100-Gb/s DQPSK Transmission Experiment Without OTDM for 100G Ethernet Transport

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Abstract—In order to realize a future 100-Gb Ethernet (100 GbE) transport, 100-Gb/s transmission without 100-GHz-class electronics and optical time-division-multiplexing technique was demonstrated. By using a differential quadrature phase-shift-keying (DQPSK) modulation format and commercially available electronics, 2- and 50-km transmissions of 100-Gb/s signal were successfully achieved over a standard single mode fiber. The receiver sensitivity, chromatic dispersion, and differential group delay tolerances of 100-Gb/s DQPSK signal were also evaluated. Through these evaluations, the possibility of DQPSK modulation for future 100-GbE transport is verified.

Index Terms—Differential quadrature phase-shift-keying (DQPSK), return to zero (RZ)-DQPSK, 100-gigabit Ethernet (100 GbE).

I. INTRODUCTION

ETHERNET is the most widely deployed protocol for a short distance connection in a local area network (LAN). Since Ethernet has cost effectiveness and simplicity compared to other protocols, it has been extended to metropolitan area networks (MANs) and wide area networks (WANs). Recently, a dominant traffic in the carrier's network is changing from voice to data, and wide deployment of the broadband access is continuously progressing. These trends accelerate the capacity demand of Ethernet in not only LANs but also in MANs and WANs since higher access bandwidth drives the need for higher core bandwidth to carry aggregated bandwidth. Although Ethernet has accommodated this increased demand due to the advancement from gigabit Ethernet (GbE) to 10 GbE, the traffic of these networks is still increasing at a steady pace, and more capacity will be required for the Ethernet in the future. As the bit rate of the Ethernet has been traditionally increased by ten times, the bit rate of the next-generation Ethernet will be 100-Gb/s class [1], [2]. Electrical time-division-multiplexing (ETDM) transmitters of 107-Gb/s and with duobinary [3] and nonreturn-to-zero (NRZ) modulation formats [4], and an integrated ETDM receiver operation at 100 Gb/s [5], have already

been reported, but 100-GHz-class electronics is not a mature technology, and specially designed electrical components shall be required. Although there are many reports of optical time-division-multiplexing (OTDM) transmission over 100 Gb/s [6], [7], OTDM technology requires bulky components, and it is not suited for economical systems. Then, to realize future 100-Gb Ethernet (100 GbE) transport, system demonstrations of 100-Gb/s transmission without 100-GHz-class electronics and OTDM are favorable.

In this paper, we successfully demonstrated 100-Gb/s transmission without 100-GHz-class electronic components and the OTDM technique by using a differential quadrature phase-shift-keying (DQPSK) modulation format and commercially available electronic components for 40-Gb/s systems. For short- and long-reach transports, 100-Gb/s DQPSK signals were transmitted over 2- and 50-km standard single mode fibers (SMFs). We evaluated the receiver sensitivity, chromatic dispersion (CD), and differential group delay (DGD) tolerances of the 100-Gb/s DQPSK signal. These results show the possibility of future 100-GbE transport with mature electronics.

II. EXPERIMENTAL SETUP

Fig. 1 shows a schematic diagram of the 100-Gb/s DQPSK transmitter and receiver. In the transmitter, a continuous wave (CW) light source operating at 1558 nm and an integrated LiNbO$_3$ (LN) Mach–Zehnder modulator [8] were utilized for generating the DQPSK signal. By using two high-speed delay flip-flop circuits, two 50-Gb/s pseudo random binary sequence (PRBS) data of $2^7 - 1$ length from the 50-Gb/s pulse pattern generator were divided into four sequence data for a push–pull driving of the LN Mach–Zehnder modulator. Both in-phase and quadrature arms of the LN Mach–Zehnder modulator were biased at null point and driven in push–pull configurations by utilizing two commercially available high-speed driver pairs with +22-dBm output power, respectively. Although the same PRBS data were fed to both arms, 108-bit time delay between the data sequences of the in-phase and quadrature arms was added in order to decorrelate the data patterns. Under these conditions, the optical loss of the integrated LN Mach–Zehnder modulator was almost 12 dB.

In the receiver, the 100-Gb/s signals were preamplified by using an erbium-doped fiber amplifier (EDFA) with a 1480-nm pump light and demodulated by using a 2-bit-delay Mach–Zehnder interferometer (MZI). The differential optical phase between two arms of the MZI was set to $-\pi/4$ and $+\pi/4$ to receive the in-phase and quadrature components of the DQPSK signal, respectively. The 50-Gb/s demodulated data
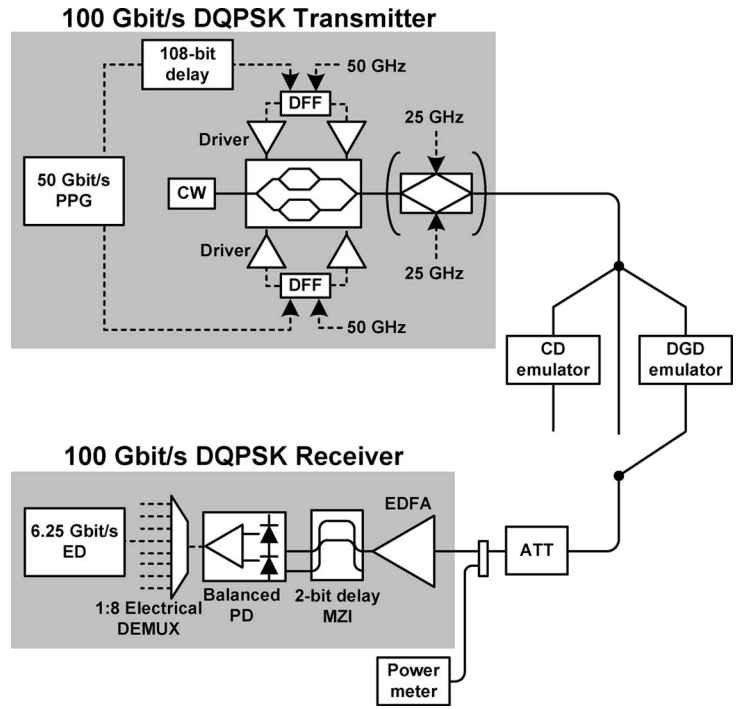
Fig. 1.   Schematic diagram of the 100-Gb/s DQPSK transmitter and receiver.

Fig. 2.   Optical spectra of 100-Gb/s DQPSK signal with 0.02-nm resolution bandwidth.

Fig. 3.   Optical waveforms of 100-Gb/s DQPSK signal [10 ps/div].

Fig. 4.   Balanced detected electrical waveforms of 100-Gb/s DQPSK signal [10 ps/div].

signals were detected by a balanced photodetector, 3-dB bandwidth of which was 45 GHz. Subsequently, the detected signal was electrically time-division demultiplexed to eight 6.25-Gb/s data signals by using an electrical time-division demultiplexer. Since the received bit stream was not a pseudo random pattern due to the nature of the DQPSK modulation, we programmed the 6.25-Gb/s error detector with the calculated patterns [9] in order to measure the bit error rate (BER). The performance of the 100-Gb/s DQPSK signal was evaluated by measuring BER for both in-phase and quadrature components.

III. RESULTS AND DISCUSSION

In order to evaluate the back-to-back characteristics, the receiver sensitivities of the 100-Gb/s DQPSK signal were
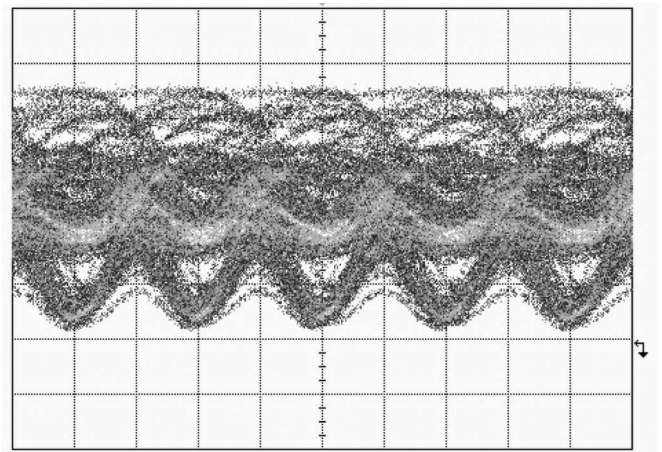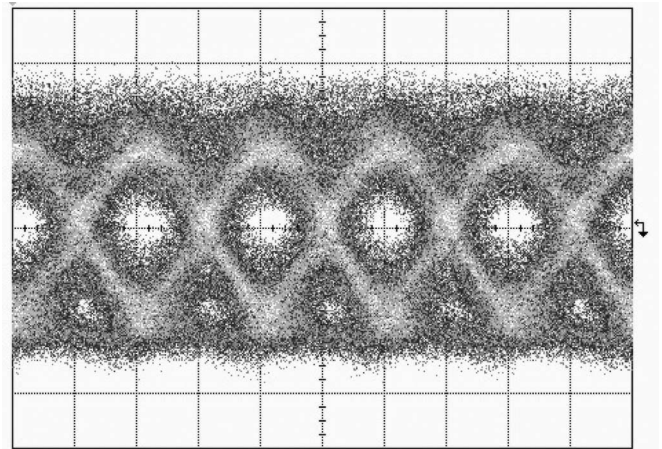
Fig. 5.   Receiver sensitivity of (a) in-phase and (b) quadrature components of 100-Gb/s DQPSK signal in the back-to-back configuration.

Fig. 6.   CD tolerances of 100-Gb/s DQPSK signal at 10^{-9} of BER.

Fig. 7.   DGD tolerances of 100-Gb/s DQPSK signal at 10^{-9} of BER.

A. Performance Evaluations in Back-to-Back Configuration

Fig. 2 shows optical spectrum of the 100-Gb/s DQPSK signal with a 0.02-nm resolution bandwidth. Fig. 3 shows the optical waveform measured by using a 65-GHz bandwidth optical head. From Fig. 3, due to the bandwidth and amplitude limitation of the electrical drivers, it was found that the optical waveform of the 100-Gb/s DQPSK signal was degraded. Fig. 4 shows the balanced detected electrical waveform of the 100-Gb/s DQPSK signal. The electrical waveform was measured by using a 60-GHz bandwidth electrical head. Although the bandwidth and amplitude of the electrical drivers in the transmitter were limited, it was found that the eye diagram was opened after the demodulation and balanced detection.

Fig. 5(a) and (b) shows the receiver sensitivity of in-phase and quadrature components of the 100-Gb/s DQPSK signal in the back-to-back configuration. From Fig. 5, it was found that receiver sensitivities at 10^{-9} of BER of the in-phase and quadrature components were about -22 and -21 dBm. In these measurements, there are no significant performance differences between the electrical tributaries. Then, we measured only one electrical tributary in each component of the DQPSK signal for the other experiments. The measured electrical tributary was tributary 2, which shows relatively worse performance than the other tributaries.

measured. To investigate the transmission characteristic, the CD and DGD tolerances of the 100-Gb/s DQPSK signal were evaluated, and a 100-Gb/s DQPSK signal was transmitted over a 50-km standard SMF with a dispersion compensation fiber (DCF) and a 2-km SMF without a DCF.

In the experiments, the output optical power of the 100-Gb/s DQPSK transmitter was set to 0 dBm. Note that the receiver sensitivity was defined as the input power to the pre-EDFA.
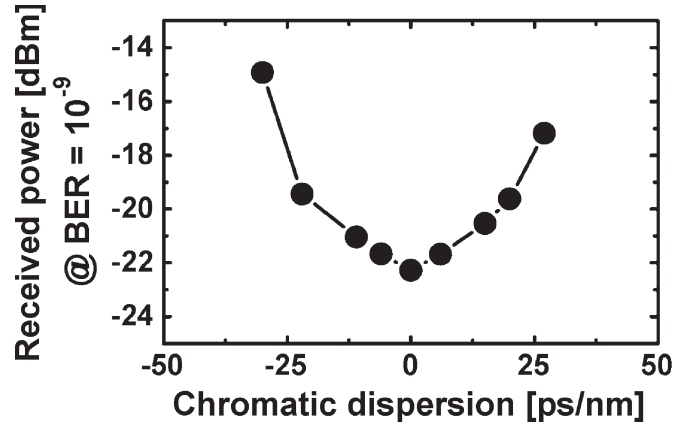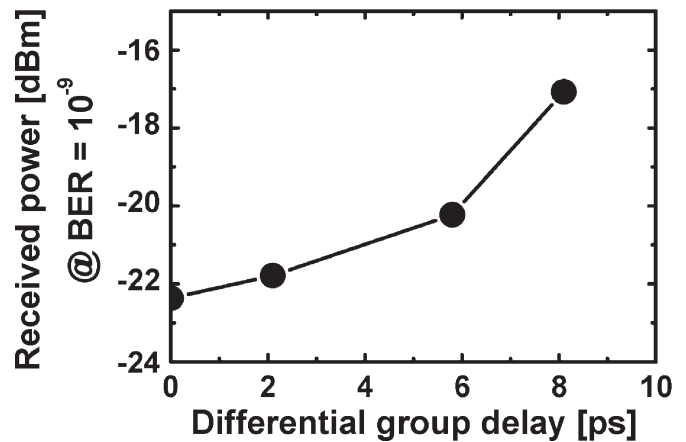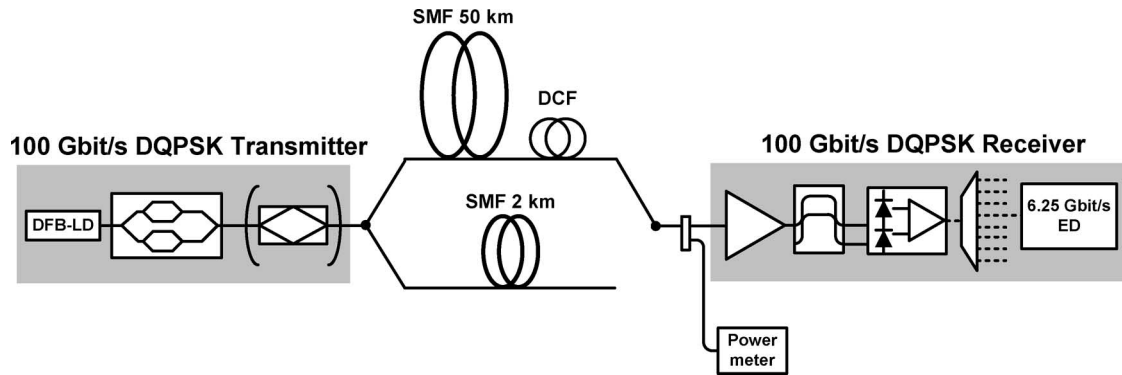
Fig. 8. Transmission experimental configuration.

B. Transmission-Performance Evaluations

In order to investigate the transmission characteristic, CD and DGD tolerances of the 100-Gb/s DQPSK signal were evaluated. Figs. 6 and 7 show the CD and DGD tolerances of the 100-Gb/s DQPSK signal at 10^{-9} of BER. In Figs. 6 and 7, the average performance of the in-phase and quadrature components of the 100-Gb/s DQPSK signal was shown. From Fig. 6, it was found that the CD tolerance for the 1-dB penalty was about 18 ps/nm, although the CD tolerance of larger than 30 ps/nm is expected in the 100-Gb/s DQPSK signal from the evaluation results of the 42.8-Gb/s RZ-DQPSK signal [10], [11]. The main reason for the smaller CD tolerance is considered to be the bandwidth and amplitude limitation of the electric driver for the LN Mach–Zehnder modulator, as mentioned in the next section. From Fig. 7, the DGD tolerance for the 1-dB penalty was about 3.3 ps. Similar to the measurement result of the CD tolerance, it is considered that the DGD tolerance decreased due to the bandwidth and amplitude limitation of the electrical drivers.

In order to confirm the applicability for short- and long-reach transports, 2- and 50-km transmission experiments were conducted over conventional SMF. Fig. 8 shows the transmission experimental configuration of the 100-Gb/s DQPSK signal. The 100-Gb/s DQPSK transmitter and receiver are the same as those of Fig. 1. In the short-reach transmission experiment, the signal was transmitted through a 2-km standard SMF, and the cumulative dispersion of the SMF was not compensated in this experiment. The loss of the 2-km SMF was about 2 dB, including optical connectors. For the long-reach transmission experiment, the signal was transmitted over 50-km conventional SMF with DCF. The CD of SMF at the signal wavelength was about $+18$ ps/nm/km, and the total loss of a 50-km conventional SMF including optical connectors and splicing points was around 11 dB. To compensate for the cumulative CD, a DCF of -900 ps/nm was inserted after the SMF. The loss of the DCF was about 8 dB.

Fig. 9(a) shows the receiver sensitivity of the 100-Gb/s DQPSK signal after 2-km transmission over SMF without DCF. From Fig. 9(a), the receiver sensitivity was -16 dBm at 10^{-9} of BER. The transmission penalty from the back-to-back configuration was about 6.5 dB. Since the CD was not compensated in this experiment, the CD increased the transmission penalty. Still, there remains a power margin, and it was

found that the DQPSK signal was the applicable modulation format for 100-GbE short-reach transport. Fig. 9(b) shows the receiver sensitivity of the 100-Gb/s DQPSK signal after 50-km transmission over SMF with DCF. From Fig. 9(b), it was found that the transmission penalty was very small, and the receiver sensitivity was -22 dBm at 10^{-9} of BER. In this case, the cumulative CD was fully compensated, and the transmission penalty due to the CD was effectively suppressed.

C. Performance Analysis and Discussion

The measured waveforms and the evaluated CD and polarization mode dispersion (PMD) tolerances indicated that there was some degradation in the obtained transmission performance of the 100-Gb/s DQPSK signal. In order to evaluate the performance degradation quantitatively, the receiver sensitivity of RZ-DQPSK, the performance of which was already reported at 42.7-Gb/s [10], was measured by adding an RZ pulse carver after the integrated LN Mach–Zehnder modulator in the transmitter. The performance degradation of 100-Gb/s DQPSK was estimated with the performance change of RZ-DQPSK by increasing the bit rate to 100 Gb/s.

To generate 100-Gb/s RZ-DQPSK signal, another LN Mach–Zehnder modulator was added for RZ pulse carving with 66% duty cycle in the transmitter of Fig. 1. Optical loss of the RZ pulse carver was almost 8 dB. In this configuration, the output optical power of the 100-Gb/s RZ-DQPSK transmitter was set to -2 dBm by maximizing the output power of CW light source.

Fig. 10 shows the optical spectrum of the 100-Gb/s RZ-DQPSK signal with 0.02-nm resolution bandwidth. Figs. 11 and 12 show waveforms of the optical signal and the balanced detected electrical signal in the same condition as the case without the RZ pulse carver. There was not much difference between waveform degradation of DQPSK and RZ-DQPSK signals.

Fig. 13(a) and (b) shows the receiver sensitivity of in-phase and quadrature components of the 100-Gb/s RZ-DQPSK signal in the back-to-back configuration. From Fig. 13, it was found that receiver sensitivities at 10^{-9} of BER of in-phase and quadrature components were about -25 and -24 dBm. From these results, it was found that by applying RZ pulse carving around 3 dB, improvement of receiver sensitivity was
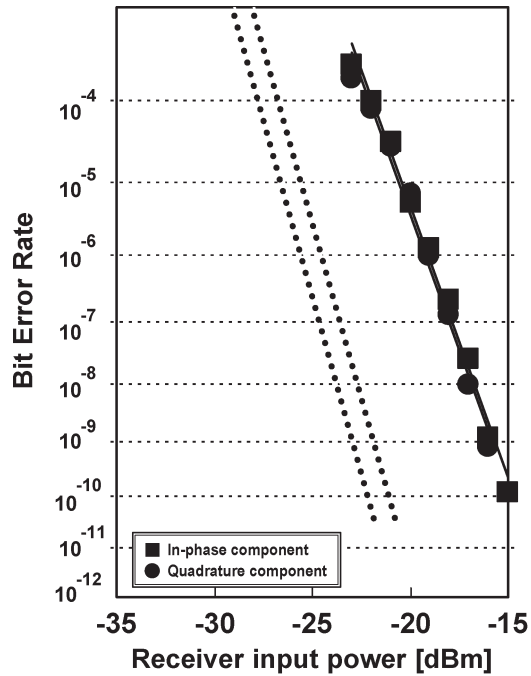
(a)
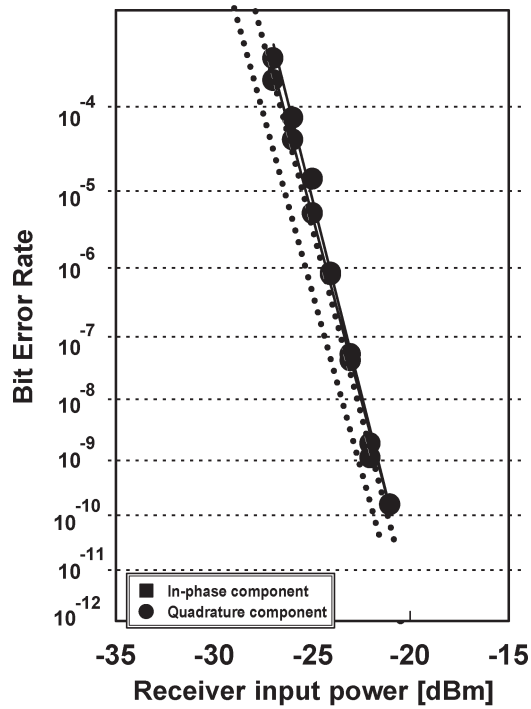
(b)

Fig. 9. Receiver sensitivities of the 100-Gb/s DQPSK signal after (a) 2-km transmission over SMF without DCF and (b) 50-km transmission over SMF with DCF. Dotted line shows in-phase and quadrature components of the 100-Gb/s DQPSK signal in the back-to-back configuration.

Fig. 10. Optical spectra of 100-Gb/s RZ-DQPSK signal with 0.02-nm resolution bandwidth.
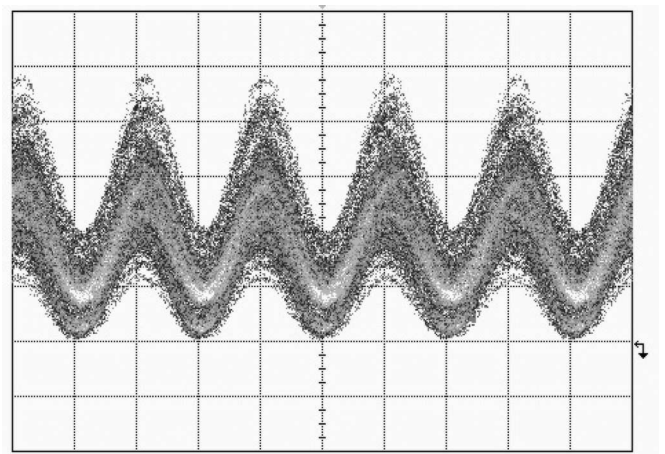
Fig. 11. Optical waveforms of 100-Gb/s RZ-DQPSK signal [10 ps/div].
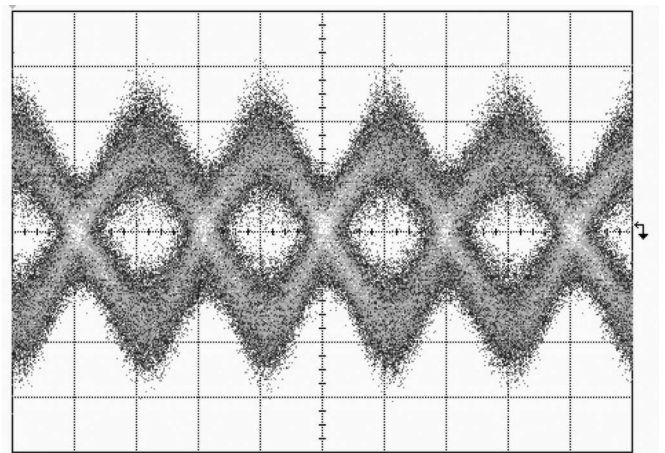
Fig. 12. Balanced detected electrical waveforms of the 100-Gb/s RZ-DQPSK signal [10 ps/div].

obtained due to reducing intersymbol interference. Compared with receiver sensitivity of the 42.8-Gb/s RZ-DQPSK signal in back-to-back configuration [10], it is expected that the receiver sensitivity of the 100-Gb/s RZ-DQPSK signal is around -29 dBm at 10^{-9} of BER. These results indicate that the limited bandwidth and amplitude of the electric drivers for the
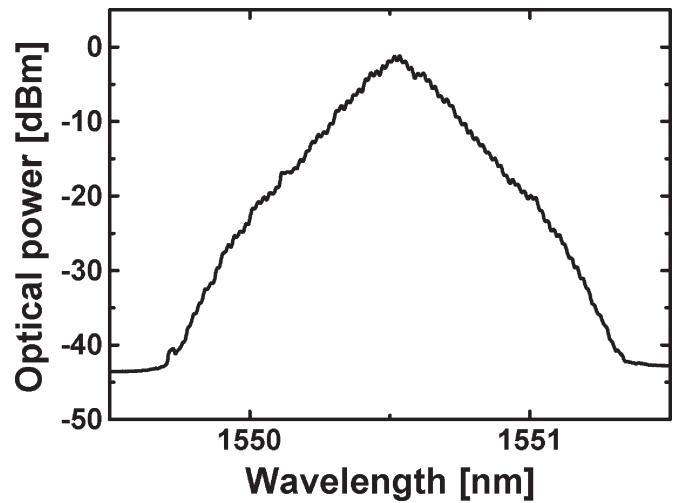
LN Mach–Zehnder modulator caused around a 4-dB penalty for the 100-Gb/s DQPSK signal. From this consideration, it is expected that an increase of the bandwidth and amplitude
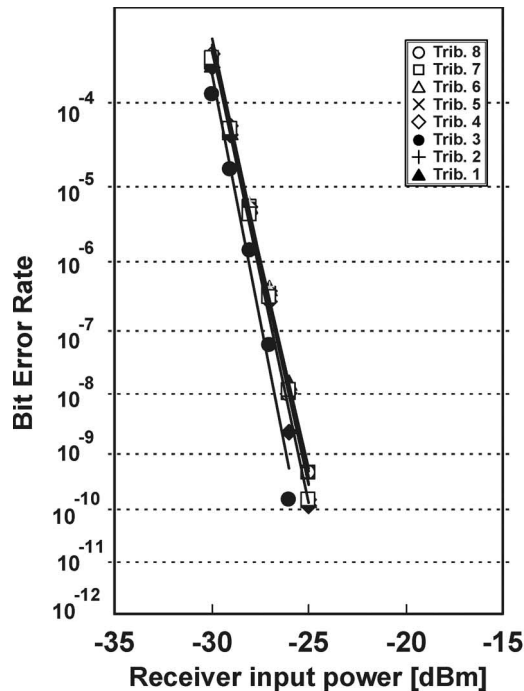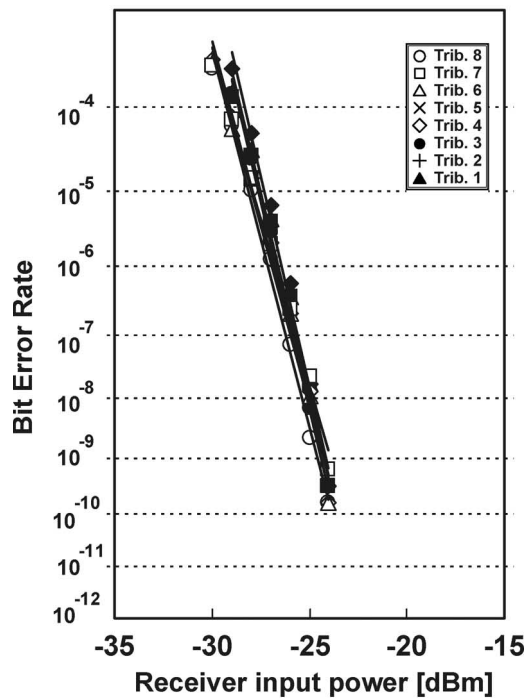
Fig. 13.   Receiver sensitivity of (a) in-phase and (b) quadrature components of the 100-Gb/s RZ-DQPSK signal in the back-to-back configuration.

of electric drivers can further improve the 100-Gb/s DQPSK signal performance.

IV. CONCLUSION

We successfully demonstrated 100-Gb/s signal transmission without 100-GHz-class electronics and OTDM by using a DQPSK modulation format and commercially available electronic components for 40-Gb/s systems. The receiver sensitivity

of the 100-Gb/s DQPSK signal was evaluated. Moreover, CD and DGD tolerances were also evaluated by measuring the receiver sensitivity at 10^{-9} of BER. The receiver sensitivity of the 100-Gb/s DQPSK signal was around -22 dBm, and the CD and DGD tolerances for a 1-dB penalty were about 18 ps/nm and 3.3 ps, respectively. In order to confirm the applicability for short- and long-reach transports, 2- and 50-km transmission experiments were conducted over conventional SMFs. These evaluated results show that the DQPSK signal can be one of the candidates for 100-GbE short- and long-reach transports. In order to evaluate the performance degradation quantitatively, the receiver sensitivity of RZ-DQPSK was measured by adding an RZ pulse carver after the integrated LN Mach–Zehnder modulator in the transmitter. From this measurement, it was found that the limited bandwidth and amplitude of the electric drivers for the LN Mach–Zehnder modulator caused around a 4-dB penalty for the 100-Gb/s DQPSK signal. Further improvement of the transmission performance is expected by increasing the bandwidth and amplitude of the electric drivers for the LN Mach–Zehnder modulator. Since there is almost no penalty after 50-km transmission of the 100-Gb/s DQPSK signal, we found that the transmission distance is not limited at 50 km when the cumulative CD is compensated. This result implies that a distance transmission of longer than 50 km can be expected.

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