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All-fiber few-mode multicore photonic lantern mode multiplexer

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Abstract: The emergence of space division multiplexing (SDM) for ultrahigh capacity networks has heralded pioneering Petabit-class optical transmission systems. In parallel to novel SDM fibers, a new class of components to enable scalable, low-loss schemes for unlocking fiber capacity is being developed. In this work, an all-fiber mode selective photonic lantern mode multiplexer designed for launching into few-mode multicore fibers is demonstrated. This device is capable of selectively exciting LP_{01}, LP_{11a} and LP_{11b} modes in a seven-core configuration, resulting in 21 spatial channels, with less than 38 dB core-to-core crosstalk and insertion loss below 0.4 dB. The multicore photonic lantern multiplexer is scalable to larger number of cores and modes per core, and can be easily integrated with emerging ultra-high bandwidth few-mode multicore optical communication systems.

OCIS codes: (060.4230) Multiplexing; (060.2340) Fiber optics components; (060.2330) Fiber optics communications.

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1. Introduction

The exponentially increasing internet traffic in recent years is driving a rapid approach towards the fundamental nonlinear Shannon capacity limit of single mode transmission systems [1]. This has highlighted the demand for exploring a new physical dimension to

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achieve ultrahigh spectral efficiency per fiber. Thus far, capacity scaling in single mode fibers (SMFs) has been achieved by exploiting multiple degrees of freedom; including polarization, wavelength, phase and amplitude modulation [2]. To deal with the rapid traffic growth in optical networks, space division multiplexing (SDM), relying on the multiplicity of spatial channels, has emerged as an additional physical dimension for dramatically boosting capacity of a single fiber [2]. Meanwhile, a key advantage of SDM over simply increasing the number of SMFs, is its inherent device integration and resource sharing capability. This can potentially provide significant benefits in terms of the cost per bit in future optical networks.

To date, single-core multimode fibers (MMF), few-mode fibers (FMFs) [3–7] and multicore transmission fibers [8–10] have been extensively investigated. More recently, the growing potential of multicore fibers to meet the requirements for high capacity data transmission networks has been demonstrated. To scale up the available capacity in a single fiber, single-mode multicore fibers (SM-MCFs) have been presented as a promising candidate to overcome the limitation of the conventional transmission systems based on SMFs [2]. In order to more efficiently address capacity scaling in a single optical fiber, few-mode multicore fibers (FM-MCFs) with even higher multiplicity in spatial channels have emerged [11–15]. The design and performance of a suitable mode multiplexer is crucial to launch light into this new class of fibers. Until now, a plethora of technologies have been investigated based on phase-plates, 3D waveguides and multi-plane light conversion. However, these implementations have produced devices that have large insertion losses due to inefficient coupling and alignment to the transmission fibers or are bulky [16,17]. Considering future transponders, criteria such as low-loss coupling, ease of fabrication and integration, point towards solutions based on all-fiber photonic lantern. Photonic lantern mode multiplexers allow low-loss transformation of an array of single mode to MMF modes [18–21]. Furthermore, photonic lanterns are desired for spatial-multiplexing in order to minimize mode coupling, reduce the complexity of multiple input multiple output (MIMO) digital signal processing, compensate differential mode group delay and mode dependent loss, and for building various network components [22–25]. So far, single core all-fiber photonic lanterns capable of exciting the first 3, 6, 10 and 15 spatial modes have been demonstrated [5,26–30]. Although not yet addressed, suitable low-loss multicore spatial mode multiplexers to launch into FM-MCFs are still in great demand.

In this letter, we report the first multicore, few-mode all-fiber photonic lantern spatial mode multiplexer capable of selectively exciting 21 spatial channels of a single strand of multicore fiber. This multiplexer efficiently couples into the individual LP_{01}, LP_{11a} and LP_{11b} modes of a 7-core FM-MCF whose cores are arranged in a hexagonal pattern. The device is broadband, exhibits ultralow core-to-core crosstalk, low insertion loss and high mode purity across the full telecommunications C-band. By exploiting a photonic lantern fabrication method based on a capillary template, the number of modes, the number of cores and the core arrangement can be customized. This new class of spatial multiplexers could be a critical component for the evolution of high capacity, high-density SDM transmission networks based on MCFs.

2. Design and fabrication

A photonic lantern consists of a collection of single mode waveguides that are interfaced to a multimode waveguide through an adiabatic physical transition [18–20]. To fabricate a photonic lantern, a bundle of SMFs is inserted into a low refractive index glass capillary tube which is then fused and tapered down in a glass processing machine to form a multimode fiber at the taper waist. A compelling feature of photonic lantern based mode multiplexers is that their mode-selectivity can be adjusted by judiciously selecting the set of SMFs. If for example, the SMFs are identical, non-mode selective devices can be achieved where each fiber excites an orthogonal combination of all output modes. On the other hand, if the input

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fibers are dissimilar, the photonic lantern can be made mode-selective. In this latter case, light from each input fiber excites only one spatial mode.

The fabrication of the 7-core, 3-mode-selective photonic lantern is based on the recently reported microstructured template approach, as it allows the realization of complex device layouts and scaling up to much larger number of input fibers than possible before [25]. For this purpose, a capillary consisting of 7 low-refractive index fluorine-doped tubes arranged in a hexagonal array was manufactured using the stack-and-draw fiber fabrication method. These channels are used to insert 21 SMFs, thus forming the seven cores at the photonic lantern end. The structured capillary allows to correctly position the input fibers, simplifying the manufacturing process and improving repeatability [31].

A cross section microscope image of the multicore capillary template with an inner/outer diameter (ID/OD) of 1.610 mm/2 mm is presented in Fig. 1(a). In this figure, the dark layers surrounding each void are indicative of the fluorine-doped silica with a refractive index contrast of -9×10^{-3} with respect to the undoped background glass. Silica rods of various diameters were used to fill air-gaps in order to prevent deformations and core misalignment during tapering.

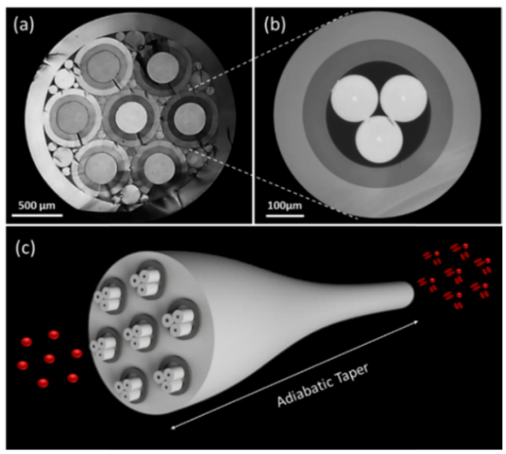

Fig. 1. (a) Microscope image of the cross section of the capillary template consisting of 7 fluorine doped tubes in a hexagonal array with an OD of 2 mm. (b) Cross section image of one fluorine-doped capillary with ID = 275 µm, filled with 3 graded-index fibers of two different core sizes of 13 µm and 11 µm designed to selectively excite LP_{01} and $LP_{11a,\ b}$ modes, respectively. (c) Illustration of the 3-mode 7-core multiplexer.

In order to achieve mode selectivity, the propagation constants of each input fiber should be distinct, resulting in different modal evolution along the tapered transition. In this case, the fundamental mode of each input fiber can evolve into one particular mode of the output MMF. To obtain this, three in-house fabricated graded-index fibers with an OD of 125 µm and two different core sizes of 13 µm and 11 µm, were inserted into each void with inner diameter (ID) of 275 µm, as depicted in Fig. 1(b). By utilizing two dissimilar cores sizes, we were able to selectively generate the LP_{01} (a 13 µm core fiber) and $LP_{11a,\ b}$ (two 11 µm core fibers) modes with low crosstalk. All fibers had a maximum refractive index contrast of ~$16x10^{-3}$ with respect to the silica cladding. Moreover, graded index fibers were intentionally chosen to improve the taper adiabaticity by providing a more gradual fundamental mode field variation compared to step index profiles [21,29]. The final assemble, with 21 input fibers, was tapered down using a CO_2 laser as the heat source.

Figure 1(c) depicts the schematic of the few-mode multicore mode selective mode multiplexer. A 5 cm long linear taper profile guaranteed an adiabatic transition [29]. The scaling factor was 1/16, thus reducing the size of the individual single mode cores to <700 nm

- assuring that light is not guided in these residual cores at the lantern end-facet. The device was then cleaved to yield an all-glass few-mode multicore waveguide that can be directly spliced to a multicore transmission fiber.

Figure 2(a) displays the cross section design of the multicore multiplexer, where Λ is the core-to-core distance, a is the core diameter and d is the cladding diameter. A microscope image of the end-facet of the fabricated device with OD = 125 µm, a = 16 µm, d = 22 µm and Λ = 33.5 µm, is shown in Fig. 2(b). Analyzing cross sectional images, we found that the positions of individual lanterns on the grid are within 2% of the pitch from the intended positions. A picture of the 21-mode photonic lantern is presented in Fig. 2(c).

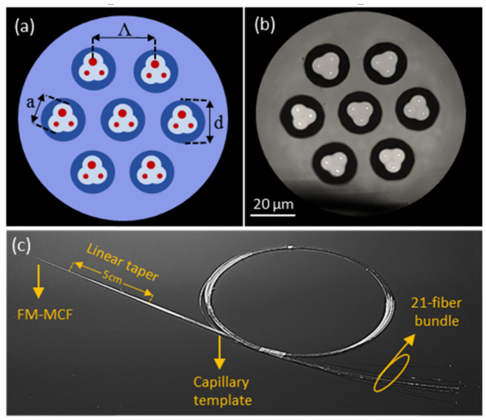

Fig. 2. (a) Schematic cross section of the few-mode multicore photonic lantern (Λ: core-to-core distance, a: core diameter, d: cladding diameter). (b) Microscope image of the end-facet of the fabricated device. (c) Device combining 21 input fibers with the FM-MCF.

3. Device characterizations

The mode selectivity of the multiplexer was verified by launching light from a broadband ASE source centered at 1550 nm into the 21 individual input fibers. Figure 3(a), shows the near field mode profiles at the multicore end-facet recorded by an infrared camera focusing the image via a 20x microscope objective. Additionally, Fig. 3(b) illustrates sample intensity profiles for the LP_{01}, LP_{11a} and LP_{11b} modes of the central core, i.e. core # 7.

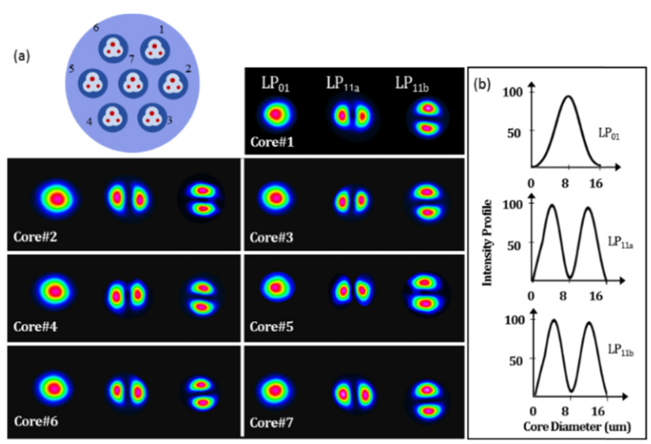

Fig. 3. (a) Near filed intensity profiles of the excited modes in all seven cores. (b) Sample intensity profiles of individual modes in core # 7.

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The measured near field patterns show that selective excitation of the three supported modes is achieved with high mode-purity across all cores. The $LP_{11a,\,b}$ mode purities were estimated from the ratio between the minimum and peak intensities of the two lobes [20,29]. Using this method, our results indicate that the photonic lantern features mode purities in excess of 12 dB for all seven cores. Meanwhile, the insertion loss was determined by comparing the output power to the input power for each mode. The results of this measurement are presented in Fig. 4, where it can be seen that the device exhibits insertion loss [27] below 0.4 dB across the telecommunication C-band (1530 nm to 1565 nm). The LP_{01} modes have lower loss than the LP_{11} modes with a maximum differential mode loss of 0.15 dB between all cores and modes.

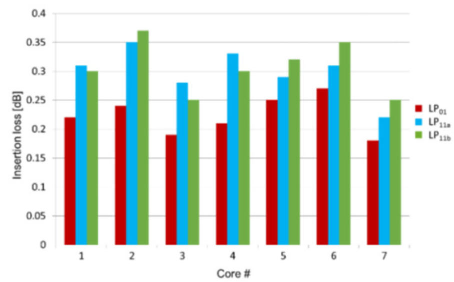

Fig. 4. Measured insertion loss for LP_{01} and $LP_{11a,\,b}$ modes for each core.

In order to evaluate the mode dependent core-to-core crosstalk in the wavelength range of C-band, the LP_{01}, LP_{11a} and LP_{11b} were independently excited into the central core (core #7). The position of each individual core at the end-facet of the multicore photonic lantern was located by launching power into each corresponding input port, one at a time. Using a high precision translation stage, the power coupled to the surrounding cores (cores #1-6) –while exciting the central core#7- was collected and butt-coupled into a 17 µm core diameter, graded index FMF and analyzed using an optical spectrum analyzer. The mode coupling efficiency into the FMF was in the range of 85%-90% for all 21 modes. Figures 5(a)-5(c) depicts the measured crosstalk spectra for the LP_{01}, LP_{11a}, and LP_{11b} modes, respectively. The core-to-core crosstalk stays below −38 dB for all cores and modes within the full C-band. Subsequently, all cores were simultaneously excited with each set of modes. The clean spatial intensity profiles presented in Fig. 5(d) confirm weak coupling between spatial channels, which ensures all cores and modes are well isolated.

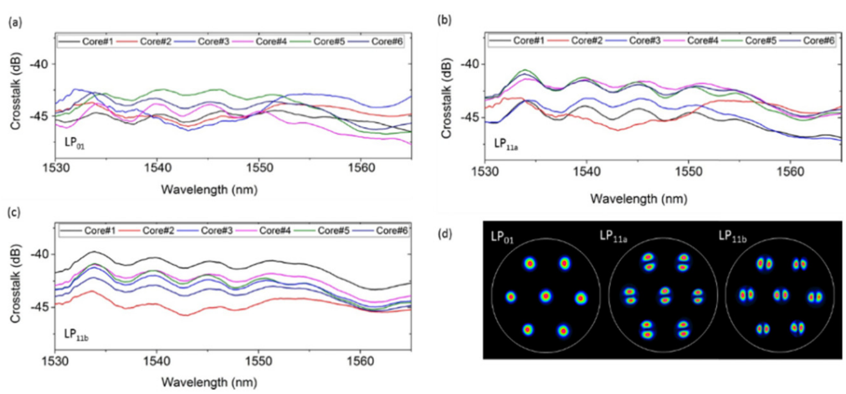

Fig. 5. Mode dependent core-to-core crosstalk as a function of wavelength when launching all (a) LP_{01}, (b) LP_{11a} and (c) LP_{11b} modes into the central core. (d) Near field intensity profiles at the output of the photonic lantern when all seven cores are simultaneously excited with LP_{01}, LP_{11a} and LP_{11b} modes. The white circles indicate the edge of the lantern.

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4. Summary

In summary, we have demonstrated the first all-fiber few-mode multicore photonic lantern spatial mode multiplexer. Fabrication of the device was accomplished through a microstructured capillary template approach that allows overcoming mode count scaling. The 7-core, 3-mode-selective photonic lantern efficiently excites the LP_{01} and $LP_{11a,\ b}$ modes in a multicore fiber configuration, thus addressing a total of 21 spatial channels. In this case, the seven cores are positioned in a hexagonal arrangement, however different geometries are feasible by customizing the capillary template. This device offers key benefits including low loss, ultra-low crosstalk, broadband operation and scalability to larger number of cores and modes. Moreover, it can be directly spliced to emerging few-mode multicore transmission fibers thus assuring photonic integration and high reliability. We expect that multicore photonic lanterns will become critical components for future ultrahigh bandwidth optical networks based on SDM.

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