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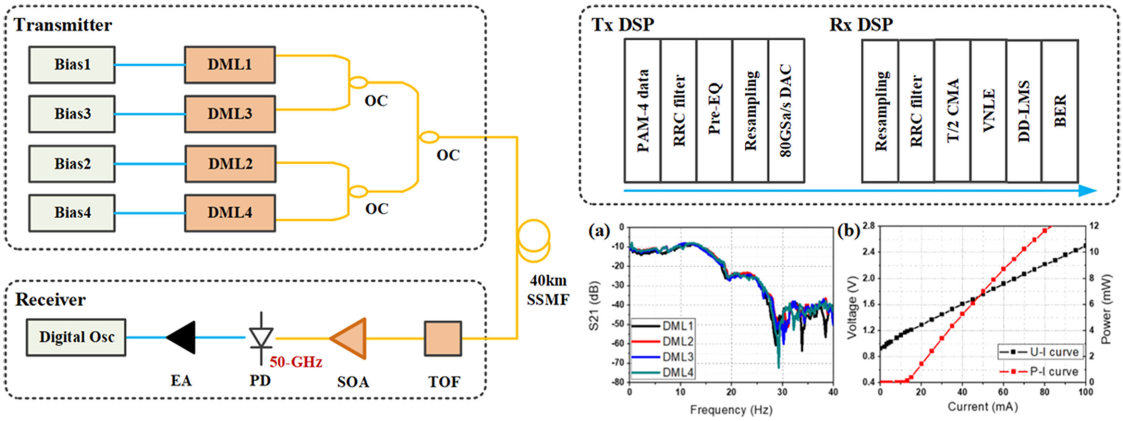

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Abstract: We demonstrate a four-lane wavelength division multiplexing (WDM) intensity modulation and direct detection (IM/DD) system at O-band. The 3-dB bandwidth of directly modulated lasers (DMLs) in this experiment is only 15 GHz. To support 100-Gbit/s/lane PAM-4 transmission in each lane, digital pre-equalization and advanced receiver-side DSPs are adopted to compensate for bandwidth limitation. Moreover, semiconductor optical amplifier (SOA) is utilized at the receiver to compensate for the optical power loss during fiber transmission so that 40-km transmission distance can be achieved. To the best of our knowledge, it is the first time to successfully transmit 400-Gbit/s PAM-4 signals over 40-km SSMF with 15-GHz DMLs.

Index Terms: Fiber optics links and subsystems, optical interconnects.

1. Introduction

Driven by the upcoming high-speed services, such as clouding networking, 5G/6G, and VR/AR applications, the metro traffic has been explosively increased and surpassed the long-haul traffic in recent years [1–3]. Considering large-scale deployment scenarios, the IM/DD system is the most attractive solution to cost effectively achieve a data rate of 100 Gbit/s/channel and a transmission distance of 20 km or beyond. Up to now, the non-return-to-zero (NRZ) coding is still widely spread in short reach systems, however, the spectral efficiency (SE) of NRZ is only 1bit/s/Hz. To support higher capacity, the advanced modulation formats with higher SE should be adopted. Compared with discrete multi-tone (DMT) and carrier-less amplitude phase (CAP) modulation, pulse amplitude modulation (PAM) has lower complexity and power consumption in hardware implementation [3]. Therefore, PAM is an ideal modulation format for IM/DD systems. To further improve the transmission rate and meet the demand of 400G data connection, four-lane IM/DD transmission system with low transceiver cost and simple system integration is a promising solution [2].

The transmission distance in a metro optical network is more than 10 km, and the fiber link deployment is mainly based on standard single mode fiber (SSMF) [3], [4]. Therefore, optical power attenuation and chromatic dispersion (CD) are the two most important factors which limit the transmission distance. The optical power attenuation in C-band is low and can be compensated by

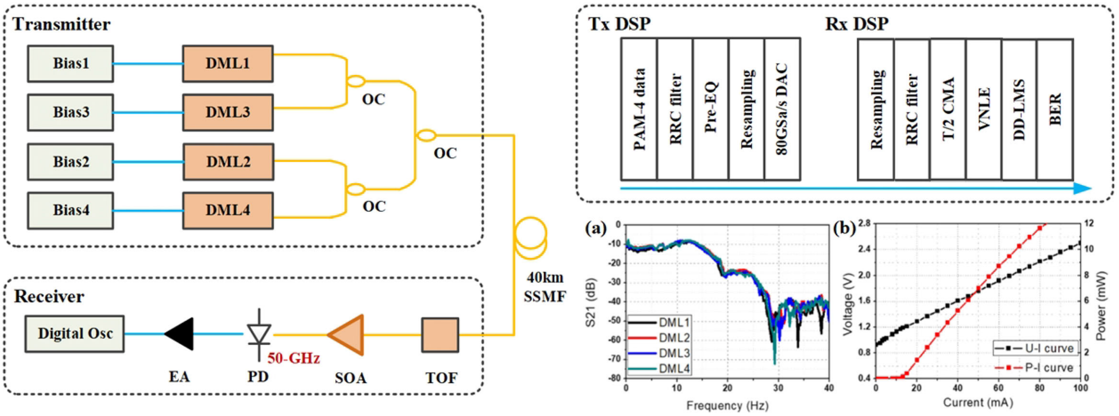


Fig. 1. Experimental setup and DSPs of the four-lane IM/DD system at O-band: (a) S21 curves of the four O-band DMLs; (b) the measured voltage-power-current curve of DML1.

optical amplifier, such as erbium-doped fiber amplifier (EDFA). However, the signal transmission at C-band suffers from CD-induced frequency-dependent power loss. For O-band transmission based on conventional SSMF, the CD coefficient around 1310.0 nm can be approximated to zero [5], [6]. However, due to the lack of suitable optical amplifier in O-band transmission, it is difficult to achieve long transmission distance in previous researches. Recently, SOA has attracted great attention due to its simple structure, low cost, and small power consumption [4]–[6]. Moreover, the mature manufacturing process of SOA has made it a suitable optical amplifier for O-band transmission.

Compared with the Mach-Zehnder modulator (MZM) based external modulation, some modulators such as electro-absorption modulator (EML) and directly modulated laser (DML), have the advantages of low cost and small size. Therefore, in terms of system complexity, cost, and power consumption, EML and DML are better choices for data transmission. Ref. [7] demonstrates 4 × 96-Gbit/s PAM-8 transmission enabled by low-cost DMLs. However, the transmission distance is only 15 km. In Ref. [8], a 112 Gbit/s/lane PAM-4 transmission over 40 km is experimentally demonstrated by using 28-GHz DML with high launch power. The demonstrations above can support about 100 Gbit/s/lane signals transmission based on DML, but the transmission distance is short or larger bandwidth DML is needed. Considering the 10G class optical devices are still widely used nowadays, it is meaningful to extend the distance of 400G transmission based on narrow band DML.

In this paper, we demonstrate a four-lane WDM IM/DD transmission system. Four commercial DMLs, whose 3-dB bandwidth are 15 GHz, are used for O-band sources and optical modulation. The detailed experimental setup is presented in section 2. In section 3, we investigate the system dispersion tolerance and optimize the experimental parameters. Finally, the measured BER results are depicted and discussed in section 4. Thanks to SOA amplification, linear partial pre-compensation and advanced DSPs at the receiver, the 400G (4 × 100 Gbit/s) PAM-4 signals can be successfully transmitted over 40 km, which is the longest reported distance achieved by the four-lane 400-Gbit/s system based on 15-GHz DMLs.

2. Experimental Setup of the O-Band WDM System

Fig. 1 shows the experimental setup of the SOA-based four-lane IM/DD transmission system at O-band. We use four DMLs for O-band optical sources and signal modulation. By adjusting four different bias current, the working frequency of the four DMLs is 1305.5 nm, 1309.0 nm, 1312.6 nm, and 1316.8 nm, respectively. Fig. 1(a) depicts the S21 curves of the four O-band DMLS used in this experiment. The four curves of the four DMLs are close to each other, and the 3-dB bandwidth is about 15 GHz. Moreover, the voltage-power-current curve of DML1 is also measured, as shown in Fig. 1(b). The DML only starts to work when the bias voltage is larger than 0.9V. In addition, the DSPs at the transmitter and receiver are shown in Fig. 1. In the transmitter-side DSPs, the pseudo-random binary sequence (PRBS) data is firstly mapped into PAM-4 symbols. Subsequently, the spectrum of the PAM-4 sequence is shaped by a rooted raised cosine filter (RRCF) with a roll-off factor of 0.1. In this experiment, since the 3-dB bandwidth of DMLs is only 15 GHz, the signals suffer from power loss due to the limited bandwidth. To pre-compensate the frequency response, a 33-taps CMA equalizer is used to obtain the system response and pre-equalization is implemented. Such linear pre-equalization can pre-compensate the narrow filtering effect, and can reduce the MMSE of the post-equalization at the receiver side [18]. The 50-Gbaud PAM-4 signals are generated by an 80-GSa/s DAC after resampling. Subsequently, the four lane optical signals are combined by optical couplers (OCs), and then transmitted through 40-km SSMF. The launch power of the four channels is 9.0 dBm.

At the receiver, a tunable optical filter (TOF) with 0.9-nm optical bandwidth is adopted to separate the signals in each WDM channel. Since the attenuation of the SSMF link at 1310 nm is 0.33-dBm/km, an SOA is used to compensate power loss through transmission. The amplified signals are detected by a 50-GHz PD and finally captured by a 160-GSa/s real-time digital oscilloscope with a 3-dB bandwidth of 62 GHz. In the receiver-side DSPs, the received data is first resampled, and a same RRCF with the transmitter is used as a matched filter. Subsequently, a T/2 spaced CMA equalizer with 33-taps and a Volterra series based nonlinear equalizer with 53-taps are used to compensate for the linear and nonlinear distortions during fiber transmission. The Volterra equalizer is a second-order one, which contains both linear and nonlinear components. Here, we adopt a T/2 spaced CMA equalizer to pre-compensate for a part of linear distortions, so that the following Volterra equalizer can converge faster and performs better. Finally, the DD-LMS algorithm with 73 taps is used to further improve the system performance.

3. Principles

3.1. Dispersion Tolerance Simulation

In order to investigate the dispersion tolerance for the transmission at O-band, we further simulate the BER performance of 50-Gbaud PAM4 signal transmission with different accumulated dispersion. It is known that CD can cause frequency dependent power loss and seriously degrade system performance, especially for broadband signals. The impact of CD in the frequency domain can be expressed as [10], [11]:

$$G = \exp\left(-j\frac{DL\lambda^2}{4\pi c}\omega^2\right). \tag{1}$$

Here, D is the chromatic dispersion coefficient, λ is the operating wavelength, c is the speed of light, and L is the transmission distance. In this simulation, we assume that the operating wavelength is 1310.0 nm. The measured BER versus dispersion is shown in Fig. 2(a). Here, the dispersion tolerance of the 50-Gbaud PAM4 signal with and without DSPs are both presented. In this experiment, we consider the soft decision forward error correction (SD-FEC) threshold at 2.0×10^{-2} with 20% FEC overhead. Based on the simulation results in Fig. 2(a), the dispersion tolerance of the 50-Gbaud PAM4 signal with and without DSPs are 36ps/nm and 78ps/nm, respectively. Fig. 2(b) depicts the maximum chromatic dispersion after 40-km SSMF transmission as a function of wavelength. The chromatic dispersion coefficient is specified for ITU-T G.652 type fibers [12], [13], [18]. For each wavelength point, we choose the maximum chromatic dispersion coefficient to calculate the chromatic dispersion. From Fig. 2(b), the maximum chromatic dispersion after 40 km SSMF transmission at the wavelength from 1302 nm to 1322 nm is always smaller than 78ps/nm. If we only consider the effect of chromatic dispersion, the operating wavelength of the DMLs in this experiment can theoretically support 50-Gbaud PAM4 signals transmission over 40-km SSMF.

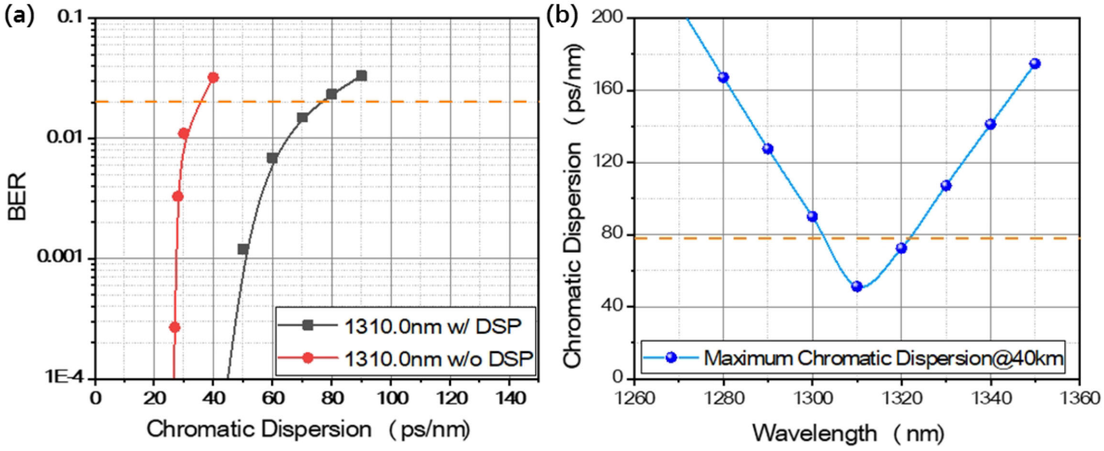


Fig. 2. (a) Simulated BER as a function of chromatic dispersion at 1310.0 nm; (b) the maximum chromatic dispersion as a function of wavelength.

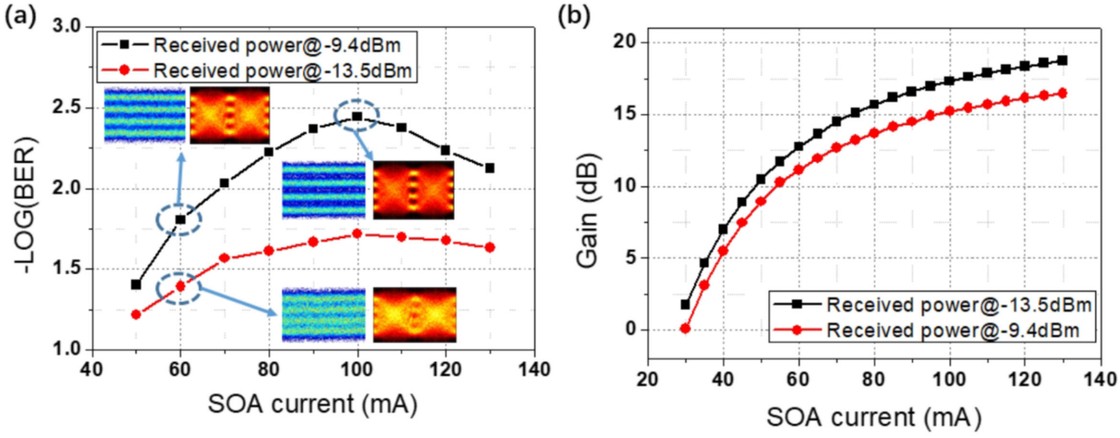


Fig. 3. (a) BER performance versus SOA current at the received optical power at −9.4 dBm and −13.5 dBm; (b) measured SOA gain curves versus SOA current at the received optical power at −9.4 dBm and −13.5 dBm.

3.2. SOA and DSP Performance Optimization

To transmitted 50-Gbaud PAM4 signals over 40-km SSMF based on 15-GHz DMLs, we should optimize the parameters of the SOA and DSPs to obtain a better system performance. In long distance transmission, the SOA current is usually high, which may cause SOA works in the nonlinear region so that the signals will suffer from the SOA-induced nonlinear noises [14], [15]. In this experiment, only one SOA is adopted at the receiver so that we adjust the SOA current to find the optimum operating point. Firstly, we measure the BER performance with different SOA bias current under the back-to-back (BTB) case. Fig. 3(a) shows the measured BER as a function of the SOA current at the optical received power (ROP) of −9.4 dBm and −13.5 dBm. Here, ROP is the measured optical power into SOA. Moreover, the corresponding PAM4 constellations and eye diagrams are also presented in Fig. 3(a). Based on the experimental result, the SOA with 100mA bias current has the best BER performance at different received optical power. Therefore, we set SOA current at 100mA in the following experiments. Fig. 3(b) is the SOA gain curves versus SOA current.

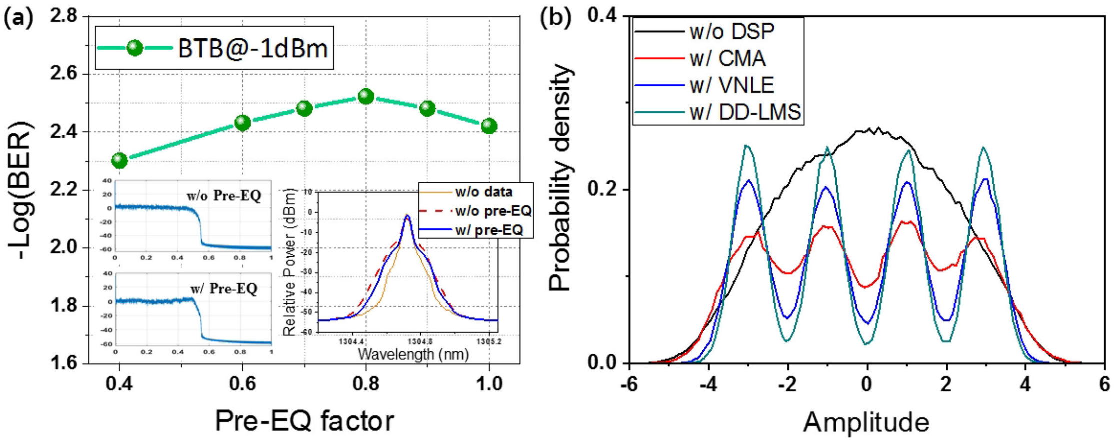


Fig. 4. (a) BER performance versus different pre-EQ factor at the received optical power of -7 dBm; (b) probability density distribution of the recovered PAM4 signals with different DSP algorithms.

Pre-equalization is a frequently used algorithm to improve system performance [16], [17]. However, when the peak voltage of DAC is fixed, the completed pre-equalization will reduce the average power of the baseband signals. In such a peak power limited case, the average power reduction can increase the peak to average power ratio (PAPR). Moreover, pre- equalization will compress the low frequency component of the transmitted signals and the amplitude of the received signals after DSO will decrease, especially for strong narrow filtering effect. Therefore, there is a trade-off between the performance improvement induced by pre- equalization and the performance degradation. For each lane, we denote the original PAM-4 signals as S_o in frequency domain. Similarly, $\widetilde{H}$ is the estimation of channel response. The transmitted signals after pre-compensation can be expressed as:

$$S_{pre} = S_o \cdot \widetilde{H}^{-1} = S_o \cdot (\widetilde{H}^{-1} - I) + S_o. \tag{2}$$

From equation (2), it can be seen that $S_o \cdot (\widetilde{H}^{-1} - I)$ is the difference of the signals before and after completed pre-compensation in frequency domain, and I is a unit matrix. For partial pre-compensation, the signals in frequency domain is:

$$S_{partial-pre} = p \cdot S_o \cdot (\widetilde{H}^{-1} - I) + S_o. \tag{3}$$

Here, p is denoted as the pre-compensation factor. Fig. 4(a) presents the spectrum of the PAM-4 signals before and after partial pre-compensation, and the corresponding optical spectra with 0.1-nm resolution is also depicted. We measure the system BER with different p to find an optimal one. The measured BER versus the pre-compensation factor under BTB case is shown in Fig. 4(a). Based on the BER results, we set p as 0.8 in the following experiments. In the offline DSPs, the linear noise is compensated by the CMA equalizer and the linear components of the Volterra equalizer. The nonlinearity can be compensated by Volterra-series-based nonlinear equalizer and DD-LMS algorithm. Fig. 5(b) shows the probability density distribution of the recovered PAM4 signals with different DSP algorithms.

3. Results and Discussions

Firstly, we investigate the system performance in BTB case. Fig. 5(a) depicts the measured BER of channel 3 versus the received optical power in BTB transmission with and without SOA amplification. When SOA is not adopted, the filtered optical signal is directly detected by the 50-GHz PD. In this experiment, the output power of each DML is about 3 dBm. Considering the

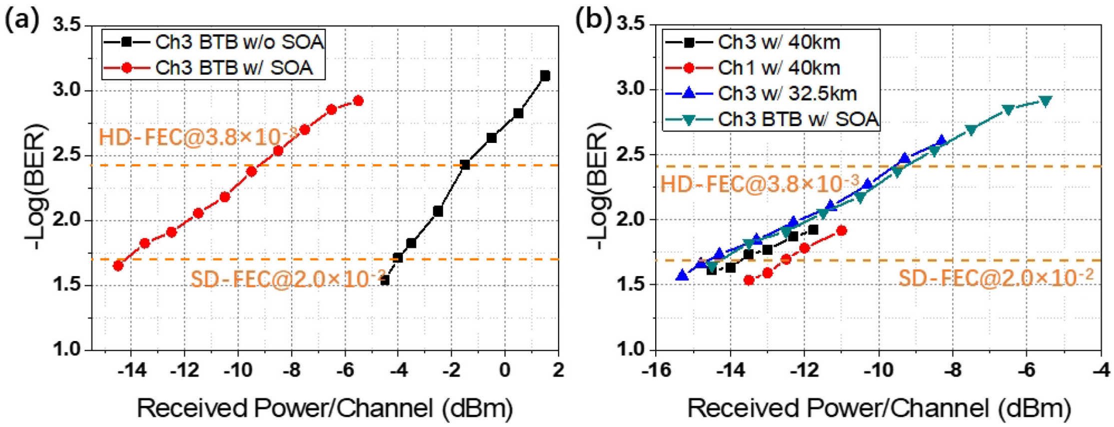
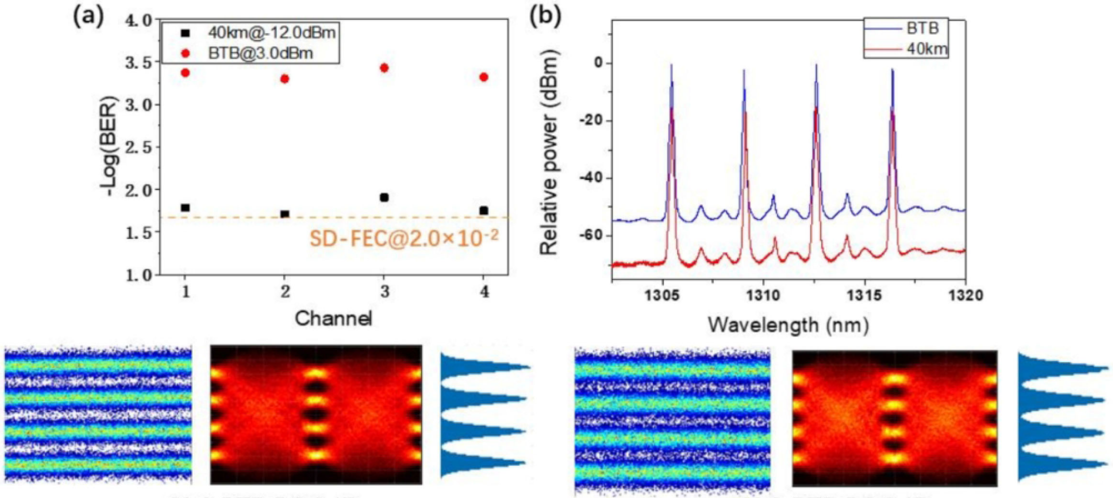
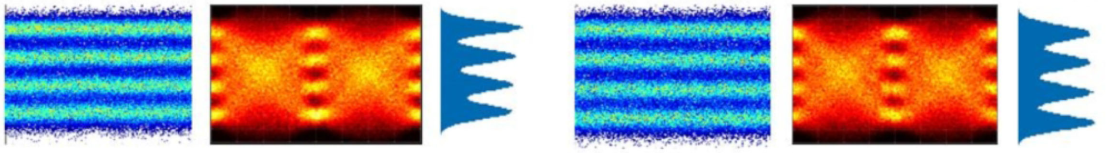


Fig. 5. (a) BER curves versus receive power of channel 3 at the BTB case; (b) BER curves versus received power of channel 3 at the BTB case. Transmitted through 32.5 km and 40 km; BER curve versus received power of channel 1 after 40-km transmission.



Ch1 BTB@3.0dBm

Ch3 BTB@3.0dBm



Ch1 40km@-12.0dBm

Ch3 40km@-12.0dBm

Fig. 6. (a) Measured BER of the four WDM channels after BTB and 40-km SSMF transmission; (b) optical spectra before and after 40-km SSMF transmission with the resolution of 0.1 nm.

insertion loss and fiber attenuation, the optical power loss of the 40-km SSMF transmission fiber is about 13dB. Therefore, to support 40-km transmission, the receiver sensitivity should be at least −10.0 dBm. Based on the results in Fig. 5(a), the receiver sensitivity of channel 3 is only −1.7 and -4 dBm at HD-FEC (3.8×10^{-3}) and SD-FEC (2.0×10^{-2}) threshold, respectively. With the aid of SOA, the corresponding receiver sensitivity can be improved to −9.0 and −14.2 dBm, respectively.

Subsequently, we further investigate the BER performance after fiber transmission. Fig. 5(b) presents the measured BER curves as a function of the received optical power after BTB, 32.5-km and 40-km transmission in channel 3. From Fig. 5(b), the BER curves of BTB, 32.5-km and 40-km transmission in channel 3 are very close. Obviously, there is only about 1-dB sensitivity penalty at the SD-FEC threshold of 40-km SSMF transmission compared to BTB case. Based on the results in Fig. 5(b), the receiver sensitivity of channel 3 after 40-km SSMF transmission is −14.0 dBm at SD-FEC threshold of 2.0×10^{-2}. To investigate the performance of other channels, we also measure the BER performance in channel 1, which is also presented in Fig. 5(b). The BER performance of channel 1 is slightly worse than that of channel 3. Considering the SD-FEC threshold at 2.0×10^{-2}, the receiver sensitivity of channel 1 is −12.5 dBm. There is about 1.5-dB sensitivity penalty existing between channel 1 and channel 3 after 40-km SSMF transmission.

From Fig. 5(b), the BER performance of channel 3 is better than that of channel 1. This shows that the BER of 50-Gbaud PAM4 signals after 40-km SSMF transmission in the 4 channels are different. It is necessary to verify whether the four WDM channels can all support 50-Gbaud PAM4 signals over 40-km fiber transmission. Therefore, we measure the BER performance of each channel after 40-km transmission at a received optical power of −12.0 dBm, which is shown in Fig. 6(a). Moreover, the BER performance under BTB case at a total received optical power of 3.0 dBm is also presented. Based on the BER results, the four WDM channels possess similar BER performance, and all channels can satisfy the SD-FEC threshold of 2.0×10^{-2} after 40-km SSMF transmission. Fig. 6(b) is the optical spectra before and after 40-km SSMF transmission with the resolution of 0.1 nm. The corresponding PAM-4 symbols, eye diagrams, and the probability distribution of the PAM-4 symbols are also shown in Fig. 6.

4. Conclusion

In this paper, we experimentally demonstrate a four-lane WDM IM/DD transmission system at O-band based on 15-GHz DMLs. The experimental results show that the four lanes have similar BER performance. Satisfying the BER threshold at 2.0×10^{-2}, all channels can support 100 Gbit/s/channel PAM4 signals transmission at the received optical power of −12.0 dBm. Considering 20% overhead, the net bit rate is 333.3 Gbit/s. To the best of our knowledge, this is the first time to realize 400-Gbit/s PAM-4 signals transmission over 40km based on 15-GHz DMLs.

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