Multi-Span Transmission over 65 km 38-Core 3-Mode Fiber

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Abstract *We demonstrate multi-span transmission over 65 (5×13) km few-mode multi-core fiber by transmitting 368×24.5 GBaud C- and L-band signals with QPSK, 16- or 64 QAM modulation. We analyze each core-combination's transmission channel characteristics and identify mode-dependent loss as the main performance limitation.*

Introduction

Space-division multiplexing (SDM) has shown a strong potential to increase the data-rates in optical fibers[1]. In SDM transmission, fibers with multiple spatial channels, such as coupled or uncoupled cores or modes within a common cladding are used to carry independent data-streams. To date, transmission of more than 10 Pb/s throughput has been demonstrated in two single-span experiments with few-mode multi-core fibers (FM-MCF) of 11.3 km[2] and 13 km[3] length. Multi-span transmission has been demonstrated in recirculating loops over single-core FMF[4] and FM-MCF in a 12-core 3-mode fiber[5].

In this paper, we investigate the potential of multi-span transmission in a high-core count 38-core-3-mode-MCF by looping 368 wavelength division multiplexed (WDM) signals ranging from 1529 nm to 1610 nm wavelength five times trough different cores of a 13 km fiber for a total of 65 km distance. Eight different core combinations are considered to ensure every core has been used for transmission. Depending on the channel quality of the considered core combination, we transmit 24.5 GBaud quadrature phase-shift keying (QPSK), 16- or 64-level quadrature amplitude modulation (QAM) to achieve the maximum data-rate for the given core combination. We analyze each core combination's transmission channel characteristics and identify mode-dependent loss (MDL) as the main source of signal degradation. Nevertheless, the demonstrated potential data-rate of more than 6.2 Pb/s underpins the promise of high-core count FM-MCFs for ultra-high data rate transmission.

Experimental Setup

The experimental setup for multi-span transmission is shown in Fig. 1. A wideband optical comb source generated more than 100 nm of 25 GHz spaced optical carriers. The output of the comb source was split for a high quality sliding test-band and dummy-channel modulation. For the test-band, a tunable filter selected three carrier lines that were then split into odd and even channels in interleavers (INT) and independently modulated in two dual polarization IQ-modulators (DP-IQ). The modulators for the test-band were driven by four arbitrary waveform generators (AWG), operating at 49 Gsample/s, generating 24.5 GBaud root-raised cosine shaped QPSK, 16- or 64-QAM signals with 0.01 roll-off. Odd and even channels where optically de-correlated by 150 ns, combined and amplified in C- or L-band erbium doped fiber amplifiers (EDFA). The remainder of the comb spectrum was modulated in a single-polarization IQ modulator with a polarization-multiplexing emulation stage, followed by EDFAs and optical processors (OP) to flatten the optical spectrum as well as to carve a notch into the dummy channels to accommodate the test-band. Test- and dummy channels were then combined and amplified.

The signal was split into three paths that were optically de-correlated by 100 ns with respect to each other to emulate independent spatial channels. The three signals were transmitted through 3-D waveguide inscribed mode-multiplexers and subsequently through a free-space core-multiplexers into one core of the 13 km FM-MCF. Details on the fiber and multiplex-

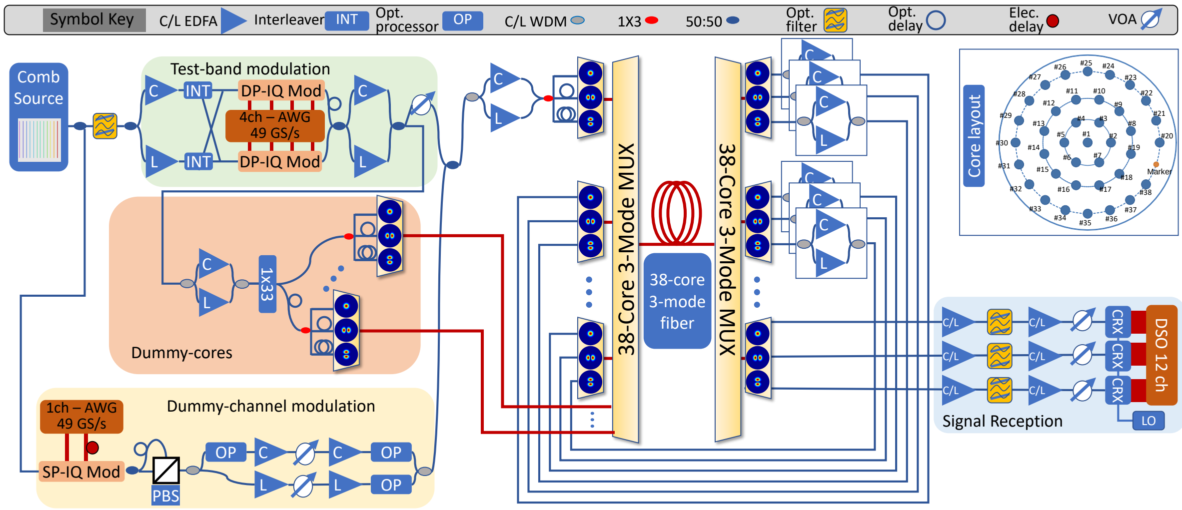

Fig. 1: Experimental setup for C- and L-band multi-span transmission through five-cores of a 38-core 3-mode fiber.

Tab. 1: Used cores and modulation format for each core combination.

Core combination	A	B	C	D	E	F	G	H
Used cores	1	4	9	14	19	24	29	34
	2	5	10	15	20	25	30	35
	3	6	11	16	21	26	31	36
	4	7	12	17	22	27	32	37
	5	8	13	18	23	28	33	38
Modulation format	64-QAM	16-QAM	16-QAM	QPSK	64-QAM	QPSK	16-QAM	64-QAM

ers can be found in[6]. After transmission through the first core, the signals were core- and mode demultiplexed and independently amplified in single-mode C- and L-band EDFAs before being sent to the input of another core. This was repeated five times for a total of 5×13 km transmission distance. After transmission, the signals were demultiplexed, amplified and the wavelength channel under test selected with tunable band-pass filters. The signals were mixed with a common local oscillator (linewidth $<$ 100 kHz) and received in three coherent receivers. The electrical signals were digitized in a 12-channel oscilloscope with 80 Gsample/s sampling rate and electrical bandwidth of 36 GHz. Offline DSP consisted of frequency-offset compensation and a 6×6 time-domain multiple-input / multiple-output (MIMO) equalizer with 671 half-symbol-duration-spaced taps that was initialized in a data-aided mode before switching to decision-directed mode. Phase-recovery was performed in within the equalizer loop. Data-rates after forward-error correction (FEC) were estimated through generalized mutual information (GMI) and an implemented FEC-coding scheme, detailed in[4].

We used 8 different core combinations that are shown in table 1, ensuring that every core was used for transmission. All remaining cores that were not used to transmit the test signal were loaded with de-correlated replicas of the three-channel test-band. This ensured that crosstalk generating signals in all fiber cores were launched at the same power as the test-channel in the test core combination.

Results

Figure 2(a) shows the MDL of two wavelength channels for all eight core combinations. The MDL ranges between 15 and 28 dB, being substantially larger than in previously reported experiments with single-core FMF. Figure 2(b) shows the length of the impulse response, represented by the full-width half maximum (FWHM) of a Gaussian fit with the impulse response, calculated from the inverse MIMO equalizer as described in[7]. While relatively short for lower wavelengths, we observed strong variations of the impulse responses for different core combinations, in accordance with previous characterizations of this fiber[8].

Figure 2(c) shows the data-rate for each three-mode spatial super channel, measured through generalized mutual information (GMI) or by an implemented FEC decoding scheme that is detailed in[4], here with code-rate puncturing for higher code-rate granularity. Total data-rates after 65 km transmission ranged between 74.51 Tb/s

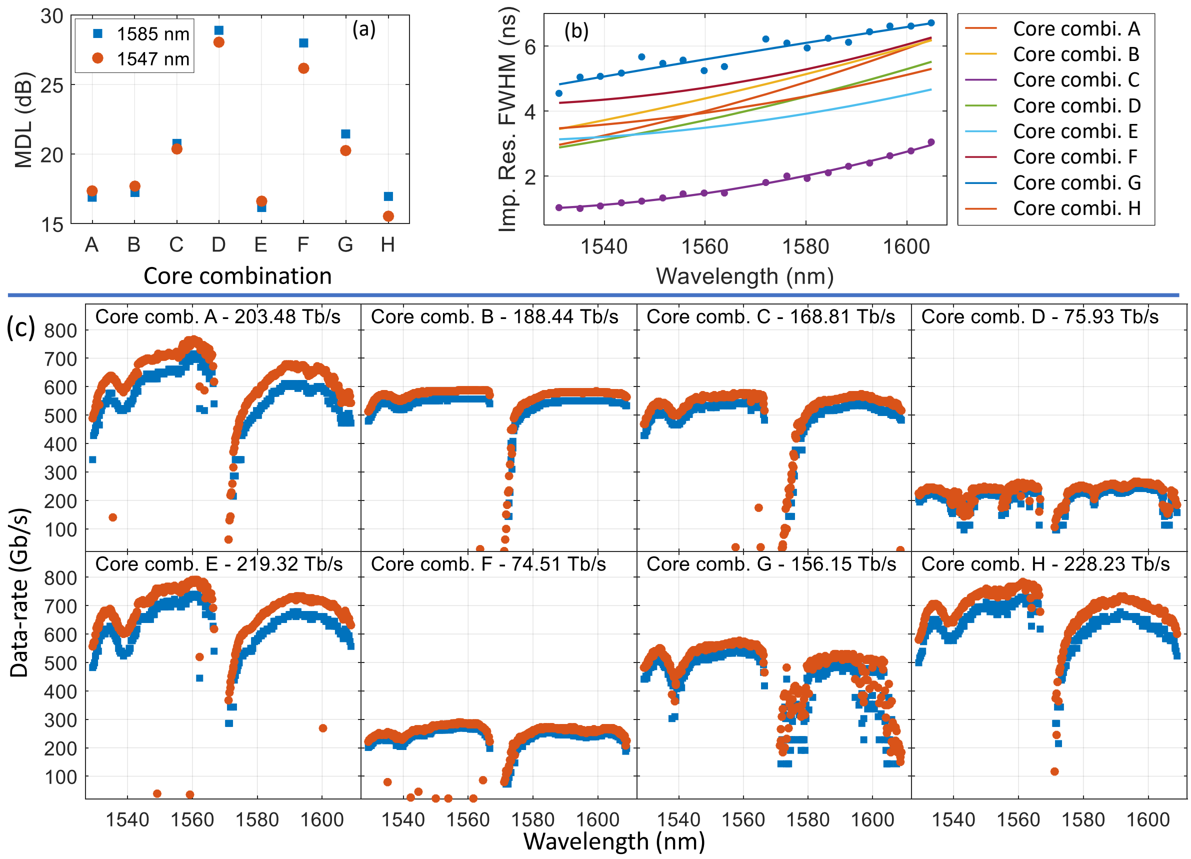

Fig. 2: (a) Mode-dependent loss (MDL) for two wavelengths of all eight core combinations. (b) Wavelength-dependence of the full-width half maximum (FWHM) of the impulse response for all 8 core combinations, as defined in table 1. All measured points shown for the combinations with lowest and largest time spread, second-order polynomial fits are shown for all core combinations for better readability. (c) Data-rate of all 368 WDM-three-mode channels for all eight core combinations, based on generalized mutual information (GMI, red circles) and implemented de-coding scheme (blue squares). Data-rate in top of each plot after the implemented de-coding scheme.

and 228.23 Tb/s when calculated with the FEC decoding scheme and between 83.99 Tb/s and 250.73 Tb/s when estimated by GMI. Lower-order modulation formats were chosen for those core combinations where the MDL was very large, as can be seen by comparing Fig. 2(a) and 2(c). A steep performance drop can is observable for some core combinations at the lower L-band that is attributed to the operation of EDFAs in a sub-optimal gain regime.

When extrapolating the total data-rate from the core-looping scheme as e.g. in[9], the transmission system carries a potential aggregate data-rate of more than 6.2 Pb/s, calculated as the average of the measured data-rates after FEC decoding in Fig. 2(c), being 164.36 Tb/s$\times$38 cores over the total distance of 65 km. This demonstrates the large potential of high core-count FM-MCFs for future transmission systems, despite the very strong impact of MDL that we attribute to prototype components such as core- and mode-multiplexers.

Conclusions

We have demonstrated multi-span transmission of 368$\times$24.5 GBaud QPSK, 16- or 64-QAM signals in C and L-band over 65 km 38-core three-mode fiber. We observed varying impulse-response lengths for different core combinations with a strong wavelength dependence. We further found that the data-rate is mostly limited by mode-dependent loss, presumably introduced by non-optimal prototype components, such as mode- and core multiplexers. Nevertheless, the transmission system can carry a potential data-rate exceeding 6.2 Pb/s over 65 km, highlighting the strong promise of large-core count few-mode MCFs for high-throughput and short-reach applications.

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