100-Gbit/s/λ PAM-4 signal transmission over 80-km SSMF based on an 18-GHz EML at O-band

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Abstract: For the first time, we experimentally demonstrate 100-Gbit/s PAM-4 signal transmission over 80km at O-band using an 18-GHz EML. After two spans of SOA-based 40-km SSMF transmission, a receiver sensitivity of -17.3dBm is achieved.

OCIS codes: (060.2330) Fiber optics communications, (060.2360) Fiber optics links and subsystems

1. Introduction

To meet the demand of explosively growing data traffic in mobile Internet, cloud networking, and HD-video applications, low-cost intensity modulation and direct-detection (IM/DD) system with a transmission rate of 100Gbit/s/λ or beyond is urgently needed. Different from high-speed data-center-interconnections (DCI) optical links, passive optical network (PON) requires higher power budget and much longer reach distance [1,2]. However, longer fiber links will cause many problems, such as chromatic dispersion and optical power loss.

Compared to the C-band, O-band (1260-1360nm) is more suitable for high-baud rate signals delivery over a long distance since the zero-dispersion wavelength of conventional single mode fiber (SMF) is around 1310nm. Dispersion compensation is no needed for the signal transmission at O-band, so the transceiver complexity can be reduced. However, signal transmission at O-band suffers from larger fiber attenuation than C-band. Previously, due to lack of suitable optical amplifiers like Erbium-doped optical fiber amplifier (EDFA), it is hard to realize long reach O-band transmission. An optional solution is to use avalanche photodiode (APD) at the receiver to improve receiver sensitivity, but the dynamic range of APD based receiver would be a challenge [3,4]. Recently, semiconductor optical amplifier (SOA) has attracted great attention for simple structure, low cost [5], small power consumption, and easy integration with other optical devices. Therefore, it is regarded as a promising solution for O-band amplification.

Considering the transceiver size, complexity, power consumption and cost, pulse amplitude modulations (PAM)-4 signal transmission based on IM/DD system is a promising technology for next-generation TDM-PON. Demonstrations about high-speed IM/DD system based on external modulation, such as Mach-Zehnder modulator (MZM), have been widely reported [6, 7]. Thanks to low power consumption and cost, electro-absorption modulated laser (EML) and directly modulated laser (DML) would be better choices for transmitters, but the system performance is usually restrained by the limited modulation bandwidth. Besides, SOAs would easily work in the nonlinear region due to low saturation power, so nonlinearity is another important limitation on the EML/DML based IM/DD system at O-band. Recently, some demonstrations of 100-Gbit/s/λ transmission based on EML have been reported [8, 9]. In Ref. [8], a single-line 112-Gbit/s PAM-4 40-km transmission is realized, however, a 25G-class EML and APD are needed. Ref. [9] demonstrate a 400G(4×112.5Gbit/s) PAM-4 signal transmission over 80-km SSMF at C-band with the aid of DCF and a wide band (40GHz) EML, which increases the system complexity and cost.

In this paper, we successfully transmit 100-Gbit/s/λ PAM-4 signal over 80-km SSMF at O-band based on a narrow band (18GHz) EML. The 80-km fiber link consists of two spans of 40-km SSMF. Thanks to the Volterra series based nonlinear equalizer, the nonlinearity induced by SOA can be effectively compensated and a receiver sensitivity of -17.3dBm is achieved. To the best of our knowledge, it is the first time to transmit 100Gbit/s/λ PAM-4 signal over 80-km (40km×2) SSMF at O-band with an 18-GHz EML supporting 20.3-dB power budget.

2. Experimental setup

Fig. 1 depicts the experimental setup of the EML-based IM/DD 100Gbit/s/λ PAM-4 signal transmission over 80-km (40km×2) SSMF at O-band. At the transmitter, an 18-GHz EML operating at 1298.5nm is used for optical signal generation and modulation. Due to the narrow bandwidth of EML, root raised cosine filter (RRCF) and pre-equalization (pre-EQ) are needed to compensate for bandwidth limitation in Tx-DSPs. The roll-off factor of the RRCF is 0.05, and the finite impulse response (FIR) of pre-EQ is trained by a 133-tap constant-modulus algorithm

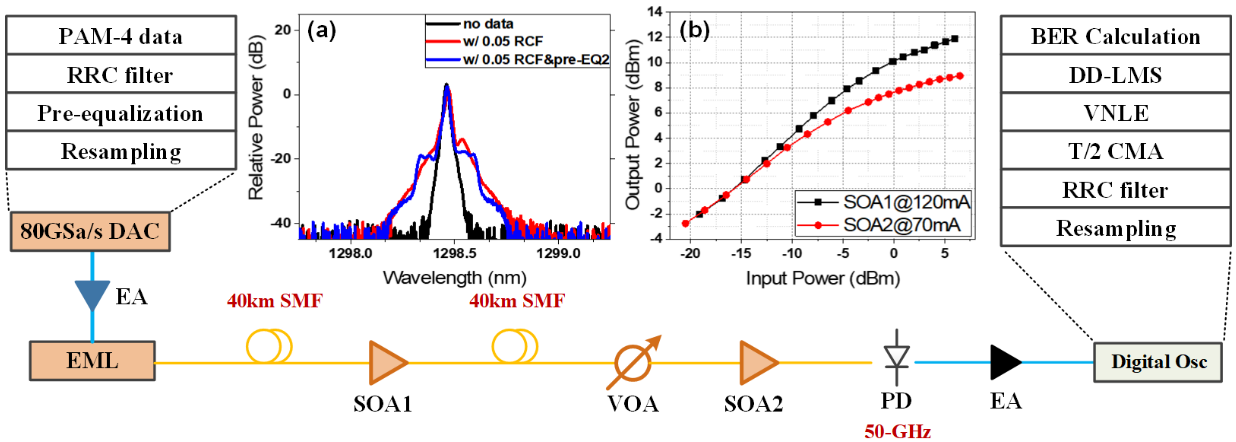

Fig. 1. Experimental setup of the EML-based IM/DD 100Gbit/s/λ PAM-4 signal transmission at O-band: (a) spectra of the modulated optical signal (0.02nm); (b) output power curves vs. input power for SOA1 and SOA2.

(CMA) equalizer in T/2 space. After resampling, the shaped PAM-4 signals are loaded into the 80-GSa/s DAC. Driven by an electrical amplifier (EA) with 40-GHz 3-dB bandwidth, the generated 50-Gbaud PAM-4 signals are sent into EML for optical signal modulation. The output optical power of the EML is 2.0dBm. Fig. 1(a) presents the spectra of the modulated optical signal with or without RRCF and pre-EQ under the resolution of 0.02nm.

Subsequently, the optical signals are launched into the SSMF fiber link with 0.33-dBm/km attenuation at 1310nm. The 80-km fiber link consists of two spans of 40-km SSMF with two in-line SOAs. SOA1 is set between two spans of the 40-km fiber. At the receiver, the received optical signal is amplified by SOA2 and then detected by a 50-GHz PD. With the aid of EA, the 50-Gbaud PAM-4 signals are sampled by a 160-GSa/s real-time digital oscilloscope. To obtain a lager power gain, SOA works at nonlinear region, so there is a trade-off between optical power gain and SOA-induced nonlinearity. We firstly investigate the BER performance after 40-km SSMF with only SOA1 for amplification. The measured BER and SOA1 output power versus bias current are presented in Fig 2(a). Based on the experimental results, the optimal bias current for SOA1 is about 120mA. Similarly, we measured the BER after 80-km SSMF transmission with SOA1 (the current is fixed at 120mA) and SOA2. When the current of SOA2 is ~70mA, best BER performance is obtained.

The offline DSP at receiver-side is presented in Fig.1. Firstly, a 2×sampling RRCF with a roll-off factor of 0.05 is adopted as a matched filter. Then, a 33-taps CMA equalizer in T/2 space can compensate for the linear impairment. For nonlinear distortion, a 53-taps Volterra series based nonlinear equalizer is used after CMA. Finally, we use a DD-LMS equalizer to further improve the BER performance.

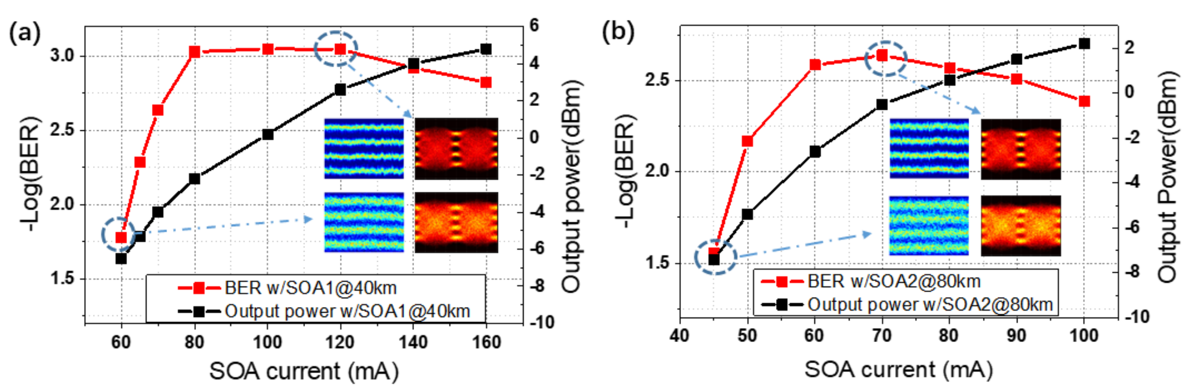

Fig. 2. The measured BER and output power versus SOA current: (a) after 40-km transmission with SOA1; (b) after 80-km transmission with SOA1 and SOA2.

3. Experimental results and discussions

We test the BER performance of BTB and 40-km SSMF transmission first, and the measured results are shown in Fig. 3(a). For BTB transmission, the optical signal generated by EML is directly detected by PD without SOA amplifying. In this case, the measured BER performance will rapidly degrade as optical power decreases. Satisfying the hard-decision forward error correction (HD-FEC) threshold, the receiver sensitivity is only about -8.0dBm in

BTB transmission. When it comes to 40-km SSMF transmission, an SOA is added at the receiver for optical signal amplifying. Based on the results in Fig. 2, the SOA current is fixed at 120mA. With the aid of receiver-side DSP, the receiver sensitivity is -18.6dBm at the BER threshold of 3.8×10^{-3}. From Fig. 3(a), the Volterra series based nonlinear equalizer brings little BER improvement after 40-km transmission because SOA1 works in linear region now.

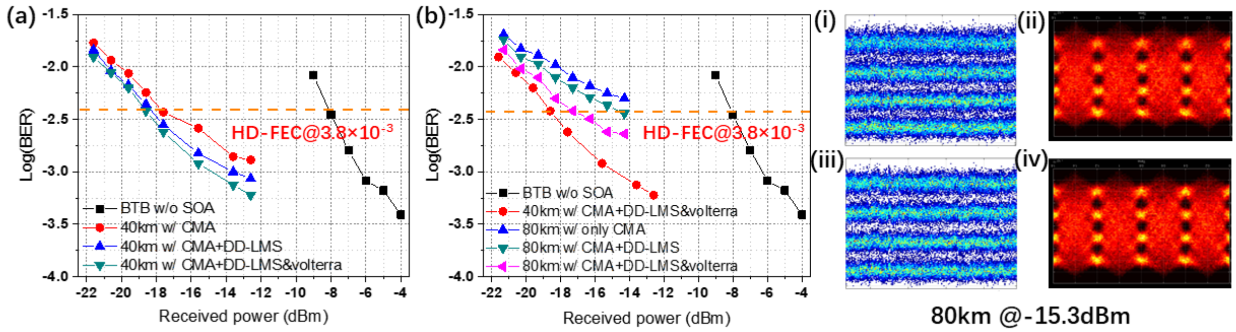

Fig. 3. The measured BER curves versus received optical power after (a) 40-km and (b) 80-km SSMF transmission; the constellation (i) and eye diagram (ii) with only linear equalization; the constellation (iii) and eye diagram (iv) with linear and nonlinear equalization

Fig. 3(b) depicts the BER performance after 80-km SSMF transmission with SOA amplifying. SOA1 and SOA2 work at the current of 120mA and 70mA, respectively. The output power curves versus input power of SOA1 and SOA2 are shown in Fig. 1(b). With the linear equalizer, CMA and DD-LMS, the receiver sensitivity of -14.3dBm is obtained. The inset (i) and (ii) in Fig. 4 are the constellation and eye diagram of the PAM-4 signals after CMA & DD-LMS when the received power is -15.3dBm after 80-km transmission. The 3rd and 4th PAM-4 levels are relatively indistinct, which is the nonlinearity induced by the two SOAs. After Volterra series based nonlinear equalization, the nonlinearity can be effectively compensated. The corresponding constellation and eye diagram are shown in Fig. 4(iii) and (iv). Now, the receiver sensitivity after 80-km SSMF transmission can be improved to -17.3dBm. Compared to 40-km transmission, there is 1.3-dB receiver sensitivity degradation. Considering the launch power of 3.0dBm, the 100-Gbit/s PAM-4 signal can be successfully delivered over 80-km SSMF with 20.3-dB power budget.

4. Conclusions

To the best of our knowledge, for the first time we have experimentally demonstrate a point-to-point IM/DD system at O-band with a narrow band (18GHz) EML. Two SOAs are used for optical in-line amplification. With the aid of receiver-side DSPs, the SOA-induced nonlinearity can be compensated. The 100-Gbit/s/λ PAM-4 signal is successfully transmitted over 80-km SSMF link with receiver sensitivity of -17.3dBm. Considering 7% FEC overhead at 3.8×10^{-3}, the net bit rate is 94.3Gbit/s.

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