# 45.7 Tb/s over 12 053 km Transmission with an All-Multi-Core Recirculating-Loop 4-Core-Fiber System

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**Abstract:** We demonstrate 45.7 Tb/s transmission of $4\times175\times24.5$ GBd DP-QPSK signals over 12 053 km of four-core fiber using multi-core C-band EDFAs and Raman amplification. This is the first all-multi-core component recirculating-loop-based long-haul transmission system. 

## 1. Introduction

Space-division multiplexing (SDM) has emerged as a highly promising technology to address the ever-increasing demand for transmission capacity [1]. While SDM can be implemented using various optical fiber types, current SDM systems are evolving towards the adoption of low-core-count MCFs [2]. These MCFs have a standard 125 µm cladding diameter, compatible with existing manufacturing, cabling and connectorization processes for standard single-mode fibers (SMFs), while also reducing vulnerability to mechanical failures [3]. Although data rate enhancement remains a major goal for SDM systems, an equally relevant driver for the development of these systems is the need for hardware integration and reduced power consumption [4]. In particular, the availability of efficient SDM amplifiers is key to SDM system development. Nonetheless, the vast majority of SDM transmission experiments reported to date rely on single-mode amplification, which requires demultiplexing and multiplexing of all spatial modes at every amplification stage [5–7]. Notable exceptions are recent experiments where various types of SDM erbium-doped fiber amplifiers (EDFAs) were used for inline amplification, encompassing both multi-mode (MM-) [8] and multi-core (MC-) [9–15] EDFAs. However, even in these experiments, it is noteworthy that single-mode amplifiers have continued to be used to compensate for the loss introduced by the loop components during recirculating transmission. This practice can significantly affect the gain tilt and transmission performance, often resulting in an unfair evaluation of an SDM amplifier's suitability for long-haul transmission.

In this work, we demonstrate for the first time, an all-MCF trans-pacific-equivalent transmission distance based on a hybrid amplification scheme combining core-pumped MC-EDFAs and distributed Raman amplification. We employ C-band, 4-core-EDFAs to amplify $4\times175\times24.5$ GBd dual-polarization quadrature phase-shift keying (DP-QPSK) signals within a spectral range extending from 1528.8 nm to 1563.5 nm. These signals are transmitted over a recirculating loop comprising two spans of low-loss standard-cladding diameter 4-core uncoupled-core MCFs, with lengths of 96.5 km and 101.1 km, respectively. Additionally, a 4-core EDFA with an identical gain profile to those used to compensate fiber loss is also used to mitigate the extra losses introduced by the recirculating-loop-circuit components. We evaluate the performance of all the $4\times175$ SDM and WDM channels in terms of generalized mutual information (GMI) as well as implementing forward error correction (FEC) codes compliant with the digital video broadcasting (DVB-S2) standard. We measure a GMI-estimated aggregate throughput and a decoded throughput of 49.9 Tb/s and 45.7 Tb/s, respectively, after transmission over a distance of 12 053 km, achieving a per-spatial-mode capacity-distance product of 137.8 Pb/s$\times$km. This is the longest reach ever reported in SDM transmission experiments exploiting SDM amplifiers.

## 2. Experimental Setup

The experimental transmission setup is shown in Fig. 1. A three-channel sliding test-band was generated by modulating carriers produced by three tunable lasers (TLs) using two dual-polarization IQ-modulators (DP-IQMs). Both DP-IQMs, one dedicated to the center-test channel and one shared by the two neighboring channels, were driven by a common 49 GS/s 4-channel arbitrary waveform generator (AWG) to produce 24.5 GBd DP-QPSK signals, with a 1% roll-off root-raised cosine pulse shape. Additionally, a dummy-band was generated by spectrally flattening the amplified spontaneous emission noise produced by two erbium-doped fiber amplifiers using an optical processor (OP), which was also used to carve a notch accommodating the test-band. The combined test-

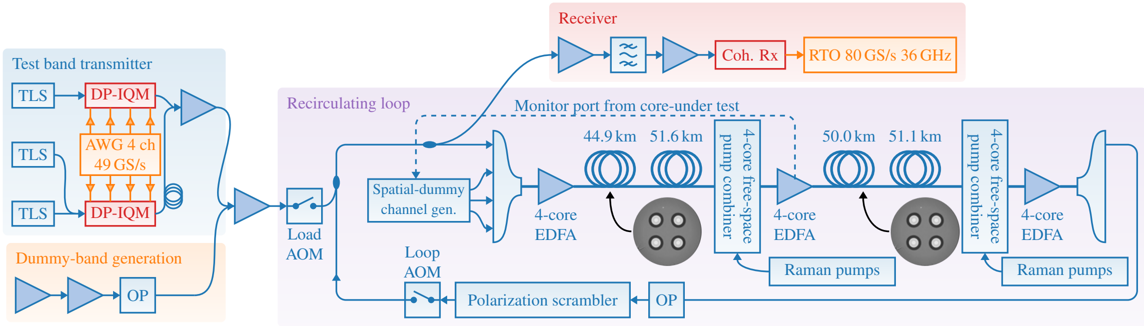


Fig. 1: Experimental setup of the all-multi-core recirculating-loop-based 4-core multi-core fiber link.

and dummy-band signal was amplified and fed into a 4-core recirculating loop containing two MCF spans and three MC-EDFAs. A copy of the signal was obtained from the monitoring output port of the MC-EDFA and amplified. This signal was then used to generate spatial dummy channels, ensuring that all the cores were constantly loaded with signals that had propagated the same distance as the test signal at each recirculation. The signals in the four fiber cores were simultaneously amplified using two 4-core-EDFAs preceding two fiber spans of 96.5 km and 101.1 km. Each span was obtained by connecting two spools of uncoupled-core 4-core fibers. The second fiber section of each span was a zero-water-peak fiber, thereby allowing for more efficient Raman amplification, similar to [7]. Raman pumps were added in each core at the end of the two fiber spans using free-space 4-core pump combiners. Pumps at 1410.8 nm and 1417.5 nm were injected into each core of the MCF with a power level of 270 mW, while pumps at 1424.3 nm were set to 150 mW. An additional pump per core at 1431 nm was injected at the end of the first fiber span with a power level of 80 mW. These pump settings mostly amplified the shorter-wavelength region of the C-band, allowing for a reduction in the amplifier gain tilt at the end of the two fiber spans. The outputs of the second span were amplified again using an additional 4-core EDFA, prior to demultiplexing the spatial channels using a free-space 4-core-demultiplexer. The outputs of the dummy cores were terminated, while the signal in the core under test was connected back to the loop input after passing through an OP, which was used to compensate for the amplifiers' gain tilt and a polarization scrambler.

At the output of the recirculating loop, the spatial channel under test was amplified prior to filtering out the channel of interest (COI), which was amplified again and detected with a coherent receiver (Coh. Rx), using a local oscillator (LO) with a linewidth of less than 60 kHz. The electrical signals were digitized by using a 4-channel 80-GS/s real-time oscilloscope. The offline DSP included a time-domain $2\times2$ multiple-input multiple-output (MIMO) equalizer that was initially updated in a data-aided least-mean squares (DA-LMS) mode before switching to decision-directed (DD) operation, after convergence. Data rates were calculated based on GMI and implementing the FEC coding scheme described in [16]. This coding scheme used codes from the DVB-S2 standard [17] in conjunction with code-rate puncturing to achieve a bit error rate (BER) below $5 \times 10^{-5}$, with an additional 10% hard-decision outer-FEC to guarantee error-free transmission [18]. Signal performance estimation was performed on all the $4 \times 175$ SDM and WDM channels individually.

## 3. Experimental Results

Figure 2a displays the dependence of the decoded throughput on the transmission distance for three WDM channels distributed across the C-band for distances up to 16 005 km. Increasing performance differences between the three channels can be observed as transmission distance increases, and the figure illustrates the inherent trade-off between throughput and reach. Figure 2c shows the data-rates per core of all the channels after 12 053 km transmission, estimated using FEC decoding. It also shows the combined data rates across the spectrum using FEC decoding and the GMI estimates. Most of the channels exhibited a Q-factor exceeding 2 dB, with approximately 4% of the total having a Q-factor ranging between 1 dB and 2 dB. The differences in the total throughput among wavelength channels can be ascribed to the wavelength-dependence of the amplifiers' gains, as well as to the filtering applied in the loop OP, which was programmed to ensure a flat spectrum across the entire bandwidth at the input of the first fiber span in the recirculating loop. Figure 2b illustrates the signal spectrum at the input of the first fiber span and at its output, with and without Raman amplification. The Raman gain profile that emerges from the figure was obtained in an effort to optimally compensate for the 4-core amplifier gain tilt. No noticeable performance differences were observed between cores, with the best and worst cores providing a total decoded throughput of 11.7 Tb/s and 11.2 Tb/s, respectively. The average GMI-based and decoded throughput per space and wavelength channel reached 71.3 Gb/s and 65.3 Tb/s, respectively. This resulted in a total GMI-based throughput of 49.9 Tb/s and a total decoded throughput of 45.7 Tb/s, at a transmission distance of 12 053 km. We anticipate that improved system performance can be achieved by further optimizing the design of the first-generation MC-EDFAs used in this work, and, upon system deployment, by replacing the recirculating-loop experimental system with field-installed coupled core fiber and amplifiers.

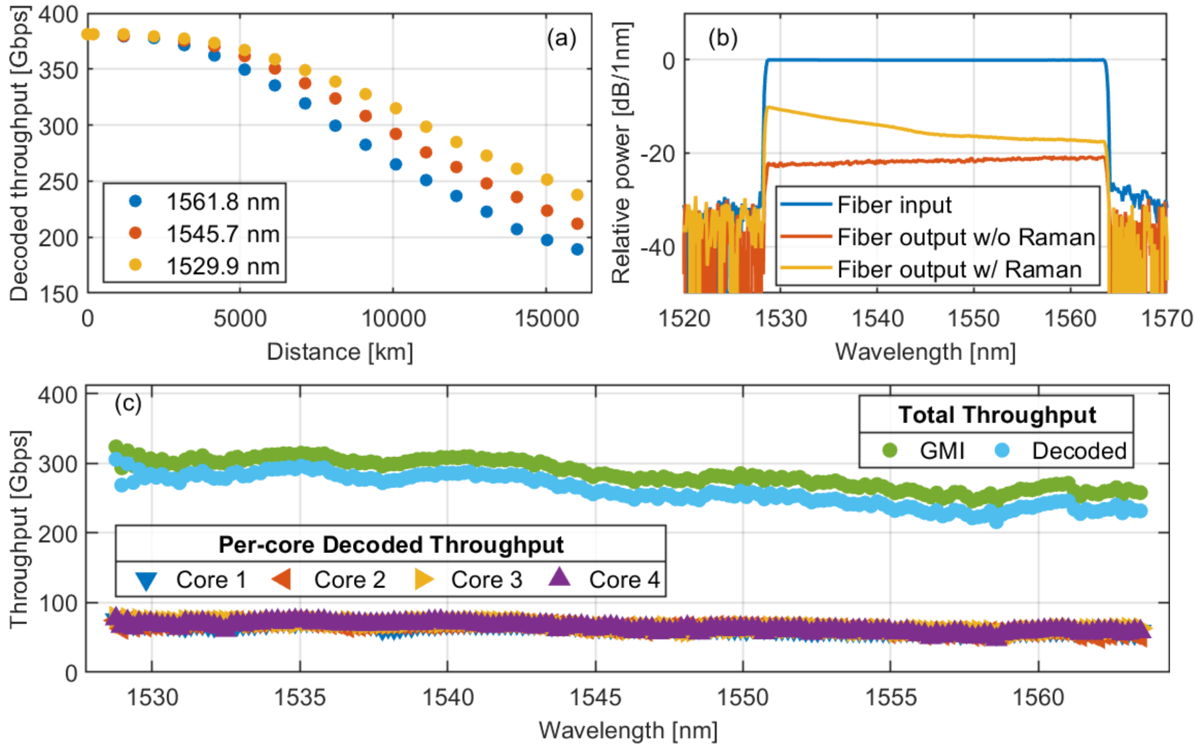


Fig. 2: (a) Total decoded throughput vs distance for three WDM channels with wavelengths displayed in the legend. (b) Signal spectrum at the input of the first fiber span and at its output, with and without Raman amplification. (c) Throughput of the $4 \times 175$ SDM and WDM channels after 12 053 km transmission. Circles and squares show the GMI-based and decoded aggregate throughput, respectively. Triangles show the decoded per core throughput.

## 4. Conclusions

We have demonstrated a trans-pacific transmission distance of 12 053 km in an all-multi-core uncoupled-core 4-core fiber system. We achieved a total decoded throughput of 45.7 Tb/s by transmitting $4 \times 175 \times 24.5$ GBd DP-QPSK SDM and WDM channels within a spectral range extending from 1528.8 nm to 1563.5 nm. We used an all-multi-core component recirculating-loop configuration based on a hybrid amplification scheme that seamlessly integrates core-pumped MC-EDFAs and distributed Raman amplification. This is the longest reach demonstrated in spatially multiplexed transmission experiments relying completely on SDM amplifiers.

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