Mode-Multiplexed Transmission Within and Across Mode Groups of a Multimode-Fiber

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Abstract: We show mode-multiplexed transmission over individual mode groups up to 9 groups of a 27 km long graded-index multimode fiber. We also investigate transmission distances up to 500 km using a recirculating loop arrangement for the first 6 mode groups using QPSK and 16-QAM signals.

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1. Introduction

Graded-index multi-mode fibers (GI-MMF) are commercially available and in widespread use for short reach optical interconnection due to their relaxed connector tolerances and the efficient and low-cost coupling to low-cost laser sources. Recently the use of GI-MMF fibers gained popularity in the field of mode-multiplexed transmission [1] due to their favorable modal dispersion properties [2]. In previous work we demonstrated 16-QAM transmission over a GI-MMF link of 27 km length using 45 spatial modes across 20 WDM channels resulting in a record spectral efficiency of 202 bit/s/Hz [1]. However, the impact of crosstalk between mode groups and the performance of the time multiplexing scheme, were not investigated in detail. In this work, we report intra-mode-group mode-multiplexed (IMGM) transmission results in each of the first 9 mode groups of an optimized 50 μm diameter 27 km long GI-MMF [2]. We observe a considerable crosstalk penalty for the higher order mode groups due to crosstalk predominately into the adjacent mode groups. We also investigated the IMGM transmission performance at longer distances using a recirculating loop for the first 6 mode groups demonstrating the impact of the crosstalk between mode group for cascaded GI-MMF spans, extending the investigation presented in [3].

2. Multi-Mode Fiber and Mode-Multiplexer

The used graded-index MMF has a dimension of 50/125 μm core/cladding diameter and maximum index difference between core center and cladding of 15×10^{-3} at 1550 nm. This fiber theoretically supports 10 mode groups at 1550 nm, with a strong intra-group and minimized inter-group coupling, due to the effective index differences for modes within the same group ($\leqslant 0.02 \times 10^{-3}$) and between ($> 1.4 \times 10^{-3}$), respectively. The attenuation and effective area of the 1st mode group were measured to be 0.22 dB/km and 170 μm^2 at 1550 nm. In order to reduce the bending sensitivity of the modes a trench was added to the design, however, even for a high bending radius (> 10 cm) the bend losses of the 10th group are substantial, making only 9 mode groups usable (45 modes). To reduce differential group delay (DGD) the trench position and alpha parameter of the fiber were optimized. To mitigate the remaining accumulated DGD the whole fiber span was comprised of four spools with lengths of 8.878, 4.35, 8.878 and 4.445 km and DGD values of -0.057, 0.0140, 0.172 and 0.171 ps/m, respectively, resulting in a total accumulated DGD of 2.4 ns. For spatial mode multiplexing a pair of mode multiplexers (MMUx) was used based on multi-plane light conversion (see Ref. [4] for a detailed discussion of the MUX used and Ref. [5] for a comparable device). These MUXs consist of a finite number of phase masks separated by free space, through which the traversing beams can be transformed into the desired modal base. Using off-axis interferometry, modal content, crosstalk, insertion loss (IL), and mode-dependent loss (MDL) of the MMUXs and fiber spools were determined [6]. Each MUX was measured to have an IL of 4 dB and peak-to-peak MDL of 3 dB. The total IL and MDL for the span and MMUXs was 14 dB and 8 dB respectively when considering all nine mode groups.

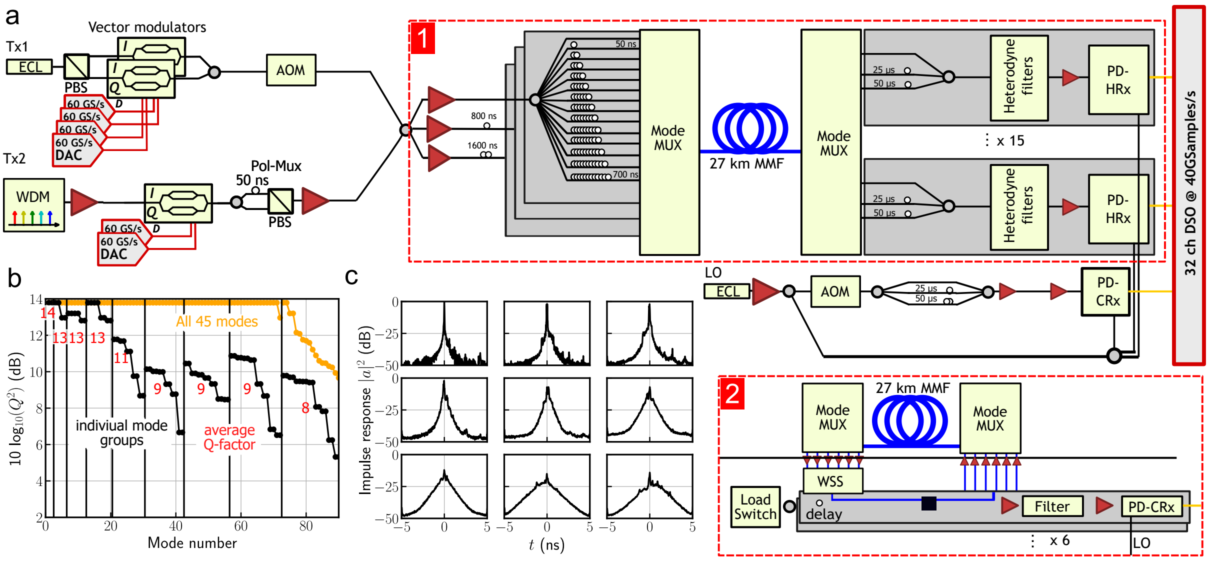

Fig. 1. Setup and results for individual and cumulative group transmission experiment. (a) Experimental setup for MIMO based QPSK transmission for up to 45 spatial modes. For loop experiments the components marked in red-dashed square 1 are exchanged with the ones from 2. (b) Q-factors for 90 tributaries for QPSK transmission over 27 km multimode fiber for 45 mode transmission (orange, top) and individual group transmission from group 1 to 9 (black, bottom) with average Q-factors (red). Data is arranged in mode groups and therein sorted by performance. (c) Average impulse response calculated from a channel estimation for individual mode-group transmission from group 1 to 9, supplementing (b).

3. Transmission

A schematic of the transmission setup is shown in Fig. 1 (a). The transmission side consists of two parts: the frequency channel under test (Tx1) and a frequency comb of adjacent channels (Tx2). In Tx1, an external cavity laser (ECL) is modulated by a polarization multiplexed double-nested Mach Zehnder modulator (DN-MZM) driven by four digital-analog converters (DACs) operated at 60 GS/s to produce a dual carrier 15-Gbaud pulse-shaped QPSK or 16-QAM signals. The frequency comb consists of 10 WDM channels which are spaced by 50 GHz and are modulated with a dual-carrier 15-Gbaud signal resulting in 20 logical QPSK or 16-QAM wavelength channels. For polarization-multiplexing the signals from the single-polarizaiton DN-MZM are decorrelated with 50 ns long delay arm and recombined with a PBS. Consequentially, both transmitters (Tx1 and Tx2) were combined, split three ways and separately amplified by high power erbium-doped amplifiers (EDFAs) with 30 dBm maximum output powers. In order to have up to 45 decorrelated spatial channels, each arm was split 15 times and delays were introduced to obtain 45 spatial channels with a relative delay of 50 ns between them. A selected subset of these signals were then coupled to the mode multiplexer (MUX) to excite individual mode groups of the 50 μm GI-MMF or a set of mode groups, respectively. In particular, all first 9 mode groups were individually excited and consequentially groups were added in sequence to the first group up to the 9th group resulting in a 45-spatial mode transmission. After a span of 27 km long MMF fiber a second mode MUX was used to demultiplex the spatial channels. As only 30 oscilloscope channels were available for detection, we employed temporal multiplexing [7] by introducing an AOM into the Tx1 arm operated at a 33.3% duty-cycle and distributing all demultiplexed modes over 15 sets of 0, 5 and 10 km fiber spools, adjusted to within < 1 m. Note that individual group transmission for all nine mode groups and combined group transmission up to group 5 could have been carried out without temporal multiplexing, but was nonetheless applied to guarantee consistency when more than 15 modes were transmitted. Each combiner output was connected to a two-stage EDFA which enveloped a programmable filter to provide the optical filtering necessary for heterodyne detection. The resulting 15 single-mode fibers were individually detected by 15 polarization-diverse heterodyne receivers (PD-HRx) and electronically fed into the 30 channels of a 40 GSamples/s digital storage oscilloscope (DSO). Consequently the data was down-sampled to 30 GSamples/s (2 samples per symbol). To compensate for phase fluctuations of the local oscillator (LO), we time-multiplexed a LO copy similarly to the signal and detect the three copies delayed by 0, 25 and 50 μs respectively with a single-polarization coherent receiver (PD-CRx). The arrangement is illustrated Fig. 1 (a) between the red-squares.

All complex amplitude signals were processed with a frequency domain N x N MIMO (with N ranging from 2 to 90) with 600 half-symbol-spaced taps. The initial convergence is obtained through the data aided least-means-squared (LMS) algorithm with a stepsize of $\mu_{LMS} = 2 \times 10^{-7}$. Bit-error-rate (BER) counting is performed and

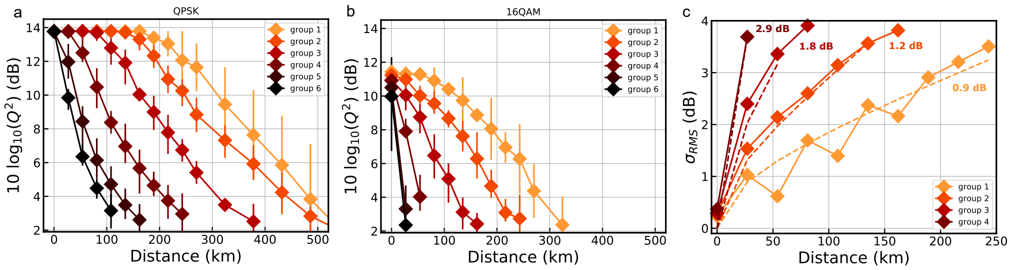

Fig. 2. Q^2-factors for up to 500 km transmission in first 6 groups of 50 µm MMF for (a) QPSK and (b) 16-QAM modulation. (c) MDL_{RMS} for the first 4 groups with value of the per segment MDL_{RMS} next to each dataset (continuous line) and fit (dashed line) [8]

translated into Q^2 factors. The obtained Q^2 factors at a wavelength of 1549.7 nm are reported in Fig. 1 (b) for groups transmitted individually (black) and all 9 groups together (orange). The individual groups are impacted strongly by crosstalk, which can be mostly mitigated when all 9 groups are jointly processed. Whether a larger bending diameter and/or less constraints applied to the fiber can improve the results for individual groups has to be further investigated. Furthermore, we performed a channel estimation for both individual, Fig. 1 (c), and summed group transmission. When transmitting all 45 modes the overall length of the impulse response is 2.5 ns, matching the total DGD of the fiber. To verify the impact of time-multiplexing scheme on transmission, we compared the transmission of the first 15 modes measured directly using the 15 PD-HRx and by using the time multiplexing scheme. With direct detection we observe Q^2-factors around 2 dB larger than when time multiplexing is used, which can be attributed to the lower loss for direct detection which results in a larger SNR at the receiver. In both cases, we observe a rollover within the groups where some modes have a lower Q than others. Finally, we investigated multi-span transmission over single mode groups by using a recirculating loop experiment for the first 6 groups, similar to Ref. [3]. The setup was therefore modified to incorporate both MUXs with the MMF into an optical amplified loop as indicated in the inset 2 of Fig. 1 (a). In contrast to before, the ECL was modulated with 30-Gbaud signal and the WDM comb was comprised of 15 channels spaced at 33 GHz. We transmitted both QPSK and 16-QAM modulation and recorded the transmitted signals up to 20 loops, the respective Q^2-factors are shown in Fig. 2 (a) and (b) in dependence of distance. Compared to previously reported result for group 6 performed over a 10 km long span [3], we observe a performance degradation at comparable distances, that can be explained by the longer span length of 27 km, where a larger amount of crosstalk is accumulated before a filtering through the mode MUX occurs. Furthermore, we determined the RMS MDL values for the first 4 groups, Fig. 1 (c), according to Ref. [8]. The oscillation of MDL values in group 1 are produced by an unfavorable polarization rotation within the recirculating loop, whereas an increased MDL value is observed for higher order mode groups.

4. Conclusion

We experimentally investigated intra-mode-group mode multiplexed transmission in the first 9 groups of a 27 km long graded-index multimode fiber. We observe a degradation in transmission performance and increased mode dependent loss for the higher order modes groups, as a consequence of the crosstalk from neighbouring mode groups.

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