Mode Selective Photonic Lantern with Graded Index Core

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Abstract: We demonstrate a mode selective photonic lantern with a graded index core, which modes are a better match when splicing to graded index transmission fiber compare to those from a photonic lantern with step index core.
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1. Introduction

Recently, new alternatives to overcome the capacity limit of a single mode fiber (SMF) have been explored, including few mode fibers (FMFs) and multicore fibers (MCFs) [1]. Space division multiplexing (SDM) has emerged as an attractive solution to support future exponential growth in data traffic [2]. One of the key components for FMF transmission are the spatial multiplexer (SMUX) and demultiplexer (SDeMUX), photonic lanterns (PLs) are now considered as one of the most versatile mode multiplexers, they can provide low insertion loss, low mode dependent loss (MDL) and can work over a broad bandwidth [3-7]. One of the main requirements of a PL is to have low loss to be used in a transmission link, including low MDL, low insertion loss and modal crosstalk. The design of PLs that better matches the properties of a FMF is of great importance. PLs can be scaled to a larger number of modes with the advantage that they can be easily splice to a transmission fiber [8]. Unfortunately, all previous PLs have a step index refractive index profile whose modes are slightly different than the modes of the typical graded index transmission fiber. This causes additional losses and crosstalk at the splice point between the PL and the transmission fiber.

In this work we propose a novel method to fabricate a PL with a graded index core. It consist of having a capillary tube with three layers as shown in Fig. 1, an outer layer of silica, a second layer of fluorine doped silica and a third layer of a fluorine doped silica with a graded index profile as shown in Fig. 1c). To measure the refractive index profile of the different layers, a collapsed tube drawn to a fiber size was used. Fig. 1c) shows the parabolic index profile of the tube used for the fabrication of a graded index core PL.

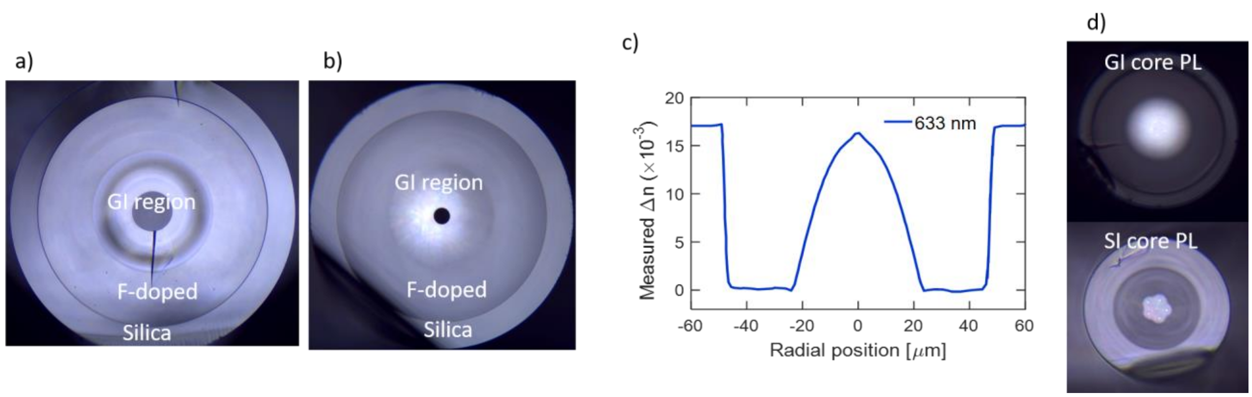

Fig. 1 a) Cross section of the tube used for the fabrication of the graded index photonic lantern, consisting of a three-layer structure, the inner layer is the graded index region, the middle layer is a fluorine doped region to confine the modes at the lantern output after tapering, the outer layer is a silica layer. b) Partially collapsed tube for measuring the refractive index profile. c) Refractive index measurement of the tube used to fabricate the PL, we can clearly see the parabolic profile corresponding to the inner layer.

Fig. 2a) shows the calculated mode profiles of the proposed photonic lantern with a graded index core designed to perfectly match the modes of the transmission fiber represented in Fig. 2c. The case in Fig. 2b) represents the mode profiles of a photonic lantern with a step index core, they resemble the transmission fiber modes, however, due to the pentagon shape of the core, the modes are slightly distorted compared to the proposed graded index core PL, this leads to a slight mismatch when splicing to the transmission fiber.

Fig. 2d) shows the modal evolution as the lantern diameter is decreased along the taper. In an adiabatic taper, the launched modes follow each effective index line (propagation constants). If the lines do not cross then there is a one-to-one mapping between the output modes and input modes. At the point C the light is mainly confined in the individual cores with some coupling to adjacent cores, in B the modes are almost formed but are distorted and in C the whole set of modes match the GIF. The mode effective indices are plotted against the core diameter of the PL along the transition starting at 140 µm. At the input, we have 4 different core sizes for the input fibers, i.e. 4 different propagation constants (4 separated blue curves at 120 µm), as the diameter decreases the cores begin to couple and then evolve into each specific mode of the final few mode PL output. At the PL output, there are only 3 groups of degenerate modes. The propagation constants are separated during the entire taper, ensuring that the output mode profiles corresponding to each propagation constant evolve into the modes of the PL output.

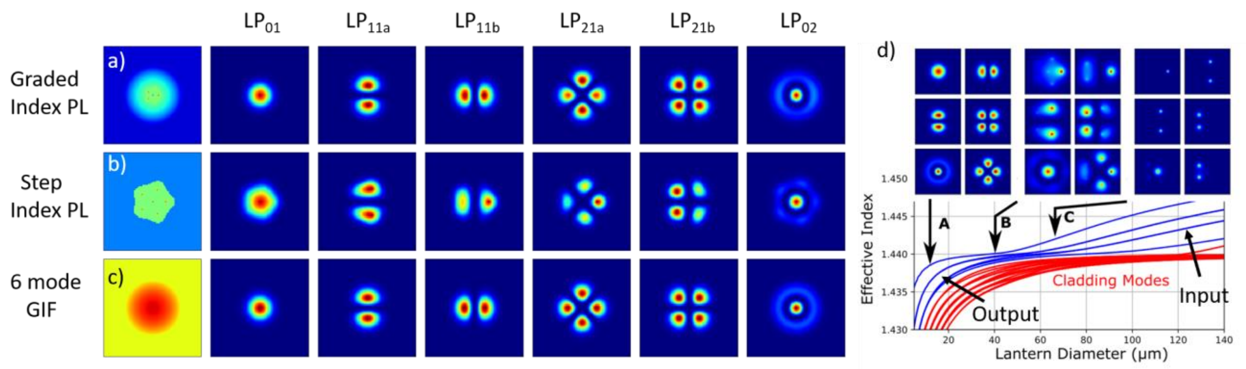

Fig. 2 Calculated mode profiles of a) Graded index core photonic lantern b) step index core photonic lantern and c) six mode transmission fiber. d) Modal evolution along the tapered transition of the graded index core PL.

2. Fabrication of a six-mode photonic lantern with a graded index core

The fabrication process for the graded index lantern proceeds as follows. Dissimilar fibers were inserted into the capillary showed in Fig. 1 a), to ensure mode selectivity on the device, the input fiber cores used are 1x23 µm, 2x18 µm, 2x15 µm and 1x11 µm for each LP_{01}, LP_{11}, LP_{21}, and LP_{02} modes respectively with 125 µm cladding for the first three and 86 µm for the smallest core fiber. The capillary is tapered adiabatically by a factor of 44 using a CO_2 laser tapering station with a total transition length of 8 cm, the obtained PL is 52 µm in diameter and has a core diameter of 22 µm as we can see in Fig. 2 a). As the capillary is tapered down, the light cannot be confined in each individual core and starts coupling to the neighboring cores, then the light is coupled to the graded index ring in the initial tube and is confined by the fluorine doped region. The contribution from the pentagon-shape is negligible as the PL is tapered by a factor of 44.

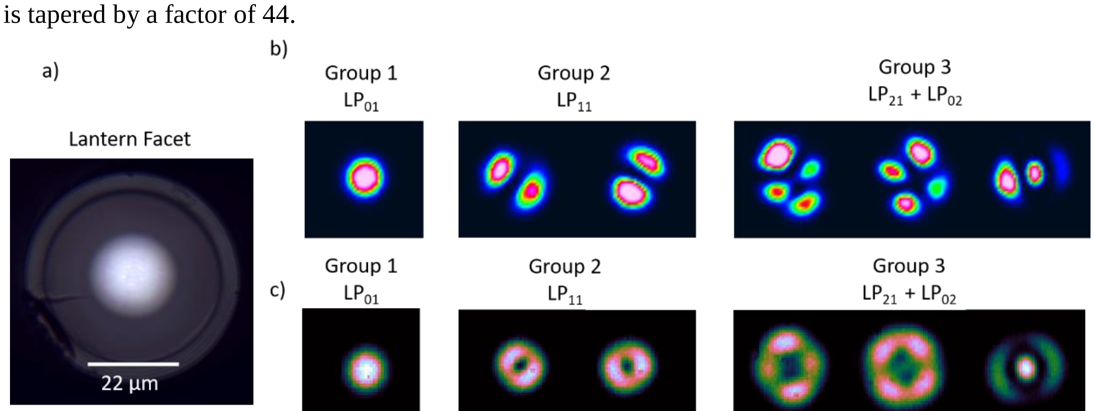

Fig. 3a) Cross sectional microscope image of the fabricated graded index core photonic lantern with a core diameter of 22 µm and 52 µm cladding diameter. b) Near field mode profiles at the output of the fabricated photonic lantern at 1550 nm. c) Near field mode profiles after transmission over 8 m of few mode graded index fiber supporting 6 spatial modes.

Fig. 3 a) shows the cross section of the fabricated device, the core of the lantern is formed by the cladding of the input fibers and the graded index region represented in the capillary in Fig. 1 a), the light from the input fibers experience a smooth transition to the graded index region of the tube. Fig. 2 b) shows the near field mode profiles at the output of the lantern facet at 1550 nm using a super luminescent diode (SLD), we can clearly see nice and rounded mode shapes compare to those from a step index core lantern as showed in Fig. 3 b). Fig. 3 c) shows the mode profiles after transmission through 8 m of few mode fiber supporting 6 spatial modes. The measured insertion losses at the lantern output are 0.1 dB for the LP_{01}, 0.2dB for the second mode group and average 0.4 dB for the last mode group, which is comparable to the losses of step index PL [6], after splicing to FMF the insertion losses are between 0.5 for the LP_{01}, 0.5dB average for the second mode group and 1.9 dB average for the last mode group, this is due to mismatch between the PL and the FMF cores and can be improved by the fabrication process.

As a comparison we show the results for a fabricated PL with a step index core. The device consists of a capillary tube with a fluorine doped region with a lower refractive index compare to the cladding of the input fibers, the same input fibers were used and the device was tapered down adiabatically by a factor of 18 to obtain a final diameter of 90 µm with 17 µm core diameter as shown in Fig. 4 a). From this cross section we can see that the final core of the PL is not circular and so the output mode profiles shown in Fig. 4b) are not as rounded and instead take the shape of the PL core. In Fig. 4c) we can see the transmission through the same few mode fiber where we see that there is more mixing compared to the graded index PL where we see modes with deeper nulls.

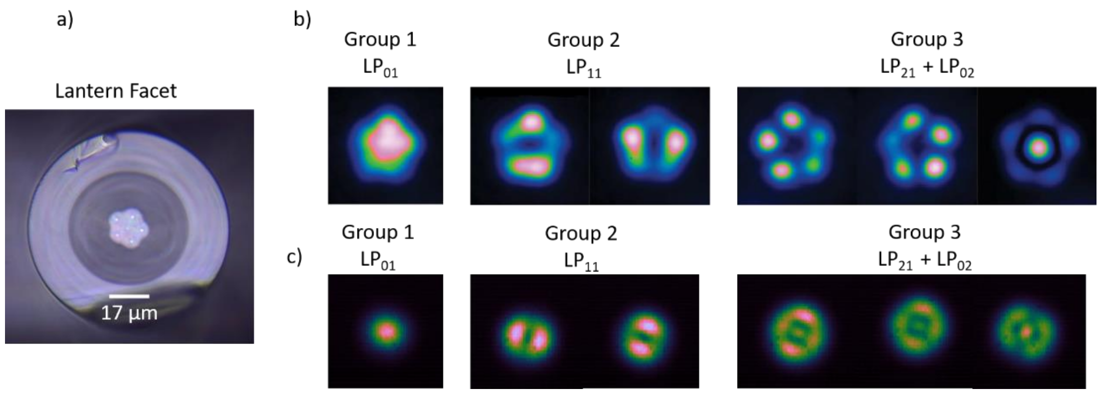

Fig. 4a) Cross sectional microscope image of a fabricated step index core photonic lantern with a core diameter of 17 µm and 90 µm cladding diameter. b) Near field mode profiles at the output of the fabricated photonic lantern at 1550 nm. c) Near field mode profiles after transmission over 8 m of few mode graded index fiber supporting 6 spatial modes.

3. Conclusions

We have demonstrated a mode selective PL with a graded index core, the modes at the output of the PL are a much better match to a graded index transmission fiber than those from a PL with step index core. Ultimately, the GI shape will enable mode multiplexers without any insertion loss, that perfectly match the transmission fiber.

Acknowledgments

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4. References

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