372 Tb/s Unrepeated 213 km Transmission Over a 125 µm Cladding Diameter, 4-Core MCF

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Abstract: We demonstrate a 372.8 Tb/s unrepeated 213.3 km link using a 4-core multi-core fiber with standard cladding diameter and bidirectional Raman amplification. We transmit 424×24.5 GBaud PM-64QAM signals in the C+L bands for a capacity-distance product of 79.5 Pb/s·km. © 2022 The Author(s)

1. Introduction

Unrepeated point-to-point links are a important component of undersea communications [1]. The absence of active inline components reduces cost and complexity, which renders them as viable solutions to interconnect islands or isolated landing stations. Unrepeated links have also been under consideration for terrestrial low-cost inter-datacenter links or locations with insufficient infra-structure to support repeaters [1]. The reported capacities of unrepeatered links have been steadily increasing in recent years [2–8]. The search for increased capacity has led to developments such as wideband amplification [7], compensation of fiber nonlinearities [9], and use of advanced modulation formats [5]. Space division multiplexing (SDM) using weakly-coupled multi-core fibers (MCFs) [10] has also been proposed to multiply the capacity of unrepeatered links for the same fiber count [2]. Recently, novel MCFs have been developed with similar physical dimensions, tensile strength, and long-term reliability as single-mode fibers (SMFs) that are compatible with standard cabling systems [11, 12]. Such fibers allow a significant capacity increase of unrepeatered links whilst maintaining the characteristics of the fiber cables.

Here, we report the first demonstration of an SDM unrepeatered link above 200 km using a MCF with a standard cladding diameter of 125 µm. We achieve a throughput of 372.8 Tb/s over a 213.3 km link of 4-core MCF. This is a 3-fold improvement over the previous record using MCFs, as shown in Fig. 1-a). It also corresponds to a capacity-distance product of 79.5 Pb/s·km, nearly 4-fold over the previous record using SMFs [7]. Bidirectional distributed Raman amplification (DRA) is used to support transmission of 424×24.5 GBaud polarization-multiplexed 64-ary quadrature amplitude modulated (PM-64QAM) channels spanning the C and L bands from 1527.994 nm to 1615.261 nm. Backwards DRA uses a custom free-space multi-core pump combiner to reduce pump loss. Forward error correction (FEC) with low density parity codes (LDPC) and code puncturing deliver a throughput per core above 92.1 Tb/s. These results show the potential of SDM systems to extend the capacity of unrepeatered links.

2. Experimental Demonstration

Fig. 1-b) shows a simplified schematic of the experimental setup. The transmitted signal consisted of a sliding 3-channel test band within a 421 channel dummy band. The test channel was produced by modulating the light of a 60 kHz linewidth external cavity laser (ECL) with a dual-polarization dual parallel Mach-Zehnder (DP-IQ)

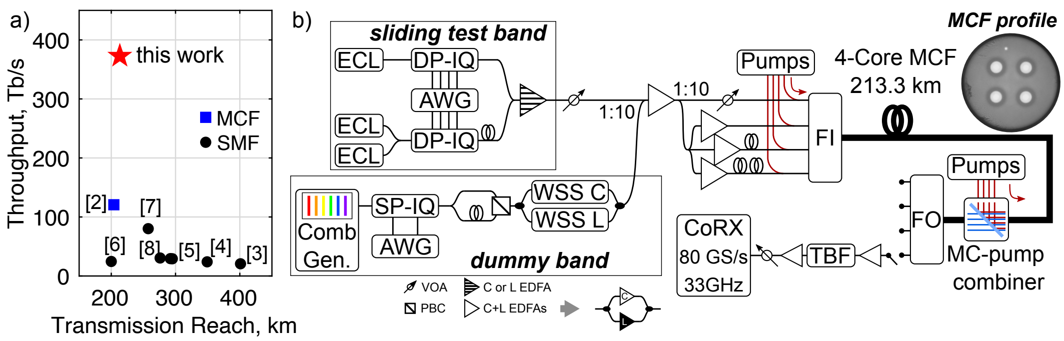

Fig. 1. a) Throughput of recent unrepeatered transmission reports. b) Simplified schematic of the experimental setup in this work. The inset shows the profile of the 4-core MCF.

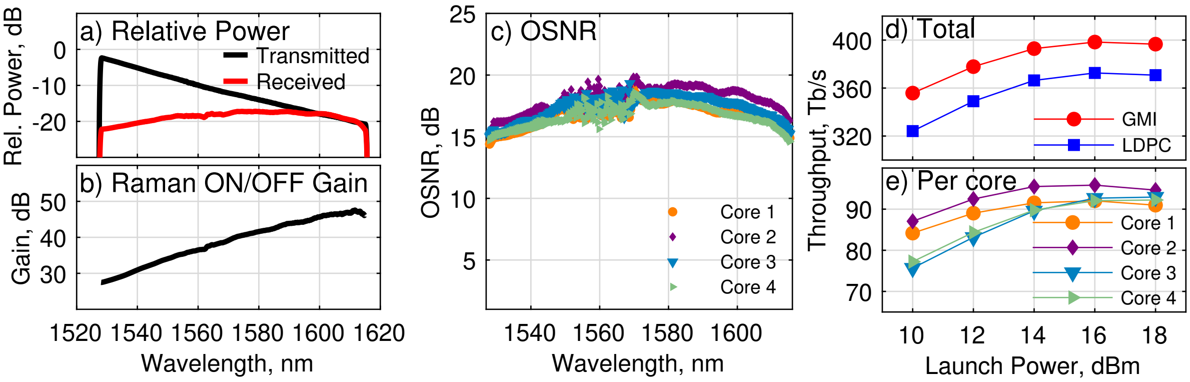

Fig. 2. a) Transmitted and received spectra. ON/OFF Raman gain (b) and OSNR for each of the cores after transmission (c) with 16 dBm launch power. Dependence of the (d) combined throughput using GMI and LDPC decoding and (e) throughput per core after transmission on launch power.

modulator. Two neighbor channels were produced by modulating the light from two ECLs with a second DP-IQ modulator. Both modulators were driven by 4 arbitrary waveform generators (AWGs) operating at 49 GS/s to produce 24.5 GBaud, PM-64QAM signals with root-raised cosine shape and a roll-off of 0.01. The 3-channel sliding test band, was amplified by C or L-Band erbium doped fiber amplifiers (EDFAs), depending on its wavelength.

The dummy band was produced using a wideband comb source, which generated 25 GHz spaced carriers over more than 100 nm bandwidth encompassing the C and L bands. The carriers were modulated by a single-polarization dual parallel Mach Zehnder (SP-IQ) modulator followed by a polarization division multiplexing emulation stage. A single 49 GS/s AWG with an electrically delayed replica of its output was used to drive the SP-IQ modulator. The wideband signal was amplified using a C+L amplifier consisting of C and L band EDFAs in between WDM couplers to split and recombine the two bands. C and L-band wavelength selective switches (WSS) were used to limit the bandwidth to the range between 1527.994 nm and 1615.261 nm and set a pre-emphasis tilt of 16 dB to partially counter the impact of stimulated Raman scattering (SRS). The WSS also carved a notch in the dummy band to accommodate the test band. Both bands were combined at a 1:10 coupler. Fig. 2-a) shows the spectrum of the transmitted signal. Three dummy spatial channels were obtained by taking a 10% tap of the original signal, which was split, amplified and delayed for decorrelation.

The transmission line consisted of 8 spools of 4-core MCF connected via SC-type connectors with a total length of 213.3 km. The fiber had a cladding diameter of 125 µm with trench-assisted cores in a square with a minimum core pitch of 40.1 µm, as shown inset Fig. 1-b). The worst-case accumulated crosstalk between neighbor cores at 1615 nm was -33 dB and observed to have negligible impact. The signals were multiplexed into and out of the 8-spool link using free-space fan in (FI) and fan out (FO) devices. The forward propagating Raman pumps were combined with each spatial channel prior to the FI. The backwards propagating Raman pumps were combined with the spatially multiplexed channels prior to the FO using a free-space multi-core Raman pump combiner. It had losses of approximately 0.5 dB on the signal and pump paths. The total losses of the fiber, FIFO devices and Raman pump combiners at 1550 nm were 45.3 dB, 44.2 dB, 45.0 dB, and 45.3 dB, for cores 1 to 4, respectively. For each propagation direction, we used 12 Raman pumps per spatial channel, with wavelengths between 1410.8 nm and 1502.7 nm. The pump powers varied from 50 mW to 200 mW and the total pump power per spatial channel was 1.25 W for each propagation direction. This configuration allowed a minimum ON/OFF Raman gain of 27.5 dB at the short edge of the C-band and more than 45 dB at the long edge of the L-band, as shown in Fig. 2-b). In the long L-band wavelengths, the Raman gain canceled the span loss, as shown in Fig. 2-a). Fig. 2-c) shows the optical signal-to-noise ratio (OSNR) after transmission for a launch power of 16 dBm per core. It ranged from 14.5 dB for the short C-band in core 1 to 19.7 dB in the L-band for core 2. Fig. 2-c) shows that despite the strong pre-emphasis, SRS still resulted in tilt of the achievable OSNR across the spectrum.

After transmission, the signal went through two C or L band amplification stages on either side of a filter used to select the channel under analysis. A coherent receiver (CoRX) with a 100 kHz linewidth local oscillator followed by a 80 GS/s real-time oscilloscope were used to detect and acquire 5×10 µs traces for offline processing with a total of 8.8×10^6 bits per WDM/SDM channel. Digital signal processing consisted of a resampling to 2 samples per symbol, followed by dispersion compensation, timing recovery and a 2×2 multiple-input multiple output stage with 17-tap equalizers. These were initially updated using a data-aided-least mean squares algorithm, switching to decision directed after convergence. Carrier recovery was performed within the equalizer loop.

The recovered signals were used to estimate the throughput based on the generalized mutual information (GMI) [13]. The post-FEC throughput was estimated by decoding the received signals using LDPC codes from the DVB-S2 standard, as previously described [12]. We implemented code puncturing of the LDPC codes to achieve a rate-granularity of 0.01. Each code rate was evaluated by generating at least 100 random code words using the

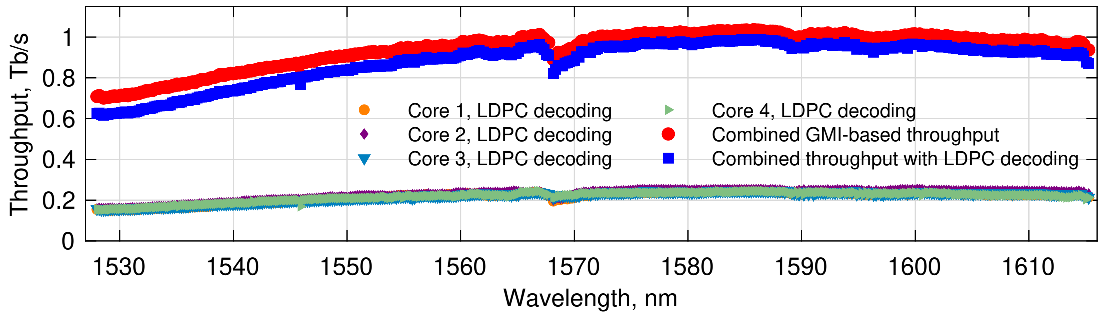

Fig. 3. Post-FEC throughput per channel and core after LDPC decoding as well as total combined throughput after decoding and based on the estimated GMI for a launch power per core of 16 dBm.

received symbols until a post-FEC BER of 4.5×10^{-5} was reached. It is assumed that any remaining errors could be removed by a 1% overhead outer hard-decision code, which was included in the throughput estimate [12].

The achievable throughput depends on the complex interplay between SRS, other fiber nonlinearities, and OSNR. As such we measured the total combined throughput of the system for launch powers between 10 dBm and 18 dBm. Fig. 2-d) and -e) show the combined and per core throughput, respectively, as a function of the launch power. The maximum throughput of 372.8 Tb/s was reached at 16 dBm launch power with throughput per core above 92.1 Tb/s. Lower launch powers led to OSNR degradation despite approaching uniform performance with reduced SRS. Higher launch powers led to strong power tilt, degrading the short C-band channels. The maximum GMI-based estimate of 398.3 Tb/s shows the potential to achieve a throughput of nearly 400 Tb/s. Fig. 3 shows the throughput estimated for the 424 channels within each core as well as the combined throughput for the optimum signal launch power of 16 dBm per core. For comparison purposes, it also includes the throughput estimated using the GMI. For all channels and cores, we obtained throughput above 200 Gb/s per channel in the L-band. In the C-band, the throughput decreased, following the trend of the OSNR, to a minimum of 150 Gb/s. The throughput of each spatial super channel ranged from 620 Gb/s to 980 Gb/s, approximately 5% below the GMI-based value.

3. Conclusions

We demonstrated a throughput of 372.8 Tb/s for an unrepeatered transmission link above 200 km using a 4-core multicore fiber with standard dimensions. This corresponds to a 3-fold improvement over the last record using multicore fibers for a similar reach. The achieved capacity-distance product of 79.5 Pb/s·km is nearly 4-times the previous record with SMFs showing the potential of SDM systems to extend the capacity of unrepeatered links.

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