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Low-Loss Mode Coupler for Mode-Multiplexed transmission in Few-Mode Fiber

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Abstract: We present a novel low-loss 3-spot mode coupler to selectively address 6 spatial and polarization modes of a few-mode fiber. The coupler is used in a 6×6 MIMO-transmission experiment over a 154-km hybrid span consisting of 129-km depressed-cladding and 25-km graded-index few-mode fiber.

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1. Introduction

Recent demonstrations of mode-multiplexed long-distance transmission and modal gain equalized optical amplification in few-mode fibers (FMF) [1, 2] clearly show the potential of mode multiplexing to increase the capacity of a single optical fiber. Launching the modes at the transmitter and demultiplexing at the receiver is currently done using phase plate based mode-multiplexers [3] that are lossy (typically around 9-10 dB for 6 spatial and polarization modes) and scale unfavorably with the number of supported modes. In this work we present results for a novel and simple mode coupler based on collimators that illuminate the facet of a few-mode fiber (FMF) in multiple spatially separated locations. Theoretical calculations show that an insertion loss of 2 dB can be achieved for a FMF with 6 spatial and polarization modes, and we experimentally demonstrate a loss <4 dB . The new couplers do not directly excite particular modes of the fiber, but excite a set of 6 orthonormal mode mixtures in a way that distributes each channel homogeneously among the fiber's LP modes. As the 6 launched signals are spatially orthogonal upon launch (but in a non-LP mode basis), multiple-input-multiple-output (MIMO) signal processing can recover the transmitted channels. In order to demonstrate the coupler, we successfully transmit over a record 154-km long hybrid few-mode-fiber span consisting of 129-km depressed-cladding FMF (DC-FMF) followed by a differential-group-delay-compensating 25-km-long graded-index FMF (GI-FMF). A single wavelength channel is carrying 6 space- and polarization-division multiplexed 40-Gbit/s quadrature phase shift keying (QPSK) signals, for an aggregate line-rate of 240 Gbit/s.

2. Multi-spot based mode coupler

Illuminating the end facet of a FMF with a focused spot generally excites multiple modes. The exact amount and phase of the excited modes can be determined by evaluating the overlap integral between the spots and the modes of the FMF. The problem is greatly simplified in FMF where only a small set of modes is present. In particular, for a FMF supporting 3 spatial-modes (LP_{01}, and the twofold degenerate LP_{11} mode) the mode structure can be shown to be equivalent to a multi-core fiber with 3 equidistant cores [4]. The required relative phase and intensity relations between the 3 illumination spots and the desired LP_{01} and LP_{11} modes are graphically represented in Fig.1 a), where the first column shows the LP_{01} mode, the second and third column are the degenerated LP_{11} modes and the forth and fifth column show an equivalent basis mode set for the representation of the degenerated LP_{11} mode. In order for the MIMO digital signal processing to reconstruct the correct signals without capacity loss, the linear transformation describing the coupling between the spots and the true FMF waveguide modes has to be unitary. It can be shown, by evaluating the corresponding overlap integrals, that for a symmetric and centered arrangement of the spots the transformation is unitary if the amount of power coupled from a single spot into LP_{01} and the alternative representation $LP_{11a}+iLP_{11b}$ is exactly the same. The coupling ratio between the spot and the two modes can be controlled by radially moving the spot. Near the center, the spot will predominately excite the LP_{01} mode, whereas the LP_{11} mode will be coupled preferentially when moving the spot away from the center. The optimal distance from the center and the resulting coupler insertion loss are reported in Fig.1 b) for a step-index FMF with a core diameter of 17μm and a normalized frequency of $V=3.92$, where the spot diameter is normalized to the mode-field diameter of a standard single mode fiber. The simulation shows that a theoretical minimum loss of 2 dB can be achieved for this kind of coupler. Note that in this simulation we assume that there is no spatial overlap between the intensity profiles of the 3 spots and each spot is restricted to a corresponding 120° angular sector. Practically this can be achieved, e.g., by combining collimated beams using a pyramid with a triangular basis. In our experiment, however, the spots were separated using turning mirrors with sharp edges. The resulting intensity profiles of the spots, and the corresponding mirror configuration are shown in Fig.1 c), whereas the complete experimental arrangement of the spot-based mode multiplexer (SMUX) is reported in Fig.1 d). The spots are generated using 3 collimators that are reflected by turning mirrors M1, M2, and M3, which allow to place the spots closely together. The 3-spot pattern is then projected on the end facet of the FMF using an imaging system formed by two lenses with focal length of $f_1 = 100$ mm and two different lenses of focal length of $f_2 = 3$ mm and $f_2 = 4.6$ mm were used to couple into the GI-FMF and DC-FMF respectively. The mode field diameters are related to the square root of the effective areas of the FMFs and are 155 and 159 μm^2 for the LP_{01} and LP_{11} modes of the DC-FMF respectively, and 64 and 67 μm^2 for the LP_{01} and LP_{11} modes of the GI-FMF. The loss and dispersion values for both FMF types were around 0.2 dB/km and 18 ps/nm/km, respectively. Experimentally, we

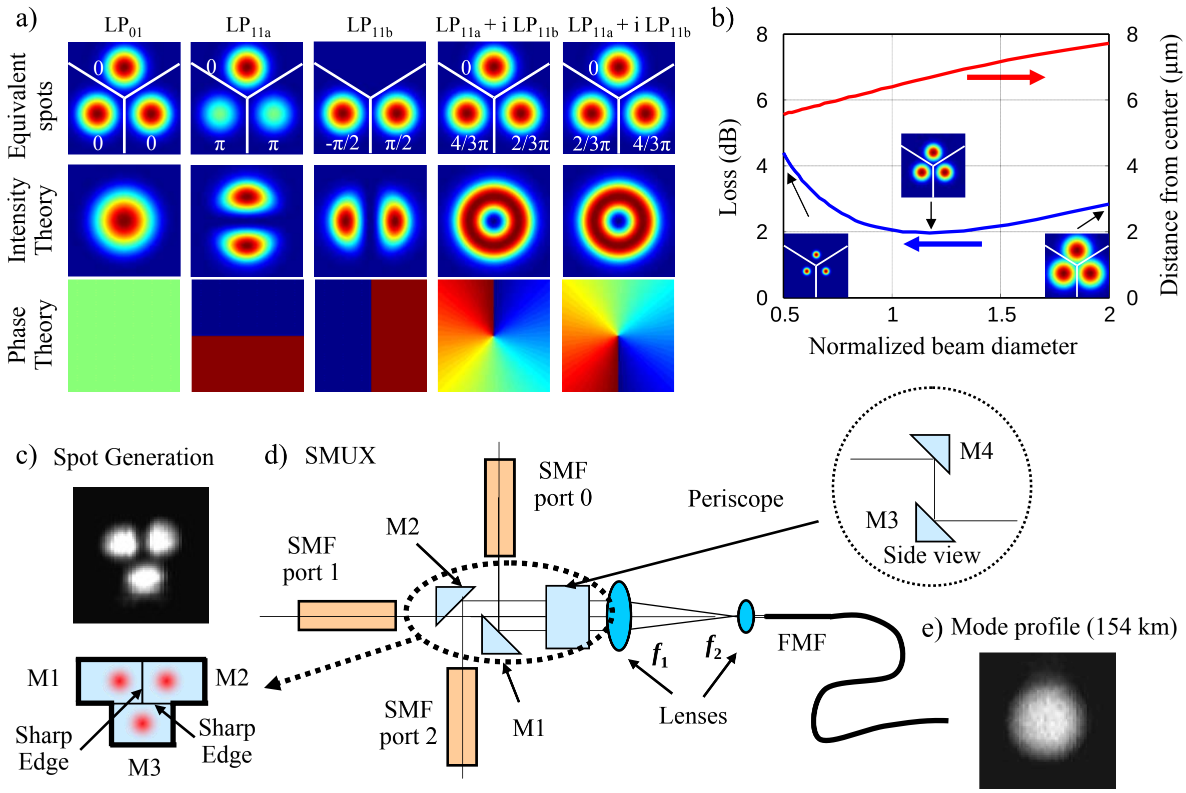

Fig. 1. a) Relation between the phase and intensity of the illuminated spots (first row) and launched LP mode intensity and phase profiles (second and third row, respectively). b) Insertion loss and optimum distance from the center for all spots as function of the normalized spot diameter. c) Experimental generation of 3 spots using mirrors with sharp edges. d) Experimental arrangement of the SMUX. e) Light intensity profile at end facet of the 154-km hybrid FMF during transmission.

achieved minimum insertion losses of 3.95, 3.85, and 3.7 dB for the 3 ports of the SMUX, and the power in each mode was verified using a “traditional” phase mask based demultiplexer, confirming that all modes were excited equally. The < 2 dB higher-than-theoretically-expected insertion loss is consistent with independently reported coupling losses for the used collimators. Better performance is expected by the use of improved optical components.

3. Hybrid few-mode fiber span and transmission experiment

The performance of the SMUX was verified in a single-span mode-multiplexed transmission experiment. The span consists of two spools of DC-FMF with 33 km and 96 km, respectively, followed by a 25-km spool of GI-FMF, which were accurately spliced using a commercial fusion splicer. The experimental arrangement is shown in Fig.2 a). An external cavity laser (ECL) was modulated with a double-nested $LiNbO_3$ modulator, set to generate a 20-GBaud QPSK signal. Two independent De Bruijn bit sequences (DBBS) of length 2^{12} were used for the in-phase (I) and quadrature (Q) components. The signal was polarization multiplexed using a polarizing beam splitter (PBS) and introducing a delay of 25 ns between the polarizations and subsequently mode multiplexed by a SMUX where two additional delays of 49 and 97 ns were introduced between two arms of the SMUX input section. After transmission the modes were separated by a second SMUX and fed into three polarization-diversity coherent receivers (PD-CRX). The resulting

12 electrical signals were captured by the LeCroy LabMaster 9zi modular digital storage oscilloscope operating at 40 GS/s with a bandwidth of 20 GHz. A separate ECL was used as local oscillator (LO) to perform intradyne detection.

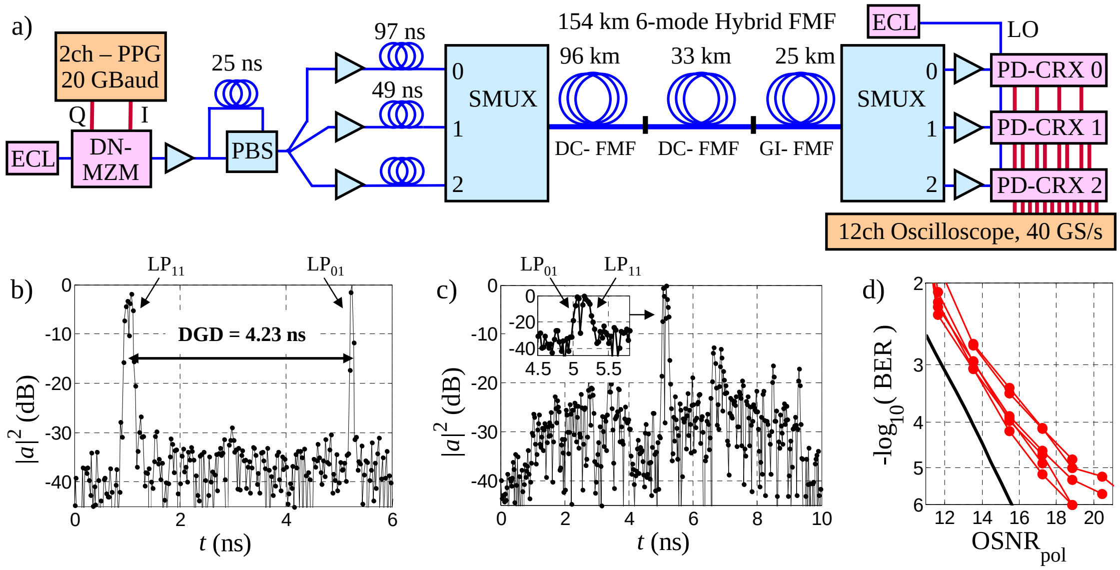

Fig. 2. a) Experimental setup for 6 space- and polarization-multiplexed coherent MIMO transmission. Triangles denote Erbium-doped fiber amplifiers. b) Impulse response of a 25-km GI-FMF. c) Impulse response of the 154-km hybrid FMF. d) BER as function of $OSNR_{pol}$ for 154 km transmission.

The captured waveforms were off-line processed using the MIMO DSP as described in [5]. In order to verify the correct operation of the mode-coupler, the impulse response of a 25 km GI-FMF with 4.23 ns DGD was determined from the transmission measurement based on the least square estimator (LS). The results are summarized in Fig. 2 b) where the amplitude square $|a|^2$ of only one impulse response is shown as the complete 6×6 set of impulse responses look qualitatively similar. Two peaks representing the LP_{01} and LP_{11} modes are clearly visible, confirming that the the mode coupler is correctly launching and detecting both modes with approximately the same amount of power. The impulse response of the 154 km hybrid span is shown in Fig. 2 c). Two peaks corresponding to the LP_{01} and LP_{11} modes are still present, but much closer due the DGD compensating effect of the 25-km GI-FMF with approximately the opposite amount of DGD of the 129 km DC-FMF.

The transmission results were evaluated using a network of 6×6 feed-forward equalizers (FFEs) with 400 taps. The FFE coefficients were obtained using the least-mean-square algorithm (LMS), and the phase was tracked using the fourth-power algorithm. In order to assure rapid initial convergence, the algorithm is operated in data-aided configuration and then switched to decision-directed mode. The bit-error rate (BER) measurements for the 6 space and polarization channels as function of the optical signal-to-noise ratio $OSNR_{\mathrm{pol}}$ (OSNR per polarization) for 154 km transmission are shown in Fig. 2 d). A BER of 10^{-3} is achieved with a small penalty of 3 dB in respect to the theoretical limit (black curve). However, this performance is 3 dB better than the results reported in [1] for a 137 km DC-FMF with phase-plate based couplers, confirming the good performance of the new couplers.

4. Conclusion

We have demonstrated a novel low loss mode coupler for coherent MIMO based mode-multiplexing in few-mode fibers. The mode coupler is simple to realize and for a few-mode fiber, supporting 6 space- and polarization modes, an experimental loss of < 4 dB was observed. The couplers were used to demonstrate a record-length single-span mode-multiplexed transmission distance of 154 km based on a hybrid few-mode fiber, resulting in a single wavelength channel aggregate line-rate of 240 Gbit/s.

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