Demonstration of Few Mode Fiber Transmission Link Seeded by a Silicon Photonic Integrated Optical Vortex Emitter

Jun Liu(1)+, Shimao Li(2)+, Long Zhu(1), Charalambos Klitis(3), Yueyang Chen(2), Andong Wang(1), Shuhui Li(1), Yun Long(1), Shuang Zheng(1), Shi Chen(1), Marc Sorel(3), Cheng Du(4), Qi Mo(4), Siyuan Yu(2), Xinlun Cai(2)*, Jian Wang(1)*

(1) Wuhan National Laboratory for Optoelectronics, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China.
(2) State Key Laboratory of Optoelectronic Materials and Technologies and School of Physics and Engineering, Sun Yatsen University, Guangzhou 510275, China.
(3) School of Engineering, University of Glasgow, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, UK.
(4)Fiberhome Telecommunication Technologies Co. Ltd, Wuhan 430074, China

+These authors contributed equally to this work.

**Corresponding Author: caixlun5@mail.sysu.edu.cn, jwang@hust.edu.cn*

Abstract *We experimentally demonstrate a chip to few mode fiber (FMF) transmission link with on-off-keying (OOK) signal. The device emits TM_{01} and TE_{01} vortex modes which propagate through a 1.1 km FMF with measured OSNR penalties less than 2 dB at a BER of 2e-3.*

Introduction

Few mode fiber (FMF) transmission is currently subject to intense research of future mode division multiplexing (MDM) communication system to increase the transmission capacity and avoid the foreseen “capacity crunch”[1-3]. One such MDM method, orbital angular moment (OAM) multiplexing has seen its potential use in optical communications to enhance the transmission capacity and spectral efficiency in FMF transmission. Recently, multiplexing and demultiplexing of OAM modes has led to record-breaking data communication rates both in free space[4] and in optical fibers[5]. Using 54.139-Gbit/s OFDM-8QAM signals over 368 WDM polmuxed 26 OAM modes, a high spectral efficiency of 112.6 Gbit/s/Hz and a transmission capacity of 1.036 Pbit/s was achieved in free space and using 20-Gbaud/s 16-QAM signals over two OAM modes at 10 wavelengths, 1.6-Tbit/s transmission capacity through a 1.1-km specially designed vortex fiber was reported[6].

To date, many OAM transmission experiments relies on complex and bulky optical components, which are slow to respond, and cumbersome to use. This severely limits the prospect of its wide use in future practical systems. In this paper, we experimentally demonstrate a FMF link based on a micro-meter-sized silicon integrated optical vortex beam emitter[7]. The device is cable of generating radially polarized beam and azimuthally polarized beam, both of which can be considered as superposition states of circularly polarized vortex beams. The two beams can be coupled to FMF with high efficiency as they are the eignmodes of the FMF. Using this device, two modes, each modulated by 1Gbit/s on-off keying (OOK) signal have been successfully transmitted through 1.1 km FMF.

Concept and principle

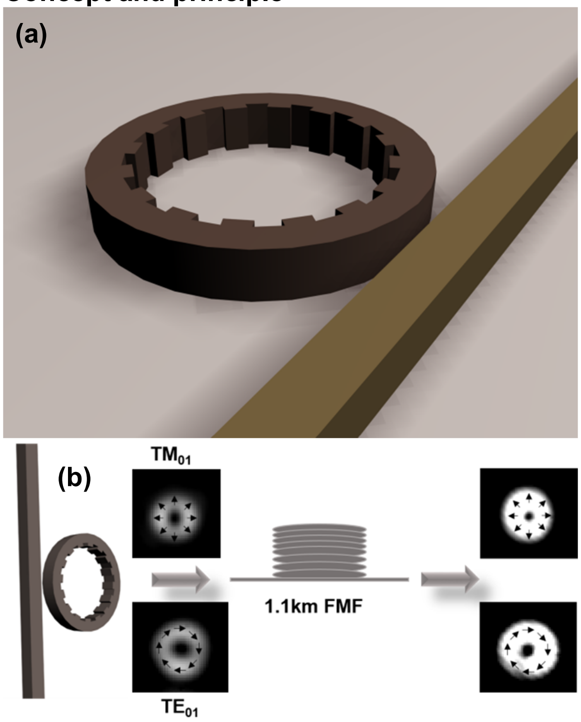

Fig. 1: (a) Illustration of the device with angular grating patterned along the inner wall of a microring resonator that is coupled to an access waveguide for optical input. (b) Concept and principle of the chip to FMF transmission link based on a micrometersized silicon photonic waveguide OAM emitters.

The principle of operation of this integrated device is to couple the rotating whispering gallery mode (WGM) in the micro-ring resonator to a vertically propagating cylindrical symmetric vector vortex mode. By matching the wavelength of the light with the micro-ring resonance, and by detuning from the grating Bragg wavelength, this

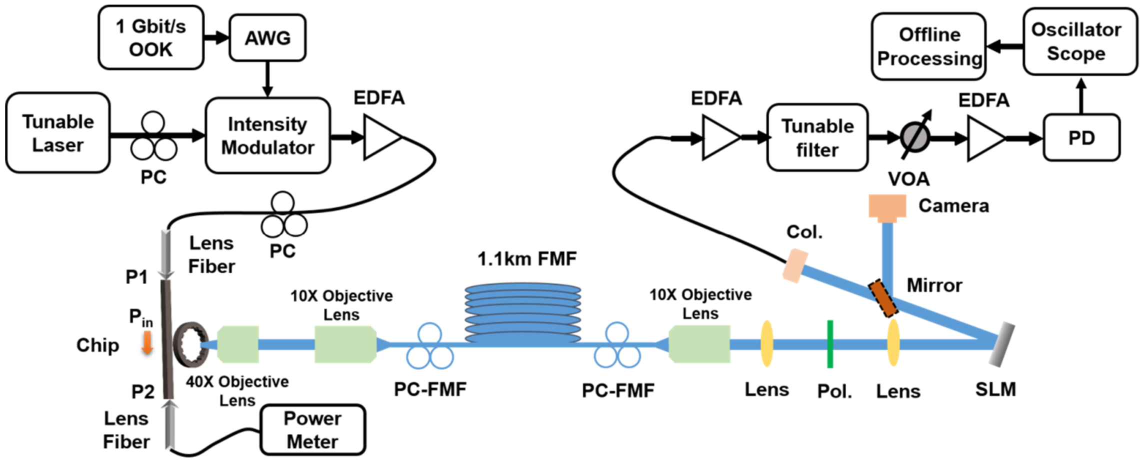

Fig. 2: Experimental setup of FMF transmission system based on a micrometersized silicon photonic waveguide OAM emitters. PC: polarization controller. EDFA: erbium-doped fiber amplifier. AWG: arbitrary waveform generator. FMF: few mode fiber. PC-FMF: polarization controller on few mode fiber. Pol.: polarizer. SLM: spatial light modulator. Col.: collimator. VOA: variable optical attenuator. PD: photodetector.

device is capable of emitting a propagating field of desired vortex topological charge *l*.

At *l*=0, there is a mode split due to strong cross-coupling between the otherwise degenerate clockwise and counter-clockwise travelling waves in the micro-ring, caused by the Bragg reflection of the grating. It was found that the shorter and longer wavelength resonances of this split mode are associated with radially and azimuthally polarized beams, respectively. The mechanism of the generation of the two orthogonal vector beams from the device will be discussed elsewhere. The vector beam emitted into free space will be coupled into and then propagate through the FMF, followed by the detection and imaging to form a complete FMF transmission link. The FMF is designed to support two modes (i.e., LP_{01} and LP_{11}).

Experimental setup and results

The experimental setup of the FMF transmission system is shown in Fig. 2. A 1 Gbit/s optical OOK signal is generated by a tunable laser followed by an optical intensity modulator (IM), which is modulated by an arbitrary waveform generator (AWG). Then the signal is coupled into the input waveguide of the micro-ring resonator. A polarization controller (PC) is used to launch light in the quasi-TE mode in the emitter chip waveguide, and the power is monitored by a power meter placed at the output port of the waveguide. FMF mode of TM_{01} is excited when the center wavelength of the tunable laser is 1547.93 nm and TE_{01} is excited when the center wavelength of the tunable laser is 1548.81 nm, corresponding to the radial and azimuthal polarized vortex modes emitted from the emitter. The beam is collimated by a 40X objective lens and coupled into the FMF by a 10X objective lens. After propagating through the 1.1 km FMF, the beam is collimated again by another 10X objective lens. To make it easy to detect, a linear polarizer is used to transform TM_{01} and TE_{01} mode to a LP_{11}-like beam (LP_{11a} and LP_{11b} correspondingly) and then they are converted to a Gaussian-like beam by the spatial light modulator (SLM). The Gaussian-like beam is coupled into a single mode fiber (SMF) for detection.

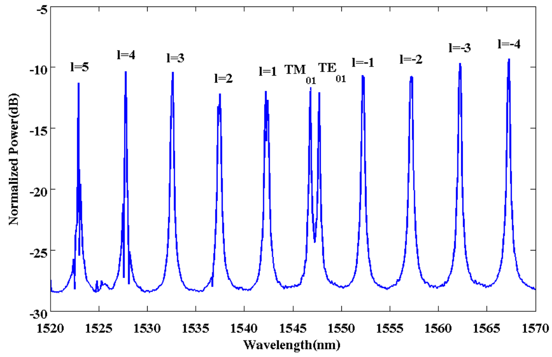

Fig. 3: Measured radiation spectrum for a device with a radius of 36 µm.

Shown in Fig. 3, we first measure the radiation spectrum for a device with the radius of 36 µm by scanning input laser wavelength. The wavelengths for exciting TM_{01} and TE_{01} in the

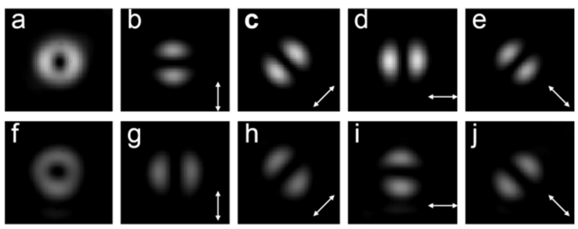

Fig. 4: (a) Measured near-field intensity distribution of the TM_{01} mode of the device. (b)- (e) Measured intensity distributions of TM_{01} mode after a polarizer in the directions indicated by the arrows. (f) Measured near-field intensity distribution of the TE_{01} mode of the device. (g)- (j) Measured intensity distributions of TE_{01} mode after a polarizer in the directions indicated by the arrows.

FMF are 1547.93 nm and 1548.81 nm respectively.

Fig.4 (a) shows the measured near-field intensity distribution of the TM_{01} mode of the device. Fig. 4 (b) - (e) Measured intensity distributions of TM_{01} mode after a polarizer in the directions indicated by the arrows. The degree of the polarizer is response to 0, 45, 90 and 135. When the polarizer is rotated, the two-lobe pattern rotates in the same manner, confirming that the radiated beam is with radial polarization. Fig.4 (f) shows the measured near-field intensity distribution of the TE_{01} mode of the device. Similar to Fig. 4(b) - (e), we can confirm that the radiated beam is with azimuthal polarization. Fig. 5 is similar to Fig. 4 while it demonstrates the intensity profile of the two modes after propagating through 1.1 km FMF.

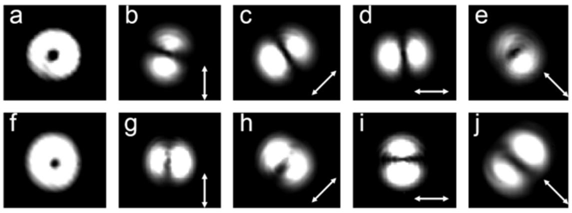

Fig. 5: (a) Measured near-field intensity distribution of the TM_{01} mode after propagating through 1.1 km FMF. (b)-(e) Measured intensity distributions of TM_{01} mode after a polarizer in the directions indicated by the arrows. (f) Measured near-field intensity distribution of the TE_{01} mode after propagating through 1.1 km FMF. (g)- (j) Measured intensity distributions of TE_{01} mode after a polarizer in the directions indicated by the arrows.

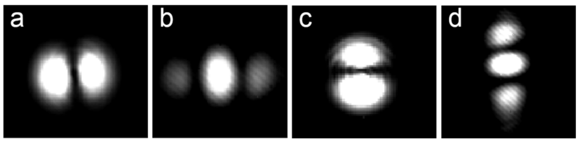

Fig. 6: Intensity profile of TM_{01} mode (a) after a polarizer in the directions indicated by the arrows and (b) after SLM, TE_{01} mode (c) after a polarizer in the directions indicated by the arrows and (d) after SLM.

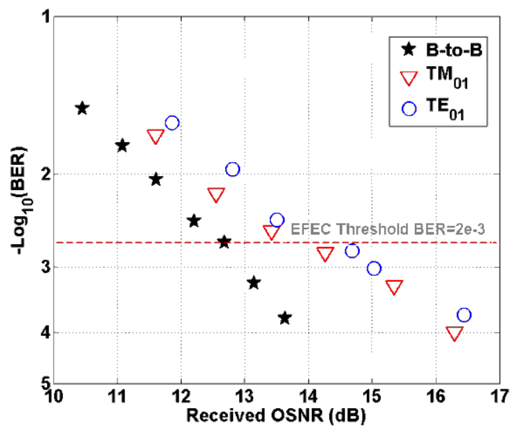

Fig. 7: Measured BER verus OSNR for TM_{01} mode and TE_{01} mode over the chip to FMF link.

The intensity profile of TM_{01} mode and TE_{01} mode after a polarizer in the directions indicated by the arrows with the degree reads 0 is illustrated in Fig.6 (a) and (c). We utilize a polarizer as the TM_{01} mode and TE_{01} mode cannot be coupled into single mode fiber, thus it is difficult to detect. Using a polarizer followed by a SLM loaded with a LP_{11} -like mode phase pattern can transform the TM_{01} mode and TE_{01} mode to Gaussian-like beams shown in Fig. 6 (b) and (d) which can be coupled into single mode fiber for the detection.

We further demonstrate performance of the chip-FMF link with 1Gbit/s OOK signal of TM_{01} mode and TE_{01} mode. The measured bit-error rate (BER) curves of the two modes are shown in Fig. 7. The observed optical signal-to-noise ratio (OSNR) penalties are less than 2 dB at a BER of 2e-3 (EFEC limit).

Discussion and Conclusions

In conclusion, we experimentally demonstrate a FMF transmission link with 1Gbit/s OOK signal, using a micro-meter-sized silicon photonic waveguide device to generate the TM_{01} and TE_{01} modes that propagate through 1.1 km FMF with the OSNR penalties are less than 2 dB at a BER of 2e-3 (EFEC limit).

The main loss items in the chip-FMF link are (i) the emission efficiency of the chip device; (ii) the coupling efficiency of beam emitted by the chip into the FMF; (iii) the coupling efficiency of the transformed Gaussian-like beam into single mode fiber. In order to get a better performance, we will focus on these three parts to improve performance of the chip to FMF transmission link.

Acknowledgements

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