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Generation of high-speed PAM4 signal by overdriving two Mach-Zehnder modulators

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Abstract: We propose the generation of a high-speed four-level pulse amplitude modulated (PAM4) signal by combining two on-off keying (OOK) signals obtained by overdriving two Mach-Zehnder modulators (MZMs). By using this method, we can overcome the limited modulation bandwidth of the MZM and generate the high-speed PAM4 signal (faster than the PAM4 signal generated by modulating an MZM with a four-level electrical signal). For a demonstration, we generate the 95-Gb/s PAM4 signal by combining two OOK signals obtained from the bandwidth-limited MZM having a 3-dB bandwidth of only 10.5 GHz. In comparison, when we generate the PAM4 signal by using the conventional method, it is not possible to increase the bit rate to be faster than 60 Gb/s. We also successfully demonstrate the transmission of the 95-Gb/s PAM4 signal generated by the proposed method over 4 km of the standard single-mode fiber.

1. Introduction

Recently, there have been many interests in developing the high-speed transmission systems operating at >100 Gb/s per lane to support the ever-increasing data traffic in various short-haul applications [1–11]. For this purpose, the four-level pulse amplitude modulation (PAM4) has become the most popular modulation format because of its superb spectral efficiency, simplicity, and cost-effectiveness [3–5]. However, even with the use of the PAM4 format, it is still quite difficult to increase the transmission speed to be >100 Gb/s due to the insufficient electro-optic (E/O) bandwidth of the currently available commercial optical modulators [3–11]. Thus, there are many efforts now underway to develop the high-speed optical modulators capable of generating >100-Gb/s signals [5–11].

In this paper, we investigate the possibility of generating the high-speed (>100 Gb/s) PAM4 signal by using a couple of low-speed Mach-Zehnder modulators (MZMs). We note that, in the case of using the on-off keying (OOK) signal, it is possible to extend the E/O bandwidth of the MZM simply by overdriving it due to its nonlinear transfer characteristics. However, in the case of using the PAM4 signal, we should operate the MZM in the linear region to obtain the equi-spaced intensity levels. Thus, unlike the OOK signal, it would not be possible to generate the high-speed PAM4 signal by overdriving the low-speed MZM. To solve this problem, we propose to generate the PAM4 signal by combining two orthogonal OOK signals (i.e., in different polarizations or in-phase and quadrature (I/Q) space) obtained by overdriving two low-speed MZMs. In this case, we can overdrive the MZMs since they are used for the generation of the binary OOK signals. For a demonstration, we generate the 95-Gb/s PAM4 signal by using two MZMs having a 3-dB bandwidth of only 10.5 GHz. In this experiment, we assume that the required bit-error rate (BER) is 10^{-3} and generate the PAM4 signal by combining two OOK signals obtained from these bandwidth-limited MZMs by using the power-unbalanced polarization-division-multiplexing (PDM) technique [12,13]. The results show that, in comparison with the case of generating the PAM4 signal by modulating the same MZM with a 4-level electrical signal, we can increase the transmission capacity by 64% by using the proposed method. We also demonstrate the transmission of the 95-Gb/s PAM4 signal generated by the proposed technique over 4 km of the

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standard single-mode fiber (SSMF) at 1550 nm. No equalizer is used in this demonstration as we operate the MZMs to have negative chirp.

2. Background

Our objective is to develop an effective method for the generation of the high-speed PAM4 signal by using the bandwidth-limited MZM. For this purpose, we first model the bandwidth-limited MZM as a combination of a low-pass filter (LPF), a phase modulator, and a Mach-Zehnder interferometer, as shown in Fig. 1(a). Thus, if we neglect the insertion loss, the output intensity of the MZM, $I_{\text{out}}(t)$, can be expressed as [14]

$$I_{\text{out}}(t) = \frac{I_{\text{in}}}{2}\left\{1 - \cos\left(\frac{\pi(V_{\text{sig}}(t) * h(t))}{V_\pi}\right)\right\}, \tag{1}$$

where I_{in} is the input intensity, $V_{\text{sig}}(t)$ is the electrical driving signal applied to the phase modulator, (*) is the convolution operator, $h(t)$ is the impulse response of the LPF, and V_π is the half-wave voltage. In this model, the E/O bandwidth of the MZM is determined by the LPF. We assume that the 4$^{\text{th}}$-order Bessel filter shown in Fig. 1(b) is used as the LPF and the performance of the modulated signal is constrained by only the limited E/O bandwidth of the MZM (and not by noises). We then evaluate the quality of the generated PAM signal by using the eye height between the N^{th} and $(N-1)^{\text{th}}$ levels, which is defined as

$$(\text{Eye height}) = \frac{(I_N - 3\sigma_N) - (I_{N-1} + 3\sigma_{N-1})}{I_N - I_{N-1}}, \tag{2}$$

where, I_N and σ_N are the average amplitude and standard deviation of the N^{th} level of the PAM signal, respectively [15].

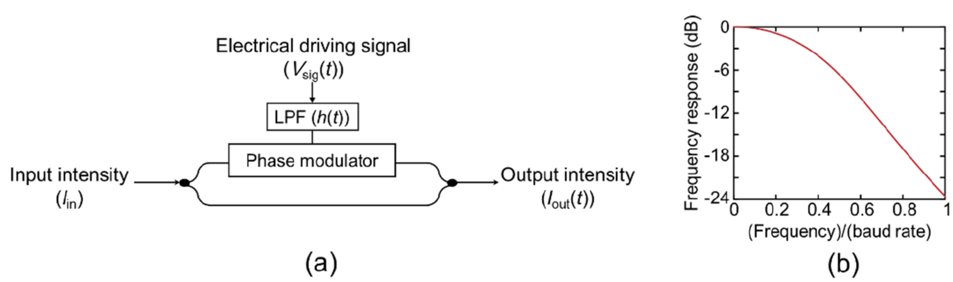

Fig. 1. (a) MZM model and (b) frequency response of the 4$^{\text{th}}$-order Bessel LPF (of which the 3-dB bandwidth is assumed to be 35% of the baud rate of the signal to be transmitted).

In the case of using the binary OOK signal, we can extend the E/O bandwidth of the MZM to a certain degree simply by overdriving it (since the transfer function of the MZM is nonlinear). To explain the operating principle of this overdriving technique, we assume that the phase modulator shown in Fig. 1(a) is biased at the quadrature point and modulated with a sinusoidal driving signal. We then firstly consider the case when the E/O bandwidth of the phase modulator is sufficiently large for this driving signal. In this case, the peak value of the output intensity, $I_{\text{out}}(t)$, becomes identical to the input intensity, I_{in}, if the peak amplitude of the driving signal, $V_{\text{sig}}(t)$, is same with the half-wave voltage, V_π, as expected from Eq. (1). However, if we increase $V_{\text{sig}}(t)$ to be larger than V_π, the peak value of $I_{\text{out}}(t)$ does not occur at the same time when $V_{\text{sig}}(t)$ has the peak amplitude (i.e., the $I_{\text{out}}(t)$ is distorted due to the nonlinear transfer function of the MZM). Thus, it is not recommended to overdrive the MZM if its E/O bandwidth is sufficiently large. Secondly, we consider the case when the E/O bandwidth of the phase modulator is not sufficient

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for the driving signal. In this bandwidth-limited case, the peak value of $I_{\mathrm{out}}(t)$ becomes smaller than I_{in} at the high-frequency region if the peak amplitude of $V_{\mathrm{sig}}(t)$ is set to be equal to V_π. However, we can increase the peak value of $I_{\mathrm{out}}(t)$ at the high-frequency region by increasing $V_{\mathrm{sig}}(t)$ to be larger than V_π (although it can somewhat decrease the peak value of $I_{\mathrm{out}}(t)$ at the low-frequency region). Thus, we can enhance the E/O response of the bandwidth-limited MZM at the high-frequency region by overdriving it.

To verify the effectiveness of this technique, we assume that the 3-dB bandwidth of the MZM is limited to be 35% of the baud rate of the signal, B, and numerically estimate its E/O response at various amplitudes of the driving signal, $V_{\mathrm{sig}}(t)$. The results in Fig. 2(a) show that, when ΔV is much smaller than V_π, the E/O bandwidth of the MZM is determined by the frequency response of the LPF. For example, when we set ΔV to be $0.1V_\pi$, the E/O bandwidth of the MZM is estimated to be $0.35B$ (which is identical to the 3-dB bandwidth of the LPF shown in Fig. 1(b)). However, as we increase ΔV, the E/O bandwidth is also increased. For example, the E/O bandwidth is increased to $0.48B$ when we set ΔV to be same as V_π. In addition, when we overdrive the MZM and set ΔV to be as large as $1.25V_\pi$, the 3-dB bandwidth is further increased to $0.57B$. The quality of the high-speed OOK signal can certainly benefit from these increased E/O bandwidths. For example, Figs. 2(b)~(e) show the eye diagrams of the OOK signal generated by using various values of ΔV. These results clearly show that the rise/fall time of the OOK signal is improved with the increased ΔV. However, the flatness of the E/O response can be deteriorated with the increased bandwidth. Thus, we evaluate the eye height of the OOK signal as a function of ΔV. The result in Fig. 2(f) shows that, if the 3-dB bandwidth of the LPF is $0.35B$, the eye height reaches its maximum value when we set ΔV to be $1.25V_\pi$. After this point, the eye height is rapidly reduced due to the overshoot in the eye diagram. We also evaluate the eye height as a function of ΔV for the MZMs having various E/O bandwidths. For example, when we utilize the MZM having a 3-dB bandwidth of $0.45B$, the eye height can be increased by 0.20 (by increasing ΔV from $0.1V_\pi$ to $1.1V_\pi$). On the other hand, when we utilize the MZM having a 3-dB bandwidth of only $0.25B$, the eye height can be increased by 0.58 (by increasing ΔV from $0.1V_\pi$ to $1.4V_\pi$). Thus, we conclude that the effect of overdriving the MZM is larger when its bandwidth is narrower. However, if the bandwidth of the MZM is too narrow, it may not be possible to achieve the eye height required for the error-free transmission.

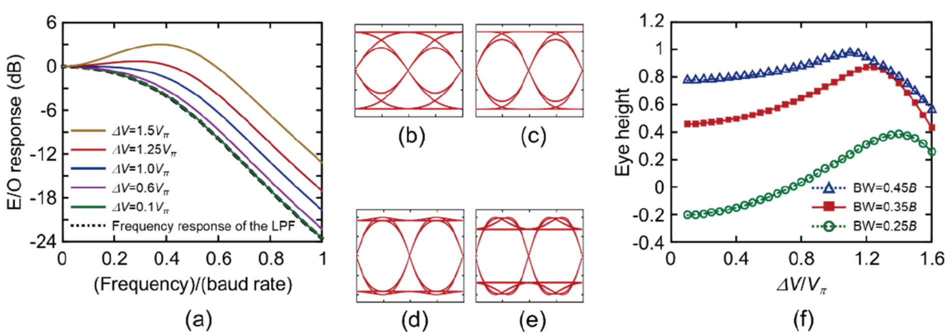

Fig. 2. (a) The E/O responses of the MZM obtained at various values of ΔV by numerical simulation. The eye diagrams of the OOK signal obtained by using an MZM (3-dB bandwidth = $0.35B$) when ΔV is set to be equal to(b) $0.1V_\pi$, (c) V_π, (d) $1.25V_\pi$, and (e) $1.5V_\pi$. (f) The eye heights of the OOK signals obtained by using the MZMs having various E/O bandwidths plotted as a function of ΔV.

Unfortunately, when we generate the PAM4 signal by using the conventional method (i.e., modulating an MZM with a four-level electrical signal), it is not possible to extend the E/O bandwidth of the MZM by overdriving it. This is because, in this case, ΔV should be smaller

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than V_π to ensure the operation of the MZM in the linear region (so that the generated PAM4 signal can have equi-spaced intensity levels). As a result, the E/O bandwidth of the MZM is limited by the frequency response characteristics of the LPF. To overcome this problem, we propose to generate the PAM4 signal by combining two orthogonal OOK signals obtained by overdriving two MZMs. In this case, we can generate the PAM4 signal with the equi-space intensity levels even if the MZMs are overdriven. Thus, by using this method, we can utilize the bandwidth-enhanced MZMs with overdriving signals even for the generation of the high-speed PAM4 signal.

We compare the performances of the PAM4 signals generated by the conventional method (i.e., modulating an MZM in the linear region with a small four-level electrical signal) and the proposed method (i.e., modulating two overdriven MZMs with the power-unbalanced PDM technique), in the case when the E/O bandwidth of the MZM is insufficient for the generation of the high-speed PAM4 signal. We assume again that the bandwidth of the MZM is limited to be 35% of the signal's baud rate. Figure 3(a) shows the simulation setup to generate the

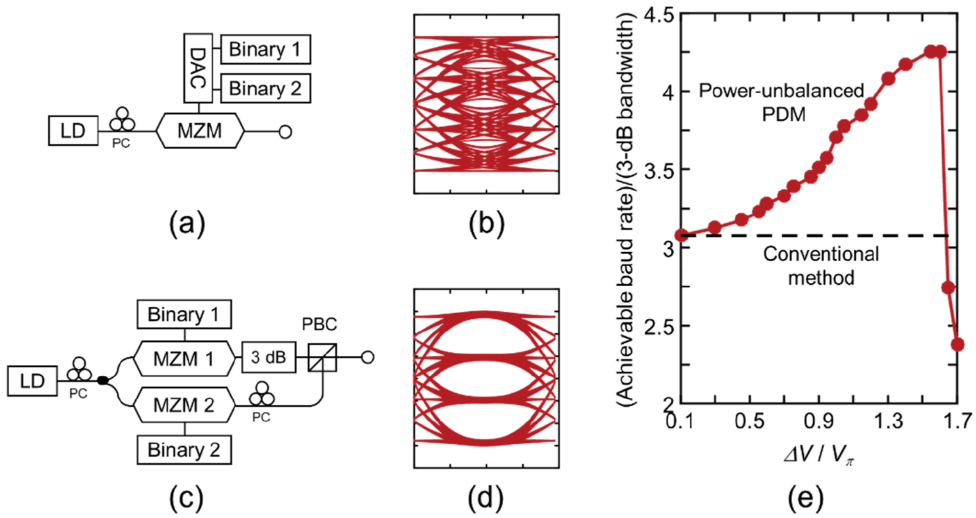

Fig. 3. (a) The simulation setup to generate the PAM4 signal by using an MZM with the conventional method, (b) the achieved eye diagram by using the conventional method, (c) the simulation setup to generate the PAM4 signal by using two MZMs with the proposed method, and (d) the achieved eye diagram by using the proposed method. (e) The ratio of the achievable baud rate of the PAM4 signal by using the proposed method to the 3-dB E/O bandwidth of the MZM estimated as a function of ΔV. The dashed line indicates the value achievable by using the conventional method (and setting $\Delta V = 0.6V_\pi$).

PAM4 signal by using an MZM with the conventional method. The MZM is modulated by an equi-spaced four-level electrical signal. We set ΔV to be as small as $0.6V_\pi$ to operate the MZM in the linear region. Figure 3(b) shows the eye diagram of the generated PAM4 signal. Under this condition, the average eye height of the PAM4 signal is estimated to be -0.23. This small value of the eye height is resulted from the signal distortions caused by the limited E/O bandwidth of the MZM since we neglect the noises in this analysis. Figure 3(c) shows the setup to generate the PAM4 signal by using the proposed method. As an example, we use two MZMs with the power-unbalanced PDM technique (instead of using an I/Q modulator). In this case, these two MZMs are modulated independently by electrical binary signals, and ΔV is set to be as large as $1.25V_\pi$ for both MZMs (since there is no need to worry about the equi-space intensity levels for the binary signal). We attenuate the output OOK signal of MZM1 by 3 dB and combine it

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with the output signal of MZM2 by using a polarization-beam combiner (PBC). Figure 3(d) shows the achieved eye diagram. Under this condition, the average eye height of the PAM4 signal is estimated to be 0.72, which is much larger than that of the PAM4 signal generated by the conventional method. These results clearly show that the PAM4 signal generated by the proposed method is more tolerant to the limited bandwidth of the MZM than the PAM4 signal generated by the conventional method.

We also compare the maximum baud rate of the PAM4 signal achievable by using the bandwidth-limited MZM with the conventional and proposed methods, assuming that the required BER is 10^{-3}. For the conventional method, we set ΔV to be as small as $0.6V_\pi$ to operate the MZM in the linear region. In this case, the achievable baud rate is estimated to be 3.1 times larger than the 3-dB E/O bandwidth of the MZM. On the other hand, for the proposed method, we evaluate the achievable baud rate as a function of ΔV applied to both MZMs. The results in Fig. 3(e) show that, if we set ΔV to be $0.1V_\pi$, the achievable baud rate is identical to the value obtained by using the conventional method. However, the achievable baud rate increases with ΔV, and reaches the maximum value when we set $\Delta V = 0.1V_\pi$. Under this condition, the achievable baud rate is 4.3 times larger than the 3-dB bandwidth of the MZM, which represents 38% improvement compared to the case of using the conventional method.

3. Experiments and results

We first evaluated the effects of overdriving a bandwidth-limited MZM on the generation of the high-speed OOK signal. For this purpose, we generated the OOK signal at various bit rates by using an MZM and a 92-GSample/s arbitrary waveform generator (AWG). The output of the AWG was amplified by using an electrical amplifier (3-dB bandwidth: 38 GHz) before being applied to the MZM. Figs. 4(a) and (b) shows the eye diagrams of the 40-Gb/s and 47.5-Gb/s electrical

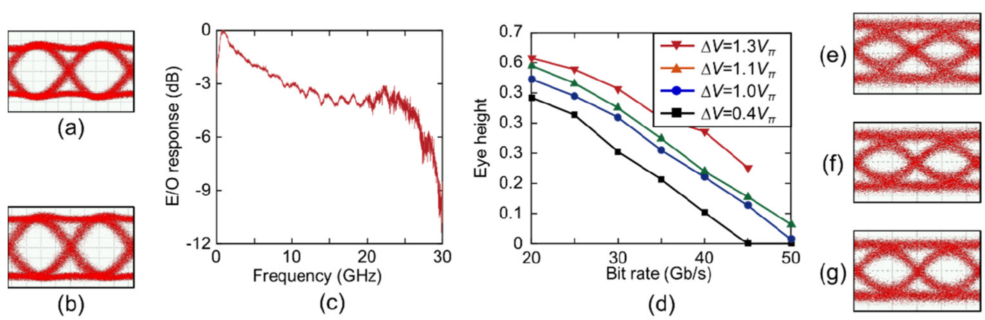

Fig. 4. Measured eye diagrams of the (a) 40-Gb/s and (b) 47.5-Gb/s electrical binary signals applied to the MZM. (c) Measured E/O response of the $LiNbO_3$ MZM used in this experiment and (d) measured eye heights of the OOK signal generated by using this MZM as a function of the bit rate for various values of ΔV. Measured eye diagrams of the 40-Gb/s OOK signal when ΔV was set to be (e) $0.4V_\pi$, (f) V_π, and (g) $1.3V_\pi$.

binary signals applied to the MZM. We could observe clear eye openings for both signals due to the sufficient bandwidth of the electrical amplifier. The 3-dB bandwidth of the commercial $LiNbO_3$ MZM used in this experiment was measured to be 10.5 GHz, as shown in Fig. 4(a). The V_π voltage of this MZM was 5.0 V. We boosted the output power of the modulated OOK signal to 15 dBm by using an erbium-doped fiber amplifier (EDFA). The amplified spontaneous emission noise was suppressed by using an optical bandpass filter (OBPF) with 1-nm passband. We set the optical power incident on the receiver to be as high as 9 dBm in order to neglect the effects of the receiver noises. We then measured the eye height and eye diagram of the OOK signal by using a digital sampling oscilloscope (DSO). Figure 4(b) shows the eye heights of the OOK

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signal measured as a function of the bit rate at various values of ΔV. In this experiment, the maximum value of ΔV was set to be $1.3V_\pi$ due to the limited saturation power of the driving amplifier. The larger eye height was observed at the higher value of ΔV regardless of the bit rate. This was because, when we overdrove the MZM (i.e., by setting $\Delta V > V_\pi$), its limited bandwidth was enhanced by the nonlinear transfer curve. We also observed that the effect of overdriving the MZM was larger at the higher bit rates. For example, when we overdrove the MZM by setting $\Delta V = 1.3V_\pi$, the eye height was increased by 0.25 for the 45-Gb/s OOK signal, while it was increased by only 0.13 for the 20-Gb/s OOK signal. However, we could not generate the 50-Gb/s OOK signal at $\Delta V = 1.3V_\pi$ due to the limited saturation power of the driving amplifier. The eye diagram of the OOK signal was also improved by overdriving the MZM, as shown in Figs. 4(c)~(e). From these results, we concluded that, even when the E/O bandwidth of the MZM was insufficient, it would be possible to generate the high-speed PAM4 signal by combining a pair of OOK signals generated by overdriving two MZMs.

To demonstrate the effectiveness of the proposed method for the generation of the high-speed PAM4 signal operating faster than the E/O bandwidth of the MZM, we compared the BER performances of the PAM4 signals generated by the conventional and proposed methods at various bit rates. Figure 5(a) shows the setup to evaluate the BER performance of the PAM4

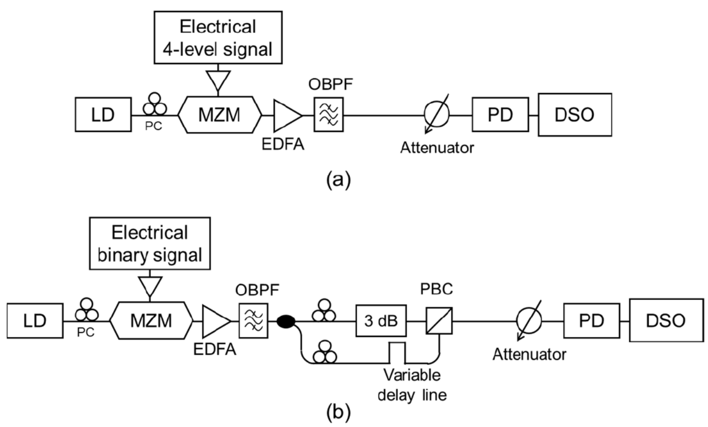

Fig. 5. Experimental setups to generate the PAM4 signal by using (a) the conventional and (b) proposed methods.

signal generated by using an MZM with the conventional method. We modulated the output of a 1.55-μm laser by using an MZM (3-dB bandwidth: 10.5 GHz) with a four-level electrical signal at various bit rates in the range of 40 ~ 72.5 Gb/s. The electrical signal was amplified by using a linear amplifier (3-dB bandwidth: 40 GHz) before being applied to the MZM. The extinction ratio of the PAM4 signal was set to be 7.5 dB to operate the MZM in the linear region. We boosted the optical power of the modulated PAM4 signal to 15 dBm by using an EDFA and sent to the PIN receiver (bandwidth: 50 GHz) through a short patch cord. This receiver had a sufficient bandwidth for our experiment. However, the sensitivity of this PIN receiver was poor as it had no integrated front-end amplifier. We sampled the received signal by using a DSO at 160 GSample/s and measured the BER performance. Figure 5(b) shows the setup to evaluate the BER performance of the PAM4 signal generated by using two MZMs with the proposed method. We modulated the output of a 1.55-μm laser by using an MZM with a binary signal at various bit rates in the range of 40 ~ 51.25 Gb/s. To enhance the E/O bandwidth of the MZM, we increased ΔV of the binary driving signal up to $1.3V_\pi$ by using a driving amplifier with a high saturation power (3-dB bandwidth: 38 GHz). However, when the binary signal was faster than 47.5 Gb/s, we could not increase ΔV to $1.3V_\pi$ due to the limited saturation power of the driving amplifier.

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Thus, we generated the OOK signal in the range of 47.5 ~ 51.25 Gb/s by using the maximum achievable value of ΔV from the driving amplifier (which was in the range of $1.1V_\pi \sim 1.3V_\pi$). The modulated OOK signal was amplified by an EDFA and then split into two parts by using a 1×2 coupler. The state-of-polarizations of the signals in these two parts were adjusted to be orthogonal from each other. One part was attenuated by 3 dB, and the other part was delayed (to decorrelate and synchronize two OOK signals). These two parts were then combined by using a PBC. The generated PAM4 signal was sent to a PIN receiver through a short patch cord. The received signal was sampled by using a DSO for the BER measurements.

Figure 6(a) shows the BER performances of the PAM4 signals generated by using the conventional and proposed methods. In this measurement, we set the optical power incident on the receiver to be 5 dBm (it was necessary to utilize such high optical power at the receiver since the PIN receiver used in this experiment had no integrated preamplifier). Thus, we could still neglect the effects of the receiver noises and attribute the BER degradations mostly to the signal distortions caused by the limited E/O bandwidth of the MZM. The results showed that, when we utilized the conventional method for the generation of the PAM4 signal with the MZM having a 3-dB bandwidth of 10.5 GHz, the maximum achievable bit rate was 58 Gb/s (assuming that the required BER was $<10^{-3}$). When we attempted to increase the bit rate further to 60 Gb/s by using the four-level electrical signal shown in Fig. 6(b), the eye diagram of the generated PAM4 signal was severely closed as shown in Fig. 6(c) due to the limited E/O bandwidth of the MZM. In comparison, when we utilized the proposed method with the same MZM, it was possible to increase the bit rate of the PAM4 signal to ~100 Gb/s. For example, unlike in the case of using the conventional method, a clear eye opening was observed even when we increased the bit rate to 60 and 80 Gb/s, as shown in Figs. 6(d) and (e), respectively. These results indicated that, by using the proposed method, we could increase the transmission capacity of the PAM4 signal by 64% (assuming that the required BER was $<10^{-3}$ by considering the Reed-Solomon (2720, 2550) code [16]).

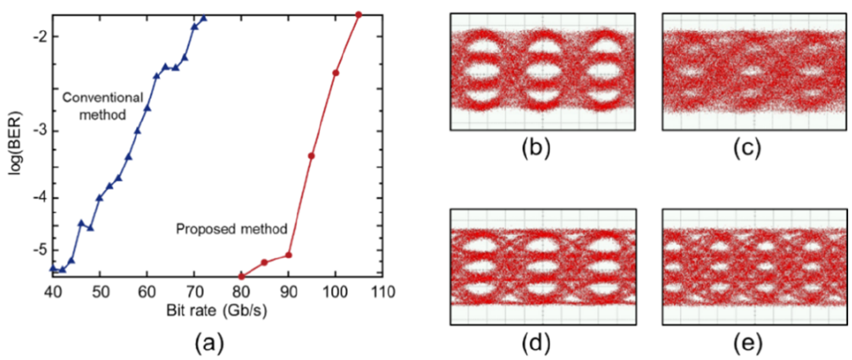

Fig. 6. (a) Measured BER curves of the PAM4 signals generated by using the conventional and proposed methods. Measured eye diagrams of (b) the 60-Gb/s four-level electrical signal and (c) the 60-Gb/s optical PAM4 signal generated by using the conventional method. Measured eye diagrams of (d) the 60-Gb/s and (e) 80-Gb/s optical PAM4 signals generated by using the proposed method.

We also evaluated the transmission performances of the 95-Gb/s PAM4 signals generated by the proposed method. In this experiment, we operated the MZM to have a negative chirp parameter of −1. Figure 7 shows the measured BER curves of the 95-Gb/s PAM4 signal after the transmission over up to 4 km of SSMF (dispersion: 17.3 ps/km/nm at 1550 nm). Under the back-to-back condition, the receiver sensitivity was measured to be −2.2 dBm (@ BER = 10^{-3}). However, the receiver sensitivities were improved to −9.4 and −6.6 dBm after the 2- and 4-km long SSMF transmissions, respectively. This was because the high-frequency components of the modulated signal were enhanced by the interaction between the fiber dispersion and the negative chirp of the MZM [17,18]. No equalization technique was used in this experiment.

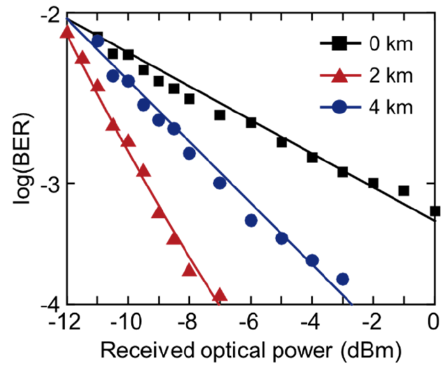

Fig. 7. Transmission performances of the 95-Gb/s PAM4 signal generated by the proposed method.

4. Summary

In the case of using the OOK signal, we could extend the E/O bandwidth of the MZM simply by overdriving it (i.e., by setting $\Delta V > V_\pi$) due to its nonlinear transfer function. However, when we generated the PAM signal by using the conventional method (i.e., generated the PAM4 signal by modulating an MZM with a four-level electrical signal), this technique could not be applied since ΔV should be smaller than V_π to operate the MZM in the linear region and generate the PAM4 signal with equi-spaced intensity levels. To overcome this problem, we proposed to generate the PAM4 signal by combining two orthogonal OOK signals (i.e., in different polarizations or I/Q spaces) obtained by two overdriven MZMs. For demonstration, we generated the high-speed PAM4 signal by combining two OOK signals using the power-unbalanced PDM technique and compared its performance with the result obtained by using the conventional method. The 3-dB bandwidth of the MZM used in these experiments was only 10.5 GHz. The results showed that we could generate the 95-Gb/s PAM4 signal by using the proposed method (assuming that the required BER was $<10^{-3}$). In comparison, when we utilized the conventional method, it was not possible to increase the operating speed of the PAM4 signal to be faster than 60 Gb/s under the same conditions. These results indicated that, when the 3-dB bandwidth of the MZM was limited to be only 10.5 GHz, we could increase the transmission capacity of the PAM4 signal by 64% by using the proposed method instead of the conventional method. We could also demonstrate the transmission of the 95-Gb/s PAM4 signal generated by the proposed technique over up to 4 km of SSMF. We believe that the proposed technique could be useful to overcome the bandwidth limitation of the optical modulator and generate the high-speed PAM4 signal operating at the speed much faster than 100 Gb/s.

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