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Published in:
Optics Express

Link to article, DOI:
10.1364/OE.18.004673

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Noordegraaf, D., Skovgaard, P. M. W., Maack, M. D., Bland-Hawthorn, J., & Lægsgaard, J. (2010). Multi-mode to single-mode conversion in a 61 port photonic lantern. *Optics Express*, *18*(5), 4673-4678. https://doi.org/10.1364/OE.18.004673

Multi-mode to single-mode conversion in a 61 port Photonic Lantern

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Abstract: Efficient multi-mode (MM) to single-mode (SM) conversion in a 61 port splitter or "Photonic Lantern" is demonstrated. The coupling loss from a 100 µm core diameter MM section to an ensemble of 61 SM fibers and back to another 100 µm core MM section is measured to be as low as 0.76 dB. This demonstration shows 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.

OCIS codes: (060.2340) Fiber optics components; (350.1260) Astronomical optics.

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1. Introduction

In astronomy, optical fibers have been used for many years to transport light from the telescope to the optical spectrograph. For collecting a large amount of light, large core multi-mode fibers (MMFs) are preferred [1,2]. In the near infrared part of the spectrum from 1000 nm to 1800 nm, 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 only work in SM fibers, so in order to make use of these gratings, a Photonic Lantern that efficiently couples light from a large-core MMF to an ensemble of single-mode fibers (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

#121645 - $15.00 USD Received 17 Dec 2009; revised 6 Feb 2010; accepted 7 Feb 2010; published 22 Feb 2010

MMF core. The principle of the Photonic Lantern was first demonstrated in 2005 by Leon-Saval *et al.* [5].

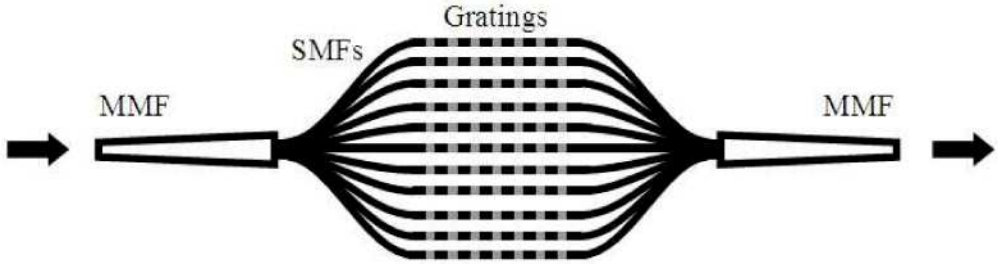

Fig. 1. Schematic illustration of an optical system with two Photonic Lanterns in a back-to-back configuration and fiber Bragg gratings in each of the SMF ports.

The Photonic Lantern features a bundle of SMFs surrounded by a low refractive index layer. The bundle of SMFs is adiabatically tapered to form a MM waveguide with the low-index layer acting as cladding material. Due to the gradual change from MM waveguide to SMF ensemble, a low-loss coupling of light can be achieved if the number of degrees of freedom in the SMF ensemble is higher than in the MM waveguide (follows from the brightness theorem). This means that efficient coupling or transformation of modes from the MM waveguide to the SMF ensemble is possible, when the number of excited modes in the MM waveguide is less than or equal to the number of SM ports. Recently, a low-loss few-mode Photonic Lantern with 7 SM ports was demonstrated [6]. In the current paper we demonstrate, to the best of our knowledge, the first high port count low loss Photonic Lantern. A higher number of SM ports will increase the throughput of the system due to the higher number of modes in the MM section that can be excited. A higher throughput is important since the light from the stars is weak and it is therefore important to have as much light as possible reach the spectrometer. The supported NA of the Photonic Lantern MM tip given by the refractive index difference between the fiber bundle and cladding material 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.

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 diameter of the core, cladding and coating of the SMFs is 8.2 µm, 125 µm and 250 µm, respectively, and they are single-mode for wavelengths longer than 1260 nm. 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 [7]. The thin end acts as a MM waveguide with a core consisting of the 61 fused SMFs and a cladding formed by the low refractive index glass capillary tube. Figure 2(a) 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. In Fig. 2(b), 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.

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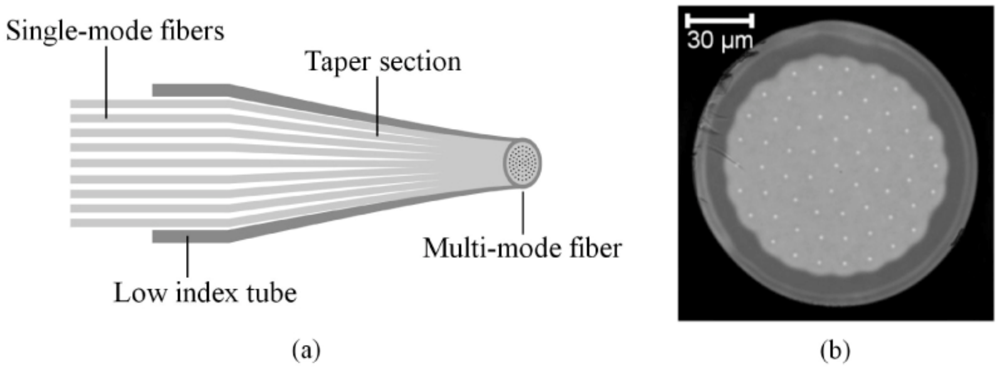

Fig. 2. (a) Schematic illustration of the fabricated Photonic Lantern. (b) Microscope image of the cross section of the MM tip of the Photonic Lantern.

The number of modes M supported by a long MM waveguide is given by

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

where V is the V-parameter of the waveguide [8]. This parameter is defined as

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

where λ is the wavelength, a is the radius of the core and NA is the numerical aperture of the waveguide, which for the Photonic Lanterns is given by the refractive index difference between the low index tube and the cladding material of the SMF-28 fibers. The MM waveguide needs to support M=61 modes at a wavelength of λ=1.55 µm and by rearranging Eq. (1) and (2), the NA of the waveguide that fulfills this requirement can be found:

$$NA \approx \frac{\lambda}{a}\sqrt{\frac{(M-1)}{8}} = \frac{1.55\mu m}{50\mu m}\sqrt{\frac{(61-1)}{8}} = 0.085 \tag{3}$$

A tube with an NA of ~0.09 is used in the fabrication of the Photonic Lanterns. With this tube the V-parameter of the waveguide is ~18 and the number of supported modes is slightly higher than 61. Two Photonic Lanterns are fabricated, such that MM-SM-MM characterization can be performed.

3. Single-mode to multi-mode characterization

The SM to MM transmission loss of the two Photonic Lanterns is measured for 10 randomly chosen SMFs. Incoherent light from an ASE source centered at 1530 nm and with a 10 dB width of 40 nm is coupled into the SMF 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 SM fiber ensemble.

Figure 3 shows the measured integrated far-field (FF) out of the MM end of device #1 (solid blue line) and device #2 (dashed red line). The FFs are averaged over 10 measurements made with light coupled into 10 randomly chosen SM ports one at the time. The average NA filling out of the Photonic Lanterns corresponds to 95% of the light having an NA below 0.10 for device #1 and 0.11 for device #2. For 61 modes excited in the MMF, the corresponding NA is approximately 0.09. Since the measured NA is close to the theoretical NA of 61 excited modes and the SM to MM transmission loss is low, this means that the devices have no backscattering and only little scattering to higher NAs. This confirms that the length of the

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tapered section is long enough to ensure that light couples adiabatically from the SMFs to the MMF.

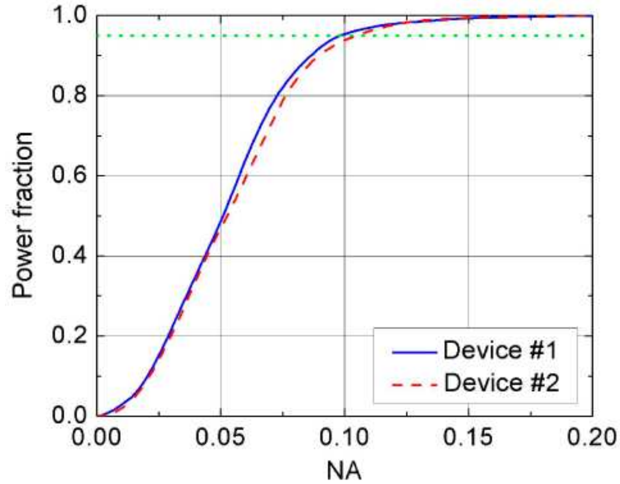

Fig. 3. Measured integrated far-field out of the MM end of the Photonic Lanterns. The far-fields are averaged over 10 measurements made with light coupled into 10 randomly chosen SM ports one at the time.

4. Multi-mode to multi-mode characterization

In the final application, interest is focused on the transmission through a full optical system, with two Photonic Lanterns coupled back-to-back and gratings in the SMFs. To imitate this system 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. For this system the MM to SM to MM transmission loss is measured. The characterization setup is shown in Fig. 4. It is ensured that light is only guided between device #1 and #2 in the core of the SMFs. This is done by having a 3 m length of coated SMF in each of the 61 lines between the two.

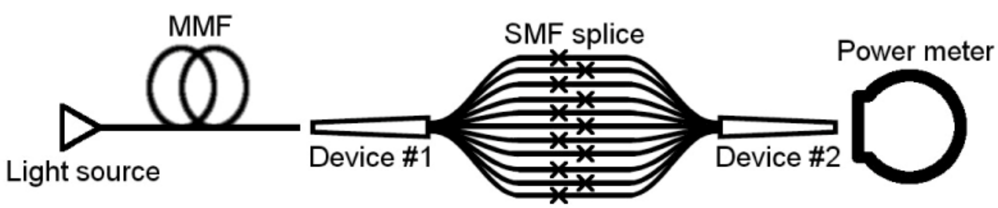

Fig. 4. Schematic illustration of the setup used to characterize two Photonic Lanterns coupled back-to-back.

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 may 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. The measured integrated far-field out of the MM fiber is shown in Fig. 5 as the solid blue line. This NA filling corresponds to 95% of the light having an NA below 0.09, matching that of the Photonic Lanterns. 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%. The resulting integrated far-field measured at the output of device #2 is shown in Fig. 5 as the dashed line. The NA filling corresponds to 95% of the light having an NA lower than 0.10, and is in agreement with the average NA measured over 10 randomly chosen SM ports within measurement uncertainty. For the transmission measurement, the input field is chosen to match the output for the 95% power fraction. The shape of the integrated far-fields are not identical (see Fig. 5), suggesting that the power in each mode (modal power distribution) of the input and output are not the same. This is expected, since the SMFs of the two devices are spliced together randomly.

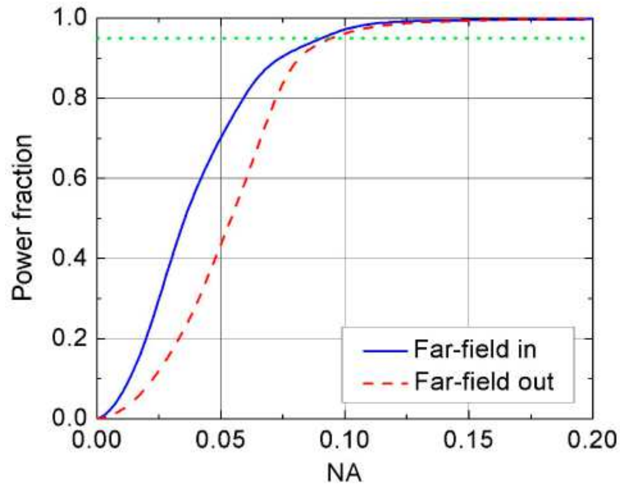

Fig. 5. Measured integrated far-field coupled into device #1 (solid blue line) and resulting far-field out of device #2 (dashed red line).

The transmission loss of the two Photonic Lanterns in the back to back configuration is also characterized as a function of wavelength. This is done by replacing the power meter with an optical spectrum analyzer and replacing the ASE source with a white light source. To control the NA coupled into device #1 the 95 µm core MM fiber with 95% of the power in an NA below 0.09 is used. Figure 6 shows the measured transmission loss (solid blue line). The transmission measurement made with the ASE source is indicated by the red square and the cut-off wavelength for higher order modes is indicated by the green dashed line. The measurement shows that the transmission loss is practically independent of wavelength. Some oscillations in the transmission spectrum can be observed. These are caused by both Fresnel reflections and a low spectral power density of the white light source causing a low signal to noise ratio.

Although the MM fiber is designed such that ~61 modes are excited in the fiber, the actual number of excited modes and the modal power distribution is unknown. Figure 6 shows a very weak wavelength dependence. This indicates that the lower order modes excited in the Photonic Lantern tip have a higher content of power than the higher order ones. To further investigate the importance of the launched modal power distribution, a measurement of the transmission loss through the Photonic Lanterns was made with two lanterns coupled MM end to MM end. In this setup one device is used as source for coupling light into the other. The transmission loss in this measurement increased 0.34 dB, compared to using the NA tailored MM fiber. This indicates a strong dependence of the transmission loss on the modal power distribution of the light launched into the devices. This dependence and the optical processes taking place within the tapered section of the Photonic Lanterns are not yet fully understood, and will be the topic of future investigation.

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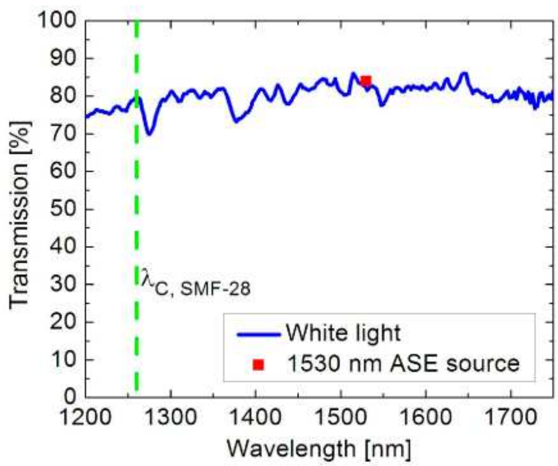

Fig. 6. Spectral transmission loss through two Photonic Lanterns spliced back-to-back (solid blue line). Light is coupled into device #1 with the 95 µm core MM fiber with 95% of the power in an NA below 0.09. The 0.76 dB transmission loss measured with a 1530 nm ASE source is shown by the red square. The dashed green line indicates the higher-order mode cut-off wavelength of the SMF-28 fibers.

5. 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 MM fiber into a 61 SMF ensemble and back into a MM fiber. This coupling is done with a total transmission loss of 0.76 dB at a wavelength of 1530 nm. Furthermore, it is demonstrated that the transmission spectrum is flat at wavelengths from 1200 nm to 1750 nm. This demonstrates the feasibility of the Photonic Lanterns in transferring spatially incoherent skylight into SMFs. Thereby, enabling precise and complex spectral filtering that previously only has been available in single-mode fibers.

Acknowledgements

The project is supported with funding from the UK Research Council, grant reference PP/D002494/1. Joss Bland-Hawthorn is supported by a Federation Fellowship from the Australian Research Council.

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