A novel ring-core fiber supporting MIMO-free 50km transmission over high-order OAM modes

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Abstract: We design and fabricate a novel ring-core fiber with modulated refractive index profile to suppress the micro-bending induced modal coupling. Two OAM mode-group transmission over 50-km fiber without using MIMO equalization is also experimentally demonstrated.

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1. Introduction

Mode-division multiplexing (MDM) based on few-mode fibers (FMFs) has been widely considered as a promising candidate to overcome the capacity crunch of conventional single-mode fiber (SMF)-based wavelength-division multiplexed (WDM) systems and networks [1,2]. However, modal crosstalk combined with modal-group delay (MGD) in long-haul FMF transmission necessitates coherent detection and multiple-input-multiple-output (MIMO) digital signal processing (DSP) to demultiplex all the MDM channels, whose fast increasing computation complexity severely limits the practical application of MDM [3,4]. Weakly-coupled MDM approaches have been proposed and verified in short-reach transmission scenarios [5,6], in which the modal crosstalk is greatly suppressed so that signals in multiple linearly-polarized (LP) modes/mode groups could be independently transmitted and received without MIMO processing. The approaches to suppressed crosstalk include designing new FMFs with large effective refractive index difference between modes or mode groups (MGs) [7], adopting low-crosstalk mode multiplexer/demultiplexer (MUX/DEMUX) [8] and optimizing the design of transmission system[9].

OAM modes are an alternative modal basis-set for MDM systems [10]. In 2013, OAM-based MDM communication over a 1.1 km vortex fiber was successfully demonstrated without using MIMO DSP [11]. In 2014, an air core annular index fiber was fabricated to support 36 OAM modes [12]. However, the transmission distance remained short. In 2015, a km-scale air-core fiber supporting 12 high-order OAM modes were fabricated and experimentally demonstrated [13]. OAM mode multiplexing transmission was also widely demonstrated in conventional FMF and MMF [14]. However, their available OAM modes are limited to the lowest orders. Despite the ability of supporting high-order OAM modes in conventional MMF [15], the co-existing radially high-order modes make the multiplexing of the high-order OAM modes all but impossible. Thus, it remains challenging to implement long-distance low-crosstalk high-order OAM-based MDM transmission, limited by the unavailability of a suitable fiber. Therefore it is important to design and fabricate optical fibers that support high order OAM modes with low mode coupling and low attenuation over long distances.

In this paper, we proposed a novel ring-core fiber (RCF) with modulated refractive index profile (RIP). By carefully adjusting the RIP of the RCF to suppress the micro-perturbation induced modal coupling, the crosstalk between adjacent high-order OAM mode groups (MGs) can be significantly improved. Based on this RCF, we experimentally demonstrate transmission of two OAM MGs each carrying 7.5-Gb/s OOK signals over 50-km single-span with MIMO-free direct detection, verifying its ability to support weakly-coupled long distance MDM systems.

2. Fiber design strategy and fabrication

According to the analysis in [16], micro-bending-induced power coupling efficiency of a mode pair in the RCF with single radial order can be expressed as

$$2\gamma_{lm} = \frac{Ck_0^2\sigma^2}{2[1+(\Delta\beta L_c)^{2p}]} \frac{\left[\int_0^b r\frac{\partial n}{\partial r}A_l A_m dr\right]^2}{\int_0^b |A_l|^2 rdr \int_0^b |A_m|^2 rdr} \tag{1}$$

where $C = \left[\int_{-\infty}^{\infty}\frac{1}{1+(\Delta\beta L_C)^{2p}}d\Delta\beta\right]^{-1}$. k_0 is the wave number in the vacuum. σ is the standard deviation of fiber perturbation and L_c is the correlation length of the perturbations. $\Delta\beta = 2\pi\Delta n_{eff}/\lambda$ is the propagation constant difference between the coupling modes l and m. A_l and A_m are the normalized amplitudes of mode l and m, respectively. A typical value of p is 1, 2, or 3 depending on the external stress on the fiber and fiber fabrication processing. r represents the fiber radius while n refers to the refractive index. It can be derived from Eq. (1) that in addition to maximizing inter-MG Δn_{eff}, the micro-bending-induced modal coupling can be decreased by modulating the fiber RIP $n(r)$ to reduce the overlap integration between the modal fields and the RI gradient ($\int_0^b r\frac{\partial n}{\partial r}A_l A_m dr$). This is particularly so in RCFs because they naturally have a rising and falling edge in its radial RI distribution resulting in positive and negative RI gradient that can cancel out each other, while the modal field in RCF is always positive due to the radially single mode condition， which is a significant difference from FMFs with conventional graded or step-index profiles.

Based on above analysis, the RIP of the specially designed RCF is depicted in Fig. 1(a). The fiber preform was manufactured by PCVD technique. Suitable furnace temperature and power was set to ensure the homogeneity and consistency of the fiber. And then the preform was drawn into fiber in a standard drawing tower. The diameter of the fiber is 125 μm. A ring-shape index trench, whose inner radius, outer radius and index difference from the fiber cladding are around 4.5 µm, 5.5 µm, and 0.009, respectively, modulates the ring-core RIP and serves to decrease the micro-bending induced inter-MG coupling, especially between between MGs of $|l|$=1 and 2. The proposed RCF supports a total of four OAM MGs($|l|=0$ to $|l|=3$). All high-order radial modes are suppressed, leaving only the lowest radial order, so that each mode group (except the 0th order) contains four degenerate OAM modes <$\pm l$, $\pm s$>, $\pm s$ being the left- or right-hand circular polarizations. The effective refractive index separations (Δn_{eff}) between all supported OAM MGs are above 0.9 × 10^{-3}, with Δn_{eff} increasing with the MG order, as shown in Fig. 1(b). The Δn_{eff} between OAM MG $|l|=2$ to $|l|=3$ is 3.3 × 10^{-3}, which ensures reduced crosstalk between these two MGs, whereas the RIP modulation has a more profound effect on suppressing the coupling between MGs of $|l|$=1 and 2 despite a smaller Δn_{eff}. The fiber design therefore equalizes the coupling between the two MG pairs ($|l|$=1-2 and $|l|$=2-3) as shown in Table II. Hence, favorable performance should be achievable using high-order OAM mode group multiplexing, even without using MIMO DSP. The measured characteristics of the fabricated fiber at 1550 nm are listed in Table 1.

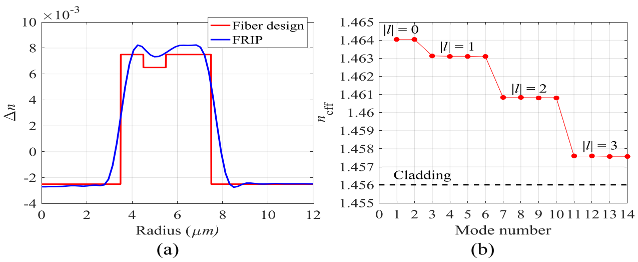


Fig. 1(a) Designed and measured refractive index profile of proposed fiber; (b) Calculated n_{eff} of 4 supporting OAM mode groups.

Table I. Characteristics of fabricated ring-core fiber with modulated refractive index profile

		OAM_0	$OAM_{\pm 1}$	$OAM_{\pm 2}$	$OAM_{\pm 3}$
Δn_{eff}	× 10^{-3}	0.9	2.2	3.3	--
Propagation Loss	dB/km	0.313	0.314	0.312	0.313
Bending Loss(R=10 mm)	× 10^{-2} dB/turn	0.2	0.7	2.8	3.5
Dispersion	ps/nm/km	16.5	23	29	30.5

3. Transmission experiment and results

The experimental setup of high-order OAM-based MDM in the 50 km OAM fiber is shown in Fig. 2. At the transmitter, 7.5-GBaud OOK signal is generated by an arbitrary waveform generator (AWG). Then the electrical OOK signal is amplified and applied to a 10-GHz Mach-Zehnder modulator (MZM). The optical carrier is generated by a DFB laser at a wavelength of 1550.12 nm. After optical amplification with an erbium doped fiber amplifier (EDFA), the optical signal is split into two branches by an 1×2 optical coupler (OC). One branch is delayed by a single mode fiber (SMF) with large relative length for data pattern decorrelation. The two optical data beams are linearly polarized and incident on the programmable spatial light modulator (SLM) whose area is divided into two separate patterns, generating OAM beams of l = + 2, + 3, respectively. After being combined by a polarization beam splitter (PBS) and changed to circularly polarization state by a quarter-wave plate (QWP), the two OAM beams are multiplexed and focused into the 50-km RCF. The output light after 50-km transmission is converted into linear polarization and split into two branches. The two branches, both contain l = +2 and l = +3 OAM beams, each passes through a commercial vortex phase plate (VPP) with l = -2 or l = -3, therefore converting one of OAM beams into a Gaussian beam, and then collimated into the SMF pigtail for photo-electric detection or power measurement with a SMF-pigtailed power meter (PM). In each received branch, the optical signal is detected by an optically pre-amplified receiver, which consists of a variable optical attenuator (VOA), an EDFA followed by an optical band-pass filter and a PD. Then the detected electrical signals are digitized and stored by a real time oscilloscope (OSC) for BER counting.

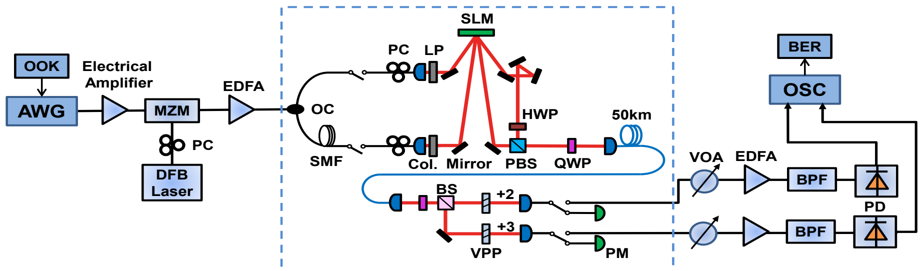


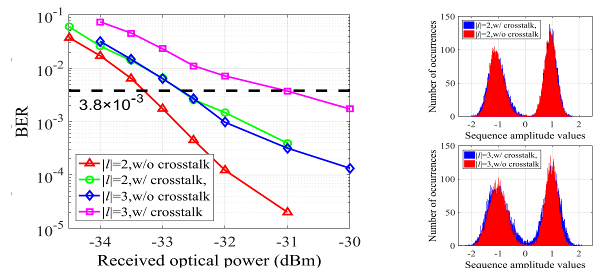
Fig. 2 Experimental setup. Note that the optical switches are utilized to switch between setups for fiber characterization and data transmission.

The OAM mode transfer matrix is measured to study mode coupling properties between different mode channels. Table II shows the power distribution of the measured mode transfer matrix of one of the four channels. It can be seen that the inter-MG coupling among the three high-order MGs (|*l*| = 1, |*l*| = 2, & |*l*| = 3) is average of -11.5 dB over the whole 50km RCF. It can also be seen that the crosstalk between mode groups |*l*| = 2 and |*l*| = 3 is relatively low.

Fig. 3(b) shows the BER results for 2×7.5 Gbit/s OOK NRZ transmission using mode groups |*l*| = 2 and |*l*| = 3. Compared with single MG channel transmission using one of the two MG, mode-group multiplexed transmission using both |*l*| = 2 and |*l*| = 3 results in around 0.6 dB and 1.6 dB power penalty over 50-km RCF at a BER of 3.8×10^{-3}, respectively. The received sequence diagrams for mode groups |*l*| = 2 and |*l*| = 3 at a ROP of −31 dBm after 50-km RCF transmission are shown in Fig. 3(c).

Table II. Measured inter-mode-group crosstalk among the three high-order OAM mode groups (unit: dB)

Input \ Output	|*l*|=1	|*l*|=2	|*l*|=3
|*l*|=1	0	-13.62	-16.78
|*l*|=2	-10.14	0	-12.55
|*l*|=3	-15.15	-10.02	0



(a) (b)

Fig. 3 (a) measured BER versus ROP for 15-Gbit/s transmission over 50-km RCF and (b) corresponding sequence histograms at a ROP of -31 dBm.

4. Conclusion

In this paper, we have proposed and demonstrated a novel RCF design with modulated RIP to suppress the micro-bending induced modal coupling. The proposed RCF is fabricated using commercial fabrication technique and has an average mode loss of 0.31dB/km as well as inter-MG coupling among the three high-order MGs average of -11.5 dB/50km. We have also experimentally demonstrate 2-MG multiplexed transmission over 50-km RCF, in which two channels of 7.5-Gb/s OOK signals have been independently transmitted in parallel over 50 km and received with simple direct detection.

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