Contrib. Astron. Obs. Skalnaté Pleso **49**, 119 – 124, (2019)

Astrophotonic technologies for small telescopes

R.J. Harris, Th. Anagnos and P. Hottinger

Zentrum für Astronomie der Universität Heidelberg, Landessternwarte,
Königstuhl 12, 69117 Heidelberg, (E-mail: rharris@lsw.uni-heidelberg.de)

Received: November 1, 2018; Accepted: January 24, 2019

Abstract. Astrophotonics is a field combining astronomical instrumentation and photonics, with the aim of making instruments cheaper, smaller or increasing their functionality. Small telescopes are perfectly placed to take advantage of these technologies, as their size reduces the complexity of instruments. In our group at the Landessternwarte we are working on two experimental technologies that could greatly benefit spectrographs behind small telescopes. The first is photonic reformatting, akin to image slicing, but using a photonic lantern to sample the telescope point spread function. The second technology is a sensor at the focal plane of the telescope, allowing increased coupling efficiency. This sensor is composed of a 3D printed microlens array coupled to a fibre bundle. We summarise both of these devices and their potential in future small telescope instruments.

Key words: astronomy – photonics – astrophotonics – instrumentation – photonic lantern – spectroscopy – wavefront sensing

1. Introduction

The field of astrophotonics combines astronomical instrumentation and photonics, with the aim of making instruments cheaper, smaller or increasing their functionality (e.g. Bland-Hawthorn & Kern, 2009). Examples of devices developed in the field include integrated spectrographs known as arrayed waveguide gratings (e.g. Cvetojevic et al., 2009)) and wavelength filters such as fibre bragg gratings (e.g. Trinh et al., 2013). Over the last decade the challenge has been adapting these technologies to compete with conventional instrumental technologies and prove the added functionalities are useful. However, many challenges have come from the fact that most astrophotonics technologies were designed for the telecommunications industry. They generally work in the single-mode (SM) (diffraction limited) or few-mode (close to diffraction limited) regime covering wavelengths of tens of nanometers. By contrast in astronomy sources are usually multi-mode (MM) (seeing limited) and the filters used operate over wavelength ranges of hundreds of nanometers. This has required the development of new devices to allow the transition between the two. The best example of this is the photonic lantern (PL) (Leon-Saval et al., 2005), a device that allows a MM PSF to be 'split up' into many single modes. In order to retain throughput (or conserve etendue), an equal number of SMs is required to those contained in the telescope PSF.

In order to reduce the complexity of these challenges, it is necessary to close the gap on the two regimes, this requires a reduction in the number of modes. The equation governing the number of modes (e.g. Harris & Allington-Smith, 2012; Spaleniak et al., 2013) is

$$M = \left(\frac{\pi \chi D_{\mathrm{T}}}{4\lambda}\right)^2 . \tag{1}$$

Here, χ represents the seeing, or the angular point spread function (PSF) size to couple to the fibre, D_{T} is the telescope diameter and λ is the wavelength.

This shows that instruments on large telescopes in visible wavelengths require many thousands of modes. For example, we can use equation 1 to calculate the number of modes for ELT HIRES. Assuming a seeing limited mode, with a seeing of 0.6 arcseconds, at a wavelength of 400 nm and a 39.5 m telescope, we require $\approx$ 60,000 modes to efficiently sample the telescope PSF. To use SM technologies would require a more complex instrument than the current plan of using fibre bundles containing roughly 100 MM fibres. The fibres would need to operate reasonably uniformly across the seeing disc, then need to be put into a spectrograph or multiple spectrographs. Assuming an SM slit would lead to the slit being 30 cm long, which would be difficult to accurately re-image in an Echelle configuration and require very large detectors. Whilst these problems can be overcome, they are not trivial. In addition, due to the conservative nature of instrument builders, the first demonstration of the technology on these scales is unlikely. This means it is much better to start with simpler, more manageable instruments.

These simpler instruments can be for small telescopes, or large telescopes with adaptive optics (AO) systems where the PSF is SM, or contains few modes. Whilst both options have their advantages, small telescopes are normally more amenable to new technology demonstrations, with more time available. In our group at the Landessternwarte we are working on two experimental technologies that could greatly benefit small telescopes.

2. Work being undertaken at the Landessternwarte

The working group at the Landessternware consists of Robert Harris, Theodoros Anagnos and Philipp Hottinger and is mostly funded through the DFG NAIR grant. Below we detail the two main projects that benefit small telescopes.

2.1. Photonic Reformatting

Photonic reformatting is akin to image slicing, but fully integrated within the fibre. At the focal plane the tapered end of a PL acts like a conventional MM fibre, to efficiently sample the whole seeing limited PSF. This is then split up into individual SMs, or single waveguides, each of which carries a fraction of the light.

These can then be reformatted into a slit, straight line, or other shapes to be fed into a spectrograph e.g. Bland-Hawthorn et al. (2010); Spaleniak et al. (2013). Due to the nature of the reformatting, spatial information is not preserved, helping scramble the image.

As the number of modes is related to the length of the slit, fewer modes are preferable as the slit is simpler to re-image (Harris et al., 2016). This means smaller telescopes are ideally placed to test reformatting technologies.

Previous practical work (e.g. Thomson et al. (2012); Jovanovic et al. (2012); Harris et al. (2015)) and theory work (Anagnos et al., 2018) have shown the technology is viable and we are currently working on the next generation, for use with the Minerva-red spectrograph (see Figure 1).

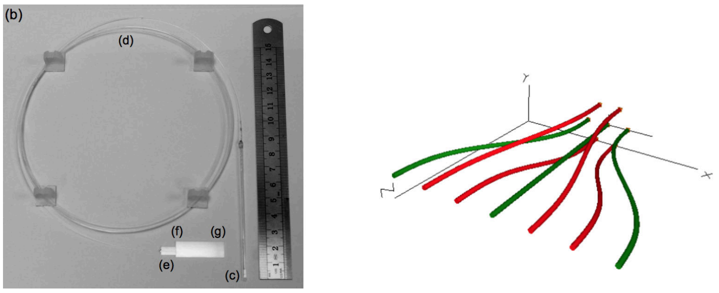

Figure 1. Example images of reformatters : **Left)** The Hybrid reformatter, modified from MacLachlan et al. (2016). (c) contains the multimode end of the photonic lantern, which is placed at the telescope focal plane. This gradually expands into a multicore fibre, containing many single mode cores (d). (e) is is the interface to the reformatter and (f-g) show the ultrafast laser inscribed (ULI) reformatter chip which takes the arrangement of fibre cores and repositions them into a slit. **Right)** The preliminary design of the Minerva-red ULI reformatter, showing the re-arrangement of cores that also takes place in the Hybrid reformatter. Once this model has been optimised, the full device will be built and packaged.

2.2. Tip-tilt sensing

Fibre fed astronomical instruments tend to use larger MM fibres, due to ease of coupling. However, to efficiently use these requires larger spectrographs (e.g. Lee & Allington-Smith, 2000), which are more difficult and costly to build and are less stable. In order to reduce the size of instruments, it helps to use smaller fibres, equivalent to smaller slits. This makes the instrument smaller, but is more difficult to efficiently couple to the telescope.

Firstly, the PSF must be diffraction limited, or close to diffraction limited in order to couple light efficiently. With small telescopes or complex AO systems this is possible; however these still suffer from residual tip-tilt motion, reducing the coupling efficiency. With such small system it is essential to solve this problem and remove this tip-tilt motion.

Our solution, a focal plane tip-tilt sensor, allows increased coupling efficiency. This sensor is composed of a 3D printed microlens array coupled to a fibre bundle. In the centre, an SM fibre is fed to the spectrograph and surrounding this fibre are six MM fibres. In order to increase the fill fraction these surrounding fibres have a freeform microlens array printed on top (see Figure 2). The outer fibres are coupled to a fast detector, which feeds the signal to a tip-tilt mirror, stabilising the beam and reducing coupling error. It is currently under development for testing with the near diffraction limited extreme AO system at the Large Binocular Telescope (LBT), which makes it easily modifiable to allow it to work with much smaller telescopes. For more information, see Hottinger et al. (2018).

Figure 2. Example images of the tip-tilt sensor system : **Left)** The camera image of the fibre bundle. The end on the left hand side contains seven fibres, a single mode central core and six larger sensing cores. These are split off into two bundles (terminating on the right), one with a sole single mode core and the other with six larger cores for sensing. **Right)** The preliminary microlens design, adapted from Hottinger et al. (2018).

3. Conclusions and future

As astrophotonics matures it is showing that it can provide useful instrumentation for both smaller and larger scale telescopes. However, due to the complexity and practical difficulties of building these instruments lots of technologies are ideally suited for smaller telescopes or larger telescopes with extreme adaptive optics (AO) systems. This means the more practical solution is commonly using smaller telescopes for technology development. Our research at the Landessternwarte focusses on two devices with few modes that could be of particular use to smaller telescopes.

The first is a photonic reformatter, a device akin to an image slicer for use with a high resolution spectrograph. At the focal plane of the telescope it is a large multi-mode (MM) fibre, which splits off into lots of single modes (SMs) using a photonic lantern. These SM waveguides can then be reformatted into a long slit, or other formation, to increase spectral resolving power and stability. The device is created by drawing a fibre down at one end and reformatted using ultrafast laser inscription. This device is similar in concept to an image slicer, but with a gaussian point spread function (PSF) and fully integrated, reducing alignment constraints.

The second is a tip-tilt sensor to increase coupling efficiency into SM instrumentation. Both small and large telescopes with extreme AO systems tend to suffer from tip-tilt variations, either due to the atmosphere or structural vibrations. The conventional system can compensate, though usually with an element of light loss or incomplete correction. Our solution aims to maximise the light into the SM fibre. We do this by creating a fibre bundle, with the SM fibre in the centre and six surrounding MM fibres. The inner fibre is used to transmit the science light, while the larger outer fibres are used for sensing.

We envision both technologies will help increase the coupling efficiency into few or single mode fed instruments on small telescopes and enable the new generation of astrophotonic instrumentation on telescopes.

Acknowledgements. Robert J. Harris is supported by the Deutsche Forschungsgemeinschaft (DFG) through project 326946494, 'Novel Astronomical Instrumentation through photonic Reformatting'.

References

Anagnos, T., Harris, R. J., Corrigan, M. K., et al., Simulation and optimisation of an astrophotonic reformatter. 2018, *Monthly Notices of the Royal Astronomical Society*, **478**, 4881, DOI: 10.1093/mnras/sty1396

Bland-Hawthorn, J. & Kern, P., Astrophotonics: a new era for astronomical instruments. 2009, *Optics Express*, **17**, 1880

Bland-Hawthorn, J., Lawrence, J., Robertson, G., et al., PIMMS: photonic integrated multimode microspectrograph. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **7735**, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*

Cvetojevic, N., Lawrence, J. S., Ellis, S. C., et al., Characterization and on-sky demonstration of an integrated photonic spectrograph for astronomy. 2009, *Optics Express*, **17**, 18643

Harris, R. J. & Allington-Smith, J., Applications of integrated photonic spectrographs in astronomy. 2012, *Monthly Notices of the Royal Astronomical Society*, **428**, 3139

Harris, R. J., Labadie, L., Lemke, U., et al., Performance estimates for spectrographs using photonic reformatters. 2016, in *Performance estimates for spectrographs using photonic reformatters*, 9912 – 9912 – 8

Harris, R. J., MacLachlan, D. G., Choudhury, D., et al., Photonic spatial reformatting of stellar light for diffraction-limited spectroscopy. 2015, *MNRAS*, **450**, 428, DOI: 10.1093/mnras/stv410

Hottinger, P., Harris, R. J., Dietrich, P.-I., et al., Micro-lens arrays as tip-tilt sensor for single mode fiber coupling. 2018, in *Micro-lens arrays as tip-tilt sensor for single mode fiber coupling*, 10706 – 10706 – 15

Jovanovic, N., Spaleniak, I., Gross, S., et al., Integrated photonic building blocks for next-generation astronomical instrumentation I: the multimode waveguide. 2012, *Optics Express*, **20**, 17029

Lee, D. & Allington-Smith, J. R., An experimental investigation of immersed gratings. 2000, *Monthly Notices of the Royal Astronomical Society*, **312**, 57, DOI: 10.1046/j.1365-8711.2000.03151.x

Leon-Saval, S. G., Birks, T. A., Bland-Hawthorn, J., & Englund, M., Multimode fiber devices with single-mode performance. 2005, *Optics letters*, **30**, 2545

MacLachlan, D. G., Harris, R. J., Gris-Sánchez, I., et al., Efficient photonic reformatting of celestial light for diffraction-limited spectroscopy. 2016, *Monthly Notices of the Royal Astronomical Society*, **464**, 4950

Spaleniak, I., Jovanovic, N., Gross, S., et al., Integrated photonic building blocks for next-generation astronomical instrumentation II: the multimode to single mode transition. 2013, *Optics Express*, **21**, 27197, DOI: 10.1364/OE.21.027197

Thomson, R., Harris, R., Birks, T., et al., Ultrafast laser inscription of a 121-waveguide fan-out for astrophotonics. 2012, *Optics Letters*, **37**, 2331

Trinh, C. Q., Ellis, S. C., Bland-Hawthorn, J., et al., GNOSIS: the first instrument to use fiber Bragg gratings for OH suppression. 2013, *The Astronomical Journal*, **145**, 51