Few Mode Multicore Photonic Lantern Multiplexer

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Abstract: We demonstrate an all-fiber multi-mode, multi-core photonic lantern mode multiplexer for SDM applications. Selective excitation of 21 spatial channels, LP_{01} and $LP_{11a,b}$ modes in 7 cores, with insertion losses below 0.4dB is obtained.
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1. Introduction

Due to the exponentially increasing internet driven demand, the fundamental capacity limit of the single-mode fiber (SMF) transmission systems is being approached [1]. Previous capacity increases in SMFs have been achieved by utilizing additional degrees of freedom including polarization and wavelength division multiplexing (WDM). To further increase the system's capacity, spatial division multiplexed (SDM) transmission has been investigated in which multiple spatial modes in a single core multimode fiber (MMF), few mode fiber (FMF) [2], multicore fiber [3], or a combination of both [4] are exploited. In order to more efficiently address capacity scaling in a single optical fiber, few-mode multi-core fibers with high number of spatial channels have been reported [4,5]. Mode multiplexers (MUX)/de-multiplexers (DEMUXs), a key SDM sub-system, have widely been implemented using bulk phase masks, integrated devices or 3D waveguides which introduces large insertion losses and severely limit scaling of spatial channels/modes [2-4].

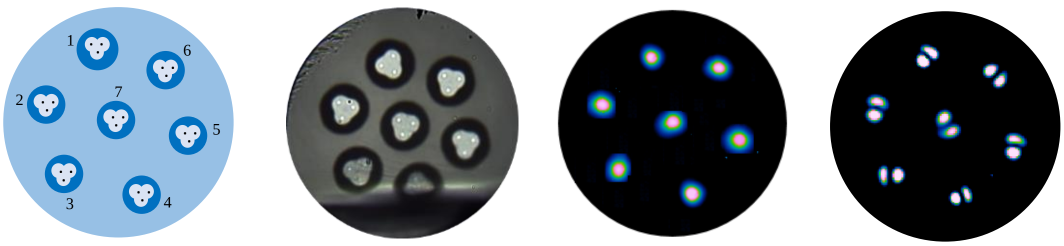
Recently all-fiber photonic lanterns (PL), which allow low-loss transformation of an array of SMF modes to MMF modes, have emerged as a promising MUX/DEMUX for mode division multiplexed transmission [6-8]. A mode selective PL (MSPL), in which the mode degeneracy has been reduced, consists of an array of dissimilar SMF as opposed to the typical non-mode selective PLs with similar SMFs placed inside a low index cladding, gradually tapered down to a MMF. If the number of SMFs matches the number of spatial modes of the MMF, the transition is a reversible low-loss splitter–combiner between the MMF and the SMFs [5,6]. In addition to the ease of splicing PLs to the transmission fiber, mode selective PLs are desired for SMUX implementations in order to avoid or minimize mode coupling, reduce or remove the complexity of multiple input multiple output (MIMO) digital signal processing, compensate differential mode group delay (DMGD) and mode dependent loss. 3-mode MSPLs to excite the LP_{01} and $LP_{11a,b}$ modes using three fibers with different core diameters and different outer diameters, have been reported [9,10]. Furthermore, MSPLs consisting of dissimilar core fibers that excite the first 6, 10 and 15 spatial modes were reported [11-14].

In this work, we present the first demonstration of a 7-core, 3-mode PL MUX capable of selectively generating the 21 spatial modes of a few-mode multi-core fiber. In order to fabricate the 21 mode multiplexer 21 graded index fibers of two different core sizes of 13μm and 11μm were inserted into a structured capillary consisting of 7 low refractive index fluorine doped capillaries. The device efficiently excites the first three modes (LP_{01} and $LP_{11a,b}$) in a multi-core multi-mode configuration with ultra-low core-to-core crosstalk. The measured insertion loss is less than 0.4dB for all modes. This type of PL is promising for future high-density SDM transmission experiments in multi-mode, multi-core fibers, which previously relied on femtosecond inscribed fan-in-fan-out devices with larger insertion loss [4, 5]. The key benefit is that this all-fiber device can be easily handled, is stable and can be easily scaled to multiplex larger number of cores and/or modes per core.

2. 21 Spatial Mode Photonic Lantern

A standard PL consists of an array of isolated identical SMFs inserted inside a low refractive index capillary. The whole structure is then adiabatically tapered such that the SMF cores reduce in size and nearly disappear. As a result, the SMF cladding becomes the new MMF core with the low-index capillary behaving as its cladding.

In order to couple light into individual spatial modes by lunching through each independent SMF, the degeneracy between modes should be removed. This can be fulfilled by using unequal SMF cores which results in dissimilar propagation constants of the initial modes which consequently avoids mode coupling in a PL during the transition stage [10]. To fabricate the 7-core, 3 mode MSPL mode MUX, 21 graded index fibers fabricated in-house were used, seven 13µm core fiber (to excite the 7 LP_{01} mode) and fourteen 11µm core fiber (to excite the $LP_{11a,b}$ modes). Graded index fibers were used to relax the length requirement for achieving an adiabatic transition [11, 12]. All fibers have an outer diameter of 125µm. A structured preform consisting of 7 fluorine doped capillaries with $\Delta n=-9\times10^{-3}$ and 2 mm outer diameter was used to maintain all fibers in an hexagonal arrangement of the few-mode cores. The structure was then tapered to a multi-core fiber with an OD of 125µm, the tapered transition length was 5 cm. Each of the resulting few-mode cores has a diameter of 16µm and the core-to-core spacing is 33.5 µm. Numerical simulations using a fast Fourier transform beam propagation method (FFT-BPM) and modal analysis were used to ensure an adiabatic transition of the device during the tapering stage. Figure 1(a) shows the schematic cross-section of the fabricated multi-core PL, microscope image of the fabricated device (Fig.1(b)), and near field mode profile excitation of all seven (Fig.1(c)) LP_{01} and (Fig.1(d)) LP_{11a} ports.



(a) (b) (c) (d)

Fig.1. (a) Schematic representation of the cross section of the MSPL, (b) microscope image of the fabricated device, (c) excitation of all LP_{01} modes, (d) excitation of all LP_{11a} modes.

To characterize the fabricated 21 mode multiplexer we used a super-luminescent diode centered at 1550 nm. Near field mode profiles were recorded by employing an infrared camera (Xenics, XEVA-1.7-320) focusing the image via a 20x microscope objective. The output beam profiles of the lantern as well as a sample intensity profile for each mode of the central core are presented in Fig. 2.

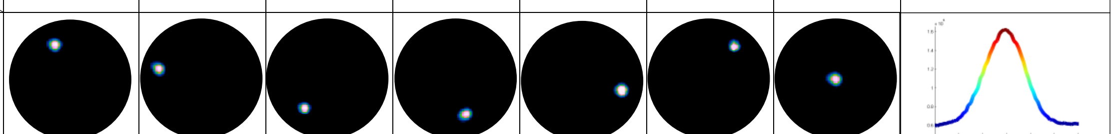
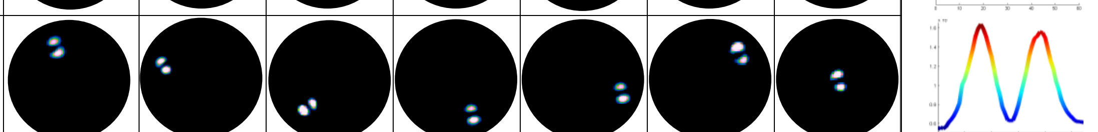
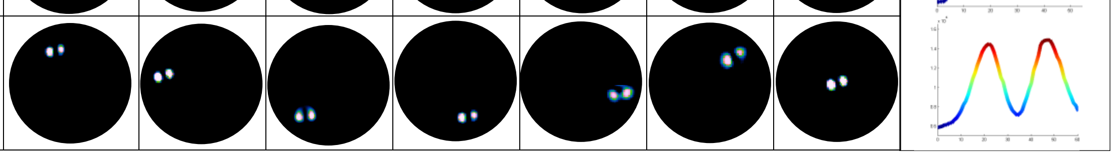
Core / Mode	#1	#2	#3	#4	#5	#6	#7	Intensity Pattern
LP_{01}								
LP_{11a}								
LP_{11b}								

Fig.2. Near filed Images of the excited modes for 7-core MSPL at 1550nm. A sample intensity profile of each mode of the central core is presented on the left.

In figure 2 Independent cores are excited, indicating low inter core crosstalk. The inter core crosstalk measurement was limited by the dynamic range of our camera of 60dB. In addition, selective launching of the LP01 and LP11 modes in all cores is achieved. The intensity profiles shown on the left panel of Fig.2 are comparable to single core MSPL.

3. Conclusions

We have demonstrated the first few-mode, multi-core mode-selective photonic lantern. The device is a 7-core, 3-mode MUX capable of exciting the LP_{01} and $LP_{11a,b}$ modes of the individual cores with low core to core crosstalk. Selective excitation of the LP_{01} and $LP_{11a,b}$ modes is achieved for individual PL cores. By inserting 21 graded-index fibers at two different sizes of 13μm (to excite LP_{01} mode) and 11μm (to excite LP_{11} modes) in a fluorine doped preform and tapered down to 125μm OD, we obtained a multi-core facet with individual core diameters of 16μm and 33.5μm core to core distance. The seven cores are positioned in a hexagonal arrangement. However, different core arrangements are feasible. Device characterization was performed by coupling a super-luminescent diode centered at 1550nm. The experimental observations confirmed low insertion losses of less than 0.4 dB for all modes. The proposed multi-core, few-mode PL is a compact component that can play an important role for emerging few-mode, multi-core transmission systems. In addition, the device is scalable to larger number of cores and/or modes per core.

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