C Band Single Wavelength 1.68Tb/s Optical Interconnect over 12.18-km 7-core Multicore Fiber

Qibing Wang[1], Chao Li[1], Yuanyuan Zhao[1], Zichen Liu[1], Hui Chen[1], Siyue Jin[1], Xi Xiao[1,2], Lei Wang[1], Zhixue He[1,*], Shaohua Yu[1]

[1]*Peng Cheng Laboratory, Nanshan District, City of Shenzhen, China*
[2]*National Information Optoelectronics Innovation Center, City of Wuhan, China*
[*]*hezhx01@pcl.ac.cn*

Abstract: We demonstrate a single-wavelength 112GBaud PAM4 signal transmission over 12.18-km 7-core MCF at C band using FFE, under 7% HD-FEC threshold. Furthermore, a maximum data rate of 1.68-Tb/s is achieved with PAM8 and simplified VNLE.

1. Introduction

The demand for high speed optical interconnects is growing rapidly in recent years due to the deployment of many bandwidth-hungry applications such as high-definition streams, datacenters, artificial intelligence and so on. Currently, intensity modulation and direct detection is still the preferred solution for long-reach (LR) optical interconnect. However, when the data rate is above 200Gb/s per wavelength, the transmission distance is difficult to be extended beyond 10km due to the severe power fading caused by chromatic dispersion (CD) even in the O band, let alone the C band [1,2]. Vestigial sideband (VSB) signal generated by optical filter has been proved to be able to reduce the influence of CD [3-5], with the demonstrated data rate up to 112Gb/s. The remaining nonlinear interference will be largely lowered down, therefore only requiring linear feed-forward equalizer (FFE) or Volterra-based nonlinear equalizer (VNLE) to recover the data in the receiver.

The Spatial-division multiplexing (SDM) optical interconnect has been demonstrated to increase the data rate significantly [6,7]. By using 8 wavelength division multiplexing (WDM) and 8-core multi-core fiber (MCF), a total 12.8Tb/s throughput (200Gb/s × 8 core per wavelength) has been achieved recently in an intra-datacenter O band optical interconnect network within 1-km distance [8]. However, even in the O band, all these SDM optical interconnect distance is far below LR standard of 10km.

In this paper, we demonstrate a 12.18-km 7-core MCF optical interconnect at C band enabled by VSB and simplified VNLE, with a maximum net data rate of up to 1.68-Tb/s (240Gb/s × 7 core) in a single wavelength, achieved by 96Gbaud PAM8 signal transmission under the 20% SD-FEC (2.4×10^{-2}) bit error ratio (BER) threshold. The VSB signal is generated by optical filter in the transmitter. Besides, 112Gbaud PAM4 signal is also successfully transmitted using only FFE, under the 7% HD-FEC (3.8×10^{-3}) BER threshold.

2. Experimental Setup

The optical signal transmission link is depicted in Fig. 1(a). In the transmitter (Tx), offline digital signal processing (DSP) was used to generate the digital signal, which then was loaded into a 256GSa/s arbitrary waveform generator (AWG M8199A) to generate a single-ended output signal with the Vpp of 300mV. Then the signal was fed to a wideband amplifier with 3-dB bandwidth of 66GHz and 11-dB gain. Therefore, An electrical signal with a Vpp of around 1.1V was obtained to drive a thin film lithium niobate (TFLN) mach-zehnder modulator (MZM) with a 3-dB bandwidth of 60GHz. The optical signal was generated by an external cavity laser (ECL), whose wavelength and power were set to 1550nm and 15dBm. After being modulated by the MZM biased at the quadrature point, the optical signal was amplified to be 18dBm through one Erbium-doped fiber amplifier (EDFA) to compensate the signal loss in the MZM and the following optical filter (XTM-50). The optical filter was manually adjusted to suppress one sideband to produce the VSB signal. The input and output power of the 1:8 splitter was 9.3dBm and -0.8dBm. Seven outputs were connected to the fan-in (FI) devices of the 7-core MCF and the remaining one was connected to the optical spectrum analyzer (OSA) to assist a better removal of one sideband of the signal. The 7-core MCF has one core in the center while the other 6 cores are uniformly distributed around, with 62μm pitch and 200μm diameter cladding. The overall loss for FI, fiber and FO is around 5.8dB and the crosstalk is lower than -45dB. After transmission over a 12.18-km 7-core MCF and the optical signal was then fanned out to produce all the 7 signal outputs, of which were tested one by one. Another EDFA was adopted to boost the optical power to be 10dBm, followed by a variable optical attenuator (VOA), in order to sweep the received optical power (ROP). Afterwards, the signal was detected by a 60GHz photodetector (PD N7005A). Finally, a 256GSa/s real-time digital storage oscilloscope (DSO UXR0594AP) of 59GHz bandwidth was used to capture the data for offline DSP in the receiver (Rx).

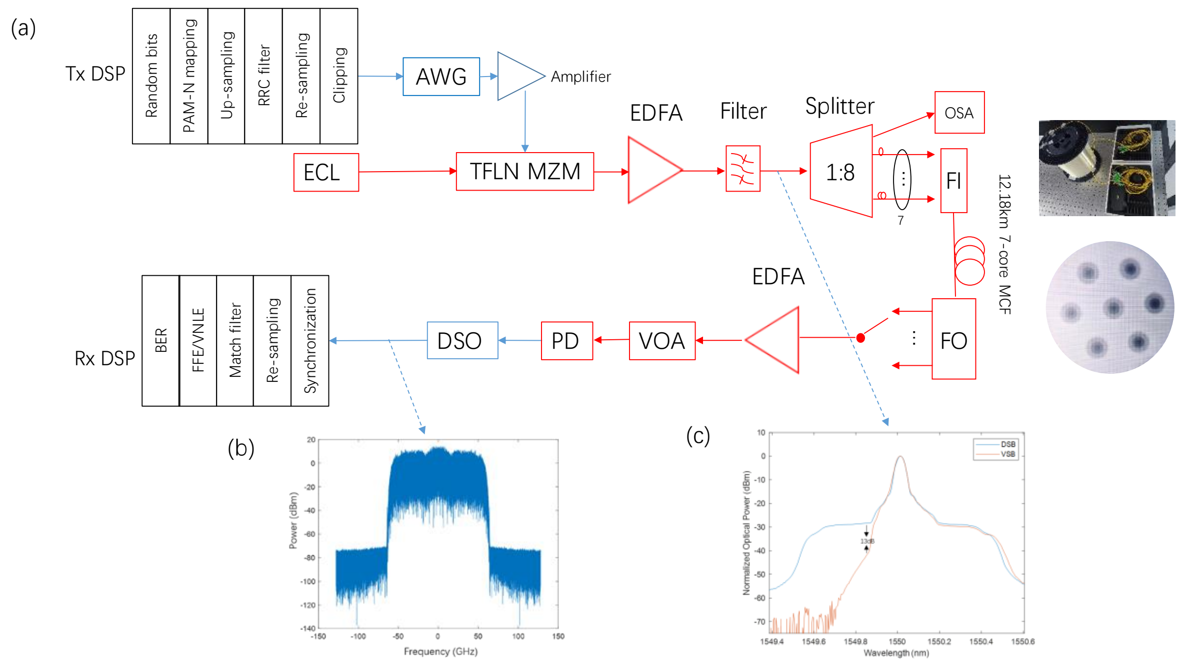

Fig. 1. (a) Single wavelength optical VSB signal transmission experimental setup over a 12.18-km 7-core MCF; (b) The electrical spectrum of the received waveform; (c) The optical spectrum of DSB and SSB signal.

The offline DSP in the Tx and Rx are also illustrated in Fig. 1(a). In the Tx, random data was produced and then mapped to PAM-N (N = 4 or 8). After up-sampling, RRC filter with a roll-off factor of 0.1 was used to narrow down its spectrum. Then the digital signal was resampled to 256GS/s and clipped. In the Rx, the captured waveform was firstly synchronized and resampled to 2 samples per symbol. Then a match filter was executed, followed by FFE and VNLE to recover the data. Finally, the BER was calculated.

The spectrum of the double sideband (DSB) signal and VSB signal are normalized and shown in Fig. 1(c). As the limited edge roll-off of the optical filter, perfect single sideband (SSB) signal cannot be generated. The VSB signal has a suppression ratio of 13dB around the left optical carrier with an increased suppression ratio of more than 30dB in the high frequency domain. The VSB can lead to the residual nonlinear distortion due to the square law detection of the PD. Fig. 1(b) plots the electrical spectrum of the received waveform, only a power dip appears and the others are not very obvious, indicating a minor remaining nonlinear distortion, which needs VNLE to deal with. FFE has been widely used in the DSP-enabled optical receivers to combat the linear damage of the signal, but VNLE is still struggled to be accepted in the commercial DSP modules, mainly due to its huge computational complexity. In order to reduce the VNLE's complexity, a simplified VNLE was adopted in this experiment, using only 25 second order nonlinear kernels and then truncated to the closest 11 product terms [9].

3. Experimental Results and Discussion

Firstly, 112GBaud PAM4 signal was generated and transmitted over the 12.18-km 7-core MCF. We manually tested each of 7-core output signals and calculated its BER by adjusting the received optical power (ROP). 61-tap FFE was used to compensate the linear distortion in the transmission link. As shown in Fig. 2(a), the receiver sensitivity for all the 7-core output signals is around 6dBm when the 7% HD-FEC is adopted.

We then measured the BER of different symbol rates by fixing the ROP to 6dBm. Fig. 2(b) shows the BER versus different symbol rates of PAM4 signal in all the 7 cores. It can be seen that the BER for all the cores are similar. When only FFE is adopted, the BER floor is above 1×10^{-3}. Simplified VNLE outperforms the FFE in all the symbol rates and the BER floor is reduced to 1×10^{-4} because the nonlinear distortion introduced by the VSB signal can only be compensated by VNLE rather than FFE. By using both FFE and Simplified VNLE, the largest achieved symbol rate for PAM4 in this experiment is 120GBaud for the 7% HD-FEC threshold, mainly because of the rapidly reduced electrical signal power above 59-GHz of the DSO.

To further increase the data rate, PAM8 signal was adopted with the BER versus symbol rate for all the 7 cores plotted in the Fig. 2(c). As PAM8 requires a larger SNR than PAM4, both FFE and Simplified VNLE were carried out to improve the transmission performance. Assuming 20% SD-FEC, the achieved maximum symbol rate is 96GBd, leading to a line data rate of 2.016Tb/s (96GBd × 3 × 7 core) and net data rate of 1.68Tb/s of all the 7-core MCF.

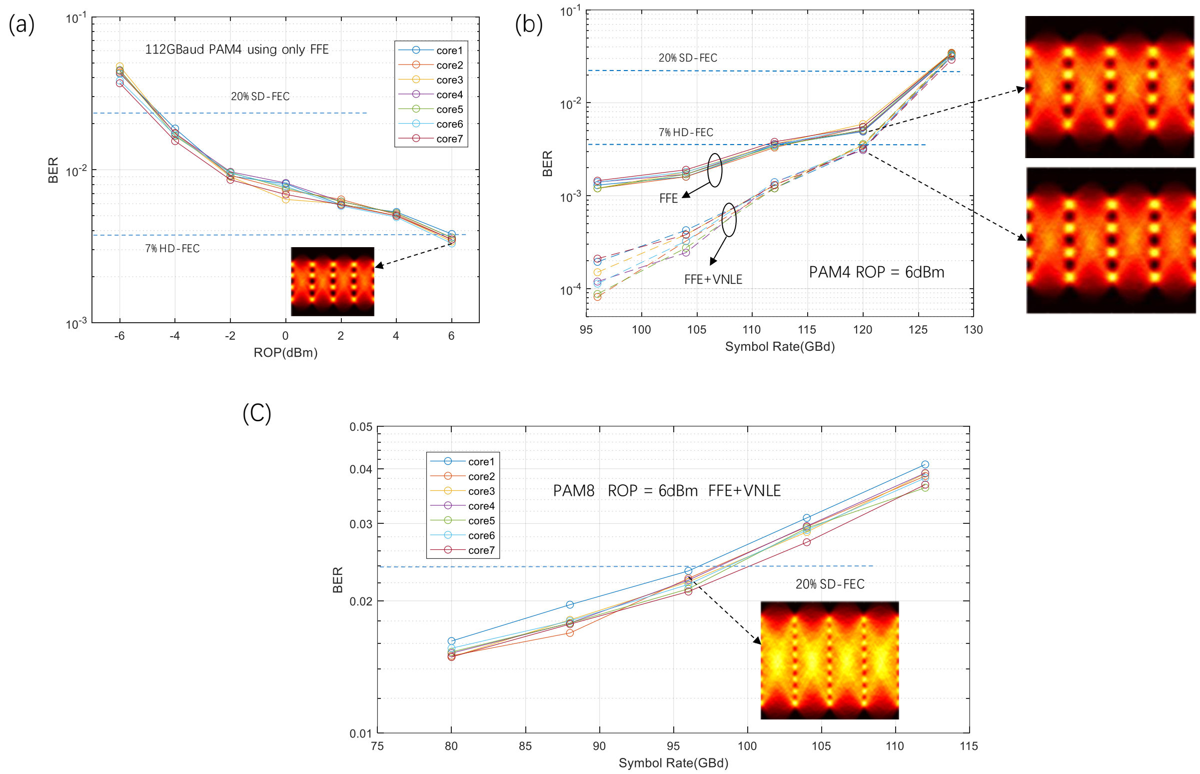

Fig. 2. (a) BER versus ROP for 112GBaud PAM4 signal transmitted over all the 7-core MCF; (b) BER versus symbol rate for PAM4 signal transmitted over all the 7-core MCF; (c) BER versus symbol rate for PAM8 signal transmitted over all the 7-core MCF.

4. Conclusions

A simple solution for the SDM optical interconnect over 10-km distance with the net data rate above 200Gb/s in a single wavelength of each core is provided. We show that VSB signal generated by an optical filter is sufficient to mitigate the power fading result of the large CD at C band in direct detection optical interconnect system. Using only 61-tap FFE, a single wavelength 12.18-km 7-core MCF transmission experiment is successfully demonstrated for 112GBaud PAM4 signal with the BER below the 7% HD-FEC threshold. Besides, by upgrading the modulation format to PAM8, a maximum net data rate of 1.68Tb/s in a single wavelength is achieved with simplified VNLE, supposing 20% SD-FEC is adopted.

5. References

[1] 800G Pluggable MSA. Online Available at https://www.800gmsa.com/H.
[2] T. Bo, *et al.*, "Optical Single-Sideband Transmitters," Journal of Lightwave Technology, **41** (4), 1163-1174 (2023).
[3] J. Lee, N. Kaneda and Y. Chen, "112-Gbit/s Intensity-Modulated Direct-Detect Vestigial-Sideband PAM4 Transmission over an 80-km SSMF Link," in *proc.* ECOC 2016, pp. 1-3.
[4] H. Chen, *et al.*, "Optical Filter Requirements in an EML-based Single-Sideband PAM4 Intensity-Modulation and Direct-Detection Transmission System," Opt. Express, **25** (6), 5852-5860 (2017).
[5] Z. Xing, *et al.*, "Filter Response Aware Iterative KK Algorithm for VSB systems," in *proc.* ECOC 2020, pp. 1-4.
[6] S. Beppu, *et al.*, "56-Gbaud PAM4 Transmission over 2-km 125-μm-Cladding 4-Core Multicore Fibre for Data Centre Communications," in *proc*. ECOC 2017, pp. 1-3.
[7] A. Masuda, *et al.*, "255-Gbps PAM-8 Transmission under 20-GHz Bandwidth Limitation using NL-MLSE Based on Volterra Filter," in *proc.* OFC 2019, pp. 1-3.
[8] R. S. Luis, *et al.*, "12.8 Tb/s SDM Optical Interconnect for a Spine-Leaf Datacenter Network with Spatial Channel Connectivity," in *proc.* ECOC 2022, pp. 1-4.
[9] H. Xin, *et al.*, "50 Gbps PAM-4 over up to 80-km Transmission with C-Band DML Enabled by Post-Equalizer," IEEE Photonics Technology Letters, **32** (11), 643-646, (2020).