4.8 Tb/s PS-PAM-8 Bidirectional Transmission over 10-km 24-core Fiber Using Linear Equalization at O-Band

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Abstract: 4.8-Tb/s PS-PAM-8 bidirectional transmission is experimentally demonstrated over 10-km 24-core fiber with SOA using only linear equalization at O-band. The experimental results indicate that the MCFs are well-suited for optical short-reach systems employing IM/DD.
OCIS codes: (060.4080) Modulation; (060.2330) Fiber optics communications

1. Introduction

Due to the rapid development of mobile devices, cloud computing and big data, the traffic of data centers has exploded. Therefore, there is an urgent need for short-reach systems that have lower cost and higher capacity. Pulse amplitude modulation (PAM) based on intensity modulation and direct detection (IM/DD) is preferred due to its low system complexity and high spectral efficiency [1-2]. Probabilistic shaping (PS) technique is an effective means to improve system performance in high-order modulation. It reduces the probability of constellation points in the outer circle, which can reduce the average power of the signals and improve the receiver sensitivity. Many experiments have been reported. By using thin-film LiNbO3 MZM modulator, 200-GBaud PS-PAM-16 have been successfully transmitted over 10-km SMF [3]. Meanwhile，800Gb/s PS-PAM-8 transmission in a four-lane IM/DD system has also been demonstrated [4].

In order to improve the capacity for the short-reach system different methods have been studied. Space division multiplexing (SDM) technologies is regarded as a promising solution to increase the transmission capacity [5]. Single-mode multi-core fibers (MCFs) offer cost-effective migration path to increase the transmission capacity by effectively increasing the number of transmission channels. Actually, MCFs are also suitable for optical interconnects in data centers or short-reach systems which are mostly based on IM/DD without additional optical amplification. Tb/s transmission experiment using IM/DD based MCFs has also been experimental demonstrated [6]. However. with the increase of the number of cores, the crosstalk between cores cannot be ignored, which limits the application of MCFs in optical short-reach transmission.

In this paper, we experimentally demonstrate the IM/DD based bidirectional transmission of 4.8-Tb/s (200-Gb/s×24) PS- PAM-8 signals over 10-km 24-core single-mode fiber. We use an optimized design of 24-core fiber produced by CICT (China Information Communication Technologies Group), which can ensure that the signal transmission direction of two adjacent cores is opposite, so as to minimize the interference between cores. Besides, probabilistic shaping technique, linear equalization and SOA are applied to improve the receiver sensitivity of high-order modulation systems under low-cost conditions. Finally, the transmission of a 4.8-Tb/s PS-PAM-8 signal is successfully achieved over 10-km 24-core fiber with only linear equalization at O-band. The bit error rate (BER) is below the 20% soft-decision forward error correction (SD-FEC) threshold of 2×10^{-2}.

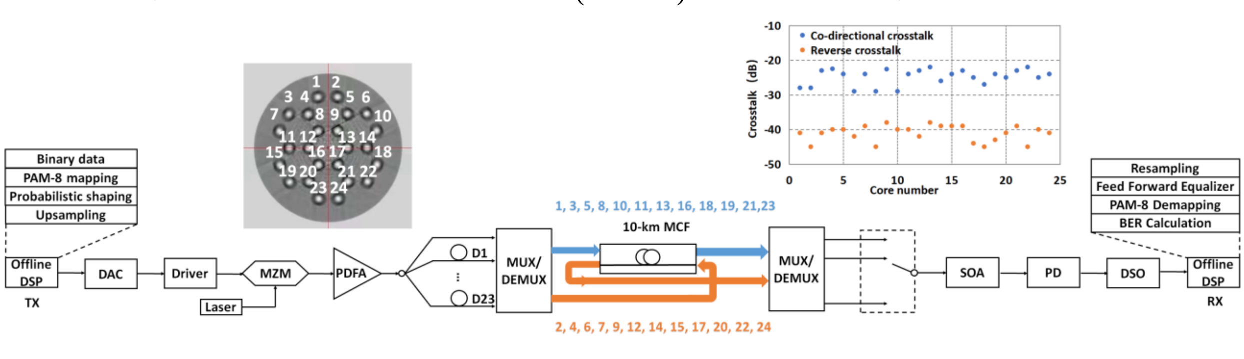

Fig. 1. Experimental setup for the 24-core fiber transmission of 4.8-Tb/s PS-PAM-8 signal based on linear equalization at O-band.

2. Experimental Setup and Results

Figure 1 shows the experimental setup for the 24-core fiber transmission of 4.8-Tb/s PS-PAM-8 signals based on linear equalization at O-band. At the transmitter side, signal coding and probabilistic shaping methods are shown in Fig. 1. The original binary data is firstly mapped into PS-PAM-8 symbols. The ununiformed probability distribution PS-PAM-8 signal follows the Maxwell-Boltzmann distribution with different net entropy for different baud rate (75-GSa/s and 79-GSa/s), while the effective transmitted bit rate of all different sampling rate signals is 200-Gb/s. Then, signals with different baud rates are uniformly unsampled to 120-GSa/s, which is send to a Keysight arbitrary waveform generator (AWG) M8194A, running at 120-GSa/s. The driver with bandwidth of 40-GHz is employed to amplify the signal before injecting into the Mach-Zehnder modulator (MZM). The electrical bandwidth of the MZM used for intensity modulation is around 25-GHz. In the experiment, we use an EXFO O-band optical source, whose operation wavelength is set to around 1310-nm. The modulated optical signal is then amplified using praseodymium doped fiber amplifier (PDFA) with operation wavelength ranging from 1280nm to 1320nm. The output signal of the optical amplifier is then divided among all cores of the 24-core fiber by SDM MUX. Signals in neighboring SDM channels are decorrelated by transmission through fibers of different lengths.

The transmission link is composed of 10-km 24-core fiber, which is independently designed and produced by China Information Communication Technologies Group. The cross-sectional view of the fiber can be seen in the inset of Fig. 1. According to the practical measured data, the core diameter of each fiber in the MCF is about 8.4 μ m, and the core pitch is 33 μ m, and the cladding diameter is 250 μ m. As we known, with the increase of the number of cores in multi-core fibers, the inter core crosstalk will increase. The inset of Fig. 1 shows the crosstalk for the neighboring SDM channels, when optical signals transmitted in the same directions or in the opposite directions. We can see that the maximum inter core crosstalk is about -22dB in the same transmission directions and -38dB in the opposite directions. Therefore, we set cores 1, 3, 5, 8, 10, 11, 13, 16, 18, 19, 21, and 23 to transmit in the same direction and cores 2, 4, 6, 7, 9, 12, 14, 15, 17, 20, 22, and 24 to transmit in the opposite direction. Based on the optimization design of MCF, when we perform bidirectional transmission under the above conditions, the transmission direction between each core and its adjacent core is opposite, which minimizes the inter core crosstalk.

After propagating in 24-croe fiber at a distance of 10-km, the signals are amplified by a O-band semiconductor optical amplifier (SOA), which is employed to increase received power for the photo detector (PD) without TIA. Then the PD with a bandwidth of 40-GHz converts the received optical signal to electrical domain. Finally, the electrical signal of PD is injected into a digital sampling oscilloscope (DSO) operating at 256-GSa/s which has cutoff frequency of 70-GHz, and the signals is processed offline.

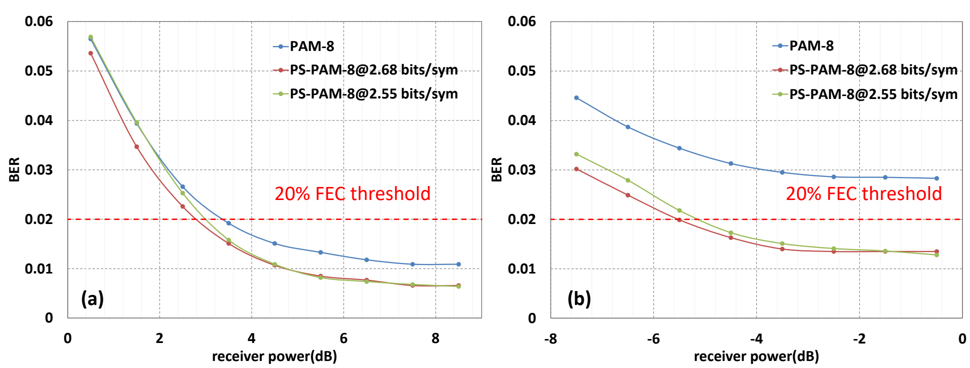

Fig. 2 Receiver sensitivity measured at back-to-back (B2B) for the 200-Gb/s PAM-8/PS-PAM-8 signals with different probability distribution. (a) without SOA; (b) with SOA

3. Experimental Setup and Results

We first investigate the PS-PAM-8 performance in the optical back-to-back (OBTB) case. Since the crosstalk between the neighboring cores is low when its transmission direction is opposite, the measurements are only conducted for one core each time. Fig. 2 shows the measured curve of BER versus receiver power of the 200Gbit/s PAM-8 or PS-PAM-8 signals with and without SOA. It is observed that the performance has been improved when probabilistic shaping is utilized. When the SOA is used, the receiver sensitivity is increased from 2.4 dBm to -5.8 dBm for the PS-PAM-8 with the entropy of 2.68 bits/sym. The main reason for performance improvement is that the PD without TIA requires large input optical power to ensure proper operation.

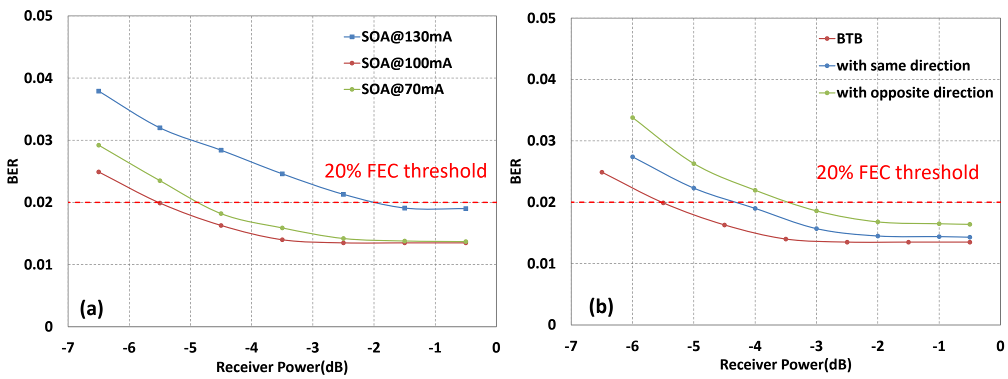

Fig. 3 Receiver sensitivity measured for the 200-Gb/s PS-PAM-8 signals the entropy of 2.68 bits/sym (a) with different drive current of SOA; (b) with different transmission direction

We also investigate transmission performance of PS-PAM-8 in 24-core fiber. Results show that the optimal value of the current of the SOA is about 100mA as shown in Fig. 3 (a). Meanwhile, the transmission performance is discussed under the optimal condition of SOA current and PS-PAM-8 probability distribution. The Fig. 3 (b) shows that the BER performance decrease when multi-core transmission is performed, which is caused by inter core crosstalk. When all signals have the same transmission direction, the receiver sensitivity is -3.5dB, corresponding to 2dB penalty. When the proposed transmission direction distribution is adopted, the penalty is only 1.2dB.

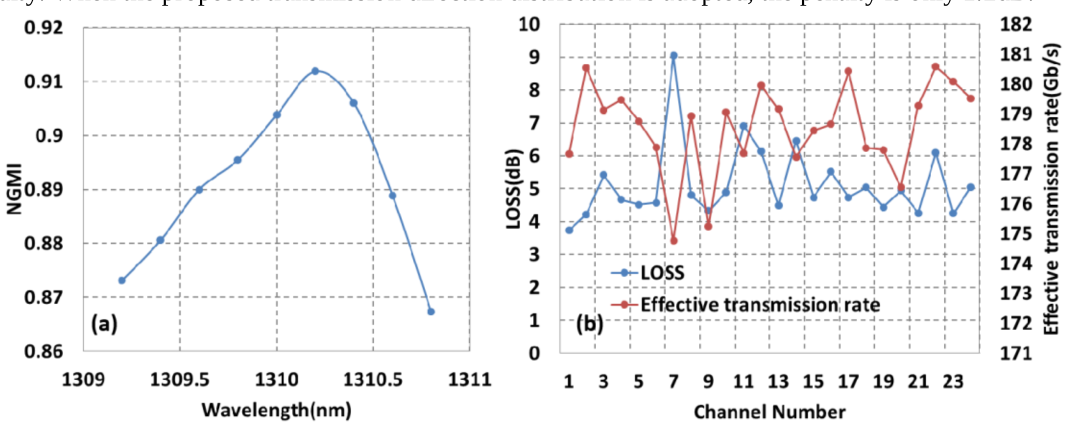

Fig. 4 (a) Measured curve of normalized generalized mutual information (NGMI) versus wavelength; (b). Measured curve of channel number versus transmission loss and effective transmission rate

Finally, we also study the transmission performance of PS-PAM-8 in the 24-core fiber. Fig. 4 (a) shows the performance of the PS-PAM-8- signals in 10-km MCF transmission under the condition of different wavelength. It is shown in Fig. 4 (a) that the optimal wavelength in the proposed method is about 1310.2nm. In order to better describe the quality of the received PS-PAM-8, we define effective transmission rate as: R = GMI $\times$ Baud Rate. Fig. 4 (b) depicts the transmission loss and effective transmission rate for different channel. As shown in the Fig. 4 (b), the minimum effective transmission rate is about 174.75-Gb/s for the maximum 9dB loss and the total effective transmission capacity is over 4.3-Tb/s.

4. Conclusion

A bidirectional transmission of 4.8-Tb/s (200-Gb/s×24) PS-PAM-8 signal over 10-km 24-core single-mode fiber based on IM/DD has been successfully achieved with only linear equalization at O-band. The inter crosstalk caused by the limited distance among cores are mitigated by the proposed method, which enables to transmit 24 channels signals at high baud rates. The experimental results indicate that MCFs are well-suited in the IM/DD system, and it offers an upgrade path to higher data rate for the short reach optical communication.

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