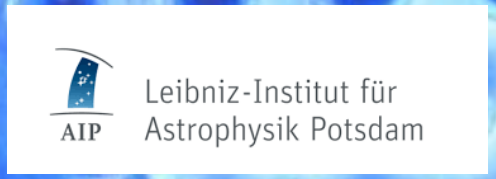
OPTICON

" Optical Infrared Co-ordination Network for Astronomy "

JRA6 - Astrophotonics

Roger Haynes



JRA 6 - Astrophotonics

WPs & Deliverables

Work Packages

- 6.1 - Systems Engineering
- 6.2 – MCF & PL Developement
- 6.3 – Photonic reformatters and 3D waveguide structures
- 6.4 – AO Coupling with phtonics devices
- 6.5 – Coordination, Outreach, Innovation and Dissemination

Deliverables

- D1. Requirements – 6.1 : [Month 20] - done
- D2. Development report – 6.2, 6.3 & 6.4 combined: [Month 48]
- D3. Outreach report – 6.5 [Month 48]

Objective & Key Outcomes

Develop photonic technologies enhancing the sensitivity and functionality of ground-based optical/infrared instrumentation

- Low mode noise multicore scrambling fibres and photonic reformatters for precision spectroscopy, improving detection sensitivity and enabling implementation of small diffraction-limited spectrographs.
- Enhanced understanding of telescope and AO coupling with photonic and fibre based systems.
- Transfer of technology and techniques between applications outside astronomy, such as telecommunications, medical, biophotonics and earth science.

Maintaining Europe's lead in this international and multidisciplinary field.

6.1- System Engineering

WP lead AIP with HWU, UBATH and UDUR

- Use case scenarios for European project such as ELT-HIRES and ELT-MOS
- Develop the top-level requirements, interfaces, specifications, and device/system architectures (including packaging) for each of the targeted applications, verifying the devices on-sky where possible.
- Consider Mode numbers between 5-50,000
- Wavelengths from 360-2500nm
- Additonal functionality - scrambling, reformatting, etc

Deliverable: Requirements D6.1 - August 2018.

6.2- MCF & PLs

WP lead UBATH with AIP

- Photonic lanterns will be made from multicore fibres (MCFs) for both seeing-limited and AO-corrected PSFs, e.g. E-ELT and VLT.
- Detailed lab characterisation
- Packaged on-Sky testing where possible
- Up to 50,000 cores and 360-2200nm wavelength.
- All fibre photonic reformatters

6.3 – Reformatter & 3D Waveguide Structures

WP lead HWU with AIP & UBATH

- Fabrication of 3D waveguide structures and developing photonic reformatters (both ULI-only and hybrid fibre/ULI)
- Detailed ULI parameter and material investigation
  - Pulse energy, pulse repetition frequency, translation velocity, substrate material etc
- Minimise propagation and coupling losses out to 2500nm
- Develop understanding of mode-field, scatting and bend losses to optimise the design of 3D waveguide structures
- Lab and on-sky testing of devices

6.4 – AO coupling with Photonic devices

WP lead UDUR with AIP & AO community

- Optimisation of AO system PSFs to optimise coupling into fibres and photonic devices
- Understand how phase aberration in PSFs impact guided modes in photonic devices
- Combine custom AO simulations with commercial photonic propagation codes
- Characterise devices with UDUR AO test-bed

  Lead on-sky with CANARY AO system at WHT

6.5 – Coordination, Outreach innovation and dissemination

WP lead AIP with All work package and OPTICON Exec

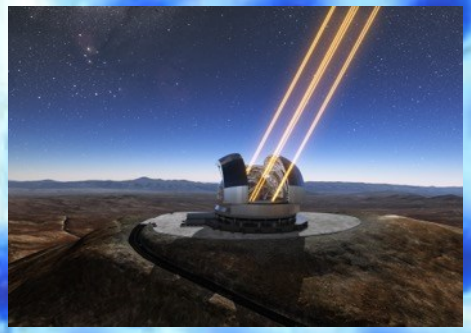
- Efficiently and effectively coordinate and disseminate astrophotonic developments within astronomy and other disciplines
  - Open Data Access
- Collaboration with other JRA, NA and TA activities;
  - technology transfer and dissemination into the community via websites, public media, publication, conference, workshop, trade fairs and industrial networking events
  - Organise self funded summer schools
  - Market and roadmap analysis
  - Maintaining community interaction

Research topics and what we did

System Engineering

Astrophotonics Requirements

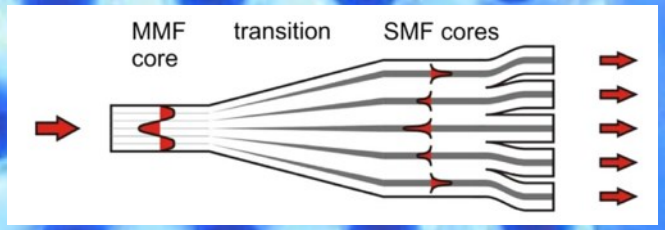
- Define the requirements of the photonics devices for ELT and large telescopes;
- Define the main parameters.



Credit: ESO/L. Calçada

Multicore optical fibre and optical photonics lantern

- Development and detailed characterisation of an multicore scrambling fibres;
- Coupling and mode propagation modelling in photonic lanterns.

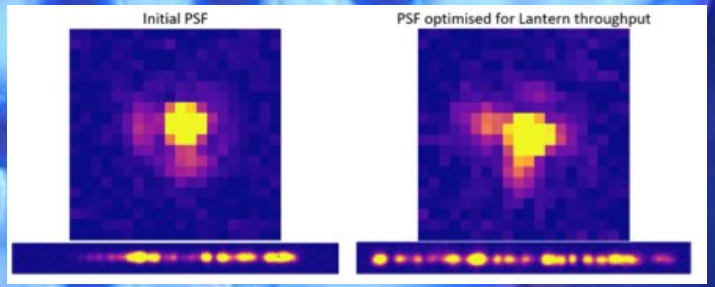


Photonic reformatters and 3D waveguide Structures

- Develop applications where photonic reformatters are significantly advantageous;
- Improve manufacturing methods to optimise devices.

AO coupling optimisation & wavefront sensing

- Develop alternate low order wavefront sensors using photonic devices;
- Test in lab and on sky.



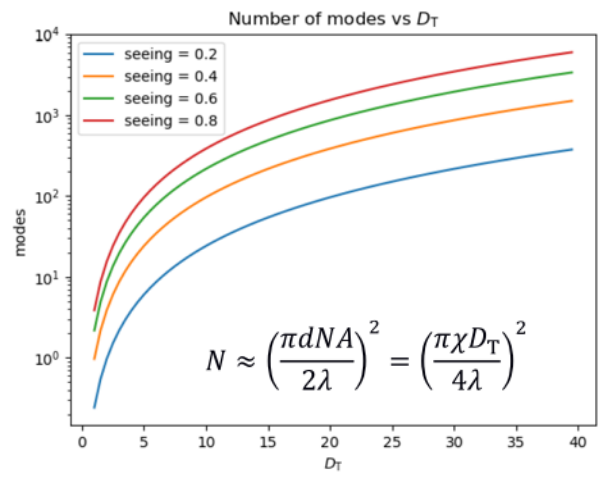
Top-level requirements for ELT instrumentation (D6.1)

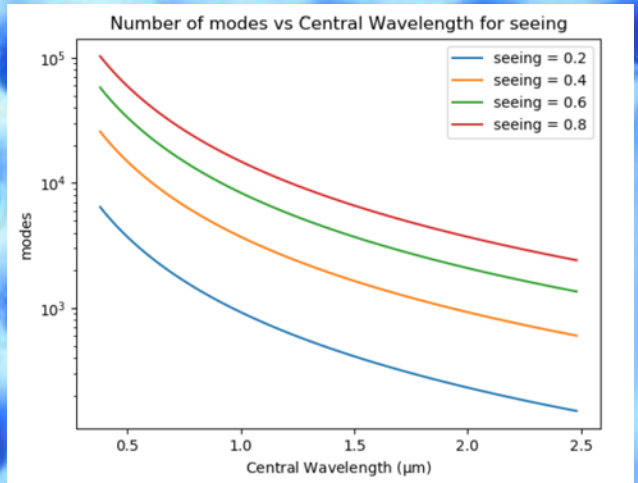
Number of waveguide modes: The device/system should be mode matched to the respective input and output interface to maximise system efficiency.

Wavelength range: The device/system should be design to operate over the full wavelength range required for the intended application.

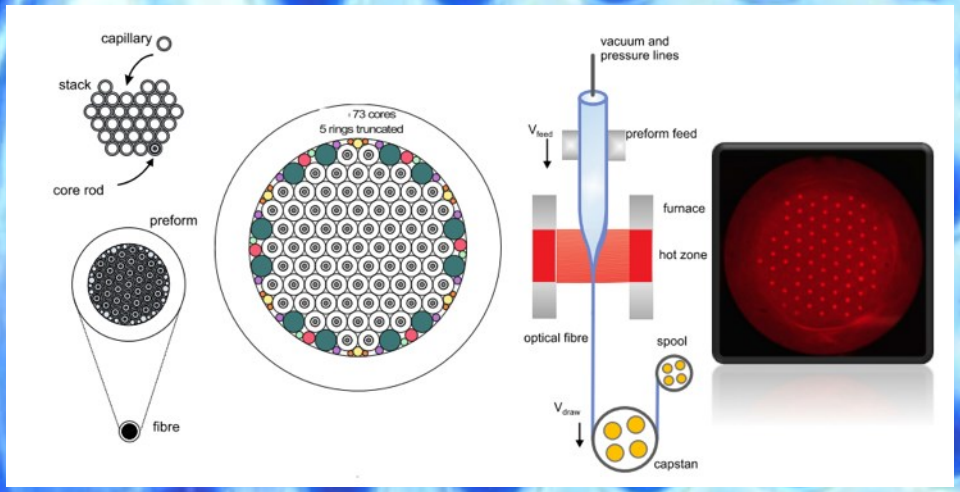
Scrambling Gain: The device/system should not be significantly contribute to the overall instrument/system wavelength precision uncertainty budget.

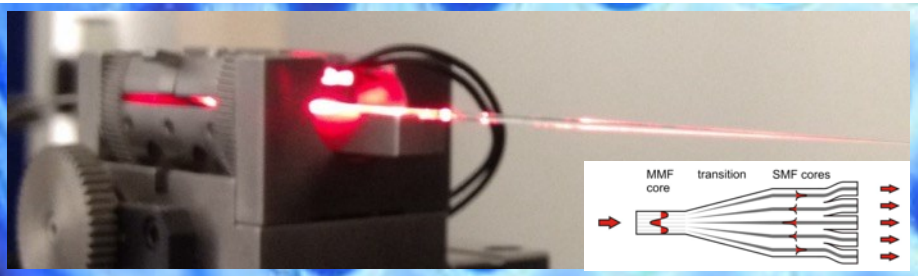
Wavefront cleaning and management. Spatial/mode filter properties of photonic devices should be optimised to maximise system S/N.





Multicore fibres & photonic lanterns for PRV science





- The 73 core MCF was fabricated using the standard stack and draw technique;
- The photonic lantern is fabricated by tapering multicore down in a multimode fibre;
- Easy tailoring of both SM core structure and MM side to accommodate the target modes.

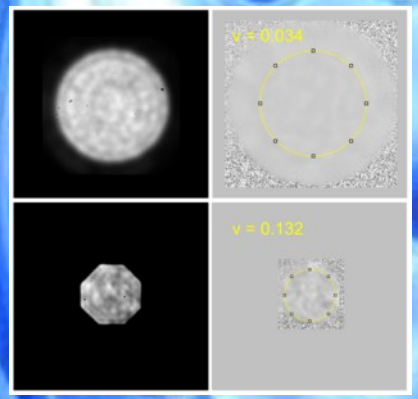
Spatial scrambling for high precision RV applications

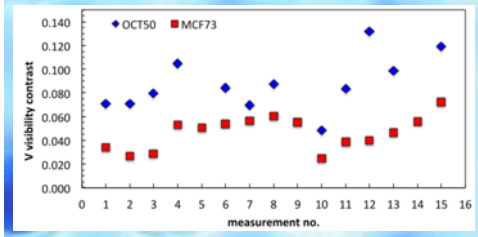
Modal noise suppression for high precision RV applications

MCF-PL for modal noise suppression

In the NIR:

- Device with 73 SM cores (same diameter) working at 1.64 µm (N=84), core 85 µm and NA 0.11 (~f/5 beam);
- Comparison with octagonal fiber (N=83 modes);



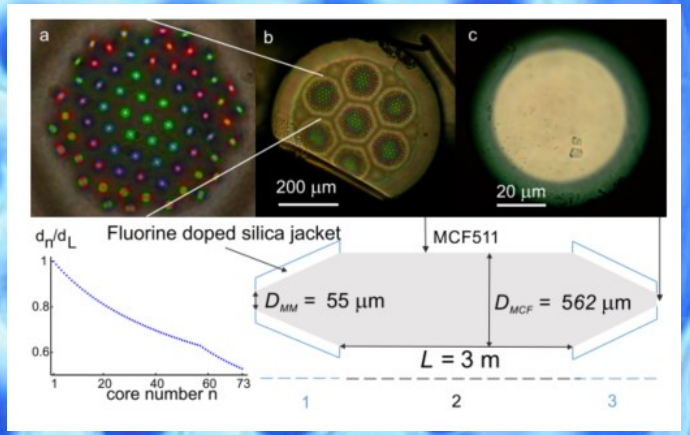


MCF-PL device shows:

- lower visibility contrast in the residual speckle patterns;
- higher SNR with similar number of modes;
- performs better in terms of modal noise reduction than an octagonal multimode silica.

For high precision radial velocity:

- Device with 7x73 SM cores (different diameter) for 0.38 – 0.86 µm;
- Comparison with octagonal fiber.



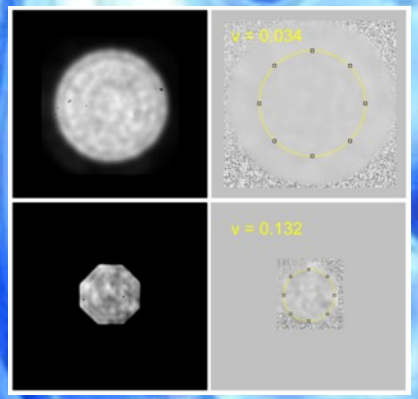
Different core diameters:

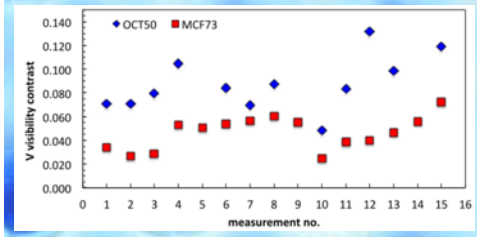
- enhance phase and amplitude scrambling of supermodes, thus suppressing modal noise
- permit low-loss operation over a wide range of λ

MCF-PL for modal noise suppression

In the NIR:

- Device with 73 SM cores (same diameter) working at 1.64 μm (N=84), core 85 μm and NA 0.11 (~f/5 beam);
- Comparison with octagonal fiber (N=83 modes);





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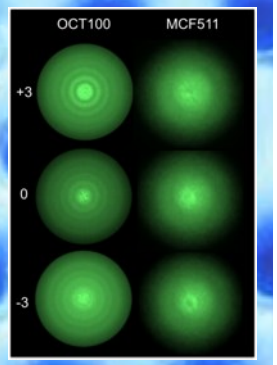

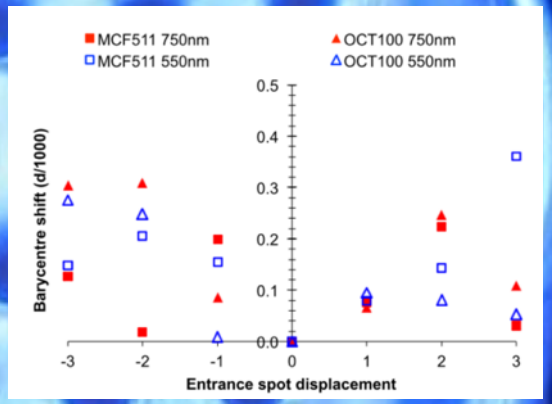

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- lower visibility contrast in the residual speckle patterns;
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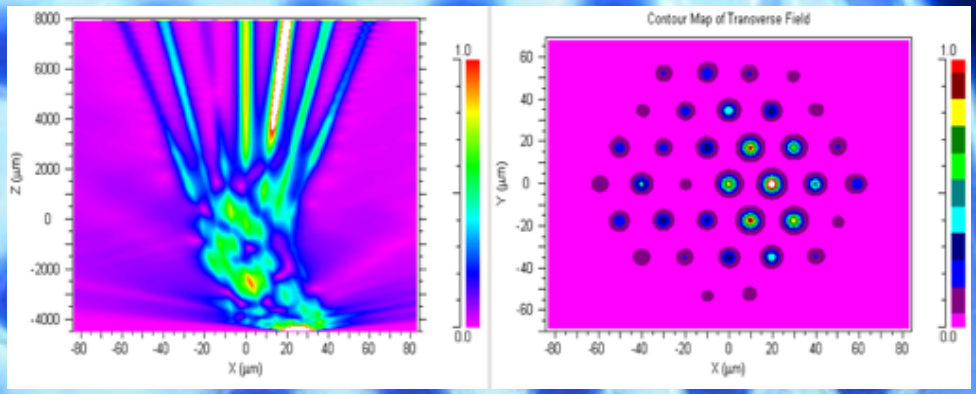
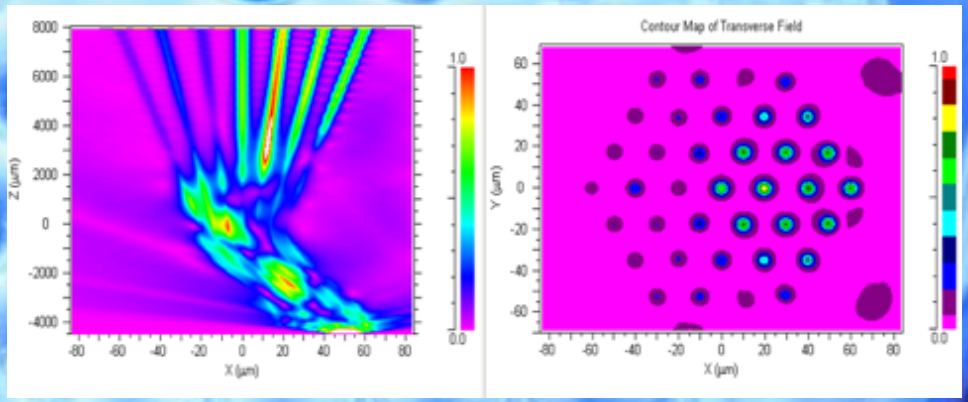
- performs better in terms of modal noise reduction than an octagonal multimode silica.

MCF-PL modelling

Simulation of 37 core photonic lantern devices

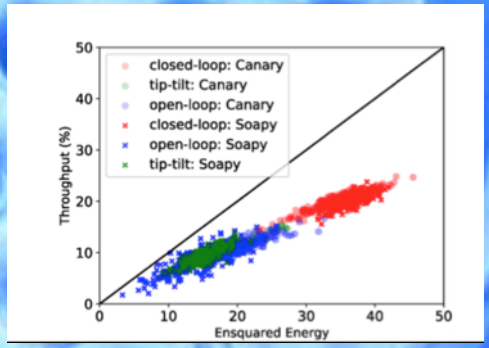
- Show similar changing light intensity distribution as a result of displacement of the location of the light injection as experimental results for 73-core device.
- Show similar light distribution changes for simulated bending of the multi-mode input section as 73-core device during the detailed laboratory characterisation.





Photonic Reformatter Modeling

- Modelling done by combining SOAPY and BeamProp
- Shows that we can accurately model on sky performance of devices
- Shows we can optimise the devices further in theory and that designing for the correct performance is important

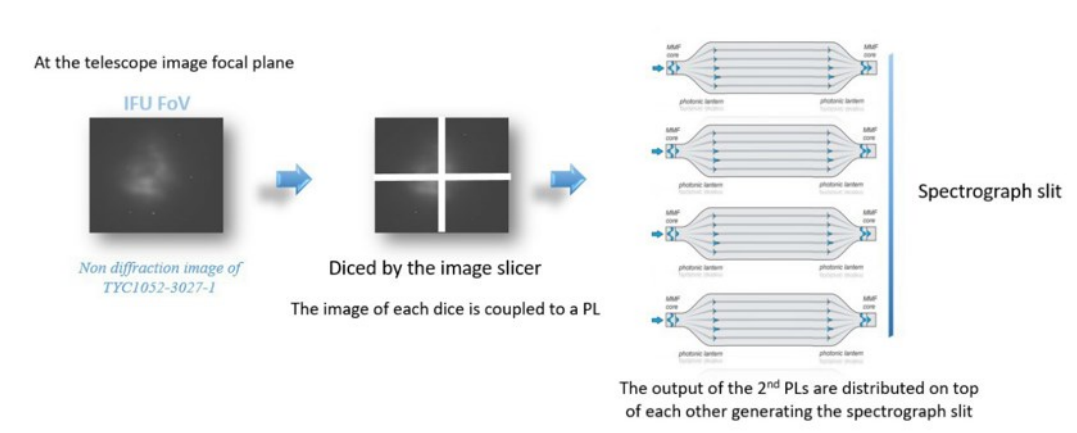


Photonic reformatters for photonic IFU

IDEA: design an IFU based on photonic lanterns (ELT in mind).

Advantages:

- Reduce the entrance aperture size of spectrograph (image slicing) enabling must higher R for a given design ;
- Stability of the output PSF, for high precision Spectroscopy;
- IFU suitable for remote mounted spectrographs (stability, gravity invariance and also environment invariance);
- Embedded functionality such as spectral filtering for OH in the IR;
- Spatial filtering that allows to obtain a clean PSF, improving the S/N.



Specifications for ELT

Sampling	0.22 arcseconds/dice
Slicer mirror width	0.73 mm
Input F/D	F/17.7
Output F/D	F/2.17
Magnification	0.12
Slicer image size	0.087 mm

Image size (ELT) focal plane: 6.8 mm x 6.8 mm, fully covered with 10 x 10 dicers.

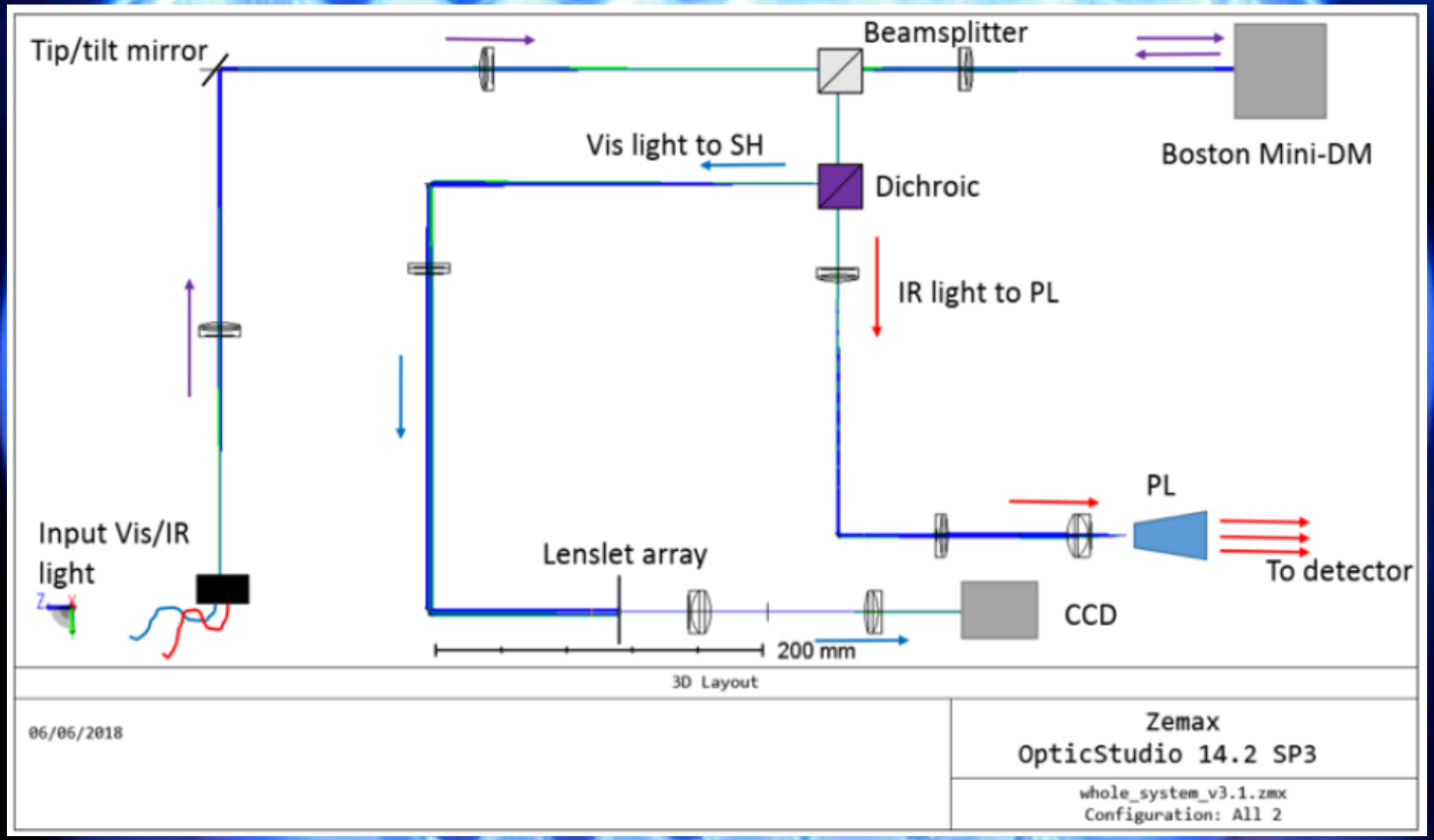
Photonic devices for Adaptive Optics

Key requirements that drive the design, complexity and performance of the devices/systems are:

- The device/system shall sense at least the Tip, Tilt and Focus terms of the wavefront in unambiguous and predictable manner.
- The device/system shall be able to determine the wavefront error in Focus to better than 10 nm RMS for a focus error up to 100 nm RMS in magnitude.
- The device/system shall be able to determine the wavefront error when Tip and Tilt are within one diffraction limited Point Spread Function (PSF).
- The response of the device/system to changes in input wavefront shall be linear after calibration. (Note: this is required by both wavefront error requirements above).
- The device/system shall have a theoretical coupling efficiency into a single-mode fibre competitive with conventional systems. For example, a maximum of 65 % for the SCExAO system (Subaru telescope), or a

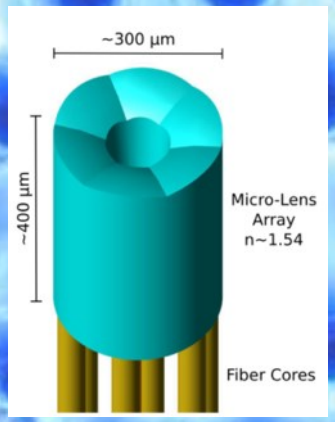
Photonic devices for Adaptive Optics

Test bench for photonics devices equipped with a new tip/tilt mirror to make faster and more accurate the characterization of the devices before on-sky tests.



Photonic devices for Adaptive Optics

Micro-lens arrays as tip-tilt sensor with integrated single-mode fiber.

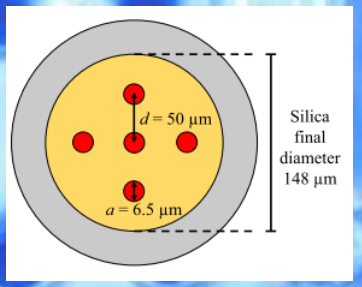


- Detect vibrations of the optical train;
- Designed for iLocater HR@LBT;
- Updated design;

«Three fibers» Shack-Hartmann WFS

- Decouple collection and measurement;

Photonic lantern as low order wavefront sensor



- 5 core photonic lantern to stabilize the PSF;

Publications

1. DG MacLachlan, RJ Harris, I Gris-Sánchez, TJ Morris, D Choudhury, E Gendron, AG Basden, I Spaleniak, A Arriola, TA Birks, JR Allington-Smith, RR Thomson: "Efficient photonic reformatting of celestial light for diffraction-limited spectroscopy", Monthly Notices of the Royal Astronomical Society, 464, 2017, 4950-4957.

2. K Harrington, S Yerolatsitis, D Van Ras, DM Haynes, TA Birks: "Endlessly adiabatic fiber with a logarithmic refractive index distribution", Optica, 4, 2017, pp.1526-1533.

3. S Yerolatsitis, K Harrington, TA Birks: "All-fibre pseudo-slit reformatters", Optics Express, 25, 2017, pp.18713-18721.

4. Philipp-Immanuel Dietrich, Robert J Harris, Matthias Blaicher, Mark K Corrigan, Tim M Morris,Wolfgang Freude, Andreas Quirrenbach, Christian Koos, “Printed freeform lens arrays on multi-core fibers for highly efficient coupling in astrophotonic systems”, Optics Express, 25 (15), 2017, pp. 18288–18295.

5. Th Anagnos, RJ Harris, MK Corrigan, AP Reeves, MJ Townson, DG MacLachlan, RR Thomson, TJ Morris, C Schwab, A Quirrenbach, “Simulation and Optimization of an Astrophotonic Reformatter”, Submitted MNRAS, 2018.

6. Theodoros Anagnos, Robert J Harris, Mark K Corrigan, Andrew P Reeves, Matthew J Townson, David G MacLachlan, Robert R Thomson, Tim J Morris, Christian Schwab, Andreas Quirrenbach, “Optimizing astrophotonic spatial reformatters using simulated on-sky performance”, Proc. SPIE, 10706H, 2018.

7. Philipp Hottinger, Robert J Harris, Philipp-Immanuel Dietrich, Matthias Blaicher, Martin Glück, Andrew Bechter, Jonathan Crass, Jörg-Uwe Pott, Christian Koos, Oliver Sawodny, Andreas Quirrenbach, “Micro-lens arrays as tip-tilt sensor for single mode fiber coupling”, Proc. SPIE, 1070629, 2018.

8. Ariadna Calcines; Robert J. Harris; Roger Haynes; Dionne Haynes, “The reformatting advantage: Photonics vs conventional optics!”, Proc. SPIE, 107062G, 2018.

9. K Harrington, S Yerolatsitis, TA Birks: "All-fibre wave front sensor", Optical Sensing and Detection (Photonics Europe, Strasbourg, France), 2018, paper 10680-54.

10. I Gris-Sánchez, DM Haynes, K Ehrlich, R Haynes, TA Birks: "Multicore fibre photonic lanterns for precision radial velocity science", Monthly Notices of the Royal Astronomical Society, 475, 2018, 3065-3075.

11. Dionne M. Haynes, Itandehui Gris-Sánchez, Tim A. Birks, Roger Haynes: "Modal noise suppression in the NIR region using multicore fibre and photonic lanterns", Proc. SPIE, 1070665, 2018.

12. Mark K. Corrigan; Timothy J. Morris; Robert J. Harris; Theodoros Anagnos, “Demonstration of a photonic lantern low order wavefront sensor using an adaptive optics testbed”, Proc. SPIE, 107035H, 2018.

JRA6 activities plan for 2019

- Develop devices for on sky application
- Detailed modelling and characterisation of devices in lab and on sky
- Scrambling devices for use with Hertfordshire spectrographs and AIP GANS spectrograph
- Reformatting devices for testing with several different spectrographs
- On sky testing of microlens tip-tilt sensor at the LBT in January
- Further lab tests of photonic lantern wavefront sensor concepts

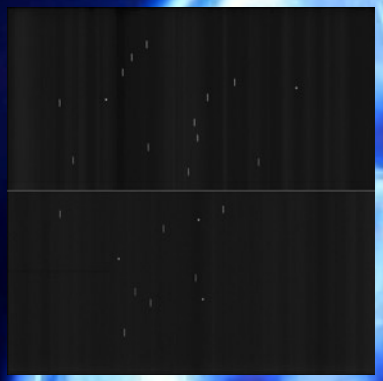
Transition – Post 31.03.2019

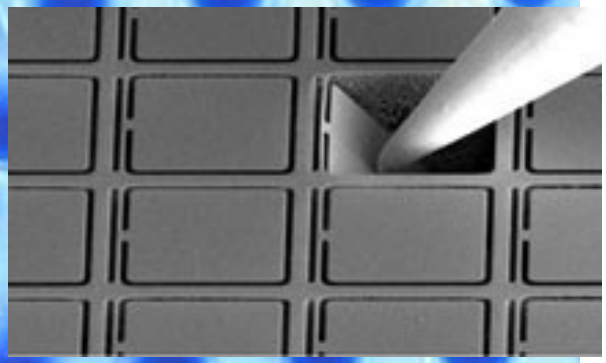
- **31st March 2018.** Roger Haynes moves to ANU Canberra
  - Stand down as JRA6 coordinator & AIP work package manager
- **Proposed changes**
  - JRA6 Coorodinator – Dr. Robert Harris (ZAH)
    - Career in Astrophotonics since 2009
    - Already collaborating and coordinating with current JRA6 team.
    - Would require funds for OPTICON travel
  - AIP program manager – Prof. Martin Roth (innoFSPEC/AIP)
    - innoFSPEC founder: Astronomy, Astrophotonics & Instrumentation
  - AIP-JRA6 staffing:
    - Dionne Haynes [0.2 FTE] (moving to ANU April 2019)
    - John Davenport [0.25 FTE] will increase to 0.45 FTE.
    - Martin Roth, Kalaga Madhav and Andreas Kelz at AIP have the technical & managerial skills to ensure the delivery of the AIP work activities.
- **The song remains the same**
  - No significant change in the JRA6 work program
  - AIP would remain engaged in all WPs & retain lead of WP6.1 and WP6.5.

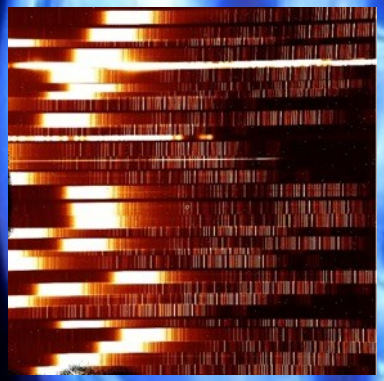
Future of Astrophotonics

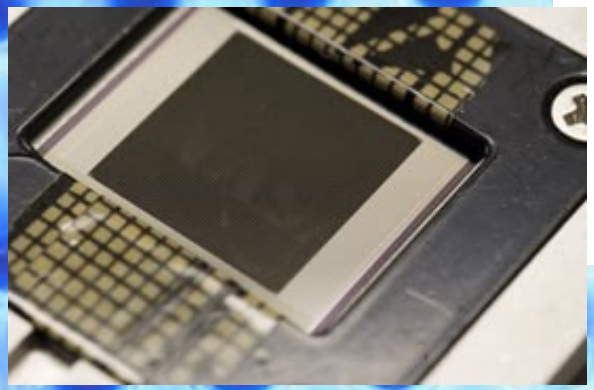
- Photonic target selection
- Increase near IR sensitivities by factor of >10 via fibre based OH-suppression
- Improved stability and sensitivity for precision spectroscopy by factor of >10 (science and calibration light)
- Photonics calibration systems
- Diffraction limited mode noise free spectrographs that are independent of telescope PSF parameters
- Improved throughput via optimises coupling (e.g. sensitivity) for seeing limited and partial AO corrected instruments
- Simple and sensitive photonic wavefront sensors

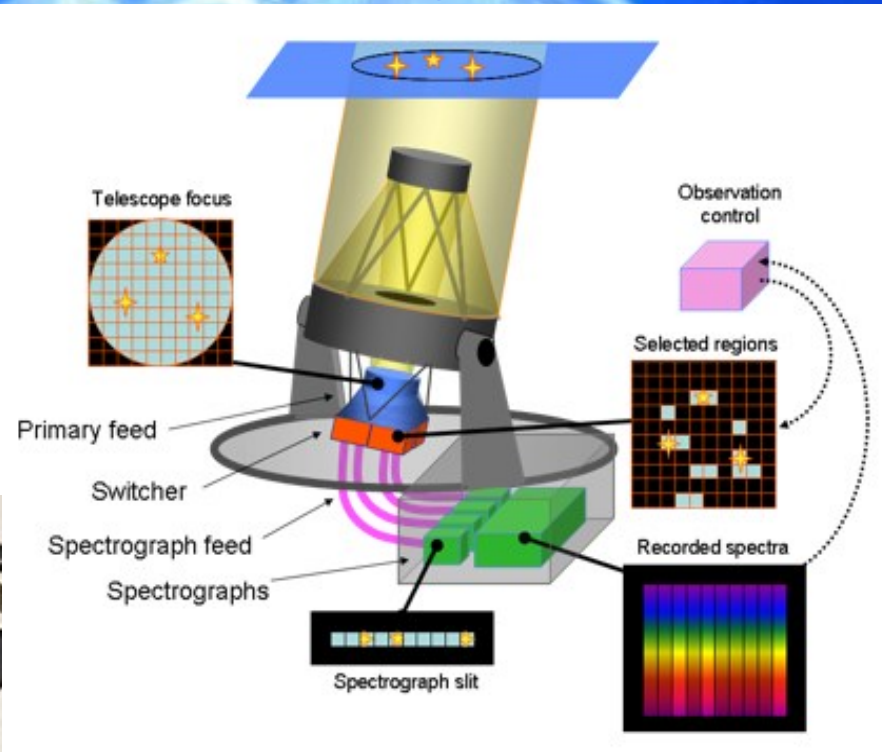
Target selection today







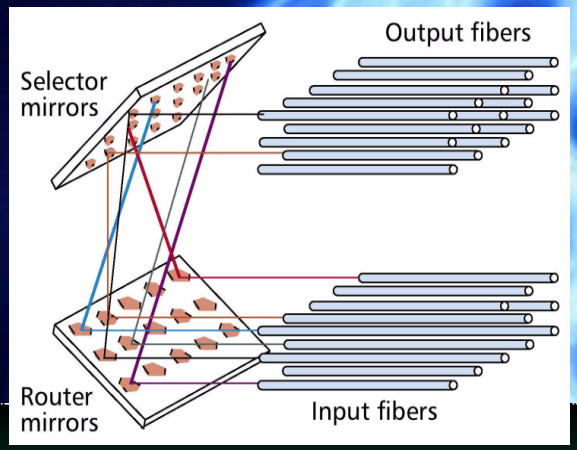




Technologies

- MOS slit masks
- Micro-shutters
- Fibre positioner
- Photonic switching

3D MEMS switch matrix

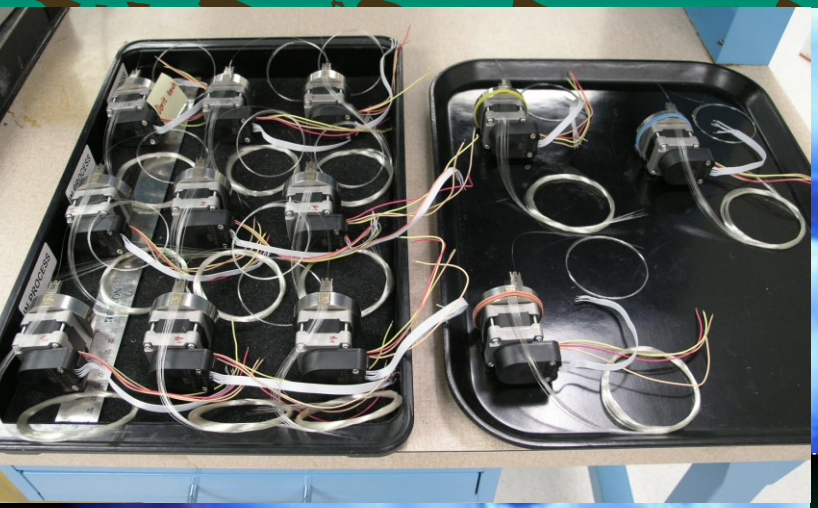


Mirrors analog - require *complex closed-loop control*

Loss increases only as $N^{1/2}$

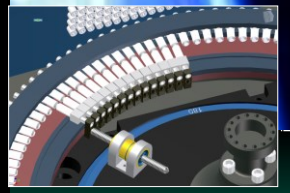
For N inputs and N outputs we need only 2N mirrors

Needs auxiliary optics to reduce beam spread

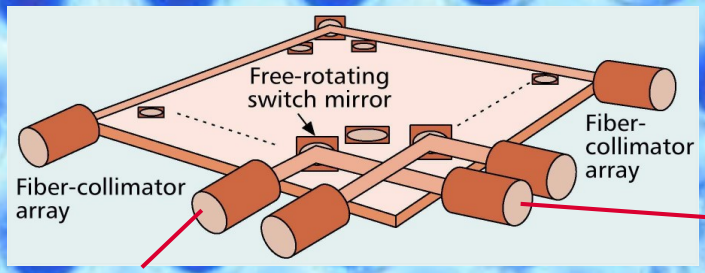


Photonic switching

Proximity switches



2D MEMS switch matrix



Mirrors binary – simple control

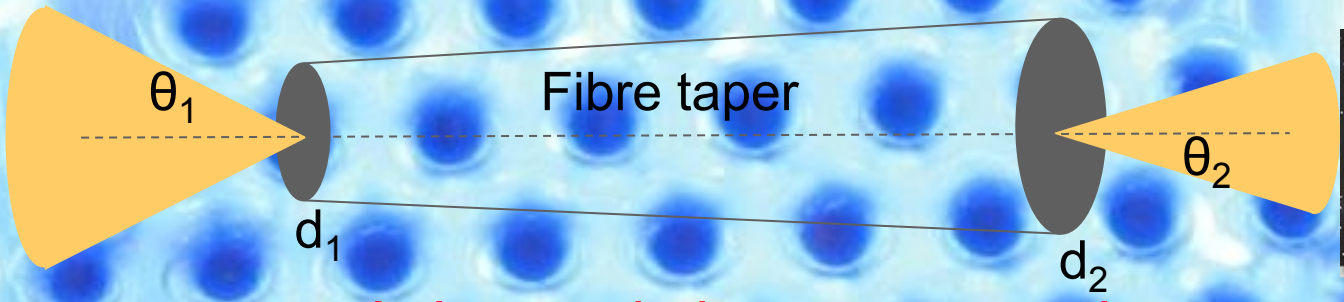
For *N* inputs and *N* outputs we *need* N^2 mirrors

Path length variation -> Loss increases rapidly with N

Embedded function

- Beam manipulation (fibre tapers)
- Wavelength management (HCF)
- Mode manipulation
- Wavelength filtering
- Beam combination
- Phase shifting
- Image/Pupil reformation
- Coronagraphy
- Mode Filtering (Spatial Filtering)
- Polarisation control/manipulation

Fibre tapers



Achromatic beam conversion

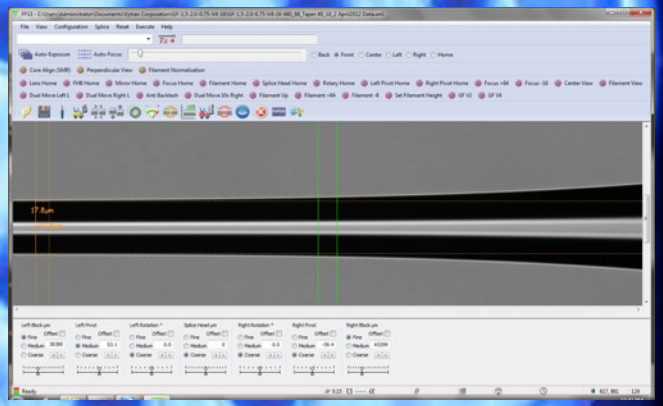
- Imaging
- Single fibre

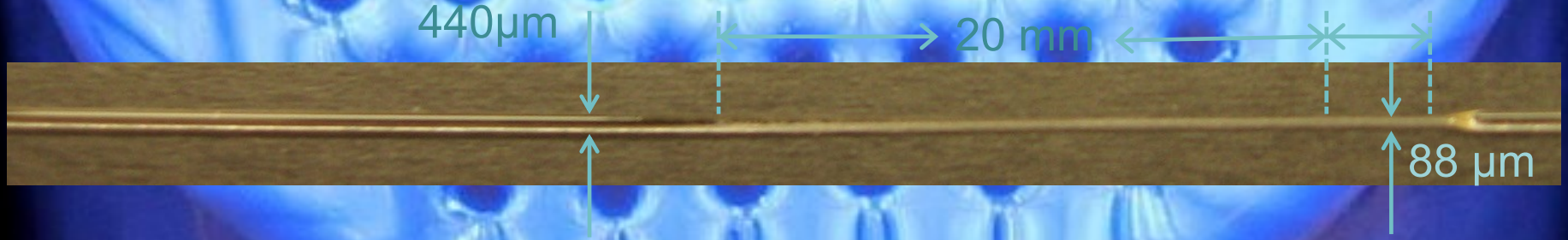
Mode conversion

- Multimode
- Single mode

Mode stripping

Wavefront Sensing

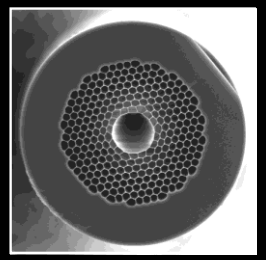


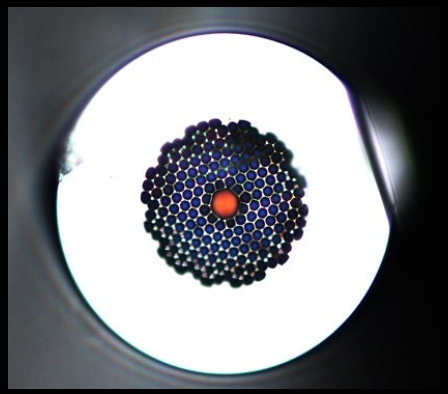


Hollow core fibres

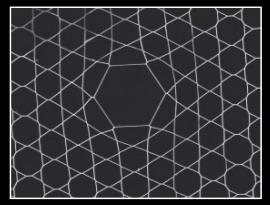
Hollow-core familly

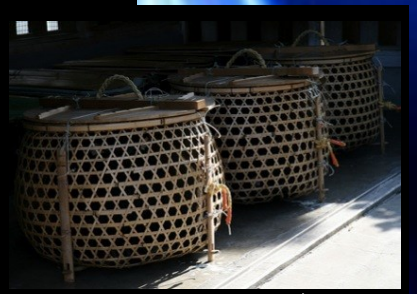
bandgap fiber



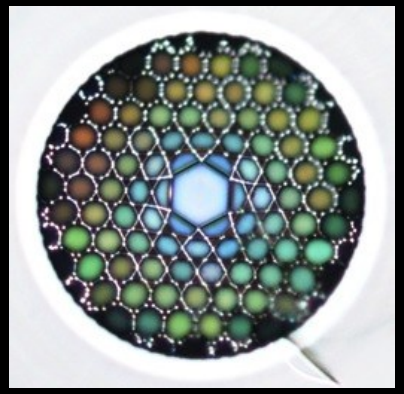


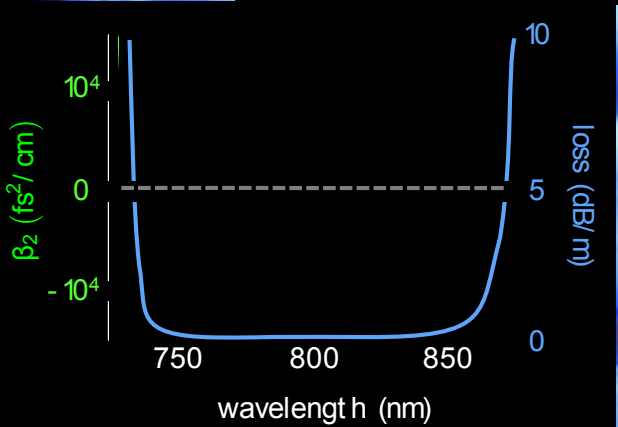
fibre kagomé





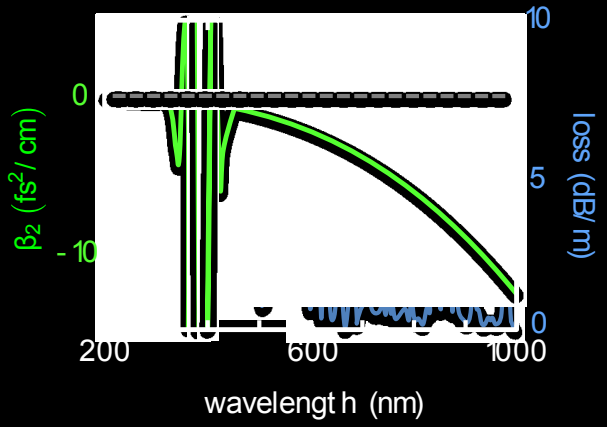
Kagomé basket [かごめ]





Air transmission

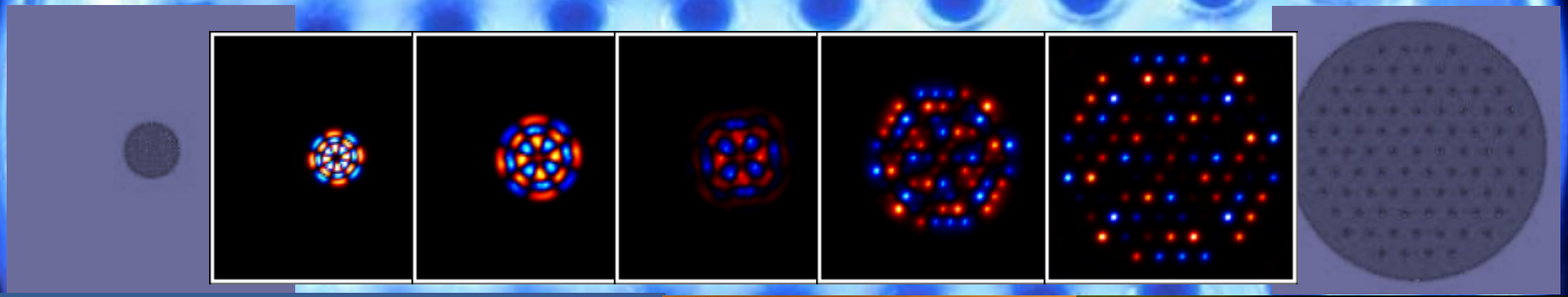
- Extended Wavelength
- Airy disc matching
- Fast Data Rates (30%)
- Super-continuum
- Calibration Cells

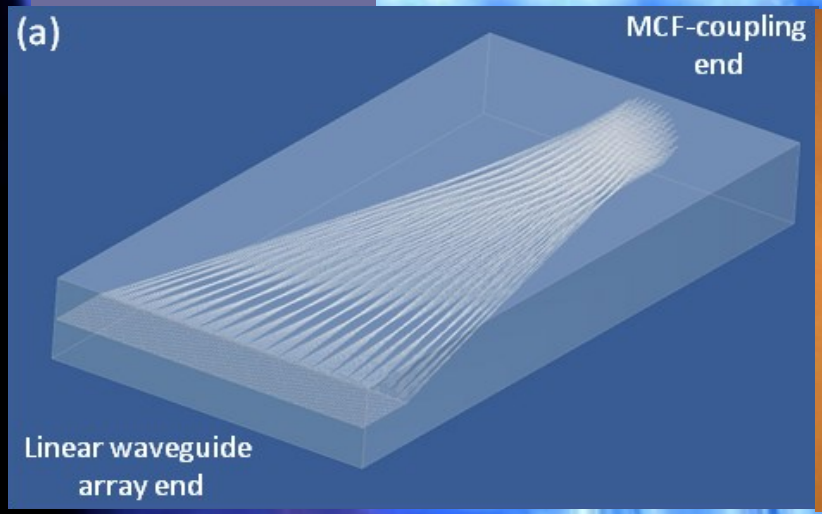


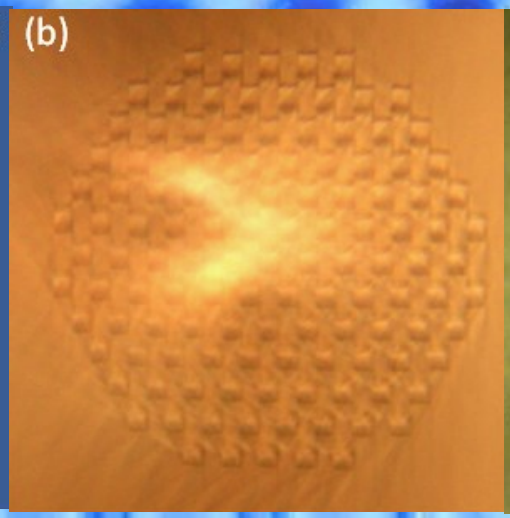
Mode manipulation

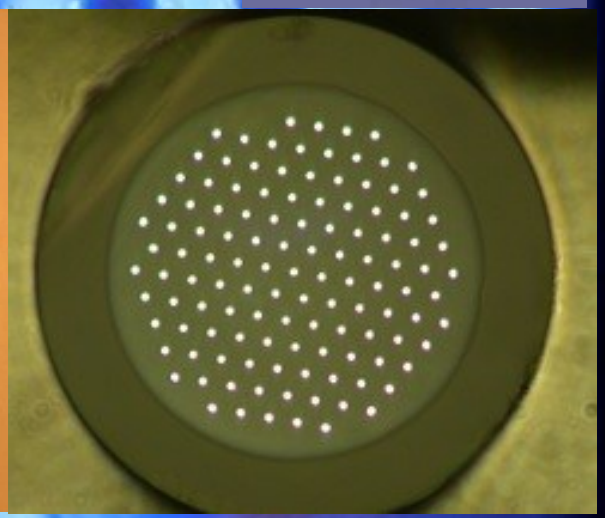
Motivation

- Working at diffraction limit
- Enables photonics function
- Efficient telescope coupling
- Modal noise suppression

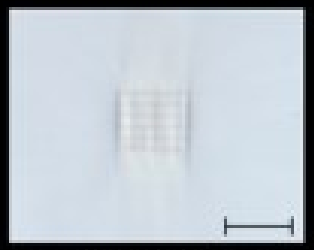






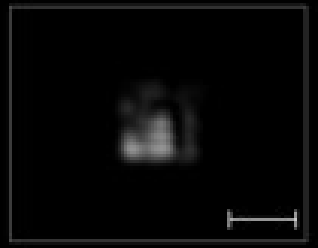


Hybrid Photonic Devices

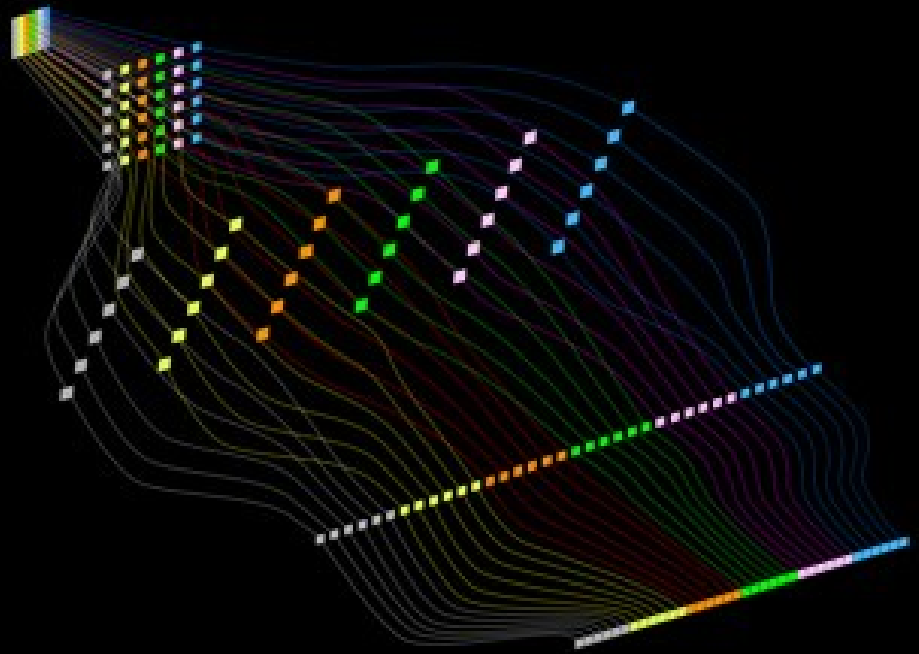


(a) Multimode end

(b) 1320 nm

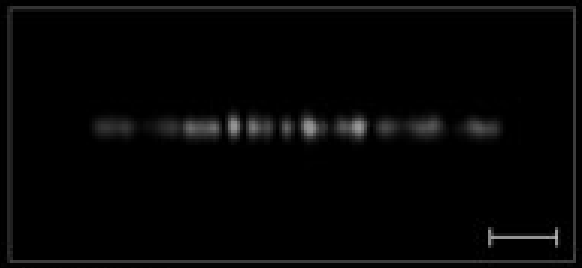


(c) 1580 nm

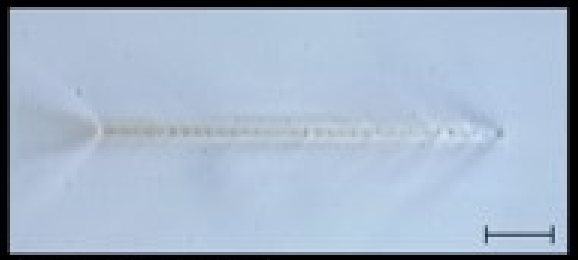


(d) Photonic-dicer transitions

(e) 1320 nm

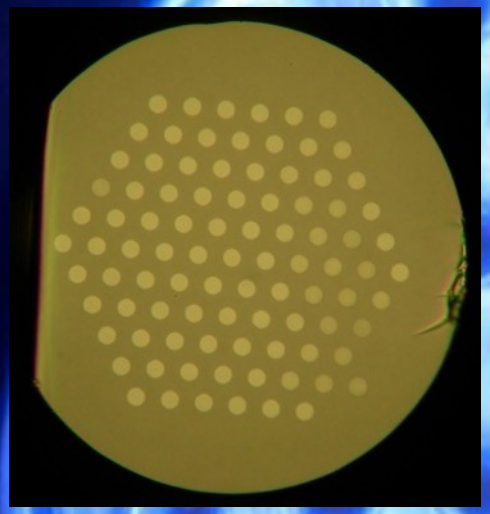


(f) 1580 nm

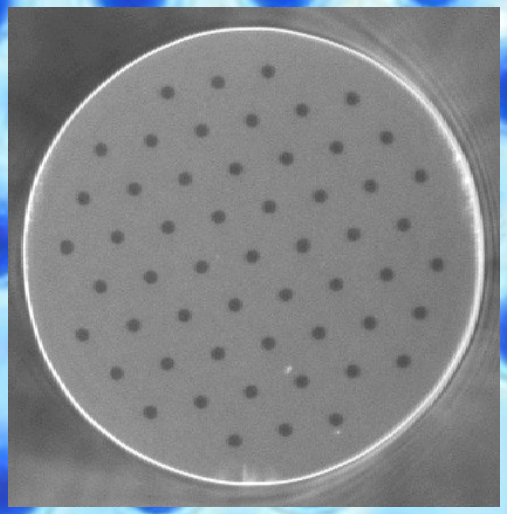


(g) Pseudo-slit end

Multicore Fibres (MCF)



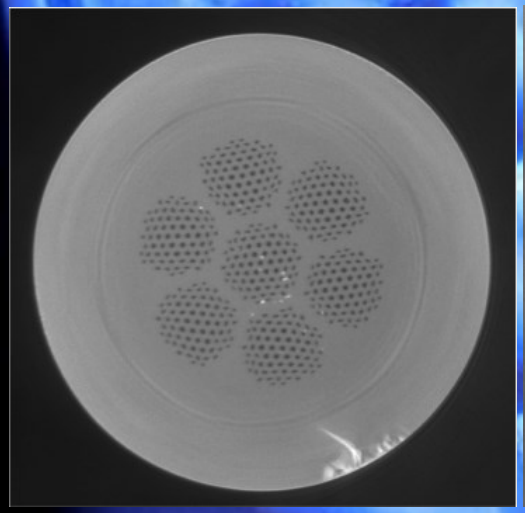
MCF 100 core for Hybrid PL

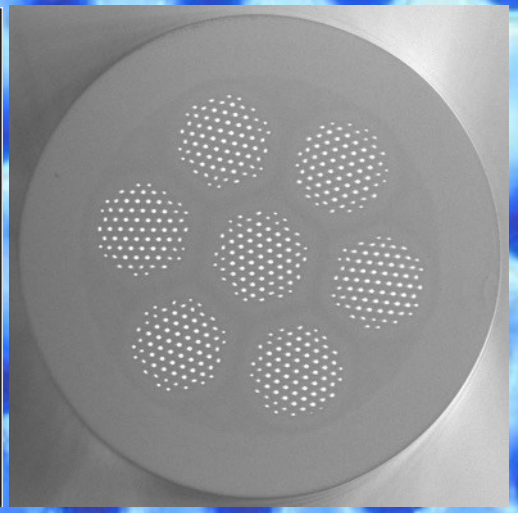


MCF 55 core

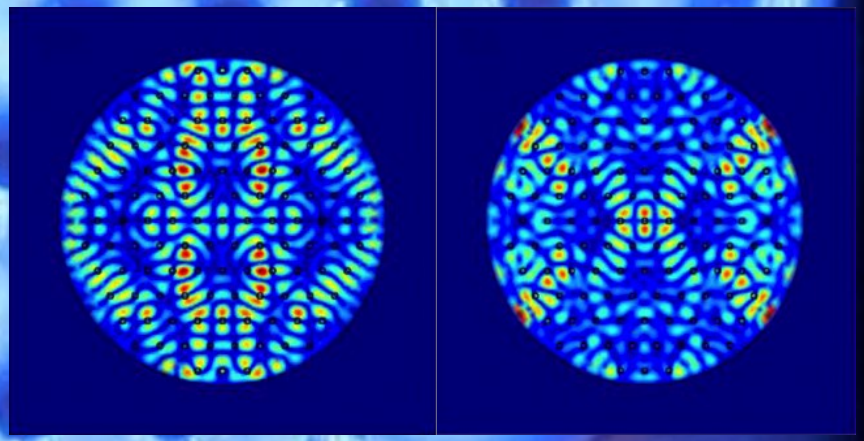
Developments

- **Multicore fibre Photonic Lanterns**
  - Multi-mode to single-mode conversion
  - Diffraction limited spectrographs
  - Hybrid PL: MCF and 2D ULI waveguides
- **Complex filters with fibre Bragg gratings**
  - Background suppression
  - High time resolution astronomy
- **Fibre-based sensors**
  - Deformation & environmental sensing
- **Scrambling Fibres for High R spectroscopy**
- **Adaptive Optics Wavefront Sensing**





High-R MCF: 511 cores (7x73) for wavelengths 380-860nm

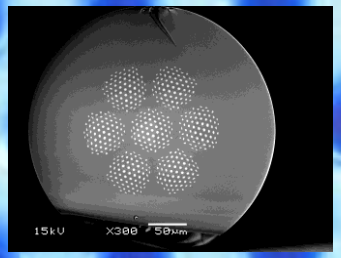


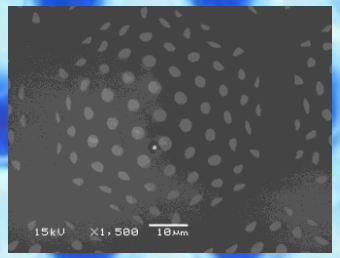
Shape Sensing with Long Period Grating

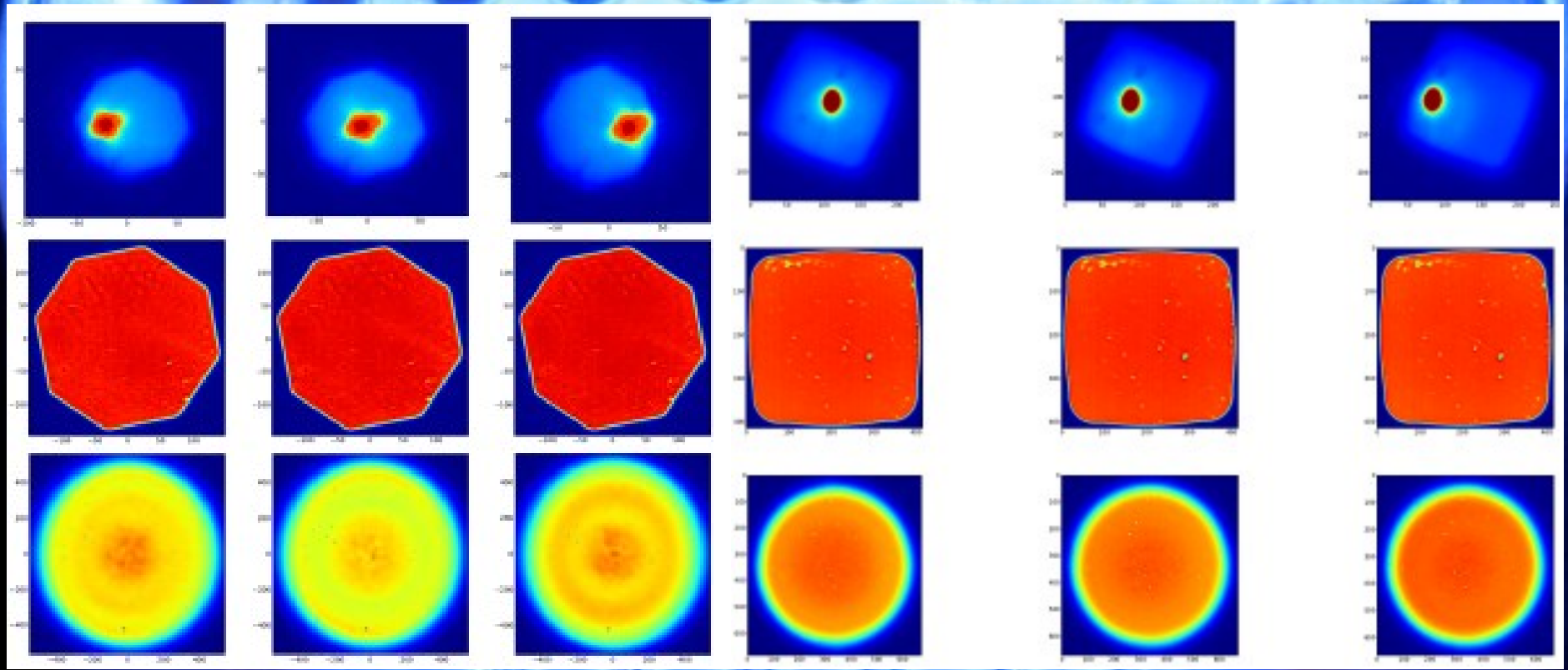
Scrambling Fibres

Mode noise limited fibre for High R Spectroscopy and comb feeds

- Octagonal fibre
- Square Fibres
- Multicore fibres



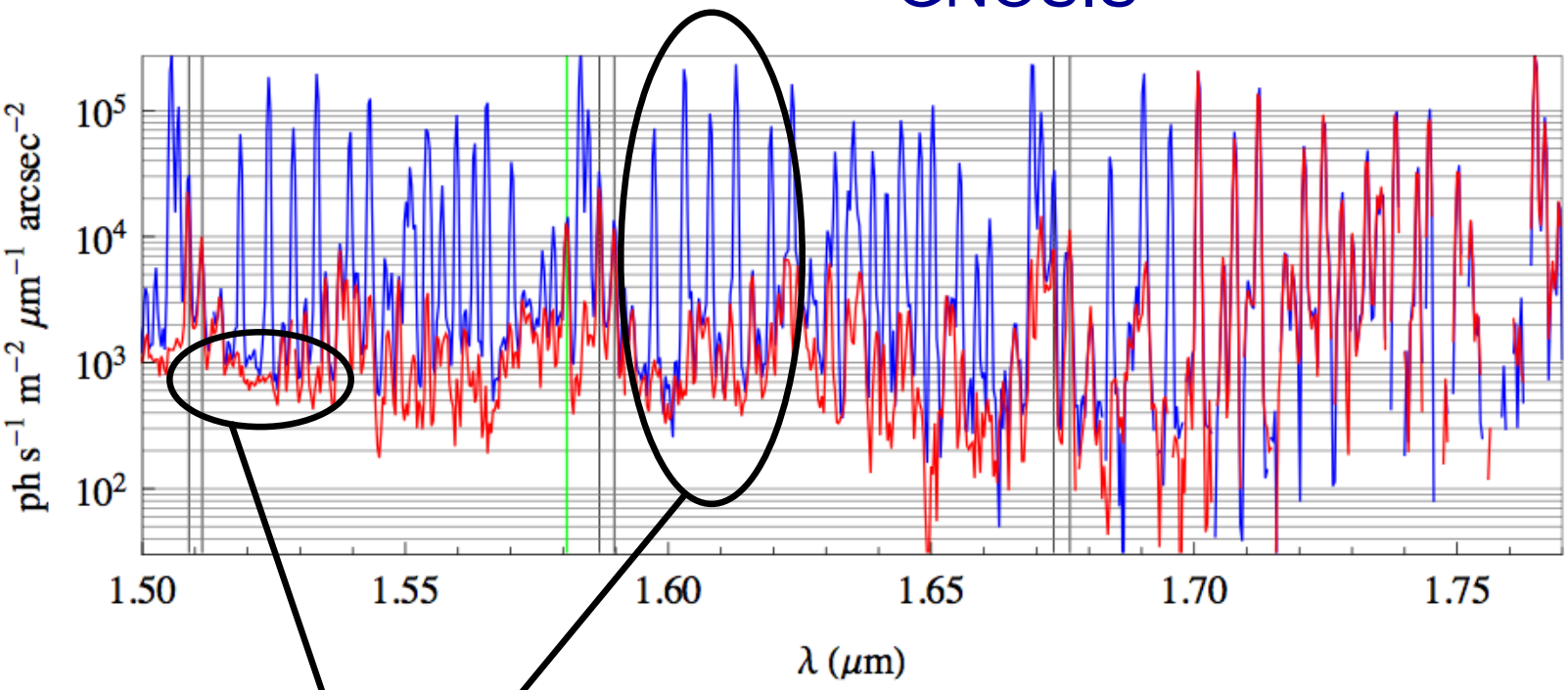




OH Suppression Filter

Suppression of the near-infrared OH night-sky lines with fibre Bragg gratings – first results

GNOSIS

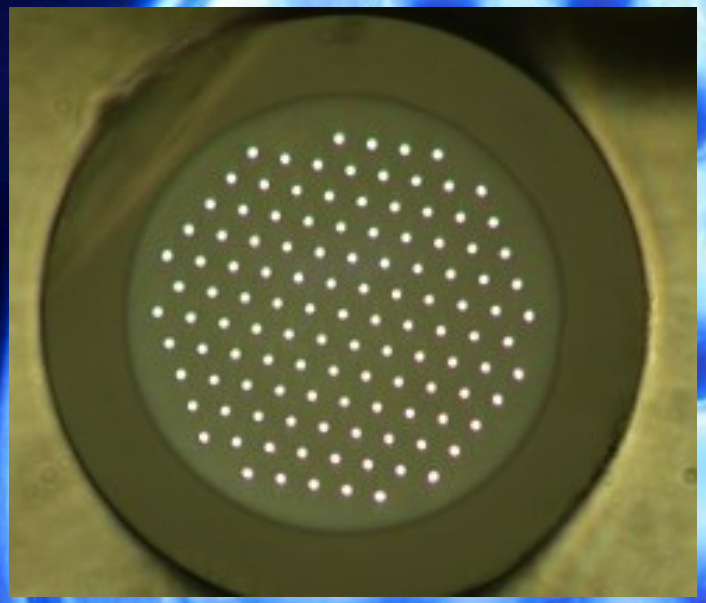


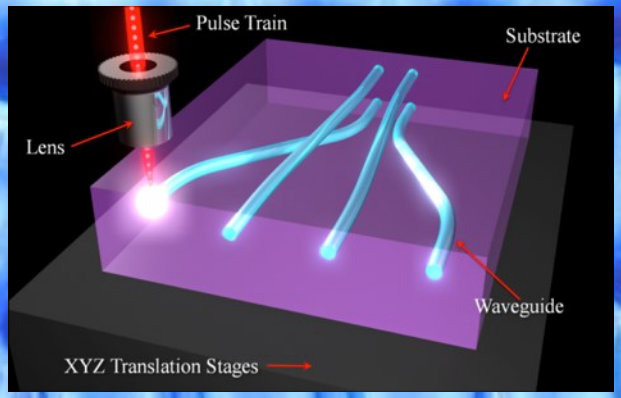
78 % of the target lines are suppressed at the specified level, or greater

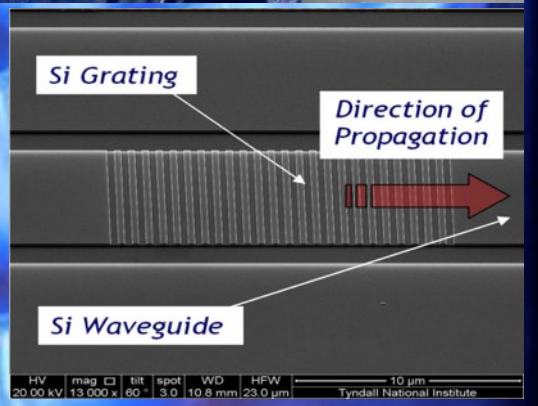
interline component $\approx 860 \pm 210$ photons s^{-1} m^{-2} arcsec^{-2} μm^{-1}

integrated reduction factor of 9

Next Gen. Photonic Filters



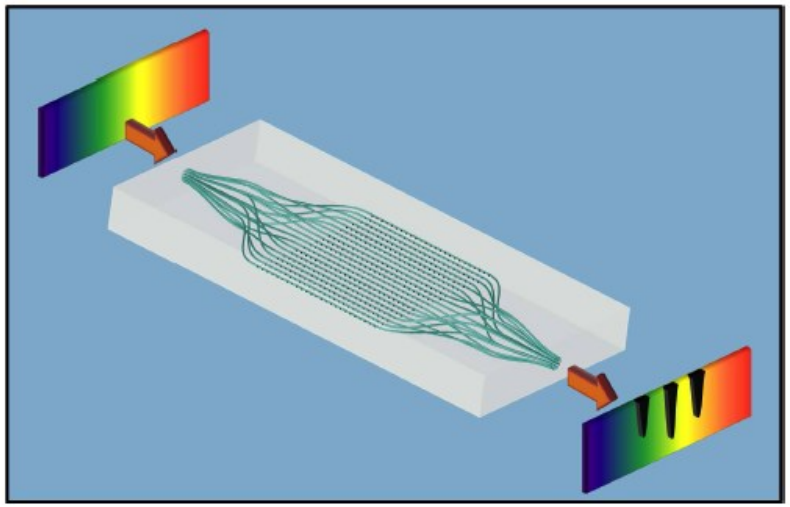




Multiband processing of multimode light: combining 3D photonic lanterns with waveguide Bragg gratings

Izabela Spaleniak,[1,2,*] Simon Gross,[1,3] Nemanja Jovanovic,[4] Robert J. Williams,[1] Jon S. Lawrence,[1,2,5] Michael J. Ireland,[1,2,5] and Michael J. Withford[1,2,3]

Laser Photonics Rev. **8**, No. 1, L1–L5 (2014) / **DOI** 10.1002/lpor.201300129



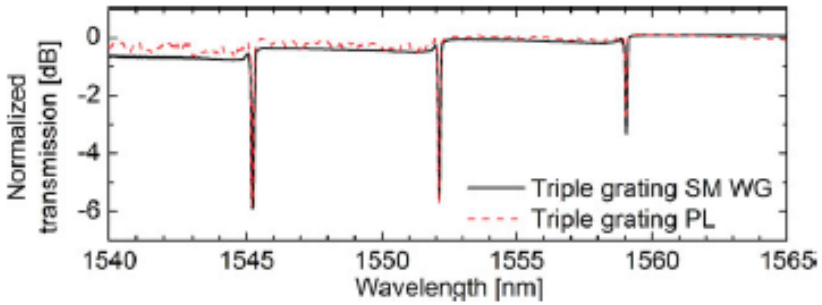


Figure 3 Normalized transmission spectra of the triple grating SM waveguide and triple grating photonic lantern. The transmission losses on the short wavelength side are caused by coupling into radiation modes.

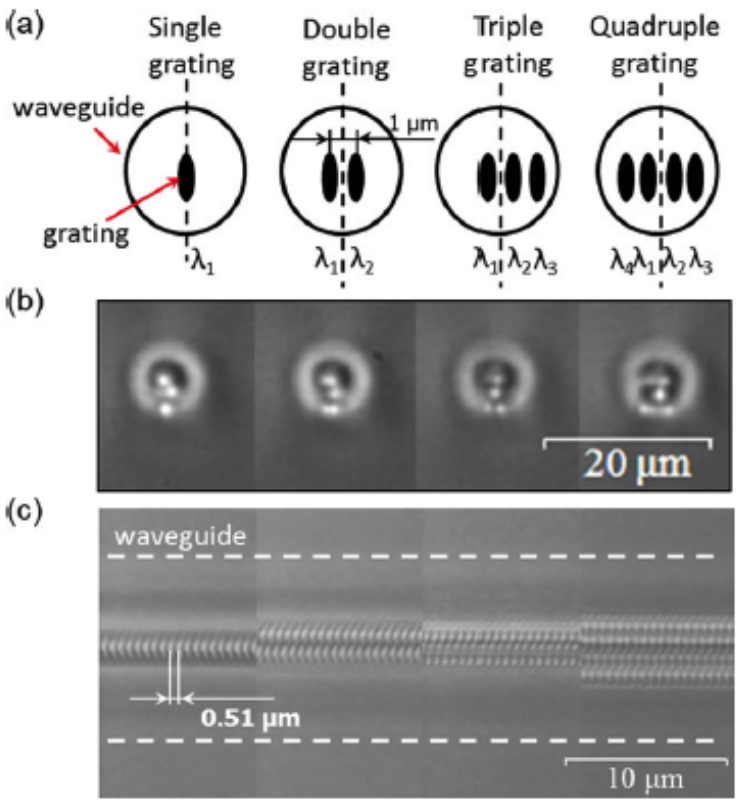
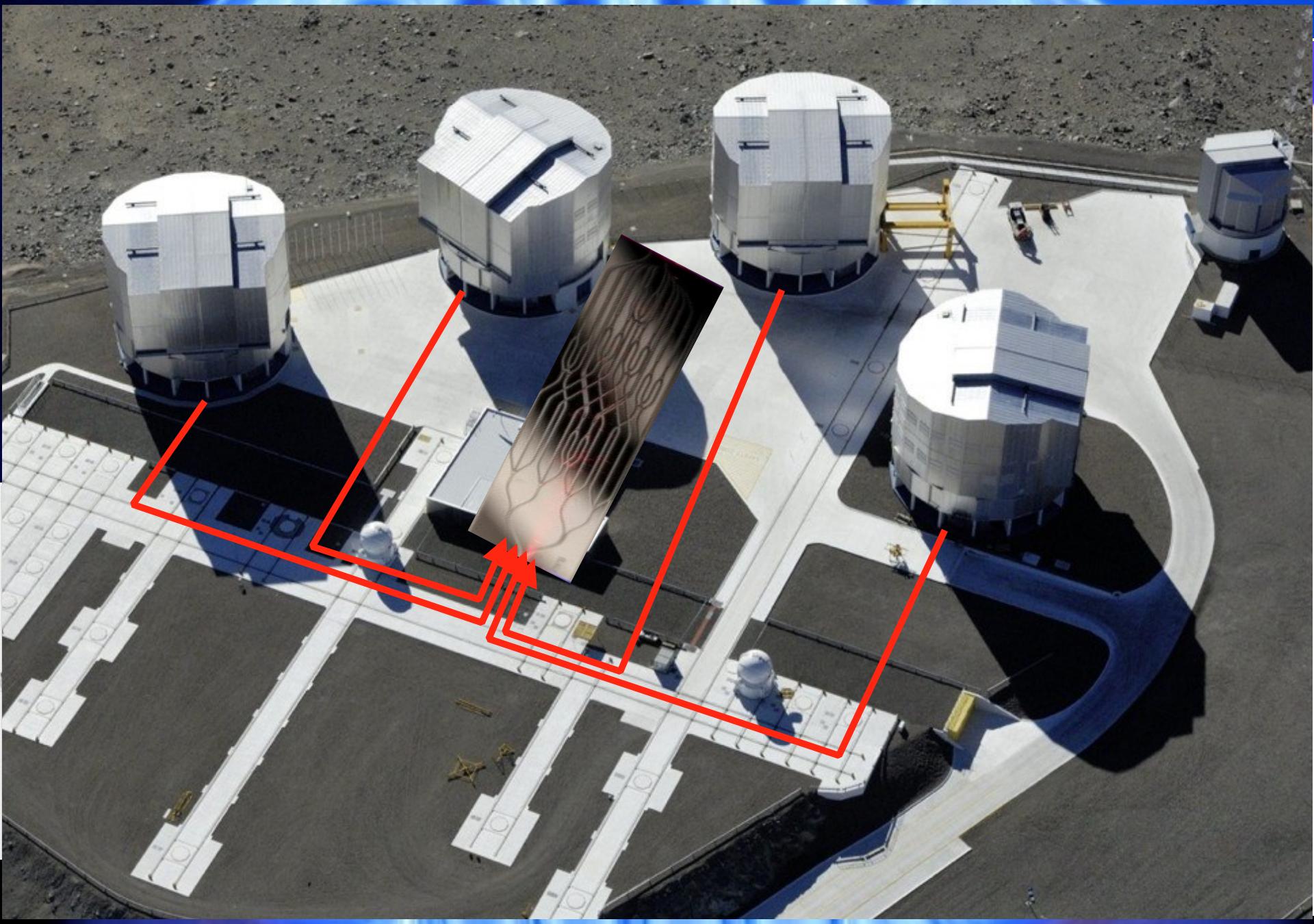
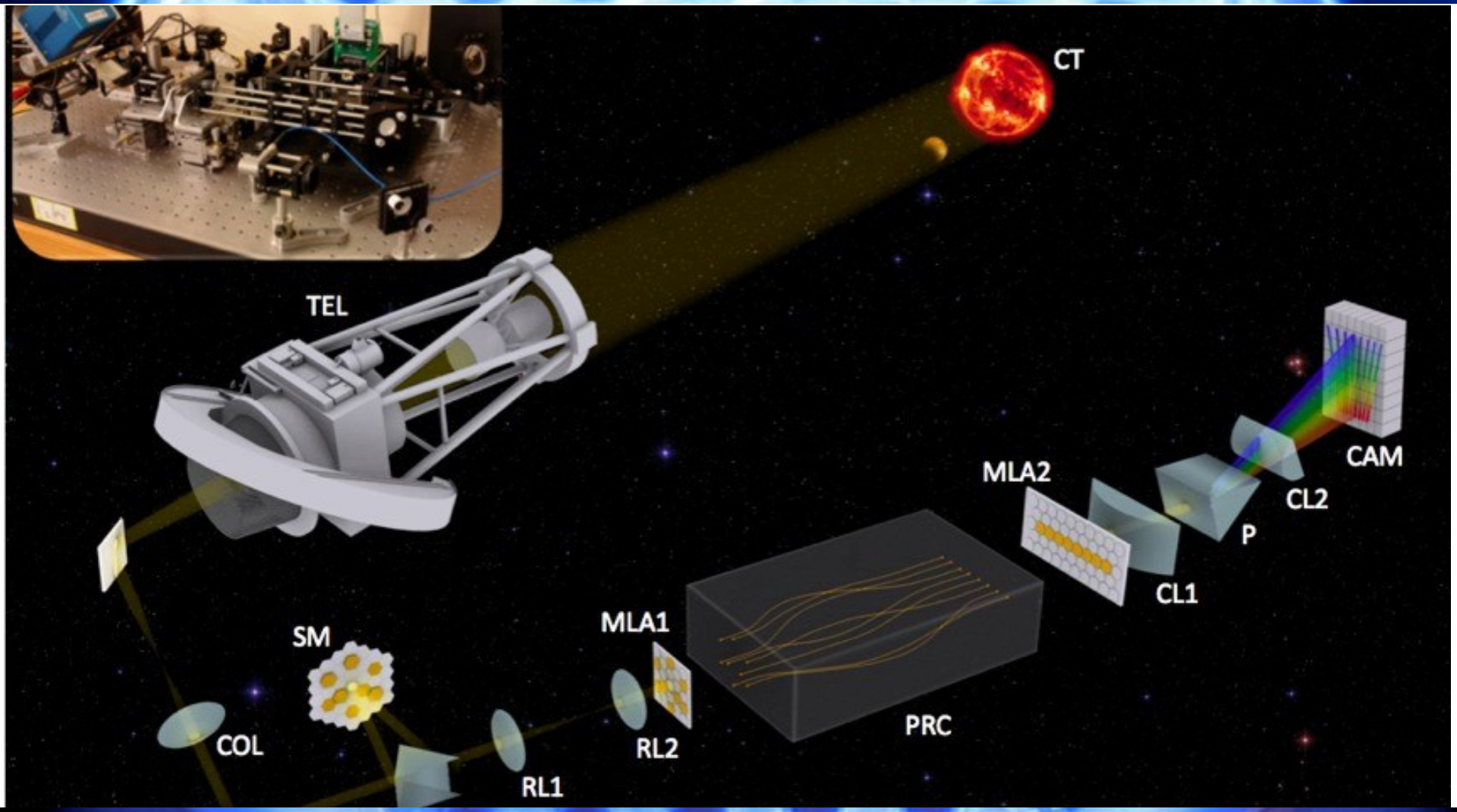


Figure 1 (a) Sketch of the cross-section of the waveguides (circles) with the gratings (elipses) with indicated position of the center of the waveguide (dotted line); $\lambda_1 = 1545$ nm, $\lambda_2 = 1552$ nm, $\lambda_3 = 1559$ nm, $\lambda_4 = 1563$ nm; microscope images of the SM waveguides seen from the front (b) and top (c) with one, two, three and four gratings.

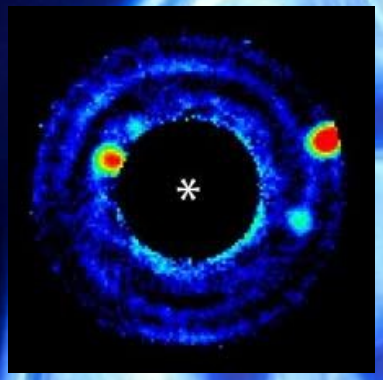
Beam combination

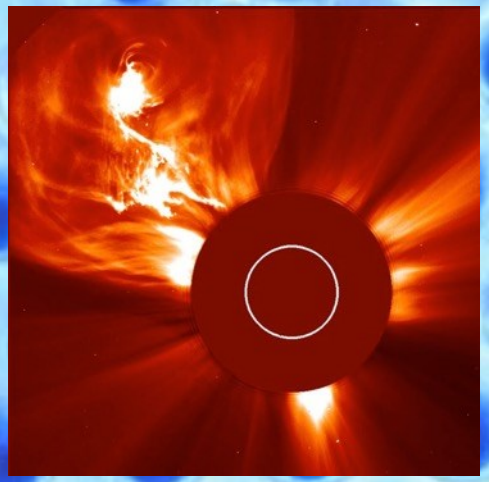


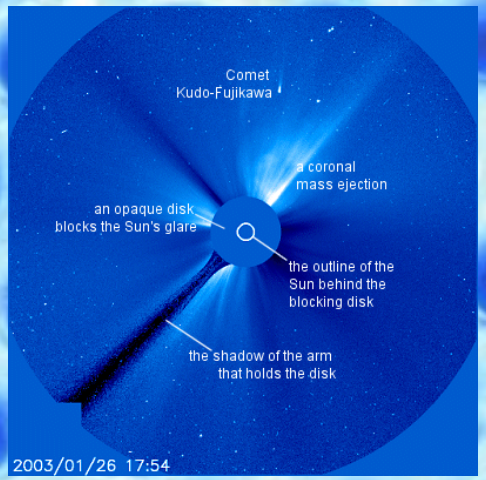
Pupil re-formatting

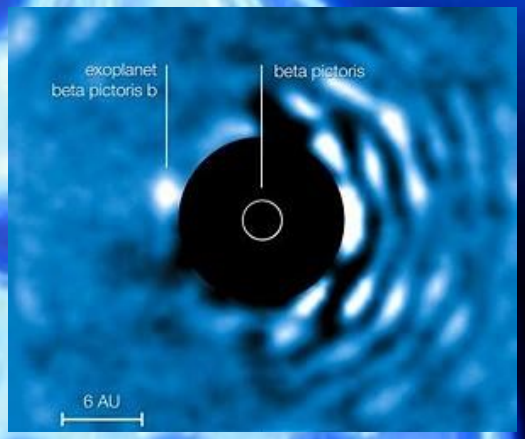


Coronagraphy



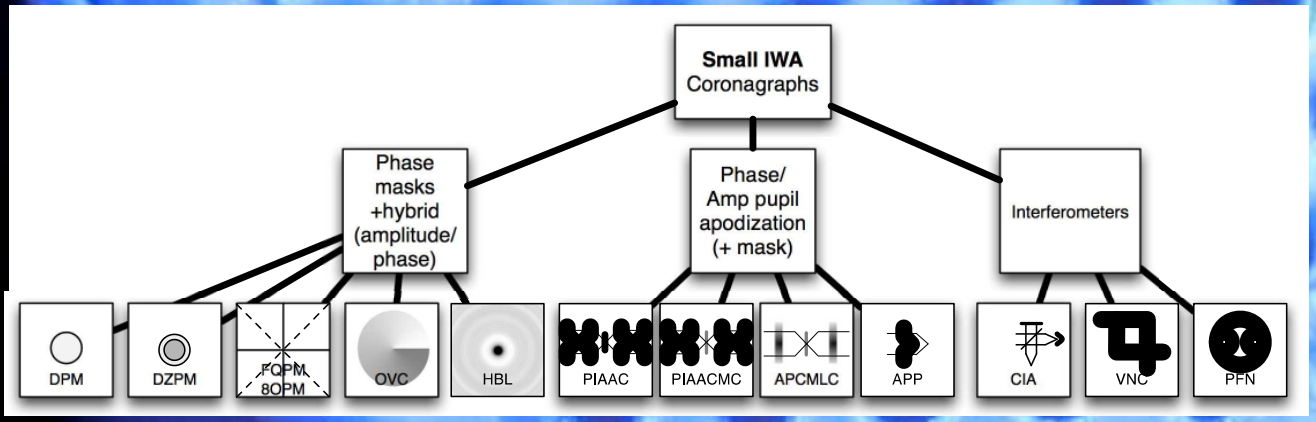






Three main families

1) Phase masks
2) Phase/amplitude pupil apodization + focal plane masks (phase and/or amplitude)
3) Interferometers.

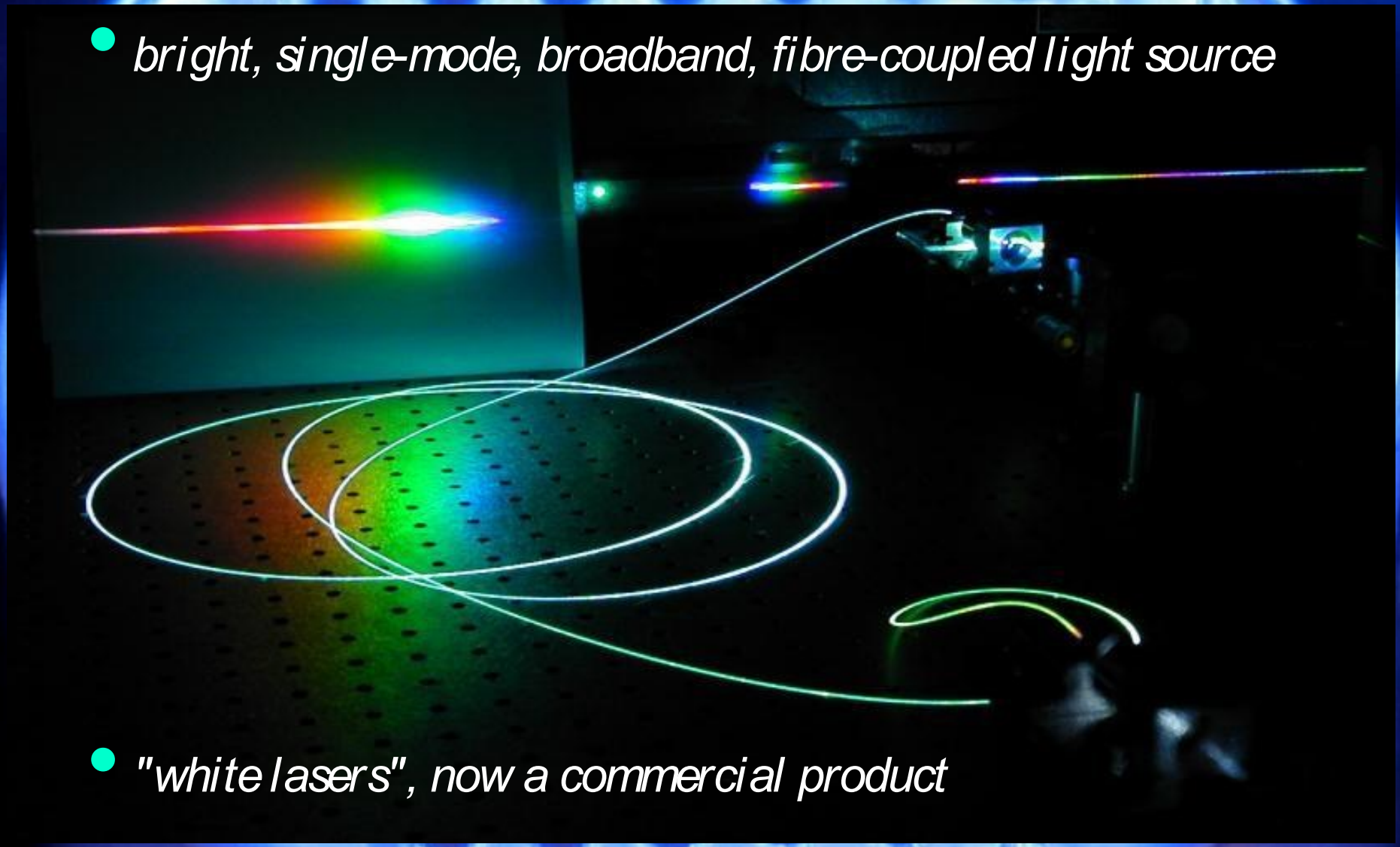


Family tree of small-angle coronagraphs.

1. DPM: disk phase mask.
2. DZPM: dual zone phase mask.
3. FQPM/8OPM: four-quadrant phase mask, 8 octant phase mask.
4. OVC: optical vortex corona- graph.
5. HBL: hybrid band-limited.
6. PIAAC: phase induced amplitude apodization.
7. APP: apodizing phase plate. CIA: “coronagraphe interferentiel achromatique”.
8. VNC: visible nuller coronagraph.
9. PFN: Palomar fiber nuller.

Super-continuum

- *bright, single-mode, broadband, fibre-coupled light source*

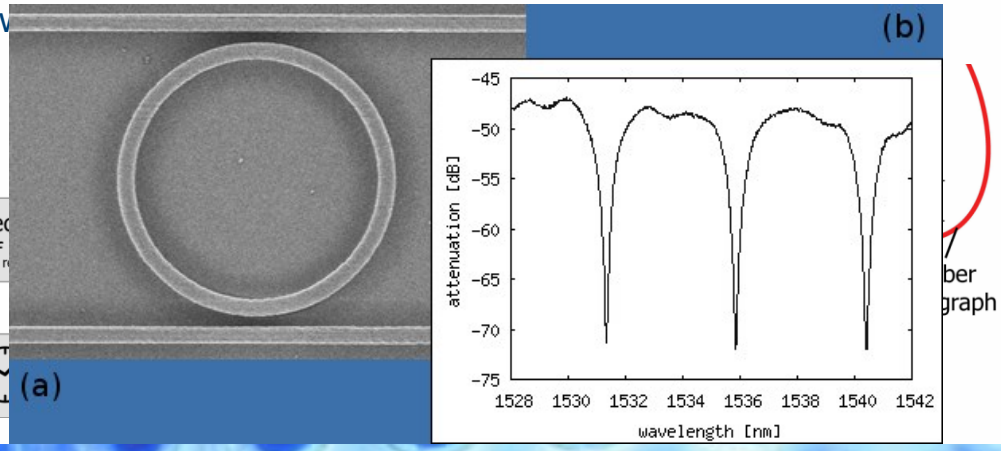


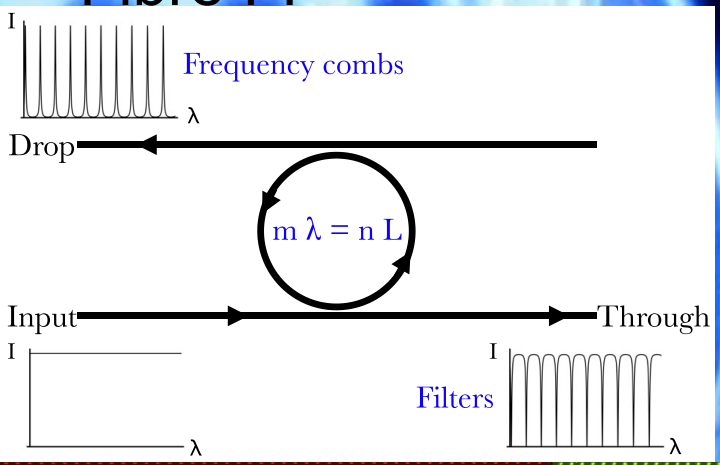
- *"white lasers", now a commercial product*

Astro-Combs

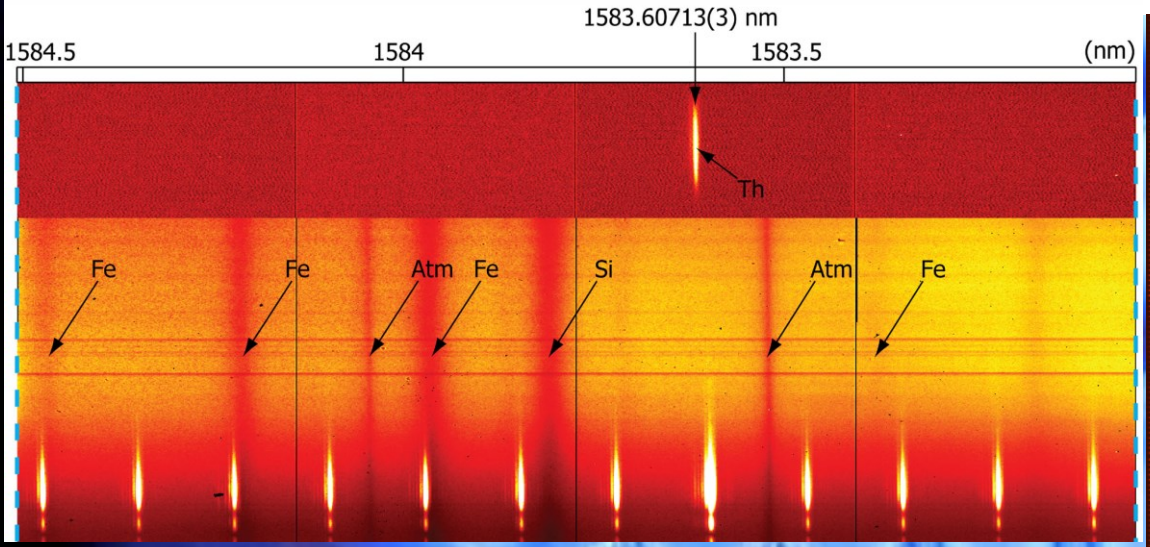
- Comb + FP
- Fibre (Four wave mixing)
- Ring Resonators
- Fibre FP

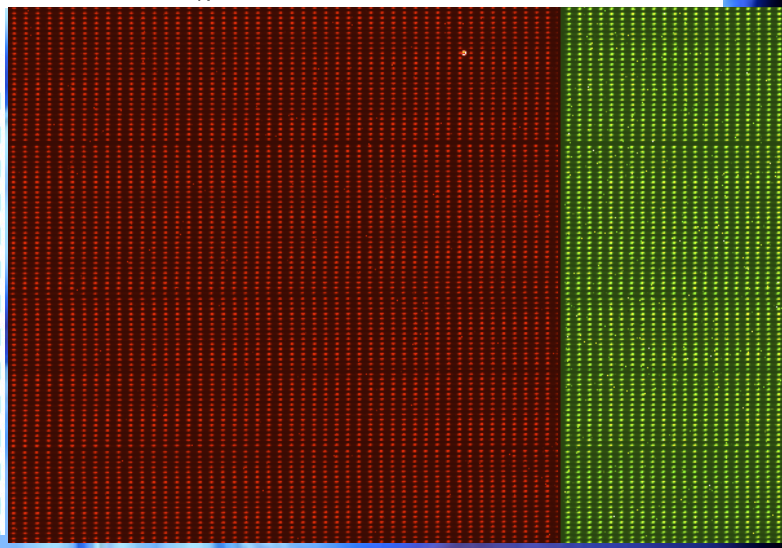
- Reference lines with well known (atomic clock accuracy)



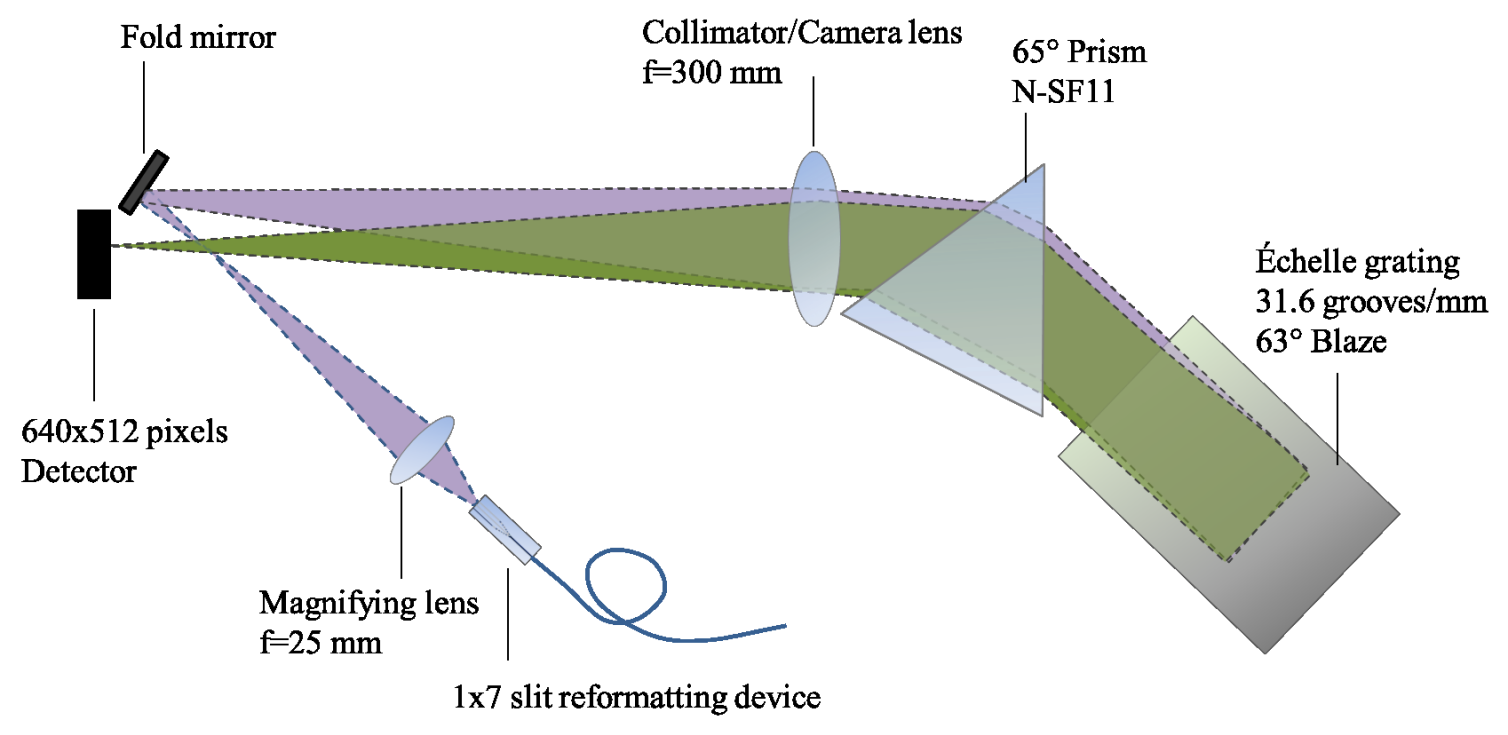


- Project Laser Comb lines with observation

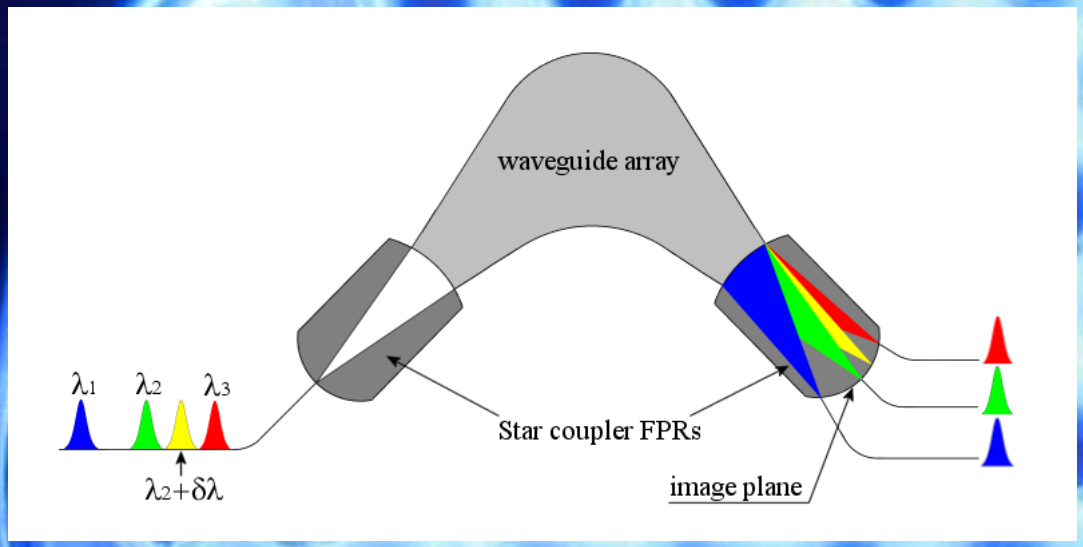


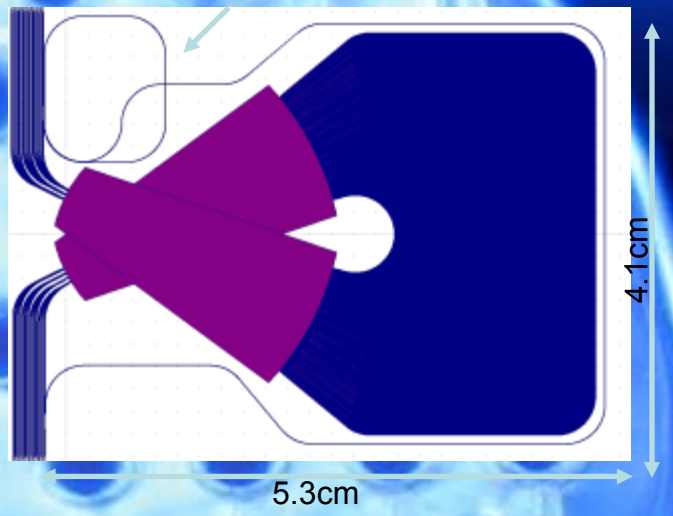


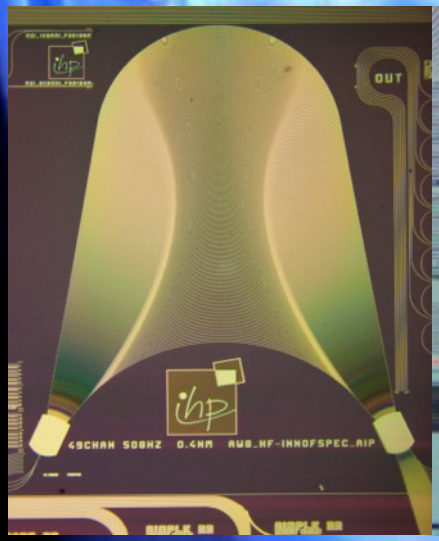
Single-mode échelle spectrograph

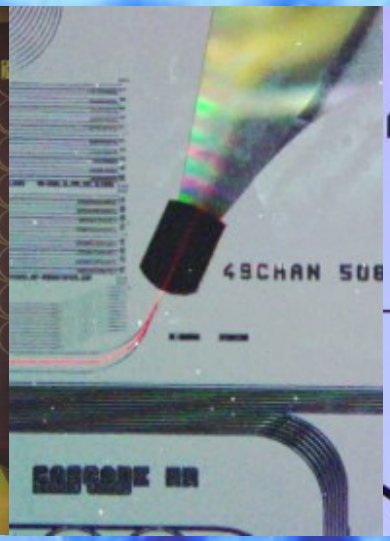


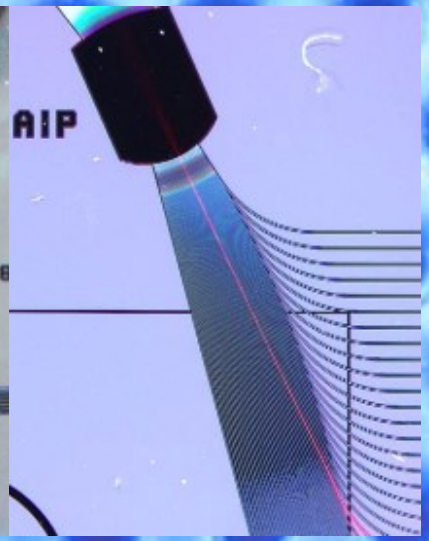
Integrated Photonic Spectrograph

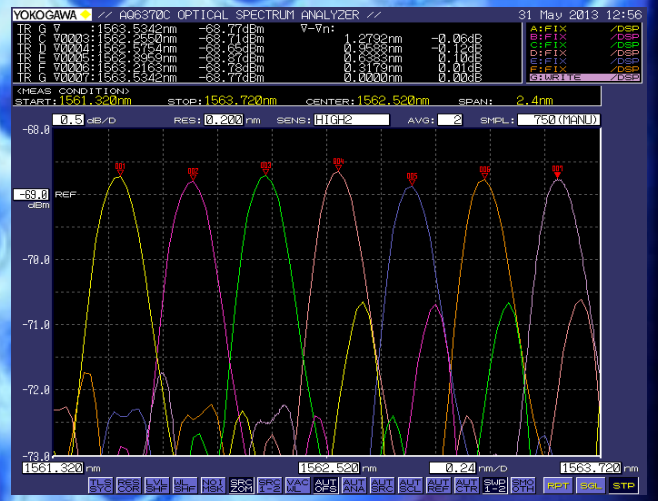












More interesting stuff

Bulk Optics

- ULI inscribed gratings
- ULI lenses, alignment plates
- Phase correction plates
- Active optics
- Micro-optics
- Aspheric optics

Detectors

- Photonic Integrated Detectors

Astrophotonics “benefits for society”

- Photonics European market ~€ 100bn
- Technology transfer: telecom, spectroscopy, bio-sensing, quantum optics, laser technology
- Collaborative developments with communities
- Training new generation of instrument scientists
- Links with photonics experts in academia and industry
- Regular outreach activities
- Community access to “state of the art” fabrication, modelling and characterisation facilities for maintain European/Australian leadership in Astrophotonics