Ultra-wide band transmission in few-mode fibers

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Abstract *Space-division multiplexing (SDM) enables the transmission of independent data channels over different fiber modes of multi-mode fibers. In this talk, we review key characteristics of devices and fibers for SDM transmission and summarize recent SDM transmission demonstrations, including 1.01 peta-bit/s transmission in a 15-mode fiber.*

Introduction

Space-division multiplexing (SDM) is a strong candidate to increase the per-fiber capacity for future short-, medium-, and long-haul optical communications systems[1]. Of all fibers proposed for SDM transmission, Few- or multi-mode fibers[2] (FMF, MMF) probably offer the highest spatial channel density. This may be of special importance when considering fibers with a limited cladding diameter, e.g. those that maintain the current standard of 125 µm. Such SDM fibers have recently been a focus of research[3]–[9] as they allow current cabling technologies and increase the yield and reliability compared to SDM fibers with larger cladding diameters[10],[11]. FMF-based SDM transmission has been demonstrated with up to 45 modes[6] over a relatively narrow bandwidth. For a maximum capacity utilization of SDM fibers, it is necessary to transmit data rates per spatial channel that are comparable to those transmitted in single-mode fiber (SMF) transmission. This was demonstrated over a three-mode FMF, where signals were transmitted over more than 75 nm bandwidth, spanning C- and L-bands with a per-mode data rate of 93 Tb/s. This paper describes our recent experiment demonstrating transmission of 64 quadrature amplitude modulated (64-QAM) signals spanning 82 nm bandwidth over a 23 km long 15-mode fiber, with a total data rate exceeding 1 Pb/s[12].

15-Mode Multiplexer

Mode-multiplexers (MUX) were used to excite individual fiber modes of a FMF. Here, mode-selective MUX used multi-plane light conversion (MPLC), where the 15 spots of a linear input SMF array were converted through 15 reflections on phase-masks into modes that could be guided by the FMF[14]. A photograph of one of the MUX is shown in figure 1(a), where the MPLC device is implemented through reflections between a dielectric mirror and the actual phase-masks. Figure 1(b) shows the insertion loss (IL) spectrum of one of the used MUX, measured with 3 nm wide amplified spontaneous emission noise (ASE), centered at various wavelengths between

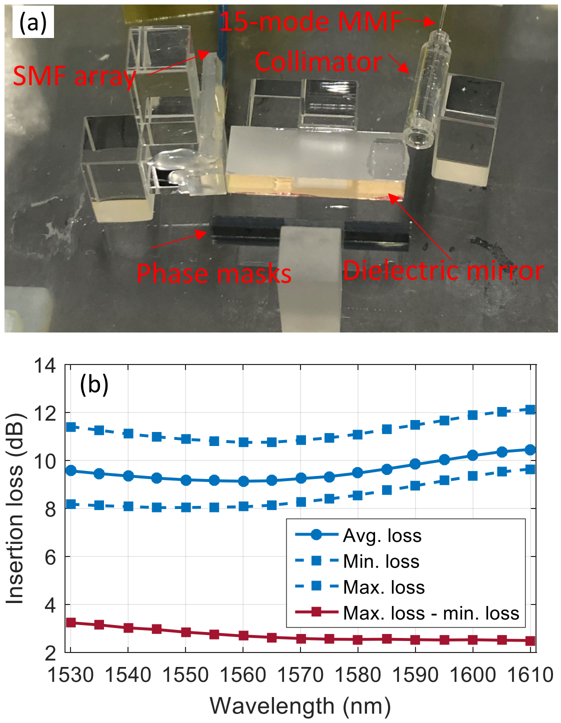

Fig. 1: (a) Photograph of the mode-multiplexer assembly. (b) Attenuation spectrum of one of the mode-multiplexers[13].

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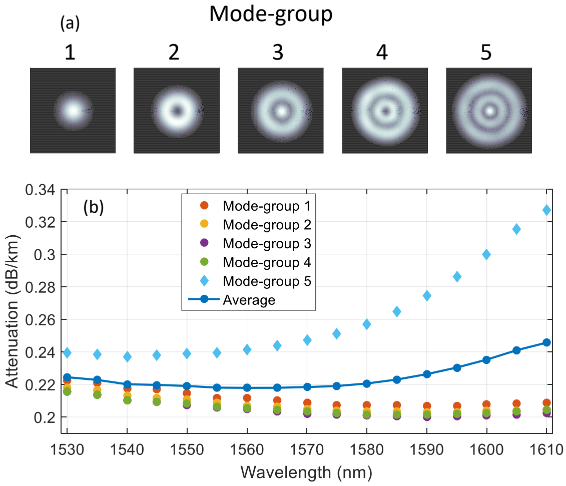

Fig. 2: (a) Infrared camera image of the output field intensity when exciting one mode in each mode-group with wideband ASE. (b) Mode-group averaged attenuation spectrum of the 23 km FMF link[13].

1530 nm and 1610 nm wavelength. The mode-averaged IL is around 10 dB, while the loss difference between the highest and lowest modes' IL is between 2.7 dB and 3.7 dB. This metric should not be confused with mode-dependent loss (MDL), as discussed later in this paper.

15-Mode Fiber

The 23 km long 15-mode FMF[15] used for transmission had a trench-assisted, graded-index profile with a core-radius of 14.1 µm. The fiber had cladding- and coating diameters of 125 µm and 243 µm, respectively, in agreement with the current standard. Benefiting from tight production tolerances, the fiber was manufactured using standard MMF processes. The main differences compared to those was the adoption of the profile-index exponent to minimize the differential mode group delay (DMGD) within the transmission window around 1550 nm wavelength and the core-radius to lower the number of guided modes compared to standard MMF (25 µm vs. 14.1 µm). This was achieved by increasing the diameter of the pre-form to 25/14.1 = 1.77 times of a standard MMF. The 15 fiber modes were grouped in 5 mode-groups. Figure 2(a) shows camera images of the output fields after 15 km FMF, when exciting only one mode within each mode-group with broadband ASE (40 nm). This leads to strong mode coupling within each mode-group, hence the output patterns are independent of the excited mode within one mode-group. Clear radial discrimination between the modes is observed, suggesting high mode-selectivity of the MUX and stable propagation of the mode-groups along the fiber. Figure 2 shows the FMF's spectral attenuation profile, measured again with 3 nm wide ASE and averaged across modes within each mode-group. The total output power out of the 23 km FMF span was measured with a free-space power meter. While the first 4 mode-groups had similar attenuation profile with an attenuation minimum of below 0.21 dB/km at 1590 nm, the fifth mode-group had an increased attenuation between 0.24 dB/km at 1530 nm up to 0.33 dB/km at 1610 nm because of an increased micro-bending sensitivity.

Transmission Experiment

A schematic of the transmission experiment is shown in Fig. 3. 15-SDM $\times$ 382-WDM 24.5 GBaud DP-64-QAM signals with a root-raised cosine pulse-shape with a roll-off factor of 0.01 were modulated on 25 GHz spaced carrier lines that were generated by an optical comb source. The signals spanned a bandwidth of 82 nm between 1528 nm and 1610 nm wavelength. The signals were mode-multiplexed, transmitted over the 23 km FMF and then mode-multiplexed. Finally, the 15 output signals of each wavelength channel were received in coherent receivers (CRXs), where the signals were mixed with the light of a 60 kHz linewidth local oscillator laser. The electrical signals were digitized in a real-time oscilloscope with 36 GHz electrical bandwidth and operating at 80 GSample/s. To reduce the required number of CRXs and oscilloscope channels, a time-division multiplexing scheme was applied that enabled reception of all signals in five coherent receivers. As the signals mixed during transmission, coherent multiple-input multiple output (MIMO) digital signal processing (DSP) was performed in an offline process. It consisted mainly of a 30 $\times$ 30 time-domain equalizer with 271 half-symbol spaced taps that were initiated in a data-aided mode before switching into a decision-directed mode for signal performance estimation. Both modes used the least-mean square (LMS) algorithm to update the equalizer taps.

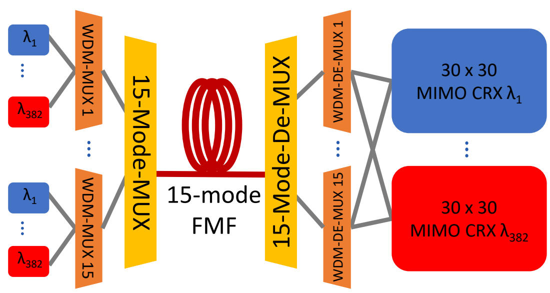

Fig. 3: Schematic of the transmission experiment. Details of the laboratory implementation can be found in[13]

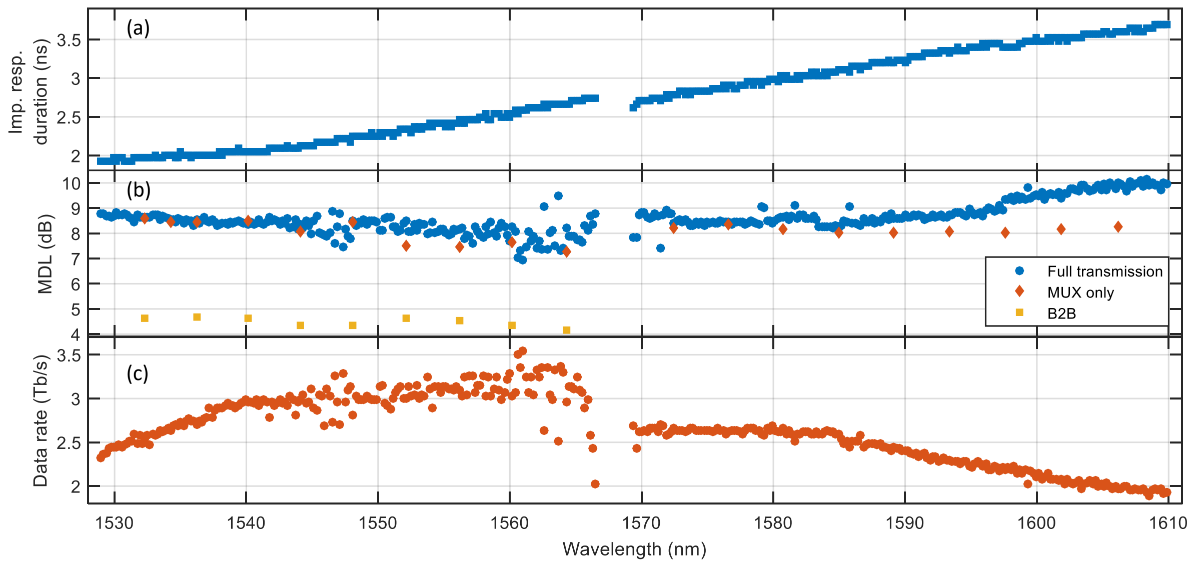

Fig. 4: (a) Impulse response length, (b) mode-dependent loss (MDL) and (c) decoded data rate of all 382 WDM/SDM channels.

Results and Discussion

First, we analyzed the propagation channel properties. One of them is the temporal spread that signals experience during transmission as a result of modal coupling and the fiber's DMGD. This can be analyzed from the channel's impulse response spread that can be calculated from the channel matrix. We extract the channel matrix by running the MIMO equalizer in the reverse direction, so that the input to the MIMO equalizer is the undisturbed signal from the transmitter and the training signal is the received output of the experiment. We then define the impulse response length as the time interval that covers 95% of the energy in the sum-intensity impulse response. It is shown in Fig. 4(a) for all 382 SDM-WDM channels. The impulse response is shortest at the lowest C-band channels at about 2 ns, equivalent to approximately 100 taps. The impulse response length increases with wavelength, reaching a value of 3.7 ns at 1610 nm wavelength, equivalent to 180 taps at 24.5 GBaud. The wavelength dependence of the impulse response length is a dispersion property of FMF that have a minimized DMGD only for one certain wavelength.

A channel property that fundamentally limits the channel capacity is the mode-dependent loss (MDL), originating in unequal loss of different spatial channels. MDL can be estimated from the singular values of the channel matrix[16]. Figure 4(b) shows the MDL for all SDM-WDM channels. To identify the origins of MDL, we estimated it for selected channels in a back-to-back setup, where only the transceiver MDL was extracted, at a value of approximately 4.5 dB. When adding MUX and de-MUX, MDL increased to 8-9 dB. Further adding the 23 km FMF did not change the MDL for low wavelength channels, while it increased MDL above 1585 nm wavelength, with additional MDL of 2 dB at 1610 nm. This can be explained by the increased attenuation of the highest mode-group at high wavelength channels.

Finally, Fig. 4(c) shows the data rates after an implemented forward-error-correction coding (FEC) scheme that was based on the DVB-S2 codes in combination with code rate puncturing and an outer hard-decision FEC code for any remaining bit errors. The data rate per SDM-WDM channel ranged between 1.9 Tb/s and 3.5 Tb/s. Spectral data rate variations are believed to originate in power- and subsequent SNR-variations of transmitter comb-lines, and increased phase-noise of comb-lines with increased spectral separation to the comb seed at 1558 nm. Additionally, increased MDL towards the high L-band lowered the signal quality for those channels. Nevertheless, the sum of all SDM-WDM channels yielded a total data rate of 1.01 Pb/s, the highest data rate reported in a FMF to date.

Conclusions

We have demonstrated transmission of 382 WDM-SDM channels over 23 km 15-mode fiber using multi-plane light conversion based mode multiplexers and coherent 30 $\times$ 30 multi-input / multiple-output digital signal processing. The total data rate of 1.01 Pb/s is the highest in a standard cladding diameter fiber and highlights the strong potential of few-mode fibers for future high capacity transmission systems.

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