Real-time 2.5-Pb/s Bidirectional Transmission over 24-core Single-Mode Fiber in S+C+L Bands

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Abstract: 2.5-Pb/s real-time bidirectional transmission leveraging commercial 400G coherent transponder is experimentally demonstrated over 10.3-km 24-core fiber at S+C+L bands, utilizing 6288 combined SDM/WDM channels with 75-GHz spacing across a 19.65-THz optical spectrum.

1. Introduction

The continuous growth of internet traffic is driving the evolution of optical communication networks, spurring the exploration of new optical fibers and advanced signal multiplexing techniques. To overcome the capacity bottleneck in single-mode fiber (SMF) communication systems, space division multiplexing (SDM) has emerged as a leading candidate. Transmission capacities exceeding 1 Pb/s have been successfully demonstrated using various SDM technologies, including both weakly and strongly coupled multi-core fibers (MCFs) [1], few-mode fibers (FMFs) [2], and their combination in multi-core FMFs (FM-MCFs) [3]. Although coupled-channel SDM systems, such as coupled-core multi-core fibers and multi-mode fibers, enable high spatial channel density, their practical deployment at high speeds is hindered by the necessity for complex multi-input multi-output (MIMO) processing to track the temporal variations of spatial channel coupling. Weakly-coupled SDM fibers are therefore a preferred solution for enabling high-capacity transmission that closely mirrors multiple parallel SMF systems. This approach sidesteps the need for complex, computation-intensive digital signal processing (DSP), requiring only simple 2×2 MIMO equalization and maintains compatibility with commercial optical modules. Typical commercial transmission systems using C/L-band wavelength-division multiplexing (WDM) over standard single-mode fibers (SSMF) are nearing their capacity limit. To expand capacity further, multi-band transmission (MBT) is critical. To overcome the capacity crunch, the field is turning to S+C+L-bands WDM, enabled by recent advances in S-band device technology, to unlock vast new optical spectrum [4].

In this paper, we experimentally demonstrate a record real-time bidirectional transmission capacity of 2.5 Pb/s by integrating SDM with wideband WDM across the S+C+L bands. The system, leveraging commercial 400G coherent transponders over a 10.3-km MCF with 24 cores, employs 262 dense WDM channels with 75-GHz channel spacing, which occupies a 19.65 THz bandwidth (spanning from 1465.3 nm–1625.5 nm) and creates an aggregate of 6288 simultaneous SDM/WDM channels, underscoring the scalability of this approach for future optical networks.

2. Experimental Setup and Results

Fig. 1 illustrates the experimental setup for real-time bidirectional transmission over the 24-core fiber. On the transmitter side, three separate laser sources are independently tuned to the S, C, and L bands to generate the foundational optical carriers. These carriers are then used to drive a commercial 400G coherent optical transponder, which performs the 64 GBaud PDM-16QAM modulation to encode the data streams onto the respective wavelengths before injection into the fiber cores. The system employs a simplified channel generation scheme where the WDM dummy channels are sourced from channelized ASE noise, rather than from hundreds of individual modulators. After band-specific amplification (EDFAs for C/L and TDFA for S), wavelength-selective switches (WSSs) are used to flatten the combined spectrum, define the 75-GHz channel grid, and introduce a notch for the 400G test channel. To compensate for inter-band stimulated Raman scattering (ISRS) and achieve a roughly equal received optical signal-to-noise ratio (OSNR) across all channels, we flattened the spectrum by configuring the WSSs, as shown in Fig. 2. This was applied to the full optical spectrum from 1465.3 nm to 1625.5 nm, which comprises 262 channels (102 in the S-band, 80 in the C-band, and 80 in the L-band). The transmission medium was a 24-core single-mode fiber

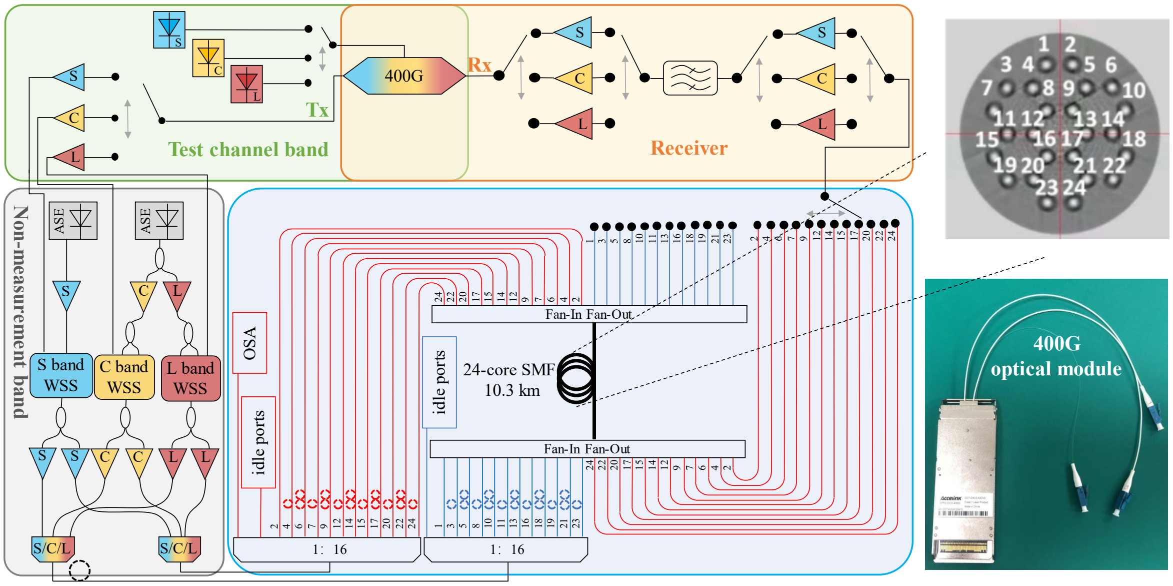

Fig. 1 Experimental setup to evaluate the real-time bidirectional transmission over 24-core single-mode fiber

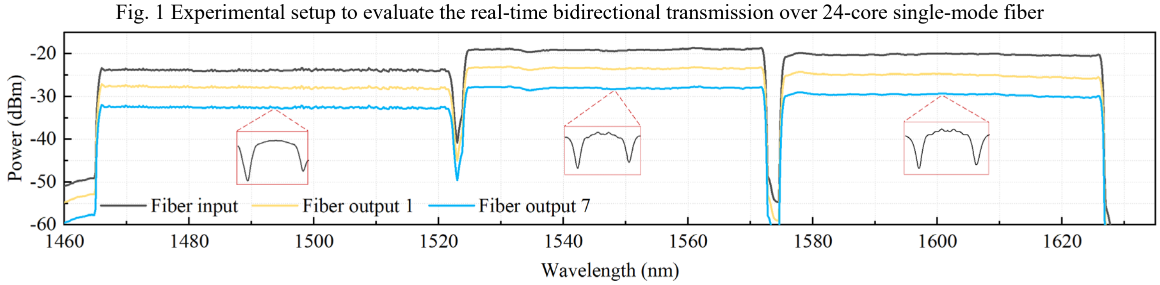

Fig.2 Optical spectrum of the system at the transmitter and receiver sides

(Fiberhome Fujikura Optic Technology). With a cladding diameter of 250 µm, this fiber features a 9 µm core diameter and an average nearest-core pitch of 33 µm. This new design increases the number of SDM channels within the same cladding diameter, albeit at the cost of a smaller pitch and significantly higher crosstalk. The cores are arranged in a structured lattice of seven hexagons, limiting each core to a maximum of three nearest and six next-nearest neighbors. This configuration results in measured crosstalk values of approximately -15 dB in the obverse direction and -30 dB in the reverse direction. Thanks to the hexagonal core layout, in which adjacent cores carry counter-propagating signals, the 24-core MCF operates as an uncoupled system. This eliminates the need for complex MIMO-based SDM demultiplexing. The obverse direction is assigned to Cores 1, 3, 5, 8, 10, 11, 13, 16, 18, 19, 21, and 23; the remaining cores carry reverse-direction signals. To fully populate all 24 cores of the multi-core fiber, the broadband signal is first divided into 32 paths via a power splitter. These paths are then fed into a fan-in fan-out (FIFO) device, which couples the light into the fiber, leaving several ports unused. On the receiver side, an optical tunable filter separates the test channel from the dummy channels. The isolated channel is then processed and evaluated in a real-time scenario by the commercial 400G optical module.

We evaluated the transmission performance of the commercial 400G optical module across the S, C, and L bands by measuring its bit error rate (BER) against received optical power (ROP), as shown in Fig. 3. The module demonstrated nearly identical performance in all three bands. Crosstalk from neighboring reverse-propagating cores resulted in only minimal degradation by the proposed method compared to the same transmission direction. The ROP thresholds required to reach the 20% soft-decision FEC (SD-FEC) limit of 2.4×10^{-2} were consistent across the bands, confirming the feasibility of real-time bidirectional transmission in the S+C+L spectrum using standard 400G modules.

Lastly, we conducted a full-system transmission measurement spanning the 19.65-THz S+C+L band (1465.3 nm to 1625.5 nm), utilizing 262 WDM channels and 24 SDM channels for a total of 6288 individual transmission paths. The results, presented in Fig. 4, confirm that the BER for all channels remained below the 20% SD-FEC threshold. This successful transmission validates a per-core capacity of 105.6 Tb/s, derived from 262 channels per core operating at 400 Gb/s. Consequently, the aggregate real-time bidirectional transmission capacity achieved over the 24-core single-mode fiber is 2.515 Pb/s.

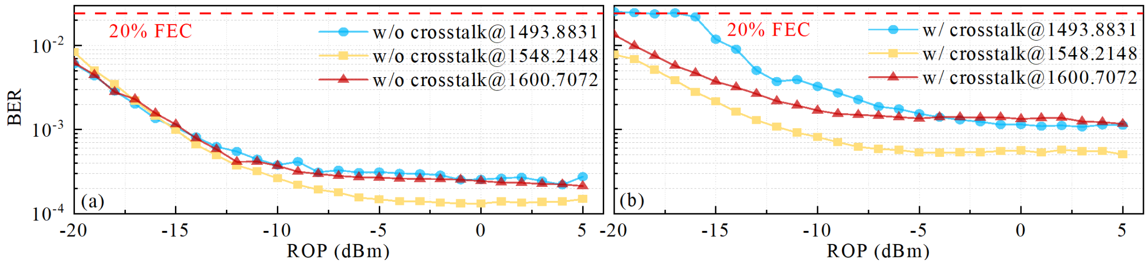

Fig3. Receiver sensitivity measured for the different wavelength signals (a) without crosstalk (b) with crosstalk

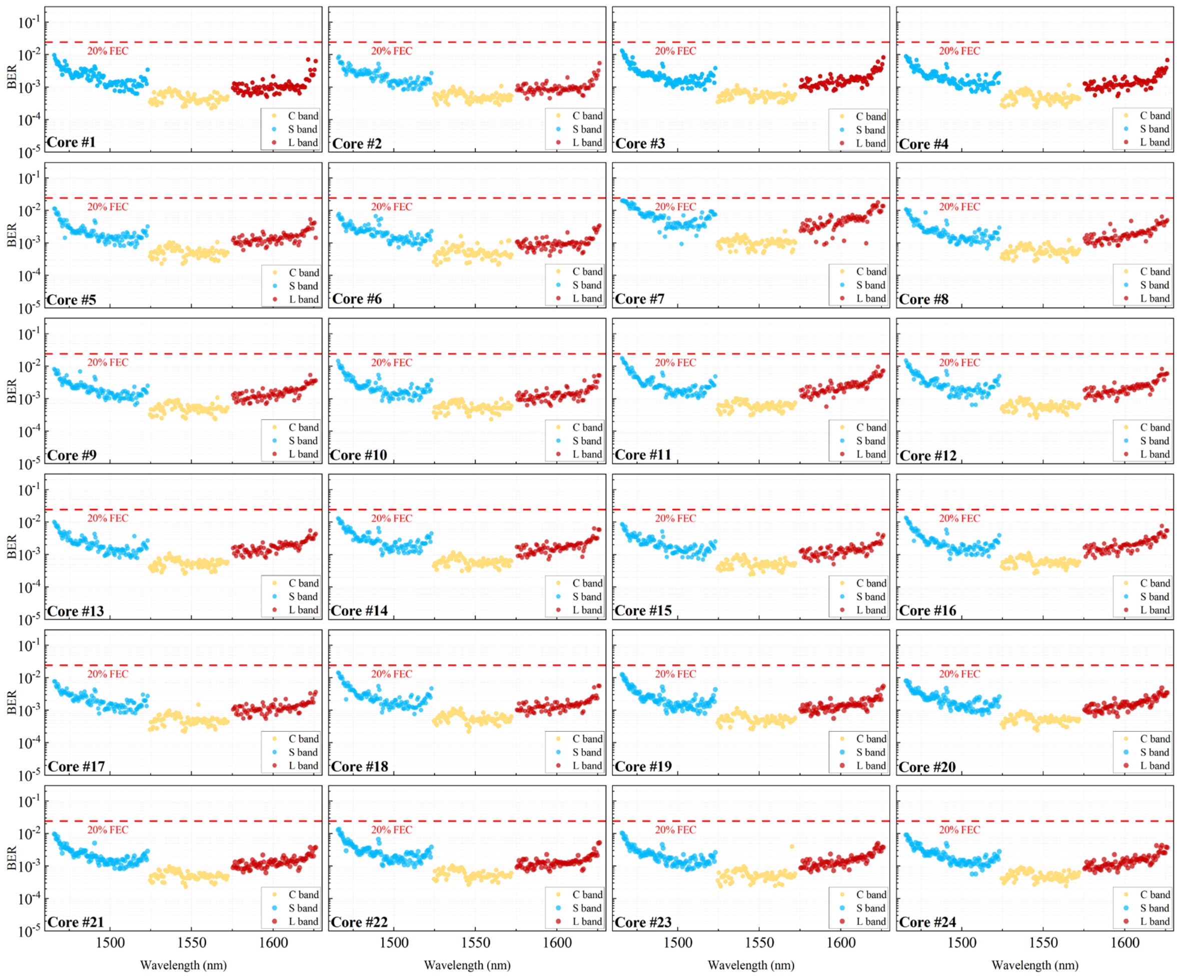

Fig.4 Measured curve of all the BER of each core

3. Conclusion

We successfully demonstrated a 2.5 Pb/s real-time bidirectional transmission over a 24-core single-mode fiber, utilizing the S+C+L bands and commercial 400G coherent transponders. The system configuration, which spans 19.65-THz optical spectrum with 75-GHz spacing, confirms a viable path toward the practical and robust deployment of extreme-capacity field applications.

This work was supported by the National Key Research and Development Program of China (2024YFB2908400), the Science and Technology Development Program of Hubei Province(2024CSA077), the Hubei Provincial Science and Technology Plan Project (2024BAA001), and Major Key Project of Peng Cheng Laboratory (PCL).

4. References

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