Annular Core Photonic Lantern OAM Mode Multiplexer

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Abstract: We demonstrate an all-fiber, ring core photonic lantern to generate high quality OAM modes up to the second order at 1550nm. We achieved low-loss coupling of the lantern OAM modes into a ring core fiber.
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1. Introduction

Orbital angular momentum (OAM) beams are characterized by a helical phase front of $\exp(il\varphi)$ where, l is an integer, referred to as topological charge number and φ is the azimuthal angle [1]. Due to intrinsic spatial orthogonality of the OAM beams with different topological charge numbers, OAM states have gained considerable interest for a variety of applications in classical and quantum optics [2–5]. So far, various techniques have been employed to generate OAM beams in both free space and fiber configurations [6–9]. However, an essential limitation of the current OAM fiber-based mode generators, is the necessity to employ multiple elements to transform a Gaussian input beam to an OAM mode and their limited scalability. In addition, OAM beams generated in fiber devices, strongly depend on the input beam polarization, fiber length, and launching condition [8,10].

Here, we report the first demonstration of an all-fiber ring core photonic lantern mode (de)multiplexer as a compact, scalable and robust OAM mode generator. Our device is a 5-mode mode selective photonic lantern (MSPL) with an annular refractive index profile which is fully compatible with well-established ring core and vortex delivery fibers. Through simultaneous excitation of the pairs of degenerate linearly polarized (LP) modes of the MSPL, we demonstrate the generation of high quality OAM beams up to the second order. Modes with topological charges of ±1 and ±2 are characterized. By splicing the end-facet of the device to a ring core fiber, we achieve low-loss coupling of OAM modes while maintaining high contrast spiral phase patterns. Furthermore, our results demonstrate the great potential of PLs for generating complex optical beams.

2. Demonstration of an all-fiber OAM mode multiplexer

The output modes of a MSPL mode (de)multiplexer are composed of two fiber eigenmodes with different propagation constants ($LP_{lm} = HE_{(l+1)m} + EH_{(l-1)m}$). Here, l refers to the mode order in azimuthal direction and m (>=1) refers to the mode order in the radial direction. Regardless of the polarization term, for l (>=1), all LP_{lm} modes are two-fold degenerate. By combining a pair of degenerate LP_{lm} modes with a phase difference of $\pm\pi/2$, one can obtain two degenerate OAM modes with opposite sign of topological charge.

To fabricate an OAM mode multiplexer, we follow a similar procedure as that used for fabricating 6-mode MSPL [11]. However, in this work the central input fiber of the MSPL is replaced by a core-less fluorine-doped fiber with 86 μm diameter and a refractive index contrast of -16×10^{-3} to create a low refractive index defect in the center of the final few-mode core at the taper waist. This characteristic index profile is the key feature of our OAM mode multiplexer, leading to a donut shaped intensity profile.

Figure 1(a) shows a microscope image of the cross-section of the fabricated ring core photonic lantern. The inner core diameter, ring thickness and outer diameters are 6 μm, 11 μm and 125 μm, respectively. The near field intensity profiles of the excited modes at the output of the photonic lantern mode multiplexer, measured at 1550 nm are presented in Fig. 1(b).

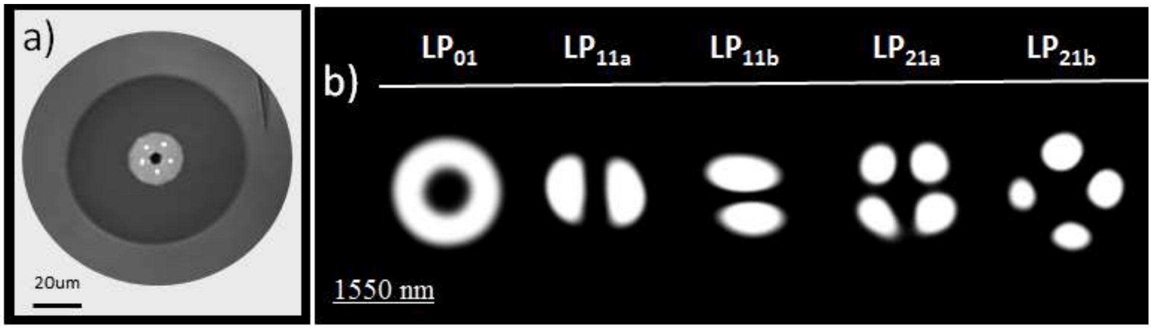

Fig. 1. Microscope image of the cross section of the fabricated annular MSPL (a), near field mode profiles of the fabricated device at 1550nm (b).

Figure 2 shows the schematic representation of the experimental setup used for the generation and detection of the OAM modes based on the proposed all-fiber OAM mode (de)multiplexer. A standard single mode fiber (SMF) at the output of a 1550 *nm* laser diode (LD) is directly spliced onto a 50:50 optical coupler. One port of the 50:50 coupler is used to deliver a reference Gaussian beam to the interferometer. The other arm of the coupler is spliced to a second 50:50 splitter whose output ports are spliced to two input fibers of the PL multiplexer corresponding to degenerate modes (l = 1, 2). A 20x microscope objective and a CCD camera were used to image the output beam.

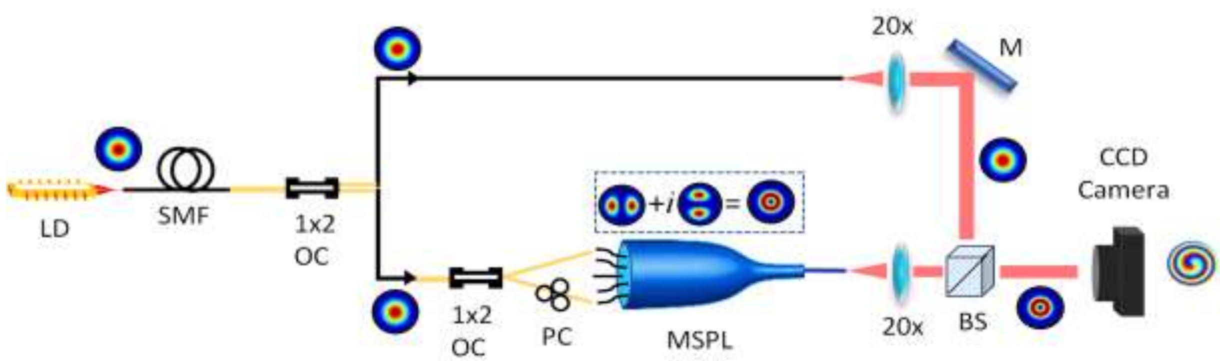

Fig. 2. Schematic of the experimental setup used for the generation and detection of OAM modes. LD, laser diode; SMF, single-mode fiber; OC, optical coupler; PC, polarization controller; MSPL, mode selective photonic lantern; M, mirror; BS, beam splitter.

Through simultaneous excitation of the two ports of the degenerate $LP_{11;a,b}$ (or $LP_{21;a,b}$) modes, donut shaped intensity profiles at the output facet of the ring core PL mode (de)multiplexer are obtained. It should be noticed that the required phase difference of $\pm\pi/2$ to generate OAM beams, is adjusted by employing a polarization controller on one PL input fibers, as it is shown in Fig.2.

The near field intensity profiles of the generated OAM_l modes (with $l = \pm 1, \pm 2$) at 1550 *nm*, are shown in Fig. 3(a,b). In order to reveal the phase singularity of the OAM modes, we recorded the interference pattern of the output beam of the ring core PL with a reference linearly polarized Gaussian beam. The high quality interferograms shown in Fig. 3(c,d) confirm effective conversion of the LP_{01} modes (at the PL input) into high quality OAM states. Moreover, to verify the low-loss and stable coupling of the generated OAM modes to a delivery fiber, we spliced the end facet of the OAM mode (de)multiplexer to a 1 m long ring core fiber of approximately 6.5 μm inner core diameter, 11 μm ring thickness and 123 μm outer diameter. Coupling losses <3 dB were measured for all modes. As shown in Fig. 3(e-h), the high quality donut-shaped intensity profiles at the output of the ring core fiber accompanied by the clean spiral phase patterns, indicate stable coupling of the OAM modes into the few mode fiber.

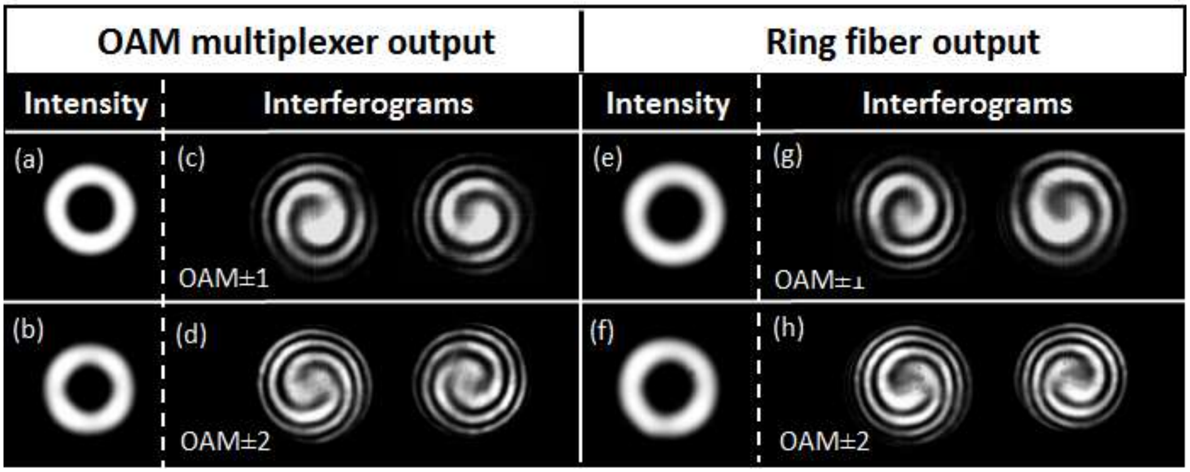

Fig. 3. Near filed intensity profiles (a, b) and phase patterns (c, d) of the generated OAM_l (l=±1, ±2) beams at the output of the fabricated OAM mode multiplexer at 1550 nm. Near field intensity profiles (e, f) and phase patterns (g, h) of the generated OAM beams after 1 m propagation in a vortex fiber at 1550 nm.

3. Conclusions

We demonstrated a new class of all-fiber photonic lantern mode (de)multiplexer to generate OAM modes. The proposed device is a 5-mode MSPL with an annular refractive index profile. By simultaneously exciting the pairs of degenerate LP modes of the MSPL, OAM modes up to the second order were generated. The OAM modes are well preserved after splicing the end facet of the photonic lantern to a 1 m long ring fiber. Besides, high contrast spiral phase patterns were measured for all OAM modes. In addition, insertion losses <3 dB were obtained for all modes. Based on these features, the proposed all-fiber OAM mode multiplexer could find applications in advanced classical and quantum physics studies.

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4. References

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