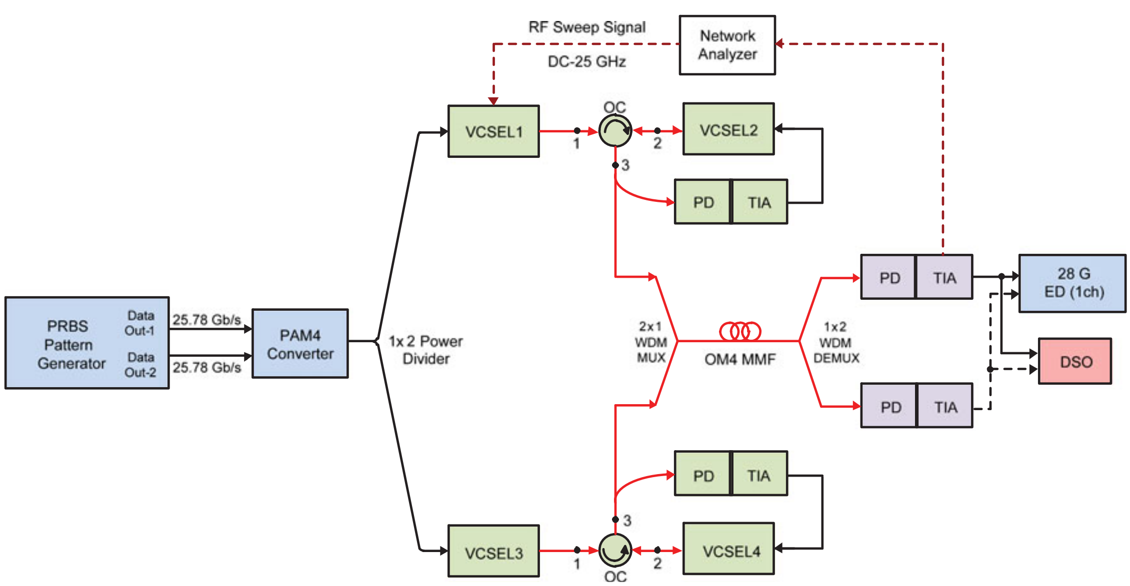
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

A 103.12-Gb/s WDM PAM4 VCSEL-Based Transmission With Light Injection and Optoelectronic Feedback Techniques

Volume 9, Number 1, February 2017

Hai-Han Lu, *Senior Member, IEEE*
Chung-Yi Li
Chang-Kai Lu
Chun-Ming Ho
Hwan-Wei Chen
Ming-Te Cheng
Zih-Yi Yang
Sheng-Jhe Huang



DOI: 10.1109/JPHOT.2016.2646364
1943-0655 © 2017 IEEE

A 103.12-Gb/s WDM PAM4 VCSEL-Based Transmission With Light Injection and Optoelectronic Feedback Techniques

Hai-Han Lu,[1] *Senior Member, IEEE*, Chung-Yi Li,[1] Chang-Kai Lu,[2] Chun-Ming Ho,[1] Hwan-Wei Chen,[3] Ming-Te Cheng,[1] Zih-Yi Yang,[1] and Sheng-Jhe Huang[1]

[1]Institute of Electro-Optical Engineering, National Taipei University of Technology, Taipei 10608, Taiwan
[2]Department of Electronic Engineering, Jinwen University of Science and Technology, New Taipei City 231, Taiwan
[3]Department of Biomedical Engineering, Yuanpei University of Medical Technology, HsinChu 300, Taiwan

DOI:10.1109/JPHOT.2016.2646364
1943-0655 © 2017 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Manuscript received November 28, 2016; revised December 23, 2016; accepted December 26, 2016. Date of publication December 29, 2016; date of current version January 16, 2017. This work was supported by the Ministry of Science and Technology of Taiwan under Grant MOST 104-2221-E-027-072-MY3 and Grant MOST 104-2218-E-007-024. Corresponding author: H.-H. Lu (e-mail: hhlu@ntut.edu.tw).

Abstract: A 103.12-Gb/s wavelength-division-multiplexing (WDM) four-level pulse amplitude modulation (PAM4) transmission based on 850-nm and 880-nm vertical-cavity surface-emitting lasers (VCSELs) with light injection and optoelectronic feedback techniques is proposed and experimentally demonstrated. Results show that two such 7.5-GHz VCSELs with light injection and optoelectronic feedback techniques are potent for 103.12-Gb/s WDM PAM4 transmissions. To the authors' knowledge, it is the first one to successfully adopt two VCSEL transmitters with light injection and optoelectronic feedback techniques in a WDM PAM4 transmission. A total transmission rate of 103.12 Gb/s (51.56 Gb/s/$\lambda \times 2$ λs) is achieved in the proposed WDM PAM4 transmissions. The link performances of the proposed WDM PAM4 transmissions have been evaluated in real time. Good real-time bit error rate performance and three independent clear eye diagrams are obtained at a 180-m OM4 multimode fiber operation. Such a proposed 103.12-Gb/s WDM PAM4 VCSEL-based transmission has great potential for providing efficient bandwidth in short-reach optical communications.

Index Terms: Four-level pulse amplitude modulation (PAM4), light injection and optoelectronic feedback, vertical-cavity surface-emitting laser (VCSEL), wavelength-division-multiplexing (WDM).

1. Introduction

The exponential growth of data rate requires highly congregate bandwidth in optical communications. Over the years, engineers have been dealing with different data formats that can satisfy the bandwidth and data rate requirements. Currently, four-level pulse amplitude modulation (PAM4) modulation has been proposed to increase the transmission rate of lightwave transmissions [1]–[6]. Compared with a non-return-to-zero (NRZ) signal, PAM4 signal provides 2 bits in each symbol with the advantages of high spectral efficiency, high transmission rate, and less bandwidth requirement for the optical devices. PAM4 transmission is thereby considered as one of the major solutions for short-reach lightwave transmissions.

A 45 Gb/s PAM4 transmission based on vertical-cavity surface-emitting laser (VCSEL) with light injection and optoelectronic feedback techniques has been demonstrated previously [7]. However, the transmission rate can be further enhanced by adopting wavelength-division-multiplexing (WDM) scheme. A WDM PAM4 transmission that utilizes different optical wavelengths to transmit the combined PAM4 signals would be quite useful for providing higher transmission rate. The use of WDM scheme provides a spectrally efficient way to increase the total transmission rate. Four 45 Gbps PAM4 VCSEL-based transmissions over wide-band OM4 multimode fiber (MMF) have been illustrated formerly [8]. Nevertheless, sophisticated short-wave WDM scheme and expensive ribbon wide-band OM4 MMFs are required. Further a 94-Gb/s PAM4 transmission over a few meters MMF using an 850-nm VCSEL, pre-emphasis, and receiver equalization has been presented in a previous study [9]. Nonetheless, expensive and sophisticated analog pre-emphasis and digital offline equalizer are needed. In addition, the transmission distance of 2 m MMF is much smaller than 180 m MMF adopted in our proposed WDM PAM4 transmissions. In this study, a 103.12 Gb/s WDM PAM4 VCSEL-based transmission with light injection and optoelectronic feedback techniques is proposed and experimentally demonstrated. This study presents a WDM PAM4 VCSEL-based transmission by using a 2-wavelength as an demonstration, for each wavelength carrying PAM4 signal with a transmission rate of 51.56 Gb/s (25.78 Gbaud/s). Thereby, a total transmission rate of 103.12 Gb/s is obtained in this WDM PAM4 VCSEL-based transmission. To authors' knowledge, it is the first one to successfully set up a WDM PAM4 VCSEL-based transmission with light injection and optoelectronic feedback techniques. The link performances of the proposed WDM PAM4 transmissions have been analyzed in real-time in terms of bit error rate (BER) performances and eye diagrams. BER values stay well below the 10^{-9} limit over a 180-m OM4 MMF transport. Clear eye diagrams (three independent eye diagrams) are also obtained at a 180-m OM4 MMF operation. OM4 MMF is the primary fiber media for short-reach PAM4 signal transmission. OM4 MMF provides a high bandwidth-distance product at 850-nm and 880-nm. To adopt the OM4 MMF into the 850-nm and 880-nm operations, the bandwidth-distance product has reached 4700 MHz·km [8]. As a result, a maximum reach of 180 m is achieved. Such a 103.12 Gb/s WDM PAM4 VCSEL-based transmission is a promising option for achieving high transmission rate. It reveals a prominent one with efficient bandwidth in short-reach lightwave transmissions.

2. Experimental Setup

Fig. 1 shows the experimental configuration of the proposed 103.12 Gb/s WDM PAM4 VCSEL-based transmissions with light injection and optoelectronic feedback techniques. Two binary pseudorandom bit sequence (PRBS) data streams at a length of $2^{15}-1$ at 25.78 Gb/s are generated from a two-channel PRBS generator. The amplitudes of the binary data streams are 1.6 and 0.8 V, respectively. These two 25.78 Gb/s NRZ signals are fed into a PAM4 converter to create a 51.56 Gb/s PAM4 signal with four levels and three independent eye diagrams. Then, the PAM4 signal is split into two PAM4 signals by a 40-GHz 1×2 power divider. VCSEL1, with a 3-dB bandwidth of 7.5 GHz, is directly modulated by a 51.56 Gb/s PAM4 signal. The optical output of VCSEL1 (849.75–850.17 nm) is injected into VCSEL2 (849.71–850.13 nm) through an 850-nm optical circulator (OC). The optical output of VCSEL3 (879.75–880.17 nm) is also injected into VCSEL4 (879.72–880.13 nm) through an 880-nm OC. Port 3 of the OC is separated by a 1×2 optical splitter. A portion of the laser light is used for feedback through an optoelectronic feedback loop. The photodiode (PD) with trans-impedance amplifier (TIA) converts the laser light into a 51.56 Gb/s PAM4 signal to modulate the VCSEL2 (VCSEL4) directly. Another portion of the laser light is utilized for 51.56 Gb/s PAM4 transmission. The optical signals are multiplexed by a 2×1 WDM multiplexer (MUX). The WDM MUX, with a channel spacing of 30 nm, is thin-film filter based. System links have different transmission lengths in the range of 0–200 m

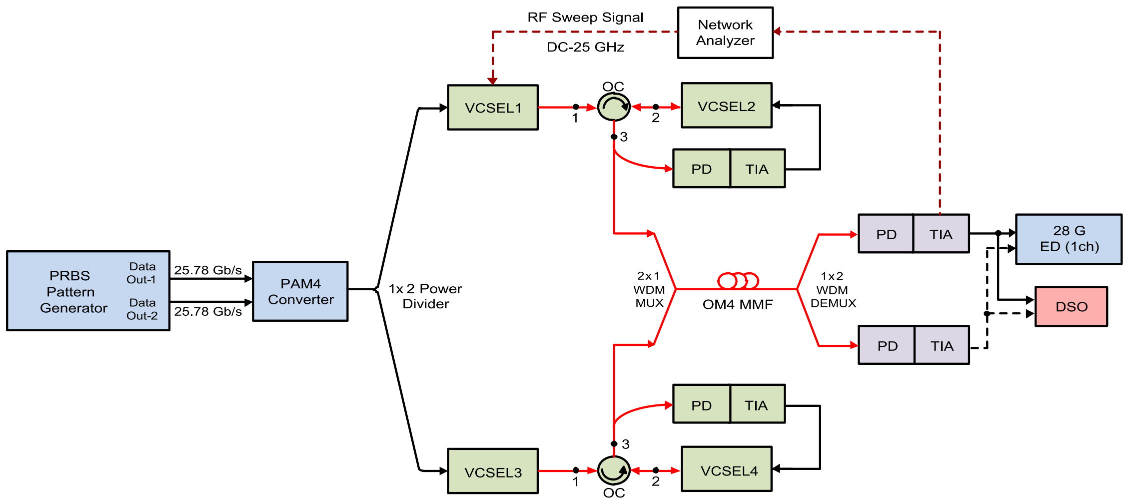


Fig. 1. Experimental configuration of the proposed 103.12 Gb/s WDM PAM4 VCSEL-based transmissions with light injection and optoelectronic feedback techniques.

OM4 MMF (with core diameter of 50 $\pm$ 2.5 μm, cladding diameter of 125 $\pm$ 1.0 μm, and numerical aperture of 0.200 $\pm$ 0.015). The transmitted optical signals are then demultiplexed by a 1 $\times$ 2 WDM demultiplexer (DEMUX) with performance characteristics similar to that of the WDM MUX. After demultiplexing, each optical PAM4 signal reaches a PD with TIA, with a 3-dB bandwidth of 25 GHz. The PD exists responsivity of around 0.42 A/W (at 860 nm). The received 51.56 Gb/s PAM4 signal is inputted into a one-channel 28 Gb/s error detector (ED). BER measurement is performed by auto-searching using a one-channel 28 Gb/s ED and the PAM4 3-eye sampling approach [7], [10], [11]. The eye diagrams of the transmitted 51.56 Gb/s PAM4 signal are seized using a digital storage oscilloscope (DSO) at the receiver side.

Meanwhile, the measurement setup of the frequency response of the PAM4 VCSEL2-based transmissions is also shown in Fig. 1. RF sweep signal (DC – 25 GHz) generated from a network analyzer is fed into the VCSEL1. The function of the network analyzer is to measure the frequency response of the PAM4 VCSEL2-based transmissions. After PD detection and TIA amplification, the RF sweep signal is fed into the network analyzer. Thus, the frequency response of the PAM4 VCSEL2-based transmissions is measured under the scenarios of free-running, as well as light injection and optoelectronic feedback. It should be noted that two signals (51.56 Gb/s PAM4 signal and RF sweep signal) from two different ports to modulate VCSEL1 are not transmitted at the same time. As the 51.56 Gb/s PAM4 signal modulates VCSEL1, we turn off the RF sweep signal. In the same manner, as the RF sweep signal modulates VCSEL1, we turn off the 51.56 Gb/s PAM4 signal.

3. Experimental Results and Discussions

The optical spectrum of VCSEL2 for free-running scenario (849.71–850.13 nm) is shown in Fig. 2(a). If VCSEL2 is injection-locked, its optical spectrum shifts to a longer wavelength (849.75–850.17 nm) by a small amount, as shown in Fig. 2(b). Similarly, the optical spectrum of VCSEL4 for free-running scenario (879.72–880.13 nm) is shown in Fig. 2(c). If VCSEL4 is injection-locked, its optical spectrum shifts to a longer wavelength (879.75–880.17 nm) by a small amount, as shown in Fig. 2(d). Since in injection locking the injected laser is coerced to oscillate at the injection wavelength rather than at the free-running wavelength, the wavelength range of VCSEL1 is deduced to be 849.75–850.17 nm, and that of VCSEL3 is 879.75–880.17 nm. The wavelength of the master laser (VCSEL1/VCSEL3) must be longer than that of the slave laser (VCSEL2/VCSEL4) by a small amount to achieve a high 3-dB bandwidth.

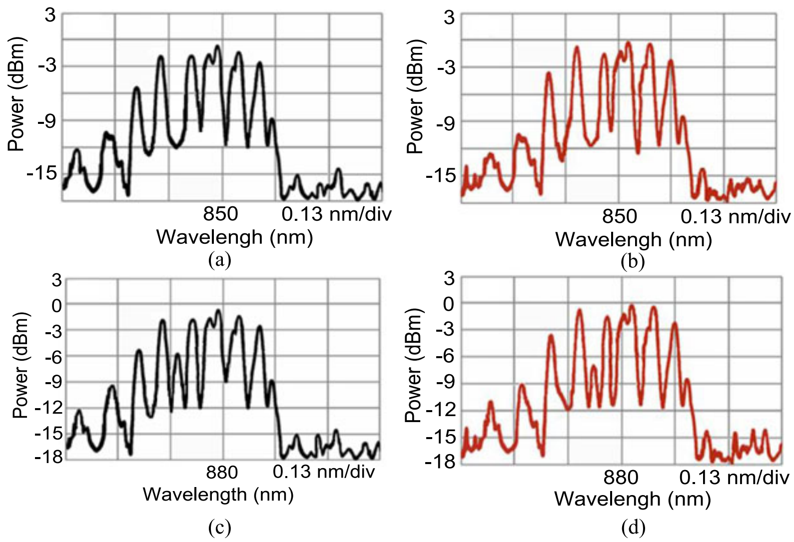


Fig. 2. Optical spectrum of VCSEL2 for (a) free-running (849.71–850.13 nm) and (b) injection-locked (849.76–850.17 nm) scenarios and the optical spectrum of VCSEL4 for (c) free-running (879.72–880.13 nm) and (d) injection-locked (879.75–880.17 nm) scenarios.

The rate equations for laser diode with light injection and optoelectronic feedback techniques can be stated as [12]

$$\frac{\partial n}{\partial t} = \frac{I}{eV} - \frac{n}{\tau_n} - GP + k_{loop}[P(t-\tau) - P_{av}] \tag{1}$$

$$\frac{\partial P}{\partial t} = \left(G - \frac{1}{\tau_p}\right)P + \frac{2}{\tau_g}\sqrt{PP_i}\cos(\theta) \tag{2}$$

$$\frac{\partial \theta}{\partial t} = -d\omega + \frac{1}{2}\alpha\left(G - \frac{1}{\tau_p}\right) - \frac{1}{\tau_g}\sqrt{\frac{P_i}{P}}\sin(\theta) \tag{3}$$

where n is the carrier density, I is the slave pumping current, V is the laser active volume, τ_n is the carrier lifetime, G is the gain related to the carrier density n, P is the photon density, k_{loop} is the feedback coefficient, τ is the delay of the feedback loop, P_{av} is the average photon density, τ_p is the photon lifetime, τ_g is the cavity transit time, P_i is the external injection power, θ is the phase difference between slave and master lasers, $d\omega$ is the frequency detuning, and α is the linewidth enhancement factor.

The relaxation oscillation damping rate Γ_f of a slave laser with light injection and optoelectronic feedback can be derived from the above rate equations [12]. Light injection and optoelectronic feedback increase the laser stability when $\Gamma_f > \Gamma_o$, where Γ_o denotes the damping rate of a slave laser only with light injection, and lead to out-of-phase carrier re-injection. The laser resonance frequency (f_o) of a master laser with light injection and optoelectronic feedback can be expressed as

$$f_o^2 = \frac{GP}{4\pi^2\tau_\rho}. \tag{4}$$

From (4), it can be seen that out-of-phase carrier re-injection increases the photon density (P), which results in the improvement of laser resonance frequency (f_o). The frequency responses of the PAM4 VCSEL2-based transmissions for free-running, light injection, as well as light injection and optoelectronic feedback scenarios are shown in Fig. 3. The 3-dB bandwidths are 7.5, 13.2, and 21.8 GHz for the scenarios of free-running, light injection, as well as light injection and optoelectronic feedback, respectively. To compare with previous studies [7], [13], the bandwidth expansion by light

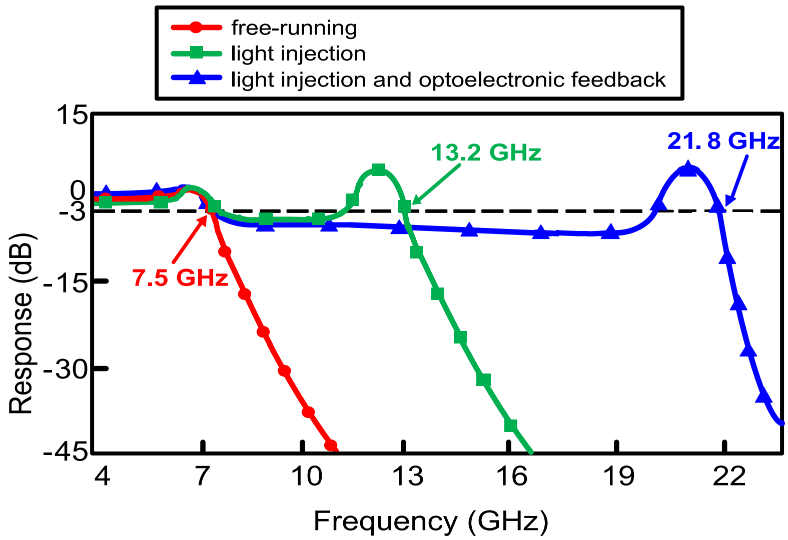


Fig. 3. Frequency responses of the PAM4 VCSEL2-based transmisions for free-running, light injection, as well as light injection and optoelectronic feedback scenarios.

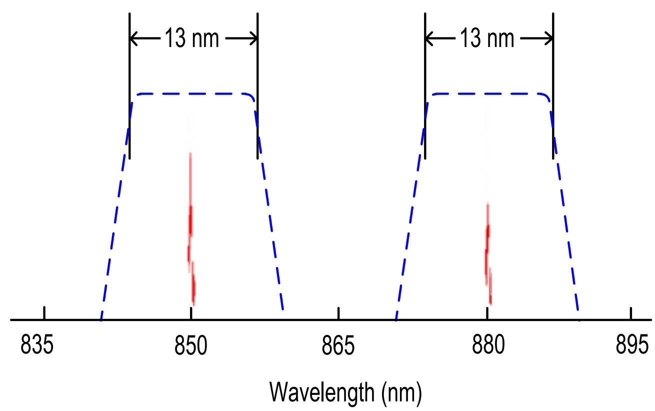


Fig. 4. Combined optical signals of VCSEL2 and VCSEL4 with light injection and optoelectronic feedback techniques.

injection and optoelectronic feedback techniques are consistent with data reported in the literature. Light injection and optoelectronic feedback techniques further enhance the frequency response of the PAM4 VCSEL2-based transmissions to approximate 3 times ($21.8/7.5 \sim 2.9$), indicating that such a 850-nm VCSEL transmitter with light injection and optoelectronic feedback techniques is an option for 51.56 Gb/s ($21.8 \times \sqrt{2} \times 2 = 61.66 > 51.56$) PAM4 signal transmission.

Given that the VCSEL1 and VCSEL3 are directly modulated by a 51.56 Gb/s PAM4 signal, the combined optical signals of VCSEL2 and VCSEL4 with light injection and optoelectronic feedback techniques are illustrated in Fig. 4. Clearly, the channel spacing of these two wavelengths is 30 nm and the channel passband width of WDM MUX WDM DEMUX is 13 nm. Given that the optical PAM4 signal is picked up by the WDM DEMUX, the 51.56 Gb/s PAM4 signal can be obtained over different lengths of OM4 MMF.

The total BER of the PAM4 signal can be obtained from the symbol error rate (SER) of the bottom (SER_{bot}), middle (SER_{mid}), and top (SER_{top})

$$\mathrm{BER} = \frac{1}{2}\mathrm{SER}_{bot} + \mathrm{SER}_{mid} + \frac{1}{2}\mathrm{SER}_{top}. \tag{5}$$

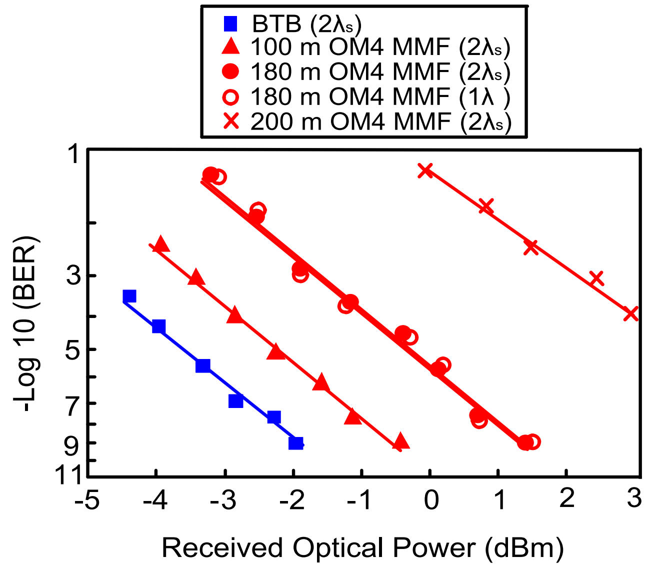


Fig. 5. Measured BER curves of the 51.56 Gb/s PAM4 VCSEL-based transmission (VCSEL2 with light injection and optoelectronic feedback techniques).

BER measurement is carried out by auto-searching using a one-channel ED and the PAM4 3-eye (top/middle/bottom) ampling approach. This approach is a low-cost PAM4 BER measurement approach for calculating the total BER [7], [10], [11]. It is worth employing due to a converter from PAM4 back to NRZ is not needed. The measured BER curves of the 51.56 Gb/s PAM4 VCSEL-based transmission (VCSEL2 with light injection and optoelectronic feedback techniques) over different lengths of OM4 MMF in the range of 0–200 m are presented in Fig. 5. It can be seen that the BER performance degrades as the OM4 MMF transmission length is increased. However, as the OM4 MMF transmission length increases, the effect of modal dispersion introduced by the OM4 MMF increases as well. Such increase of modal dispersion leads to the decline of BER performance. Since there is a trade-off between the OM4 MMF transmission length and the BER performance, system designers must address the maximum OM4 MMF transmission length to assure the working implementation of WDM PAM4 transmissions. A 1.7-dB power penalty exists between back-to-back (BTB) and over a 100-m OM4 MMF transport at a 10^{-9} BER operation. Further, a power penalty of about 3.4 dB exists between BTB and over a 180-m OM4 MMF transport scenarios at a 10^{-9} BER operation. Over a 200-m OM4 MMF transport, the BER value declines to 10^{-4} because of the significant increase of modal dispersion. The bandwidth of MMF (B_{MMF}) is given by the following equation [14]:

$$B_{MMF} = \frac{1}{DL} \tag{6}$$

where D is the modal dispersion, and L is the length of MMF. According to (6), larger modal dispersion and longer MMF length cause lower transmittable bandwidth, by which leading to poor BER performance. As the OM4 MMF transmission length is 180 m, the bandwidth-distance product is 4640.4 MHz·km (25.78 GHz $\times$ 0.18 km). It satisfies the bandwidth-distance product requirement of OM4 MMF ($<$4700 MHz·km). Nonetheless, as the OM4 MMF transmission length is 200 m, the bandwidth-distance product is 5156 MHz·km (25.78 GHz $\times$ 0.2 km), which cannot satisfy the bandwidth-distance product requirement of OM4 MMF ($>$4700 MHz·km).

To show a direct relation with crosstalk and BER performance, we turn off another optical PAM4 signal (VCSEL4 with light injection and optoelectronic feedback techniques) and measure the BER values for the scenario of over a 180-m OM4 MMF transport. Clearly, crosstalk does not exist, and

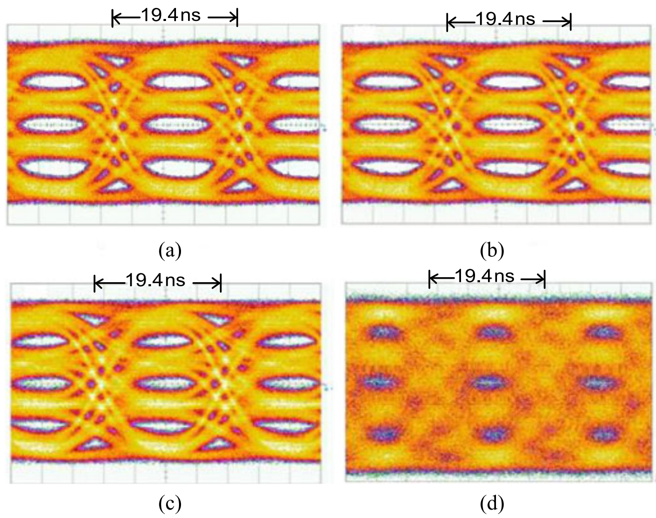


Fig. 6. Eye diagrams of the 51.56 Gb/s PAM4 signal (VCSEL4 with light injection and optoelectronic feedback techniques) (a) for BTB, (b) over a 100-m OM4 MMF transport, (c) over a 180-m OM4 MMF transport, and (d) over a 200-m OM4 MMF transport scenarios.

BER performance is not affected due to a large channel spacing of 30 nm between two optical PAM4 signals.

The eye diagrams of the 51.56 Gb/s PAM4 signal (VCSEL4 with light injection and optoelectronic feedback techniques) over different transmission lengths of OM4 MMF are shown in Fig. 6(a)–(d). The traces of the 51.56 Gb/s PAM4 signal are observed in BTB [Fig. 6(a)] and over a 100-m OM4 MMF transport [see Fig. 6(b)] scenarios. Some amplitude and phase fluctuations can be observed for over a 180-m OM4 MMF transport scenario [see Fig. 6(c)]. The modal noise induced by the multimodal VCSEL will degrade the BER performance. Many modes are generated in VCSEL when the optical output power increases. However, an adequate driving current of 10 mA is employed to drive the multimodal VCSEL to decrease the modal noise. Moreover, when the VCSEL driving current is increased from 10 mA to 14 mA, the extinction ratio (ER) is decreased from 3.4 dB to 3.2 dB. Such ER decrement makes the eye diagrams of the PAM4 signal at the receiver side to be more sensitive to amplitude and phase fluctuations. Thereby, an adequate driving current of 10 mA and an optimum ER of 3.4 dB are adopted for over a 180-m OM4 MMF transport scenario. Eye diagrams are closed for over a 200-m OM4 MMF transport scenario [see Fig. 6(d)].

4. Conclusion

A 103.12 Gb/s WDM PAM4 transmission based on VCSELs with light injection and optoelectronic feedback techniques is proposed and successfully demonstrated. Results show that two 7.5-GHz VCSELs with light injection and optoelectronic feedback techniques are sufficiently powerful for a 103.12 Gb/s WDM PAM4 transmission. To authors' knowledge, this study is the first to adopt two VCSEL transmitters with light injection and optoelectronic feedback techniques in WDM PAM4 transmissions. The link performances of the WDM PAM4 transmissions have been evaluated on-line. Good real-time BER performance of 10^{-9} and three independent clear eye diagrams are achieved at a 180-m OM4 MMF operation. Such an innovative WDM PAM4 transmission can become an attractive option to accelerate the development of the short-reach lightwave transmissions.

References

[1] R. Motaghiannezam *et al.*, "52 Gbps PAM4 receiver sensitivity study for 400GBase-LR8 system using directly modulated laser," *Opt. Exp.*, vol. 24, no. 7, pp. 7374–7380, 2016.

[2] S. Zhou, X. Li, L. Yi, Q. Yang, and S. Fu, "Transmission of 2 × 56 Gb/s PAM-4 signal over 100 km SSMF using 18 GHz DMLs," *Opt. Lett.*, vol. 41, no. 8, pp. 1805–1808, 2016.
[3] C. Yang, R. Hu, M. Luo, Q. Yang, and C. Li, "IM/DD-Based 112-Gb/s/lambda PAM-4 transmission using 18-Gbps DML," *IEEE Photon. J.*, vol. 8, no. 3, Jun. 2016, Art. no. 7903907.
[4] S. Lange *et al.*, "Low switching voltage Mach-Zehnder modulator monolithically integrated with DFB laser for data transmission up to 107.4 Gb/s," *IEEE/OSA J. Lightw. Technol.*, vol. 34, no. 2, pp. 401–406, Jan. 2016.
[5] S. M. R. Motaghiannezam *et al.*, "Single chip 52 Gb/s PAM4 transmission through −58 and +10 ps/nm chromatic dispersion using directly modulated laser," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2016, Paper Th2A.59.
[6] D. Sadot, G. Dorman, A. Gorshtein, E. Sonkin, and O. Vidal, "Single channel 112 Gbit/sec PAM4 at 56 Gbaud with digital signal processing for data centers applications," *Opt. Exp.*, vol. 23, no. 2, pp. 991–997, 2015.
[7] H. H. Lu *et al.*, "45 Gb/s PAM4 transmission based on VCSEL with light injection and optoelectronic feedback techniques," *Opt. Lett.*, vol. 41, no. 21, pp. 5023–5026, 2016.
[8] R. Motaghiannezam *et al.*, "Four 45 Gbps PAM4 VCSEL based transmission through 300 m wideband OM4 fiber over SWDM4 wavelength grid," *Opt. Exp.*, vol. 24, no. 15, pp. 17193–17199, 2016.
[9] K. Szczerba, T. Lengyel, M. Karlsson, P. A. Andrekson, and A. Larsson, "94-Gb/s 4-PAM using an 850-nm VCSEL pre-emphasis, and receiver equalization," *IEEE Photon. Technol. Lett.*, vol. 28, no. 22, pp. 2519–2521, Nov. 2016.
[10] K. Szczerba *et al.*, "4-PAM for high-speed short-range optical communications," *J. Opt. Commun. Netw.*, vol. 4, no. 11, pp. 885–894, 2012.
[11] E. Agrell, J. Lassing, E. G. Ström, and T. Ottosson, "On the optimality of the binary reflected Gray code," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3170–3182, Dec. 2004.
[12] P. Saboureau, J. P. Foing, and P. Schanne, "Injection-locked semiconductor lasers with delayed optoelectronic feedback," *IEEE J. Quantum Electron.*, vol. 33, no. 9, pp. 1582–1591, Sep. 1997.
[13] C. Y. Chen, P. Y. Wu, H. H. Lu, Y. P. Lin, T. W. Jhang, and C. L. Ying, "Hybrid lightwave subcarrier CATV/16-QAM/16-QAM OFDM transmission system," *Opt. Lett.*, vol. 38, no. 22, pp. 4538–4541, 2013.
[14] M. K. Liu, *Principles and Applications of Optical Communications*. Homewood, IL, USA: Irwin, 1996, ch. 4, pp. 140–151.