3.56 Peta-bit/s C+L Band Transmission over a 55-mode Multi-Mode Fiber

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Abstract *We demonstrate transmission of 383 WDMx55 SDMx24.5 GBd 16-QAM signals spanning C- and L-bands over 12.5 km 55 mode fiber. The resulting data rate of 3.56 Pb/s more than doubles the previous record data rate in optical fibers with standard cladding diameter.*

Introduction

Space-division multiplexing (SDM) is regarded as one of the most promising technologies to drastically increase the per-fiber data rates in optical fiber transmission systems[1]. In SDM transmission, multiple independent data channels are transmited over spatially diverse paths. Such paths include cores of multi-core fibers (MCFs) and modes of multi-mode fibers (MMFs). High core count MCFs with e.g. 38 cores have been demonstrated with enlarged cladding diameter of more than 300 µm[2]. However, for compatibility with current cabling technologies and for increased mechanical reliability and production yield, it is beneficial to use fibers that adhere to the current standard cladding diameter of 125 µm[3]. When restricting to such cladding diameters, MCFs have been demonstrated with 4 weakly coupled- and 19 strongly coupled cores for C/L-band transmission[4]. MMFs on the other hand have been demonstrated with 55 modes using fibers with standard cladding diameter[5],[6]. Previously, such a fiber was used to show transmission of 1.53 Pb/s using only C-band channels[6]. In this work, we demonstrate transmission of 383 wavelength-division multiplexed (WDM) $\times$55 SDM$\times$24.5 GBd 16-Quadrature-Amplitude Modulated (QAM) signals, spanning more than 80 nm bandwidth over a 12.5 km long, graded-index, 55-mode fiber. The wideband transmission was enabled by low-loss and high bandwidth mode-multiplexers, a low-loss and low differential-mode-delay (DMD) 55-mode fiber and a coherent 110$\times$110 multiple-input / multiple-output (MIMO) transceiver system. The resulting data rate of 3.56 Pb/s is a two-fold increase compared to the latest reported data rate record in a standard cladding diameter optical fiber[4]. This experiment demonstrates the strong potential of MMF-based SDM transmission to support ultra high data rates.

Experimental Setup

The experimental setup for the investigation of C+L-band transmission in a 55-mode MMF is shown in Fig. 1. Three tunable laser sources with 25 GHz channel spacing and nominal linewidth of less than 10 kHz were used to form a three-channel tunable test band. The center and the two outer channels were modulated in individual dual-polarization IQ-modulators with root-raised cosine shaped 24.5 GBd 16-QAM signals with a roll-off factor of 0.01. Those were produced by a four-channel arbitrary waveform generator (AWG), operating at 49 GS/s. WDM dummy channels were based on the laser lines produced by an optical frequency comb that generated 25 GHz-spaced carriers across the C- and L-bands. The dummy channels were modulated in a single-polarization IQ-modulator, driven by another AWG producing 24.5 GBd 16-QAM signals. A polarization multiplexing emulation, including a splitter, 10 ns optical delay line and a polarization-beam combiner, was used to generate dual-polarization dummy channels. The

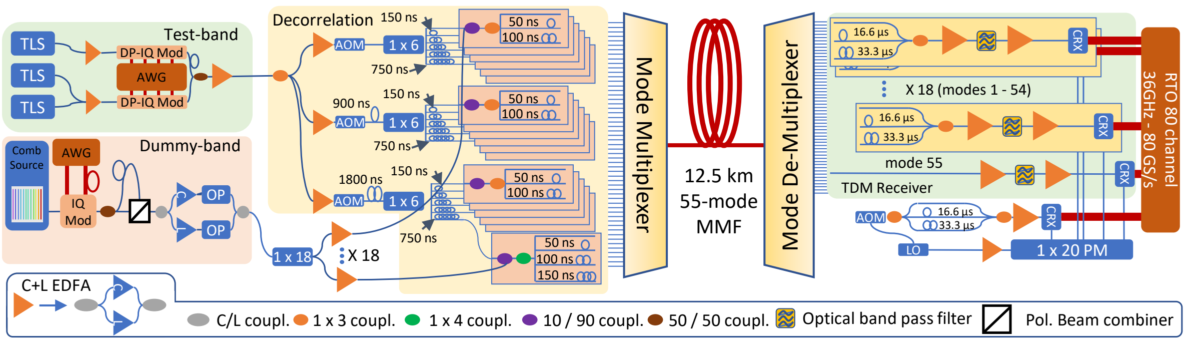

Fig. 1: Experimental setup for transmission of 383 WDM, 55 SDM, PM-24.5 GBaud 16-QAM channels over 12.5 km 55-mode fiber.

dummy channels were spectrally flattened in separate C- and L-band optical processors (OP) that were also used to carve a notch to accommodate the sliding test-band.

To produce 55 decorrelated copies of the generated signal for transmission over the 55 fiber modes, a three-stage split-and-delay technique was used. This generated 55 copies of the transmitted signal, each delayed by multiples of 50 ns. An array of C- and L-band amplifiers was used to amplify the dummy channels to approximately 20 dBm per fiber mode. The 55 signals were launched into the 55-mode fiber using a multi-plane-light-conversion (MPLC)-based mode-multiplexer (MUX)[7]. The MUX had an insertion loss of approximately 5 dB. The 55-mode fiber was 12.5 km long and had a trench-assisted design, resulting in an arrangement of the 55 modes in 10 mode-groups (MGs). The attenuation profile of the 10 MGs is shown in Fig. 2(a). The fist MG had slightly increased attenuation of approximately 0.25 dB/km, with MGs 2-8 ranging between 0.18 dB/km and 0.22 dB/km. MGs 9 and 10 had increased attenuation, with MG 10 up to 0.4 dB/km at 1530 nm. More details on the fiber can be found in[5]. After transmission, the signals carried by the 55 fiber modes were demultiplexed in another MPLC-based MUX.

A time-domain multiplexing (TDM) receiver scheme[8] was used to receive the signals from the first 54 modes using 18 coherent receivers (CRX). For this, three acousto-optic modulators (AOMs) were used on the transmitter side to switch the test-band on for 16.6 µs and off for the remainder of a 50 µs period. On the receiver side, groups of three signals were combined in power couplers after fibers with 0, 16.6 µs and 33.3 µs delays to time-arrange the signals in three time slots for reception in a single coherent receiver. The signal from the last mode was received in another coherent receiver. The coherent receivers used the light from a 60 kHz linewidth tunable laser as local oscillator (LO). To detect the relative phase changes of the LO light over the three time slots of

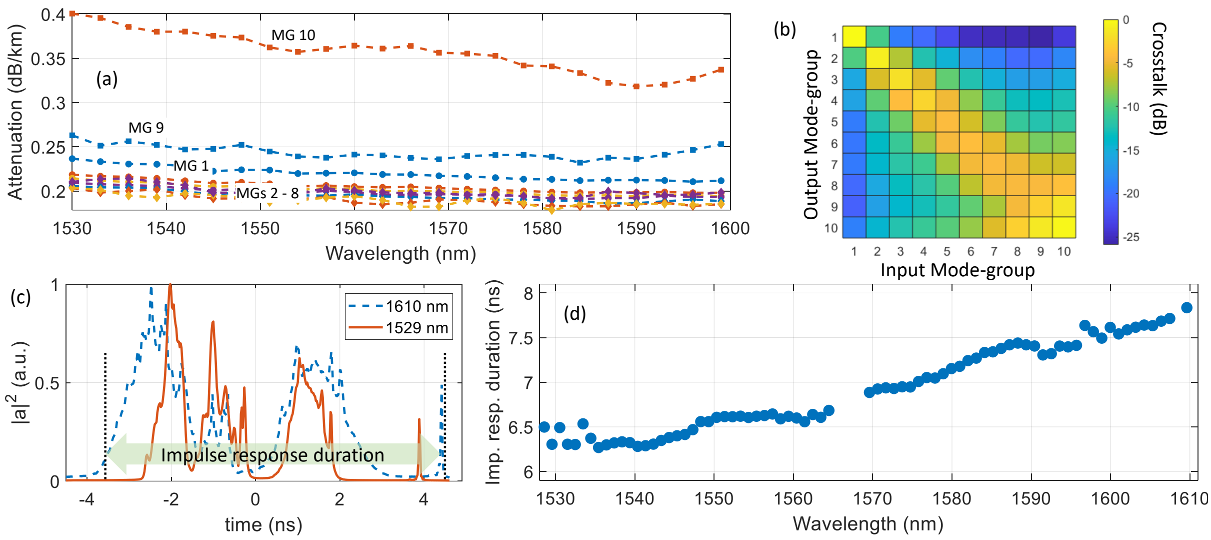

Fig. 2: (a) Attenuation profile of the 10 mode-groups (MGs), measured using 3 nm wide tunable ASE noise. (b) Coupling matrix of the wavelength channel at 1550 nm, estimated from the MIMO equalizer taps. (c) Intensity impulse response (IIR) of the WDM channels at 1610 nm and 1529 nm wavelength, the definition of the impulse response duration is marked for the channel at 1610 nm. (d) Impulse response duration as a function of wavelength.

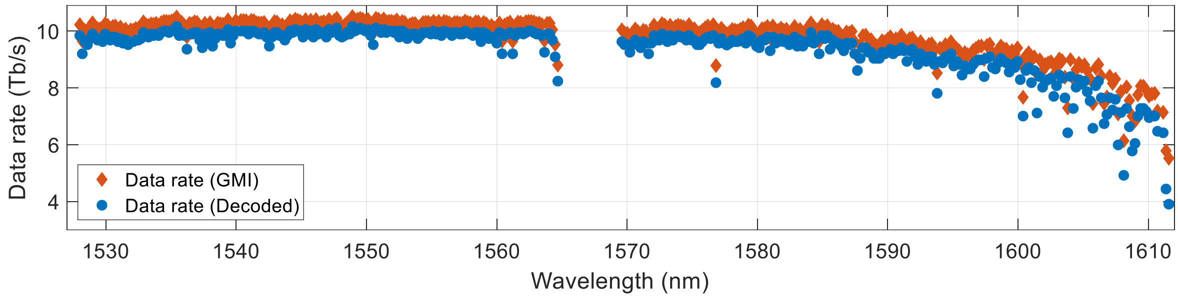

Fig. 3: Data rates of 383 measured wavelength division multiplexed channels.

the TDM receiver, a similar TDM setup was used on the LO path, using another CRX. The electrical signals from the 20 CRXs were digitized in an 80 channel real-time oscilloscope (RTO) with electrical bandwidth of 36 GHz and operating at 80 GS/s. Offline digital signal processing (DSP) consisted mostly of a front end for compensation of the TDM-related phase changes and a time-domain 110×110 MIMO equalizer, using 451 half-symbol-spaced taps. The equalizer was initialized in a data-aided mode before switching to a decision directed more for signal performance estimation. A blind phase-recovery algorithm was included in the equalizer loop.

Results and discussion

Figure 2(b) shows the MG-resolved coupling matrix of the WDM channel at 1550 nm, calculated from the MIMO equalizer taps. Due to high mode-selectivity of the MUXs and stable transmission within each MG, values are strongest on the diagonal of the matrix, with coupling to closest neighbors of each MG evident by non-negligible entries in the coupling matrix. Figure 2(c) shows the intensity impulse response (IIR) of the WDM channels at 1610 nm and 1529 nm. Figure 2(d) shows the IIR duration, defined as the time interval that covers 99% of the area under the IIR, as a function of the wavelength. The IIR is shortest in the low C-band with approx. 6.3 ns length, increasing to 7.7 ns at 1610 nm wavelength. This is a typical behavior reported also for other types of graded-index MMFs[9]. However, the IIR duration increases here only about 30% across C- and L-bands, which is less than previously reported for other MMFs[9].

Figure 3 shows the data rates for all 383 received WDM channels. The data rates were estimated using generalized mutual information (GMI) as well as an implemented coding scheme. The latter one was based on codes from the DVB-S2 standard combined with code-rate puncturing for high code-rate granularity. Randomly selected received symbols were used to generate code-words of 64000 bit length that were then decoded with variable code-rates until reaching a bit-error rate (BER) of less than 5×10^{-5}. A further outer hard-decision code with 1% overhead was assumed to guarantee error free transmission[10]. Further details on the coding scheme can be found in[9]. The data rate per WDM channel reached between 9 Tb/s and 10 Tb/s in the C-band, while the GMI-based estimate was generally around 5 % higher than the decoded data rate. In the low L-band, data rates continue with values around 9-10 TB/s, but reduced towards the high L-band with minimum values of around 4 Tb/s, presumably due to bandwidth limitations of the MUX and De-MUX, as well as transmitter and receiver EDFAs. The spectral efficiencies were 372 bit/s/Hz and 390 bit/s/Hz using the coding scheme and GMI, respectively. The total data rate, being the sum off all WDM channels was 3.56 Pb/s using the coding scheme and 3.74 Pb/s using GMI. This is the highest reported data rate in any standard cladding diameter optical fiber.

Conclusion

We have demonstrated space-division multiplexed transmission of 383 WDM×55 SDM×16-QAM signals, spanning more than 80 nm bandwidth in the C- and L-bands over a 12.5 km long, graded-index 55-mode fiber. This was enabled by mode-multiplexers with high-bandwidth and low insertion loss, a 55-mode fiber with low mode-dependent attenuation over a wide bandwidth and a transceiver using coherent 110×110 MIMO signal processing. The resulting data rate of 3.56 Pb/s is the highest reported in any fiber with standard cladding diameter and more than doubles the previously reported record. These results highlight the high potential of MMFs for optical fiber transmission with ultra-high data rates.

Acknowledgement

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