MIMO-free two-mode-multiplexing transmission over 10-m hollow-core fiber

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***Abstract*—A mode-division multiplexing (MDM) transmission by two orbital angular momentum (OAM) modes over 10-m anti-resonant hollow-core fiber (AR-HCF) is demonstrated. Each channel carries 25-GBaud PAM-4, achieving a 100 Gb/s MIMO-free link, with BER $<$ 2.4×10^{-4}.**

Keywords—mode-division multiplexing; orbital angular momentum mode; anti-resonant hollow core fiber; intensity modulation and direct detection.

I. Introduction

In recent years, Hollow-core fiber (HCF) with microstructure has drawn significant attention due to its extraordinary advantage of light guidance in the hollow region [1]–[3]. Compared to the conventional solid fiber which guides light based on total internal reflections, HCF has the potential to realize low-latency, low-loss, high-power large- bandwidth transmission. As one type of HCF, Anti-resonant hollow core fiber (AR-HCF) fiber is a form of microstructured fiber that consists of an air core surrounded by a cladding of smaller air regions delineated by thin glass tubes [4]–[6]. Light is trapped in the hollow region in the AR-HCF to achieve a reduction of transmission attenuation and an enhancement of operational bandwidth.

To keep up with the exponentially growing demand for high-capacity transmission, multiplexing technologies by employing different physical dimensions including wavelength, polarization, amplitude and phase have been fully implemented based on conventional signal-mode fiber (SMF). Lately, mode-division multiplexing (MDM) scheme, as an emerging technology that can upscale the capacity proportional to the number of transmitted modes, has also been widely investigated by several research groups around the world. Furthermore, the performance of different basis sets of fiber modes based on few-mode fiber (FMF) or specially-designed fiber has also been studied widely [7]–[9].

In this paper, by using two orbital angular momentum (OAM) modes of $l = 0$ and $l = +1$, each mode carries 25-GBaud four-level pulse amplitude modulation (PAM-4) signal, we successfully demonstrate a 100 Gb/s MDM multiple-input-multiple-output-free (MIMO-free) transmission over 10-m AR-HCF link. The performance of averaged bit error rate (BER) of two channels are both below the forward error correction (FEC) threshold at 2.4×10^{-4}. The experimental results present that such a scheme could find great potential in future optical interconnects.

II. Experimental setup and results

Hollow core fiber based on anti-resonant confinement could guide light essentially within its air region. Before the data transmission experiment, the characterization of the used 8-tube AR-HCF in our experimental setup is performed, shown in Fig. 1. According to the cross-sectional diagram, the core and cladding diameters of the AR-HCF are approximately 52.7 μm and 273 μm, respectively. Due to the imperfection of the fiber fabrication, the microstructure of AR-HCF is slightly asymmetric. The measured outer and inner diameters of each tube corresponding to Fig. 1(a) are illustrated in Fig. 1(b). According to COMSOL simulation, the confinement losses of OAM modes of $|l| = 0$ and $|l| = 1$ over 1550 nm are 0.046 dB/m and 0.222 dB/m, respectively.

Figure 2 illustrates the experimental setup of the OAM-based MDM data transmission system. At the transmitter, the lightwave from the external cavity laser (ECL, 1550.12 nm) is launched into an intensity modulator (IM) and is modulated by the 25-GBaud PAM-4 signal generated from an

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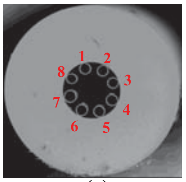

(a)

Parameter	1-tube	2-tube	3-tube	4-tube	5-tube	6-tube	7-tube	8-tube
Outer diameter (μm)	17.9	17.9	17.8	18.6	17.9	18	18.9	16.9
Inner diameter (μm)	15.4	15.4	15.3	15.8	15.6	15.7	16.5	14.6

(b)

Fig. 1: (a) Cross-sectional diagram of the used AR-HCF; (b) Measured outer and inner diameters of each tube in used AR-HCF.

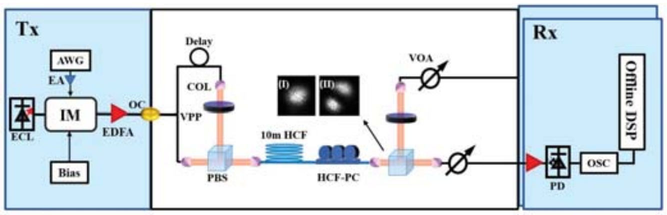

Fig. 2: The experimental setup of the OAM-based MDM transmission over 10 m AR-HCF link. Insets (I) and (II): The captured intensity profiles of the two OAM channels after 10-m AR-HCF transmission, respectively.

arbitrary waveform generator (AWG). Afterward, the signal is amplified by an erbium-doped fiber amplifier (EDFA) and divided into two branches by a 20:80 optical coupler (OC, because of the difference in fiber coupling and transmission loss of OAM modes of $|l| = 0$ and $|l| = 1$) and then are optically de-correlated. At the OAM-based MDM transmission part, one branch is directly employed as the OAM mode of $l = 0$ and another is converted to OAM mode of $l = +1$ by the vortex phase plate (VPP, $l = +1$). Then, the two channels are combined by a polarization beam splitter (PBS) and coupled into AR-HCF. During the AR-HCF transmission, a HCF-based polarization controller (HCF-PC) is used to further adjust the intensity pattern of the output beams. Insets (I) and (II) in Fig. 2 respectively show the output intensity profiles of two OAM channels captured by the charged-coupled device (CCD) camera. After 10-m AR-HCF transmission, the MDM signal is separated into two branches by a PBS. One branch is directly coupled into the SMF and only OAM of $l = 0$ could be detected. Another branch passes through another VPP ($l = -1$) and only OAM channel of $l = +1$ is demultiplexed and then is fed into the SMF for direct detection. At the receiver, A variable optical attenuator (VOA) is employed to adjust the received optical power (ROP) for sensitivity measurement. After being amplified by another EDFA and received by the photodetector (PD), the converted electrical signal is finally collected by a real-time sampling oscilloscope (OSC) for further off-line digital signal processing (DSP).

The crosstalk between two OAM channels in the demonstration is first measured, with mode isolation >17.1 dB. Fig. 3 shows the measured BER properties versus ROP under single channel (OAM of $l = 0$, blue curves in Fig. 3) and multiplexed channels transmission (red and orange curves in Fig. 3). Compared with single channel transmission, there are respectively 3.4 dB and 2.5 dB power penalties for OAM of $l = 0$ and $l = +1$ under the FEC threshold at 2.4×10^{-4} .

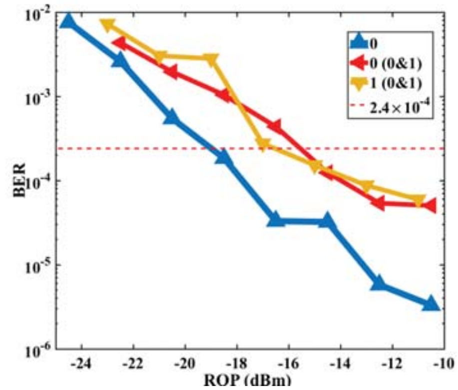

Fig. 3: Measured BER versus ROP of 25-GBaud PAM-4 for this two-mode multiplexing transmission.

Hence the data capacity of such MIMO-free MDM demonstration realizes 100 Gb/s (25 × 2 × 2 = 100 Gb/s).

III. Conclusion

In conclusion, we experimentally demonstrate the OAM-based MDM transmission over 10-m anti-resonant hollow core fiber. In this demonstration, by using two OAM modes, each carrying 25-GBaud PAM-4 signal, we have successfully realized a 100 Gb/s transmission without MIMO DSP processing.

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