Transmission of 138.9 Tb/s over 12 345 km of 125 µm cladding diameter 4-core fiber using signals spanning S, C, and L-band

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Abstract *We demonstrate recirculating loop transmission of 4 × 518 × 24.5 GBd DP-QPSK signals spanning the S, C, and L-band over 12 345 km of 4-core fiber. The throughput of 138.9 Tb/s results in the highest data-rate-distance product measured in any standard cladding diameter optical fiber.*

Introduction

The use of transmission windows outside the C and L-band has been widely proposed as a means to meet the ever-increasing demand for data transmission capacity[1]. Recent works have demonstrated the potential of the S-band to significantly increase the transmission capacity of an optical fiber[2]–[5] over a single fiber span, and long-haul transmission in[6],[7]. A high per-core capacity is particularly desirable for space-division multiplexing (SDM) systems based on multi-core fiber (MCF). These systems have evolved towards low-core-count fibers with a standard 125 µm cladding diameter due to concern over yield and mechanical reliability[8], as well as being compatible with current cabling and manufacturing processes.

In this work, we demonstrate long-distance SDM transmission using wideband S, C, and L-band signals. Such a system has the potential to enable future ultra-high-capacity links. We transmit 4 × 518 × 24.5 GBd dual-polarization (DP) quaternary phase-shift keying (QPSK) signals spanning 112 nm over a low-loss 125 µm cladding diameter 4-core MCF in a recirculating loop consisting of two spans of 82.8 km and 81.8 km of fiber. The link uses a hybrid amplification scheme of erbium-doped fiber amplifiers (EDFAs) and thulium doped-fiber amplifiers (TDFAs), with distributed Raman. The total throughput after transmission over 12 345 km is 151.2 Tb/s in terms of generalized mutual information (GMI) and 138.9 Tb/s after decoding.

In Fig. 1 notable long-haul high-capacity transmission demonstrations in 125 µm cladding diameter fibers are summarized for single mode fiber[7],[9]–[11], MCF,[6],[12],[13], and multi-mode fiber (MMF)[14]–[18] transmission. It is seen that the transmission distance achieved in this work exceeds previous transmission demonstrations in 125 µm SDM fibers. Moreover, the combination of high-capacity and long-distance results in the highest reported data-rate-distance product of 1714.7 Pb/s · km, approximately a factor of 2 higher compared to the previous record demonstration in a standard cladding diameter MCF[6]. This work also confirms the ability of MCFs with a low core count to enable high data rates with conventional transceiver hardware. These results show that wideband transmission including the S-band has potential for substantial enhancement of the achievable data rates in long-haul optical fiber transmission systems.

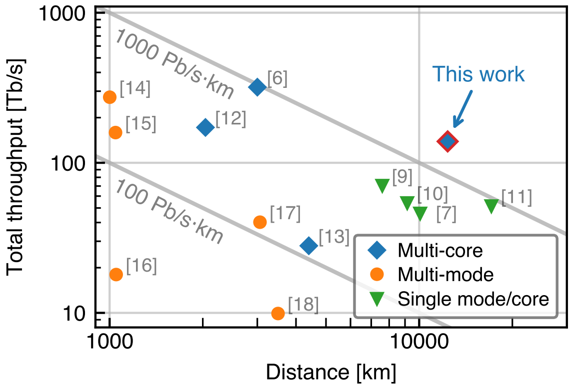

Fig. 1: Overview of total throughput versus distance for recent long-distance high-capacity transmission experiments in standard 125 µm cladding diameter fibers.

Transmission setup

Figure 2 shows the experimental transmission setup which comprised of a 3-channel sliding test band and a noise loading stage filling the S, C and L-bands to emulate wavelength-division multiplexing (WDM) transmission[19]. The 25 GHz

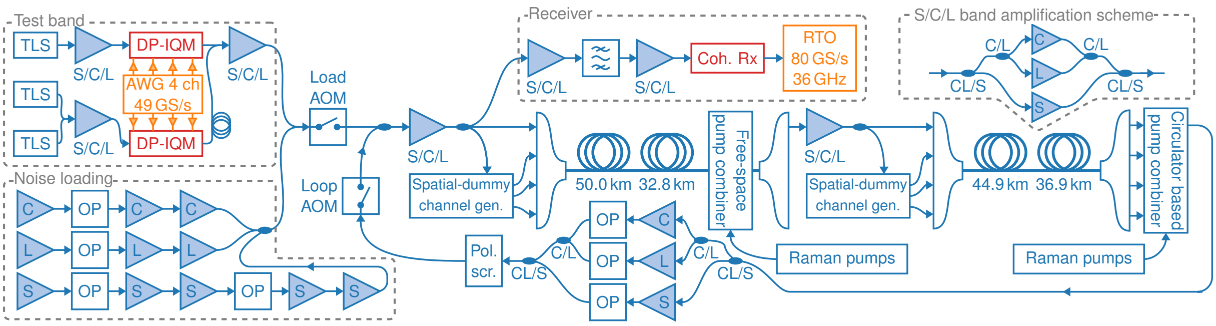

Fig. 2: Experimental setup used for long-haul transmission of 518 WDM channels over a 4-core MCF. Amplifiers labeled *S/C/L* consist of WDM couplers to split and combine the signal in S, C, and L-bands, with a per-band amplifier in between (see inset).

spaced 3-channel test band was generated by modulating tones produced by 3 external cavity lasers (ECLs) with a linewidth below 10 kHz using two dual-polarization IQ-modulators (DP-IQMs). Before modulation, the ECL output was amplified using EDFAs for C and L-band, and a TDFA in the S-band. The center test channel was modulated using a dedicated DP-IQM, while the two neighbouring tones were combined and modulated using a second DP-IQM. Both DP-IQMs were driven by the same 4-channel 49 GS/s arbitrary-waveform generator (AWG) that was programmed to generate 24.5 GBd DP-QPSK signals with a pattern length of $2^{16}-1$, pulse shaped with a 1% roll-off root-raised cosine filter.

Noise loading of the S, C, and L-band was achieved by generating amplified spontaneous emission (ASE) from either EDFAs or TDFAs, combined with spectral filtering in optical processors (OPs) to flatten the resulting noise spectrum. The OPs were also used to carve a notch in the noise loading band around the frequencies of the test band, allowing the combination of the test band and noise loading band using a power combiner.

Recirculating loop transmission was realized using acousto-optic modulator (AOM) based optical switches to load and recirculate the signal in the transmission fiber that consisted of two spans of 82.8 km and 81.8 km of 4-core weakly-coupled MCF. Both spans comprised of two spools of MCF, with the second spool being a zero water peak fiber, allowing for more efficient Raman amplification. Amplification stages before the fiber spans amplified the signal to approximately 18 dBm per band. Spatial dummy channels were generated by tapping and amplifying the recirculated signal such that for every recirculation, the dummy channels had traversed the same distance. At the output of the fiber span, Raman pumps were added using either a free-space-based pump combiner or a circulator in the S-band path. Pumps at 1410.8 nm and 1417.5 nm had 50 mW of power versus 25 mW for pumps placed at 1424.3 nm, 1431 nm, 1437.9 nm, 1444.8 nm and 1451.6 nm, and about 500 mW for 1385 nm. Furthermore, the loop consisted of an additional amplification stage to compensate for losses due to other loop components, which included a per band OP for spectral flattening and a polarization scrambler.

To receive the signal and estimate the performance, signal was tapped from the recirculating loop and amplified, filtered using a 0.4 nm wide tunable bandpass filter (BPF) and amplified again. A coherent receiver with a local oscillator (LO) that had a linewidth below 10 kHz detected the signals before being digitized by a 80 GS/s, real-time oscilloscope with a bandwidth of 36 GHz. The resulting traces were processed by an offline digital signal processing chain that consisted mostly of a 2×2 time-domain multiple-input multiple-output equalizer that was initialized in a data-aided least means squares (LMS) mode before switching to a decision-directed mode LMS for signal performance estimation. Inside the equalizer loop, a decision-directed phase recovery algorithm[20] was running.

Net data rates were calculated based on GMI and using the decoding scheme described in more detail in[21]. This applied codes from the DVB-S2 standard[22] in combination with code-rate puncturing to achieve a bit error rate (BER) below 5×10^{-5} with an additional hard-decision outer forward error correction (FEC) code with 1% overhead to eliminate remaining bit errors[23]. Signal quality estimation was performed for all 518 WDM channels for each core in turn.

Results

Figure 3 shows the estimated combined 4-core performance of all the 518 measured channels after transmission over 12 345 km based on both GMI and after decoding, with the per-core decoded data rates also shown. Fairly uniform performance is observed within each

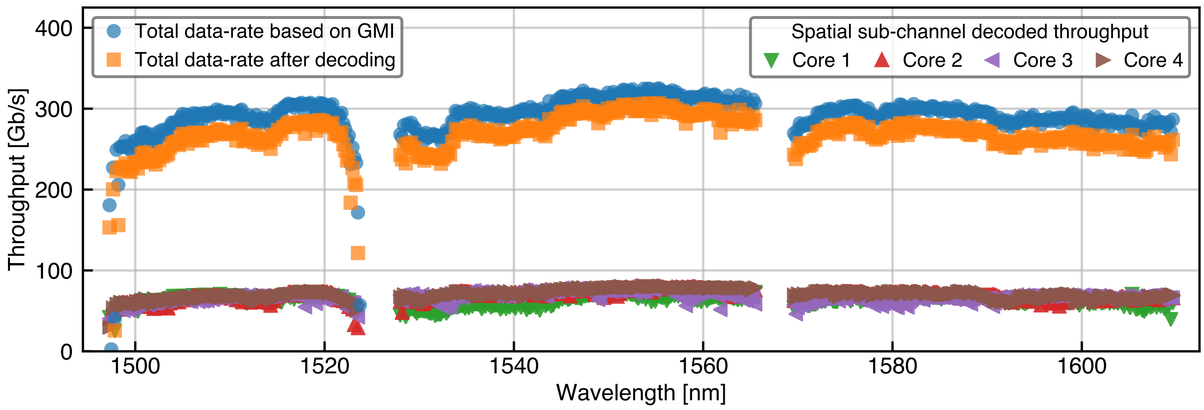

Fig. 3: Throughput after 12 345 km for the 518 measured wavelength channels ranging from 1497mnm to 1609.6 nm

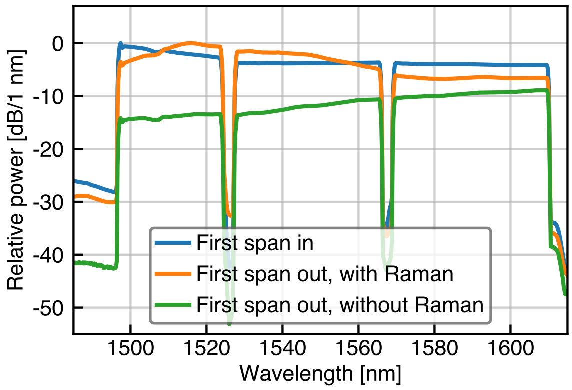

Fig. 4: Spectra at the input and output of the first fiber span, indicating the obtained gain through Raman amplification.

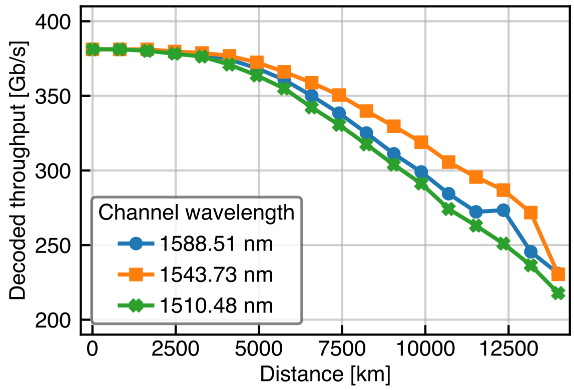

Fig. 5: Throughput versus distance for a wavelength channel in the S, C, and L-band.

core with the data-rate of 4-core spatial super-channels varying between 210 Tb/s and 300 Tb/s and total data-rate estimated from the GMI being 151.2 Tb/s and 138.9 Tb/s after decoding. The total decoded throughput is 35.2 Tb/s for 138 S-band channels, 52.9 Tb/s for 189 C-band channels, and 50.7 Tb/s for 191 L-band channels.

The variation in signal quality across wavelengths is mostly attributed to the combination of doped fiber amplifier (DFA) and Raman gain profiles, shown in Fig. 4, and stimulated Raman scattering that causes power transfer to higher wavelengths. Indeed, the performance in S-band follows the Raman gain profile from Fig. 4 and combined with higher fiber losses results in reduced transmission performance. The lower performance of the edge channels of S-band is related to a sub-optimal filter programmed in the loop OP. Performance in C-band does not resemble the Raman gain profile, possibly due to EDFA gain tilt related to sub-optimum input power into the EDFA. Figure 5 shows the per channel throughput as a function of transmission distance, illustrating the trade-off between transmission capacity and distance. Finally, we note that only a limited number of wavelength channels were used in the S-band, while the gain profile of TDFAs potentially allows for more. Therefore, it is expected that, in combination with suitable Raman pumps, additional S-band channels can be available for transmission.

Conclusions

We have demonstrated long-haul, high-capacity transmission over 12 345 km of 4-core multi-core fiber. We transmitted $4\times518\times24.5$ GBd PDM-QPSK signals, spanning more than 112 nm across the S, C, and L-band, obtaining total data rate of 151.2 Tb/s based on GMI and a decoded net data rate of 138.9 Tb/s. This resulted in a data-rate-distance product of 1714.7 Pb/s · km, a factor of 2 higher when compared to previous long-haul transmission demonstrations in fibers with a standard 125 µm cladding diameter. These results highlight the potential of ultra-wideband signals for enabling high-capacity transmission in low-core-count MCF fibers.

Acknowledgements

Partial funding is from the KPN-TU/e Smart Two program and from Vitality (CUP E13C22001060006).

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