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4 ×56 Gb/s MIMO-less Fiber-eigenmode multiplexing transmission over 3 km FMF

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Abstract: We experimentally demonstrate a mode-division-multiplexing (MDM) system using 4 vector modes (VMs) over 3 km few mode fiber (FMF). Each mode carries 14 Gbaud 16-ary quadrature amplitude modulation (16 QAM) signal, achieving a 2×2 multiple-input-multiple-output-less (MIMO-less) 224 Gb/s fiber-eigenmode multiplexing transmission link. © 2021 The Author(s)

1. Introduction

With the rapid pace of development in emerging applications, such as internet of things, online business, cloud computing and storage, these applications will undoubtedly fuel the demands for high-speed optical transmission systems [1-2]. In order to overcome the current capacity crunch of single mode fiber communications, mode division multiplexing (MDM) scheme which utilizes spatial modes as parallel channels to upscale the optical system capacity has attracted great attention and shown enormous potential in deal with data explosion [3-4].

In the MDM system, channel crosstalk induced by mode coupling is a huge challenge. Multiple-input-multiple-out-free (MIMO-free) is only suitable for mode channels with large enough mode isolation [5-6]. For strong-coupled mode channels, full-MIMO digital signal processing (DSP) is introduced to demultiplex and equalize all used mode channels [3-4,7]. MIMO-less scheme is a tradeoff between full-MIMO and MIMO-free, in which MIMO block is applied to one mode group (MG) or partial MGs with large MGs crosstalk [8-9]. In addition, different types of spatial modes have been exploited in the MDM systems, such as linearly polarized (LP) modes [3-4], orbital angular momentum (OAM) modes [8,10] and vector modes (VMs) [5-6]. To suppress mode coupling in propagating fiber, lots of specially designed fibers for certain type spatial modes have been proposed and demonstrated [8-9], which promises the possibility to further develop and optimize MDM link.

In this paper, by using 2 VMs of l = 0 (HE11o and HE11e modes) and 2 VMs of l = +2 (EH11o and EH11e modes), each mode carrying 14 Gbaud 16 QAM, we successfully implement a 224 Gb/s MIMO-less vector mode division multiplexing (VMDM) link over 3 km step-index FMF. In this system, 2×2 MIMO block is applied to each mode group and the bit-error rate (BER) properties of all VM channels are below the 7 % hard decision forward error correction (FEC) BER threshold at 3.8×10^{-3}. The experimental results indicate that such scheme should be a good candidate for high-capacity short-reach system.

2. Experiment and results

Fig. 1 illustrates the experimental setup for the VM-based MGDM transmission over 3 km FMF. At the optical transmitter, there is an external cavity laser at 1550.12 nm with less than 100-kHz linewidth. The continuous-wavelength (CW) lightwave from ECL is separated into 2 branches by optical coupler (OC). One branch is employed as the local oscillator (LO) for coherent detection. And another is modulated by the I/Q modulator (FUJITSU FTM7962EP) which is driven by electrical 14 Gbaud 16 QAM signals generated by an arbitrary waveform generator (AWG, Keysight M8196A). Then, polarization division multiplexing (PDM) is emulated by polarization beam splitter (PBS) and polarization beam combiner (PBC). After amplified by an erbium-doped fiber amplifier (EDFA), the signals are split into 2 parts. One part is directly utilized as the VMs of l = 0 (HE11o and HE11e modes) and another is converted to VMs of l = 2 (EH11o and EH11e modes) after passing through the vortex wave plate (VWP). Next, these 4 VM channels are multiplexed by a non-polarization beam splitter (NPBS) and coupled into the 3 km FMF. The used FMF is the step-index FMF with a core diameter of 19 μm and a cladding diameter of 125 μm. The effective refractive index difference between VMs of l = 0 and l = 2 is about 3×10^{-3}. After

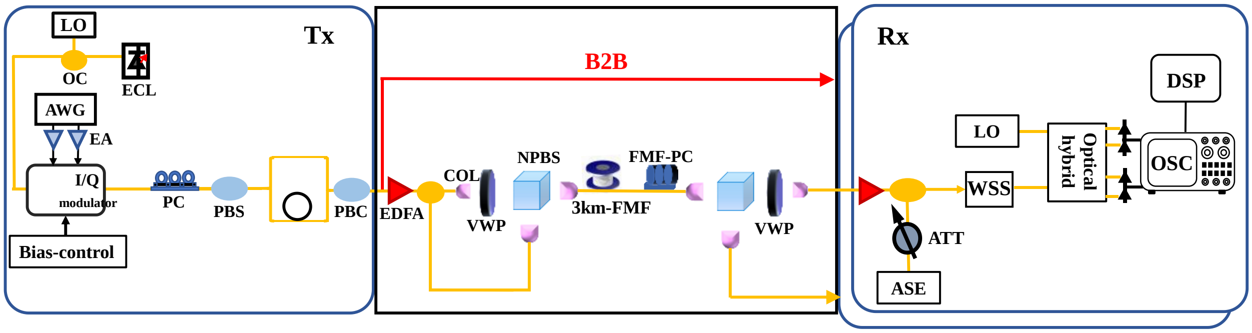

Fig. 1. The experimental setup of the VM-based MGDM transmission over 3 km FMF. AWG: arbitrary waveform generator; EA: electrical amplifier; ECL: external cavity laser; OC: optical coupler; LO: local oscillator; PC: polarization controller; PBS: polarization beam splitter; PBC: polarization beam combiner; EDFA: erbium-doped fiber amplifier; COL: collimator; VWP: vortex wave plate; NPBS: non-polarizing beam splitter; FMF: few-mode fiber; PC-FMF: polarization controller on few-mode fiber; ATT: attenuator; ASE: amplifier spontaneous-emission noise; WSS: wavelength selective switch; OSC: oscilloscope; DSP: digital signal processing, B2B: back-to-back.

FMF transmission, the light beam is split into two branches. One branch is directly fed into the single-mode fiber (SMF) and only VMs of l = 0 can be detected. Another branch passes through the VWP and only VMs of l = 2 are demodulated. At the receiver, after filtered by a wavelength selective switch (WSS), the dual-polarization signals from VMs of l = 0 or l = 2 are coupled by an OC with LO and then are fed into 90^o hybrid and then 4 balanced photo-detectors (PDs) for coherent detection. Finally, the converted 4 electrical signals are sampled by an oscilloscope (OSC, Keysight DSAZ594A) with a sample rate of 80 GSa/s, and further processed by the offline DSP which includes resampling, synchronization, 2×2 constant modulus algorithm (CMA) as pre-convergence and 2×2 radius directed equalizer (RDE) as further demultiplexing and equalization, frequency offset compensation, carrier phase noise compensation and BER decision.

Fig. 2 shows the comparison of the intensity patterns before (insets (a_1), (a_2), (c_1) and (c_2)) and after (insets (b_1), (b_2), (d_1) and (d_2)) transmission over 3km FMF, respectively. By rotating the linear polarizer (LP) placed in front of the charged-coupled device (CCD) camera, the polarization distribution of the corresponding VM channels can be observed, which are shown in the Fig. 2(i) ~ 4(iv).

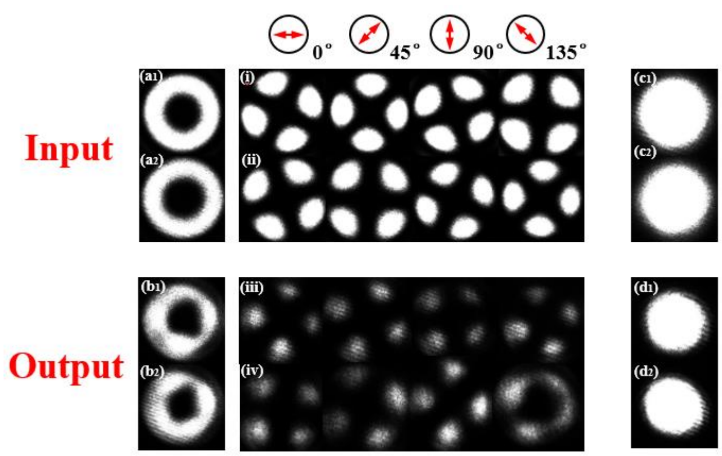

Fig. 2. The captured intensity profiles of the 4 VM channels before (insets (a_1), (a_2), (c_1) and (c_2)) and after (insets (b_1), (b_2), (d_1) and (d_2)) transmission over 3 km FMF, respectively. The arrows depict the orientations of the transmission axis of the used LP. Insets (i) ~(iv) shows the polarization distribution of the corresponding channels.

We also measured the inter-MG crosstalk when four VM channels are simultaneously transmitted, shown in Fig. 3(a). The VM MG crosstalk is around -20 dB between MGs l = 0 and l = 2. To further evaluate the propagation performance of such system, the BER properties versus the optical signal-to-noise ratio (OSNR) are measured, which are shown in Fig. 3(b). Compared with the "back to back" (B2B) channel, less than 1 dB penalties are observed for single HE11 (l = 0) channels transmitted or single EH11 (l = 2) channels transmitted (yellow and orange curves in Fig. 3(b)), and 4 dB and 4.5 dB power penalties are induced for HE11 (l = 0) and EH11 (l = 2) channels respectively (green and grape curves in Fig. 3(b)) under the FEC threshold at 3.8×10^{-3}. Hence the data capacity of this demonstration achieves 224 Gb/s (14 × 4 × 4 = 224 Gb/s).

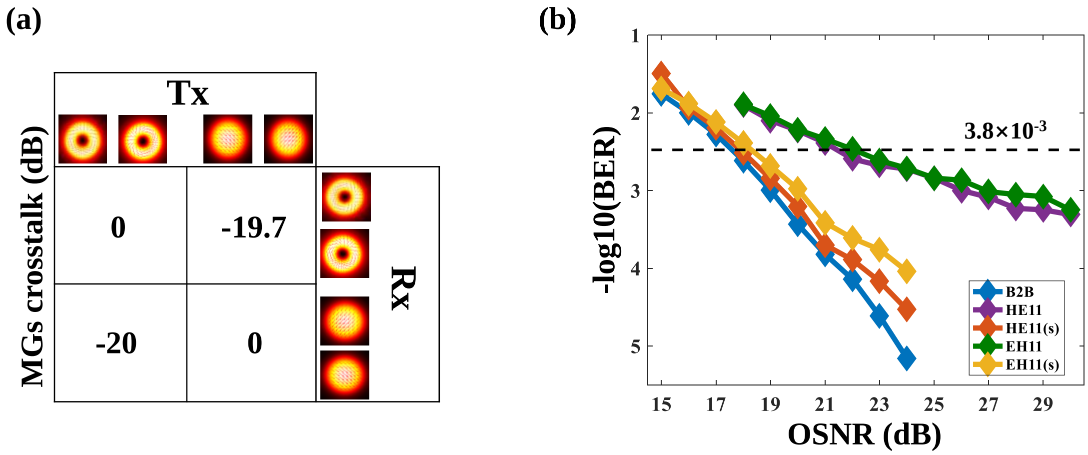

Fig. 3. (a) The normalized MG crosstalk matrix. (b) Measured BER versus OSNR of 14 Gbaud 16QAM for VM-based MGDM transmission.

3. Conclusions

In conclusion, we successfully demonstrate a MIMO-less 224 Gb/s fiber eigen-modes division multiplexing link over 3 km FMF by using 4 vector mode channels. The experimental results show that fiber eigen-modes division multiplexing has enormous potential for high-speed short-reach transmission system.

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