A focal-ratio-degradation resistant multimode fiber link using mode-selective photonic lantern

Digital Object Identifier (DOI):
10.1117/12.2561438

Published In:
Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV

A focal-ratio-degradation resistant multimode fiber link using mode-selective photonic lantern

Benoit, Aurélien, Yerolatsitis, Stephanos, Harrington, Kerrianne, Birks, Tim, Thomson, Robert

Aurélien Benoit, Stephanos Yerolatsitis, Kerrianne Harrington, Tim A. Birks, Robert R. Thomson, "A focal-ratio-degradation resistant multimode fiber link using mode-selective photonic lantern," Proc. SPIE 11451, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV, 1145120 (13 December 2020); doi: 10.1117/12.2561438

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

A focal-ratio-degradation resistant multimode fiber link using a mode-selective photonic lantern

Aurélien Benoit*[a], Stephanos Yerolatsitis[b], Kerrianne Harrington[b], Tim A. Birks[b], and Robert R. Thomson[a]

[a]SUPA, Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK;
[b]Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK

ABSTRACT

We report a new route to mitigate focal-ratio degradation (FRD) in multimode optical fiber links. Our approach uses a custom multicore fiber (MCF) with dissimilar cores, which is then tapered at both ends to form multimode cores and create mode-selective photonic lantern (PL) transitions. The cores of the MCF are single-moded at 1550 nm and sufficiently spaced such that there is no observable core-to-core cross talk after a 7 m fiber length. The mode-selective PLs at each end of the MCF, in combinations with the low core-to-core cross talk of the MCF at 1550 nm, ensure that the relative amount of power in each spatial mode is preserved throughout the fibre link. As such, a PL-MCF-PL link using this approach has the potential to be resistant to FRD by inhibiting the coupling of light from lower-order to higher-order modes. We show that the full PL-MCF-PL link exhibits lower FRD than a custom multimode fiber that guides the same number of modes. A study of how the FRD behavior of the PL-MCF-PL link varies as a function of wavelength indicates some bandwidth limitations due to the wavelength-dependent properties of the PLs and the cross coupling in the MCF.

Keywords: Focal ratio degradation, photonic lantern, integral fiber-fed spectrograph

1. INTRODUCTION

Since their first development, optical fibers had provided an outstanding way to route light for many applications, including telecommunications, medicine, and industrial laser manufacturing. Optical fibers have also become an enabling technology in astronomical instrumentation, and they are extensively used in systems such as fiber-optic integral field units and multi-object instruments. Due to their flexibility and efficiency, fibers are also used to route light from the telescope to spectrographs [1]. By facilitating the complete de-coupling of the telescope and the instrument, they play a particularly important role in enabling ultra-high precision single-object instruments such as HARPS and NIRPS [2-3]. Despites their advantages, optical fibers also have some drawbacks, such as the focal-ratio degradation (FRD) [4-5] where light is observed to exit the fiber with a lower f-ratio than the light that was injected into the fiber. FRD is the result of spatial mode coupling along the fiber propagation axis due to deformations and micro-bending, which in turn enables the transfer of energy from the lower-order (higher f-ratio) to higher-order (lower f-ratio) modes [6-7].

One technology that can enable the exquisite manipulation of spatial modes is the photonic lantern (PL) [8-9] – a guided wave transition that enables the low loss coupling of multimode light to an array of single modes (SMs). The principle of the PL is to use an adiabatic transition to slowly transition the light contained in a multimode port to an array of SM waveguides – and vice versa. Although it was initially developed using approaches that exploited degenerate single mode waveguides, it has recently been demonstrated that PLs fabricated using dissimilar SM waveguides can facilitate mode-selective operation. In mode-selective PLs, each spatial mode in the multimode port eventually couples to only one of the single mode cores at the other end of the PL and vice versa [10-11].

In this conference, we report a new approach to mitigate FRD using a fibre link based on a MCF with dissimilar cores and photonic lanterns at each end. A degree of FRD improvement is demonstrated in comparison with a custom fiber that supports the same number of guided modes, while a further study indicates that the FRD performances decreases at shorter wavelengths due to the wavelength-dependent properties of the PL and the MCF.

Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV,
edited by Ramón Navarro, Roland Geyl, Proc. of SPIE Vol. 11451, 1145120

2. THE FRD-RESISTANT FIBER LINK

2.1 The multicore fiber

The custom multicore fiber (MCF) contains six dissimilar step-index cores with diameters of 11.0, 10.3, 9.5, 8.3, 7.3 and 6.5 µm. The minimum core-to-core separation is 26 µm, which simulations indicated would keep crosstalk below 0.08 % between the two smallest cores for a 1.5 m length of fiber [10]. A schematic representation of the MCF is presented in Fig. 1(a), while Fig 1(b) presents a micrograph of the fabricated MCF. To confirm the MCF structure and ensure minimum cross-talks between the cores to mitigate FRD, we investigated the guided properties of the MCF. Light at 1550 ± 20 nm from a thermal source was first coupled in a singlemode fiber (SMF-28). We then directly butt-coupled and excited each MCF core, while imaging the opposite end of the MCF onto a Hamamatsu InGaAs camera. Figures. 1(c-h) present the recorded near field output intensity distributions of the MCF when light is coupled in each core of the MCF individually. As expected from simulations [10], no cross coupling of light could be observed when exciting any of the 6 MCF cores. For each MCF core we attempted to excite higher order modes by slightly misaligning the excitation SMF from the MCF core. We observed that the spatial profile of the light at the output of the MCF was unaffected by this procedure, confirming that all the MCF cores are single-moded at 1550 nm. Figure 1(i) is a composite image created using the near-field images in Figs. 1(c-h), where each MCF core is optimally aligned. Figure. 1(j) is a similar composite image, but in this case the MCF cores were excited using a deliberately misaligned SMF. The images in Fig. 1 confirm that the MCF is single-mode in nature and that it exhibits negligible core-to-core crosstalk over a 7 m length.

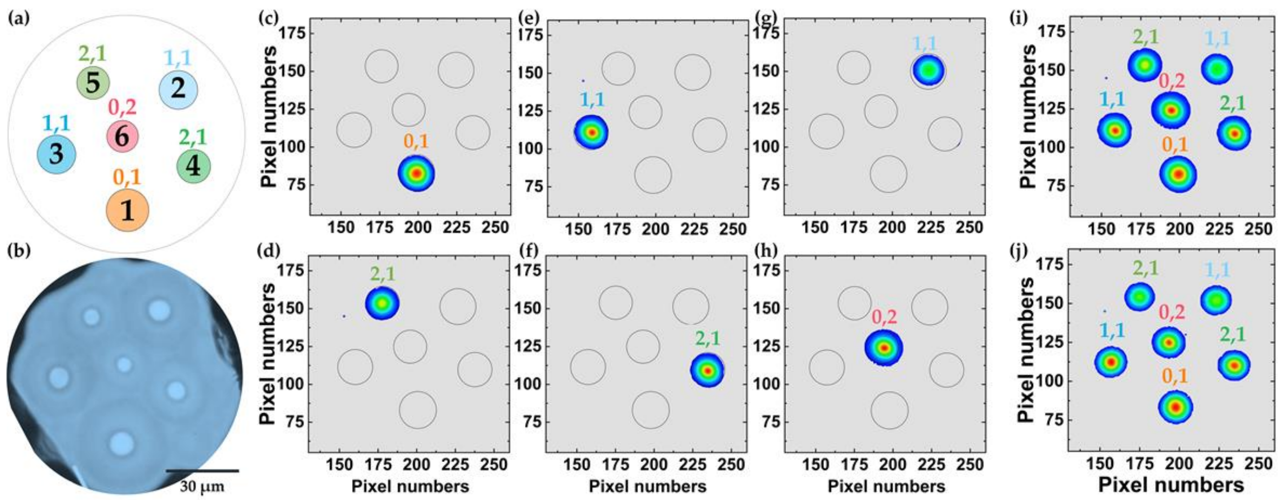

Figure 1. (a) Illustration of the cross section of the MCF that ensures a crosstalk lower than 0.08 between the two smallest cores [10]. (b) Cross-sectional micrograph of the fabricated MCF. (c-h) Near field images of the MCF modes when light at 1550 nm is coupled into each core individually. (i) Composite image created using the 6 near field images shown in (c-h) when the SMF-MCF excitation is optimized. (j) Composite image, similar to (i), obtained using deliberately misaligned SMF-MCF excitation in an attempt to excite higher order modes.

2.2 The mode-selective photonic lantern

By heating and stretching the MCF and cleaving the waist, a photonic lantern was fabricated at one end of a 7 m length of the MCF. The transition length was ~3 cm and the taper ratio was 0.09, resulting to a multimode core at the waist with a diameter of 12 µm [12]. We used two methods to investigate the mode-selective behavior of the PL. First, we coupled light at 1550 ± 20 nm into a SMF and used this to excite each MCF core individually, while imaging the multimode port of the PL onto a Hamamatsu InGaAs camera. Figure 3(a-f) presents the results of these experiments, and each image is labelled appropriately to identify the corresponding MCF core (Fig. 1(a)) which was excited. The output intensity distributions match the expected and identifiable LP modes, confirming the mode-selective nature of the PL.

The second method we used to investigate the mode-selectivity of the PL involved the use of the experimental setup presented in Figs. 2 & 2(a), Here, light with a variable f-ratio was coupled to the multimode port of the PL. The distribution of light across the MCF cores at the end of the fiber was then measured using near-field imaging for different input f-ratios. By integrating the light measured across each MCF core, it was possible to plot the relative powers in each MCF mode as a function of the f-ratio of the excitation light, as shown in Fig. 3(b). The raw near field intensity distribution observed using the lowest excitation f-ratio is presented in the inset, and each mode is labeled with the spatial mode which is excited in the PL when that core is excited. As was expected due to the mode-selective nature of the PL, only the fundamental mode (orange squares) is excited when using the excitation light with the highest f-ratio and therefore light is coupled only to the largest core at the other end. As the f-ratio of the excitation light is reduced, increasingly higher order modes are excited in the multimode port of the PL and the light becomes distributed to the other cores of the MCF. In essence, the mode-selective photonic lantern works as a spatial mode analyzer and demonstrates the mode-selective operation of the PL link.

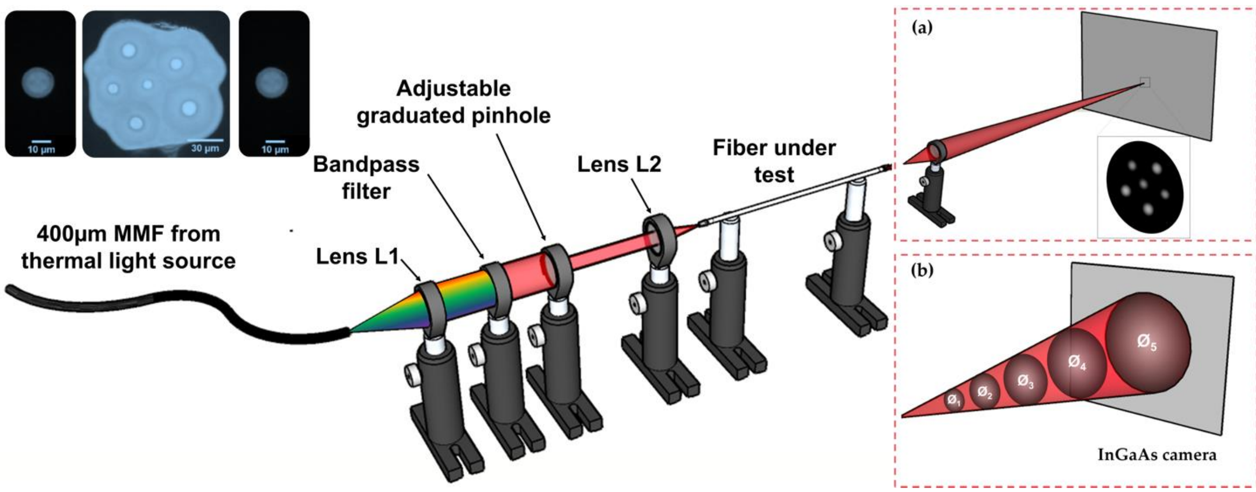

Figure 2. Illustration of the experimental setup used to characterize the mode-selective nature of the PLs, and to investigate the FRD behavior of various fiber links. The main components are the 400 μm fiber, transporting light from a thermal source. This light is collimated using L1 and filtered using a bandpass filter. An adjustable graduated iris is used to control the size of the collimated beam before it enters lens L2 and is focused onto the fiber under test. At the output of the fiber under test we could either perform (a) near-field imaging with an InGaAs camera, or (b) a series of beam profile measurements to characterize the f-ratio of the output. Inset: Cross-section pictures representing the full device with the two multimode outputs and the MCF.

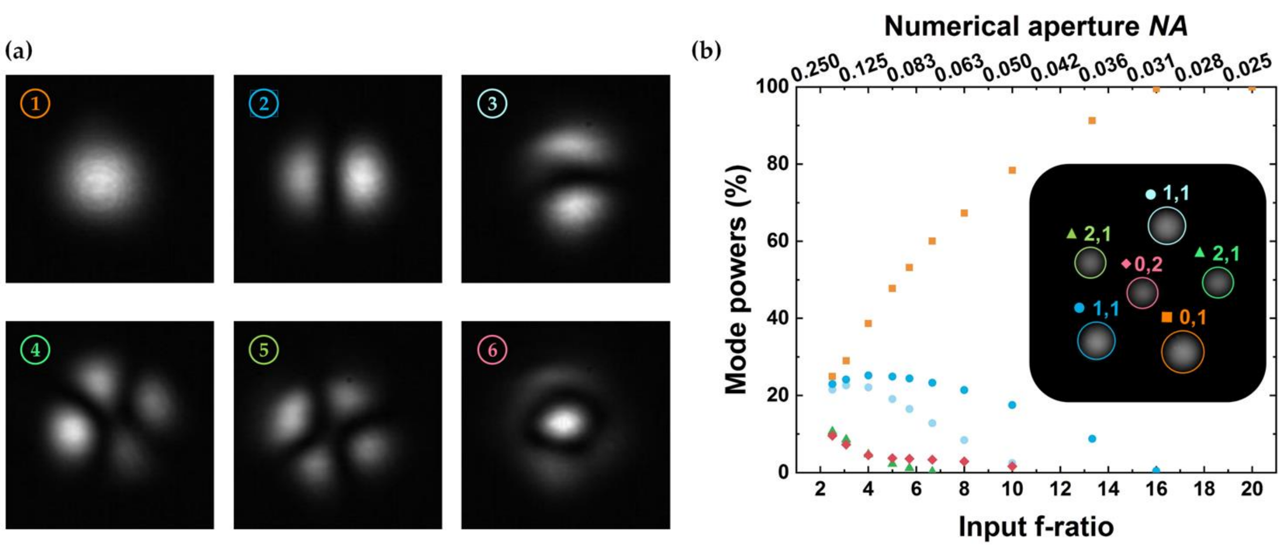

Figure 3. (a) Near field intensity distributions recorded at the output of the PL when light is coupled into each core of the MCF. The patterns from 1 to 6 corresponds to the input core labelled in Fig. 1(a) with a similar color scheme for the cores. (b) Evolution of the mode power contribution of all cores as a function of the input f-ratio. Inset: Near field intensity distribution of the MCF measured using excitation light with the lowest input f-ratio. The labels indicate the corresponding LP modes that are excited in the multimode port of the PL when that core is excited.

3. FRD MITIGATION RESULTS

The full PL-MCF-PL fiber link was obtained by fabricating PLs at both ends of a 7 m length of the dissimilar core MCF. Figs. 2 and 2(b) present the experimental setup used to characterize the FRD performance of various fiber links. To measure the f-ratio of the light exciting the fiber, an InGaAs camera with a linear range of 1:16000 (without any lens in front) is placed on a translation stage in front of the output end of the fiber. In this manner, 5 spatial profiles of the exiting light (from $Ø_1$ to $Ø_5$) are acquired at 5 different locations. This data is then processed in 3 steps: (i) use a virtual knife-edge technique to evaluate the size of the beam, (ii) apply a derivative function and then a normalization on the S-curve obtained in (i) to define the beam size at 95 % of the full beam size, (iii) determinate an output f-ratio value by averaging 10 beam sizes comparison (from the 5 output beam sizes, $Ø_1$ with $Ø_2$, $Ø_1$ with $Ø_3$…) that we acquired for each input f-ratio. The measurement campaign is repeated 5 times and Fig. 4(a) presents the evolution of the output f-ratio as a function of the input f-ratio for the PL-MCF-PL (red circles). Each data point is the average of the five-output f-ratio measurements and the errors bars show the minimum and maximum value of the 5 measurements. To obtain a fair comparison of FRD performance, we fabricated a custom step-index fiber that supports 6 modes (6-MMF) at 1550 nm. The FRD measurements of this fiber are also presented in Fig. 4(a) (blue squares). These two evolutions clearly demonstrate the FRD-mitigating capability of the PL-MCF-PL link [13].

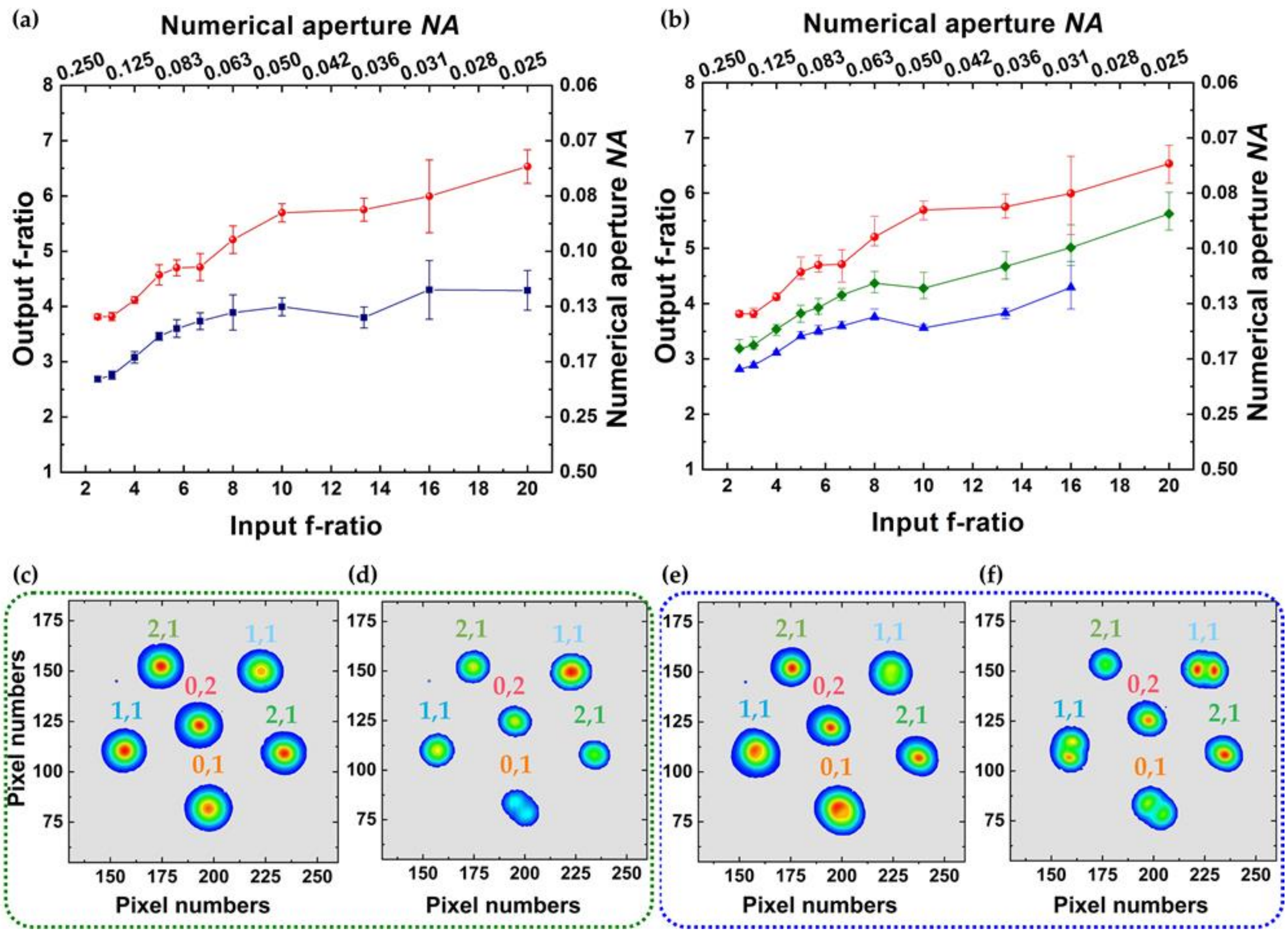

Figure 4. (a) Evolution of the output f-ratio vs input f-ratio for the PL-MCF-PL link (red points) and the 6-mode multimode fibre (dark blue squares) at the optimized wavelength of 1550 ± 20 nm. (b) Evolution of the output f-ratio vs input f-ratio for the PL-MCF-PL when using light at wavelengths of 1550 ± 20 nm (red points), 1424 ± 42 nm (green diamonds), 1064 ± 25 nm (blue triangles). (c-f) Composite image of the near field images of the MCF modes when the excitation is optimized (c, e) and when its purposely misaligned (d, f) when using light at (c-d) 1424 ± 42 nm and (e-f) 1064 ± 25 nm.

Once the FRD-mitigating properties of the PL-MCF-PL link were established at the intended wavelength of operation (1550 nm), we then investigated how these properties change as a function of wavelength. To do this, we changed the bandpass filter in the experimental setup in Fig. 2 such that the FRD performance could be evaluated using light at 1424 ± 42 nm (close to the optimized wavelength of 1550 nm) and 1064 ± 25 nm (far to the optimized wavelength span). Figure 4(b) depicts the FRD performance of the PL-MCF-PL, with the evolution of the output f-ratio as a function of the input f-ratio when using light at 1550 ± 20 nm in red points, 1424 ± 42 nm in green diamonds and 1064 ± 25 nm in blue triangles. Each data point represents the average of 5-output f-ratio values and the error bars represent the minimum and maximum values of these 5 measurements. One can see that the FRD performance of the PL-MCF-PL link decreases as the excitation light is reduced. We believe that this is due to two issues. Firstly, as the wavelength is reduced, the PL's become progressively less adiabatic and higher order modes are excited at both the input and output PLs. Secondly, as can be seen in Fig. 4(c-f) more of the MCF cores become multimoded as the wavelength is reduced. Due to the higher-order modes, the core-to-core coupling of the MCF increases and therefore unwanted light is coupled to different cores. Both of these effects act to reduce the effectiveness of the FRD mitigating properties of the PL-MCF-PL link.

4. CONCLUSION

We have presented a promising new route to mitigate FRD in multimode fiber link using a custom MCF with adiabatic mode-selective PLs fabricated at both ends. The custom MCF has 6 step-index cores with dissimilar core diameters but all single-moded at 1550 nm. The core-to-core separation was chosen such that minimal core-to-core coupling was observed with 1550 nm light after 7m of the fiber. At a working wavelength of 1550 nm, the FRD performance improvement for the PL-MCF-PL is clearly evident in comparison of a step-index multimode fiber that guides the same number of modes. These results demonstrate the potential of using the mode-selective PL-MCF-PL fiber-link concept to minimize mode coupling and inhibit the transfer of light from lower order modes to higher order modes that induces FRD. At shorter wavelengths, the FRD performance of the PL-MCF-PL link decreases. Two main factors may explain this behavior: the photonic lantern becomes less adiabatic at shorter wavelengths and the core-to-core coupling increases as the cores become multimoded at shorter wavelengths. Although this work is at an early stage, we believe that the concept we have presented here demonstrates a powerful new way to control FRD in fiber-fed systems, and that with future optimization this concept could be expanded to much higher mode-number systems.

This work was funded by the UK STFC through grants ST/N000544/1 and ST/N000625/1, and by the European Union Horizon 2020 grant 730890 (OPTICON).

REFERENCES

[1] J. P. Angel, M. T. Adams, T. A. Boroson, and al., "A very large telescope array linked with fused silica fibers", The Astro. Jour., 218, 776-782 (1977)
[2] M. Mayor, F. Pepe, D. Queloz, et al., "Settings new standards with HARPS", The Messenger, 114, 20-24 (2003)
[3] N. Blind, U. Conod and F. Wildi, "Few-mode fibers and AO-assisted high-resolution spectroscopy: coupling efficiency and modal noise mitigation," at Adaptive Optics for Extremely Large Telescopes 5 (AO4ELT5) (2017)
[4] L. W. Ramsey, "Focal ratio degradation in optical fibers of astronomical interest," Astronomical Society of the Pacific, Conference Series 3, 26-40 (1988)
[5] S. C. Barden, "The use and benefits of optical fibers in spectroscopy," Am. Soc. Pac. Conference Series 55, 130-138 (1994)
[6] E. Carrasco and I. R. Parry, "A method for determining the focal ratio degradation of optical fibres for astronomy", MNRAS 271, 1-12 (1994)
[7] C. A. Clayton, "The implications of image scrambling and focal ratio degradation in fibre optics on the design of astronomical instrumentations," A&A 213, 502-515 (1989)
[8] S. G. Leon-Saval, T. A. Birk, J. Bland-Hawthorn, and al., "Multimode fiber devices with single-mode performance" Opt. Lett. 30, 2545-2547 (2005)
[9] T. A. Birks, I. Gris-Sánchez, S. Yerolatsitis, and al., "The photonic lantern," Advance in Optics and Photonics 7, 107-167 (2015)
[10] S. Yerolatsitis, K. Harrington, R. R. Thomson, and al., "Mode-selective Photonic Lanterns from Multicore Fibres", Optical fibre Communication conference, Optical Society of America (OSA), paper Tu3J.6 (2017)

[11] S. G. Leon-Saval, N. K. Fontaine, J. R. Salazar-Gil, et al. "Mode-selective photonic lanterns for space division multiplexing", Opt. Exp. 22(1) (2014)
[12] S. Yerolatsitis, I. Gris-Sánchez, and T. A. Birks, "Adiabatically-tapered fiber mode multiplexers" Opt. Exp. 22, 608-617 (2014)
[13] A. Benoit, S. Yerolatsitis, K. Harrington, et al., "Focal-ratio degradation (FRD) mitigation in a multimode fibre link using mode-selective photonic lanterns," MNRAS *(accepted)* (2020)