tsukuba), which is subject to severe PMD conditions, we evaluated the suppression of degradation in receiver sensitivity due to PMD fluctuation, adopting 160-Gb/s APSK modulation without adaptive PMD compensators.

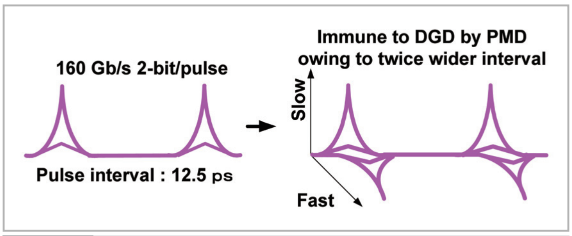

Fig.6 *Avoiding pulse overlap due to PMD by multilevel modulation*

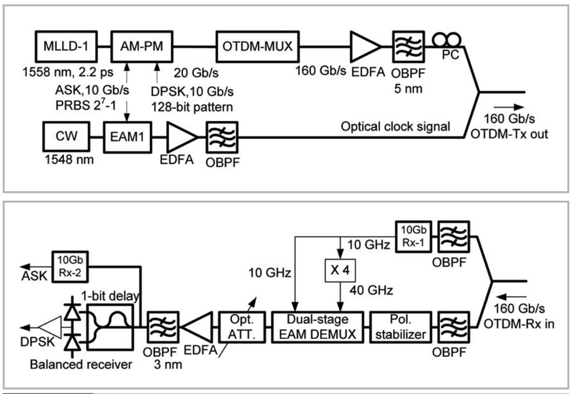

Fig.7 *160-Gb/s APSK transmitter and receiver system*

The transmitter applies 10-Gb/s ASK (with the extinction ratio degraded to approx. 6 dB) to the 10-GHz pulse train from the Mode-Locked Laser Diode (MLLD; wavelength: 1,558 nm, pulse width: 2.2 ps), superposes the 10-Gb/s ASK on the 10-Gb/s DPSK to generate 20-Gb/s APSK optical signals, and transmits the 160-Gb/s APSK optical signals (consisting of eight tributary channels) using an Optical-Time-Domain-Multiplexing Multiplexer (OTDM-MUX). The receiver receives both the 10-Gb/s ASK and PSK components using two-stage EAM, and the Bit Error Rate (BER) is evaluated. Figure 8 shows the BER characteristics of the ASK (white and black circles) and DPSK (white and black squares) components of the 160-Gb/s APSK signals before and after transmission with the 160-Gb/s RZ-ASK (white and black triangles). Here, the white symbols represent back to back conditions and the black symbols after 200 km transmission. At a BER of 10^{-7}, the receiver sensitivity penalty before and after transmission is 8 dB or more for the ordinary RZ-ASK 160-Gb/s optical signals, while the penalty for both components of the 160-Gb/s APSK optical signals is 4 – 5 dB or less. These results indicate suppression of the PMD penalty by using the 2-bit/symbol multilevel modulation format.

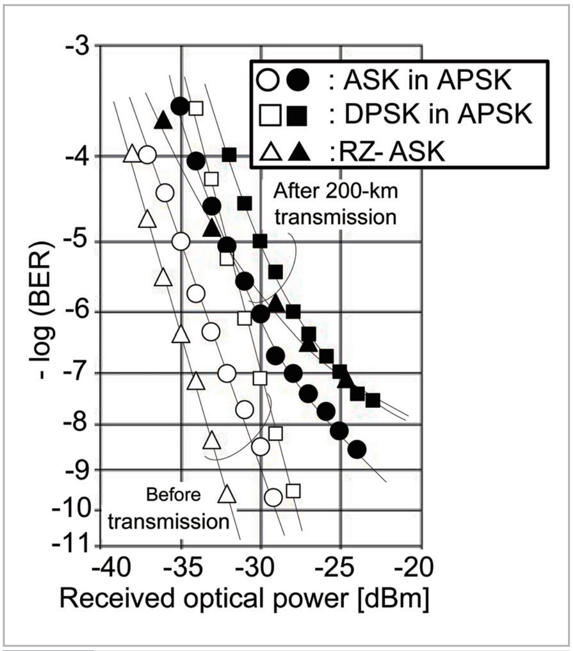

Fig.8 *Bit Error Rate characteristics of 160-Gb/s APSK*

3.3 160-Gb/s×8-wavelength division multiplexing-1.28-terabit DPSK transmission[8]

Figure 9 shows the transmitter system for 160-Gb/s × 8-WDM transmission. First, outputs of the eight CW light sources, which are spaced at intervals in the 300-GHz wavelength band, are wavelength-division multiplexed by an Arrayed-Waveguide-Grating (AWG); then, 40-GHz, 3.9-ps optical pulses are generated using a two-stage cascade $LiNbO_3$ modulator under push-pull operation, with 40-GHz sinusoidal signals for the first stage and 20-GHz sinusoidal signals for the second stage. The transmitter then applies DPSK modulation to all wavelengths together, in the same manner as the transmitter in Fig.4, and transmits the 160-Gb/s × 8-WDM DPSK-RZ optical signals. The receiver system is a DPSK receiver system featuring the same configuration as that shown in Fig.4, after selecting the receiving wavelength channel for the receiver evaluation using an optical tunable filter with a transmission bandwidth of 2 nm. The output of each channel of the repeater in the transmission route is set to 6.5 dBm for each span. Figure 10 shows the DGD dependence of the Q-factor calculated from the measured BER for each channel. Here, the input polarization status is manually adjusted on the transmitter to provide the worst BER in measurement. Additionally, for 8-WDM measurement, the automatic PMD compensator used in the single-wavelength transmission experiments described in 3.1 is introduced in the system. By using the compensator, Q-factors for the worst channel was 14.4 dB or more even for large DGD values near 2 ps. These results demonstrate that stable transmission at 10^{-13} or less is possible using standard in-band Forward Error Correction (FEC).

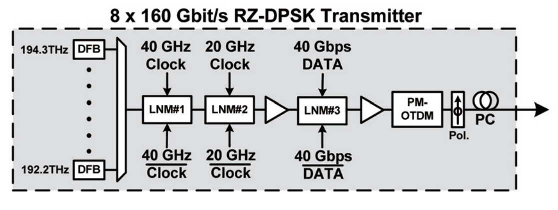

Fig.9 160-Gb/s x 8-WDM transmitter system

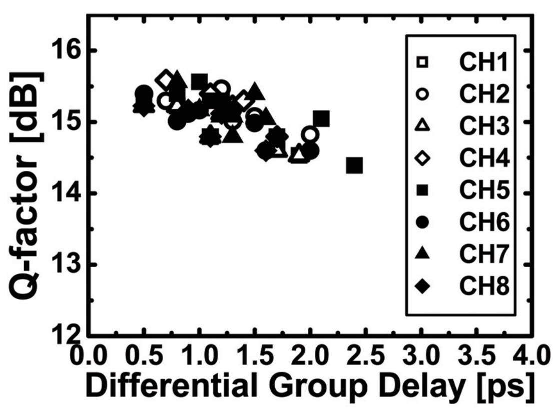

Fig.10 DGD dependence of Q-factor for each channel after 200-km transmission

4 Summary

To test the fundamental technology required for efficient photonic networks, NICT conducted a number of experiments in collaboration with KDDI R&D Laboratories, using the JGNII optical testbed. These experiments included ultrafast single-wavelength optical transmission at a bit rate of 160 Gb/s per wavelength, 2 bits/pulse multi-level 160-Gb/s optical transmission, and WDM transmission at a total capacity of 1.28 terabits per second using 8-wave WDM at a transmission speed of 160 Gb/s. In the course of these experiments NICT succeeded in the world's first stable inter-city optical transmission, covering a total 200 km. These results demonstrate that the JGNII optical testbed can be used for research and development on terabit-class optical network construction technology, as has been anticipated since initial testbed operations. JGNII will thus see continuous use in collaborative joint projects with private companies, leading the way in cutting-edge research and development in the field.

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References

1 R.Ludwig, U.Feiste, C.Schmidt, C.Schubert, J.Berger, E.Hillinger, M.Kroh, T.Yamamoto, C.M.Weinert, and H.G.Weber, “Enabling Transmission at 160 Gbit/s”, Optical Fiber Communication Conference (OFC '02), TuA1, 1-2, Anaheim, USA, 2002.

2 H.Murai, M.Kagawa, H.Tsuji, and Kozo Fujii, “Single Channel 160 Gbit/s Carrier-Suppressed RZ Transmission over 640 km with EA Modulator based OTDM Module”, European Conference on Optical Communications (ECOC '03), Mo3.6.4, Rimini, Itally, 2003.

3 S.Kieckbusch, S.Ferber, H.Rosenfedt, R.Ludwig, C.Boerner, A.Ehrhardt, E.Brinkmeyer, and H.G.Weber, “Adaptive PMD compensation in 160Gb/s DPSK transmission over installed fiber”, Optical Fiber Communication Conference (OFC '04), Post-Deadline paper, PDP31, Los Angels, USA, 2004.

4 M.Schneiders, S.Vorbeck, R.Leppla, E.Lach, M.Schmidt, S.B.Papernyi, and K.Sanapai, “Field transmission of 8×170 Gbit/s over high loss SSMF link using third order distributed Raman amplification”, Optical Fiber Communication Conference 2005, PDP39, 2005.

5 http://www.jgn.nict.go.jp/e/index.html

6 T.Miyazaki, M.Daikoku, I.Morita, T.Otani, Y.Nagao, M.Suzuki, and F.Kubota, “Stable 160-Gb/s DPSK transmission using a simple PMD compensator on the field photonic network test bed of JGNII”, Opto-Electronics and Communications Conference (OECC '04), Post-Deadline paper, PD1-3, Yokohama, Japan, 2004.

7 T.Miyazaki, Y.Awaji, Y.kamio, and F.Kubota, “Field Demonstration of 160-Gb/s OTDM Signals Using Eight 20-Gb/s 2-bit/symbol Channels over 200Km”, Optical Fiber Communication Conference (OFC 2005), OFF1, Anaheim, USA, 2005.

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