1.01 Peta-bit/s C+L-band transmission over a 15-mode fiber

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Abstract *We demonstrate transmission of 30×382×24.5 GBaud 64-QAM signals, spanning 82 nm bandwidth, over 23 km 15-mode fiber. The resulting data rate constitutes a record for any fiber with standard cladding-diameter and was enabled by high mode-count mode-multiplexers and a transmission fiber optimized for wideband operation.*

Introduction

Space-division multiplexing (SDM), where different data signals are transmitted at the same carrier wavelength over spatially diverse transmission paths, is a promising technology to support the exponentially increasing capacity demands of future transmission systems[1]. To date, all transmission demonstrations with data rates higher than 1 Pb/s in a single fiber have used fibers with cladding-diameters in excess of the current standard of 125 µm[2]–[7]. While significant economic benefits of maintaining the current cladding-diameter can be assumed from using existing cabling technologies, increasing the cladding-diameter may also be problematic for technical reasons such as mechanical reliability, coupling/splicing tolerance and production yield[8],[9]. Hence, the development of SDM transmission media with standard cladding-diameter supporting peta-bit per second data rates[10] is of crucial importance for the future deployment of SDM systems.

While some promising transmission demonstrations have been made using an uncoupled 4-core multi-core fiber[11], it is evident that the highest number of spatial channels in a standard cladding-diameter fiber can be achieved in multi-mode fibers (MMF)[14]. This work demonstrates a record transmission of more than 1 Pb/s over a 15-mode MMF with standard cladding-diameter, breaking the current data rate record in MMF by more than 2.5-fold[13] as shown in the comparison in Fig. 1. Each mode carried 382 wavelength-division multiplexed (WDM) 24.5 GBaud polarization-multiplexed (PM) 64-Quadrature amplitude modulated (QAM) channels over the C- and L-bands for a total bandwidth exceeding 80 nm. This is an increase of the bandwidth transported in MMFs with more than 10 modes by a factor of 16,[14],[16] thanks to the use of mode multiplexers and a MMF suitable for wideband operation.

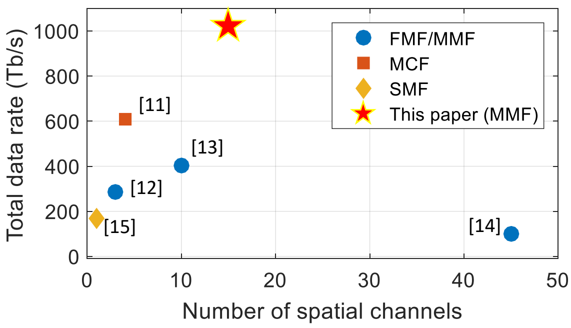

Fig. 1: High data rate transmission demonstrations in fibers with standard cladding-diameter[11]–[15].

Experimental Demonstration

The experimental setup is shown in Fig. 2. An optical comb source[17] generated more than 400 carrier lines in a 25 GHz grid. For a test-band, a tunable optical bandpass filter selected three comb lines that were split into odd and even channels in interleavers (INT). Odd and even channels were modulated in separate dual-polarization IQ-modulators. 24.5 Gbaud 64-QAM modulation, based on a pseudo random binary sequence of length 2^{19} was achieved with a 4-channel arbitrary waveform generator (AWG), operating at 49 GSample/s for root-raised cosine shaping with a roll-off factor of 0.01. Odd and even channels were optically de-correlated by 20 ns. The remainder of the comb lines were modulated in a single-polarization IQ-modulator in combination with a polarization multiplexing emulation to gen-

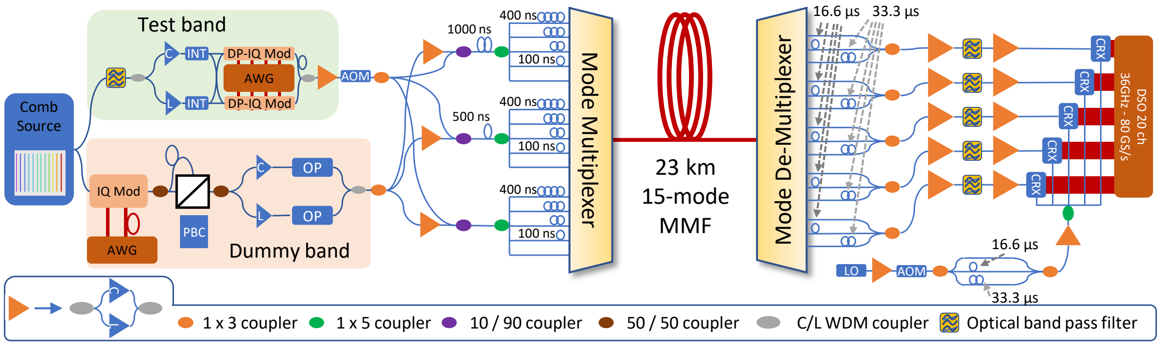

Fig. 2: Experimental setup for C+L-band transmission demonstration over 15-mode fiber.

erate a band of WDM dummy channels. After amplification in C- and L-band erbium-doped fiber amplifiers (EDFA), optical processors (OP) were used to flatten the comb spectrum and to carve a notch into the dummy band to accommodate the test-band. All WDM channels were measured in turns by sequentially tuning the test-band optical filter to the corresponding wavelength. Independent signals for each fiber mode were emulated by de-correlating 15 copies of the signal by multiples of 100 ns. The signals were launched at approximately 20 dBm per mode into the mode multiplexer.

Spatial multiplexing and de-multiplexing were achieved by multi-plane light conversion based mode-selective mode multiplexers[18],[19]. 15 spots of an input fiber array were transformed through 15 reflections on phase plates to match the fiber modes of the 15-mode MMF. The theoretical loss of each multiplexer was 3 dB, while a loss of approximately 6 dB was measured.

The 23 km long, 15-mode MMF[20] had a trench-assisted, graded-index design with a core radius of 14.1 µm and a core-cladding index step of 1%. This index step was similar to that of standard 50 µm MMF. It was thus possible to use standard trench-assisted graded-index multi-mode preforms to realize the fiber since their graded-index core exponents and trenches were slightly adjusted to minimize the differential mode group delay (DMGD) and were appropriately scaled to reach a core radius of 14.1 µm in the drawn fiber to guide only 15 spatial modes at 1550 nm wavelength[20]. This was achieved by targeting a preform diameter $25/14.1 = 1.77$ times larger than that of standard multi-mode preforms. The fiber was fabricated with standard glass (125 µm) and coating (245 µm) diameters and had loss of less than 0.22 dB/km and the lowest DMGD reported so far for this fiber type of less than 100 ps/km at 1550 nm wavelength.

A time-multiplexed receiver setup[21] was employed, where three 16.66 µs long time-slots were dedicated to one signal each so that a total of 5 coherent receivers was sufficient to capture the output signals from all 15 fiber modes. Time gating was implemented on the transmitter side with an acousto optic modulator (AOM) that had a period of 50 µs and a duty-cycle of 33.33%. After mode de-multiplexing, the 15 output signals were grouped into 5 groups of three signals. Two of the three signals in each group were delayed by 16.66 µs and 33.33 µs, respectively, and combined in power couplers. The resulting 5 optical signal were amplified, and the WDM channel under test was selected by optical bandpass filters before the signals were received in 5 coherent receivers (CRX), where the signals were mixed with the light of a 60 kHz linewidth local oscillator (LO). The LO path had the same split-and-delay structure to ensure equal phase-noise on the three time-slots. The resulting 20 electrical

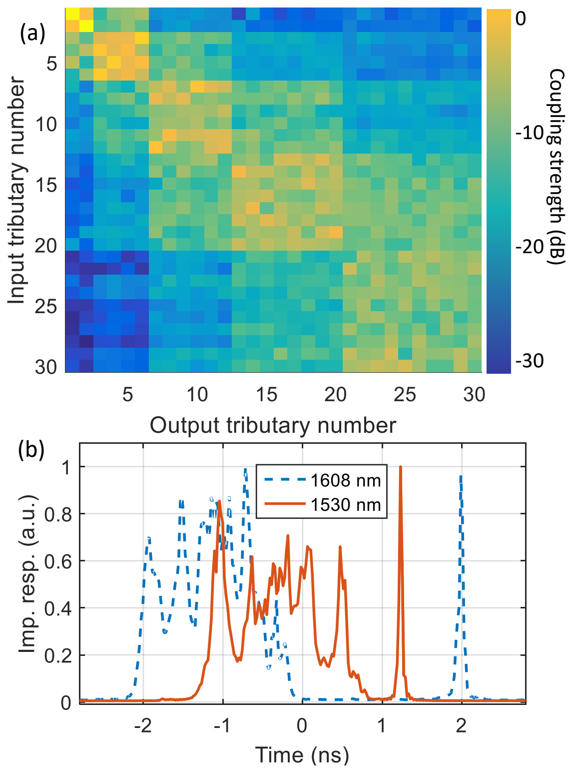

Fig. 3: (a) Coupling matrix of the WDM channel at 1550 nm and (b) impulse response of two WDM channels.

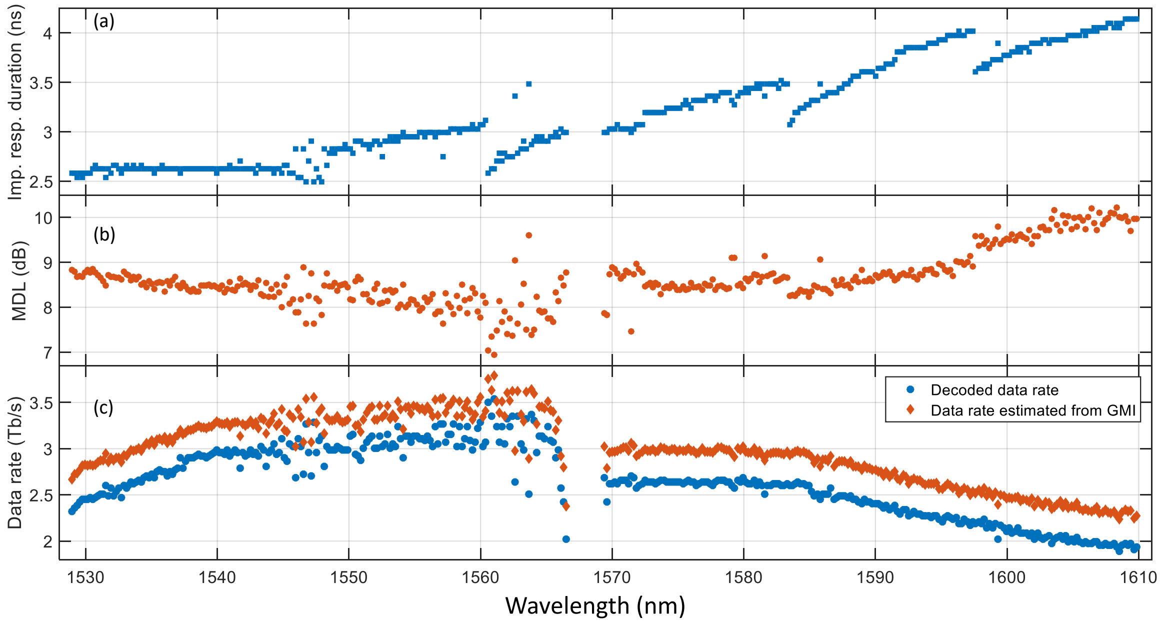

Fig. 4: (a) Impulse response duration, (b) Mode-dependent loss and (c) data rates for all 382 wavelength channels.

signals were digitized in a real-time oscilloscope (DSO) at 80 GSample/s with 36-GHz electrical bandwidth. A 30$\times$30 time-domain multiple-input / multiple-output (MIMO) equalizer with 281 half symbol-duration-spaced taps was initialized in a data-aided mode before switching into a decision-directed mode for signal performance assessment. A carrier recovery algorithm[22] was running within the equalizer loop.

Figure 3(a) shows the coupling matrix of the WDM channel at 1550 nm, estimated from the MIMO equalizer taps, indicating relatively weak coupling between the 5 mode groups of the MMF. 3(b) shows the impulse response of two wavelength channels. The delay of the fundamental mode, represented by the single peak, changes in respect to the other fiber modes with wavelength. The duration of the impulse response, as defined in[7], is shown in Figure 4(a) for all 382 WDM channels. Five areas with monotonically behaving impulse response durations can be observed that correspond to the five days that the measurements took. This suggests that the fiber's propagation properties were changing slowly over time, possibly due to temperature variations. Figure 4(b) shows the mode-dependent loss (MDL) for all 382 WDM channels, estimated as described in[12]. Values below 10.2 dB confirm broadband applicability of mode-multiplexers and transmission fiber. Increased MDL in the high L-band partially stems from growing wavelength-dependent loss of higher order modes in the MMF.

Finally, Figure 4(c) shows the data rates for all WDM spatial super-channels, estimated using generalized mutual information (GMI) as well as an implemented coding scheme, based on the DVB-2S standard[23] in combination with a low-overhead outer hard-decision forward-error-correction code (FEC)[24], as detailed in[12]. The symbol streams for data rate estimation were constructed using 2 million randomly picked symbols from the 30 received symbol streams (15 modes $\times$ 2 polarizations). Wavelength dependent performance variations are assumed to stem from fluctuations of the per-line power of the comb source and increasing phase-noise for wavelength channels with large separation from the comb-seed at 1558 nm wavelength as well as increased MDL in the high L-band. The spectral efficiency was 105.8 b/s/Hz (decoded) and 119.4 b/s/Hz (GMI). The total data rate, calculated as the sum of the data rates for all WDM channels, was 1.01 Pb/s (decoded) and 1.14 Pb/s (GMI), breaking the current data rate record in MMF[13] more than 2.5- or 2.8-fold, respectively.

Conclusions

We demonstrated a record data rate of 1.01 Pb/s in a first wideband transmission demonstration over a 15-mode MMF with standard cladding-diameter. This was enabled by a wideband transceiver sub-system generating 382 $\times$ 64-QAM wavelength channels of high signal quality as well as mode multiplexers and a transmission fiber compatible with broadband C- and L-band transmission and a coherent 30 $\times$ 30 MIMO receiver. The resulting data rate is the highest reported to date in any fiber with standard cladding-diameter and highlights the large potential of high mode-count MMF for future high capacity space-division multiplexed transmission links.

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