Experimental analysis of the modal evolution in photonic lanterns

Juan Carlos Alvarado-Zacarias(1,2), Bin Huang(1,2), Zeinab Sanjabi Eznaveh(1) , Nicolas K. Fontaine(2), Haoshuo Chen(2), Roland Ryf(2), Jose Enrique Antonio-Lopez(1), and Rodrigo Amezcua Correa(1)
(1) CREOL, University of Central Florida, Orlando, FL 32816, USA
(2) Nokia Bell Labs, 791 Holmdel Rd, Holmdel, NJ 07733, USA
jcalvarazac@knights.ucf.edu

Abstract: We experimentally analyze the modal evolution in a 10 mode-selective photonic lantern along the tapered transition using a swept-wavelength interferometer. Mode conversion to HOMs occurs closer to the beginning of the photonic lantern taper.
OCIS codes: (060.2300) Fiber Measurements; (060.2310) Fiber Optics

1. Introduction

The rapidly increasing demand for data transmission capacity has led to the development of new alternatives to overcome the limits of single mode fiber (SMF) systems. Space division multiplexing (SDM) has emerged as an attractive solution to support future exponential growth in data traffic [1]. To date, several approaches based on novel SDM fibers have been demonstrated where multiple cores and/or modes are exploited as data channels [2, 3]. Spatial mode multiplexers and de-multiplexers are fundamental components for high capacity SDM transmission networks. Photonic lanterns (PL) are now considered as one of the most versatile mode multiplexers, not only because their optical properties can be greatly tailored by device design, but also because they can be scaled to support a large number of modes [4-6]. These devices exhibit low-loss and adjustable mode selectivity; moreover, they can be directly spliced to a transmission fiber [7]. In this regard, the development of an accurate and non-destructive characterization method of PLs is fundamental in order to optimize their design and fabrication process.

Typically, characterizing the modal evolution in a PL requires cutting back the device and imaging the modes - which is a destructive method. In this paper, we propose a non-destructive technique for complete PL characterization. We use a swept-wavelength interferometer (SWI) to systematically study the evolution of the spatial modes in a PL supporting 10 modes. The SWI measures the backscatter light for each spatial mode in the PL along the adiabatic tapered transition. The proposed technique is useful for understanding the modal properties of complex mode multiplexers and for identifying new photonic lantern designs that allow scaling to larger number of modes. Additionally, fabrication defects can be easily and rapidly detected. The SWI method provides adequate spatial resolution for analyzing mode coupling and mode conversion in tapered fiber devices [8].

2. Experimental setup

The 10 mode selective PL was fabricated using a structured capillary and ten graded-index fibers of six different core sizes to selectively excite each spatial mode [3]. The core diameters of the 10 input fibers are 1x23 µm, 2x17 µm, 2x15 µm, 2x13 µm, 1x9 µm, 2x6 µm for the LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{02}, LP_{12} modes respectively. Figure 1(a) shows a microscope image of the PL at the taper waist, the core diameter is approximately 33 µm and the core-cladding refractive index difference is $16x10^{-3}$ (ensuring that 10 modes are supported). Measured near field mode profiles at the PL output at a wavelength of 1550 nm are presented in Fig. 1(b).

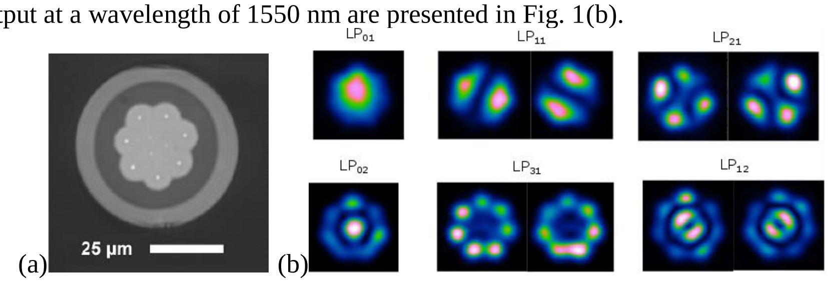


Fig.1 (a) Microscope image of the cross section of the PL at the taper waist. (b) Near field mode profiles of the 10 mode-selecive PL output, measured at a wavelength of 1550 nm.

Figure 2 shows the SWI experimental setup used to characterize the PL. The output from a swept laser is split into two arms by an optical coupler, each output, signal and reference are combined in the polarization diversity receiver, that detects both polarization states simultaneously. Light from the reference arm interferes with the backscatter light coming back from the photonic lantern under test (UT) to create an interferogram as function of the wavelength. The backscattered power in each particular mode is resolved in time domain and additional processing is used to convert it to position. Both signals are digitized for further processing. In this way, scattered light along the PL can be plotted as a function position, giving information about the mode conversion process.

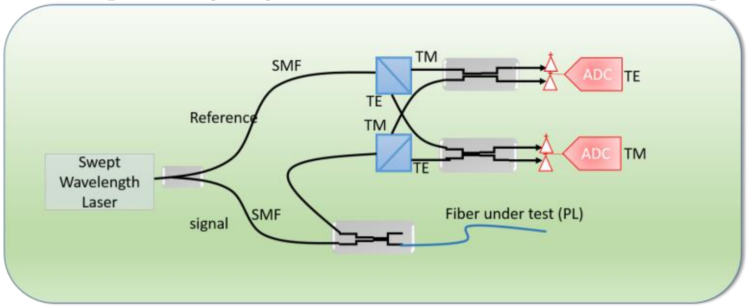
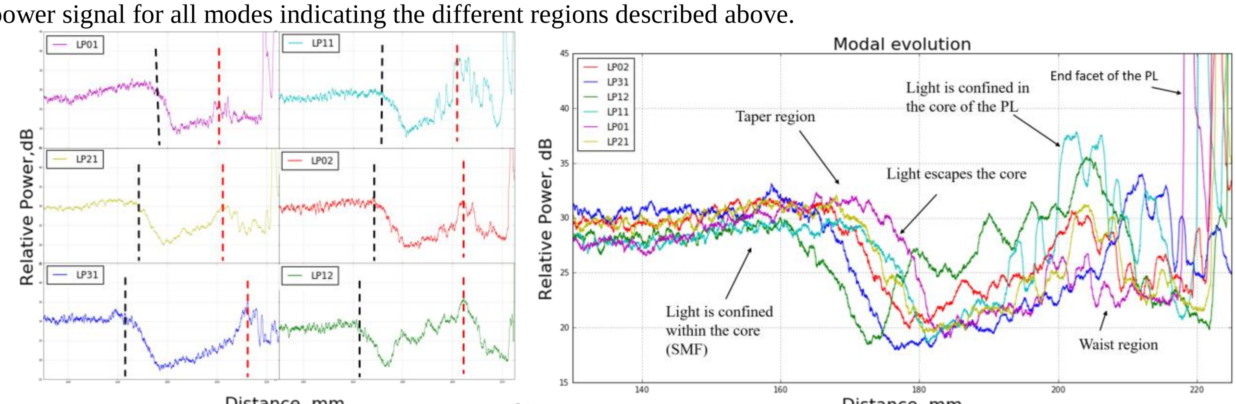


Fig. 2 Schematic of th SWI setup used to measure the backscatter light from a 10 mode-selective PL.

We characterized all input ports of the PL by launching light in each one separately and measuring the backscatter light coming out of the same port. It is important to notice that the measurements were taken 10 times for each PL input in order to improve accuracy.

3. Results and discussion

Figure. 3(a) shows the relative power of the reflected light for six LP spatial modes in the 10 mode-selective PL as a function of position (for degenerate modes only measurements for one mode are presented). As expected, at the beginning of the PL, light is well confined in each individual core (single mode fibers), and a constant back scattered signal is obtained. As the PL is tapered down, light in each individual core extends out into the cladding. Here light from some of the cores begins to couple to other fibers creating a supermode structure. At this point, the power density is transferred from the core to the cladding region and a sudden decrease in the measured relative power of the reflected light is observed. In this figure, the dashed black lines represent the positions at which the modal transition begins. This figure indicates a clear shift in this position for the different modes – for high order modes this effect happens closer to the lantern input. By further tapering the PL, light evolves into a particular mode of the PL output and is confined back to the core of the PL as long as the taper is adiabatic. This point can be seen as a peak in the intensity of the collected signal – indicated by red dashed lines in the figure. Finally, the strong reflection peaks observed after the PL correspond to the PL end-facet. Fig. 3(b) compares the measured relative power signal for all modes indicating the different regions described above.



a) b)

Fig. 3. The relative power of the reflected light for the set of spatial modes (a)Different plots for each mode group (b)Comparison of the modal evolution by plotting the six different spatial modes.

Figure 4.(a) plots the position of the beginning and end of the modal conversion process along PL, black and red curves respectively, for all the different modes. This figure indicates that the modal conversion takes place in ~1 cm and ~1.5 cm for each individual mode (separation between black and red curves). However, the different modes are fully converted at different positions along the PL taper – the fundamental mode requires a longer taper in order to be formed. Therefore, in the studied device, a total transition length of ~2.2 cm is required to create all modes. To corroborate the SWI measurements, we used a cutback method to characterize the lantern output at different positions along the taper. Figure 4.(b) presents output intensity profiles for the different PL modes at three different positions. These images clearly show that the modal evolution along the PL is in excellent agreement with our SWI

results. After the beginning of the taper light is well confined in the core for the first 4LP modes, but for the highest order modes (LP_{31} and LP_{12}) we observe that light starts to extend out of the core. At the middle of the transition light from each input couples to the other cores. At this point the the lower order modes not clearly formed and light is well confined in a few core. In contrast, HOMs are almost visible. Finally, at the waist position the different modes can be clearly seen.

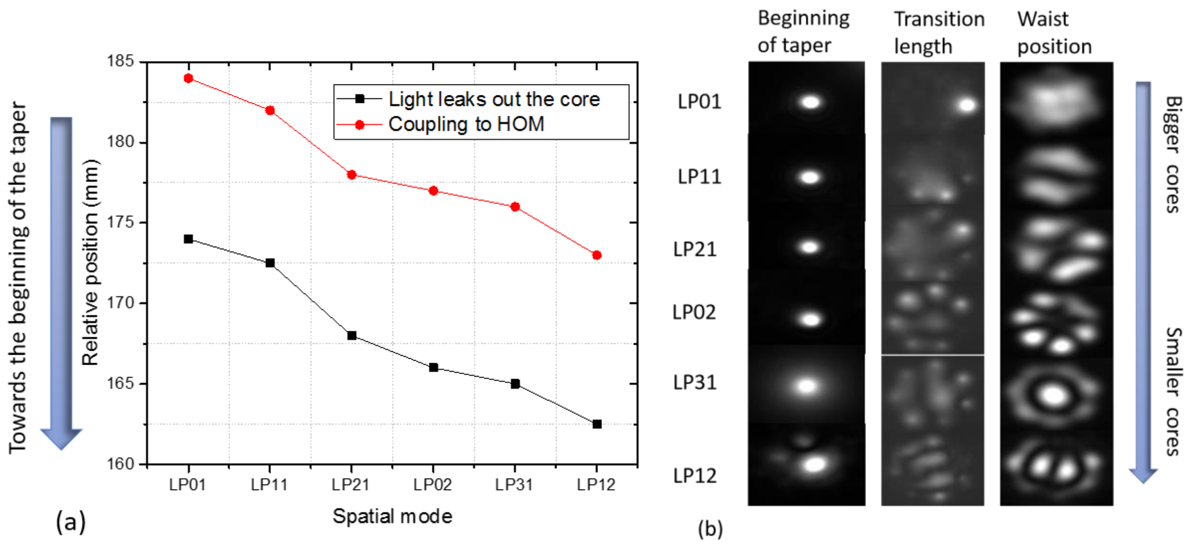


Fig. 4 (a)Position at which the light starts to escape the core for the different core sizes we used, (b) Mode profiles at the output of the lantern for different position along the taper.

4. Conclusion

We provide a comprehensive study of the modal evolution in a 10 spatial mode-selective PL using a swept wavelength interferometer. This technique has the unique advantage of providing a direct observation of the modal evolution along the PL device without the need of destructive measurements such as cutbacks. Our results indicate that for HOMs (smaller input fiber core size) modal conversion in between modes shifts towards the beginning of the PL taper before light is subsequently confined in the new few-moded core of the PL. These results are in great agreement with analytical calculations and numerical simulations. Furthermore, mode images along the taper transition confirm the accuracy of the SWI characterization method. The suggested characterization method shows to be a useful tool for understanding the modal properties of a variety of complex mode multiplexers that can allow for the improvement on the fabrication process and its scalability.

5. References

[1] Peter J. Winzer, et.al., "Optical Networking Beyond WDM", IEEE Photonics Journal, Vol. 4, No. 2, 647-651 (2012).
[2] Z. Sanjabi Eznaveh, et.al., "Few Mode Multicore Photonic Lantern Multiplexer", OFC Technical Digest (2016)
[3] Sergio G. Leon-Saval, et.al., "Mode-Selective Photonic Lanterns for Space Division Multiplexing", Opt. Express 22, 1-9 (2014).
[4] A. M. Velázquez-Benítez, et.al., "Scaling the Fabrication of Higher Order Photonic Lanterns Using Microstructured Preforms", European Conference on Optical Communication (ECOC) (2015).
[5] A. M. Velazquez-Benitez, et.al., "Six mode selective fiber optic spatial multiplexer," Opt. Lett. 4, 1663-1666 (2015).
[6] B. Huang, et.al., "All-fiber mode-group-selective photonic lantern using graded-index multimode fibers," Opt. Express 23, 224-234 (2015).
[7] J. Van Weerdenburg, et.al., "10 Spatial mode transmission using low differential mode delay 6-LP fiber using all-fiber photonic lanterns," Opt. Exp. 23, 24759-24769 (2015).
[8] B.J. Soller, et.al., "Polarization Resolved Measurement of Rayleigh Backscatter in Fiber-Optic Components", OFC Technical Digest (2005)