12 × 12 MIMO Transmission over 130-km Few-Mode Fiber

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Abstract: We demonstrate 12 × 12 multiple-input multiple-output mode multiplexed transmission over 130-km of few-mode fiber of a combined 6-space-, 2-polarization-, and 8-wavelength-division multiplex, using low-loss photonic lantern and 3D-waveguide mode multiplexers.

1. Introduction

Space-division multiplexing (SDM) over few-mode fibers (FMFs) [1,2] has recently emerged as a viable candidate to gradually extend the capacity of single-mode fibers (SMFs). First transmission demonstrations were based on fiber with only the LP_{01} and LP_{11} modes, often by making use of a subset of the modes. In this work we demonstrate for the first time transmission over a fiber supporting 12 space and polarization modes by using LP_{01}, LP_{11} LP_{21}, and LP_{02} modes. Also we demonstrate for the first time transmission over low-loss mode multiplexers based on the "photonic lantern" design, confirming that the principle of the spot based mode couplers [3] can be extended to larger number of modes. In our experiment, 40-Gbit/s QPSK signals are multiplexed over 6 spatial modes, 2 polarizations, and 8 wavelengths, resulting in an aggregate line-rate of 3.8 Tbit/s over a bandwidth of 400 GHz. The signals are transmitted over 130 km using a 65 km span in a recirculating loop and are recovered by off-line multiple-input multiple-output (MIMO) digital signal processing (DSP).

2. Photonic lantern based mode multiplexers

In the past, mode multiplexers (MMUXs) based on phase-plates [1] have been used. They offer good mode selectivity but suffer from a large insertion loss. Alternatively, in [3] we have demonstrated spot couplers that support FMF with 6 spatial and polarization modes (FMF6) and the principle was theoretically extended to more modes. In this work we show the first experimental demonstration of coupling into a FMF with 12 spatial and polarization modes (FMF12). Also, we use waveguides to generate the spots, which allows us to bring the spots closer together in a theoretically lossless way [4]. We used two different couplers in our experiment: The first coupler is based on the photonic lantern (PL) design [5], where multiple single mode fibers are fused together to form a new multimode waveguide. The principle which is shown in Fig. 1 a) is well known in astronomy where PLs are used to couple light captured by a multimode fiber into multiple single mode fibers with minimal insertion loss. The second coupler is based on a laser inscribed 3-D waveguide (3DW) design, where multiple single mode waveguides are brought close together to form super-modes, which approximate the modes of the fiber to be coupled into (see Fig. 1 b). In our experiment both coupler designs performed comparably, and we observed an insertion loss < 6dB for both versions, however the PL is expected to have a lower (almost 0 dB) loss for an optimized design, whereas the 3DW will be limited by the absorption loss produced by the waveguide writing process. In contrast to phase-plate based couplers [1] which launch and detect signals directly from a particular LP pseudo-mode, PL based MMUXs (PL-MMUXs) launch the signal power equally into a linear combination of spatial modes. In coherent MIMO transmission, this distribution of the signal power across multiple spatial modes can be undone by DSP, as long as the transformation of the coupler is unitary. The output intensity pattern of the PL-MMUX and 3D-MMUX obtained by coupling light into one single mode fiber at a time, are shown in the lower part of Fig. 1. The patterns appear very irregular, however interferometric measurements confirm the orthogonality of the patterns. In our experiment the overall mode depend loss (MDL) for the 65-km FMF12 span, including the PL-MMUX on the transmit side and the 3DW-MMUX on the receive side was 4.5 dB, which results in good transmission performance. Also, the MDL only marginally increases to 4.6 and 4.8 dB for subsequent loops.

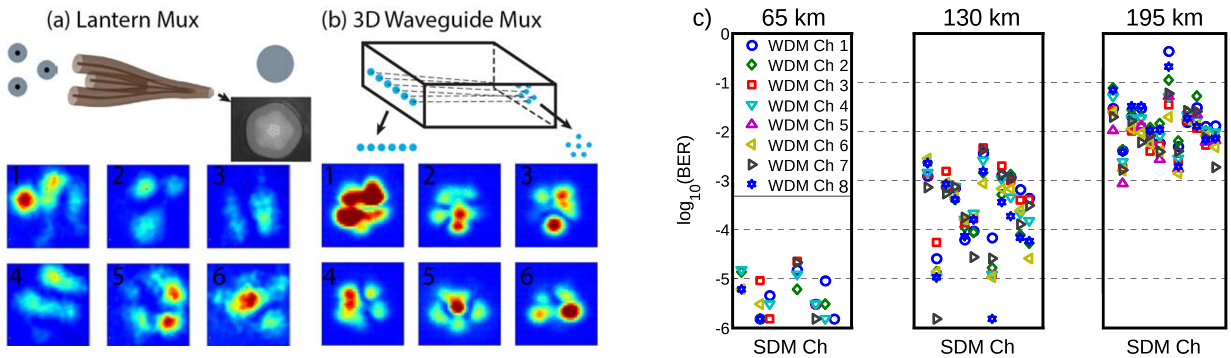

Fig. 1. a) Principle of photonic lantern based mode multiplexer for FMF12, and b) principle of 3-D waveguide based mode multiplexer with respective output intensity patterns. c) BER for 65, 130, and 195 km transmission distance for all SDM and WDM channels.

3. Few-mode fiber and coherent MIMO transmission experiment

The FMF12 span with a total length of 65.3 km was realized by using multiple spools of a graded-index (GI)-FMF that support exactly 12 spatial and polarization modes. The graded index profile keeps the differential group delay (DGD) between modes small and the fiber was designed to minimize the DGDs across the whole C-band. The maximum DGD in the 65-km span was further reduced to 4.49 ns by combining 4 fiber sections with partially compensating DGDs. A complete DGD compensation, as shown in FMF6 fibers[2], is possible but requires a greater diversity of fiber samples, since three DGD values must be matched for FMF12 vs. one for FMF6. The effective area of the FMF12 was 90 μm^2 for LP_{01} and LP_{11}, 120 μm^2 for LP_{21}, and 180 μm^2 for the LP_{02} mode. The loss is around 0.2 dB/km for the LP_{01} mode and the chromatic dispersion was 18 ps/(nm . km) for all modes.

The transmission experiment over the FMF12 span consisted of eight wavelength channels with a 50-GHz spacing generated by modulating odd and even wavelength channels from 8 distributed feedback lasers (DFBs) using two independent double-nested $LiNbO_3$ modulators (DN-MZM). The modulators were driven by a programmable pattern generator (PPG) to generate a 20-GBaud QPSK signal, with two independent De Bruijn bit sequences (DBBS) of length 2^{14} for the in-phase (I) and quadrature (Q) components of the QPSK signal, respectively. We used an external cavity laser (ECL) as the light source for the channel under test, and a second ECL as a local oscillator (LO) for intradyne detection. The modulated wavelength channels are subsequently polarization multiplexed, and a delay of 400 ns (8000 symbols) was introduced between the orthogonal polarizations. The resulting polarization multiplexed signal (PDM-QPSK), is then further split into 6 paths with a relative delay of 49 ns between subsequent paths. The delayed signal copies are fed to the ingress section of a 6-fold recirculating loop connected to the FMF12 by a MMUX based on the photonic lantern design. After transmission through the span, a second MMUX based on the 3-D waveguide design was used to reconnect the signal to the 6-fold loop. Finally the signals are extracted from the loop and further amplified by Erbium-doped fiber amplifiers (EDFAs) followed by 6 polarization-diversity coherent receivers (PD-CRXs). The 24 electrical signals from the PD-CRXs were captured by a prototype modular digital storage oscilloscope (DSO) (LeCroy LabMaster 9 Zi) with 24 channels, expandable up to 80 channels. The DSO was operating at 40 GS/s with a bandwidth of 20 GHz, and the captured waveforms were processed off-line using the MIMO DSP algorithm described in [6] extended to support 12 channels. The algorithm implements a network of 12×12 feed-forward equalizers (FFEs) with a number of taps that varied from 400 to 600 as required by the length of the impulse response for different transmission lengths. The BER curves for an input power of -6 dBm per mode-, wavelength-, and polarization are shown as function of the transmission length for all modes and wavelengths in Fig. 1 c. For 65 km transmission the observed BER is $< 2 \times 10^{-5}$ and after 130 km the BER is $< 4 \times 10^{-3}$, which is well under the limit tolerable for a state-of-the-art hard-decision FEC with 20% overhead.

In conclusion we have demonstrated the first mode-multiplexed transmission over 130 km few-mode fiber with 12 spatial and polarization modes using low-loss photonic lantern and 3-D waveguide based mode multiplexers.

References

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