Bidirectional 3.2T (400Gb/s/λ×4λ×2) Optical Interconnect Enabled by 1.4 km NANF and PS-PAM16 with Linear FFE

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Abstract: Bidirectional optical interconnect link for beyond 3.2T application in C-band is proposed and experimentally demonstrated for the first time, enabled by high-performance NANF and probabilistic shaping 4λ 116 GBaud PAM16 with linear equalizer only. © 2025 The Author(s)

1. Introduction

The recent rapid spread of artificial intelligence and high-performance computing has brought unprecedented demand for computing. Interaction between the computing resources requires the high-speed low-latency bidirectional communication links. Optical interconnects with advanced techniques like high-performance optoelectronic devices, novel fibers and signal processing have been witnessed as a high-capacity backplane for data transmission [1-3]. To build a bidirectional optical link, the elastic backscattering of light in silica-based single mode fiber (SSMF) sets the ultimate performance. Since the backscattered light equals multitudes of delayed replicas of transmitted signals and could mostly mix with the signal whenever they reached the receiver, represented as a source of noise to degrade the signal-to-noise ratio (SNR) of received signal [4]. Thereby, two-fiber bidirectional paths based on SSMF are usually used to build a full-duplex optical interconnect as shown in Fig. 1(a).

Very recently, another class of novel fiber, named as hollow-core nested anti-resonant node-less fiber (NANF), has drawn intense interests and made remarkable achievements in ultra-wideband transmission window of S+C+L-band [5], record propagation loss of <0.11 dB/km [6] and ultra-low chromatic dispersion of <3 ps/nm/km [7], as well as ultra-low backscattering coefficient (BSC) β of -118 dB/m [8]. This reported β of NANF is >40 dB lower than that of SSMF. Thanks to the ultra-low backscattering effect of NANF, a single-fiber bidirectional path would be built to fulfil the application of high-capacity optical interconnects for computing centers as shown in Fig. 1(b).

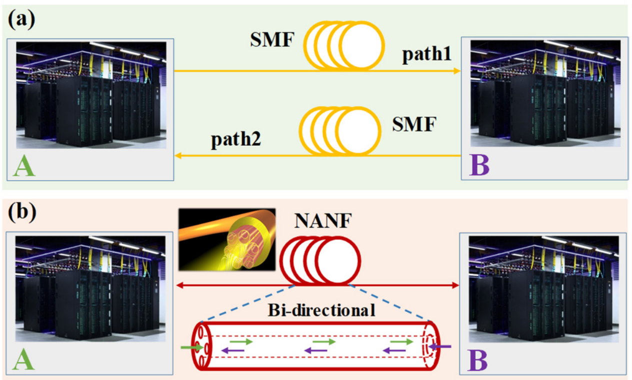

Fig. 1. Schematic diagrams of optical interconnect between the two computing centers (A and B), by using (a) two-fiber bidirectional paths and (b) single-fiber bidirectional path empowered by high-performance nested anti-resonant nodeless fiber (NANF).

In this paper, we propose the first demonstration of bidirectional optical interconnects with 3.2 Tb/s capacity in C-band, empowered by high-performance self-developed NANF, 4λ wave-length division multiplexing (WDM) technique and 116 GBaud probabilistic shaping PAM16 (PS-PAM16, 3.46 bits/symbol) with only linear equalizer at 25% FEC limit of 4.6×10^{-2}. The four channels are separated into odd and even ones and modulated by two independent self-developed high-speed thin-film lithium niobate Mach Zehnder modulators (TFLN-MZMs). The measured results indicate that the proposed scheme presents a promising route for beyond 3.2T application in a low-latency cost-effective and high-scalability manner.

2. Experimental setups

Figure 1(b) shows the schematic diagram of single fiber bidirectional optical interconnect using NANF. The received light intensity at terminals A or B is expressed as

$$I_{Rx} = \left(\vec{E}_S + \sum \vec{E}_{BS}\right)^2 = \left(\vec{E}_S\right)^2 + 2\sum(\vec{E}_S \cdot \vec{E}_{BS}) + \sum(\vec{E}_{BS})^2 \tag{1}$$

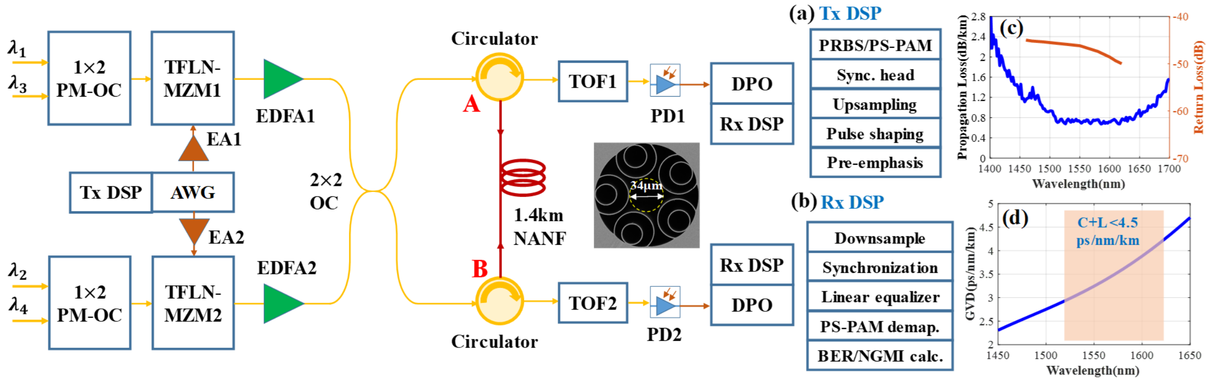

Fig. 2. Experimental setup for the bidirectional 3.2Tb/s (400Gb/s/λ×4λ×2) PS-PAM16 IM/DD transmission system over 1.4km NANF using linear equalizer only. (a) DSP flow at the transmitter, (b) DSP flow at the receiver, (c) measured propagation loss (IL) and return loss of fabricated NANF across S+C+L-band and (d) Measured group velocity dispersion (GVD) of fabricated AR-HCF across S+C+L-band. PM-OC: polarization maintaining optical coupler, TFLN-MZM: thin-film lithium niobate Mach-Zehnder modulator, AWG: arbitrary waveform generator, EA: electrical amplifier, EDFA: Erbium-doped optical fiber amplifier, TOF: tunable optical filter, PD: photodiode, DPO: digital phosphor oscilloscope.

where the first term denotes the intensity of received signal, the second term is the interaction of signal and backscattered light resulting in beat interference noise, and the third term is the intensity of backscattered light. The latter two items lead to the SNR degradation of received signals and are related to the BSC β of fiber channel. The total backscattered light is the superposition of all the contributions from distinct locations along the fiber and their mean intensity even for intensity modulated signal can be written as $\langle I_{BS}\rangle = \beta \bar{I}_S = \beta \left\langle \left(\vec{E}_S\right)^2 \right\rangle$ [9]. For NANF, the measured value of β is as low as -118 dB/m to ensure bidirectional optical communication even for high-spectral-efficiency modulation formats.

Based on the above consideration, we build a bidirectional intensity modulation direct detection (IM/DD) system in C-band based on 1.4 km NANF, 4λ WDM and 116 GBaud P-PAM16, as shown in Fig. 2. The four laser sources are divided into even and odd groups and their wavelengths are set at 1546 nm, 1548 nm, 1550 nm and 1552 nm with 13 dBm output power and 250 GHz channel spacing. The electrical PAM16 signals are produced by a high-speed arbitrary waveform generator (AWG) running at 220 GSa/s to generate 116 GBaud signal. The generated electrical signals are amplified by two electrical amplifiers and then used to drive the two independent TFLN-MZMs with a 3-dB bandwidth of >60 GHz. The modulated optical signals are optically amplified by two Erbium-Doped optical fiber amplifiers and then combined by a 2×2 50/50 optical coupler, whose outputs are connected by two circulators. For comparison, optical BTB, 1.4 km NANF, and 1 km G.652 SMF are employed as full-duplex channels between terminals A and B. The used NANF has the transmission loss of < 1dB, return loss of < -45dB and group velocity dispersion of < 4.5 dB across the wavelength range from 1520 nm to 1630 nm thanks to the 5-element structure and 34 μm core size as shown in Fig. 2(c) and (d). Such lower backscattering light enables to transmit high-order signals in bidirectional link. The received WDM signals are filtered out by a narrow tunable optical filter one-by-one and then fed into the photodetector (PD) for optical-to-electrical conversion. The electrical signal is digitalized and sampled by a digital phosphor oscilloscope with a 3-dB band-width of 59 GHz, running at 256 GSa/s for further digital signal processing (DSP). The DSP flows for both transmitter and receiver are illustrated in Fig. 2(a) and (b).

3. Experimental results and discussions

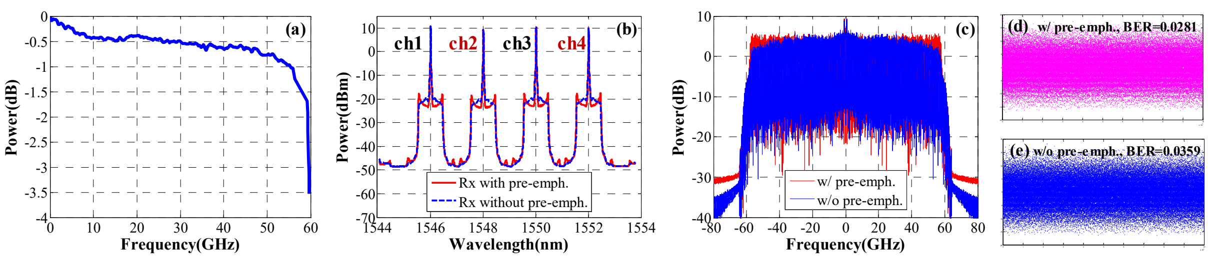

Fig. 3. Measured results: (a) System frequency response, showing 3-dB bandwidth of around 60GHz, (b) optical spectra after 1.4km NANF with and without digital pre-emphasis, (c) Received power spectrum density (PSD) of 116GBaud PS-PAM16 (3.46bits/symbol) with and without digital pre-emphasis after 1.4km NANF, (d) and (e) recovered PS-PAM16 eye diagrams with and without digital pre-emphasis, corresponding to the BER values of 2.81×10^{-2} and 3.59×10^{-2}, respectively.

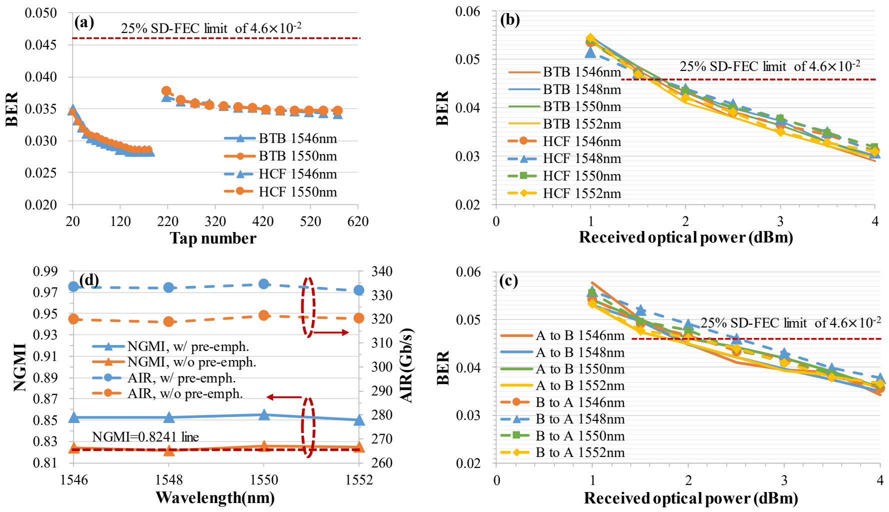

Fig. 4. Experimental results: (a) Measured BER performance as a function of tap number for the optical wavelengths at 1546nm and 1550nm, (b) Measured BER performance for single-direction as a function of received optical power (ROP) at both back-to-back and after 1.4km NANF transmission, (c) Measured BER performance for dual-direction as a function of received optical power after 1.4km NANF transmission, (d) Measured NGMI and AIR as a function of transmitted 4-channel with and without pre-emphasis. It is noted that BER values for 1km SMF keep at 1.8×10^{-1} even as increasing the ROP.

The measured total system 3-dB bandwidth including MZM, NANF and PD is ~60 GHz as shown in Fig. 3(a). As a result, with simple digital pre-emphasis the system performance can be enhanced, which is revealed by the measured BER values as illustrated in Fig. 3(d) and (e), improved from 3.59×10^{-2} to 2.81×10^{-2}. The measured optical spectra and power spectrum densities of 116 GBaud PAM16 with and without digital pre-emphasis are also shown in Fig. 3(b) and (c).

In the demonstration, we propose to use a linear equalizer to reduce the system complexity and computational time consumption, which is more suitable for low-latency applications. We further investigate the BER performance as a function of tap number as shown in Fig. 4(a). About 20-tap and 220-tap are adequate to recover PS-PAM16 for BTB and after bidirectional 1.4 km NANF with below the 25% FEC limit of 4.6×10^{-2}. In the next experiment, we use 517-tap for both single and bidirectional transmissions to achieve the best BER values. The BER performance as a function of received optical power (ROP) for single-directional transmission is measured as shown in Fig. 4(b). Compared with BTB performance, penalty-free transmission of 400 Gb/s/λ×4λ signal is achieved. The required ROP to achieve 25% FEC limit is about 1.6 dBm. For bidirectional transmission of 400 Gb/s/λ×4λ×2 signal, the receiver sensitivity at 25% FEC limit is increased to 2 dBm as shown in Fig. 4(c), achieving the total net capacity of 2.56 Tb/s. It is noted that BER values for 1 km SMF after bidirectional transmission keep at 1.8×10^{-1} even as increasing the ROP to 8 dBm. This is because high-order PAM16 modulation is more sensitive to noise and the bidirectional SMF transmission brings strong backscattering noise causing SNR degradation.

Figure 4(d) shows the NGMI and AIR performance for 4λ WDM signals with and without digital pre-emphasis. It can be seen that with pre-emphasis, the NGMI threshold of 0.8241 (overall code rate of 0.7684 [10]) is successfully achieved, resulting in a net data rate per channel beyond 330 Gb/s and total net capacity beyond 2.64 Tb/s.

4. Conclusion

We have proposed and experimentally demonstrated a bidirectional optical interconnect scheme for beyond 3.2T application in C-band, empowered by high-performance self-developed 1.4 km NANF, 4λ WDM technique and 116 GBaud PS-PAM16 signal with linear equalizer only to achieve the 25% FEC limit of 4.6×10^{-2}. Our proposed scheme has the potential of improvement in three dimensions as channel scalability, modulation effectivity and DSP simplicity. Also, NANF contributes to reduce ~33% latency compared with silica-based SMF. The measured results pave a promising route to build a high-speed, low-latency optical interconnect link for bidirectional transmission requirement.

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5. References

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