Photonic reformatting of celestial light for precision radial velocity (PRV) spectrographs

Robert R. Thomson

Scottish Universities Physics Alliance (SUPA), Institute of Photonics and Quantum Sciences (IPaQS), Heriot-Watt University, Edinburgh, UK.

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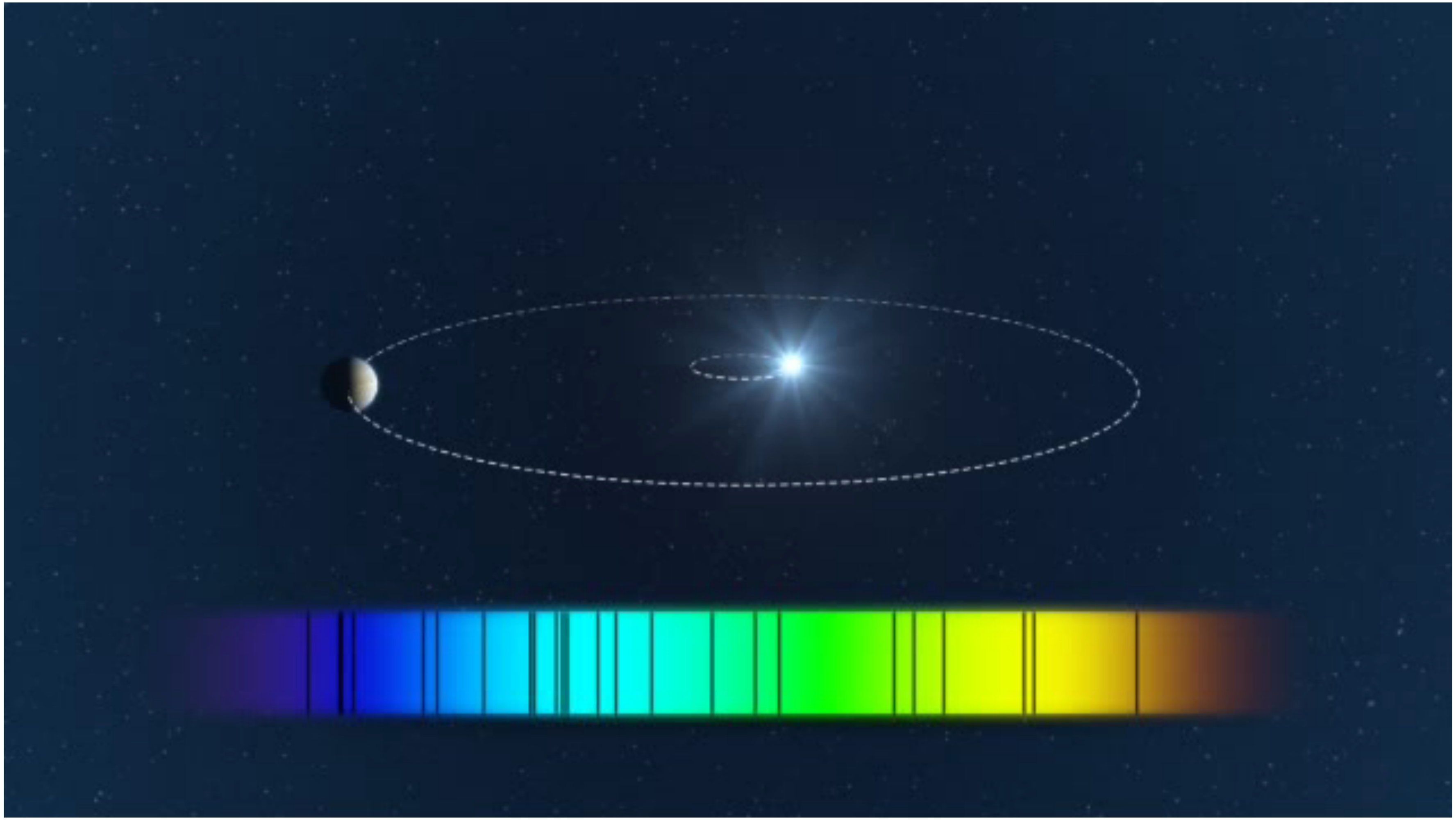
Radial velocity measurements



Animation from ESO.

Radial velocity measurements

For 1 M_{Sun} stars:

RV: ~ 30 $m.s^{-1}$ for giant planets.
~ 1 $m.s^{-1}$ for Neptune like planets.
~ 0.1$m.s^{-1}$ for Earth-like planets.

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta RV}{c}$$

RV shift (for λ_{obs} ~ 1µm):

~ 0.1 pm for giant planets.
~ 3.0 fm for Neptune like planets.
~ 0.3 fm for Earth-like planets.

Radial velocity spectrographs

PRV spectrographs must exhibit:

- High spectral resolution (R ~100,000).
- Exceptional stability and accuracy over long time periods.
- High throughput (the higher the better).

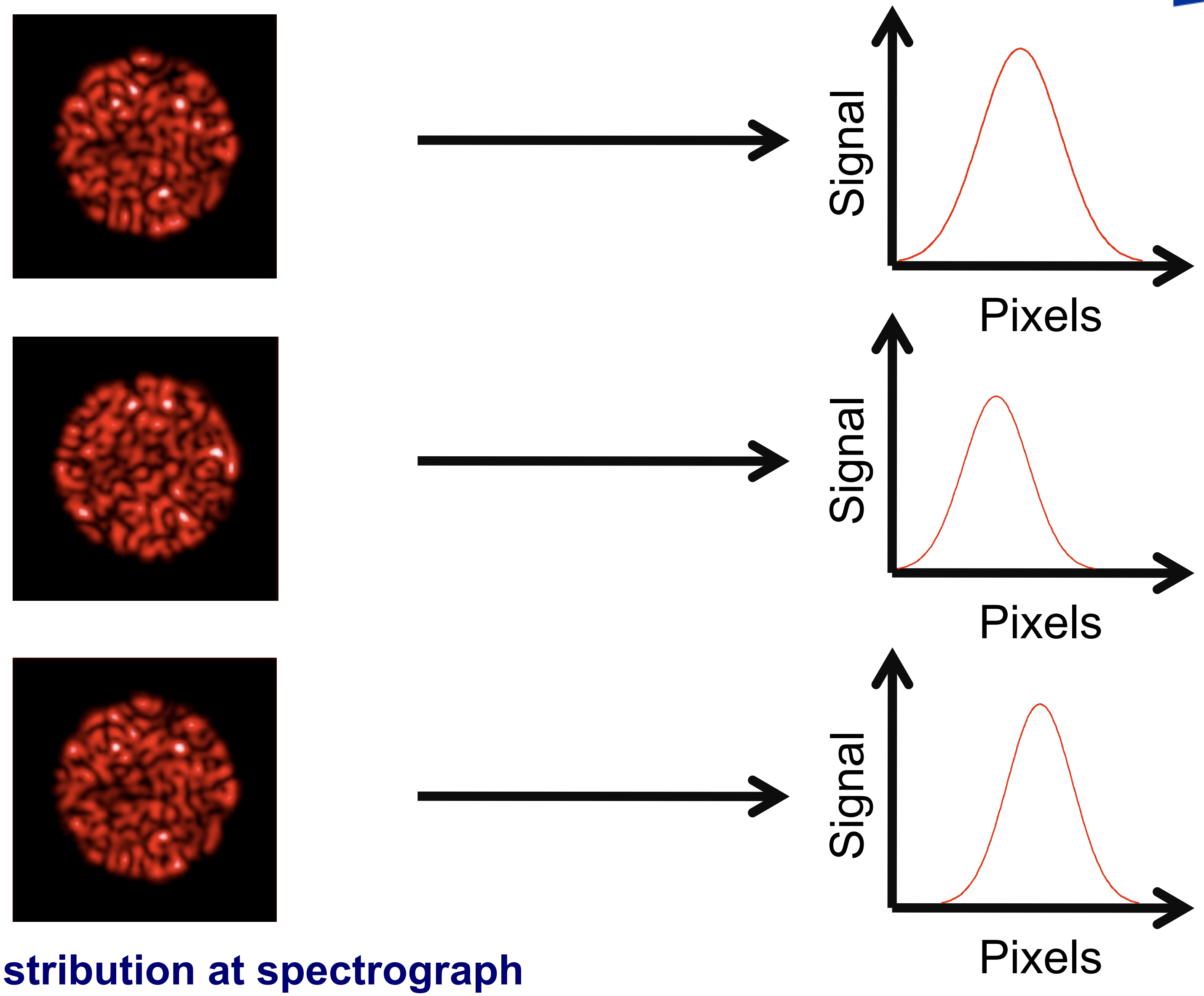
Building PRV spectrographs for larger telescopes is difficult because:

$$N_m = \frac{\pi^2}{16}\left(\frac{\theta_{seeing} \cdot D_{telescope}}{\lambda}\right)^2$$

N_m = Number of modes.
λ = Wavelength.
θ_{seeing} = The seeing of the site (in rad).
D_{tel} = Diameter of the telescope.

More modes = bigger PSF = bigger slit width = bigger spectrograph

Modal noise



Intensity distribution at spectrograph entrance / fibre output (narrow wavelength band)

What can photonics do for PRV?

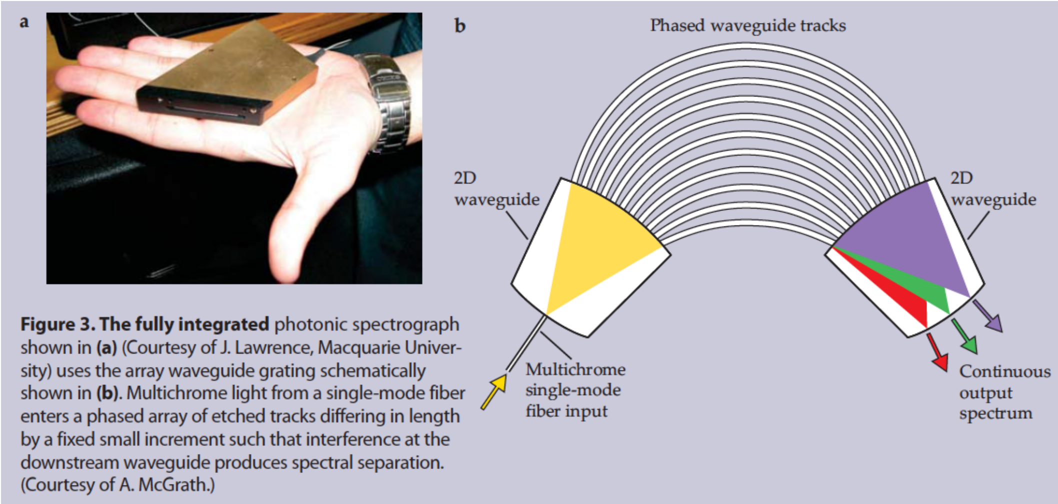
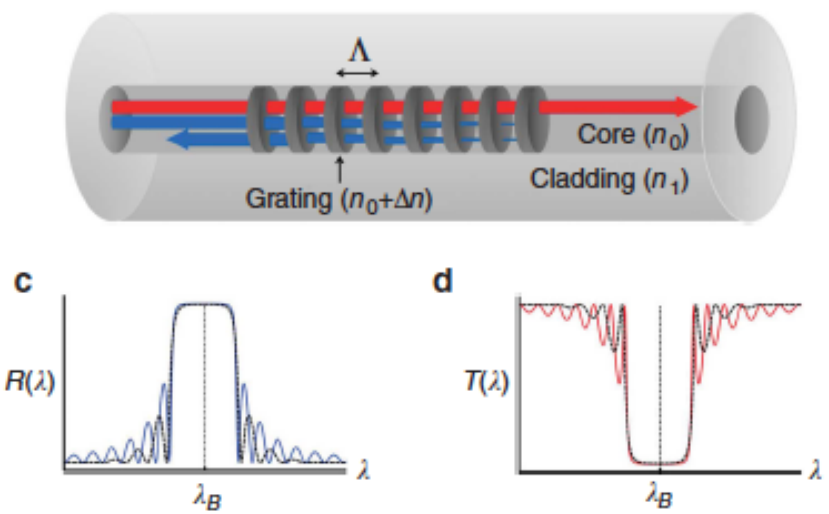


Figure 3. The fully integrated photonic spectrograph shown in **(a)** (Courtesy of J. Lawrence, Macquarie University) uses the array waveguide grating schematically shown in **(b)**. Multichrome light from a single-mode fiber enters a phased array of etched tracks differing in length by a fixed small increment such that interference at the downstream waveguide produces spectral separation. (Courtesy of A. McGrath.)

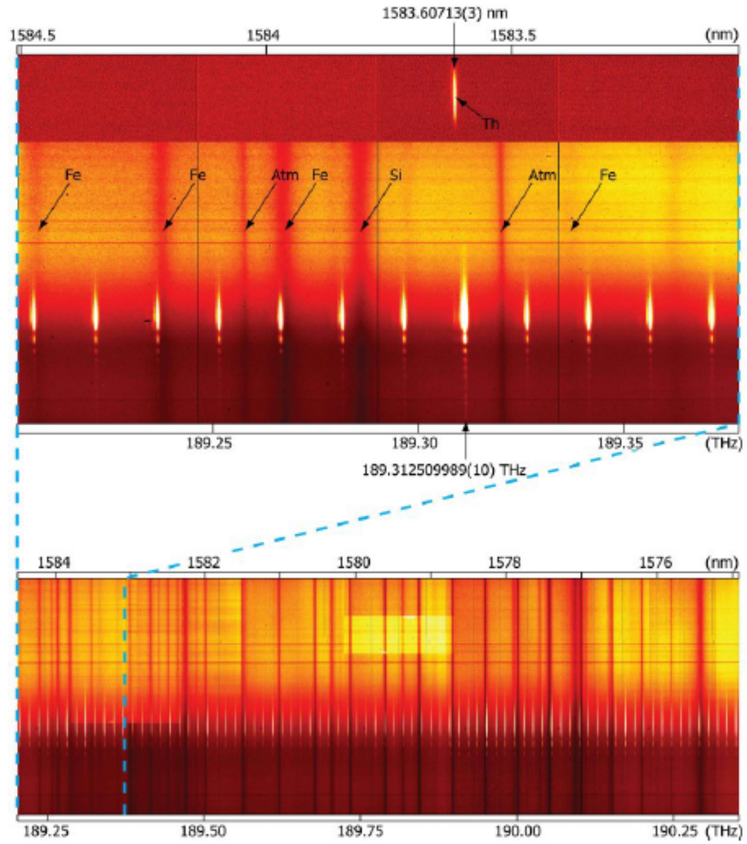
Ultra-compact high-resolution spectrographs

Bland-Hawthorn et al, Physics Today **65** (2012)



Fibre-Bragg-gratings for OH-line suppression

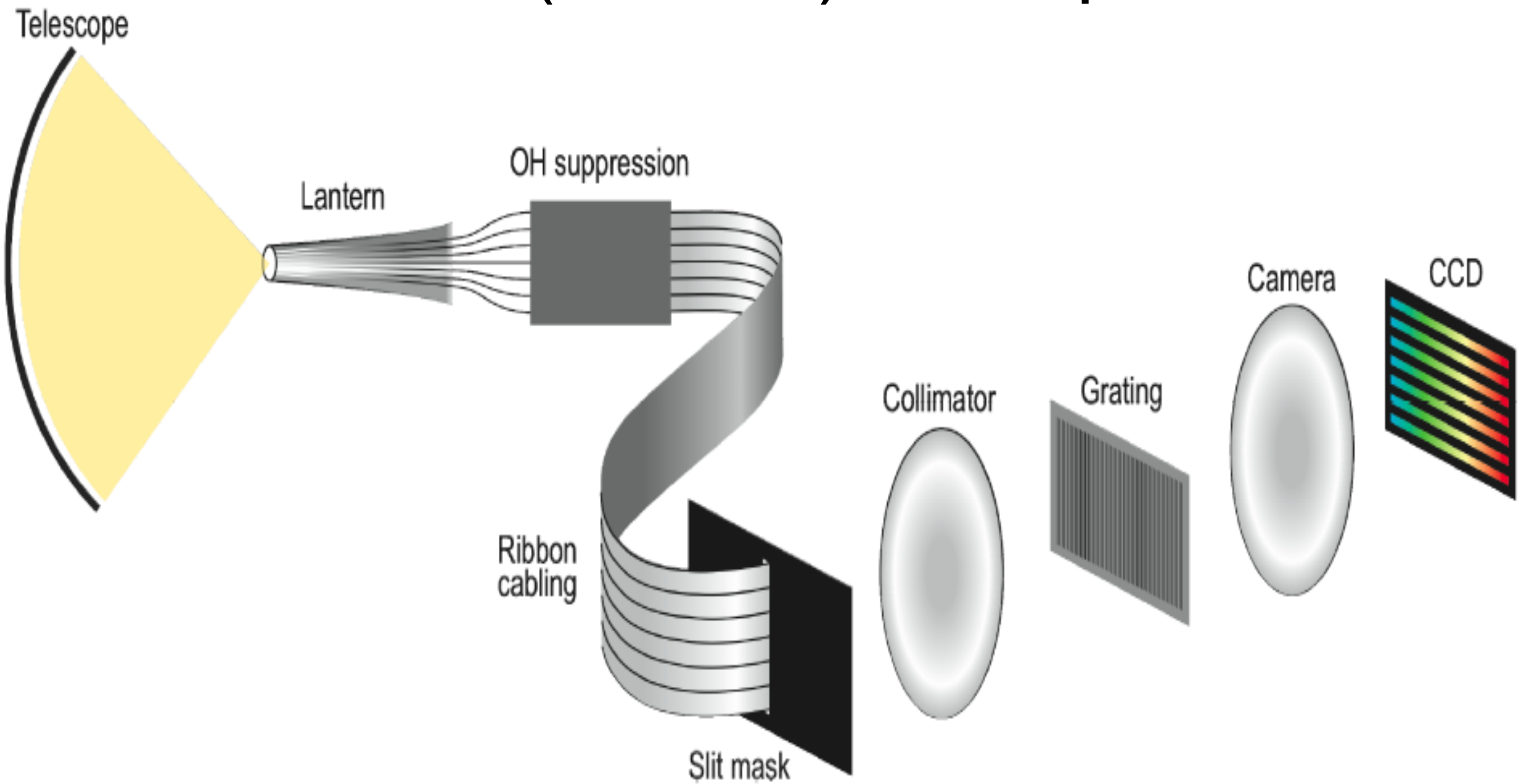
Bland-Hawthorn et al, Nat. Comms. **2** (2011)



Frequency combs for spectrograph calibration

Steinmetz et al, Science 321 (2008)

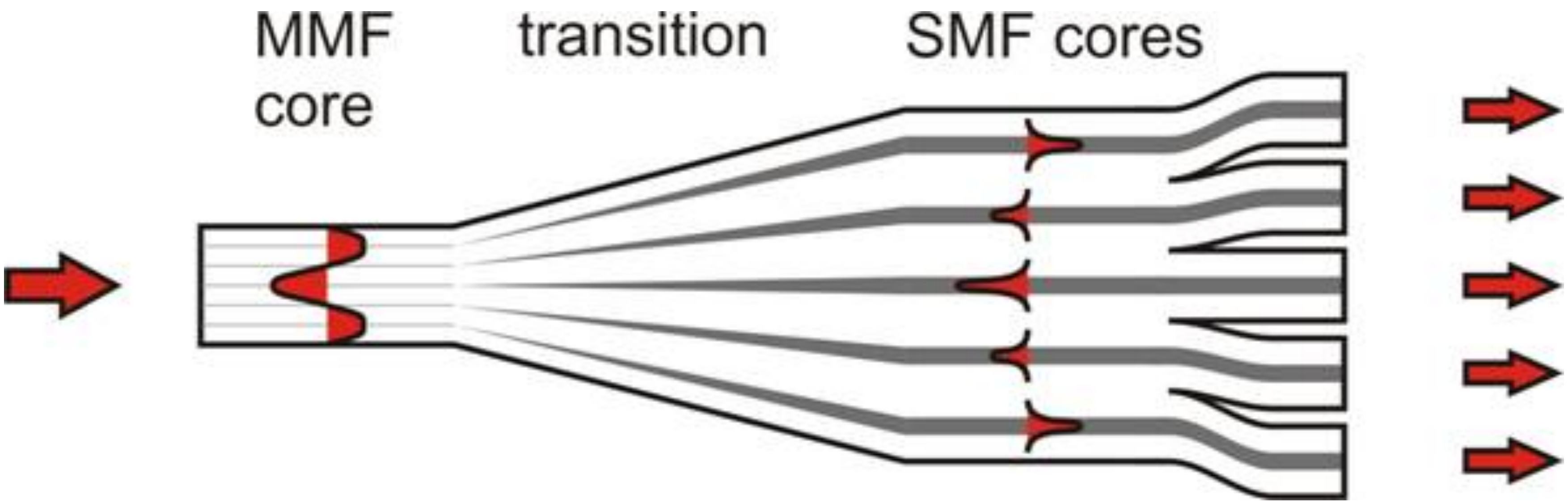
The photonic integrated multimode micro-spectrograph (PIMMS) concept



J. Bland-Hawthorn et al,
Proc. SPIE 7735, 77350N (2010)

The “photonic lantern”

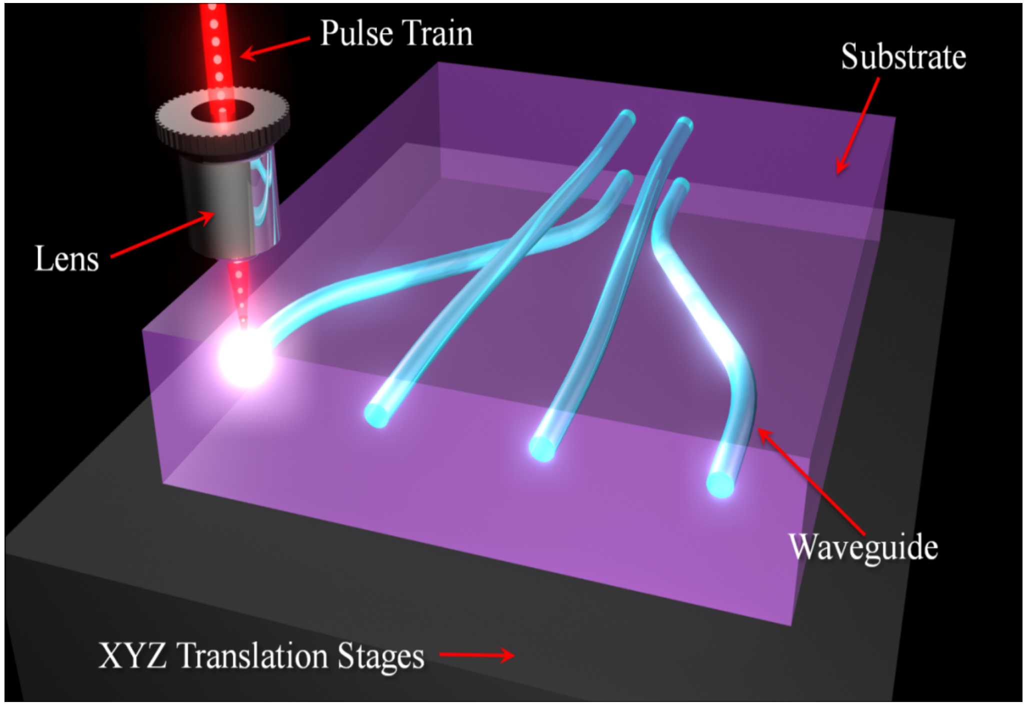
•Couple light from one MMF to several SMF cores along a gradual taper transition



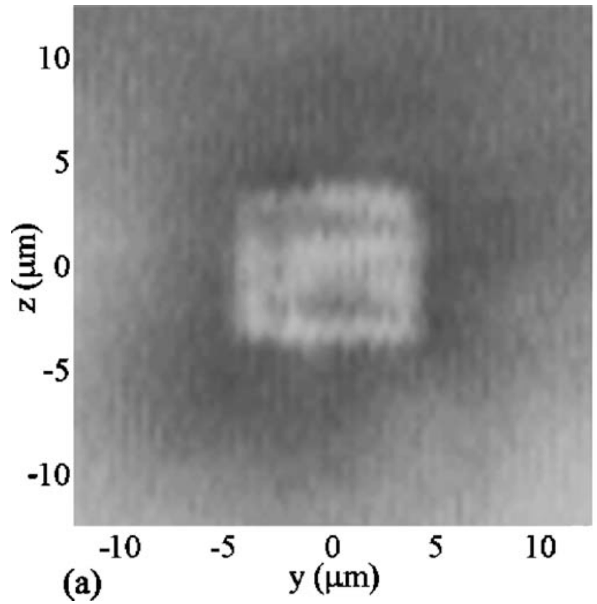
•Low loss: let N (number of single modes) = M (number of MMF modes)
$\Rightarrow$ conserve no. modes / entropy / brightness / etendue couple light from one MMF to several SMF cores along a gradual taper transition

S. G Leon-Saval et al, Opt. Lett. **30**, 2545 (2005)

Ultrafast laser inscription

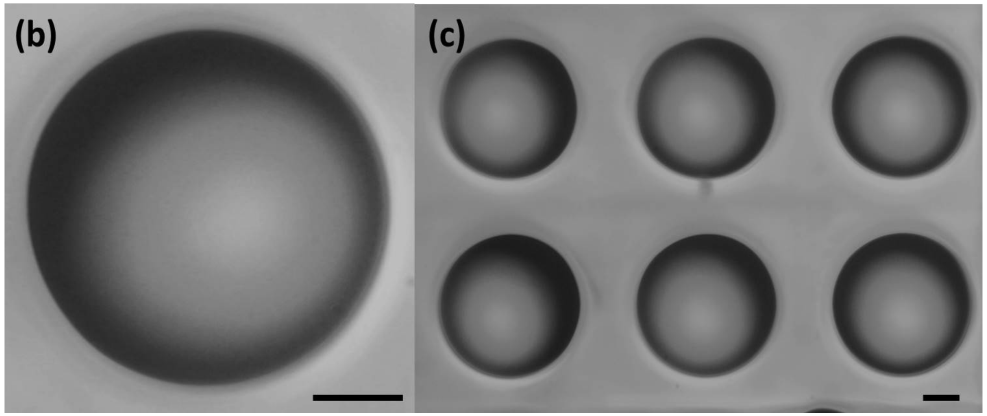


Cartoon of ULI process



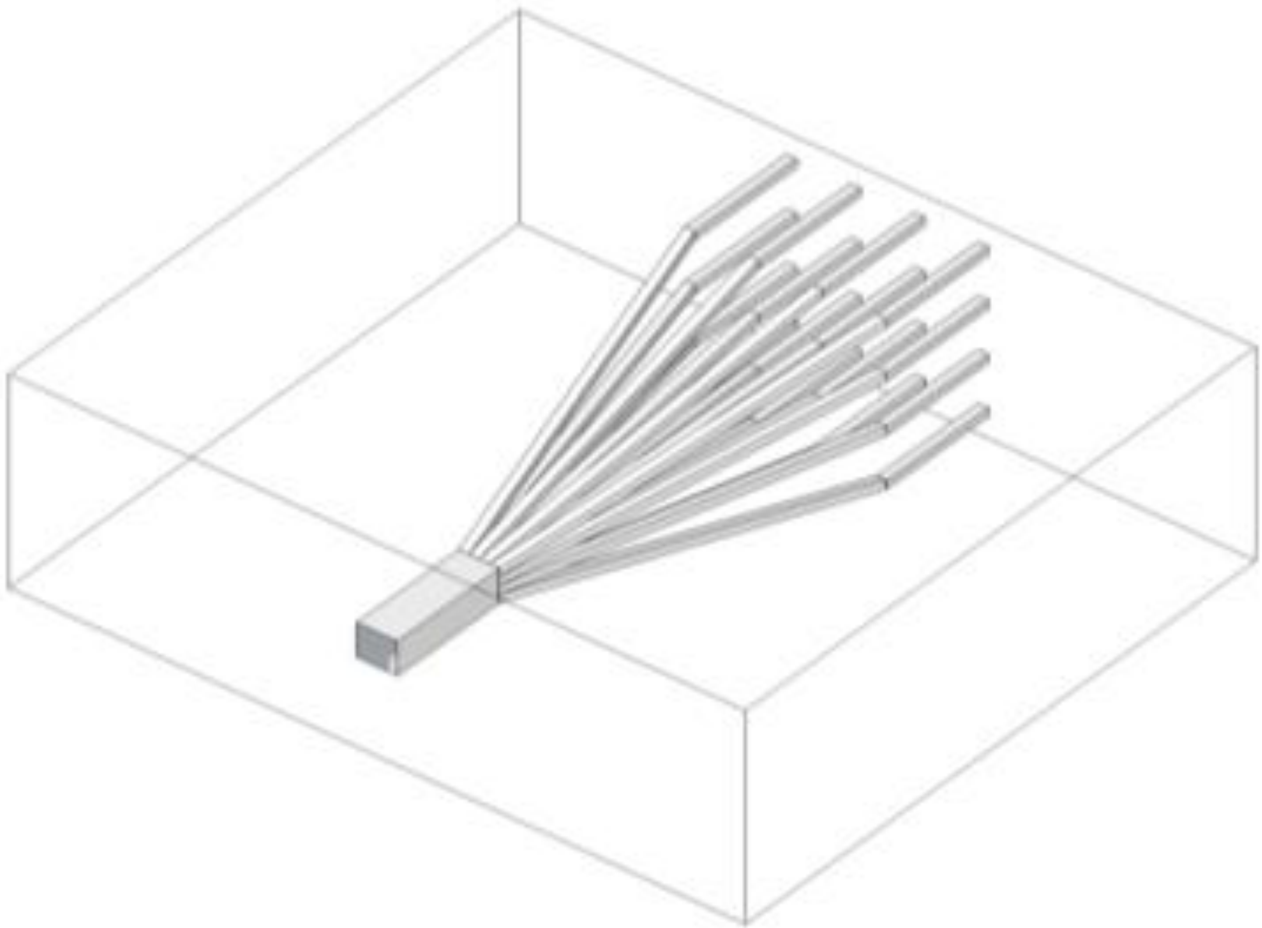
Psaila et al, Appl. Phys. Lett. **90**, 131102 (2007)

- Unique fabrication capabilities:
- 3D optical waveguides.
- Micro-optics.
- ULI is material flexible.
- ULI is a direct-write technology.



Choudhury et al, Proc. SPIE, Paper No. 9151-158 (2014)

Integrated photonic lantern development

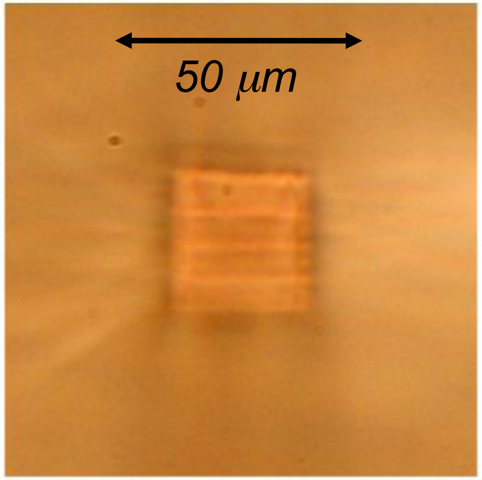


Cartoon of the proposed integrated photonic lantern

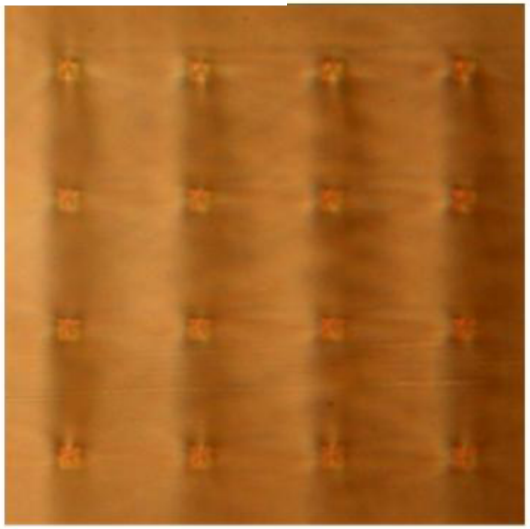
Ultrafast laser inscription of an integrated photonic lantern

R. R. Thomson,[1*] T. A. Birks,[2] S. G. Leon-Saval,[3] A. K. Kar,[1] and J. Bland-Hawthorn[3,4]

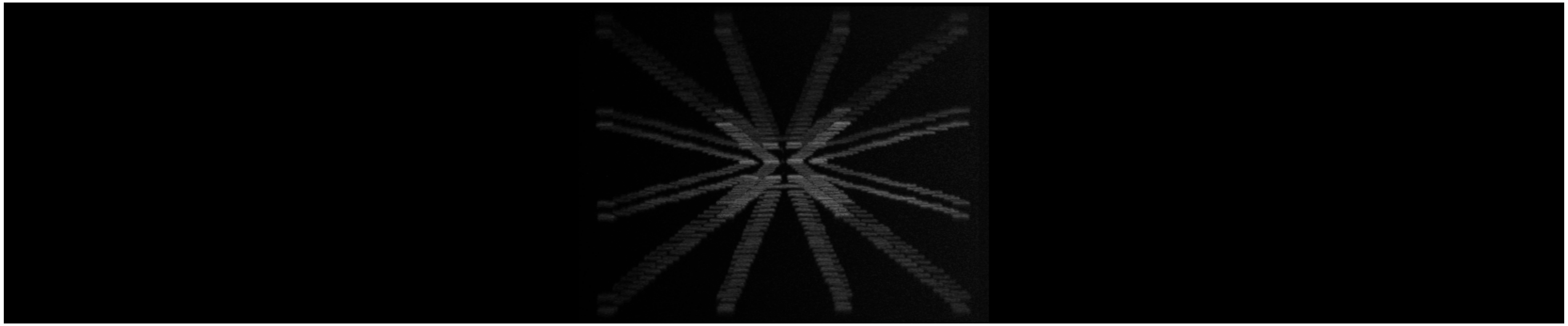
[1]Scottish Universities Physics Alliance (SUPA), School of Engineering and Physical Sciences, Physics Department, David Brewster Building, Heriot Watt University, Edinburgh, EH14 4AS, Scotland
[2]Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK
[3]Institute of Photonics and Optical Science, School of Physics, University of Sydney, NSW 2006, Australia
[4]Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia
**R.R.Thomson@hw.ac.uk*



μ-graph of multimode waveguide

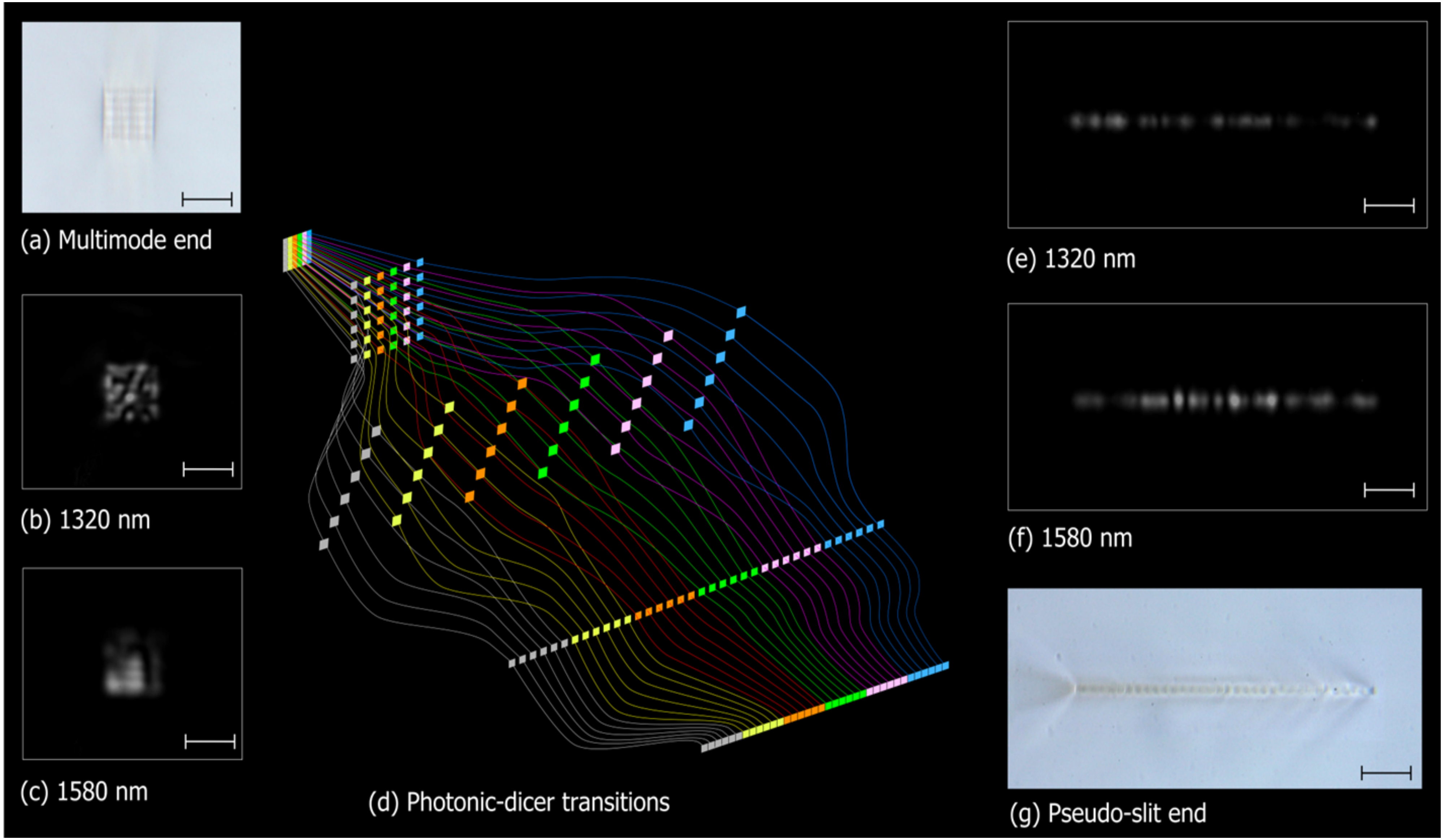


μ-graph of single mode waveguide array



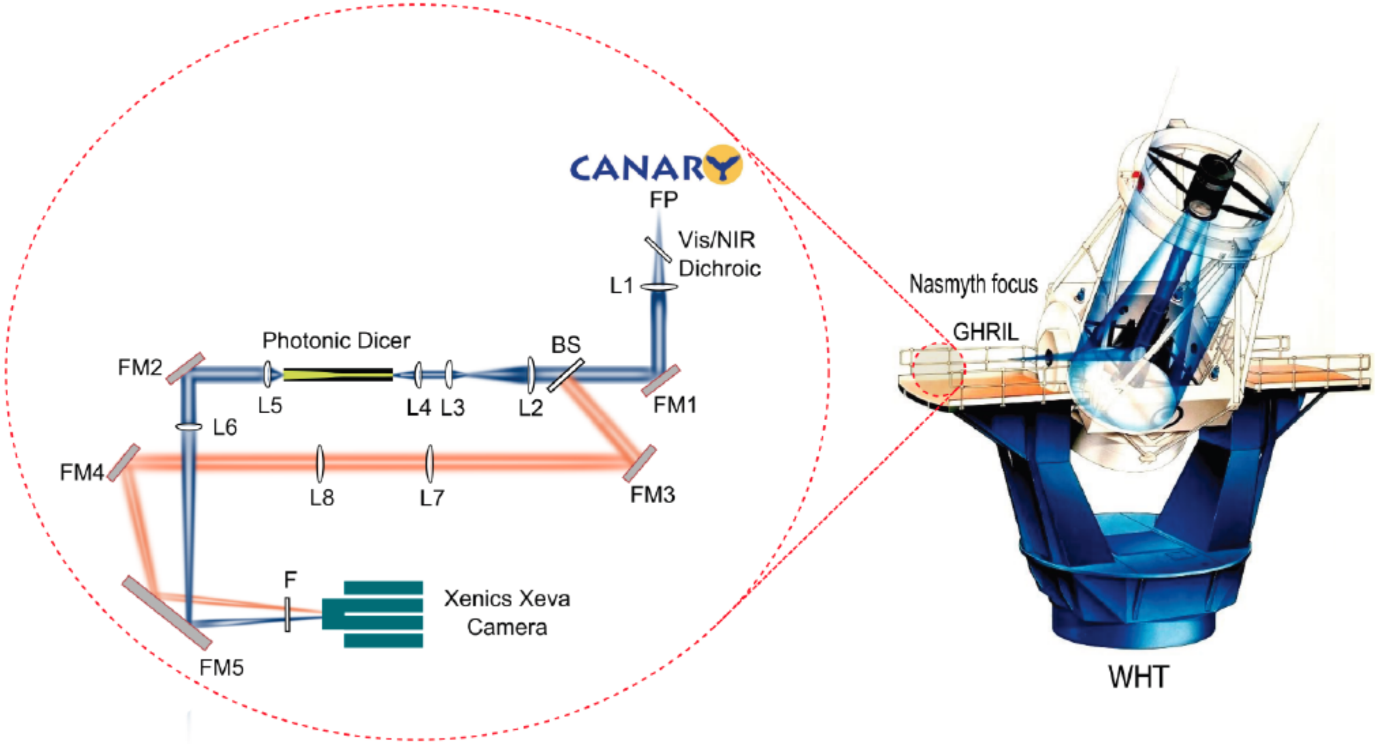
[Nonlinear imaging measurements performed by M. Booth and co-workers (U. of Oxford)]

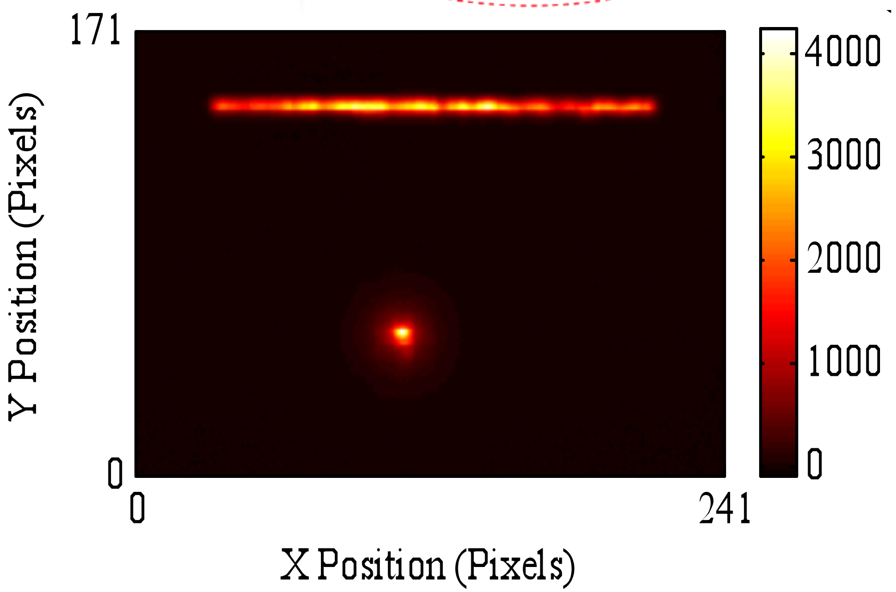
3D reformatter development

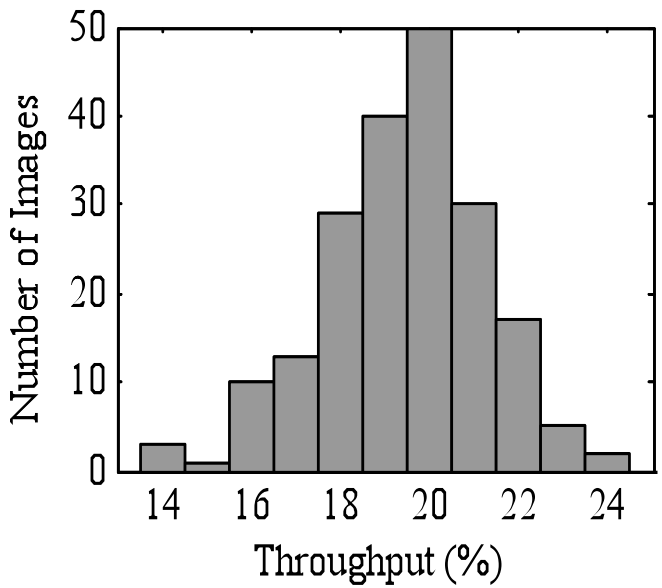


R. J. Harris et al, "Photonic spatial reformatting of stellar light for diffraction-limited spectroscopy" - arXiv:1402.2547

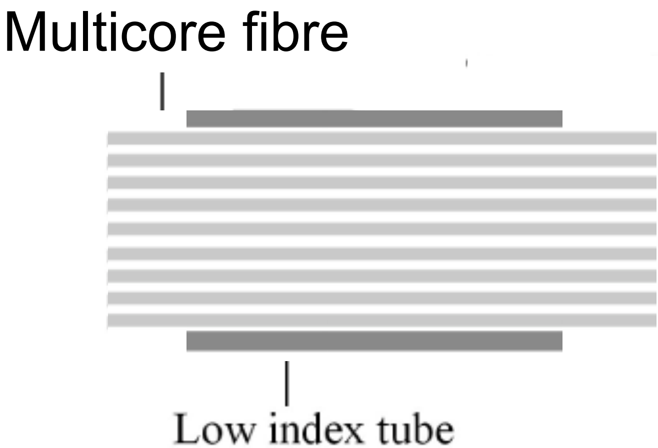
On-sky reformatter testing

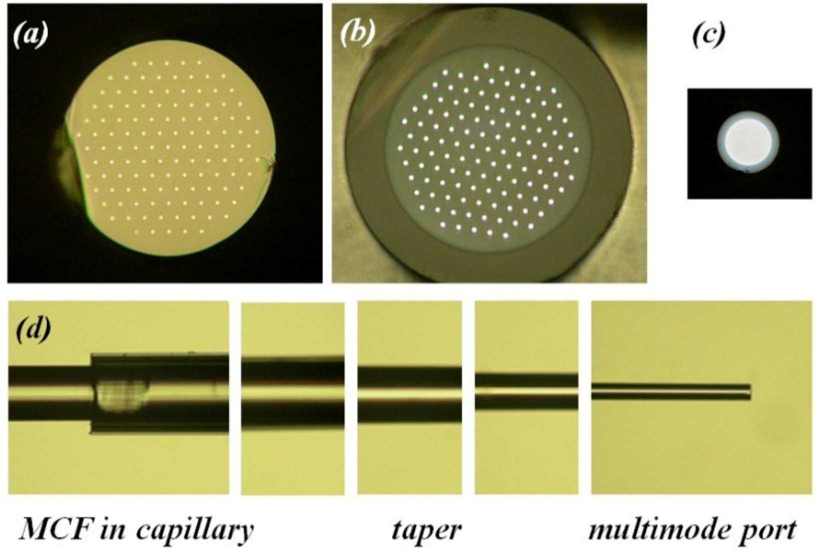


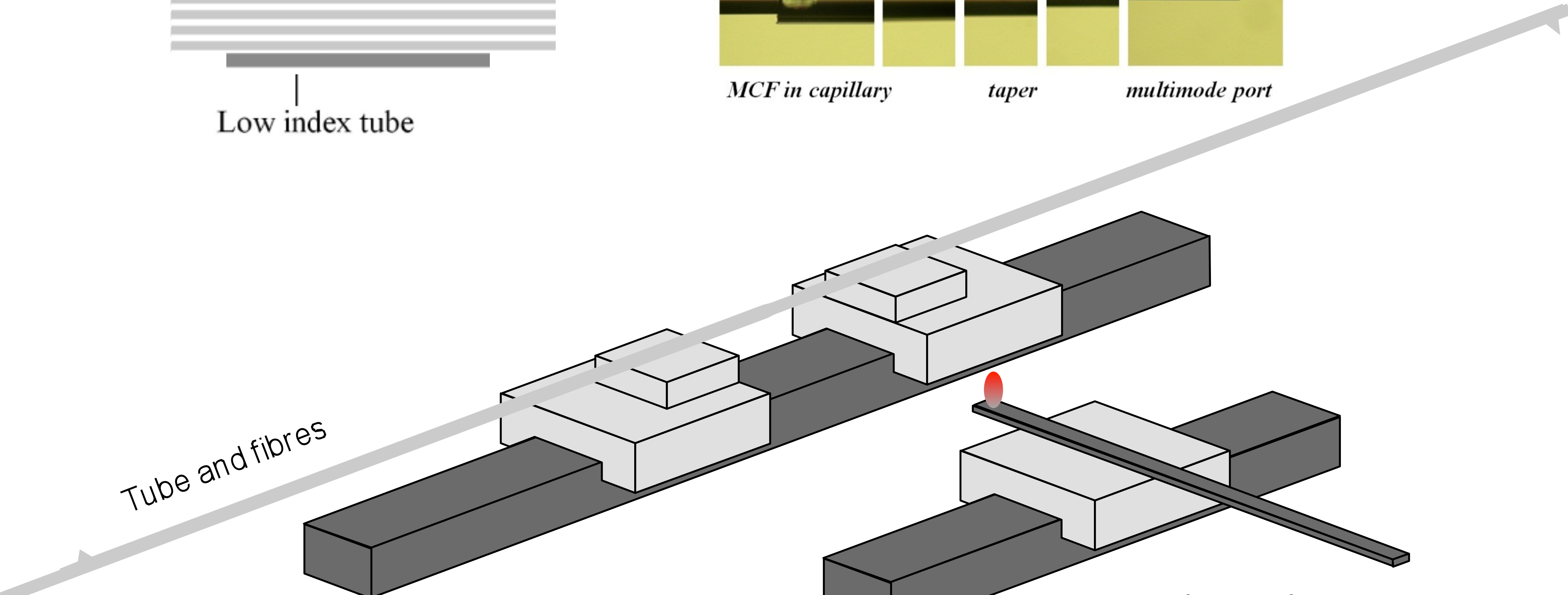




Multicore fibre “photonic lanterns”

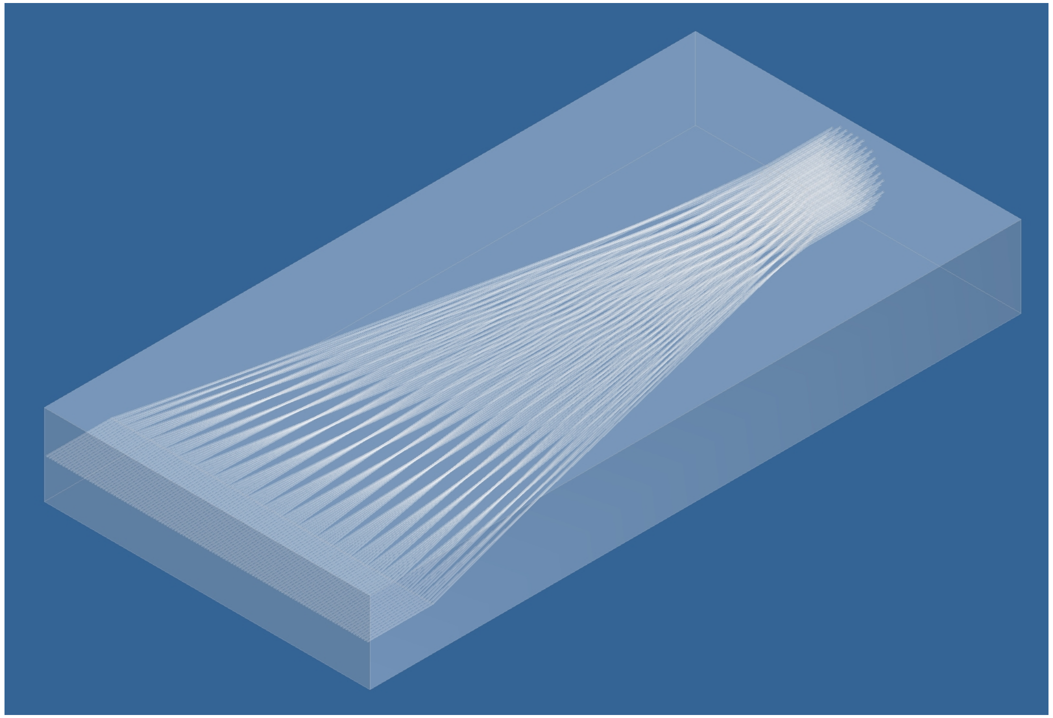






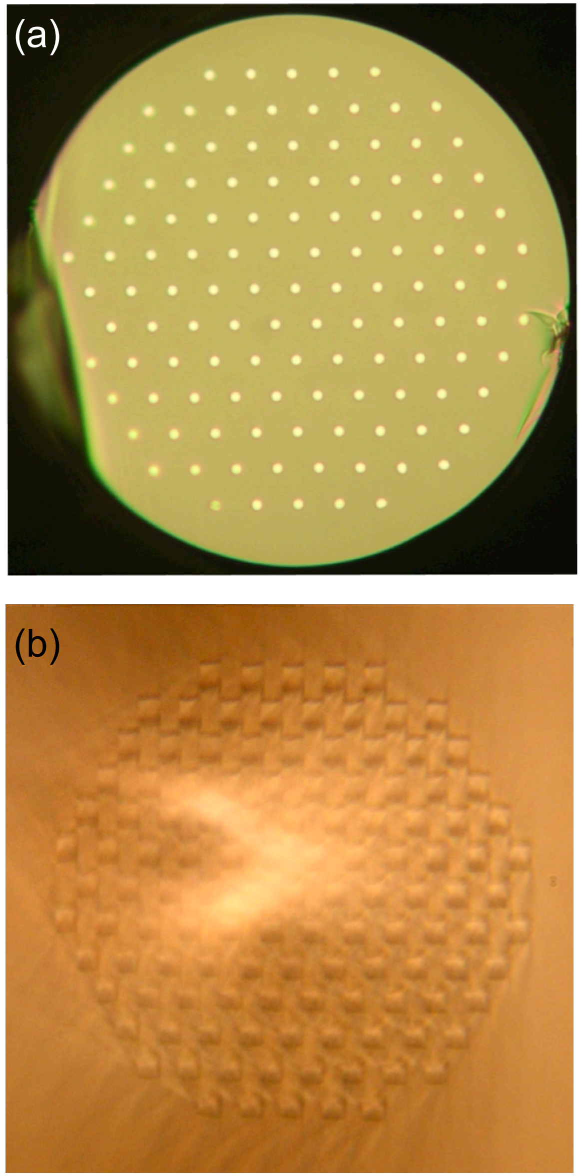
Animation by W. Wadsworth (U. of Bath)

3D interconnect development



Conceptual diagram of the 3D interconnect

For more info see:
R. R. Thomson et al, "Ultrafast laser inscription of a 121-waveguide fan-out for astrophotonics," Opt. Lett. 37, 2331 (2012)



Optical micrograph of (a) the 120 core MCF and (b) the MCF coupling end of the 3D fan-out

Ultrafast laser inscription of a 121-waveguide fan-out for astrophotonics

R. R. Thomson,[1,*] R. J. Harris,[2] T. A. Birks,[3] G. Brown,[1] J. Allington-Smith,[2] and J. Bland-Hawthorn[4,5]

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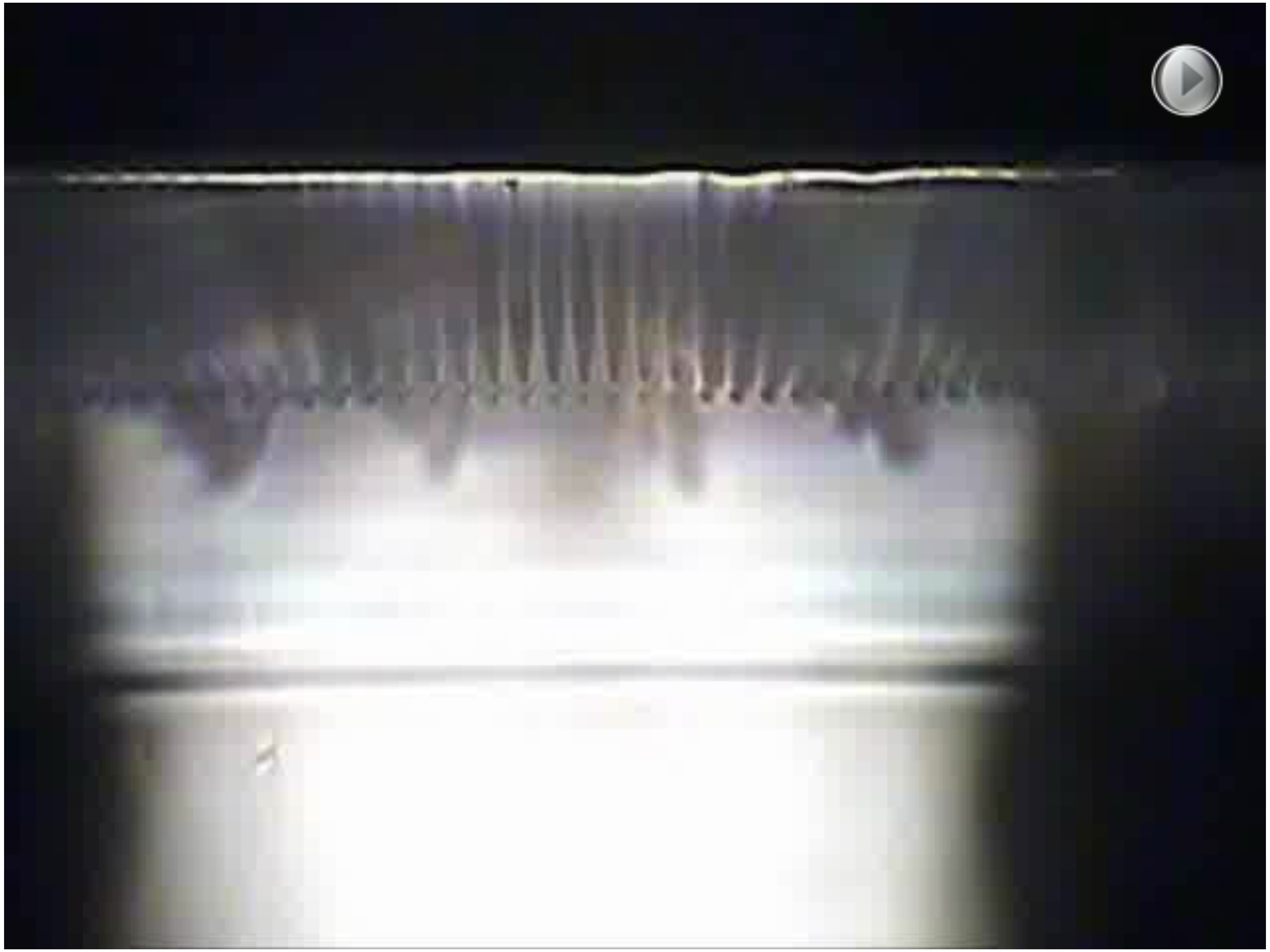
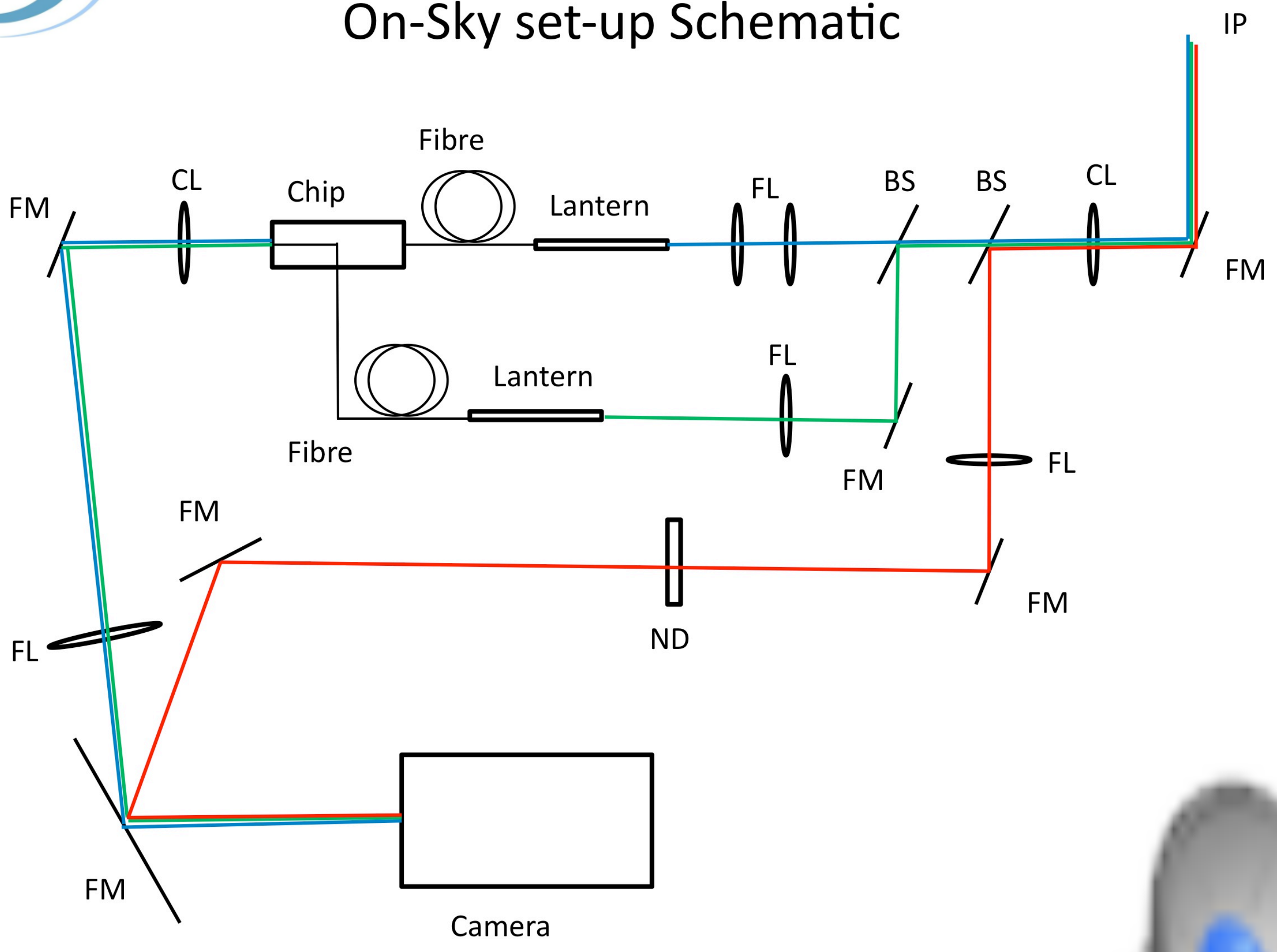


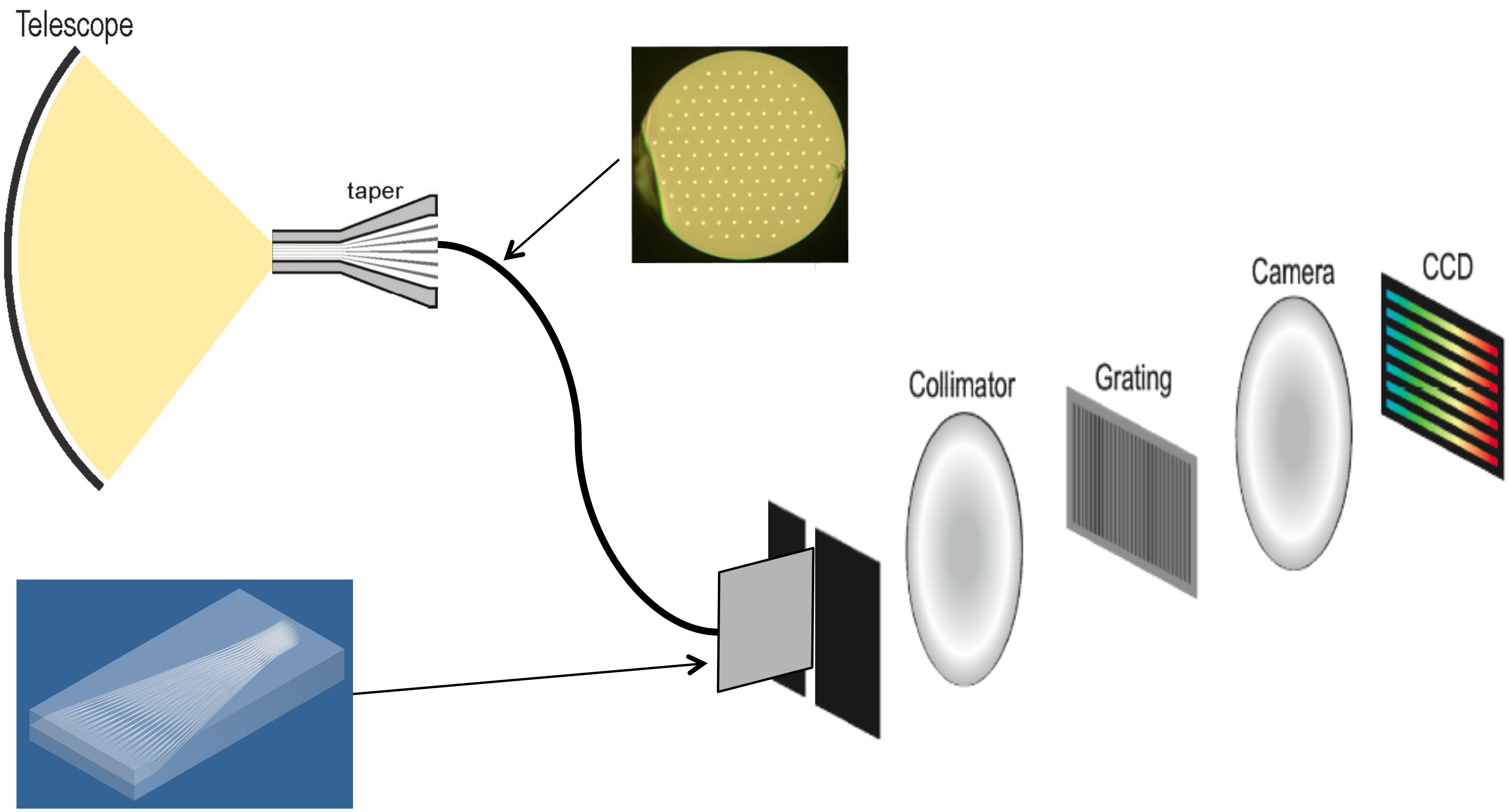
Video of interconnect output while aligning the MCF

Throughputs of > 60% are now achievable in the lab.

On-Sky set-up Schematic



The compact PRV spectrograph



Conclusions

- Astrophotonic concepts <u>may</u> revolutionise astronomical instruments.

- The field of astrophotonics is driving the development of entirely new photonic concepts and devices e.g. the photonic lantern.

- The first “real” science application for photonic lanterns may be PRV measurements using compact spectrographs that are free of modal noise.

- D. MacLachlan and D. Choudhury (Heriot-Watt)
- G.Brown (Optoscribe Ltd)
- T. Birks and I. Gris Sanchez (U. of Bath)
- J. Allington-Smith, R. Harris T. Morris, Richard Myers (Durham U.)
- R. Haynes and M. Roth (InnoFSPEC – Potsdam)
- C. Cunningham and D. Lee (UK-ATC)
- Ronald Holzwarth and Menlo GmbH
- Joss Bland–Hawthorn and S. Leon-Saval (U. of Sydney)
- P. Kern and G. Martin (IPAG-Grenoble)
- L. Labadie (U. of Köln)