172 Tb/s C+L Band Transmission over 2040 km Strongly Coupled 3-Core Fiber

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Abstract: Coupled-core multi-core fiber transmission is demonstrated across 359 C- and L-band channels with low spatial-mode-dispersion. A net-data-rate of 172 Tb/s over 2040 km is achieved, doubling the record data-rate-distance-product for standard cladding diameter SDM fibers.

OCIS codes: 060.2330 Fiber optics communications, 060.4230 Multiplexing

1. Introduction

Space-division multiplexing (SDM) has been intensely investigated as a technology to increase data-rates in optical fiber communications systems [1]. While multiple fiber types have been proposed for SDM, coupled-core multi-core fibers (CC-MCFs) and few-mode fibers (FMFs) are the only types of SDM fiber that have been demonstrated with more than 10 spatial channels [2, 3] in a standard cladding diameter (125 µm). Maintaining the standard cladding diameter is considered advantageous for long-term reliability and beneficial for near-term commercial applications [4].

CC-MCFs are the only type of SDM fiber that has been demonstrated to outperform single-mode fibers due to reduced fiber nonlinearity, as a result of strong random statistical coupling of signals between coupled cores [5]. Moreover, due to strong coupling, CC-MCFs exhibit greatly reduced spatial-mode-dispersion (SMD) and mode-dependent loss (MDL) which grow in proportion to the square-root of the transmission distance, as opposed to the linear growth in weakly coupled SDM fibers. Strong coupling relies on a careful design and fabrication of the CC-MCF geometry. As mode confinement is wavelength dependent, the optimum fiber design for strong coupling depends on the target operational wavelength and a large wavelength dependence of the SMD was observed over C- and L-band [3].

To date, transmission over CC-MCFs has been limited to a fraction of the C-band (<5 nm bandwidth) [3,5]. To show the potential for high data-rate transmission, it is further necessary to demonstrate that the advantages of CC-MCFs can be sustained over a broad wavelength range (e.g. C and L-bands). In this work, we demonstrate three-core CC-MCF transmission of 359 × 24.5 GBaud 16-quadrature amplitude modulation (QAM) signals, occupying more than 75 nm wavelength across C- and L-bands. In comparison to recently reported transmission of 159 Tb/s over 1045 km [6] and 40 Tb/s over 3060 km [7] in FMF, we achieve a data-rate of more than 172 Tb/s over 2040 km distance, which is the highest reported data-rate in multi-span transmission in any standard diameter fiber and increasing the record data-rate-distance-product for any SDM fiber with 125 µm cladding diameter by more than two-fold. This demonstration highlights the great potential of CC-MCF for wide-band, high-capacity, long-haul transmission systems.

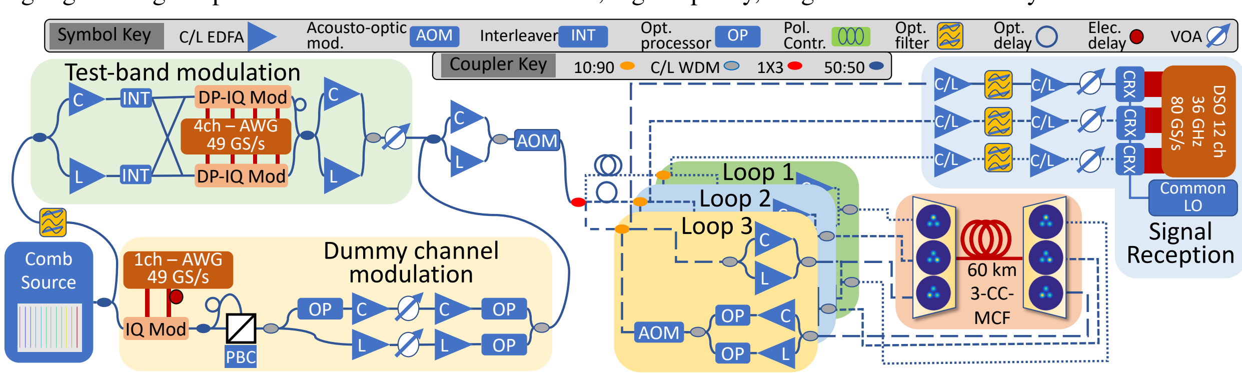

Fig. 1: Setup for long distance CC-MCF C+L band recirculating loop transmission experiment.

2. Experimental Setup

The experimental setup for the loop-transmission in a three-core CC-MCF is shown in Fig. 1. The output of an optical frequency comb with >100 nm bandwidth in a 25 GHz spacing was split into one path for a sliding test-band and one to generate dummy-channels. In the former, a tunable filter selected three comb-lines that were split into odd- and even channels for independent modulation with 24.5 GBaud dual polarization (DP) 16-QAM in two DP-IQ modulators. Four arbitrary waveform generators (AWGs) operating at 49 GSample/s were used to produce the driving signals, which were root-raised cosine shaped with a roll-off of 0.01 and had a sequence length of 2^{18}. Odd- and even channels were optically de-correlated. Dummy channels were modulated by a single-polarization IQ-modulator with 24.5 Gbaud 16-QAM signals, that was driven by a single AWG with electrically de-correlated outputs. Dual polarization signals were emulated by splitting the signal, delaying one arm by 20 ns and combining the two paths in a polarization beam combiner (PBC). Optical processors (OP) were used to spectrally equalize the dummy channels and to carve a notch in the dummy channels' spectrum, used to accommodate the test-band. The signals were then split into three optically-decorrelated copies (0ns, 94ns, 193 ns) to emulate independent data for each spatial channel.

Three recirculating loops were used for long haul transmission, containing C- and L-band erbium doped fiber amplifiers (EDFAs) and optical processors to equalize the gain spectrum of the EDFAs. Acousto-optic modulators (AOMs) were used to gate the load- and round-trip times of the recirculating loops. The round-trip times of the three loops were aligned within less than 50 ps. The fiber was a single span of 60 km three-core CC-MCF [8]. Each core had an effective area of 129 μm^2, loss of 0.18 dB/km and chromatic dispersion of 19.5 ps/nm/km at 1550 nm wavelength. Fiber-based fused photonic lantern core-multiplexers [9] were used to launch the signals into the fiber. The average loss of the three spatial channels was 14.2 dB, including multiplexers. The total launch power per core was 24 dBm.

Three receiver paths contained two stages of EDFAs with tunable optical filters in between to select a wavelength channel under test. The signals were mixed with a local oscillator (LO) with nominal linewidth of 60 kHz in three coherent receivers. The electrical signals were digitized in a 12-channel real-time oscilloscope with 36 GHz electrical bandwidth, operating at 80 GSample/s. Offline digital signal processing contained static chromatic dispersion compensation, a frequency offset estimation and a 6×6 time-domain MIMO equalizer with 350 half-symbol-duration spaced taps, running in a loop with a phase search algorithm. The equalizer was initialized in a data-aided mode before switching to decision directed mode. Q-factors were calculated for each wavelength channel by direct error counting over more than 10 million bits. We further used the generalized mutual information (GMI) to estimate the maximum achievable data-rate assuming bit-wise decoding and ideal codes. We also implemented a coding-scheme using an LDPC code from the DVB-S2 standard [10] with code-rate puncturing for code-rate granularity of 0.01 to achieve a bit error rate (BER) of less than 2.19×10^{-5}. A further 2.8% coding overhead for an outer hard-decision code was assumed for error-free transmission [11]. The coding scheme is described in detail in [6].

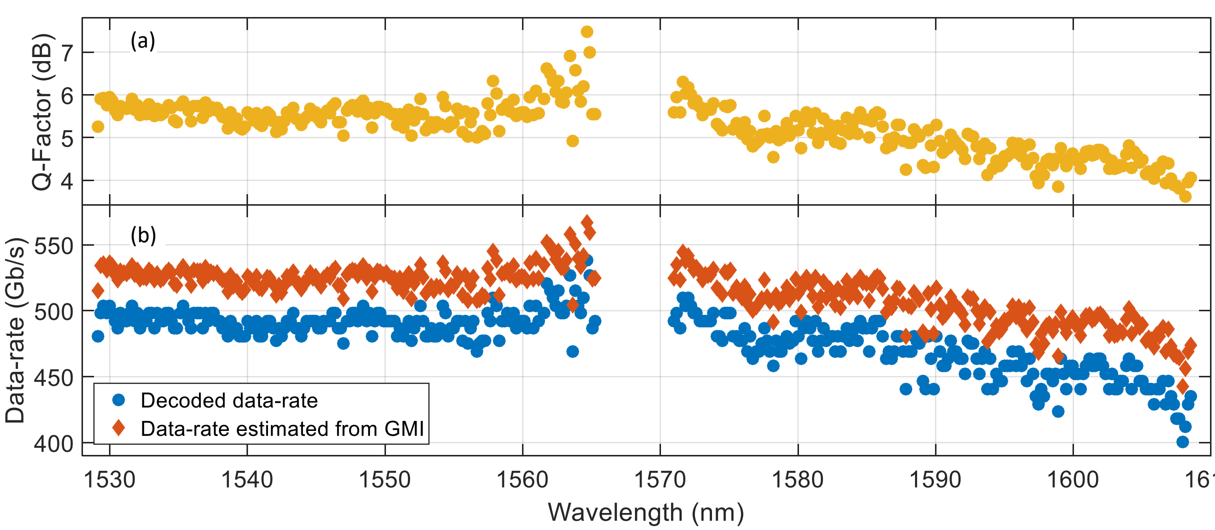

Fig. 2: (a) Q-Factors and (b) data-rate calculated by generalized mutual information (red diamonds) and implemented coding scheme (blue dots) for all 359 wavelength channels.

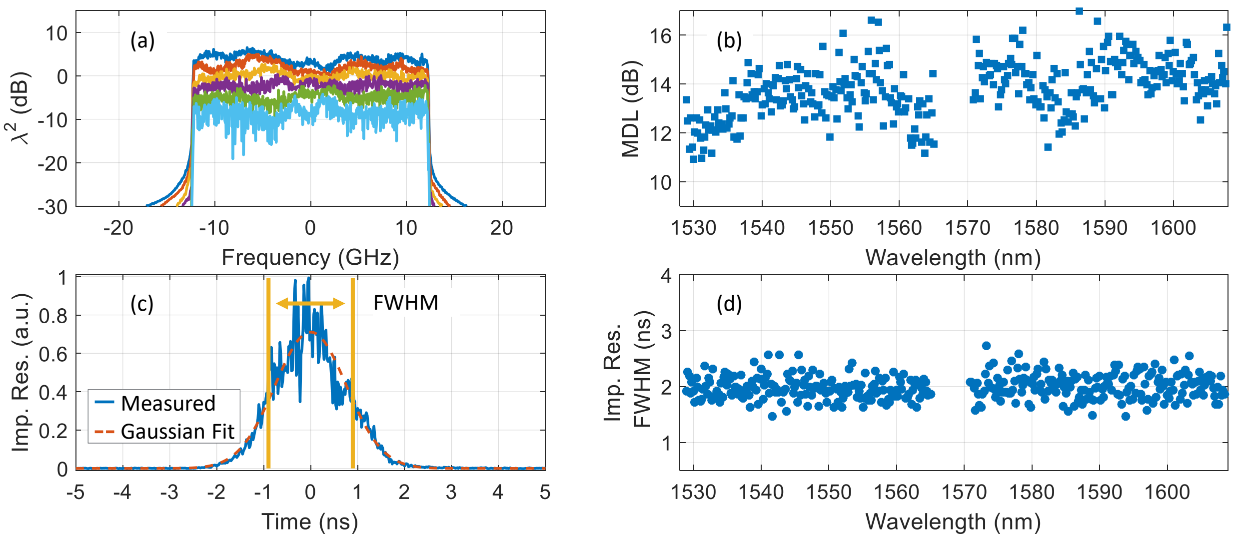

Fig. 3: Transmission channel characteristics after 2040 km: (a) The six singular values squares of the 6×6 channel matrix of the WDM channel at 1550 nm wavelength in frequency domain. (b) Mode-dependent loss (MDL) of all 359 wavelength channels. (c) Impulse response with Gaussian fit and full-width-half-maximum (FWHM) of the channel at 1550 nm wavelength. (d) FWHM of all 359 wavelength channels' impulse responses.

3. Results

Figure 2a shows the Q-factor of all 359 wavelength channels between 1529.16 nm and 1608.5 nm, ranging between 3.8 dB and 7.2 dB. The performance reduction in the high L-band is attributed to increased phase-noise and reduce OSNR on carriers away from the seed wavelength of the comb-source in combination with the spectral gain-shape of the amplifiers. Figure 2b shows the data-rate for each wavelength channel, estimated from generalized mutual information (GMI, red diamonds) and resulting from the implemented coding scheme (blue dots). The data-rate for each channel ranged between 400 and 540 Gb/s with the coding scheme and 450 to 560 Gb/s when estimated by GMI. The total data-rate was 172.25 Tb/s with the coding scheme and 185.96 Tb/s when estimated by GMI.

Figure 3a shows the squared singular values of the channel matrix for the WDM channel at 1550 nm wavelength. MDL is calculated for all WDM channels as the ratio of the maximum and the minimum of the frequency average of the squared singular values [6], shown in Fig. 3b. MDL slightly increases at longer wavelengths, likely also contributing to the wavelength dependence of the performance. Figure 3c shows an impulse response, calculated as the sum of the squares of the 36 inverse MIMO equalizers [6] of the WDM channel at 1550 nm wavelength, with a Gaussian fit and its full-width-half-maximum (FWHM). Figure 3d shows the FWHM of the impulse responses for all WDM channels after 2040 km transmission, confirming strong coupling and thus short impulse responses across all WDM channels.

4. Conclusions

We have demonstrated broadband transmission of 359×24.5 GBaud 16-QAM channels across C- and L-bands over 2040 km, strongly coupled, three-core multi-core fiber. The resulting data-rate of more than 172 Tb/s is a record data-rate in multi-span transmission for fibers with standard cladding diameter. The data-rate-distance-product of 351 Pb/s $\times$ km increases the current record in SDM fibers with standard cladding diameter by more than two-fold. Confirming strong coupling and hence short impulse responses across C-and L bands, this experiment emphasizes the strong potential of coupled-core fibers for wide-band, high-capacity transmission over medium to long-haul distances.

References

1. D.J. Richardson et al., "Space-division multiplexing in optical fibres," Nature Photonics **7**, pp. 354–362 (2013)
2. R. Ryf et al., "High-spectral-efficiency mode-multiplexed transmission over graded-index multimode fiber", Proc. ECOC, Th3B.1, (2018)
3. T. Sakamoto et al., "Twisting-Rate-Controlled 125 μm Cladding Randomly Coupled Single-Mode 12-Core Fiber", J. Lightw. Technol. **36** pp. 325 - 330, (2018)
4. S. Matsuo et al., "High-Spatial-Multiplicity Multicore Fibers for Future Dense Space-Division-Multiplexing Systems", J. Lightw. Technol. **34** pp. 1464 - 1475, (2016)
5. R. Ryf et al., "Coupled-core transmission over 7-core fiber", Proc. OFC, Th4B.3 (2019)
6. G. Rademacher et al., "High capacity transmission with few-mode fibers," J. Lightw. Technol. **37**, pp. 425 – 432 (2019)
7. K. Shibahara et al., "Full C-Band 3060-km DMD-Unmanaged 3-Mode Transmission with 40.2-Tb/s Capacity Using Cyclic Mode Permutation", J. Lightw. Technol. **38**, pp. 514 – 521 (2020)
8. R. Ryf et al., "Space-Division Multiplexed Transmission over 4200-km 3-Core Microstructured Fiber", Proc. OFC, PDP5C.2 (2012)
9. S. v. d. Heide et al., "Low-Loss Low-MDL Core Multiplexer for 3-Core Coupled-core Multi-core Fiber", Proc. OFC, T3A.3 (2020)
10. Digital Video Broadcasting (DVB); Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broadband Satellite Applications (DVB-S2), Eur. Std. ETSI EN 302 307 V1.2.1 (2009-08)
11. IEEE Computer Society, "IEEE standard for Ethernet," IEEE Std 802.3-2015 (2016)