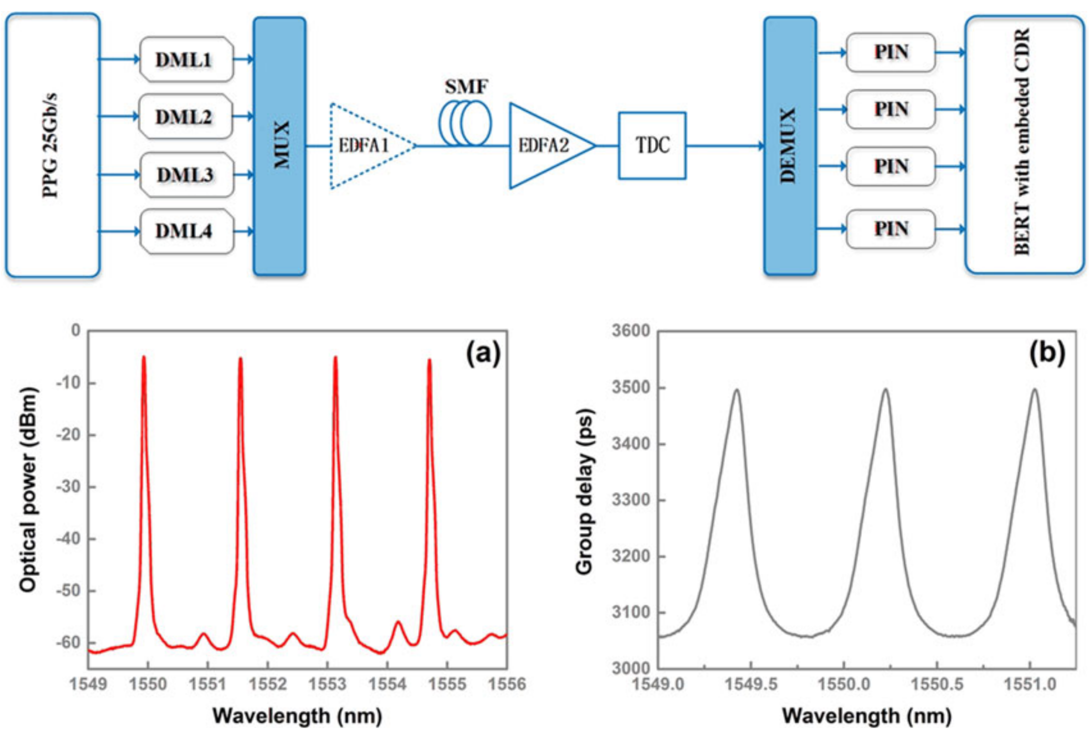
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

4 × 25-Gb/s NRZ-OOK Signals Transmission Over a 160-km Single-Mode Fiber Using 10G-Class DML and Photodiode

Volume 10, Number 3, June 2018

Lei Xue
Lilin Yi
Weisheng Hu



DOI: 10.1109/JPHOT.2018.2835574
1943-0655 © 2018 IEEE

4 × 25-Gb/s NRZ-OOK Signals Transmission Over a 160-km Single-Mode Fiber Using 10G-Class DML and Photodiode

Lei Xue, Lilin Yi, and Weisheng Hu

State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Institute for Advanced Communication and Data Science, Shanghai Jiao Tong University, Shanghai 200240, China

DOI:10.1109/JPHOT.2018.2835574
1943-0655 © 2018 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 February 4, 2018; revised April 26, 2018; accepted May 8, 2018. Date of publication May 11, 2018; date of current version June 21, 2018. This work was supported by the National Natural Science Foundation of China under Grant 61575122. Corresponding author: Lilin Yi (e-mail: lilinyi@sjtu.edu.cn).

Abstract: In this paper, we have experimentally demonstrated the C-band 4 × 25-Gb/s non-return-to-zero ON-OFF-keying (NRZ-OOK) signals over a 160-km single-mode fiber transmission based on 10G-class directly-modulated lasers and photodiodes. The excessive negative dispersion at the receiver side is used to equalize the frequency response of bandwidth-limited directly-modulated signal, therefore enables 25-Gb/s NRZ-OOK transmission based on 10G-class optical devices. By employing a multichannel chromatic dispersion compensation module in the receiver, a single optical device can be used to equalize the frequency response of multiple channels realizing low-cost and high-capacity signal transmission. The results shown in this paper reveal that our proposed scheme would be a promising candidate for a low-cost transition to 100 Gb/s (4 × 25 Gb/s) for the point-to-point metro network applications.

Index Terms: Directly modulated laser (DML), direct detection, dispersion-supported equalization (DSE), non-return-to-zero on-off-keying (NRZ-OOK).

1. Introduction

In order to meet the global explosive traffic requirement, interconnection capacity up to 100-Gb/s between the core and the access networks has to be evolved, and the bandwidth bottleneck transfers to the metro networks [1], [2]. Metro networks are very cost-sensitive, so the main challenge is to guarantee high capacity performance without great increase in capital expenditure. Among different techniques, direct modulation and direct detection (DM-DD) is the preferred solution due to the low-cost feature. Recently, experimental demonstrations of 100-Gb/s modulation on a single wavelength based on DM-DD has been reported in point-to-point transmission systems [3]–[5]. In [3] a 128-Gb/s 4-level phase-amplitude modulation (PAM-4) transmission over 2-km single-mode fiber (SMF) in O-band has been achieved based on commercial 25 Gbps electro-modulated laser (EML) and PIN. A single wavelength 100-Gb/s discrete multi-tone (DMT) signal has been transmitted over 10-km SMF in the O-band [4] and using multi-band carrier-less amplitude/phase (CAP) modulation, 102-Gb/s signal transmission over 15-km SMF have also been successful realized [5]. However, PAM-4, DMT and CAP modulation formats used in [3]–[5] are off-line processed with complex digital signal processing (DSP) algorithms at the receiver, which increases the system cost and deployment difficulty. Besides, the transmission distance of 100-Gb/s signal based on the directly-modulated laser (DML) is limited to 40 km due to chromatic dispersion and power attenuation constraints [6]. To support longer transmission distance, wavelength-division-multiplexed (WDM) based 100 Gb/s systems, such as $4 \times 25 - \text{Gb/ s}$ are preferred owing to lower bit rate per channel [6]–[8]. Compared with high-order modulation formats, non-return-to-zero on-off-keying (NRZ-OOK) is the most widely used modulation format in metro and access networks since no digital signal processing (DSP) is required for signal detection, however 25G-class optical devices are still costly. If utilizing bandwidth-limited optical devices, frequency equalization technique should be employed to improve the signal quality, which has been mostly done in digital domain [9]–[11]. In [11] a 100-Gb/s (4 × 28-Gb/s) NRZ-OOK WDM system has been demonstrated in metro networks over 80-km single-mode fiber (SMF) based on 10G-class optical components. Signal pre-distortion and maximum likelihood sequence estimator (MLSE) algorithm are used to compensate the bandwidth limitation. Therefore, DSP is still required and the transmission distance is limited at 80 km. The other solution is to equalize the frequency response in optical domain [12], [13]. A delay interferometer (DI) is employed to reshape the 25-Gb/s optical signal to achieve 40-km SMF transmission based on 10G-class DML and PIN. Although this solution is with low complexity and more cost-effective, the transmission distance is limited to 40-km SMF. Until now, there have been no experimental demonstrations of 100-Gb/s NRZ-OOK signal transmission over more than 100-km SMF based on low-cost 10G-class optical components without DSP.

In this paper, C-band 4 × 25-Gb/s NRZ-OOK signal transmission over 160-km SMF is experimentally demonstrated based on 4 sets of 10G-class directed modulated lasers (DMLs) and PINs. After 160-km SMF transmission, an optical dispersion compensator (ODC) is used to compensate fiber dispersion and the excessive negative dispersion is used to equalize the limited bandwidth of the system. Enabled by the dispersion-supported equalization (DSE) technique [14], the eye diagrams become clearly open after 160-km SMF transmission. It is noted that no DSP is required and the real-time signal detection can be successfully realized using commercial 25-Gb/s clock/data recovery (CDR) chips. Investigations show that our proposed scheme is a promising candidate to enable low complexity and low-cost DM-DD 100-Gb/s WDM, point-to-point, metro network transmission system. To the best of our knowledge, this is the first demonstration of 4 × 25-Gb/s NRZ-OOK transmission over more than 100-km SMF based on 10G-class DMLs and PINs without DSP.

2. Principle

For a DM-DD transmission system, the frequency response of fiber channel varies with the dispersion value. Multiple Frequency notches will appear at the high frequency part with the increase of fiber length, which will significantly restricts the capacity of system. On the other hand, when DML is used as modulator at the transmitter side, the optical signal will be more sensitive to fiber dispersion due to the DML chirp. However, if the fiber can generate negative dispersion at the transmission window, the transmission performance will be better than chirp-free case and long-reach transmission based on DML can be achieved [15]. Optical fiber transmission system frequency response transfer function based on DMLs can be expressed as [16]–[18],

$$\begin{aligned} H(f) &= \sqrt{\alpha^2+1}\cos\left(\theta+\tan^{-1}\alpha\right)+j\frac{\alpha\varepsilon P_0}{2\pi f}\sin(\theta) \\ &= H_{tst}(f, L) + H_{\text{adb}}(f, L) \end{aligned} \tag{1}$$

In this equation, the first term $H_{tst}(f)$ and the second term $H_{\text{adb}}(f)$ are originated from transient chirp and adiabatic chirp of DML, respectively. α is the linewidth enhancement factor, ε is the gain confinement factor, P_0 is the output power of laser and f is the frequency of modulated signal. Also, θ is given as $\pi D\lambda^2 L f^2/c$, where D is the fiber dispersion parameter, λ is the optical wavelength, L is the transmission distance, c is the speed of light in vacuum. From Eq. (1), it is obvious that, for a given output power, $H_{\text{adb}}(f)$ and $H_{tst}(f)$ will change with different fiber dispersion, and the total

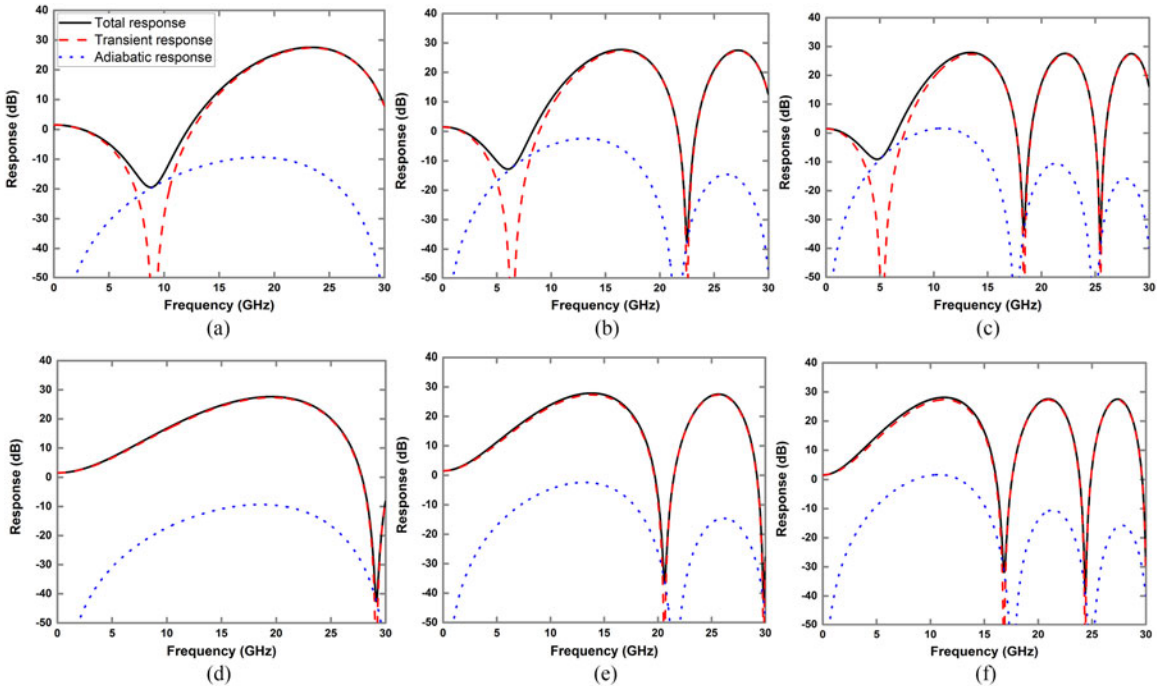


Fig. 1. Theoretically calculated frequency response curves of SMMF at 1550 nm in a DM/DD system when the dispersion values are (a) 170 ps/nm, (b) 340 ps/nm, (c) 510 ps/nm, (d) −170 ps/nm, (e) −340 ps/nm, (f) −510 ps/nm.

frequency response mainly depends on $H_{tst}(f)$. Fig. 1 shows the frequency response of SMF at 1550 nm at different dispersion values obtained by using Eq. (1). In this calculation, we used the parameters of $\alpha = 3.8$, $\varepsilon = 3.7$ GHz/mw and $P_0 = 9$ dBm. The effect of limited bandwidth of DML and DD receiver is not included in this figure. Due to the feature of Cosine and Sine function, the transient chirp induces a low-pass filter (LPF)-like frequency response, while the adiabatic chirp exhibits a high-pass filter (HPF)-like frequency response and there are multiple power notches in their response curves, as shown in Fig. 1. When the dispersion value is 170 ps/nm, the frequency notch induced by transient chirp will locate at 9 GHz, which will significantly degrade signal when its capacity beyond 20 Gb/s. With the increase of dispersion value, the frequency notch will move towards the lower frequency direction, therefore the transmission distance will also be limited. However, if the dispersion value of fiber is −170 ps/nm, the low-pass frequency notch transfers to over 20 GHz and the high frequency components between 0 to 20 GHz are also improved. Besides, with the increase of negative dispersion value, the first frequency notch moves towards to low frequency direction and more frequency notches appears in higher frequency region. Therefore, the limited bandwidth of DM-DD system can be improved through the interaction effect between a certain amount of negative dispersion and transient chirp, and we call this effect as DSE.

3. Experimental Setup and Results

Fig. 2 depicts the experimental setup of proposed 100-Gb/s metro network. The 25-Gb/s NRZ-OOK signals are generated by a four-channel pulse pattern generator (PPG, Keysight N4960A) with an output amplitude of 1.2 V. The generated electrical signals are loaded onto 10G-class DML to achieve electrical-to-optical conversion with 10-dBm output power. To achieve 100-Gb/s system capacity, we use four DMLs operating at 1549.96 nm, 1551.52 nm, 1553.12 nm, and 1554.74 nm with 200-GHz channel spacing as transmitter each carrying 25-Gb/s NRZ-OOK signal. The optical spectrum of the four DMLs is shown in inset (a) of Fig. 2. A C-band Erbium-doped fiber amplifier

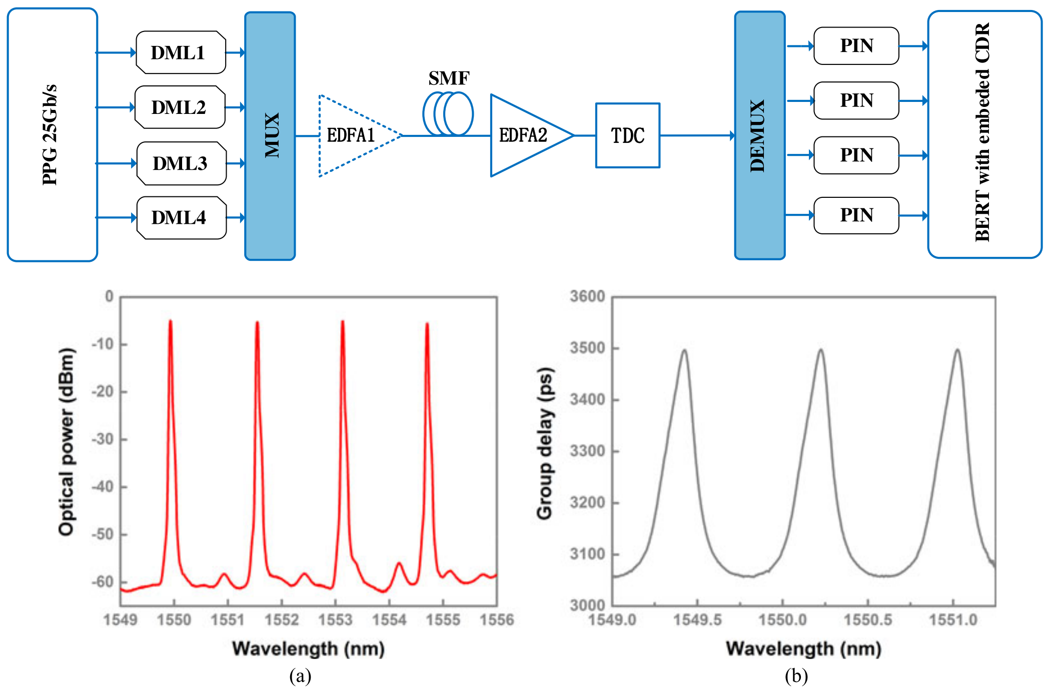
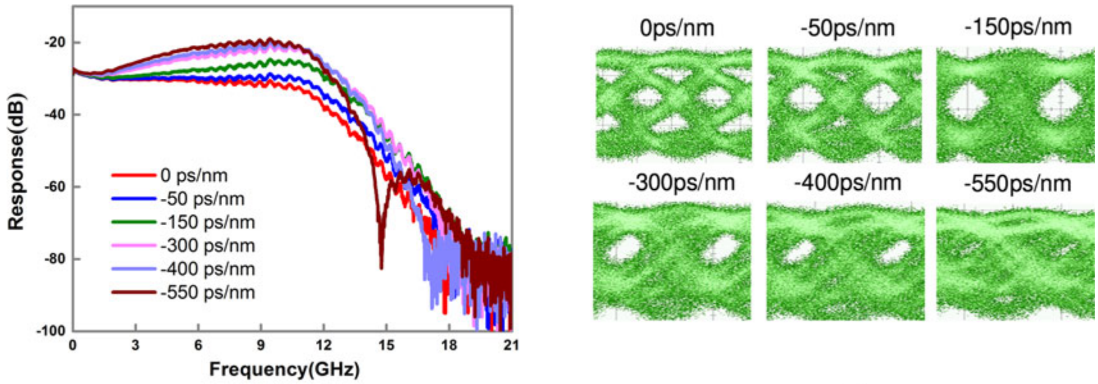


Fig. 2. Experimental setup of 100-Gb/s metro network. Inset: (a) optical spectral at the transmitter side; (b) the measured group delay curve of TDC module.

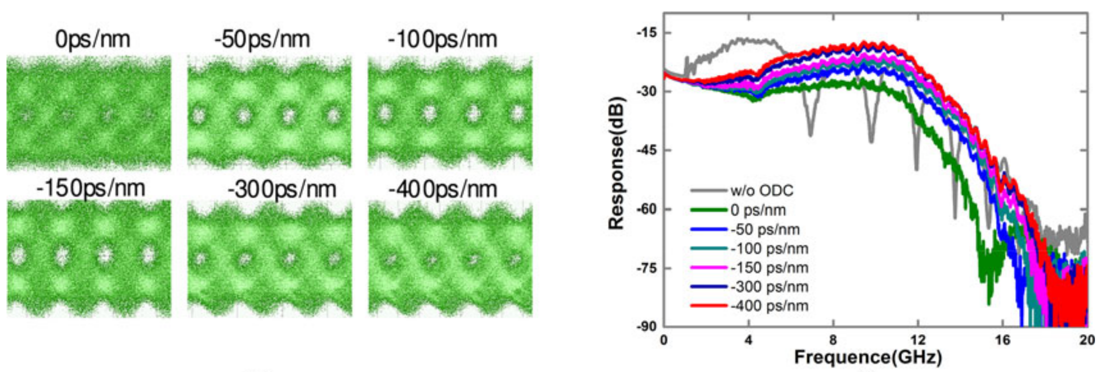
(EDFA1) following the MUX is then employed to control the launch power which is only used at 160-km transmission case in the following results. After the SMF transmission, we use another EDFA as pre-amplifier to compensate the fiber insertion loss. Then a tunable dispersion compensator (TDC, II-VI network solution PS3400 consisted of 12 cascaded G-T cavity with 100-GHz channel spacing) is used to optimize the dispersion value in the experiment. The group delay curve of TDC is shown in inset (b) of Fig. 2. As the maximal tuning range of the TDC is −2100 to 2100 ps/nm which is not enough to compensate the dispersion of 160-km SMF, a coil of dispersion compensation fiber (DCF) with a dispersion of -986 ps/nm in C-band is cascaded. Note that once the optimal value of TDC module is defined, an optical dispersion compensator (ODC) with fixed dispersion value can be used to replace these two modules. After being de-multiplexed, the optical signal of each channel is detected by a 10-GHz PIN to achieve optical-to-electrical conversion. The received electrical signals are finally sent into a 25-Gb/s bit error rate tester (BERT) with embedded CDR module to measure the bit-error rate (BER) in real-time scenario.

Firstly, we experimentally evaluate the impact of negative dispersion on the system frequency response by using an electrical vector analyzer. For simple demonstration, only channel1 at 1549.96 nm is analyzed in the following part. Fig. 3(a) shows the frequency response with different negative dispersion at back-to-back (BtB) case. The 3-dB bandwidth of the combined DML and PIN response at BtB is 10 GHz. With the increase of the negative dispersion, the high-frequency response is significantly improved. And then we add 25-Gb/s NRZ signal to the system and measure the eye diagrams. As shown in Fig. 3(b), the eye diagram at 0 ps/nm can be regarded as duobinary format due to the limited bandwidth. With the increase of the negative dispersion value, the system bandwidth is improved due to the positive chirp characteristics of the directly-modulated signal. Therefore, the eye diagram gradually opens and the duobinary format is converted into binary format. With the further increase of the negative dispersion, the eye diagrams start to degrade as the normal case. The results reveal that we can consider employing the negative dispersion as frequency equalization, which is consistent with our theoretical prediction. Note that we have not



(a) (b)

Fig. 3. System frequency responses (a) and eye diagrams of 25-Gb/s signal (b) with different negative dispersion in BtB case.



(a) (b)

Fig. 4. Eye diagrams of 25-Gb/s signal (a) and system frequency responses (b) with different excessive dispersion in 160-km case.

observed DSE for the external modulated signal since there is no strong positive chirp. After 160-km fiber transmission, we also obtain the similar results, as shown in Fig. 4. Once we completely compensate the dispersion of the SMF, the excessive negative dispersion will improve the eye opening. In Fig. 4(a) and (b) and all the following figures, the dispersion value means the excessive dispersion value after completely compensating the dispersion of the transmission fiber. Note that the phase jitter of the signal after 160-km fiber transmission is very severe therefore the eye opening seems very poor even with proper DSE. But after the CDR, the signal quality can be significantly improved.

Since the effect of DSE function only relates to dispersion, we then measure the BER performance under different dispersion value. Fig. 5 shows the BER performance versus received power at BtB and 160-km cases respectively. We use EDFA1 only at 160-km case. As shown in Fig. 5(a), with the increase of excessive negative dispersion value, the BER performance improves obviously. The sensitivity in BtB with 0 ps/nm dispersion is about −18 dBm when we take the FEC threshold of 3.8×10^{-3} for evaluation, and the optimal BER value is limited to 1×10^{-3}. However, as we set the excessive dispersion at −150 ps/nm, the sensitivity is −28 dBm with 10-dB improvement and the BER value can even go down to 1×10^{-8}. As for 160-km case, we tune the excessive dispersion from 0 to −450 ps/nm. Affected by fiber nonlinear effects, the signal after fiber transmission is seriously degraded compared with BTB case. But the BER results show the similar improvement with the dispersion shown in Fig. 5(b). We attribute the BER improvement to the optical frequency equalization effect of excessive negative dispersion. The noise power also increased when the

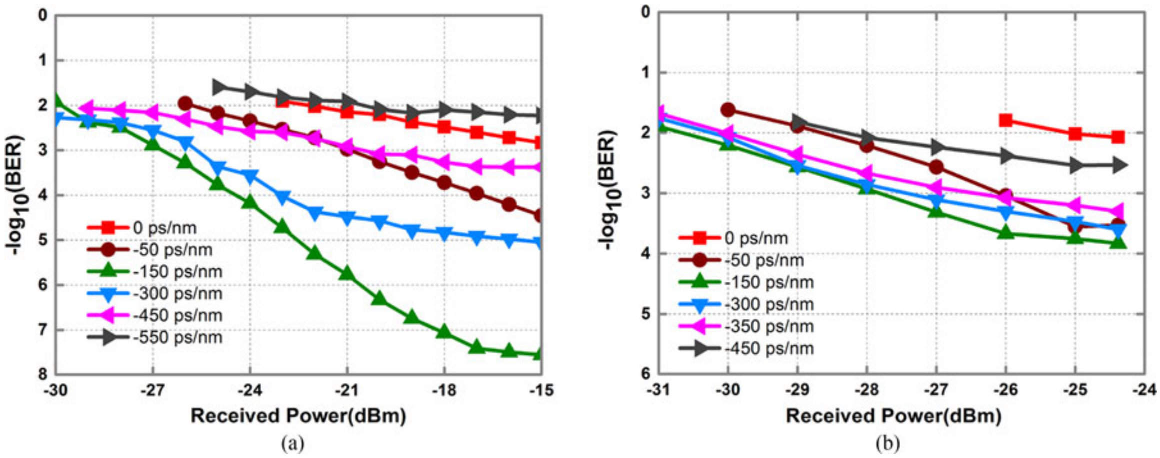


Fig. 5. BER performance of 25-Gb/s signal for different excessive dispersion at (a) BtB, (b) 160-km cases.

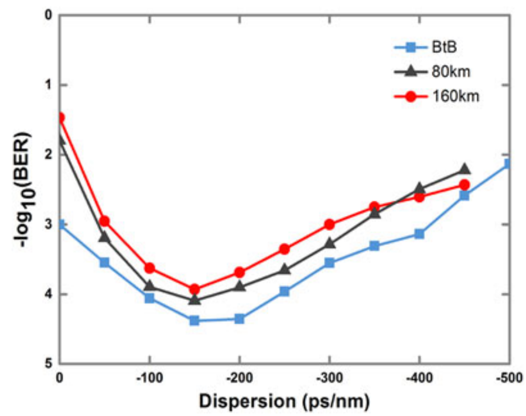


Fig. 6. BER curves with different excessive dispersion at BtB, 100-km and 160-km fiber transmission cases.

received power is big enough, therefore both in Fig. 5(a) and (b), the BER curves show error floor. Fig. 5 also indicates that the excessive negative dispersion will also degrade the performance, we should set proper compensation value for the best performance.

To find the optimal excessive dispersion value, we tune the dispersion from 0 to −500 ps/nm to evaluate the BER variation at BtB, 80-km and 160-km cases respectively. For fair comparison, we set the receive power at −24 dBm. As shown in Fig. 6, we can see that the BER performance at different cases is first improved and then degraded, and the optimal excessive dispersion value is between −100 and −200 ps/nm for all the cases. In practical applications, different transmission distance will induce different positive dispersion, a dispersion compensator with fixed compensation value cannot work effectively in all these cases. But we can just use a tunable dispersion compensator replacing the fixed dispersion device, the problem can be solved. Once we know the transmission distance in a point to point system, we just need to adjust the dispersion value to over compensate about −100 to −200 ps/nm.

Then we set the excessive dispersion at −150 ps/nm and evaluate the BER performance at different transmission distances as shown in Fig. 7. From cost-effective consideration, we remove the EDFA at the transmitter side for the transmission distance less than 140-km, where the launch power is 4 dBm per channel. Considering the transmission loss of 31 dB from the 120-km SMF,

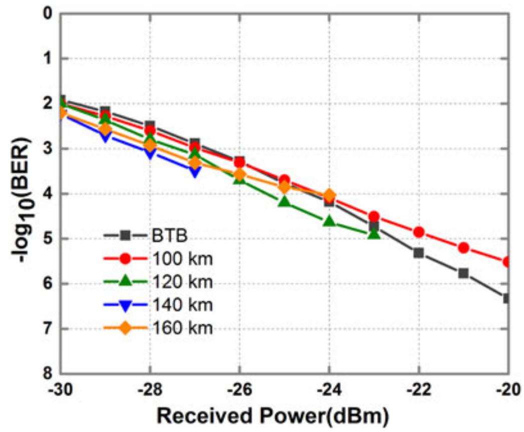


Fig. 7. BER curves versus received power with −150 ps/nm excessive dispersion for different transmission cases.

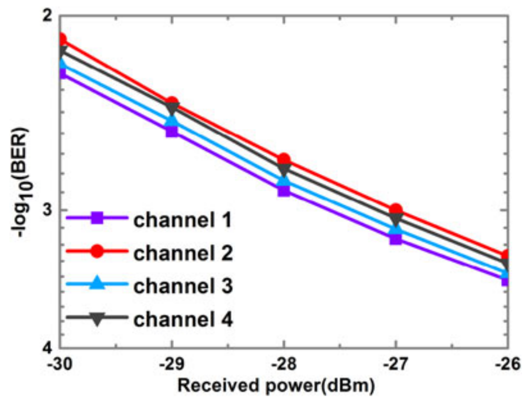


Fig. 8. BER performance versus received power after 160-km SMF transmission for four channels.

the maximal received power before EDFA2 is −27 dBm therefore we cannot achieve better BER performance for 120-km case. The sensitivities for different transmission distances are similar, which means that this scheme can adapt to different point-to-point application scenarios with different transmission distances.

Fig. 8 shows the BER performance of four different channels operating at 1550.12 nm, 1551.72 nm, 1553.33 nm and 1554.94 nm with 200-GHz channel spacing versus received power after 160-km SMF transmission. The total launching power is set at 16 dBm since higher power will induce fiber nonlinearities degrading the system performance. As shown in Fig. 8, the sensitivity is about −29 dBm when we take the FEC threshold of 3.8×10^{-3} for evaluation. The sensitivity difference of four channels is less than 0.5 dB, mainly originated from the different chirp of DMLs. Considering the dispersion compensation module can support multiple channels, the system can be easily upgraded to 8 or more channels to support 200-Gb/s or higher capacity. Since dispersion compensation module is always required for DM-DD based long-distance transmission system, the excessive dispersion based DSE technique will not induce any additional cost to improve the system frequency response. More importantly, 25-Gb/s NRZ-OOK transmission can be realized based on 10G-class optical devices, enabling real-time signal detection without any DSP. From the consideration of low cost and low complexity, this scheme is a very attractive candidate for metro, data-center and other point-to-point applications with both low cost and high capacity, long distance requirements.

4. Conclusion

In this paper, we have experimentally demonstrated DM-DD system of 4 × 25-Gb/s NRZ-OOK signal transmission up to 160-km SMF based on 10G-class DML and PIN. Optical dispersion compensator is employed at the receiver side to compensate the fiber dispersion and equalize the limited bandwidth. No DSP is required in the system and real-time BER measurement is conducted. From these results, the 10G-class DML-based four-channel NRZ-OOK combined with ODC in receiver is an attractive candidate for future low-cost 100-Gb/s wavelength division and multiplexed, point-to-point, metro networks application with both low cost and high performance requirements.

References

[1] H. Y. Chen, C. C. Wei, C. Y. Lin, L. W. Chen, I. C. Lu, and J. J. Chen, "A 200-Gbps OFDM long-reach PON over 60-km transmission without inline and pre-amplifier," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2015, Paper Th1H.2.
[2] W. Idler *et al.*, "16 × 112 Gb/s NRZ-DQPSK lab experiments and WDM field trial over ultimate metro distances including high PMD fibers," *J. Lightw. Technol.*, vol. 29, no. 15, pp. 2195–2203, Aug. 2011.
[3] K. P. Zhong *et al.*, "Experiment demonstration of 500 Gbit/s short reach transmission employing PAM4 signal and direct detection with 25 Gbps device," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2015, Paper Th3A.3.
[4] R. Okabe *et al.*, "100 Gb/s optical discrete multi-tone transceivers for intra- and inter-datacenter networks," *Proc. SPIE*, vol. 9775, pp. F1–F7, 2016.
[5] M. I. Olmedo *et al.*, "Multiband carrierless amplitude phase modulation for high capacity optical data links," *J. Lightw. Technol.*, vol. 32, no. 4, pp. 798–804, Feb. 2014.
[6] R. Okabe *et al.*, "Investigation of fiber dispersion impairment in 400 GbE discrete multi-tone system for reach enhancement up to 40 km," *Proc. SPIE*, vol. 9388, pp. G1–G6, 2015.
[7] X. Li *et al.*, "Transmission of 4 × 28-Gb/s PAM-4 over 160-km single mode fiber using 10 G-Class DML and photodiode," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2016, Paper W1A.5.
[8] H. Zhang, S. Fu, J. Man, W. Chen, X. Song, and L. Zeng, "30 km downstream transmission using 4 × 25 Gb/s 4-PAM modulation with commercial 10 Gbps TOSA and ROSA for 100 Gb/s-PON," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2014, Paper M2I.3.
[9] J. Zhou, C. Yu, M. Gurusamy, and H. Kim, "25-Gb/s OOK and 4-PAM transmission over >35-km SSMF using directly modulated 1.5-μm VCSEL," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2016, Paper Tu2J.5.
[10] S. H. Bae, H. Kim, and Y. C. Chung, "Transmission of 51.56-Gb/s OOK signal over 15 km of SSMF using directly-modulated 1.55-μm DFB laser," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2016, Paper Th1G.7.
[11] F. Karinou, N. Stojanovic, and Z. Yu, "Toward cost-efficient 100 G metro networks using IM/DD, 10 GHz components, and MLSE receiver," *J. Lightw. Technol.*, vol. 33, no. 19, pp. 4109–4117, Oct. 2015.
[12] Z. Li, L. Yi, X. Wang, and W. Hu, "28 Gb/s duobinary signal transmission over 40 km based on 10 GHz DML and PIN for 100 Gb/s PON," *Opt. Exp.*, vol. 23, no. 16, pp. 20249–20256, 2015.
[13] Z. Li, L. Yi, H. Ji, and W. Hu, "100-Gb/s TWDM-PON based on 10 G optical devices," *Opt. Exp.*, vol. 24, no. 14, pp. 12941–12948, 2016.
[14] L. Xue, L. Yi, H. Ji, P. Li, and W. Hu, "First demonstration of symmetric 100 G-PON in O-band with 10 G-Class optical devices enabled by dispersion-supported equalization," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2017, Paper M3H.1.
[15] R. H. Tomkos, R. Vodhanel, and A. Boskovic, "Metro network utilizing 10 Gb/s directly modulated lasers and negative dispersion fiber," *IEEE Photon. Technol. Lett.*, vol. 14, no. 3, pp. 408–410, Mar. 2002.
[16] L. Bjerkan, A. Royset, L. Hafskjaer, and D. Myhre, "Measurement of laser parameters for simulation of highspeed fiberoptic systems," *J. Lightw. Technol.*, vol. 14, no. 5, pp. 839–850, May 1996.
[17] E. Peral, W. Marshall, and A. Yariv, "Precise measurement of semiconductor laser chirp using effect of propagation in dispersive fiber and application to simulation of transmission through fiber gratings," *J. Lightw. Technol.*, vol. 16, no. 10, pp. 1874–1880, Oct. 1998.
[18] K. Zhang *et al.*, "Chirp-aided power fading mitigation for upstream 100 km full-range long reach PON with DBR DML," *Opt. Commun.*, vol. 407, pp. 63–68, 2018.