Efficient multi-mode to single-mode conversion in a 61 port Photonic Lantern

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ABSTRACT

We demonstrate the fabrication of a multi-mode (MM) to 61 port single-mode (SM) splitter or "Photonic Lantern". Low port count Photonic Lanterns were first described by Leon-Saval et al. (2005). These are based on a photonic crystal fiber type design, with air-holes defining the multi-mode fiber (MMF) cladding. Our fabricated Photonic Lanterns are solid all-glass versions, with the MMF defined by a low-index tube surrounding the single-mode fibers (SMFs). We show experimentally that these devices can be used to achieve efficient and reversible coupling between a MMF and 61 SMFs, when perfectly matched launch conditions into the MMF are ensured. The total coupling loss from a 100 µm core diameter MM section to the ensemble of 61 SMFs and back to another 100 µm core MM section is measured to be as low as 0.76 dB. This demonstrates the feasibility of using the Photonic Lanterns within the field of astrophotonics for coupling MM star-light to an ensemble of SM fibers in order to perform fiber Bragg grating based spectral filtering.

Keywords: Fiber optics components, Astronomical optics

1. INTRODUCTION

Optical fibers have been used in astronomy for many years to transport light from the telescope focus to the optical spectrograph. In order to increase the amount of light to the detector large-core MMFs are preferred [1,2]. In the near infrared part of the spectrum from 1.0 µm to 1.8 µm, high altitude hydroxyl in the Earth's atmosphere radiates hundreds of extremely bright, ultranarrow emission lines that completely dominates the spectral background. In recent years fiber Bragg gratings have been demonstrated that can reflect the unwanted signal while allowing the desired signal to enter the spectrograph [3,4]. These fiber Bragg gratings can only be made in SMFs. In order to build an astronomical system that combines a high optical throughput with complex optical filter functions, a Photonic Lantern that efficiently couples light from a large-core MMF to an ensemble of SMFs is needed. A sketch of an optical system with two Photonic Lanterns coupled back-to-back and gratings in the SMF ports is shown in Fig. 1. The input Photonic Lantern splits light from a MMF core to an ensemble of SMFs. Gratings in the SMFs filter out unwanted emission lines and the output right Photonic Lantern combines the light back into a MMF core.

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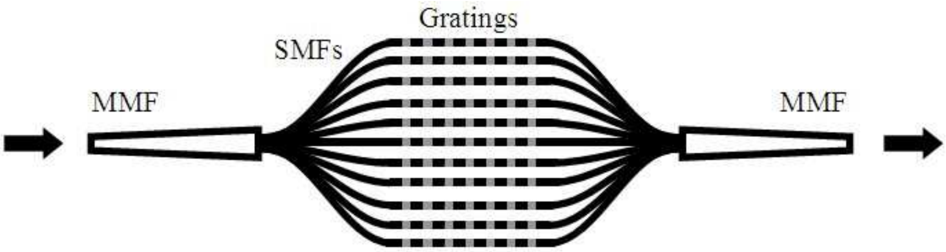

Figure 1. Schematic illustration of an optical system with two Photonic Lanterns in a back-to-back configuration and fiber Bragg gratings in each of the SMF ports.

The principle of the Photonic Lantern was first demonstrated in 2005 by Leon-Saval et al. [5], and the first low-loss few-mode Photonic Lantern with 7 SM ports was demonstrated in 2009 [6]. In the current paper we demonstrate a high port count low-loss Photonic Lantern. The Photonic Lantern features a bundle of 61 SMFs surrounded by a low-index glass capillary tube. The bundle of SMFs is adiabatically tapered to form a MM waveguide with the low-index tube acting as cladding material. Efficient coupling from the MM waveguide to the SMF ensemble is only possible if the number of excited modes in the MM waveguide is less than or equal to the number of SM ports (follows from the brightness theorem). The motivation for going to a higher number of SM ports is to increase the throughput of the system due to the higher number of modes that can be excited in the MM section. The supported NA of the Photonic Lantern MM tip is ~0.09 and the core diameter is 100 µm. In this paper, coupling of light to the MM end is performed using a step-index MM fiber that matches the NA of the MM Photonic Lantern tip. A further description of the devices can be found in [7].

2. FABRICATION OF THE PHOTONIC LANTERNS

The Photonic Lanterns are fabricated by inserting 61 SMF-28 fibers into a low refractive index glass capillary tube. The fiber filled capillary tube is fused into a solid glass element and tapered by a factor of 10 over a length of 100 mm. The tapering is performed on a filament based GPX-3100 glass processing station from Vytran [8]. The thin end acts as a MM waveguide with a core consisting of the 61 fused SMFs and a cladding formed by the low-index capillary tube. Figure 2 shows a schematic illustration of the fabricated Photonic Lantern. The 61 SMFs are seen in the left side of the image and the tapered MM tip is seen in the right side.

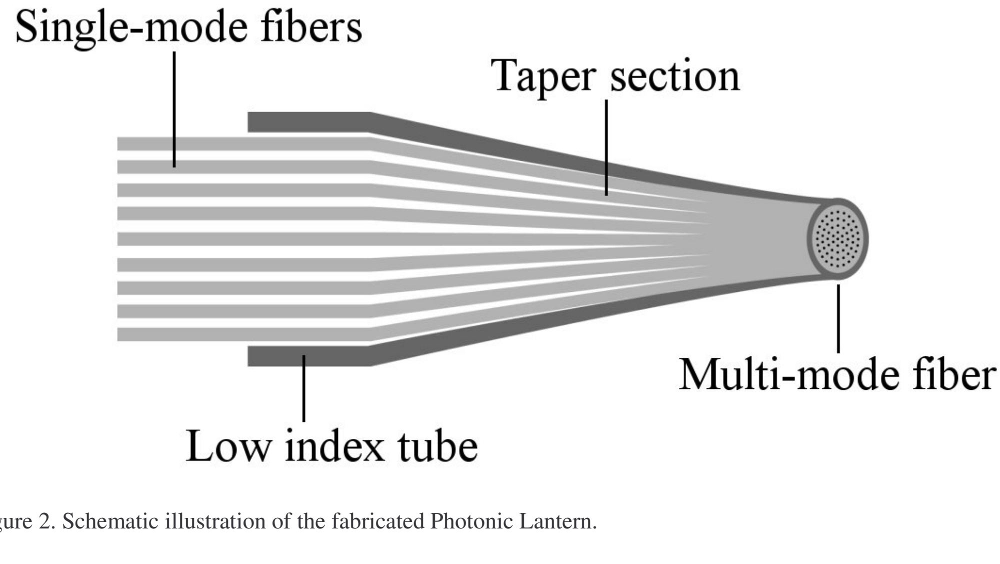

Figure 2. Schematic illustration of the fabricated Photonic Lantern.

The V-parameter of a waveguide is defined as

$$V = \frac{2\pi}{\lambda} a NA \,, \tag{1}$$

where λ is the wavelength, a is the radius of the waveguide core and NA is the numerical aperture of the waveguide, which is given by the refractive index difference between the core and the cladding of the fiber [9]. From this parameter the number of modes M supported by the waveguide can be calculated

$$M \approx \frac{2V^2}{\pi^2} + 1 \,. \tag{2}$$

The MM tip of the Photonic Lanterns need to support M=61 modes at a wavelength of λ=1.55 µm. A low-index tube with a guided NA of ~0.09 is chosen for the fabrication of the Photonic Lanterns. Consequently, the V-parameter of the waveguide is ~18 and the number of supported modes is slightly higher than 61.

Figure 3 shows an image of the fabricated Photonic Lantern. The 61 SMFs are seen in the left side of the image and the tapered MM tip with an OD of 125 µm is seen in the right side.

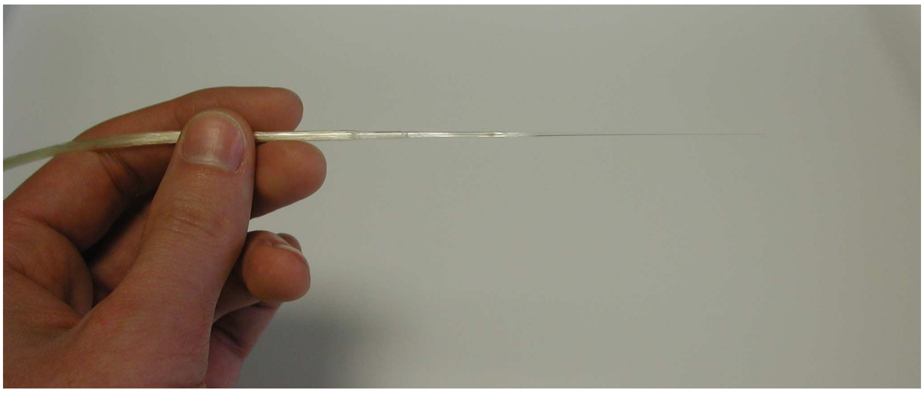

Figure 3. Image of the Photonic Lantern.

By adjusting the filament power during the taper, the point at which the fiber bundle is fully collapsed can be controlled. Figure 4 shows microscope pictures of the bundle cross section at different positions along the taper. In Fig. 4(a) the fibers are lightly stitched together and in Fig. 4(b) the interstitial holes between the fibers start to close. In Fig. 4(c) the fibers are completely fused together to form the core of the MM fiber. In Fig. 4(d), the MM tip of the Photonic Lantern is shown. The core diameter is 100 µm and the outer diameter of the tip is 125 µm. Two Photonic Lanterns are fabricated, such that MM to SM to MM characterization can be performed.

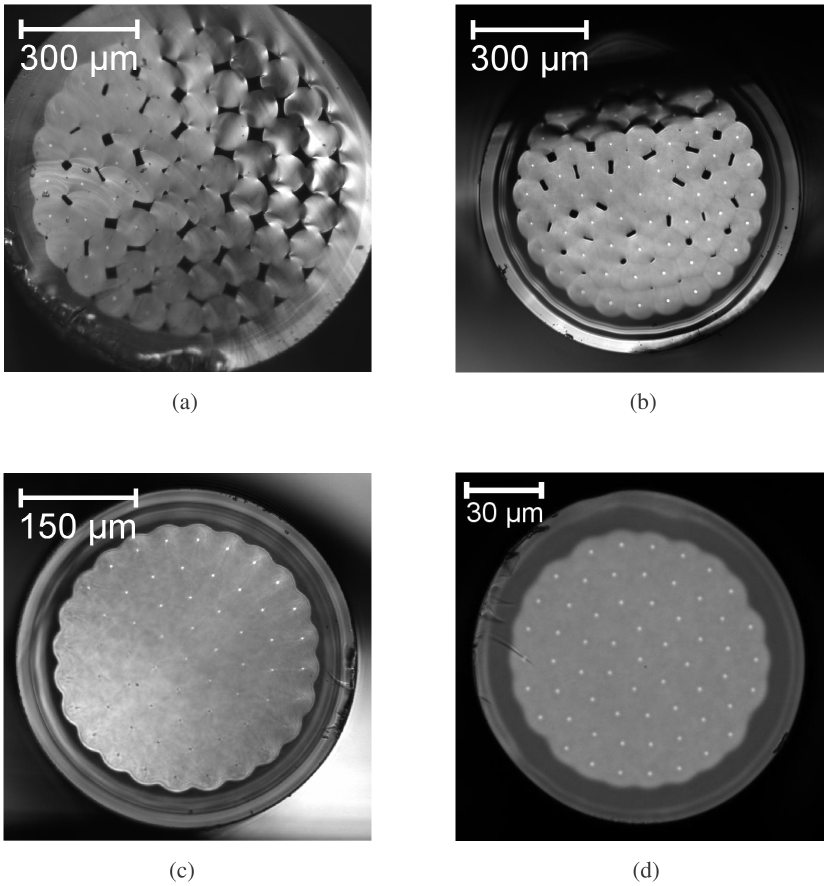

Figure 4. Microscope images of the cross section of the Photonic Lantern through the taper. In (a), (b), (c) and (d) the outer diameter of the low-index tube is 1025 µm, 840 µm, 442 µm and 125 µm, respectively. The MM tip of the Photonic Lantern is seen in (d).

3. TRANSMISSION MEASUREMENTS OF THE PHOTONIC LANTERNS

The SM to MM transmission loss of the two Photonic Lanterns is measured for 10 randomly chosen SMF ports. Incoherent light from an ASE source centered at 1530 nm and with a 10 dB width of 40 nm is coupled into the SMF port under test and the transmitted power out of the MM end of the Photonic Lantern is measured using an integrating sphere. The average SM to MM transmission loss of the two Photonic Lanterns was measured to be 0.01 dB for device #1 and 0.03 dB for device #2. This low loss from SM to MM is expected, since the degrees of freedom in the MM fiber are slightly higher than in the SMF ensemble.

In the final application, the full optical system includes two Photonic Lanterns coupled back-to-back and gratings in each of the SMFs. Accordingly, the MM to SM to MM coupling loss is of interest. To measure this coupling the two fabricated Photonic Lanterns are spliced back-to-back. The two sets of 61 SMFs are spliced together in random order and without the presence of Bragg gratings. This enables a measurement of the pure MM to SM to MM transmission loss. The characterization setup is shown in Fig. 5.

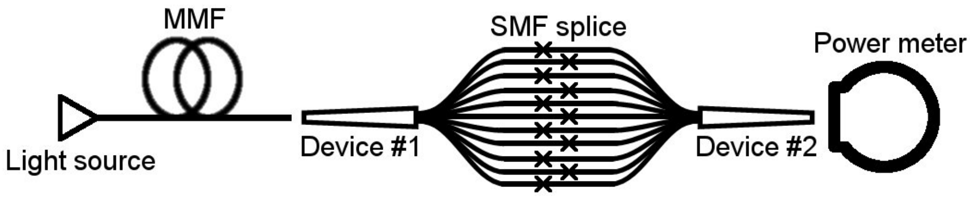

Figure 5. Schematic illustration of the setup used to characterize two Photonic Lanterns coupled back-to-back.

The coupling conditions, i.e. the spot size and NA of the light coupled into device #1 need to be carefully controlled. This is important because excitation of more than 61 modes in the MM Photonic Lantern tip will lead to excess loss due to no more than 61 SMFs being available. On the other hand, excitation of less than 61 modes will lead to false positive results, since scattering into higher order modes may not be detected. A suitable input beam is obtained by using a 95 µm core MM launch fiber. The NA filling of the launch fiber is tailored by a fiber taper section inserted between the light source and the launch fiber. Two different NA fillings are used for coupling into the Photonic Lantern. The highest NA filling corresponds to 95% of the light having an NA below 0.09 (See the blue line in Fig. 6). This NA filling matches the Photonic Lantern and should result in an excitation of ~61 modes in the MM waveguide. Launching of light into the MM tip of device #1 is done by aligning with the MM launch fiber on an XYZ-stage. The transmitted power out of device #2 is measured using a power meter. The total MM–SM-MM transmission loss is measured to be 0.76 dB corresponding to a transmission of 84%.

In order to investigate the dependence of transmission loss on the NA filling of the coupling fiber a low NA filling is also used to couple light into the Photonic Lanterns. Again the 95 µm core MM fiber is used and the NA is tailored by a taper section. The low NA filling corresponds to 95% of the light having an NA below 0.06 (See the red dashed line in Fig. 6). This will result in an under-filling of the modes in the Photonic Lanterns with only ~31 modes excited. As expected the loss decreased significantly compared to using the matched NA coupling.

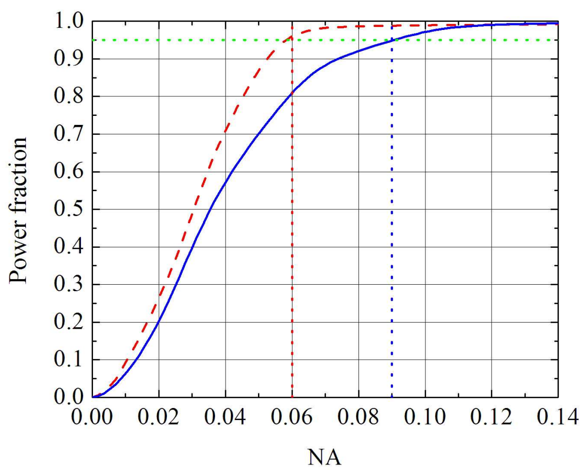

Figure 6. Measured far-field out of the 95 µm core MM fiber used to couple light into the Photonic Lanterns. The blue line shows the NA matched to the Photonic Lanterns. The dashed red line shows the low NA coupling.

4. CONCLUSION

In conclusion we have fabricated and characterized high port count Photonic Lanterns. The Photonic Lanterns feature a taper ratio of 10 and have a MM core diameter of 100 µm. A system of two Photonic Lanterns spliced back-to-back provides efficient conversion from a MMF into a 61 SMF ensemble and back into a MMF. This demonstrates the feasibility of the Photonic Lanterns in transferring spatially incoherent skylight into SMFs. Thereby, enabling MM optical systems with precise and complex spectral filtering in an intermediate SMF section. With a coupling NA matched to that of the Photonic Lanterns, the coupling from MM to SM to MM is done with a total transmission loss of 0.76 dB at a wavelength of 1530 nm. The transmission loss is highly dependent on the NA filling of the light source used to couple into the devices. By reducing the NA of the light source the transmission loss is decreased. For astronomy applications, a lower coupled NA will give a lower throughput of the system and will also be very sensitive to NA up-conversion or focal ratio degradation, which will disturb the measurement. This means that in the optical system a compromise between throughput and the degree of focal ratio degradation in the optical system needs to be found.

5. ACKNOWLEDGEMENT

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