10-Mode Photonic Lanterns Using Low-Index Micro-Structured Drilling Preforms

Bin Huang[(1,2)], J.C. Alvarado-Zacarias[(1,2)], Nicolas K. Fontaine[(1)], Haoshuo Chen[(1)], Roland Ryf[(1)], Francesco Poletti[(3)], John R. Hayes[(3)], J.E.Antonio-Lopez[(2)], Rodrigo Amezcua-Correa[(2)] and Guifang Li[(2)]

(1)Bell Labs, Nokia, 791 Holmdel Rd., Holmdel, NJ 07733, USA
(2)CREOL, University of Central Florida, Orlando, FL 32816, USA
(3)Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK.

Nicolas.fontaine@Nokia-Bell-Labs.com

Abstract: We demonstrate low mode-dependent loss 10-mode photonic lanterns using low-index micro-structured drilling preforms. The adiabaticity requirement for lantern tapering can be alleviated by the proposed solution leading to improved performances.
OCIS codes: (060.2340) Fiber Optics Components; (060.2330) Fibers Optics Communications

1. Introduction

Spatial multiplexers for mode (de)multiplexing are the key components for space-division multiplexing (SDM) over multimode fiber (MMF) [1]. Among all candidates, photonic lanterns (PLs) [2]-[4] are very promisingbecause they offer low insertion loss (IL), low mode-dependent loss (MDL), scalability and compactness. Photonic lanterns for SDM were first demonstrated in [2] where fundamental modes from 3 single mode fibers were mapped to the LP_{01} and two LP_{11} modes of an MMF. When dissimilar fibers are used, mode-selective mapping can be achieved. The geometric requirement in the lantern tapering section for mode conversion was discussed in [5]. Reduced cladding fibers [6] and graded-index multimode fibers [3] have been employed to alleviate the adiabaticity requirement for scaling to more modes. Recently, photonic lanterns supporting 15 spatial modes have been demonstrated using stack-and-draw preforms [7].

In this paper, we demonstrate 10-mode (20 vector modes) photonic lanterns using low-index microstructured drilling preforms, which not only enable scalability to a large number of modes but also alleviate the adiabatic requirement for lantern tapering. This approach reduces the IL of a single lantern to less than 2 dB and the MDL to 6-7 dB over the C- and L-band for a pair of 10-mode photonic lanterns.

2. Rationale for Using a Low-Index Micro-Structured Drilling Preform

A main constraint for scaling photonic lanterns to more modes is the adiabaticity requirement in tapering section. To achieve adiabaticity, two supported modes E_1 and E_2 would not couple to each other if[6]:

$$\left|\frac{2\pi}{\beta_1-\beta_2}\int E_1\frac{\partial E_2}{\partial z}dxdy\right| \ll 1 \quad (1)$$

where z is the tapering direction, β_1 and β_2 are the propagation constants of the modes E_1 and E_2. The term $\partial E/\partial z$ is the rate of change of the mode field along the tapering direction, which varies in the photonic lantern tapering section and reaches a highest value as the mode cannot be supported by the core and expands to the region within the outer fluorine tube [3]. Small imperfections or short tapering length along this critical taper region will cause mode perturbation and degrade the performance of the lantern in terms of IL and MDL. To alleviate this fabrication constraint, we propose to use a multi-layer perform with a lower-index outer layer.

To discuss the adiabaticity requirement and explain the solution, we use the tapering of a simplified structure consisting of a 6-mode graded-index fiber and a lower index outer layer as an example. Fig. 1(a) illustrates the 6-mode fiber with a low-index outer layer. As this fiber is tapered down, the mode filed diameter (MFD) of the fundamental mode versus the taper ratio (from 1 to 0.03) is shown in Fig. 1(c). The MFD first decreases and then sharply increases to more than 60 μm, followed by a sharp drop. The reason for the sharp increase is that at the taper ratio around 0.3, the fundamental mode starts to leave the core and become guided by the cladding instead. If we replace the standard cladding with a two-layer cladding, with refractive index as illustrated in Fig. 1(b), the mode would be first supported by the inner cladding and gradually by the outer cladding. The change of MFD can be greatly reduced in this case, as shown by the blue curve in Fig .1(c). This corresponds to a smaller rate of change of the mode field $\partial E/\partial z$, and therefore alleviates the adiabatic requirement.

Our proposed drilling preform, shown in Fig. 2(a), shares some similarities in alleviating the adiabaticity requirement as the example above. Accurate spatial arrangement for 10 fibers can be guaranteed by the drilling holes, which eases the fabrication complexity compared to the one-hole tube [3]. The inner structure is lightly fluorine-doped, leading to a slightly lower refractive index than the fiber cladding. The outer structure is heavily fluorine-doped, and has a refractive index lower than the inner structure. During the tapering process, fiber modes were guided sequentially by the fiber core, the fiber cladding, and finally the lightly fluorine doped layer.

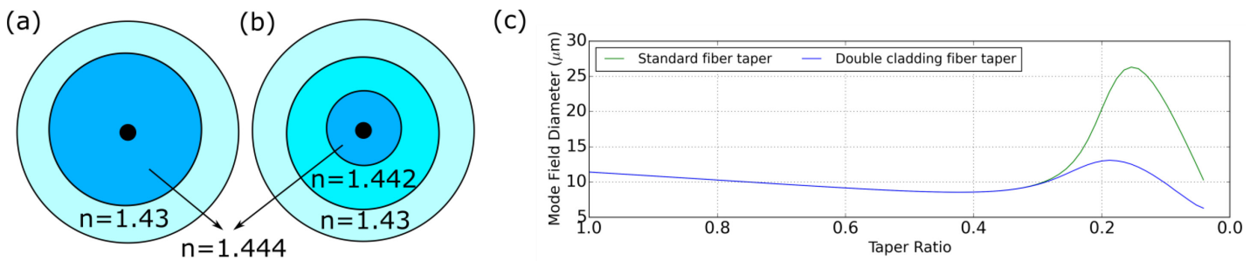

Fig. 1The facet of (a) a 6-mode graded-index fiber with a standard cladding along with a low-index outer layer (b) a double layer cladding; (c) mode field diameter vs taper ratio for both claddings.

3. Fabrication of Photonic Lanterns

Fabricating the photonic lanterns entails a two-step process. First, 10 identical 6-mode graded-index fibers were inserted into the micro-structured drilling perform, as shown in Fig. 2(b), which is then adiabatically tapered by a ratio of 1/2.4. The drilling preform is lightly doped with fluorine with a refractive index of 1.442, lower than the index of the fiber cladding around 1.444. The diameter of the preform is 780 μm and, after the first-step tapering, it is reduced to 325 μm. The 10 holes of the preform are arranged in two rings with a hole diameter of 130 μm. The inner ring has three holes with a diameter of 203 μm and the outer one has seven holes with a diameter of 528 μm.

After the first-step tapering, all the cores can still guide the fundamental mode. In the second-step tapering, the preform was inserted into a heavily doped fluorine tube with a refractive index of 1.43 as illustrated in Fig. 2(c). The heavily doped fluorine tube has an inner diameter around 350 μm and thickness of 280 μm. Then the entire structure was tapered by a ratio of 1/16, see Fig. 2(d). The diameter of the lightly-doped inner layer, which becomes the new core, is 20.2 μm.

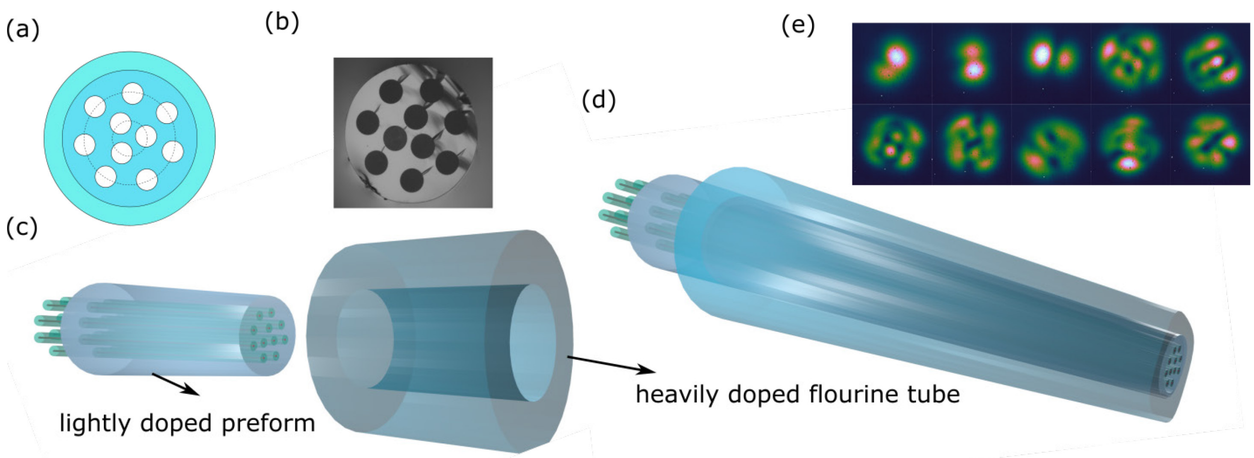

Fig. 2(a) The proposed two-layer drilling perform, (b) the facet image of the drilling preform used in experiment (c) add an outer layer after the first step and (d) the final structure after being tapered in the second step, (e) the mode intensity profile before splicing to 10 mode graded-index fiber.

4. Characterization of Photonic Lanterns

Two lanterns were fabricated following the aforementioned procedure. The mode intensity profiles were captured before [Fig. 2(e)] and after [Fig. 3(a)] splicing to a 10 mode graded-index fiber. The excited modes from the fibers located at the inner ring are mixtures of the LP_{01} and LP_{11} (first three intensity profiles in both figures). The modes from the inner ring propagate in a higher-index region compared to the other modes during the tapering process, which makes them evolve into lower-order modes. Modes from the outer ring are mainly a superposition of higher-order modes (LP_{21}, LP_{02}, LP_{31} and LP_{12}).

The IL and MDL of the photonic lanterns were characterized. One lantern has an IL in the range of 0.6-2 dB, and the other in the range of 1.2-4 dB. The higher IL of the second lantern was mainly due to a small kink at the beginning of the second-step tapering, which can be avoided using a more stable tapering station. To measure MDL, two photonic lanterns were connected together through a short 10-mode fiber. A swept wavelength interferometer was used to measure the transfer matrix across the entire C and L band [8]. The experimental setup is shown in Fig. 3(b). Light coming from the swept laser source is split into two branches, the signal and the reference. In the signal branch, a polarization multiplexer (Pol. Mux) ensures that two orthogonal polarizations are launched with same power. Fiber delays were added at the input and output of a pair of photonic lanterns to differentiate the input-output response in the time domain. Measurement of the full 20×20 (20 vector modes) amplitude and phase matrix enables the MDL calculation using singular value decomposition (SVD). The MDL for the lantern-10 mode fiber-lantern link is 6-7 dB across the C- and L-band shown in Fig. 3(c). The MDL of the better photonic lantern is estimated to be roughly 2 dB based on the ILs of these two photonic lanterns.

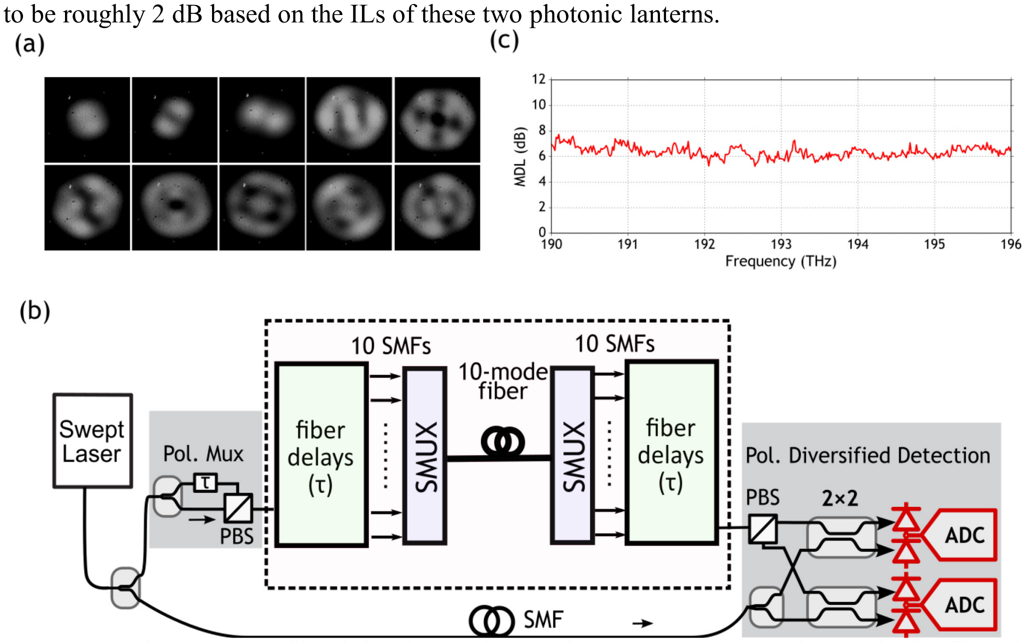

Fig. 3(a) Mode intensity profile of the photonic lantern after splicing to a 10-mode graded-index fiber, (b) experimental setup for MDL measurement, (c) MDL of a pair of 10-mode photonic lanterns covering C- and L- band.

5. Conclusion

We designed and fabricated 10-mode photonic lanterns using low-index micro-structured drilling preforms, which not only enables scalability to a large number of modes but also alleviates the adiabaticity requirement for lantern tapering. The IL and MDL can be reduced to 2 dB for a single 10-mode photonic lantern.

This work was supported by the ICT R&D program of MSIP/IITP, Republic of Korea. [R0101-16-0071, Research of mode-division-multiplexing optical transmission technology over 10 km multi-mode fiber]

References

[1] H. Chen et al., "Compact spatial multiplexers for mode division multiplexing," *Opt. Express*, vol. 22, no. 26, p. 31582, Dec. 2014.

[2] S. G. Leon-Saval et al., "Mode-selective photonic lanterns for space-division multiplexing," *Opt. Express*, vol. 22, no. 1, p. 1036, Jan. 2014.

[3] B. Huang et al., "All-fiber mode-group-selective photonic lantern using graded-index multimode fibers," *Opt. Express*, vol. 23, no. 1, p. 224, Jan. 2015.

[4] A. M. Velazquez-Benitez et al., "Six mode selective fiber optic spatial multiplexer," *Opt. Lett.*, vol. 40, no. 8, p. 1663, Apr. 2015.

[5] N. K. Fontaine et al., "Geometric requirements for photonic lanterns in space division multiplexing," *Opt. Express*, vol. 20, no. 24, pp. 27123–27132, 2012.

[6] S. Yerolatsitis et al., "Adiabatically-tapered fiber mode multiplexers," *Opt. Express*, vol. 22, no. 1, p. 608, Jan. 2014.

[7] A. M. Velázquez-Benítez et al., "Scaling the fabrication of higher order photonic lanterns using microstructured preforms," in *ECOC*, 2015, p. Tu.3.3.2.

[8] N. K. Fontaine et al., "Characterization of Space-Division Multiplexing Systems using a Swept-Wavelength Interferometer," in *OFC*, 2013, p. OW1K.2.