C-band Net 1.8 Tb/s (240Gb/s/λ× 8λ) DWDM IM/DD Transmission over 1.4km AR-HCF with Linear FFE Only

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Abstract: Record net 1.8Tb/s IM/DD optical interconnect supported by 8λ dense wavelength division multiplexing technique in C-band over wide-band low dispersion anti-resonant hollow-core fibre (AR-HCF) is experimentally demonstrated under 6.7% HD-FEC limit with linear FFE only.

1. Introduction

Driven by the booming internet traffic, caused by high-performance computing, high-definition video stream service, artificial intelligence , Internet of Thing, and so on, intra-data-center interconnects (intra-DCIs) are facing high challenge [1]. To cope with this demand in an economically and practically way, scaling the capacity to 1.6T per link is the key solution [2]. The 800G multi-source agreement (MSA) has already released 200-Gb/s per lane specifications with 100GBaud 4-level pulse amplitude modulation (PAM4) modulation and standards for intra-DCI over km-scale reach [3]. Intensity modulation direct detection (IM/DD) scheme combined with PAM4 modulation is now still regarded as the dominant scheme with low complexity transceiver digital signal processing (DSP) algorithms including equalization like linear feed-forward equalizer (FFE) and low-latency forward error correction (FEC) decoding [4]. Fig. 1 compares the typical C-band IM/DD transmissions with beyond 200Gb/s/λ capacity for short-reach intra-DCIs. The previous demonstrations mainly focus on the single wavelength IM/DD transmission systems by using complex DSP [5-14]. Even using 400-tap FFE combined with a maximum likelihood sequence estimation and 20% FEC limit, the reach is restricted to 0.8km caused by the frequency fading by fiber dispersion [15]. Anti-resonant hollow-core fibre (AR-HCF) is regarded as a powerful means to solve this issue [16, 17]. No extra performance penalty is observed for 100GBaud PAM4 signal over 1.4km AR-HCF (used in this work) transmission compared with back-to-back (BTB) performance, as illustrated in Fig. 2(a) and (b).

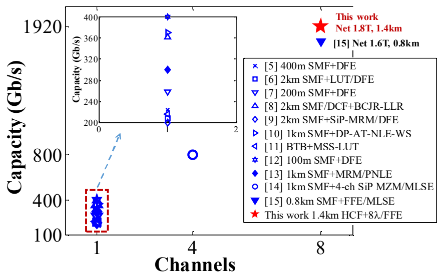

Fig. 1. Typical C-band IM/DD transmissions with beyond 200Gb/s/λ capacity for short-reach intra-DCI links.

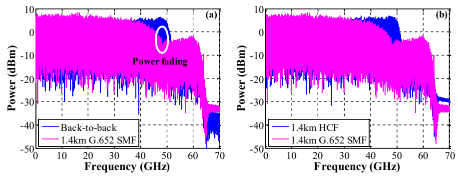

Fig. 2. Power spectrum density (PSD) of 100GBaud PAM4 signal transmitted in 1550nm. (a) comparison between back-to-back and 1.4km G.652 SMF, (b) comparison between 1.4km HCF and 1.4km G.652 SMF.

In this paper, we propose and experimentally demonstrate a record net 1.8Tb/s IM/DD transmission in C-band using 8λ dense wavelength division multiplexing (DWDM) technique over 1.4km AR-HCF within 6.7% overhead hard-decision FEC (HD-FEC) limit of 3.8×10^{-3} using linear FFE with 217-tap only. Each odd and even channels are separately modulated by 120GBaud PAM4 signal via two independent high-speed thin-film lithium niobate Mach-Zehnder modulators (TFLN-MZMs). The measured results reveal that the proposed configuration presents a promising route to the realization of beyond 1.6T optical interconnects using cost-effective DWDM IM/DD technique over high-performance low-latency AR-HCF (≈33% latency reduction compared with SMF [16]).

2. Experimental setup

Figure 3 shows the experimental setup of the proposed net 1.8Tb/s IM/DD transmission system with 8λ DWDM in C-band over 1.4km AR-HCF. The DWDM channels are constructed by eight independent tunable laser sources, which are divided into two groups according to the odd and even characteristics. The four wavelengths in each group are

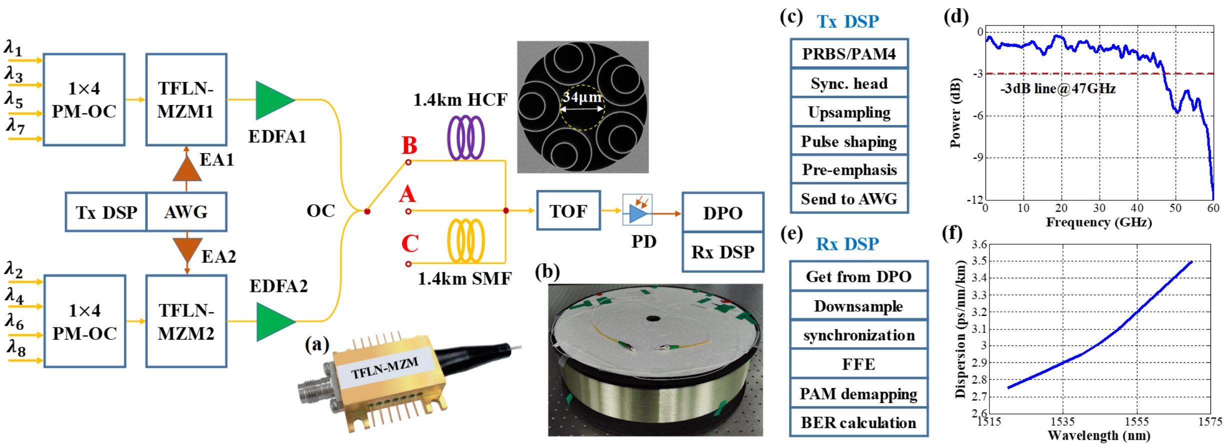

Fig. 3. Experimental setup of the proposed net 1.8Tb/s IM/DD system with 8λ DWDM in C-band. (a) photo graph of packaged TFLN-MZM, (b) photo graph of 1.4km AR-HCF connected with SMF at both end faces, (c) DSP flow at the transmitter, (d) frequency response of the whole system, including AWG, MZM, PD and DPO, (e) DSP flow at the receiver, and (f) Measured group velocity dispersion (GVD) of the fabricated HCF across wavelength range from 1520nm to 1570nm (C-band).

combined together by using two 4×1 polarization maintaining optical couplers (PM-OCs), whose wavelengths are set at 1541.6nm, 1544nm, 1546.4nm, 1548.8nm, and 1542.8nm, 1545.2nm, 1547.6nm, 1550nm, respectively. Thereby, the channel spacing is 150GHz to accommodate the 120GBaud optical PAM4 signals in the demonstration. The electrical PAM4 signals are produced by a high-speed arbitrary waveform generator (AWG) running at 240GSa/s with 2-time oversampling, resulting in 120GBaud PAM4. The generated electrical PAM4 signals are firstly amplified by two electrical amplifiers (EAs) and then used to drive the two independent TFLN-MZMs. The used TFLN-MZMs are packaged with V female connector and polarization maintaining fiber as optical input port as shown in Fig. 3(a), whose −3dB bandwidth is measured to be more than 60GHz. The modulated optical signals are optically amplified by two Erbium-Doped optical fiber amplifiers (EDFAs) and then combined by an 50/50 optical coupler (OC). The EDFA1 and EDFA2 are also used to adjust the launched optical power into the fiber. For comparison, optical BTB, 1.4km AR-HCF, and 1.4km G.652 SMF are employed as transmitted channels, represented as routes A, B and C as illustrated in Fig. 3. The used AR-HCF is designed and fabricated based on nested anti-resonant nodeless structure named as NANF and has the full length of 1.4km wrapped around a bobbin as shown in Fig. 3(b). The measured transmission losses across the wavelength range from 1500nm to 1600nm are all below 0.8dB/km based on cut-back method thanks to the 5-element structure and 34μm core size. The microscope graph of its end face is shown in the inset of Fig. 3. Both end faces of the 1.4km AR-HCF are pigtailed with a short section of SMF with APC connectors, resulting in the total transmission loss of around 2dB. After transmission link, the received DWDM signals are filtered out by a narrow tunable optical filter (TOF) one-by-one and then fed into the photo detector (PD) for optical-to-electrical conversion. It is worth noting that no optical amplifier is needed in the demonstration at the receiver side, which helps to further simplify the system configuration. The electrical signal is digitalized and sampled by an digital phosphor oscilloscope (DPO) with 3dB bandwidth of 59GHz, running at 256GSa/s for further offline digital signal processing (DSP). The DSP flows for both transmitter and receiver are illustrated in Fig. 3(c) and (e), which are processed offline in a MATLAB program. At the transmitter, we use raised cosine pulse shaping with roll-off factor of 0.05 and digital pre-emphasis algorithms to reduce the system distortion. While just linear FFE with 217-tap is adopted to recover the PAM4 signal at the receiver. The measured frequency response of the whole system including AWG, MZM, PD and DPO is displayed in Fig. 3(d), showing −3dB bandwidth of 47GHz. Fig. 3(f) shows the measured group velocity dispersion (GVD) of the fabricated AR-HCF across wavelength range from 1520nm to 1570nm (C-band), which indicates that the induced maximum fiber dispersions is below 3.5ps/nm/km for C-band based on our accurate modeling and measurement [18].

3. Experimental results and discussion

We firstly evaluate the BER performance of 8λ DWDM PAM4 signal with net 1.8Tb/s capacity as a function of optical wavelengths under different transmission channels, as shown in Fig. 4. For both BTB and 1.4km AR-HCF, the measured BER values for the eight channels are all below the 6.7% overhead HD-FEC limit of 3.8×10^{-3} by using

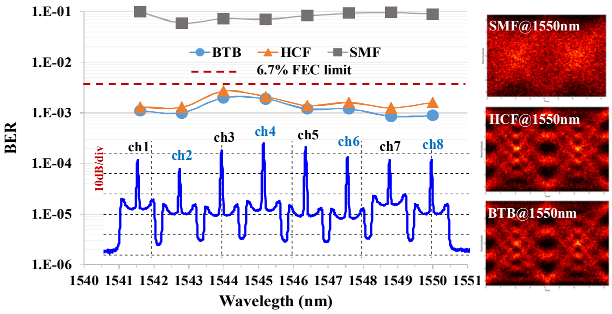

Fig. 4. BER performance of 8λ 120GBaud PAM4 signal with net 1.8Tb/s capacity. The transmitted optical wavelengths with 150GHz grid are set at 1541.6nm (ch1), 1542.8nm (ch2), 1544nm (ch3), 1545.2nm (ch4), 1546.4nm (ch5), 1547.6nm (ch6), 1548.8nm (ch7), 1550nm (ch8), respectively.

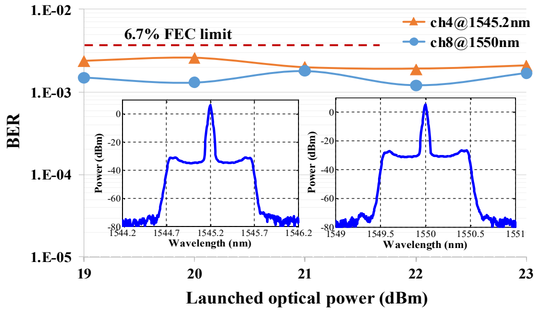

Fig. 5. BER performance of net 1.8Tb/s PAM4 signal as a function of launched optical power. The insets show the optical spectra of filtered 120GBaud PAM4 signal at the receiver side by using a narrow tunable optical filter (TOF), which is digitally pre-equalized.

linear FFE. It is also revealed that the BER performance after 1.4km AR-HCF has negligible penalty compared with BTB BER performance. While after 1.4km SMF transmission, the measured BER values approaches 1×10^{-1}. This is because the 120GBaud PAM4 signal is distorted by the fiber dispersion caused by SMF, while almost no penalty is introduced by the 1.4km AR-HCF, which is also verified by the recovered PAM4 eye diagrams at 1550nm wavelength as shown in Fig. 4. The inset shows the optical spectrum of the modulated 8λ DWDM signal with 120GBaud PAM4 and digital pre-emphasis.

Low nonlinearity and high power tolerance are two of the main advantages of AR-HCF. Thus, we can launch large optical power into the AR-HCF at the transmitter while maintaining the high-performance, so as to reduce the use of optical amplifier at the receiver side. In the experiment, Ch4 (1545.2nm) and Ch8 (1550nm) are selected as the test object. We measured the BER performance as a function of launched optical power as shown in Fig. 5. The optical powers launched into the AR-HCF is adjusted by the EDFAs and controlled from 19dBm to 23dBm by step size of 1dB. The received optical powers (ROPs) are kept at around 3.5dBm into the PD. As shown in Fig. 5, the measured BER values for the two channels are all below the 6.7% overhead HD-FEC limit as increasing the launched optical power, which verifies the employed AR-HCF with high-performance and the feasibility of the proposed receiver amplifier-free IM/DD configuration. The insets of Fig. 5 show the optical spectra of the filtered 120GBaud PAM4 signal for Ch4 and Ch8, respectively.

4. Conclusion

We have proposed and experimentally demonstrated a record 240Gb/s/λ×8 λ DWDM IM/DD transmission over 1.4km AR-HCF with the measured BER performance below the 6.7% overhead HD-FEC limit of 3.8×10^{-3} using linear FFE with 217-tap. Compared with BTB performance, negligible BER penalty is experimentally achieved. Receiver amplifier-free configuration is also verified by the experiment for the net 1.8Tb/s IM/DD system thanks to the wide band, low nonlinearity, low latency and high power tolerance AR-HCF. The measured results revealed that the proposed scheme is capable of providing a powerful means to realize a low lane count, low power consumption, low cost ad low latency solution towards >1.6Tb/s intra-DCI over >1km reach. It is also believed that the high-perfroamnce AR-HCF is a promising route to build high-capacity, low-latency optical links for short-to-metro range interconnects (≈33% latency reduction compared with SMF [16]).

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5. Reference

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