Low-loss Low-MDL Core Multiplexer for 3-Core Coupled-core Multi-core Fiber

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Abstract: A fiber-based core multiplexer is designed, fabricated, and evaluated. Insertion losses vary between 0.74 dB and 0.91 dB. Digital holography reveals mode-dependent loss fluctuates between 0.3 dB and 0.9 dB across C- and L-band.

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1. Introduction

In recent years, multi-core fibers with coupled cores have emerged as a promising candidate for space-division multiplexing (SDM) optical transmission. In particular, low (differential) attenuation, low mode-dependent loss (MDL), and low differential group delay (DGD) are very interesting from a system design point of view. Due to the strong coupling regime in which these fibers operate, MDL and DGD scale with the square root of transmission distance instead of linearly [1]. This significantly reduces the complexity of the required multiple-input multiple-output (MIMO) digital signal processing to unravel the scrambled modes and successfully recover the data [2].

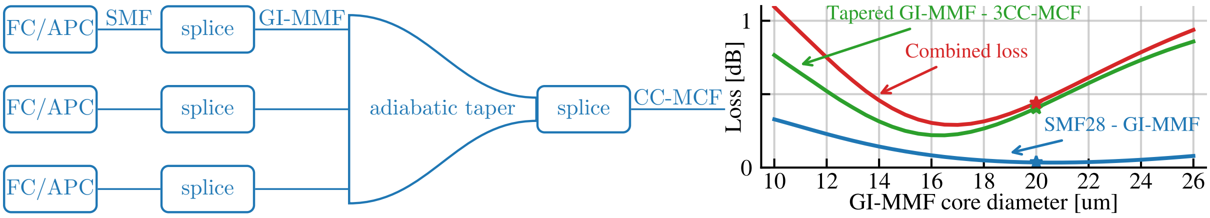
To be able to use coupled-core multi-core fibers with existing infrastructure, core multiplexers (CMUXs) are required to interface with standard single-mode fibers (SSMFs). Approaches using free-space optics [3] were first utilized to couple to 3-core coupled-core multi-core fiber (3CC-MCF). Additionally, fiber tapers similar to photonic lanterns [4] were used to couple to four-core [5] and seven-core [2] fibers. Often, only insertion loss (IL) is reported, but MDL is also a metric of interest for SDM transmission systems. Therefore, it is important to estimate both IL and MDL to properly evaluate multiplexer performance.

In this work, a fiber-based CMUX with low IL and low MDL is presented. Design considerations, fabrication of the photonic-lantern adiabatic taper, and performance measurements are addressed. Measurements using a broadband light source show IL between 0.74 dB and 0.91 dB for the input ports. Digital holography is used to capture the full complex polarization-diverse transfer matrix of the device, revealing that MDL fluctuates between 0.3 dB and 0.9 dB across the C- and L-band.

2. Core multiplexer design and fabrication

The schematic representation of the CMUX is shown in Fig. 1a. The device consists of three single-mode pig-tails, each spliced to graded-index multi-mode fiber (GI-MMF), a tapered section, and a splice to 5 meters of 3CC-MCF. The envisioned usage of this CMUX is to interface between the single-mode domain where SSMF is used and the 3CC-MCF of interest. A microscope image of the facet of the 3CC-MCF is depicted in 2a, more information about the fiber can be found in [1] where it is denoted as '3CF29' Throughout this work, unless otherwise stated, insertion losses and MDL are defined over the entire device as depicted in Fig. 1a. The photonic lantern like adiabatic taper is fabricated by inserting three GI-MMFs in a fluorine-doped capillary which is subsequently adiabatically tapered down to a designed diameter.

The 3CC-MCF consist of three step-index cores placed close together to promote strong coupling [3]. The propagation of light inside this fiber can be described using super-modes [6]. When the cores are spaced sufficiently far apart, as is the case in this work, the light is primarily confined within the individual cores instead of the area in between the cores. In this case, it is convenient to choose a modal basis consisting of three separate single-mode spots, which is a unitary transformation of the super-mode basis and therefore equally valid. This is true for both the fiber facet and the taper facet. Therefore, one can estimate the coupling loss of the splice between the taper-end and the 3CC-MCF by calculating the modal overlap between the mode in one of the spots of the 3CC-MCF with the mode present in the shrunk down GI-MMF. How much it is shrunk down is defined as the taper ratio, set by geometry of the 3CC-MCF and the cladding diameter of the GI-MMF to guarantee good alignment. This ratio is 4.25 for a core distance of 29.4 μm and a cladding diameter of 125 μm. The loss originating from the modal mismatch at the 3CC-MCF facet is depicted in Fig. 1b by the green line for a GI-MMF with a quadratic index profile, an index difference of 11.5×10^{-3}, for various core diameters. Since we are interested in the overall device loss, from single-mode connector to coupled-core fiber, the splice loss between SSMF and GI-MMF should



(a) (b)

Fig. 1: (a) Schematic of the core-multiplexer and its simulated coupling losses (b). Stars indicate fiber parameters used for the fabricated device.

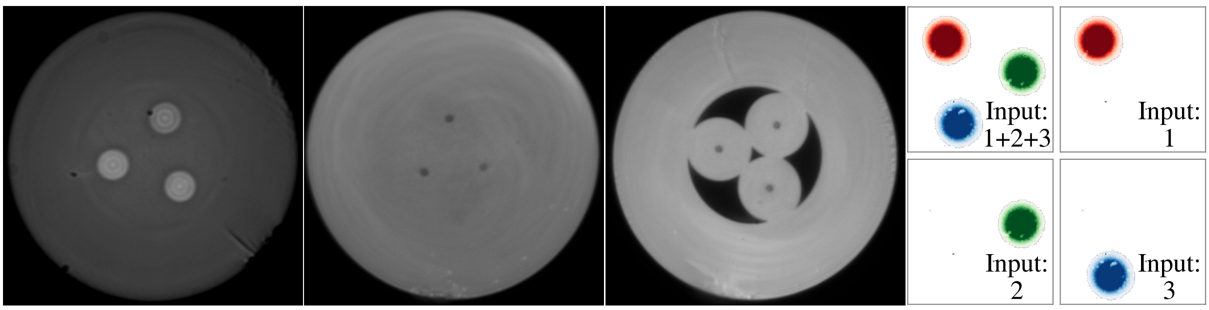
also be taken into account. This is done similarly as before by calculating the overlap integral between the mode profiles. Fig. 1b reveals that a core diameter of 17 µm would lead to a total loss of 0.3 dB. Unfortunately, a fiber with these specific parameters was not available to the authors. The modal overlap analysis was performed for the fibers that were available and the best one was selected. The expected loss of a CMUX using this 20 µm core diameter, 11.5×10^{-3} index difference, 6-mode GI-MMF is 0.43 dB.

Three pieces of GI-MMF were stripped of their coating and inserted in a fluorine-doped glass capillary with an outer diameter of 565 µm and an inner diameter of 275 µm. The structure was tapered linearly for 20 mm using a Fujikura LZM-100 CO_2 laser glass processing station. The temperature during tapering can be increased to such a degree that the capillary collapses during tapering, pushing out the air between the fibers, thus fully fusing it, see Fig. 2b. Alternatively a lower temperature can be used to preserve the airholes, see Fig. 2c. Both types gave promising results. The specific device reported on in this work is fully-fused. Generally, a fully-fused design leads to better geometry at the end-facet and allows for easier splicing to the 3CC-MCF. On the flip-side, scattering inside the taper is slightly worse due to the collapse of the capillary and the better confinement when airholes are present.

3. Measurement setup and results

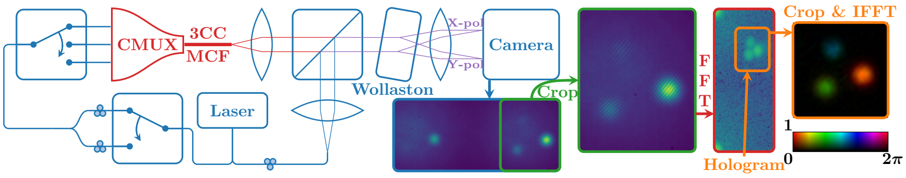
Qualitative measurements were performed to test the tapering process. The far-field intensity profile of the light emitted from the taper-facet is obtained by capturing the collimated light using an infrared camera. Fig. 2d shows the intensity from coupling broadband light into each of the inputs of the taper, respectively. These images show three well-separated spots with no observable inter-core coupling, confirming our assumptions. At this stage of fabrication, the device consisted of FC/APC pig-tails, splices to GI-MMF, and the taper. To evaluate the losses before splicing the taper to the 3CC-MCF, a large-area photodetector was slid in front of the collimated beam to measure its power. Insertion losses of 0.26 dB, 0.38 dB, and 0.17 dB were measured for this specific CMUX. Note that the quality of the splice between SSMF and GI-MMF is important for the overall device performance. Small splicing misalignments contribute to the device loss but to a larger extend, the MDL since light coupled into higher-order modes is scattered inside the taper and may end up in the other cores. Therefore, the splices at the input of the taper were later optimized and the previously mentioned loss figures could have changed as a result. Loss figures around 0.2 dB are not uncommon, with some tapers showing loss figures as low as 0.12 dB.

Before splicing the taper to 5 meters of 3CC-MCF, alignment was optimized in terms of insertion loss. The splicing was done using a so called 'cold splice' technique where temperature is kept relatively low and further re-heating improves the strength and quality of the splice. This technique prevents the soft fluorine capillary of

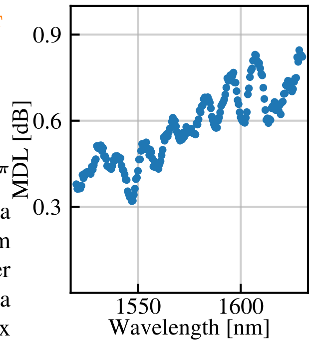


(a) 3CC-MCF (b) Fully-fused taper (c) Taper with airholes (d) Far-field of (b)

Fig. 2: Microscope images of the facets of the 3-core coupled-core multicore fiber **(a)**, a fabricated fully-fused taper **(b)**, and a taper with airholes **(c)**. **(d)** depicts the far-field intensity profile for different input ports of a fully-fused taper.



(a) Beating between signal from the core multiplexer (CMUX) and reference light creates a fringe pattern. Camera frames are recorded for each input port and polarization. Hologram extraction is performed through cropping of the interference pattern per polarization, a Fourier transform, cropping the hologram, and an inverse Fourier transform. Extracted hologram is a complex field which is used to calculate the 6x6 complex polarization-diverse transfer matrix which is needed to evaluate mode-dependent loss (MDL).



(b)

Fig. 3: Digital holography setup (a) used to characterize MDL (b) which fluctuates between 0.3 dB and 0.9 dB across C- and L-band

the taper from deforming by becoming too soft. This is especially important when attempting a splice with a taper which is not fully-fused since excess glass tends to flow in to the airholes. Where the splice quality is poor , or when losses were too high, further heating through a flame brushing technique was attempted to improve the splice. This was also the case for the CMUX reported here. After fabrication, the device was taped down on a plastic plate and the insertion loss was measured again. The 3CC-MCF was bent slightly during this measurement to ensure any cladding light escaped and was not erroneously measured. The insertion loss of the device was measured to be 0.74 dB, 0.90 dB, and 0.91 dB, respectively.

Off-axis digital holography [7,8] is used to obtain the MDL of the fabricated CMUX. This technique allows for the characterization of a single multiplexer as opposed to a pair of them. The light emitted from the 3CC-MCF of the CMUX is combined with a coherent reference beam under an angle and recorded by an infrared camera in a 4f free-space optical setup as shown in Fig. 3a. The beating between the signal and the reference produces a hologram which is revealed through the Fourier transform of the captured camera frame. This hologram contains the full amplitude and phase response of the specific input port and polarization for this particular wavelength. Using optical switches, the output for each input port and polarization is captured providing the data for a full polarization-diverse transfer matrix. The measurement is repeated for all wavelengths of interest by tuning the $<$100 kHz linewidth laser. Off-line digital signal processing is used to extract the complex optical field and to remove residual linear and quadratic phases. The transfer matrix between the excited input and the modes present in the 3CC-MCF is determined through an overlap integral with a modal basis consisting of three separate spots. MDL, plotted in Fig. 3b, is calculated through singular value decomposition of this transfer matrix. Note that the losses of the optical paths through both switches at the inputs of the CMUX were not calibrated to be equal, which influences measured MDL. Weights applied to the transfer matrix are used to minimize this effect and the effect of non-uniformity of the intensity of the reference beam. After these corrections, the MDL is measured to fluctuate between 0.3 dB and 0.9 dB in the C- and L-band.

4. Conclusions

A fiber based photonic-lantern core multiplexer is designed, fabricated, and evaluated. Due to low insertion and mode-dependent loss (MDL), the multiplexer device is an attractive solution for interfacing between 3-core coupled-core multi-core fiber (3CC-MCF) and standard single-mode fiber, paving the way towards future lossless solutions. Measurements show insertion losses between 0.74 dB and 0.91 dB for the different input ports. By digital holography, the full complex polarization-diverse transfer matrix is captured, indicating that MDL fluctuates between 0.3 dB and 0.9 dB across C- and L-band.

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