Transoceanic-Class WDM/SDM Transmission of PDM-QPSK Signals over Coupled 12-Core Fiber

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Abstract: We demonstrated long-haul transmission of 32-Gbaud PDM-QPSK over coupled 12-core fiber with standard cladding diameter. Error-free transmission after FEC was achieved up to 7280 km. The estimated rms MDL per 52-km span was 0.3 dB.

1. Introduction

Space-division multiplexed (SDM) transmission in fibers having a standard cladding diameter of 125 μm has been actively investigated to increase the capacity with current cabling technology for single-mode fibers (SMFs) [1–10]. For submarine cables, uncoupled multi-core fibers (MCF) have been developed [11], and long-haul transmission was demonstrated by using an uncoupled 4-core fiber [3, 5]. For higher spatial channel density/counts, coupled multi-core fibers or multi-mode fibers are required with a multi-input multi-output (MIMO) filter on the receiver side. Figure 1 shows recent demonstrations of SDM transmission with fibers with standard cladding diameter plotted as the number of SDM channels and the transmission distance. Notably, the transmission over 12,100 km was demonstrated with a coupled 7-core fiber [2]. However, regarding the spatial channel counts of more than ten, demonstrated transmission distances are limited to 1001 km with a 15-mode fiber [8] or 1560 km with a 10-mode fiber [10]. In order to achieve transoceanic transmission distances with a high spatial count, it is crucial to reduce the spatial mode dispersion (SMD) [12], which determines the required temporal spread of the MIMO filter, and the mode-dependent loss (MDL) [13] of the transmission line. In this regard, coupled MCF (CMCF) are promising [14, 15].

In this work, we demonstrated long-haul WDM/SDM transmission of 12 spatial channels, with 32-Gbaud PDM-QPSK over a recirculating loop composed of a single 52-km span of a coupled 12-core fiber (C12CF) with standard cladding diameter. The net bit rate of the SDM channels was 1.2 Tb/s. We believe that this is the first demonstration of an SDM transmission with spatial channels of more than ten with standard cladding diameter over transoceanic distance, enabled by the low SMD and MDL of the C12CF. Error-free transmission after forward error correction (FEC) was achieved up to 7280 km. Using the MIMO filter coefficients, we estimated SMD of 0.1 ns and MDL of 0.3 dB per span, with relatively small wavelength dependence.

2. Experimental setup

The experimental setup for WDM/SDM transmission over a C12CF is shown in Fig. 2. The transmitted signals were 9-channel WDM in a 37.5-GHz grid and 12-core SDM of 32-Gbaud PDM-QPSK signals. For the signal under evaluation at the wavelength of 1550.9 nm, a laser-diode (LD) source having a linewidth of about 100

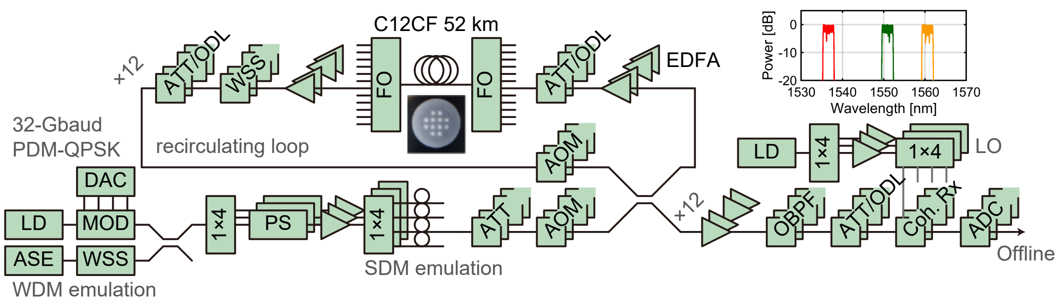

Fig. 2: Experimental setup for WDM/SDM transmission of 32-Gbaud PDM-QPSK signals over C12CF. AOM: acousto-optic modulator. The inset graph shows the transmitted spectra of the WDM signals.

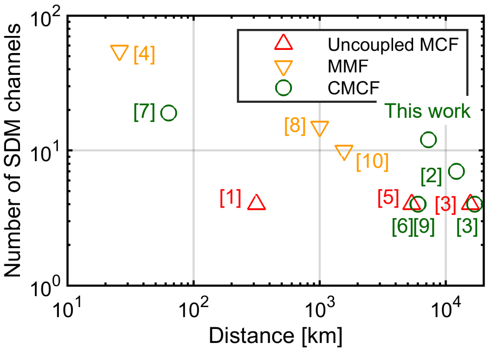

Fig. 1: Demonstrations of SDM transmission with fibers with standard cladding diameter.

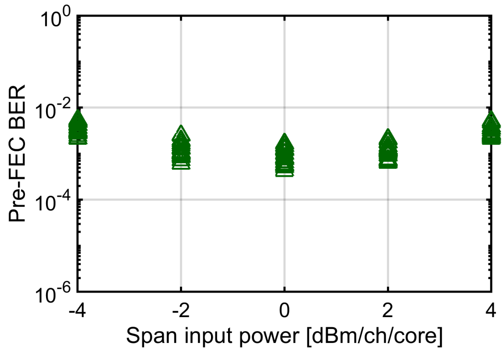

Fig. 3: Dependence of pre-FEC BER on span input power at 5200-km transmission.

kHz was modulated using electrical signals generated with a four-channel digital-to-analog converter (DAC) at a sampling rate of 64 GS/s and a vertical resolution of eight bits. The transmitted data were frames of the low-density parity-check (LDPC) code for DVB-S2 with a frame length of 64,800 and code rate of 0.8 with random bits in the payload. The data were mapped to PDM-QPSK, up-sampled to two-fold oversampling, and processed by a root-raised cosine filter with a roll-off factor of 0.1 and a pre-compensation filter for transmitter impairments. The remaining eight WDM channels were emulated with an amplified spontaneous emission (ASE) source shaped with a wavelength selective switch (WSS). The total nine WDM channels were divided into 12 with low-speed polarization scrambling (PS) and decorrelated to emulated SDM signals.

The transmission line consisted of a recirculating loop of one span of a C12CF with parallel single-mode EDFAs. The C12CF had a square lattice core arrangement [16], and the length and the cladding diameter were 52 km and 125 μm, respectively. The SMD of the C12CF was 6.9 ps/$\sqrt{\text{km}}$ at 1550 nm. The span loss including the fanouts (FOs) at both ends of the C12CF was about 11.5 dB. The relative delays among paths at the SMF-based parts were minimized by using optical delay lines (ODLs). The span input power set at the output of the optical attenuators (ATTs) was 0 dBm/ch/core, which was roughly optimum, as described later.

After transmission, the signals under evaluation were demultiplexed by optical bandpass filters (OBPFs) and received by coherent receivers. A common local oscillator was supplied to 12 receivers from an LD having a linewidth of about 25 kHz. The received waveforms were sampled by 12 four-channel 50-GS/s analog-digital converters (ADCs) with a vertical resolution of eight bits. Digital signal processing was performed offline. The waveforms were first normalized and resampled to two-fold oversampling. A root-raised cosine-matched filter and chromatic dispersion compensation were performed. Frame synchronization based on correlation with frequency offset compensation was carried out for data-aided MIMO processing. An overlap-save frequency-domain adaptive 24$\times$24 MIMO filter including phase lock loop-based carrier recovery was used for mode demultiplexing. The overlap was 50%, and the fast Fourier transform (FFT) size was 512. The filter coefficients were first controlled by data-aided least-mean square (LMS) and then switched to decision-directed LMS. The pre- and post-FEC bit error rates (BERs) were evaluated five times for each transmission condition.

3. Transmission results

We first evaluated the dependence of the transmission performance on the span input power. Figure 3 shows the pre-FEC BER of the signal under evaluation after 5200 km transmission. The BERs of 24 spatial/polarization modes for one waveform acquisition are plotted at each span input power. The optimum span input power was about 0 dBm/ch/core, which we used for the rest of the experiments.

We next evaluated the transmission performance at three wavelength ranges in the C-band: nine WDM channels centered at 1536.6 nm (195.10 THz), nine others centered at 1550.9 nm (193.30 THz), and those centered at 1560.6 nm (192.10 THz). Figure 4 shows the pre- and post-FEC BER of the signal under evaluation at the center wavelength, averaged over 24 polarization/spatial modes, as the function of the transmission distance. Markers indicate the averages for five acquired waveforms, while the error bars indicate maximums and minimums. Error-free transmissions after FEC were observed up to 7280 km (140 loops) for 1536.6 nm and to 9360 km (180 loops) for 1550.9 nm and 1560.6 nm in this single-span loop configuration.

Figure 5(a) shows the SMD estimated from the MIMO filter coefficients, calculated as the full width of the half maximum (FWHM) of the magnitude of the filter coefficients averaged over all cross terms. The solid lines are the fitting curves by the predicted square-root accumulation [12], in which only the results without post-FEC errors were included. The estimated SMDs per loop/span were 0.13 ns for 1536.6 nm, 0.09 ns for 1550.9 nm, and 0.08 ns for 1560.6 nm, resulting in 0.1 ns on average. Figure 5(b) shows the root-mean-square (rms) MDL in log

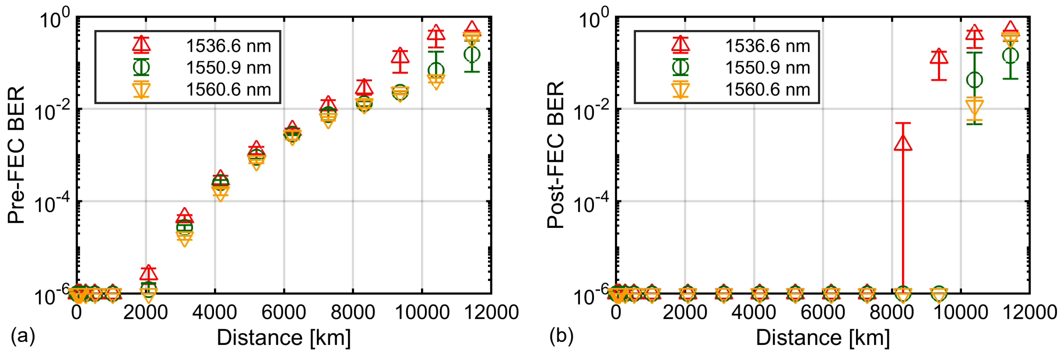

Fig. 4: Experimental results of (a) pre- and (b) post-FEC BER after C12CF transmission.

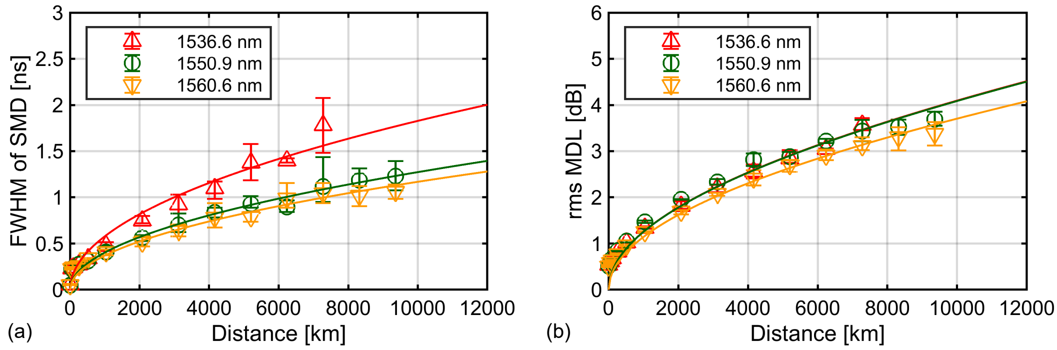

Fig. 5: Estimated (a) SMD and (b) rms MDL from the MIMO filter coefficients.

power-gain units [13] estimated from the MIMO filter coefficients [6]. The solid lines are the fitting curves by the expected accumulated behavior [13]. The estimated rms MDLs were well-fitted by this expected curve. According to the fitting results, the rms MDL per loop/span were 0.3 dB for 1536.6 nm, 1550.9 nm, and 1560.6 nm. The rms MDL was relatively low, and the wavelength dependence was also small over the three wavelengths in the C-band.

4. Conclusion

We demonstrated transoceanic-class long-haul WDM/SDM transmission of 32-Gbaud PDM-QPSK over C12CF with standard cladding diameter. Error-free transmission after FEC was achieved up to 7280 km. SMD of 0.1 ns and MDL of 0.3 dB per 52-km C12CF span, together with relatively low wavelength dependence, were confirmed.

Acknowledgements

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