Transmission of 4×28-Gb/s PAM-4 over 160-km Single Mode Fiber using 10G-Class DML and Photodiode

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Abstract: We have experimentally demonstrated C-band 112-Gb/s (4×28-Gb/s) PAM-4 transmission over 160-km SMF without inline amplifier based on 10G-class DML and photodiode. Delay interferometer and Volterra filtering are applied to compensate both linear and nonlinear distortions.

OCIS codes: (060.4510) Optical communications; (060.2230) Fiber optics communications

1. Introduction

Driven by the exponential growth of bandwidth requirement, the metro traffic will surpass long-haul traffic in 2016, where the bandwidth bottleneck shifts to the metro network [1]. Several techniques based on intensity modulation and direct detection (IMDD) have been proposed to realize low-cost, high-capacity in short-reach transmission system, including pulse amplitude modulation (PAM), discrete multi-tone (DMT) and carrier-less amplitude/phase modulation (CAP) [2-6]. Among them, four level PAM (PAM-4) is highly preferred in 100-Gb/s short reach transmission system due to its simple configuration and low-cost at the transmitter side. In [5], 100-Gb/s (4×25-Gb/s) PAM-4 is demonstrated in passive optical network (PON) over 30-km single channel single mode fiber (SMF) using feed forward equalization (FFE) for channel equalization. However, the transmission distance is limited at 30 km. In [6], maximum likelihood sequence estimation (MLSE) is applied to achieve single channel 56-Gb/s PAM-4 over 26.4-km SMF. Therefore, in current PAM-4 IMDD transmission system, the transmission distance does not satisfy the ultimate point to point distance of more than 80 km.

In this work, 160-km single mode fiber (SMF) transmission of C-band 112-Gb/s (4×28-Gb/s) PAM-4 signal is experimentally demonstrated. At the transmitter side, a 10G-class directed modulated laser (DML) is loaded with 28-Gb/s PAM-4 signal. A delay interferometer (DI) is used to filter out one sideband of the signal and manage the optical chirp [7]. After 160-km SMF transmission, only a single photodiode (PD) with bandwidth of 10 GHz is employed to detect the optical signal in each channel, which enables a simple and cost-effective system. To partially compensate various nonlinear distortions during the transmission, the Volterra filter is applied in this work [8]. To the best of the authors' knowledge, this is the first experimental demonstration of C-band DML-based 100-Gb/s PAM-4 over more than 100-km SMF transmission without inline amplification.

2. Principal

For a DML-based IMDD transmission system, beside the DML chirp effect, the signal distortions mainly come from three factors: (1) limited bandwidth of device and fiber chromatic dispersion (CD); (2) signal-to-signal beating noise (SSBN); (3) fiber nonlinearities. We apply Volterra filter to compensate these distortions simultaneously. The k-th sample of the output signal after the three kernels Volterra filter is expressed as [8]

$$y(k)=\sum_{l_1=0}^{L_1-1}h_1(l_1)x(k-l_1)+\sum_{l_1=0}^{L_2-1}\sum_{l_2=0}^{l_1-1}h_2(l_1,l_2)\prod_{m=1}^{2}x(k-l_m)++\sum_{l_1=0}^{L_3-1}\sum_{l_2=0}^{l_1-1}\sum_{l_3=0}^{l_2-1}h_3(l_1,l_2,l_3)\prod_{m=1}^{3}x(k-l_m) \quad (1)$$

where $x(k-l_m)$ is the $(k-l_m)$-*th* sample of the received signal; $h_1(l_1)$, $h_2(l_1,l_2)$ and $h_3(l_1,l_2,l_3)$ are the 1st, 2nd and 3rd Volterra kernels; L_1, L_2 and L_3 are the corresponding memory length. It is noted that 1st, 2nd and 3rd term in Eq. (1) is specifically designed to deals with the linear distortions, SSBN and fiber nonlinearities, respectively. It is noted that the number of the three kernels are L_1, $L_2\times(L_2+1)/2$, $L_3\times(\,L_3+1)\times(L_3+2)/6$, respectively. Therefore, the computational complexity of Volterra filter is more affected by L_2 and L_3. The Volterra kernels in (1) can be determined by training symbols using recursive least square (RLS) algorithm.

3. Experimental Setup and Results

The experimental setup is shown in Fig. 1. The PAM-4 signal is generated by a four-channel arbitrary waveform generator (AWG, Agilent Technologies, M9502A) operating at 14-GSa/s. The corresponding optical spectrum is shown in the inset (i) of Fig. 1. The output signals from the DMLs are multiplexed by optical coupler (OC). The chirp of DML is managed by the DI with free spectral range (FSR) of 66-GHz [7]. The channel spacing of the DMLs is 132-GHz (1.05-nm) corresponding to double of FSR, as shown in the inset (i) of Fig. 1. An Erbium-doped fiber amplifier (EDFA) is employed to control the launch power. After the SMF transmission, the signal is first amplified by another EDFA. After being de-multiplexed, the signal is received by a PD with bandwidth of 10 GHz. The received optical power is optimized at -14 dBm. The electrical signals were sampled by a Tektronix oscillator scope (DPO73304D) operating at 100 GSa/s, and processed off-line. The frequency responses of combined of DML and PD at wavelength of 1542.20 nm at optical back-to-back and after 160-km fiber transmission with and without DI are also shown in the inset (ii) of Fig. 1. It is noted that the 3-dB and 20-dB bandwidths of system at back-to-back case are 10 GHz and 13 GHz, respectively. As shown in the inset (ii), several frequency notches induced by CD are observed after 160-km SMF transmission without DI. However, these notches vanish when DI is applied at the transmitter side. This is mainly because the DI partially filters out one sideband of the signal, which can also be seen from the asymmetrical spectral of inset (i) [7]. In the offline processing, training symbols are firstly used to estimate the time-domain Volterra kernels. The memory length of each Volterra kernel is set to be 21, 11 and 9, which is defined as (21,11,9).

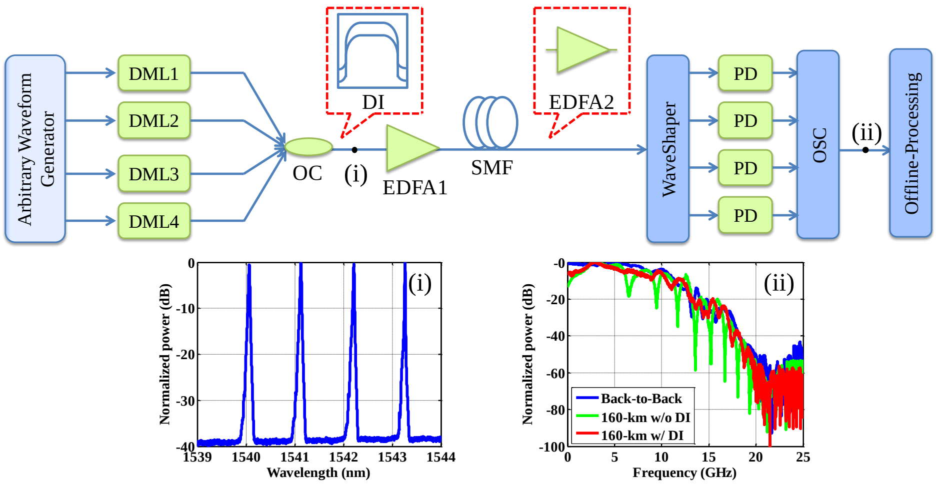

Fig. 1 Experimental setup. Inset: (i) optical spectral at the transmitter side; (ii) frequency response of DML at back-to-back and after 160-km SMF transmission with and without DI. OC: optical coupler. VOA: variable optical attenuator. OSC: oscilloscope.

Fig. 2(a) shows the BER performance of four channels versus input power after 160-km SMF transmission. As shown in Fig.2(a), the BERs of all four channels are below 7% FEC threshold (3.8×10^{-3}) after 160-km SMF transmission at the optimum input power of 17-dBm. Fig. 2(b) shows the BER performances of the channel 2 (worst case) at the optimum input power for the Volterra filter with different memory length. As shown in Fig. 2(b), the performance is degraded with reduced memory length of Volterra filter. We can also see that the Volterra filter with only 1st and 3rd kernels shows better performance than that with only 1st and 2nd kernels, which means that the 3rd fiber nonlinearity distortions are more serious than the 2nd nonlinearity distortions in the system.

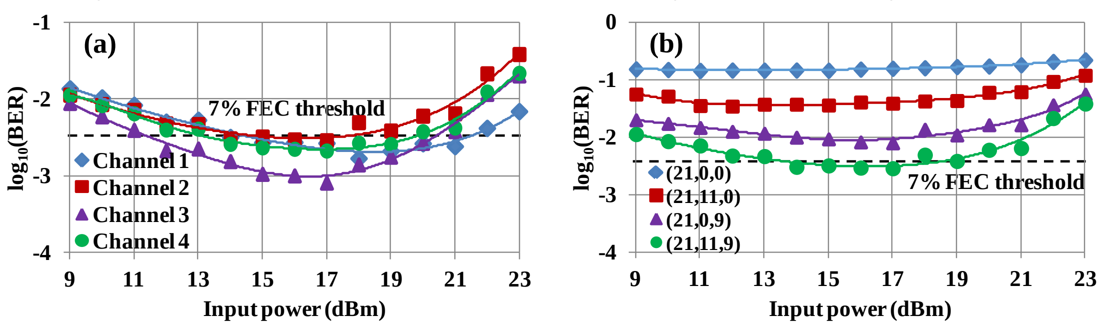

Fig. 2 BER performances versus input power after 160-km SMF transmission (a) for four channels and (b) with different memory length of Volterra filters.

We further study the effects of DI and Volterra filter with different memory length in the system. As shown in Fig. 3(a), at the 7% FEC threshold, applying DI can increase the transmission distance from 120 km to 160 km. The reason of improvement can be found in the inset (ii) of Fig. 1, where the frequency notches disappear if DI is applied at the transmitter side. The Fig. 3(b) shows the effects of memory length of Volterra filter. As can be seen in Fig. 3(b), the BER performances are improved with increased memory length. However, the memory length of Volterra filter can be adjusted according to the transmission distance at the 7% FEC threshold. The Volterra filters with memory length of (5,3,1) and (17,5,1) are sufficient for 100-km and 120-km SMF transmission, corresponding to the total number of kernels of only 12 and 33, respectively.

For cost-effective configuration, we remove the DI at the transmitter side and EDFA at the receiver side. In order to obtain sufficient SNR at the receiver side, we set the input power to be 23 dBm and memory length of Volterra filter is (41,9,9). Fig. 4(a) shows the BER performances of four channels versus received power after 100-km SMF transmission. As shown in Fig. 4, the BERs of all four channels can reach the 7% FEC threshold at the received power of -15 dBm. Since the launch power per channel is 17 dBm, the power budget for a single channel is 32 dB. Therefore, the cost-effective scheme combined with Volterra filter has the potential application in furure 100-Gb/s long-reach passive optical network. The effects of memory length for the scheme is shown in Fig. 4(b). It is noted that the BER performance is more likely to be effected by the memory length of 2nd and 3rd kernels than that of the 1st kernel, which indicates that the system performance is mainly limited by the nonlinear distortions.

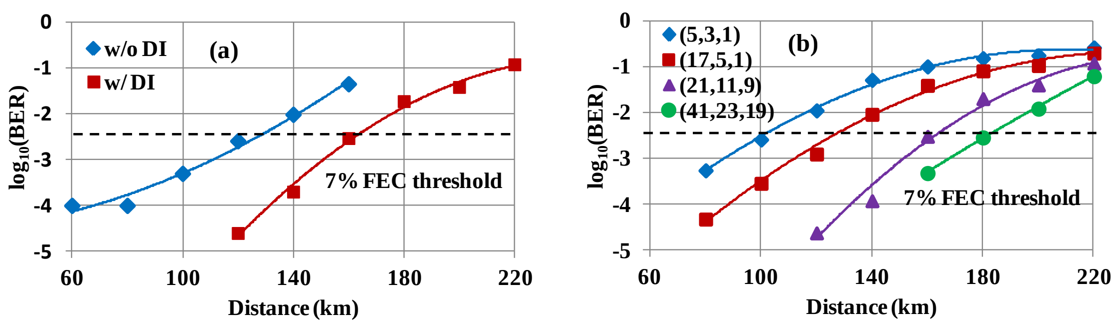

Fig. 3 BER performances versus transmission distance for the 2nd channel (a) with and without DI and (b) with different memory length of Volterra filters.

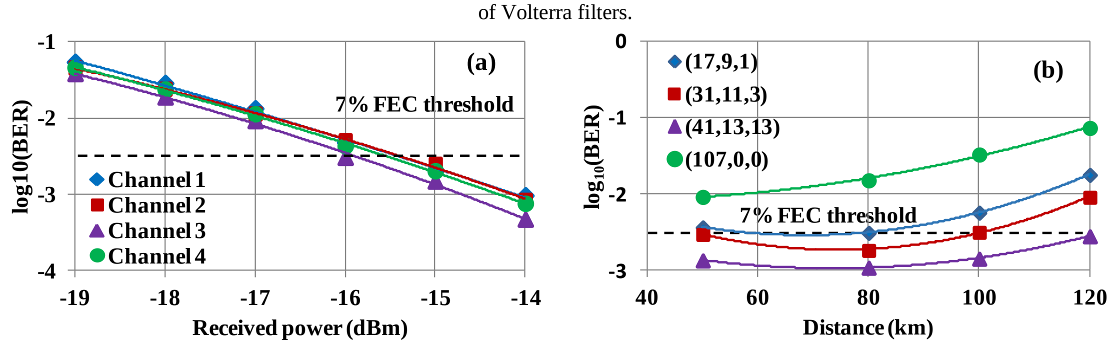

Fig. 4 (a) BER performances versus received power after 100-km SMF transmission for the four channels. (b) BER performances versus transmission distance for the 2nd channel with different memory length of Volterra filters.

4. Conclusion

We have experimentally transmitted a C-band 112-Gb/s (4×28-Gb/s) PAM-4 over 160-km SMF based on 10G-class DML and photodiode. DI is applied at the transmitter side to eliminate the frequency notches induced by CD. The nonlinear distortions are largely compensated by the digital Volterra filter. Even for cost-effective consideration without DI at the transmitter side and EDFA at the receiver side, more than 100-km SMF transmission can also be achieved. From these results and discussions, the DML-based four-channel PAM-4 combined with DI and Volterra filter is a good candidate for future low-cost 100-Gb/s short reach transmission.

5. References

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