10.66 Peta-Bit/s Transmission over a 38-Core-Three-Mode Fiber

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Abstract: We demonstrate transmission of 368-WDM-38-core-3-mode x 24.5-GBaud 64- and 256-QAM signals over 13 km. Record data-rate and spectral-efficiency of 1158.7 b/s/Hz were enabled by a low DMD 38-core-3-mode fiber with high uniformity amongst cores.

OCIS codes: 060.2330 Fiber optics communications, 060.4230 Multiplexing

1. Introduction

Space-division multiplexing (SDM) has been proposed in recent years to drastically increase the per-fiber capacity in optical transmission systems [1]. Few-mode multi-core fibers (FM-MCFs) have been reported with up to 114 spatial channels [2, 3] and a 19-core, 6-mode FM-MCF has been used in the first transmission demonstration with a data-throughput exceeding 10 Pb/s with an average data-rate per spatial channel of 89.1 Tb/s and average spectral efficiency of 1099.9 b/s/Hz [3]. To further increase the data-rates in SDM transmission, it is essential to carry similar data-rates in each spatial channel as in single-mode fibers. It is thus necessary to demonstrate the compatibility of high-spectral efficient modulation formats, such as 64- or 256-quadrature-amplitude modulation (QAM) with high core-count FM-MCFs. Here, we investigate transmission in a large core-count FM-MCF designed to have low differential-mode delay (DMD) within each core and to enable high throughput transmission in all spatial channels. The 13 km FM-MCF had 38 cores, each supporting transmission of three spatial modes. As signals in different cores of this fiber were weakly coupled, 6x6 multiple-input / multiple-output (MIMO) equalization within the signals in each core was sufficient for signal recovery. We used this fiber to transmit 368 wavelength division multiplexed (WDM) 24.5 GBaud 64- and 256-QAM signals in a 25 GHz channel grid over the C and L bands. We achieved an aggregated data-rate of 10.66 Pb/s after an implemented forward-error-correction (FEC) decoding. The corresponding average data-rate per spatial channel was 93.5 Tb/s and the average spectral efficiency was 1158.7 b/s/Hz. The data-rate per spatial channel is within 10 % of the current SMF record in the same bands [4], hence, this result highlights the large potential of high core-count FM-MCFs for future high-capacity transmission systems.

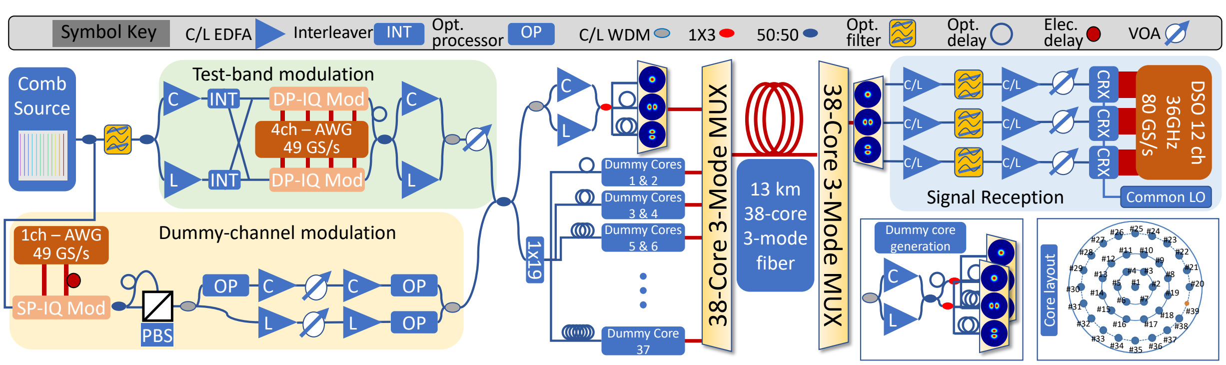

Fig. 1: Experimental setup for C+L-band transmission in a 38-core 3-mode fiber.

2. Experimental Setup

The experimental setup is shown in Fig. 1. An optical frequency comb generated 25 GHz space carrier lines with a total optical bandwidth exceeding 100 nm. A tunable filter selected three comb lines to form a test-band, separated into odd and even channels by interleavers and independently modulated in dual-polarization IQ-modulators (DP-IQ). The modulators were driven by four arbitrary waveform generators (AWGs), operating at 49 GSample/s, generating root-raised cosine shaped dual-polarization (DP) 64- or 256-QAM signals at 24.5. GBaud with a 0.01 roll-off. Odd and even channels were optically de-correlated and combined in a 3-dB coupler and amplified in erbium-doped fiber amplifiers (EDFA). The remaining comb lines were modulated in a single-polarization IQ-modulator (SP-IQ), generating 24.5 GBaud single-polarization signals with the same modulation format as the test-band for dummy channels. Polarization multiplexing was emulated after the modulator. C-and L-band signals were then separated in WDM couplers for spectral flattening in independent optical processors (OPs) with an additional OP used in the C-band where power variation between comb lines was greatest. The final OPs were also used to carve a notch into the dummy channel band to accommodate the test-band. Test- and dummy-bands were then combined and amplified.

The WDM signal was then split into three paths that were optically de-correlated by 100 ns and 200 ns to emulate independent data-streams in each spatial channel. The three signals were then mode-multiplexed in a 3-D waveguide inscribed mode-multiplexer. The few-mode output of the mode-multiplexer was then core-multiplexed in a free-space core-multiplexer that was connected to a 38-core-3-mode fiber. Each fiber core had a graded-index profile to minimize the differential mode-delay (DMD) between the fiber modes. An additional single-mode core acted as a marker to facilitate splicing. The fiber had a cladding diameter of 312 μm. Most cores had a total loss of around 10 dB, including mode and core multiplexers, while four cores had loss of up to 15 dB [2]. The cores' DMDs ranged from 0.6 ns to 3 ns [5]. Inter-core crosstalk was below -35 dB for all fiber cores. More details on the fiber span can be found in [2]. The signals for dummy cores were generated from optically decorrelated copies of the signal from the test core, as indicated in Fig. 2 and the total launch power per spatial mode was 20 dBm.

After core- and mode-demultiplexing, the three spatial channels of the core-under test were amplified and the WDM channel under test was selected in a tunable band-pass filter. A common local oscillator (LO) with a linewith of 100 kHz was mixed with the signals in three coherent receivers (CRX). The electrical signals were digitized in a 12-channel digital storage oscilloscope (DSO) with 80 GSample/s sampling rate. Offline DSP consisted mainly of a frequency offset estimation followed by a 6x6 time-domain MIMO equalizer with 249 taps. The equalizer was initialized in a data-aided mode and switched later into a decision-directed mode after convergence. Phase-recovery was performed within the equalizer loop. We calculated Q-factors from the bit-error rate (BER) that we estimated by direct error-counting. We further implemented FEC coding as described in [6] with codes from the DVB-S2 standard in conjunction with puncturing for high code rate granularity to achieve a BER of less than $2.18 \times 10^{(-5)}$ and further assumed a 2.65 % hard-decision outer-FEC to guarantee error-free transmission [7]. We also calculated the generalized mutual information (GMI) for each WDM channel to estimate the data-rate assuming an ideal code.

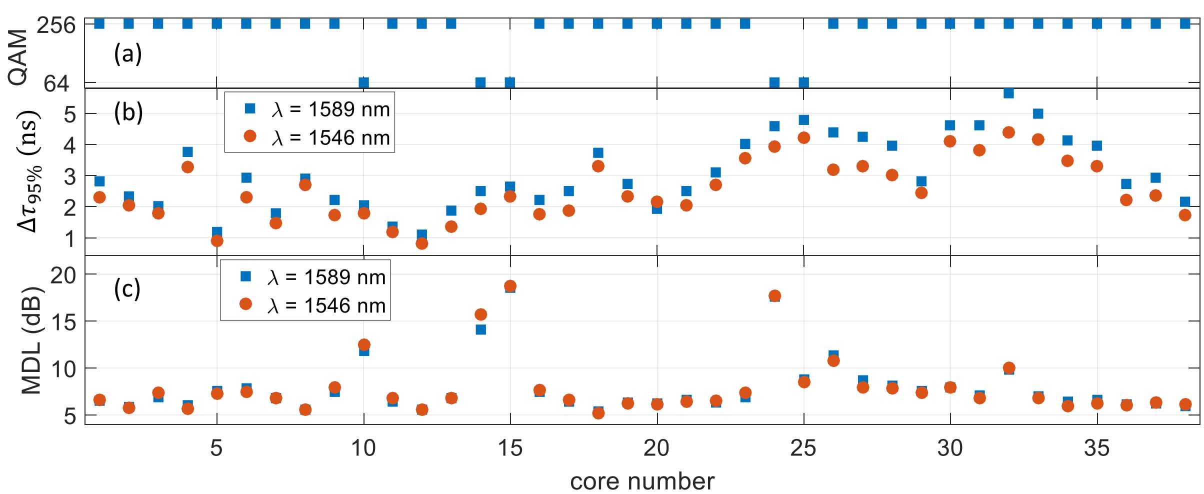

Fig. 2: (a) Transmitted QAM-order for all 38 cores. (b) Impulse response length ($\Delta\tau_{(95\%)}$) and (c) mode-dependent loss (MDL) of two different WDM channels for all 38 cores

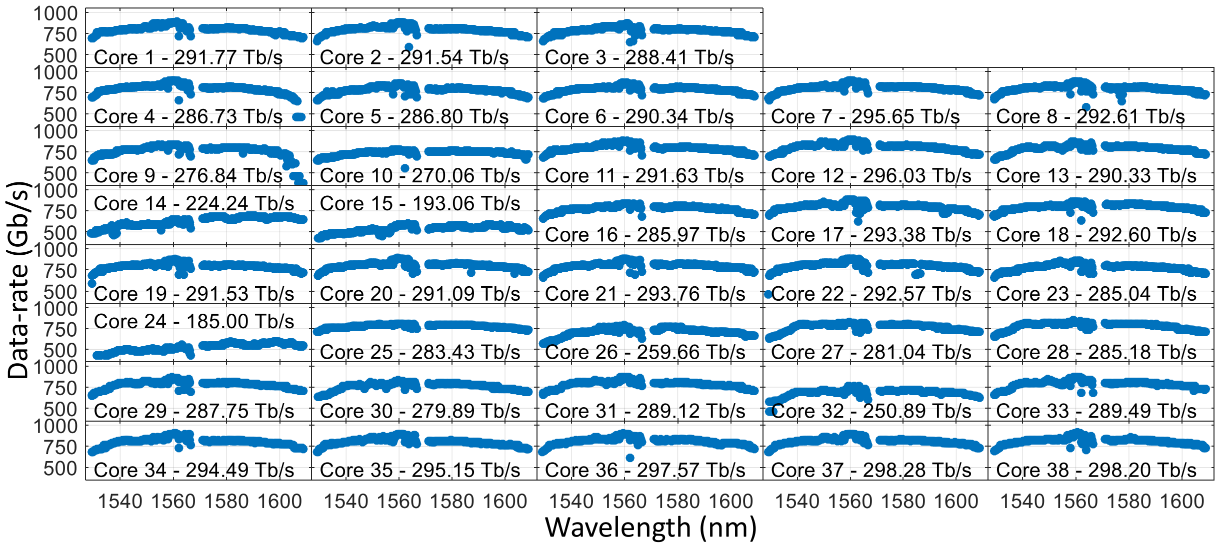

Fig. 3: Data-rates after implemented LDPC + HD-FEC coding scheme for all wavelength channels of all cores. Data-rates in each plot after the implemented de-coding scheme.

3. Results

368 WDM channels were measured for each fiber core. Fig. 2(a) shows the QAM order that was used for all WDM channels within each core. Fig. 2(b) shows the impulse response duration $(\Delta\tau_{(95\%)})$ calculated as in [8] for two WDM channels in all 38 cores. They range between 1 and 5.8 ns length and are overall slightly longer for the L band channel compared to the C band channel, as cores were designed for minimal DMD in the C-band. Fig. 2(c) shows the mode-dependent loss (MDL) for two wavelength channels for all 38 cores, calculated as described in [8]. Most cores exhibited MDL between 5 and 8.5 dB, while six cores showed increased MDL of up to 20 dB that we attribute to prototype components such as core- and mode-multiplexers. Four of the six cores with largest MDL were also those where 64-QAM reached a larger throughput than 256-QAM. Fig. 3 shows the data-rates, calculated with the implemented coding-scheme for all 368 wavelength channels of the 38 fiber cores. 32 of the 38 cores reached data-rates between 279 Tb/s and 298 Tb/s, while the core with lowest data-rate achieved 185 Tb/s. Comparing Fig. 2(c) and Fig. 3 indicates a strong impact of increased MDL on the transmission performance. The average data-rate per spatial channel was 93.5 Tb/s and the spectral efficiency was 1158.7 b/s/Hz, disregarding the guard-band between C- and L bands. When evaluating the data-rate by GMI, the total throughput reaches 11.81 Pb/s with an average data-rate per spatial channel of 103.6 Tb/s and average spectral efficiency of 1283.9 b/s/Hz.

4. Conclusion

We have demonstrated the transmission of 368 wavelength division multiplexed 24.5 GBaud 64- and 256 QAM signals over 13 km 38-core 3-mode fiber. The transmitted spectral efficiency of 1158.7 b/s/Hz as well as the total data-rate of 10.66 Pb/s constitute the highest spectral efficiency and data-rates transmitted over a single optical fiber to date. The results were facilitated by a large-core count few-mode multi-core fiber with low differential mode delay, high uniformity amongst cores and low inter-core crosstalk, in combination with a wide-band high spectral efficiency transceiver setup. Mode-dependent loss was identified as the main limitation of performance. The results highlight the large potential of high-core count few-mode multi-core fibers for large capacity short haul transmission systems.

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