Six mode selective fiber optic spatial multiplexer

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Low-loss all-fiber photonic lantern (PL) mode multiplexers (MUXs) capable of selectively exciting the first six fiber modes of a multimode fiber (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02}) are demonstrated. Fabrication of the spatial mode multiplexers was successfully achieved employing a combination of either six step or six graded index fibers of four different core sizes. Insertion losses of 0.2–0.3 dB and mode purities above 9 dB are achieved. Moreover, it is demonstrated that the use of graded index fibers in a PL eases the length requirements of the adiabatic tapered transition and could enable scaling to large numbers.

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The exponential rate of increase in Internet driven demand in recent years is leading to the nonlinear Shannon limit in single mode fibers (SMFs) being approached. As a consequence, the need for new technologies and subsystems is necessary to cost effectively increase capacity in a single fiber. Recently, an additional multiplexing layer that is actively being investigated to overcome the capacity limit is space division multiplexing (SDM). In SDM, multiple spatial modes in a single core multimode fiber (MMF) or few mode fiber (FMF) [1], multiple cores in a fiber [2], or a combination of both are exploited for data transmission [3]. Accordingly, a larger transmission capacity with respect to conventional SMFs can be achieved.

Spatial mode multiplexers (MUXs) and demultiplexers (DEMUXs) are critical components in SDM transmission systems. To date, various mode MUX/DEMUX implementations have been demonstrated by exploiting bulk phase masks or integrated devices to directly excite the modes guided by the MMF [4,5]. Alternatively, linear combinations of modes can be excited by exploiting spot launching techniques either by bulk optics or three-dimensional laser inscribed waveguides [6,7]. Resonant fiber and waveguide-based mode MUX such as fused fiber couplers, long period gratings, Y junctions, and microring resonators have also been proposed [8,9]. With phase masks, insertion losses are large and scaling to a high number of modes is severely limited [3,10]. Microring resonators give the advantage of integration in silicon or indium phosphide, although fabrication tolerances cannot achieve the required waveguide tolerances for the guiding of the modes with the desired low mode dependent losses and crosstalk performances.

All-fiber devices represent an attractive option to perform mode MUX functions because of their potential to be directly spliced to transmission fibers, allowing for more practical highly integrated SDM systems. Photonic lanterns (PLs) are passive fiber components capable of efficient conversion of multimode light into multiple single mode signals, or vice versa, originally developed for applications in the field of astrophysics [11]. In recent years, these devices have found new applications as low-loss mode MUX with tremendous potential for scaling to large numbers of modes [12].

In a PL, N input SMFs are adiabatically tapered down inside a low refractive index capillary to create an MMF at the taper waist, as illustrated in Fig. 1. During the taper transition, light propagating in the input single mode cores evolves into a linear combination of the MMF modes at the lantern output.

Fabrication of PLs is typically done employing identical fibers, where the propagating light field is a combination of modes, and the modal degeneracy is the same for all of the input SMFs [13,14]. In contrast, mode selective multiplexers map one input single mode signal into one mode of the multimode output waveguide. Mode selective couplers are desirable to minimize the complexity of the multiple-input multiple-output (MIMO) digital signal processing (DSP), and/or to compensate differential mode group delay (DMGD) and mode dependent loss. Moreover, mode selective couplers are finding applications in passive optical networks (PON), for example, to effectively eliminate combining loss for upstream traffic [15,16].

The mode selectivity feature can be obtained when the propagation constants of each input fiber are distinct, resulting in different modal evolution along the tapered transition. Hence, the fundamental mode of each input fiber can evolve into one particular mode of the output

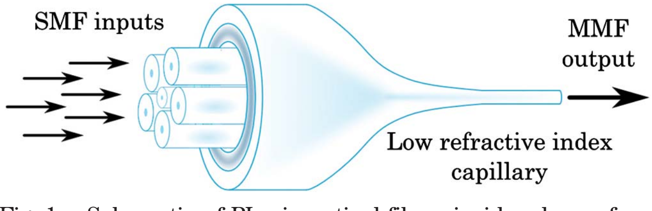

Fig. 1. Schematic of PL: six optical fibers inside a low refractive index capillary are tapered to an MMF.

MMF. In a PL, a simple way to break the mode degeneracy is to use dissimilar fibers [14,17]. Mode selectivity in PLs of three fibers has been reported for the LP_{01} and $LP_{11a,b}$ modes by using fibers of two different core diameters [18], and by using fibers of three different outer diameters [19]. Recently, a six-fiber PL mode group selective multiplexer has been reported using graded index fibers with three different core diameters, showing that the use of graded index fibers reduces the adiabaticity requirement [20]. With the increasing availability of fibers capable of propagating many modes with low DMGD [7], it is envisaged that systems capable of handling larger numbers of modes will result in a significant increase in transmission throughput in a single fiber.

In this work, we demonstrate PL mode MUXs with mode selectivity for six spatial modes. Fabrication of the PLs is achieved using six fibers of four different core diameters to selectively excite the LP_{01}, $LP_{11a,b}$, $LP_{21a,b}$, and LP_{02} modes [21]. A comparison of PLs fabricated employing step index and graded index fibers is presented. For PL fabrication, six fibers were inserted into a silica capillary with a fluorine-doped inner layer and refractive index difference -9×10^{-3} with respect to undoped silica. Five 125 μm outer diameter fibers surrounding a central 86 μm outer diameter fiber were tightly packed inside the capillary in a pentagonal arrangement [18]. A schematic of the fabricated PL cross section indicating the different core sizes and positions of the fibers is presented in Fig. 2(a). Beam propagation method (BPM) simulated output beam profiles at 1550 nm for a PL with graded index fibers are presented in Fig. 2(b). The parameters used for the simulations are 10:1 tapering ratio; 5 cm taper transition; -9×10^{-3} fluorine-doped capillary index difference; core refractive index difference 16×10^{-3}; and core sizes 20, 18, 18, 15, 15, and 6 μm, for LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02}, respectively.

The assembly was then tapered down by a factor of ~ 11 using a CO_2 laser tapering station. The resulting taper was cleaved at the waist obtaining a new MMF with a core diameter of ~ 29 μm, as shown in Fig. 3. For the mode selective PL using step index fibers, six fibers with the following core diameters were used: one 15 μm for the LP_{01}, two 10 μm for the $LP_{11a,b}$, two 8 μm for the $LP_{21a,b}$, and one 5 μm for the LP_{02}. The core refractive index difference with respect to undoped silica is 5×10^{-3} for all step index fibers. In the case of the PL employing graded index fibers, the following core diameters are

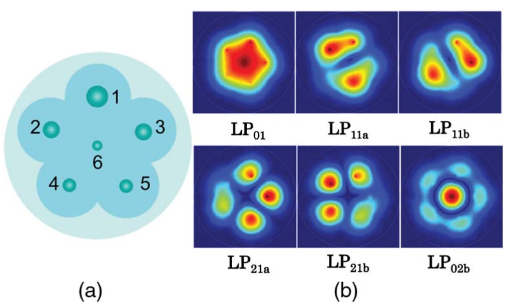

Fig. 2. (a) Cross-sectional view of the simulated PL indicating the position of the different core sizes. (b) Simulated output modes for each input fiber: 1 for LP_{01}; 2 and 3 for LP_{11}; 4 and 5 for LP_{21}; and 6 for LP_{02}.

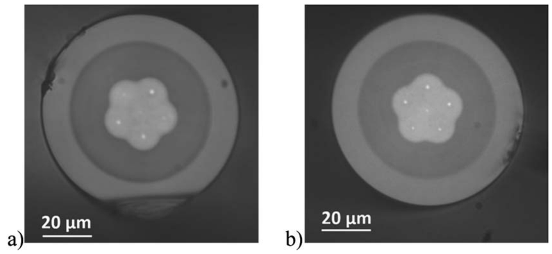

Fig. 3. Microscope images of the fabricated six spatial MUXs using (a) step index and (b) graded index fibers.

used: 20 μm for the LP_{01}, two 18 μm for the $LP_{11a,b}$, two 15 μm for the $LP_{21a,b}$, and one 6 μm LP_{02}. The core index difference is 16×10^{-3} for graded index fibers.

Characterization of the mode selective PLs was performed by coupling light into each of the input fibers. Near- and far-field profiles where taken using a 1550 nm superluminescent diode (Thorlabs, SLD1550 P-A2) and an infrared camera (Xenics, XEVA-1.7-320). Note that although some of the input fibers used are multimode at 1550 nm, excitation of the fundamental mode was achieved by careful alignment to the light source. Near- and far-field mode profiles at the output of the PLs fabricated using step and graded index fibers are shown in Figs. 4 and 5, respectively. The taper transition length is 6 cm and 4 cm for PLs using step index and graded index fibers, respectively. Experimental mode patterns are in good agreement with numerical simulations in Fig. 2(b). The observed pentagonal shape of the mode profiles is due to the geometry of the core

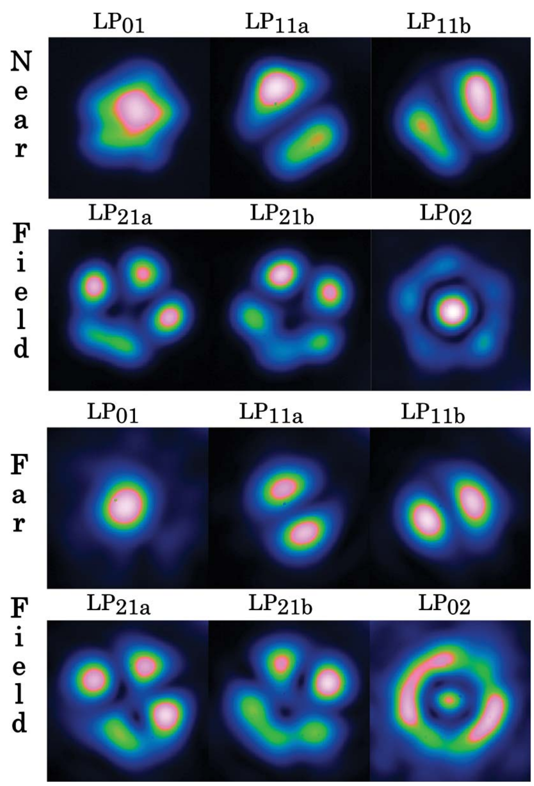

Fig. 4. Step index MSPL output signal characterization; 6 cm transition length. Near-field and far-field mode profiles.

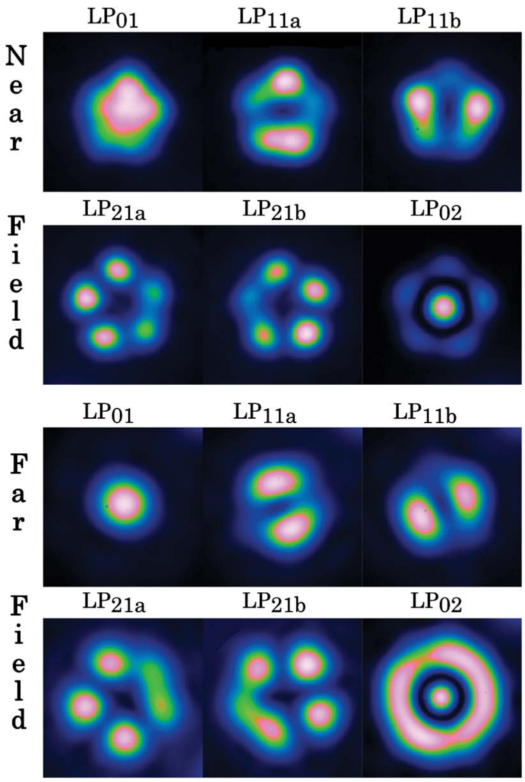

Fig. 5. Graded index MSPL output signal characterization; 4 cm transition length. Near-field and far-field mode profiles.

generated when the capillary collapses and the air gaps between fibers are filled.

The measured insertion losses are between 0.2 and 0.3 dB for all six input ports in both lantern types. An analysis of the intensity profiles to determinate mode purities was performed measuring the ratio between the minimum and maximum peak intensities of the lobes in Fig. 6. Results obtained from these measurements indicate mode purity in the range of ~9 – ~11 dB for the step index PL, and ~9 – ~17 dB for the graded index one. Measured mode purities for all six modes are listed in Table 1.

Coupling of the PL output to a low DMGD graded index FMF supporting six LP modes at 1550 nm was performed

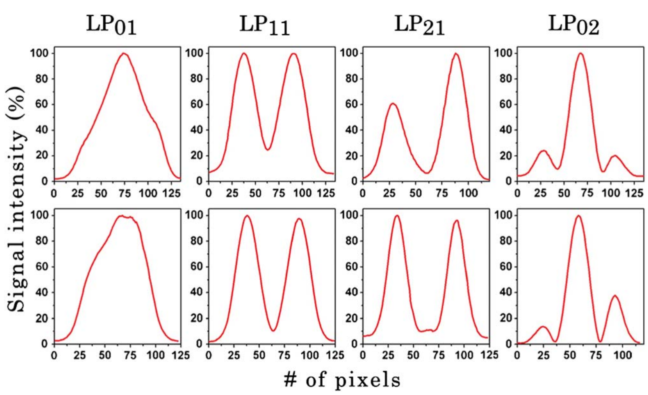

Fig. 6. Intensity of the PL near-field mode profiles. The upper row corresponds to the device fabricated using step index fibers; the lower row corresponds to the output for the graded index lantern.

Table 1. Near-Field Mode Purity Analysis

	Mode Purity (dB)	
	Step Index MSPL, 6 cm	Graded Index MSPL, 4 cm
LP_{11a}	−9.25549	−9.87163
LP_{11b}	−9.25915	−9.24088
LP_{21a}	−10.8036	−10.2711
LP_{21b}	−11.4675	−10.2949
LP_{02}	−11.7514	−17.6761

via butt coupling [22]. The fiber outer diameter and core diameter are 125 μm and 30 μm, respectively. Visualization at the output after propagation through 100 m of FMF demonstrates good mode conservation. As expected, mode coupling between the LP_{21} modes and the LP_{02} mode is observed. Output mode profiles for all input fibers are presented in Fig. 7.

In general, graded index fibers allow for larger core sizes with smaller effective mode areas for the LP_{01} mode compared to step index fibers. Therefore, the use of graded index fibers for PL fabrication reduces mode coupling along the tapered transition, reducing the length required to achieve an adiabatic transition [20,21]. Note that increasing the number of modes increases the required taper length and, therefore, the PL fabrication complexity [19]. Here, the use of graded index fibers for lantern fabrication allows for a reduction in the taper transition length from 6 to 3 cm, resulting in a factor of ~2, compared to PLs fabricated using step index fibers. Mode purities of the fabricated graded index devices were preserved at ~4 cm transition. As an example, the LP_{02} output modes from lanterns fabricated using both types of fibers with different transition lengths are shown in Fig. 8. Results demonstrate a nonadiabatic process when the transition length is reduced from 6 to 5 cm in step index fiber devices. In this case, the mode purity changes from −11.76 to −6.73 dB. For graded index fiber devices, a length reduction from 6 to 3 cm only reduces the mode purity from −17.67 to −16.28 dB.

In conclusion, we demonstrated low-loss six-fiber mode selective PL multiplexers by using either graded

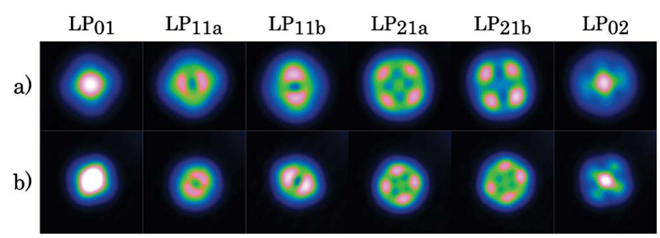

Fig. 7. Near-field mode profiles for the MSPLs signal transmission through 100 m 6 LP fiber: (a) step index and (b) graded index fibers devices.

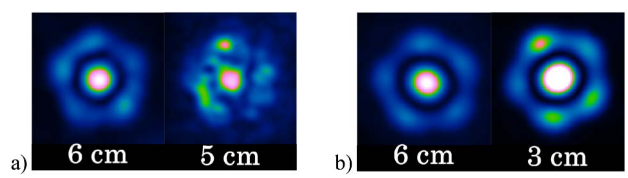

Fig. 8. Near-field LP_{02} mode profile from MSPLs with different transitions lengths: (a) step index and (b) graded index fibers.

or step index fibers and four different core sizes. The fabricated PL mode MUX allow for independent excitation of the first six spatial modes (four LP modes) of an MMF with large mode purities. Moreover, it is experimentally shown that the use of graded index fibers in PLs eases the length requirements of the adiabatic tapered transition and could enable scaling to mode MUXs supporting large numbers of spatial modes.

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