Efficient multi-mode to single-mode coupling in a photonic lantern

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Abstract: We demonstrate the fabrication of a high performance multi-mode (MM) to single-mode (SM) splitter or "photonic lantern", first described by Leon-Saval *et al.* (2005). Our photonic lantern is a solid all-glass version, and we show experimentally that this device can be used to achieve efficient and reversible coupling between a MM fiber and a number of SM fibers, when perfectly matched launch conditions into the MM fiber are ensured. The fabricated photonic lantern has a coupling loss for a MM to SM tapered transition of only 0.32 dB which proves the feasibility of the technology.

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1. Introduction

Optical fibers have been used by astronomers for many years to transport light from the telescope focus to an optical spectrograph placed either at the back end of the telescope or some more distant location [1, 2]. For the most part, observational astronomy is a photon-starved discipline, hence the need for large-core fibers to increase the étendue of the optical system compared to single-mode fibers. These large-core fibers propagate many unpolarized modes which has deterred the use of more complex photonic functions, since these are almost exclusively limited to single-mode propagation. It is therefore recognized from the outset that a multimode to single-mode converter would have major implications for astronomy.

The Earth's atmosphere is a fundamental limitation to deep astronomical observations at near-infrared wavelengths. High altitude hydroxyl radiates hundreds of extremely bright, ultranarrow emission lines that completely dominates the background at wavelengths from 1000 nm to 1800 nm. It is now possible to envisage an ultrabroadband fiber Bragg grating, that can reflect the unwanted signal while allowing the desired signal to enter the dispersing spectrograph [3-5]. In order to use these gratings, we need a photonic lantern, that efficiently couples light from the large-core MM fiber into SM fibers. The principle of a device for this purpose was first demonstrated in 2005 by Leon-Saval and coworkers. They used a special ferrule with air voids to obtain a transition from 19 SM fibers to a MM fiber. The MM fiber was defined by a silica core surrounded by air and suspended by thin silica bridges [6]. In general, the photonic lantern relies on adiabatic coupling between a MM fiber and a number of SM fibers. Such coupling is achievable given that the number of spatial modes propagating in the MM fiber is equal to or less than the number of SM ports. If the number of SM ports is less than the number of spatial modes in the MM fiber, efficient coupling cannot take place due to the insufficient degrees of freedom in the SM fiber ensemble, consistent with the brightness theorem. In previous reports no effort was made to match the number of excited modes in the MM section to the number of available SM ports, hence the overall throughput of the system was low [6].

In this paper, we demonstrate, to the best of our knowledge, the first low loss MM to SM coupling in a photonic lantern. The coupling into the MM fiber of the photonic lantern is done by fabricating two identical devices and using one of them to couple light into the other. The low loss coupling into the photonic lantern shows that it is indeed possible to make MM to SM converters that can be used for astronomy applications.

2. Fabrication of the photonic lantern

The SM fibers used are OFS Clearlite fibers, with an outer diameter of 80 µm, a mode-field-diameter of 7.5 µm, and a higher-order mode cut-off wavelength of ~1500 nm. A bundle of 7 SM fibers is inserted into a low-index glass capillary tube. The fiber filled capillary tube is then fused and tapered down by a factor of 4 into a solid glass element. This is done on a filament based GPX-3100 glass processing station from Vytran. The tapered element will act as a MM waveguide with a core that consists of fused SM fibers and a cladding formed by the low index capillary tube. Figure 1(a) shows an illustration of the tapered fiber bundle. The fabrication technique of the photonic lantern is similar to what is used for making 1x7 fused couplers [7]. This method ensures that the MM section of the photonic lantern is not defined by the means of air-holes but merely by glass of different refractive index. The all-glass approach makes the device simple to fabricate and facilitates good reproducibility.

Figures 1(b)-1(d) show microscope pictures of the bundle cross section at different positions along the taper. The tapering of the fiber bundle is done over a length of 40 mm and, by adjusting the filament power during the taper, the point at which the fiber bundle is fully collapsed can be controlled. In Fig. 1(b) the fibers are lightly stitched together and in Fig. 1(d) the fibers are completely fused together to form the core of the MM fiber.

Since the higher-order mode cut-off wavelength is ~1500 nm, the V-parameter at this wavelength will be ~2.4. This means that for a taper ratio of 4, the V-parameter of the tapered SM fibers at a wavelength of 1500 nm is less than 1. Therefore, the mode-field diameter will be much larger than the diameter of the fiber core and light will leak from the SM cores into the MM fiber [8].

The MM fiber has a core diameter of ~60 µm and an outer diameter of ~110 µm. The refractive index difference of the low index capillary tube and the fused SM fibers is $1.3 \cdot 10^{-3}$, corresponding to an NA of 0.06 of the MM section. This means that the V-number of the MM fiber at a wavelength of 1500 nm is V=7.5, and the number of spatial modes supported is ~13 [9]. The number of modes is slightly higher than the number of SM input fibers, and can be decreased by tapering the device further. This would however result in a very fragile device. Therefore, ~13 modes was the chosen compromise with the given capillary tube.
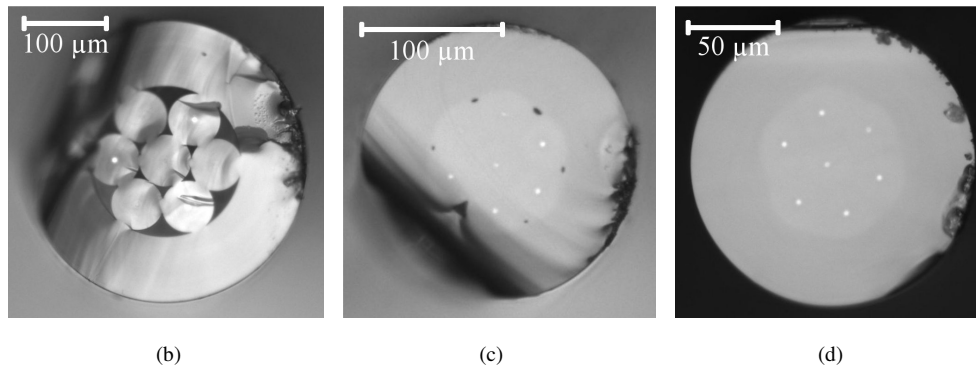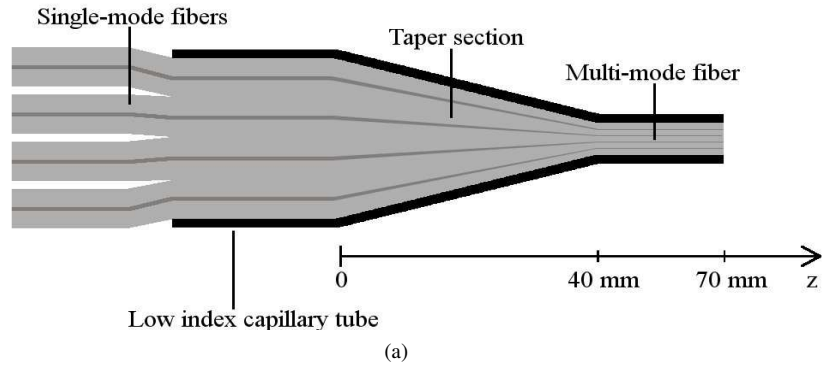
Fig. 1. Schematic illustration of the photonic lantern. (b)-(d) Microscope pictures of the fiber bundle cross section at different positions in the taper transition, at z=5 mm, z=20 mm and z=25 mm, respectively.

3. Optical characterization of the guided modes in the multi-mode section

In the tapered end the original SM cores no longer act as individual waveguides. Figures 2(a)-2(h) show near-field images of the MM waveguide at wavelengths from 1060 nm to 1600 nm. In the images light is coupled into the device through a single input port. At a wavelength of 1060 nm, the mode is still confined to the cores of the original SM fibers. At longer wavelengths, the original cores no longer confine the mode, and the light is smeared out over the entire core of the MM waveguide. A tendency for the light to have the highest intensity around the original cores can still be observed.

In Figs. 2(c)-2(h) it is shown how the field distribution of the MM waveguide changes with wavelength from a wavelength from 1500 nm to 1600 nm. It can be seen that although the intensity is higher at the positions of the original SM fiber cores, these regions do not act as individual waveguides. The near-field images suggest that the lowest order transverse modes can be viewed as a set of super-modes. Each super-mode extends across a large portion of the waveguide. By gradually tuning the laser wavelength, while keeping the device mechanically fixed, the shape of the near-field undergoes gradual changes. The coupling from one SM core to a subset of low order modes in the MM section will depend on interference (or relative phase relationship) between all these modes. Since the effective index of the different guided modes is wavelength dependent, changing the wavelength will thus induce changes in the exact power distribution of these low order modes.
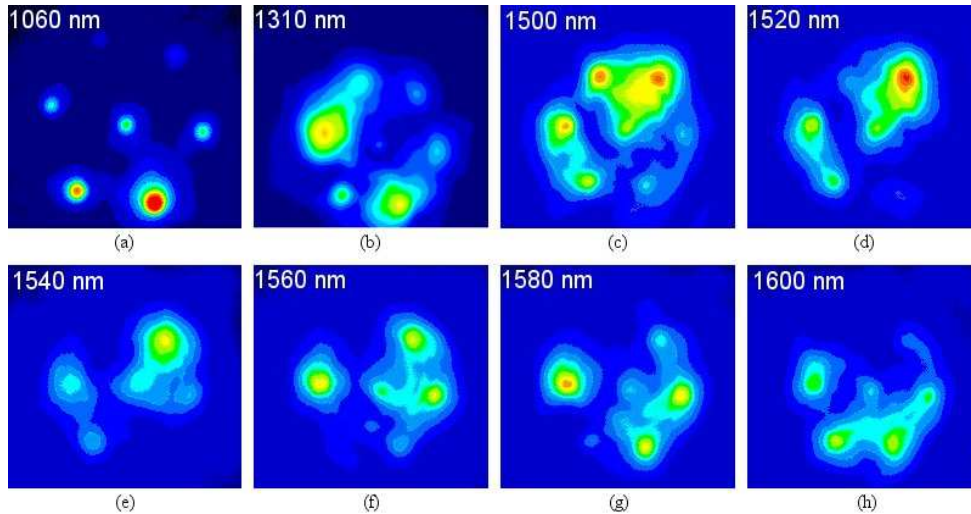
Fig. 2. Near-field images of the MM waveguide at wavelengths from 1060 nm to 1600 nm.

4. Single-mode to multi-mode transmission efficiency

In order to characterize the transmission efficiency of the device, the loss is measured for light undergoing the transition from a SM fiber to the MM waveguide. The setup used for this measurement is shown in Fig. 3(a). 7 FC/PC connectorized SMF-28 patch cords, with a known loss, are spliced to each of the 7 input fibers. The transmission loss is measured by sending 1558 nm laser light into one SM fiber at the time and measuring the transmitted power out of the MM waveguide using an integrating sphere. In Fig. 3(b) the numbering of the ports is shown and Table 1 shows the losses of the device for each of the 7 ports. In the table, the coupling loss from the laser to the input port (typically 0.15 dB) and splice loss from SMF-28 to 80 µm fibers (0.1 dB) are not included. The average SM to MM loss of the device is 0.24 dB, corresponding to 95% transmission efficiency. The result shows that the fabricated device can indeed be used to combine light from the SM fibers into a MM fiber with a low transmission loss. A low transmission loss when going from SM to MM can, however, be expected, since the degrees of freedom in the MM fiber are higher than in the SM fiber ensemble.
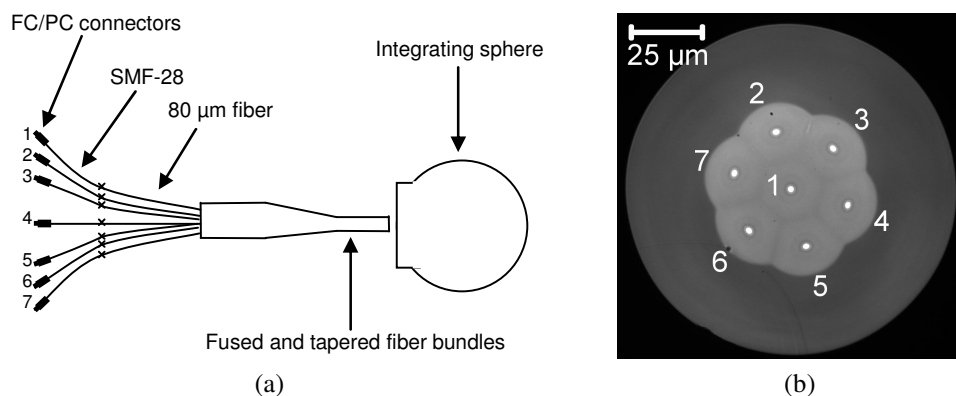

Fig. 3. (a) Illustration of setup used to measure SM to MM loss. (b) Microscope picture of the end-facet of the MM fiber. The original SM fibers are identified in the MM fiber and marked as seen in the image.

Table 1. Measured transmission loss from SM to MM.

Input port	SM to MM loss
1	0.19 dB
2	0.29 dB
3	0.36 dB
4	0.24 dB
5	0.13 dB
6	0.18 dB
7	0.28 dB
Average	**0.24 dB**

5. Multi-mode to single-mode transmission efficiency

In real applications, skylight will be coupled into the MM end of the photonic lantern. In order to achieve an efficient MM to SM coupling, it is critical to optimize the coupling optics to match both spot size and NA. This will ensure that light is coupled into the lowest order transverse modes and that the number of excited modes not exceeds the number of SM fibers. The MM section of the fabricated photonic lanterns supports ~13 guided modes. The devices have 7 SM ports which means that only the 7 lowest order modes can be coupled to the ensemble of SM fibers. If all 13 modes of the MM fiber are excited and equal coupling is assumed to each mode the loss will be: 7/13 ~ 3 dB. If only the 7 lowest order modes are excited this loss can be reduced significantly. A method of ensuring a correct number of excited modes is by coupling two devices back-to-back, i.e. using the MM output from one photonic lantern to couple into the MM end of another. In this configuration, the input SM to MM device ensures that 7 or more transverse modes are excited, which means that an optimal incoupling into the photonic lantern is achieved. This is opposed to using a lens, where it will be difficult to verify the exact number of excited modes.

In Fig. 4(a) the MM section of two photonic lanterns can be seen. A slight mismatch between the outer diameters of the two can be observed. The input device has an outer diameter of 103 µm (left side in Fig. 4), while the outer diameter of the other is 96 µm (right side in Fig. 4). Light is coupled from the larger towards the smaller (left to right). Figure 4(b) shows the two MM sections after the splice. It can be seen that the splice was not perfect, and that the MM cores are bending slightly at the interface. Both the diameter mismatch and the bending in the splice will negatively affect the transmission losses.

The setup for measuring the SM through MM to SM loss is shown in Fig. 4(c). At the output, all 7 fibers are cleaved and mounted side-by-side using double adhesive tape. A 2 cm stripped length was left on all fibers and a drop of high-index liquid was applied to remove cladding light. Adding the high-index liquid changed the measured power less than 0.01 dB, showing that all light is in fact guided in the SM cores. An integrating sphere is used to measure the total power transmitted through the 7 output fibers. Light from a 1558 nm laser is coupled to one input port at the time, and the combined light out of the 7 SM ports of the right device is measured. The transmission losses are shown in Table 2. The losses in the table include transmission losses through both devices as well as splice loss between the two MM to MM sections. Coupling loss from the laser to the input port (typically 0.15 dB) and splice loss from the SMF-28 to 80 µm fiber (0.1 dB) are not included. The numbering of the input ports follows the numbering shown in Fig. 3(b).
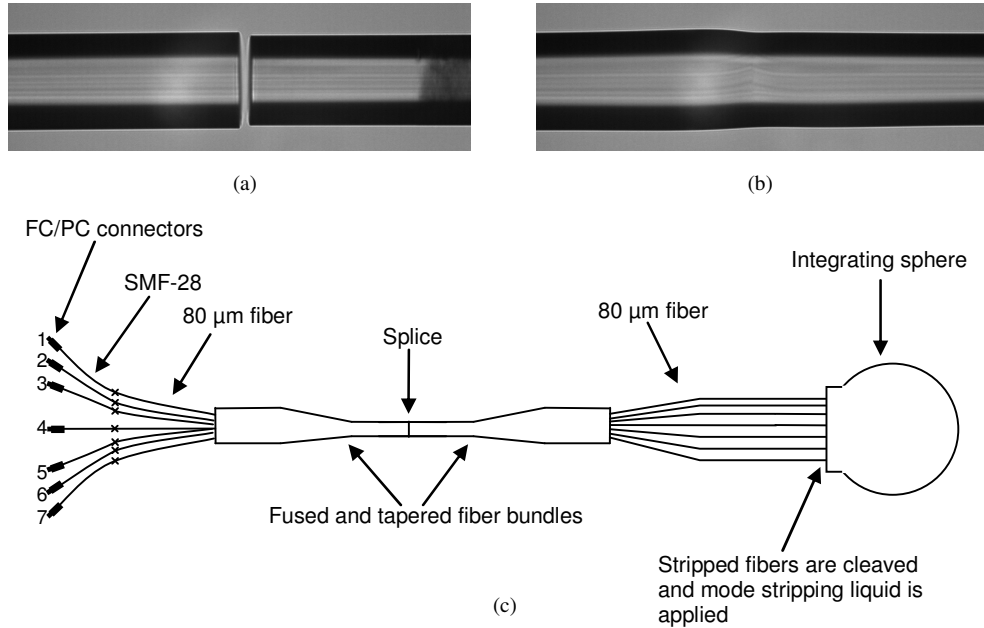
(a)

(b)

(c)

Fig. 4. (a) and (b) Microscope pictures of the splice of MM fiber to MM fiber, before and after splice, respectively. (c) Illustration of setup for measuring the SM through MM to SM loss.

Table 2. Measured transmission loss from SM through MM to SM fibers.

Input port	SM-MM-SM loss
1	0.91 dB
2	0.52 dB
3	0.52 dB
4	0.69 dB
5	0.24 dB
6	0.52 dB
7	0.49 dB
Average	**0.56 dB**

From Table 2 it can be seen that the transmission loss through the two devices is low. The average loss for light undergoing the transition from SM waveguide to MM waveguide and back into SM waveguides is 0.56 dB. Of this loss, 0.24 dB originates from the SM to MM transition shown in Table 1. Therefore, the average transmission loss from MM fiber to the SM fiber ensemble was only 0.32 dB, corresponding to a transmission of the photonic lantern of 93%. This shows that it is indeed possible to make a low loss transition from a MM fiber to a number of SM fibers.

6. Conclusion

In conclusion, we have demonstrated a low loss photonic lantern. In order to couple light into the device with the correct NA and spot size that will ensure excitation of the 7 lowest order modes of the device, a similar photonic lantern is used for incoupling of light. The achieved low transmission loss of 0.32 dB from MM to SM in the photonic lantern demonstrates the feasibility of the device in transferring skylight into a number of SM fibers. Thereby, enabling spectral filtering of the light in SM fibers that cannot be done in MM fibers.

In an application where spatially incoherent light is to be coupled into a MM fiber and split into a number of SM fibers, there are a number of challenges: Firstly, the coupling into the MM fiber must be done in such a way that the number of excited modes is less than or equal to the number of SM fibers. This can be done by making sure that the coupling lens has a sufficiently low NA. Secondly, the number of SM fibers must be large, since this will enable a large overall coupling efficiency into the MM fiber. We will report on higher port count photonic lantern devices in future publications.