

PIMMS: photonic integrated multimode microspectrograph

Joss Bland-Hawthorn^{a,b}, Jon Lawrence^{c,d}, Gordon Robertson^a, Sam Campbell^a, Ben Pope^a, Chris Betters^a, Sergio Leon-Saval^{a,b}, Tim Birks^e, Roger Haynes^{d,f}, Nick Cvetkojevic^c, Nem Jovanovic^c

^aSchool of Physics, University of Sydney, NSW 2006, Australia

^bInstitute of Photonics & Optical Science, University of Sydney, NSW 2006, Australia

^cMQ Photonics Research Centre, Dept. of Physics & Eng., Macquarie University, NSW 2109, Australia

^dAnglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia

^eDepartment of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK

^fInnoFSPEC, Astrophysikalisches Institut Potsdam, 14482 Potsdam, Germany

*Corresponding author: jbh@physics.usyd.edu.au

ABSTRACT

We present the first integrated multimode photonic spectrograph, a device we call PIMMS #1. The device comprises a set of multimode fibres that convert to single-mode propagation using a matching set of photonic lanterns. These feed to a stack of cyclic array waveguides (AWGs) that illuminate a common detector. Such a device greatly reduces the size of an astronomical instrument at a fixed spectroscopic resolution. Remarkably, the PIMMS concept is largely independent of the telescope diameter, input focal ratio and entrance aperture – i.e. one size fits all! The instrument architecture can also exploit recent advances in astrophotonics (e.g. OH suppression fibres). We present a movie of the instrument’s operation and discuss the advantages and disadvantages of this approach.

Keywords: multimode fibre; integrated photonic spectrograph; astronomical instrumentation – diffraction limited

1. INTRODUCTION

In 2006, we explored the possibility of designing and building an integrated photonic spectrograph for the first time (Bland-Hawthorn & Horton 2006; hereafter BH06). The stated goals in that paper were to revolutionize our approach to instrument building in order to halt the spiraling trends in instrument development. In the following year, such a device was made to operate with a *single-mode* fibre input (Fig. 1; Bland-Hawthorn & Horton 2007). In 2008, the instrument was used successfully at Siding Spring Observatory, NSW which led to the first continuous spectrum ever obtained with a photonic device (Cvetkojevic et al 2009). As anticipated, the coupling efficiency of diffuse incoherent skylight was very low but we still managed to observe the familiar OH atmospheric lines across the H band.

For this technology to be viable on front-line telescopes, it is imperative that we extend it to accept light from a multimode fibre. This is a more challenging prospect that has not been solved until now. In solving this problem, we arrive at a device – PIMMS #1 – with revolutionary properties as we show. In principle, the PIMMS instrument will accept light from (almost) any input f/ratio, either natural seeing or AO-corrected, any input fibre diameter, and any telescope diameter. For spectroscopic resolutions in the range of 100s to a few $\times 10^4$, the instrument is essentially the same size, limited only by the dimensions of the array waveguide measured in centimetres. This is a remarkable claim, and extraordinary claims require extraordinary evidence. While a multimode system has yet to be demonstrated, we are in a position to show most of the components that make up the system. See also the companion papers by Cvetkojevic et al (2010) and Lawrence et al (2010).

The key innovation which makes the PIMMS concept possible is the multi-to-single mode fibre converter, a device we call a “photonic lantern” (Leon-Saval, Birks & Bland-Hawthorn 2005; Noordgraff et al 2009, 2010; Leon-Saval, Argyros & Bland-Hawthorn 2010). Multimode fibres are needed to collect light that has been smeared by atmospheric turbulence; single-mode fibres are required for subsequent operations like OH suppression and dispersion (Bland-

Hawthorn et al 2004). The converters provide efficient interchange between these two formats. We start by discussing the potential of photonics to revolutionize astronomical instrumentation before introducing the photonic lantern in more detail. We then discuss some instrument concepts based on photonic lanterns and other astrophotonic devices. We close with a discussion on what the future holds for photonic technologies.

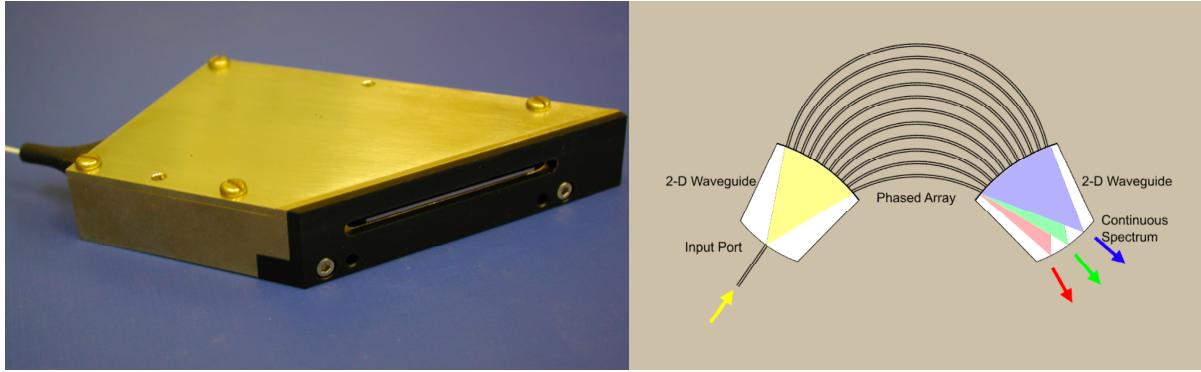


Fig. 1. (Left) The first integrated photonic spectrograph $\sim 7\text{cm}$ in size. (Right) A schematic of the same device. On-sky results from this device are presented in Cvetojevic et al (2009).

2. POTENTIAL GAINS

The photonic lantern converts an arbitrary source of illumination into a (potentially large) number of parallel propagating SM tracks. The propagation along these tracks is diffraction limited. This is light in its simplest form where it can be manipulated by extremely complex photonic functions that are inconceivable in bulk optics. In recent years, there have been serious advances in achieving efficient suppression of the OH night sky emission using fibre Bragg gratings embedded within optical fibres (Ellis & Bland-Hawthorn 2008; Bland-Hawthorn et al 2009). The night sky problem is widely viewed as one of the fundamental limitations to carrying out observational cosmology on large telescopes in the decades ahead. In order to exploit this technology, light needs to be concentrated into SMFs. If we are to go to the trouble of concentrating light into small fibre cores, it makes sense to use these fibres as pre-filters to photonic gratings. We see this as a very exciting synergy between two new technologies.

But there are other arguably more fundamental gains, in particular, the potential to miniaturize conventional spectrographs. There are several factors that argue in favour of miniaturization in the years ahead (BH06). At or near the diffraction limit, the focused spot is independent of the telescope aperture, and has a size that is compatible with photonic devices. If the light can be efficiently coupled into the device, it can remain within the device and be manipulated by it, before being imaged at the detector. The light does not need to see an air-glass boundary again. The cross-talk performance of telecomm devices already indicates that light scatter, birefringence and polarization effects can be managed to a high degree. Instruments based on integrated circuit technology will be more easily scaled to larger sizes, cheaper to mass produce, easier to control, and much less susceptible to vibration and flexure. Conventional optical design is now replaced by photonic engineering supported by a billion dollar R&D investment.

For slit-limited spectroscopy, we can write the resolving power in terms of the grating blaze angle γ as

$$R = \lambda/\delta\lambda = 2 D_{\text{COL}} \tan \gamma / \chi D_{\text{TEL}} \quad (1)$$

where $\delta\lambda$ is the wavelength resolution (e.g. Lee & Allington-Smith 2000). Since this involves only the diameters of the telescope aperture D_{TEL} and collimated beam D_{COL} and the angular slitwidth χ , equation (1) imposes a fixed upper limit on the obtainable resolving power. This is a highly informative equation. For a seeing-limited slit width and a fixed resolving power R , instruments must get larger as telescopes get larger. Furthermore, we can raise R by increasing the f/ratio of the input beam which also scales up the instrument.

However, we now show for the first time that the limits imposed by equation (1) can be overcome. As discussed by BH06, the physical size of the psf of a diffraction-limited optical system is independent of the telescope diameter. This is the fundamental limit of an optical system and therefore must be achieved in order to minimize the size of an instrument. If we can work in the diffraction limit, then the properties of the instrument need not depend on the telescope at all. But how can we speak of always working in the diffraction limit for an arbitrary input (e.g. seeing limited) aperture? Here we are referring to the performance of the *instrument* rather than the performance of the *telescope*. Our instrument concept does not require an AO-corrected input beam, although it can be further simplified in this case. So can we achieve something approaching diffraction-limited performance for an arbitrary input aperture and f/ratio? Remarkably, the answer is yes.

3. PHOTONIC LANTERNS

The photonic lantern, first demonstrated in 2005 (Leon-Saval et al 2005), features an array of SM fibres surrounded by a low index layer that is adiabatically tapered down to form an MM fibre on input and output. Efficient coupling is achieved in both directions if the number of (unpolarized) excited modes in the MM fibre is equal to the number of SM fibres in the bundle on exit from the taper. At the start of the transition, there are m uncoupled SMFs (Fig. 2). Just how these evolve through an adiabatic taper to become the m electromagnetic spatial modes of the output MMF can be appreciated by analogy with the Kronig-Penney model for the interaction of electrons in a periodic potential well. Initially, each quantum well allows only one electron in its lowest energy state (fundamental mode). The taper transition renders the quantum wells progressively shallower such that each electron begins to tunnel through its barrier. With the wells closer together, the leaky “conduction” electrons behave as if confined to a periodic crystal. At the point where the taper ends, the wells have essentially vanished, and the collective behaviour of the electrons is described by m standing waves (cf. supermodes) confined to a single broad potential well. (Note that the quantum analogy describes the energy eigenstates of an electron, whereas photonics considers the frequency eigenstates of a photon.) A more complete description is provided by Leon-Saval, Argyros & Bland-Hawthorn (2010).

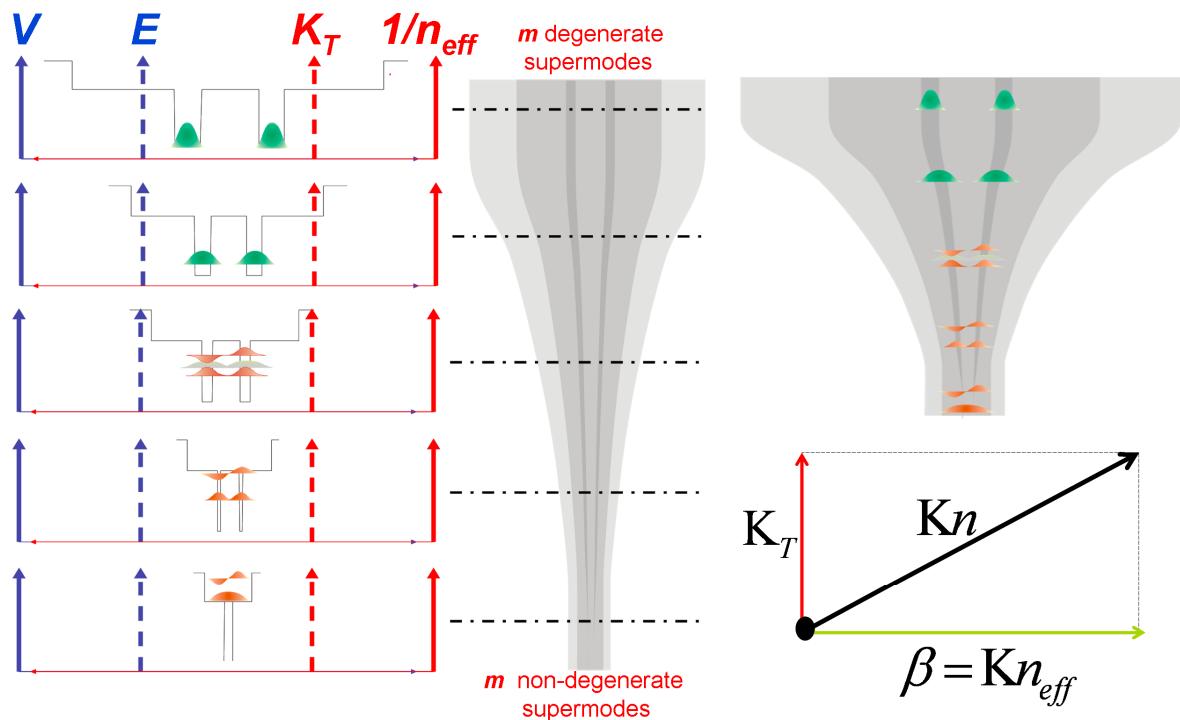


Fig. 2. A photonic lantern consists of two bidirectional tapers that are used back to back. Here we illustrate the function of one of these tapers starting at the bundle of m SMFs. Initially, the strongly guided radiation in each core is uncoupled; upon entering the adiabatic taper, the radiation is increasingly guided by the cladding. In a perfect system, this leads to m cladding supermodes that evolve to become m spatial electromagnetic modes at the MMF output. A good analogy for the

coupling of radiation between fibre cores is to consider the behaviour of electrons in closely-packed potential wells (see text). The depth of the potential well (V) is equivalent to the reciprocal of the refractive index $1/n_{\text{eff}}$ of the optical waveguide. The energy eigenstate (E) of the electron is equivalent to the transverse component K_T of the wave vector K where the waveguide mode has a propagation constant $\beta = Kn_{\text{eff}}$ (see inset).

4. NEW INSTRUMENT CONCEPTS

We present two new concepts in their simplest form that incorporate the photonic lantern on input. Strictly speaking, we are using half-lanterns, but we avoid the awkward distinction here. The first design (Fig. 3) is in some respects rather conventional. Astronomers are accustomed to the idea of using a microlens array to segment the focal (or pupil) plane to achieve a better match to the instrument downstream from the telescope. So let's look at the specific case of the photonic lantern in more detail.

The number of unpolarized modes m supported by a MM waveguide is given by

$$m = \frac{2V^2}{\pi^2} + 1 \quad (2)$$

where the familiar V parameter is given by

$$V = \frac{2\pi}{\lambda} a NA. \quad (3)$$

Here λ is the wavelength, a is the radius of the MM core and NA is the numerical aperture of the waveguide. Note that conserving m is tantamount to conserving the étendue (area \times solid angle) of the system. For the photonic lanterns, the NA is given by the refractive index difference between the low index tube and the cladding material of the SMF-28 fibers. In our initial development, the MM fibre needed to match an input f/ratio ~ 6 at $\lambda=1.55 \mu\text{m}$ required an $NA \approx 0.09$. For a $100\mu\text{m}$ core diameter (matched to the seeing on our 4m test bed telescope), the number of supported modes is 61. So to accept all the light from a point source in natural seeing, the photonic lantern must utilize 61 SMFs on output. These 1×61 devices (1 input; 61 outputs) were manufactured in collaboration with our commercial partners and found to be very efficient (~90%; see Noordgraff et al 2009).

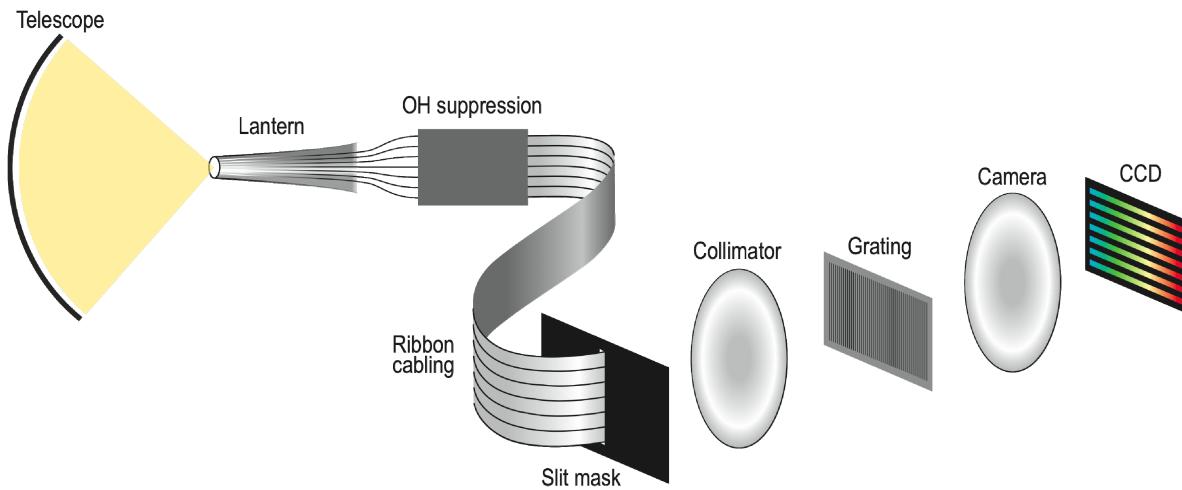


Fig. 3. PIMMS #0: Diffraction limited spectrograph that accepts light from an arbitrary source, i.e. natural seeing, AO corrected. Here, only one MM fibre input is shown although in future instruments, we anticipate many such inputs will feed to the spectrograph.

Now take a look at Fig. 3. In order to simplify the sketch, only 7 SMFs are shown. (In fact, a 1×7 device is optimal for an AO fed focus at high Strehl ratio: Horton & Bland-Hawthorn 2007; cf. Corbett, Butterley & Allington-Smith 2007). These are fed to the OH suppression module where extremely complex fibre Bragg gratings in series reject the atmospheric OH lines while allowing the good light to go forwards. The SMF ribbon cabling then forms a diffraction-limited slit ($\sim 10\mu\text{m}$ width) which illuminates a conventional spectrograph.

It may not be immediately obvious what we have gained by doing this. The first gain is the reduced size of the instrument. For a given spectroscopic resolution, the size of the instrument scales with the size of the entrance slit (Sec. 2). The diffraction-limited slit means that we can keep the size of the bulk optics in the spectrograph to a minimum. But this is no guarantee of high transmission. A compact commercial spectrograph HR4000 manufactured by Ocean Optics allows for a $10\mu\text{m}$ slit in order to operate at close to $R=4000$. The overall throughput is low (10%) and it is very difficult to direct sufficient light into the device from an incoherent (Lambertian) source. Compare this to the first of our devices – PIMMS #0 – where we can now efficiently couple with any diffuse source or point source and therefore integrate the light over, say, a $100\mu\text{m}$ aperture diameter. Such a device couples two orders of magnitude more efficiently than the prototype in Fig. 1. The emerging radiation from the SMFs has a fixed opening angle that can now be efficiently collected and dispersed by a highly optimized optical train.

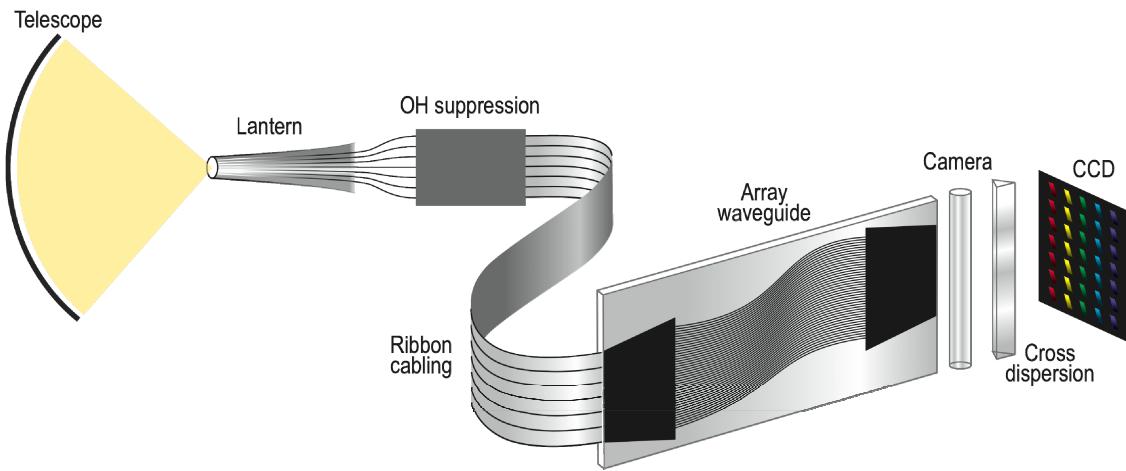


Fig. 4. PIMMS #1: Same as Fig. 3 but where the bulk optics are replaced by photonic components. A fully photonic spectrograph can be much smaller than bulk optic devices. Here we show an asymmetric rather than a folded AWG (see BH06).

Since we have divided up the MMF light into 61 distinct spectra, a major consideration is detector noise, particularly for photon-starved or low background exposures. Thus, in order for a PIMMS spectrograph to be viable, the light must be fed to state-of-the-art, low noise devices. Such devices are now under development at optical and IR wavelengths by J.-L. Gache (Marseille), J. Beletic (Teledyne CA) and D. Figer (Rochester NY).

In the next section, we discuss PIMMS #1 – a fully integrated photonic spectrograph. But first we must recap on photonic spectroscopic dispersion and, in particular, the array waveguide. The instrument resembles PIMMS #0 except that the slit entrance aperture is now coincident with the leading face of a waveguide substrate. The plane of propagation is confined to a 2D waveguide. Such an instrument can, in principle, be made much smaller than those incorporating bulk optics. This is a radical departure from conventional instrumentation. Even more radical is where this line of reasoning takes us in future years, a discussion we leave to the final section.

5. CYCLIC ARRAY WAVEGUIDE

Bland-Hawthorn & Horton (2006) discuss in detail different forms of photonic spectroscopic dispersion. While they came down on the side of photonic echelle gratings, industry has advanced the cause of array waveguides for the purpose of dense wavelength division multiplexing (DWDM). So we confine our discussion to these extraordinary devices because array waveguides are readily available, albeit not optimized, for our purposes. To date, we have examined AWGs with spectral resolutions in the range R=2000-7000.

In Sec. 4, we outlined several reasons why a photonic instrument can be made compact. In a recent paper, Allington-Smith & Bland-Hawthorn (2010) describe how a photonic dispersing element helps to retain the compactness of the instrument. The equation of interference for any grating device can be expressed as

$$\sin \theta_I + \sin \theta_D = (m\lambda + q)\rho$$

where θ_I and θ_D are the incident and diffracted angles to the grating normal, ρ is the grating line density, and q is an extra path difference in the grating structure. For ruled gratings, $q=0$, but in array waveguides, q is non-zero which allows for an arbitrary order of interference m to be achieved on axis. Note that the grating dispersion $d\lambda/d\theta_D$ is independent of q . This leads to a very compact device at a given resolving power.

In BH06, we discussed the array waveguide for a single SMF input in some detail. In Fig. 3 of that paper, we show how a single input generates multiple orders on output. But a key obstacle remains: how is it possible to convert an AWG to a multimode device? If we are to retain the compactness of the instrument, it is undesirable to feed each of the SMFs to its own AWG unless these can be made at least an order of magnitude smaller (cf. Corbett 2009). Nano/micro array waveguides are being investigated (e.g. Dumon et al 2006; Dai & He 2006) but they perform very poorly at the present time.

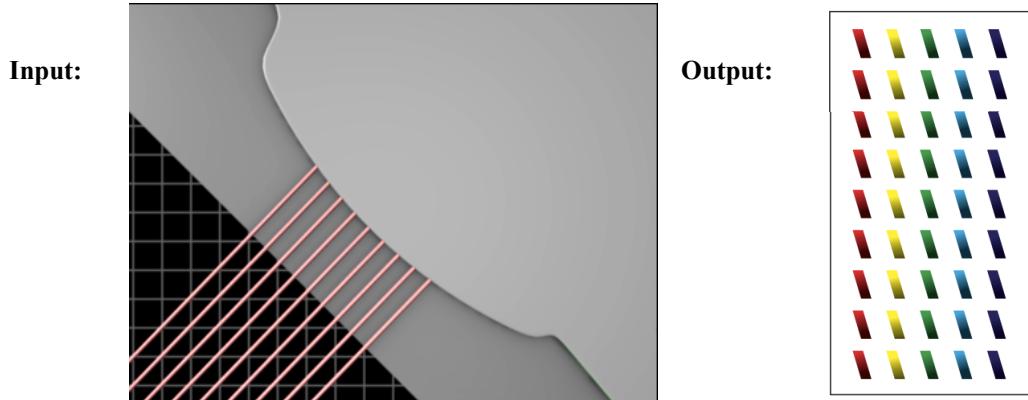


Fig. 5. (Left) Single mode fibres connected to the front face of an AWG. The separation of these fibres is set wide enough (~ 1 mm) to ensure that the continuous spectra in a given order do not overlap at the detector (Right). Along an orthogonal axis, the cross disperser spreads out the other orders to ensure that they do not overlap. While not obvious from the limited artwork, the different orders from a single input fibre track diagonally across the detector. For each fibre, when the spectra are joined end to end, they make a continuous spectrum once the variable transmission profile is corrected for.

We now introduce the concept of the *cyclic array waveguide*. For a single on-axis SMF input, the AWG produces a continuous spectrum at the detector and its length is, say, 1 mm. For the device discussed by Cvetojevic et al (2009), this spectrum corresponds to a single spectral order with a free spectral range of roughly 60 nm. If we illuminate the device with broadband light, the neighbouring orders overlap with the central order at the detector. We can rectify this by using a cross disperser to offset the other spectral windows vertically at the detector.

Note that the AWG shown in Fig. 1 is symmetric about the propagation axis. We can now connect up the front face of the AWG with N distinct SMF inputs (Fig. 5). Each of the inputs is spaced by the physical distance of a free spectral

range, i.e. one spectral order. So if we space the inputs by 1 mm, the output spectra will not overlap for a given spectral order (e.g. green spectra in Fig. 5). Once again, the cross disperser spreads out the other orders (Fig. 5) to ensure that they do not overlap. Thus, we have achieved a *broadband multimode AWG* for the first time, i.e. a solitary AWG can be used to process all of the light from a *multimode* input. There is no such device in existence today.

We now describe an instrument concept – PIMMS #1 – that uses this technology at its heart.

6. PIMMS #1: THE MOVIE

To aid the description that follows, we have attempted to render the PIMMS #1 spectrograph concept in movie form. This file is available at <http://www.physics.usyd.edu.au/research/sifa/astrophotonics/PIMMS.shtml>. The reader is encouraged to contact the first author if a different format is required. PIMMS #1 is shown in two passes, one without the OH suppression module, and one including OH suppression. This is our first attempt at visualizing a fully photonic spectrograph. We were not able to render either the lantern or the FBGs properly with the present software although we intend to fix these problems in a future version.

The key components in order are:

- a. micro beam splitter to split the near IR into two spectral windows
- b. photonic lantern
- c. OH suppression module (second part of movie only)
- d. cyclic array waveguide
- e. reimaging micro cylinder lens
- f. cross dispersing micro prism
- g. low noise detector

The micro beam splitter breaks the multimode light into two astronomical spectral windows (J, H bands) to allow better mode matching. The reason for this is the dependence of the mode count for a fixed input aperture on wavelength in equations (2) and (3). This is important for matching the MMF core size to the photonic lantern aperture. Roughly speaking, the short wavelength lantern (J band) needs twice the number of SMFs to match the étendue of the long wavelength lantern (H band).

In the second part of the movie, we include the OH suppression module to illustrate how the good light goes forwards and the unwanted sky lines are reflected in the direction from whence it came. In reality, the entire grating region is needed to do this. We show light propagation along only a few of the SMF tracks whereas in practice light propagates along all tracks. (The inset shows a zoomed up view of the light propagation.)

The parallel array of SMFs then attach to the front face of the array waveguide aligned with the 10 μm -thick guide layer. When light leaves the AWG, it is focused by a micro cylinder lens before being cross dispersed by the micro prism. The array of spectra resemble the pattern shown in Fig. 5. If the entire set of spectra is confined to a detector region whose vertical height (~ 1 mm) corresponds to the thickness of the AWG substrate, we can stack a large number of array waveguides to ensure maximal use of the CCD area. This is the PIMMS #1 concept at its core.

Note for compactness that we have used two crossed AWGs on the same substrate, a trick commonly used by commercial suppliers in case one fails (“an heir and a spare”). For completeness, we show two detectors but this is not strictly required.

Thus, we can stack q AWGs on top of each other fed by p photonic lanterns. There is no particular reason why p should be the same as q since the wiring at the lantern output can be arbitrary with respect to the AWG stack, at least in principle. An areal detector can be placed up against the re-imaged output to capture all of the light from the q stacked AWGs. This is what the movie attempts to show although the output spectra are not well packed in our illustration. We are presently investigating whether we will use a stack of micro optics in practice, or a hybrid solution with conventional (small) output optics.

In summary, the 2D areal detector is now maximally packed with spectral information. In the horizontal direction, we have N spectra arising from the N outputs of a lantern. In the vertical direction, we have $5q$ spectra from the q stacked

AWGs where we are assuming that each AWG provides 5 cross-dispersed orders (Fig. 5). In practice, this depends on the spectral resolution of the device (Lawrence et al 2010).

7. THE FUTURE

The PIMMS paradigm opens the door to a remarkable array of possible future devices. We foresee the ability of many smaller university departments and observatories involved in designing and building their own instruments without the traditional reliance on major observatories and associated funding streams.

Some discussion of future prospects for photonic spectrographs has already been given in BH06. Our group is now planning to extend this work to mid infrared wavelengths. In Figs. 3 and 4, a box is included specifically for the task of OH suppression. In practice, this could be replaced by or used in series with many interesting other functionalities. These include:

- Polarizing filters
- Time gating for variable sources
- Mode scrambling, switching or combining for interferometry
- Phase correction for “adaptive optics in a fibre”
- Laser (emission line) combs for accurate spectroscopy of faint sources
- Ring resonator (absorption line) combs for accurate spectroscopy of bright sources
- Heterodyne filters

All of these functions require additional componentry, but we refrain from presenting complete instrument concepts at the present time. Astronomers are now routinely detecting planets with the aid of extremely stable calibration sources. Here the spectrograph references either a laser or a calibration source, or observes through a gas (e.g. iodine) which imprints a known absorption line spectrum on the collected data. But it is not clear that this is necessary or even desirable with a stabilized photonic spectrograph. An array of SMFs fed to an array of micro-ring resonators can be used to imprint absorption lines on the output spectra. Alternatively, a supercontinuum source can be transformed into a laser comb by the use of these same devices. Such a transition has certain advantages over conventional laser combs, although the latter achieve higher levels of stability and precision. These prospects are presently under investigation by us.

Another foreseeable development is the use of ultrafast laser inscription to create 3D photonic devices without the need for stacking 2D devices (Thomson, Kar & Allington-Smith 2009). We envisage devices that will find wide application in oceanographic, atmospheric and space sciences. In the area of remote sensing, we foresee arrays of small devices that can be carried by robots, nano/micro satellites, dirigibles, balloons, submersibles, and so forth.

ACKNOWLEDGMENT

JBH is supported by a Federation Fellowship from the Australian Research Council. This work was completed during the Hilary and Trinity terms (2010) at the Beecroft Institute of Particle Astrophysics & Cosmology, Oxford University. JBH is indebted to the Leverhulme Foundation for sponsoring a Visiting Professorship to Oxford and to Merton College for a Visiting Fellowship.

REFERENCES

- [1] Allington-Smith, J.R. & Bland-Hawthorn, J. Astrophotonic spectroscopy: defining the potential advantage, MNRAS, 404, 232 (2010).
- [2] Bland-Hawthorn, J., Englund, M.A. & Edvell, G., New approach to atmospheric OH suppression using an aperiodic fibre Bragg grating, Optics Express, 12, 5902 (2004).

- [3] Bland-Hawthorn, J. & Horton, A.J., Instruments without Optics: An Integrated Photonic Spectrograph, SPIE, 6269, 21 (2006).
- [4] Bland-Hawthorn, J. & Horton, A.J., Instruments without Optics: An Integrated Photonic Spectrograph, AAO Newsletter, 112, 27 (2007).
- [5] Bland-Hawthorn, J. et al, Photonic OH Suppression of the Infrared Night Sky: First Results, AAO Newsletter, 115, 15 (2009).
- [6] Corbett, J.C., Butterley, T. & Allington-Smith, J.R. Fibre modal power distributions in astronomy and their application to OH-suppression fibres, MNRAS, 378, 482 (2007).
- [7] Corbett, J.C., Sampling of the telescope image plane using single- and few-mode fibre arrays, Optics Express, 17, 1885 (2009).
- [8] Cvetkojevic, N. et al, Characterization and on-sky demonstration of an integrated photonic spectrograph for astronomy, Optics Express, Optics Express, 17, 18643 (2009).
- [9] Cvetkojevic, N. et al, Experimental Characterization of Arrayed Waveguides for Astronomy, SPIE, this volume (2010).
- [10] Dai, D. & He, S. Novel Ultracompact Si-nanowire-based Arrayed Waveguide Grating with Microbends, Optics Express, 14, 5260 (2007)
- [11] Dumon, P. et al, Compact Wavelength Router based on a Silicon-on-insulator Arrayed Waveguide Grating pigtailed to a Fiber Array, Optics Express, 14, 664 (2006)
- [12] Ellis, S.C. & Bland-Hawthorn, J., The Case for OH Suppression at Near Infrared Wavelengths, MNRAS, 386, 47 (2008).
- [13] Horton, A.J. & Bland-Hawthorn, J., Coupling light into few-mode optical fibres I: The diffraction limit, Optics Express, 15, 1443 (2007).
- [14] Lawrence, J.S. et al, Miniature astronomical spectrograph using array waveguide gratings: capabilities and limitations, SPIE, this volume (2010).
- [15] Lee, D. & Allington-Smith, J.R. An Experimental Investigation of Immersed Gratings, MNRAS, 312, 57 (2000).
- [16] Leon-Saval, S., Birks, T.A. & Bland-Hawthorn, J. Multimode Fibre Devices with Single-mode Performance, Optics Letters, 30, 2545 (2005).
- [17] Leon-Saval, S., Argyros, A. & Bland-Hawthorn, J. Photonic Lanterns: A Study of Light Propagation in Multimode to Single-mode Devices, Optics Express, 18, 8430 (2010).
- [18] Noordegraaf, D. et al, Efficient multi-mode to single-mode coupling in a photonic lantern, Optics Express, 17, 1988 (2009).
- [19] Noordegraaf, D. et al, Multi-mode to single-mode conversion in a 61 port Photonic Lantern, Optics Express, 18, 4673 (2010).
- [20] Thomson, R., Kar, A.K. & Allington-Smith, J.R. Ultrafast laser inscription: an enabling technology for astrophotonics, Optics Express, 17, 1963 (2009).