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1.12 Tbit/s fiber vector eigenmode multiplexing transmission over 5-km FMF with Kramers-Kronig receiver

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Abstract: We demonstrate a 1.12 Tb/s MIMO-free vector eigenmode multiplexed signal transmission over 5-km 4-mode few-mode-fiber using 2 vector modes (HE11 and EH11), 5 wavelengths and 28 GBaud 16-QAM signal with direct-detection Kramers-Kronig receiver.

OCIS codes: (060.2330) Fiber optics communications; (060.4230) Multiplexing; (060.2360) Fiber optics links and subsystems.

1. Introduction

Short-reach optical interconnects, such as data center interconnect (DCI), is an important component in the infrastructure to support massive Internet applications based on data centers. In big-data and artificial intelligence (AI) era, the fast-increasing capacity requirement has created the need to constantly improve the transmission data rate to meet the ever-increasing traffic demand. Multiplexing techniques utilizing various physical dimensions of lightwave including wavelength, polarization, amplitude and phase have been exploited to increase data transmission rate of the links. Recently, as one kind of the spatial division multiplexing (SDM) techniques with the last un-exploited physical dimension, mode division multiplexing (MDM) has attracted substantial attention due to its enormous potential in optical communication both for long-haul and short-reach optical interconnects [1-3]. In such MDM transmissions, multiple orthogonal fiber modes can be used as parallel channels to transmit optical signal, which provide a promising solution to break the capacity crunch of single mode fiber (SMF) based transmission system due to the fiber nonlinearity [4-5]. Up to now, various MDM schemes have been successfully demonstrated including mode-group division multiplexing (MGDM) [6-7], linearly polarized mode (LPM) [8-9] and orbital angular momentum (OAM) [10-12].

Vector mode (VM), as the eigenmode of optical fiber, has also been studied and introduced as a way to realize MDM transmissions recently. Compared with spatially homogeneous polarization modes, vector modes have unique characteristics of cylindrical symmetric polarization, generally referred to as cylindrical vector beams (CVBs). Theoretically, vector modes are the eigen solutions to the Maxwell's equation, which means vector modes are intrinsic states that can propagate stably in fibers. Thus, it would be worthwhile exploiting these eigenmode bases of fibers for MDM implementation [13]. In a recent report, by employing integrated optical devices, researchers have achieved 40 Gbit/s CVB-based multiplexing transmission over 2-km circular optical fiber based on coherent detection [14]. Meanwhile, the 96 Gb/s and 240 Gb/s CVB-based multiplexing transmissions over 5m 4-mode FMF with direct-detection orthogonal-frequency-division-multiplexing (DD-OFDM) have been realized in [15] and [16] respectively.

In this paper, we demonstrate, to the best of our knowledge, the first terabit experimental realization of vector mode division multiplexing (VMDM)-wavelength division multiplexing (WDM) transmission over kilometer-scale FMF. By using 5 wavelengths with two vector modes (HE11 and EH11 modes) and 112 Gbit/s 16-ary quadrature amplitude modulation (16-QAM) signal, a total of 1.12T Gb/s signal transmission based on Kramers-Kronig (KK) receiver has been successfully realized over 5-km FMF without multiple-input multiple-output (MIMO) digital signal processing (DSP). The crosstalk of 2 vector modes is less than −21.7 dB. The measured bit-error rate (BER) of 10 used channels are all below the 7% hard decision forward error correction threshold (FEC) of 3.8×10^{-3}. Experimental results show the proposed scheme have the potential for large-capacity short-reach optical interconnects such 800 G or 1 T and beyond DCI.

2. Experimental setup

Fig. 1 illustrates the experimental setup of the VMDM-WDM transmission system. At the transmitter, 5 optical carriers (ranging from 1549.32 nm to 1550.92 nm, $\lambda_1 \sim \lambda_5$) from external cavity lasers (ECLs, 100 kHz linewidth) with the wavelength interval of 0.4 nm have been adopted as the WDM channels. The odd carriers (λ_1, λ_3 and λ_5) and even carriers (λ_2 and λ_4) are respectively modulated by two I/Q modulators, which are driven by two independent 28 GBaud 16-QAM sequences using a raised-cosine filter with a roll-off factor of 0.1 from an arbitrary waveform generator (AWG, Keysight M8196A) at 84 GSa/s sampling rate. Then, 5 optical channels are combined by a polarization-maintaining fiber coupler (PMC), amplified by an erbium-doped fiber amplifier (EDFA), and then split into 2 branches with an optical coupler (OC). One branch is converted to HE11 mode after passing through a linear polarizer (LP). By employing the vortex wave plate (VWP), another branch of these carriers is converted to EH11 mode. Two polarization controllers (PCs) are used to maximize output power of both branches. Subsequently, two branches are multiplexed by a non-polarizing beam splitter (NPBS) and coupled into the 5-km-FMF link. Fig. 2(a) shows the index profile of the 4-mode FMF used for the work with a core diameter $2r_1$ = 19 μm, a cladding diameter $2r_2$ = 125 μm, a core index of 1.449 and a cladding index of 1.444. After transmission, the output beams are divided into two parts by another NPBS. One part is fed into the single mode fiber (SMF) directly to filter EH11 mode. In the other part, EH11 mode is transformed back into the fundamental mode after passing through the second VWP. Meanwhile, HE11 mode is converted to higher-order VM which cannot be coupled into SMF. Consequently, 2 VM channels can be separated successfully by this method. The polarization beam splitter (PBS) is used to further reduce the mode crosstalk. Fig. 2(b) shows the intensity profiles of 2 VMs captured by the charged-coupled device (CCD) camera before ((A) and (B)) and after ((C) and (D)) 5-km FMF transmission, respectively. By rotating the LP after the EH11 mode, we could observe the polarization distribution of EH11 mode channel which are shown in the Fig. 2(b)(A_1)-2(C_1). The measured crosstalk of 2VMs is shown in Fig. 2(c). As can be seen that the minimum isolation is around 21.7 dB between the two channels.

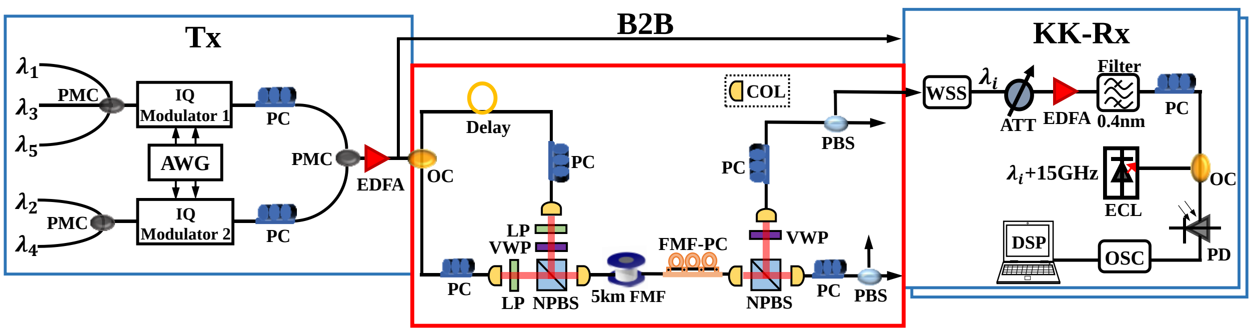
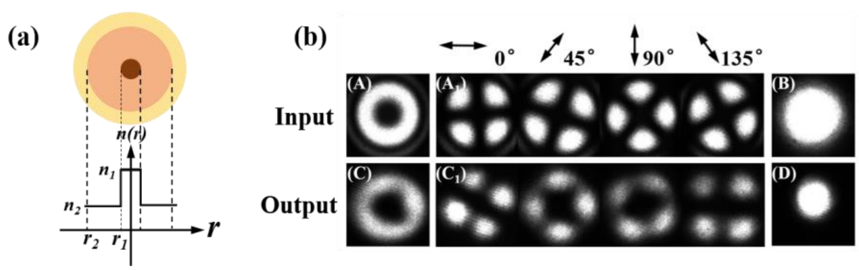


Fig.1. The experimental setup of VMDM-WDM transmission system based on KK-receiver over 5-km FMF link. PMC: polarization-maintaining coupler; AWG: arbitrary waveform generator; PC: polarization controller; EDFA: erbium-doped fiber amplifier; OC: optical coupler; COL: collimator; LP: linear polarizer; VWP: vortex wave plate; NPBS: non-polarizing beam splitter; FMF: four-mode fiber; PC-FMF: polarization controller on four-mode fiber; PBS: polarization beam splitter; WSS: wavelength selective switch; ATT: attenuator; PD: photo-detector; OSC: oscilloscope; DSP: digital signal processing, B2B: back-to-back.



(c) Mode crosstalk (dB)

Rx \ Tx	HE11	EH11
HE11	0	21.7
EH11	22.9	0

Fig. 2. (a) Refractive index profile of the FMF. (b) The intensity profiles of multiplexed VMs before ((A) and (B)) and after ((C) and (D)) transmission over 5-km FMF, respectively. Insets (A_1) and (C_1): The polarization distribution of EH11 channel with the LP. (c) Measured crosstalk matrix for 2 VM channels over 5-km FMF.

At the receiver, λ_i, one of the 5 WDM channels, is selected by wavelength selective switch (WSS) to evaluate its transmission performance. The subsequent optical attenuator (ATT) is used to adjust the received optical power (ROP). After amplified by an EDFA and filtered by a 0.4 nm optical filter, the received optical signal is then coupled by an OC with the local carrier (frequency shift of λ_i around 15 GHz) for KK reception [17]. Before direct detection, the carrier-to-signal power ratio is set to 12.5 dB which is sufficient to ensure the minimum phase property of KK relation. After detected by a 43 GHz photo detector (PD), the electrical waveform is sampled by a real-time oscilloscope (OSC) at 160 GSa/s sampling rate and then processed by offline DSP.

3. Experiment results

The measured transmission performance of VMDM-WDM is shown in Fig. 3. As shown in Fig. 3 (a), the measured bit-error-ratio (BER) performance of all 10 channels (2 vector modes × 5 wavelengths) are below the 7% FEC limit of 3.8×10^{-3} at the ROP of -20 dBm. The inset (I) of Fig. 3(a) depicts the optical spectrum of the 5 WDM channels. Then, without loss of the generality, here we only show the BER performance versus ROP of one wavelength channel at 1550.12 nm in Fig. 3 (b). The performance of the fundamental HE11 mode is better than the higher-order EH11 mode due to the lower mode crosstalk. There are 4 dB and 6.4 dB power penalty between the back-to-back (B2B) and vector mode channels respectively under the FEC limit. Insets (I) and (II) of Fig. 3 (b) show the constellations of HE11 and EH11 channels (1550.12 nm) respectively at -20 dBm ROP after 5-km FMF transmission. To the best of our knowledge, this is the highest data rate of vector mode division multiplexing demonstration over serval kilometers FMF. This realization would pave the way for high-speed large-capacity short-reach optical interconnect, such as next-generation 800 G or 1 T and beyond DCI.

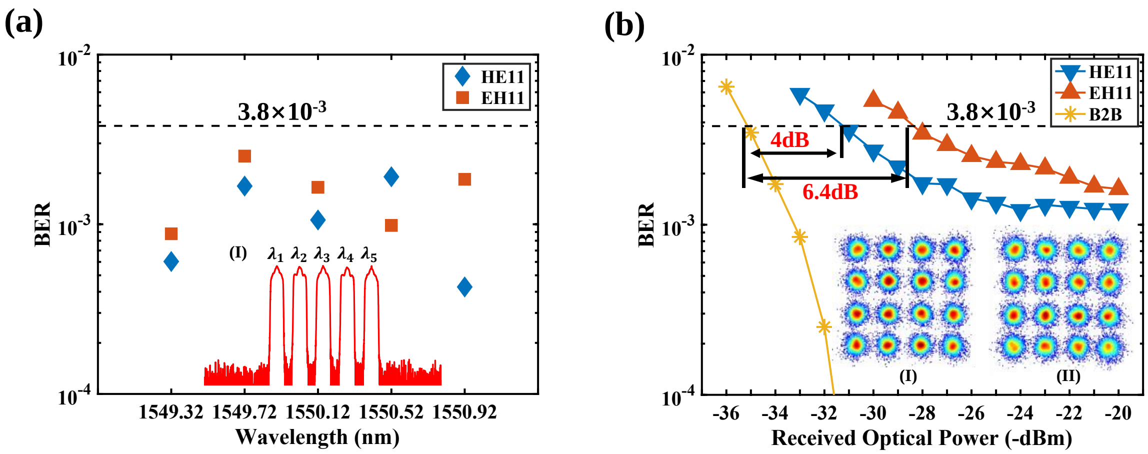


Fig. 3. (a) BER performance of all 10 channels (ROP =-20 dBm). (b) BER performance versus ROP at 1550.12 nm.

4. Conclusions

We have demonstrated a VMDM-WDM transmission system based on 2 fiber vector eigenmodes and 5 WDM wavelengths. By employing Kramers-Kronig reception, the error-free transmission of 1.12 Tbit/s 28 GBaud 16-QAM signal over 5-km few-mode fiber has been successfully realized without MIMO DSP processing. The results indicate that VMDM-based transmission scheme may be a potential candidate for high-speed high-capacity short-distance optical interconnection systems.

5. Acknowledgement

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