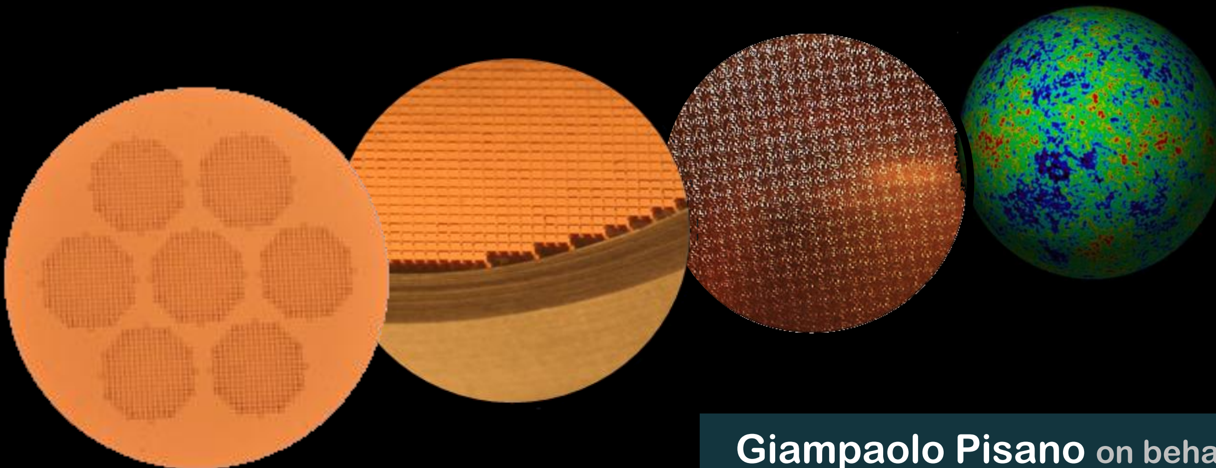
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Development of Instrumentation for Millimetre and Sub-mm Wave Astronomy at Cardiff:

QO Components & Metamaterials



Giampaolo Pisano on behalf of

Astronomy Instrumentation Group - School of Physics & Astronomy – Cardiff University

Astronomical Instrument Development, DIAS, Dublin, 2nd September 2019

Astronomy Instrumentation Group: Expertise & Techniques

CARDIFF UNIVERSITY
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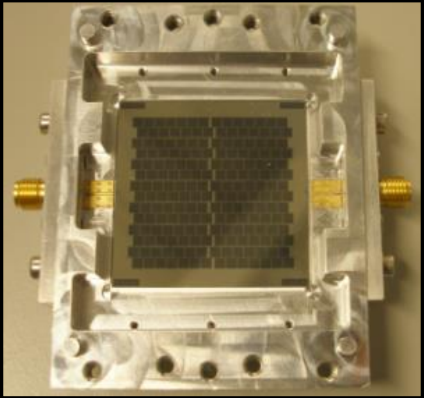
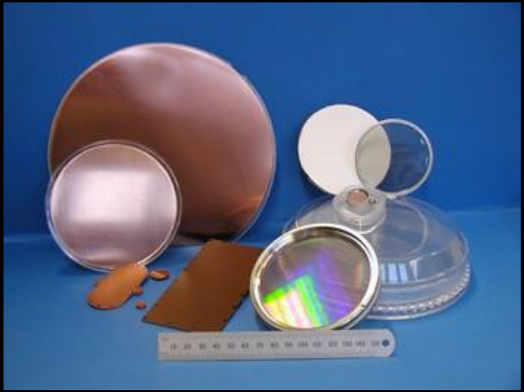
Detectors



Cryogenics

QO Filters & Metamaterials

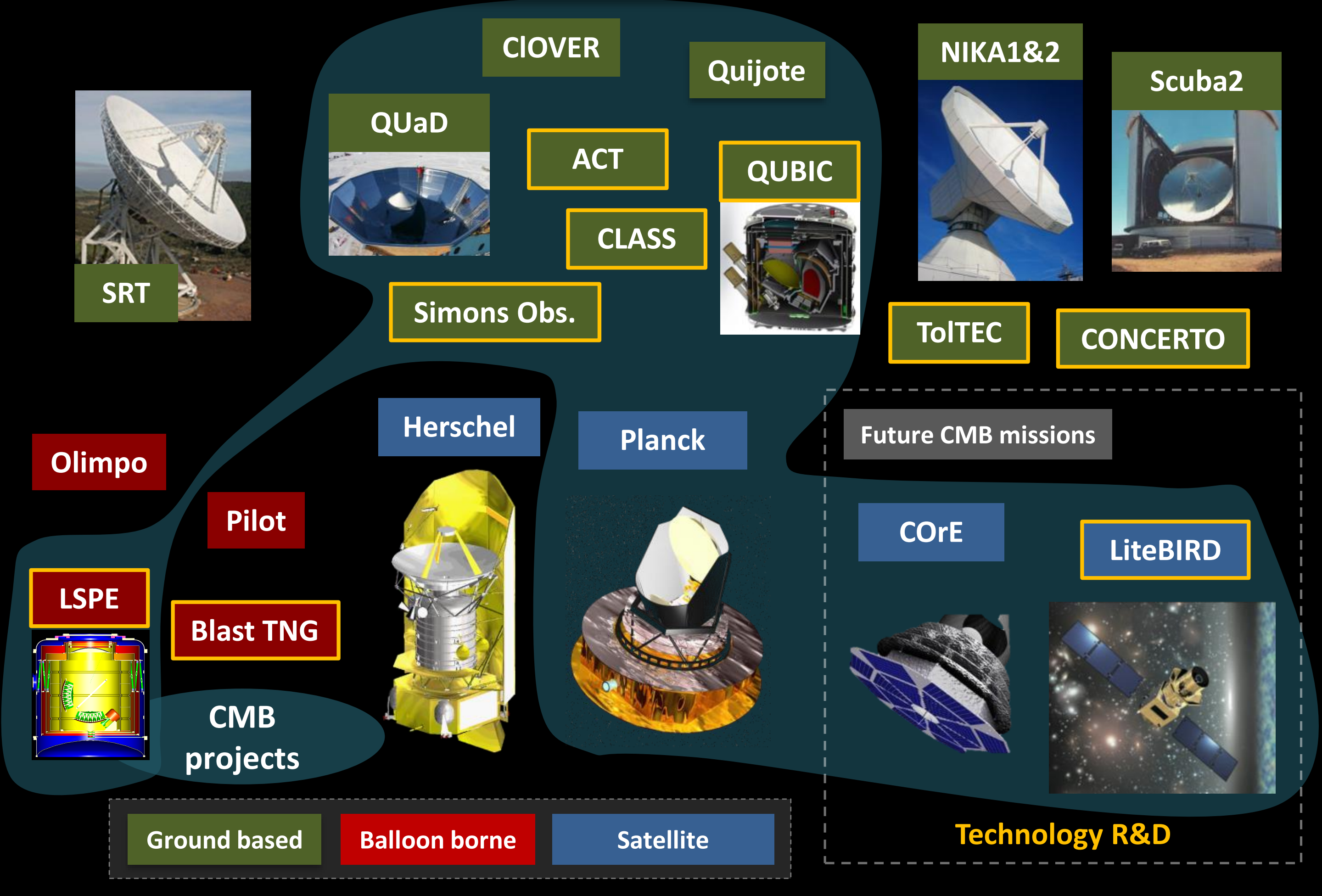


Techniques:

- Spectroscopy
- Photometry
- Polarimetry
- Interferometry

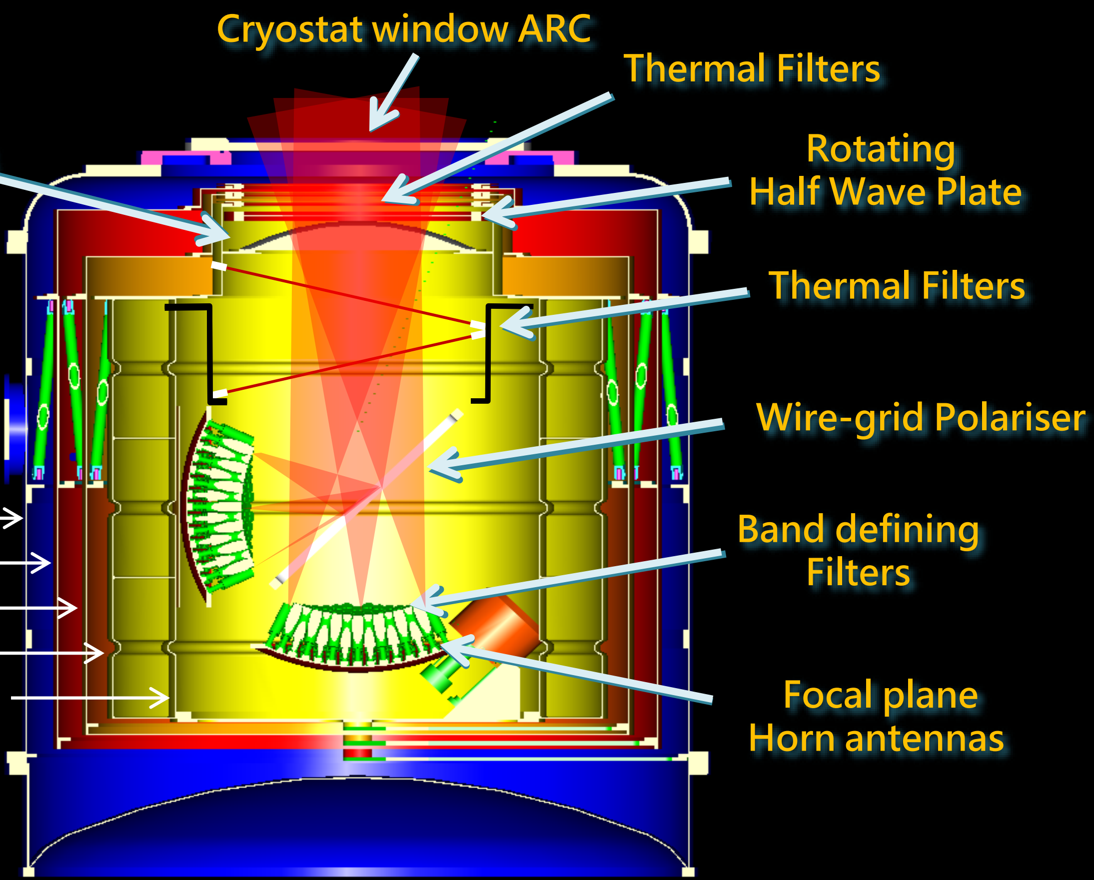
This talk ⇨

Development of instrumentation for mm and sub-mm astronomy



CMB instrument example: SWIPE instrument on LSPE

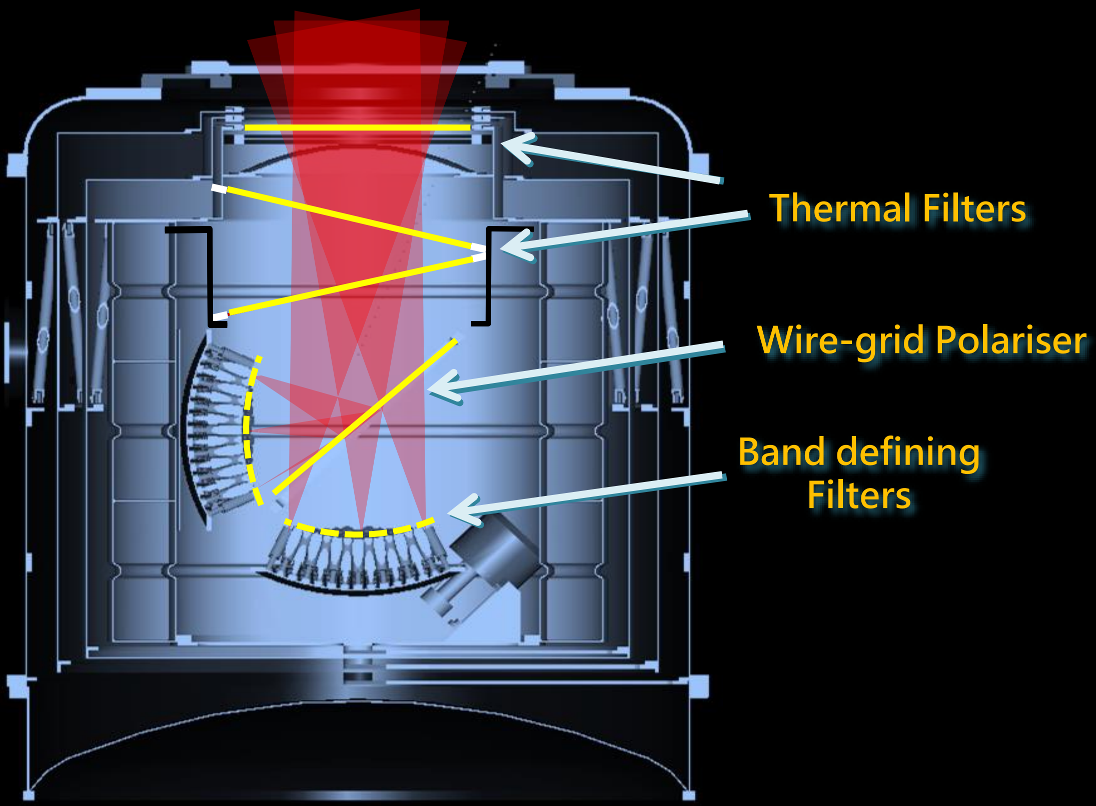
140, 220 & 240 GHz



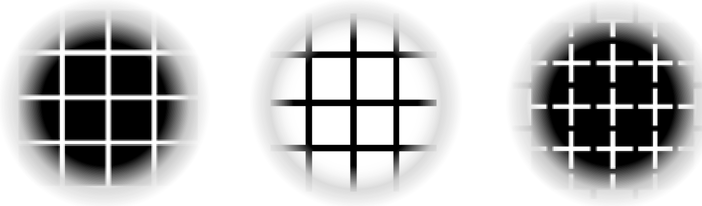
P. de Bernardis et al., *Proc. SPIE* **v.8452** (2012)

→ **All the highlighted items can be realised with Metamaterials**

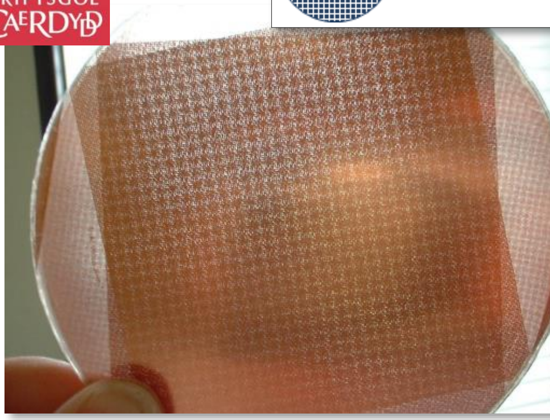
CMB instrument example: SWIPE instrument on LSPE



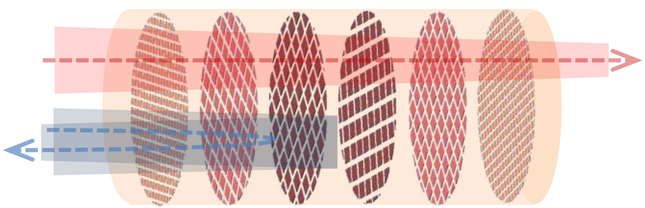
Spectral filtering: Mesh filters

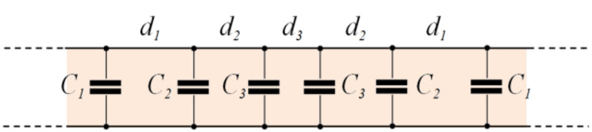


Capacitive (Low-pass) | **Inductive** (High-pass) | **Resonant** (Band-pass)

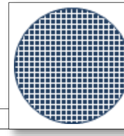


Dielectrically Embedded multi-layer filters



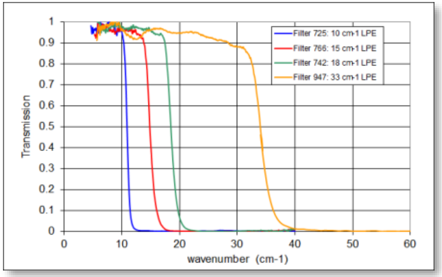


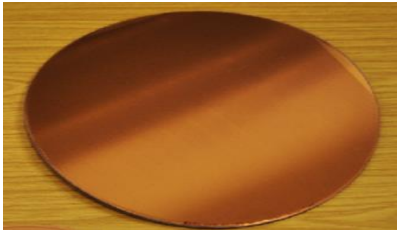
Mesh technology: Quasi-optical components

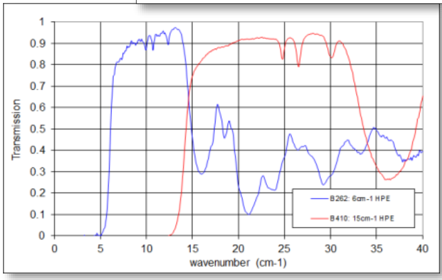


Homogeneous grids

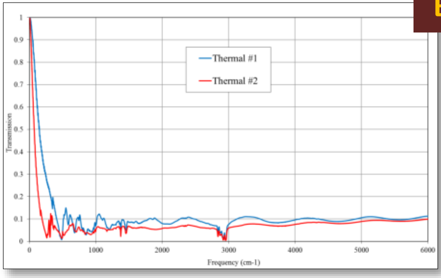
Band defining Filters

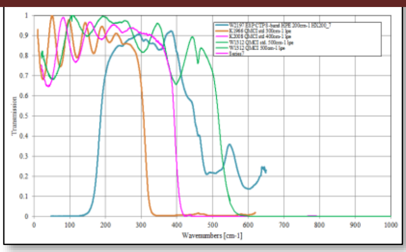


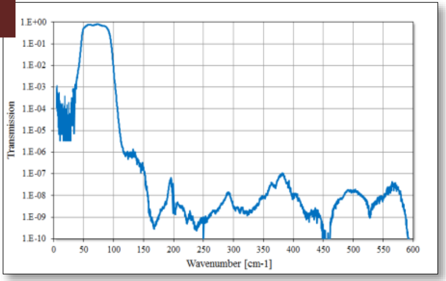




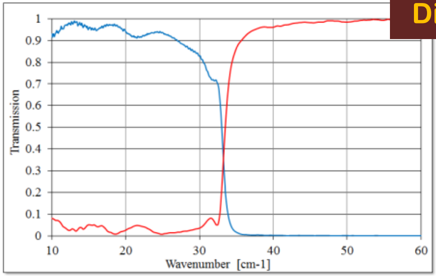
Blocking Filters and Filter Chains

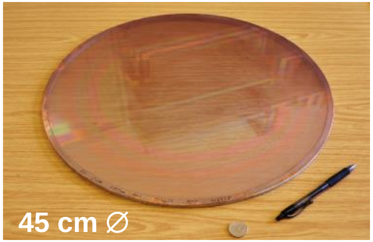


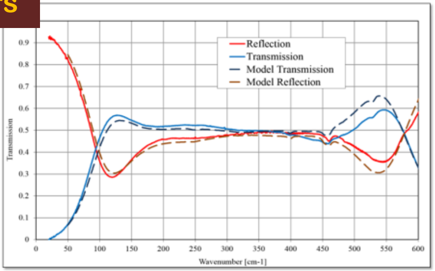




Dichroics, Polarisers, Beam dividers



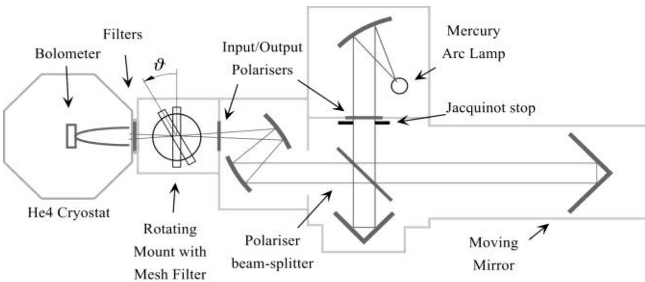




Testing facilities: Coherent and incoherent sources

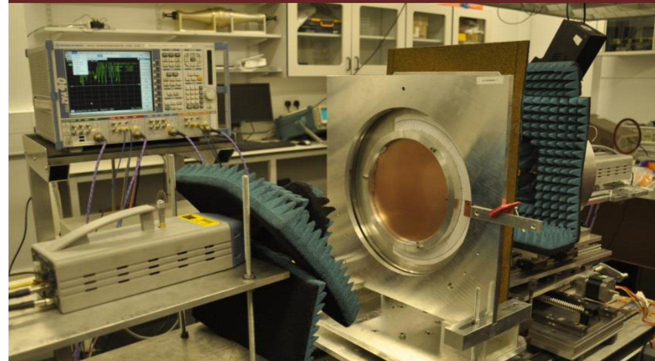
Fourier Transform Spectrometers (FTSs)

Martin-Puplett



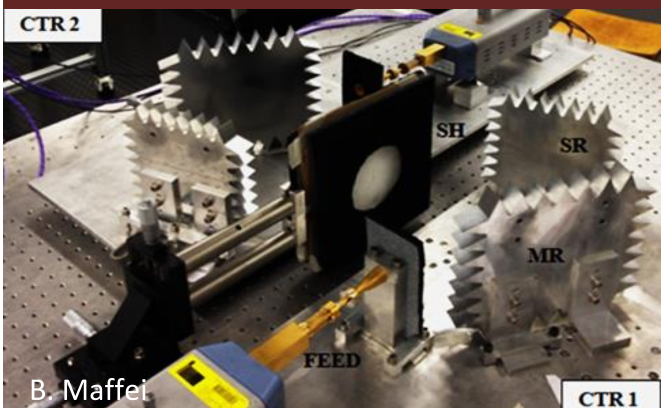
Freq range: 100GHz to many THz

Vector Network Analysers (VNAs)

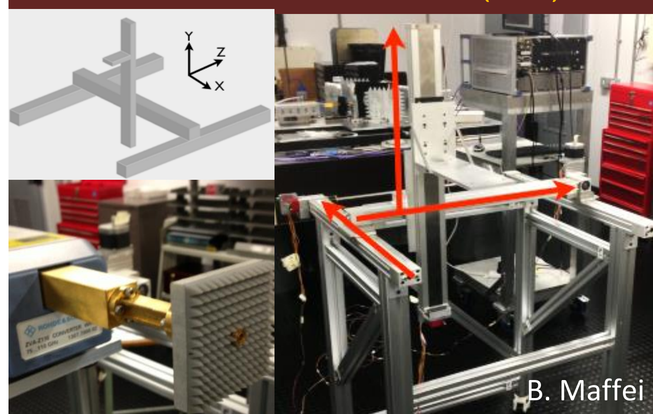


Freq range: 1-330GHz

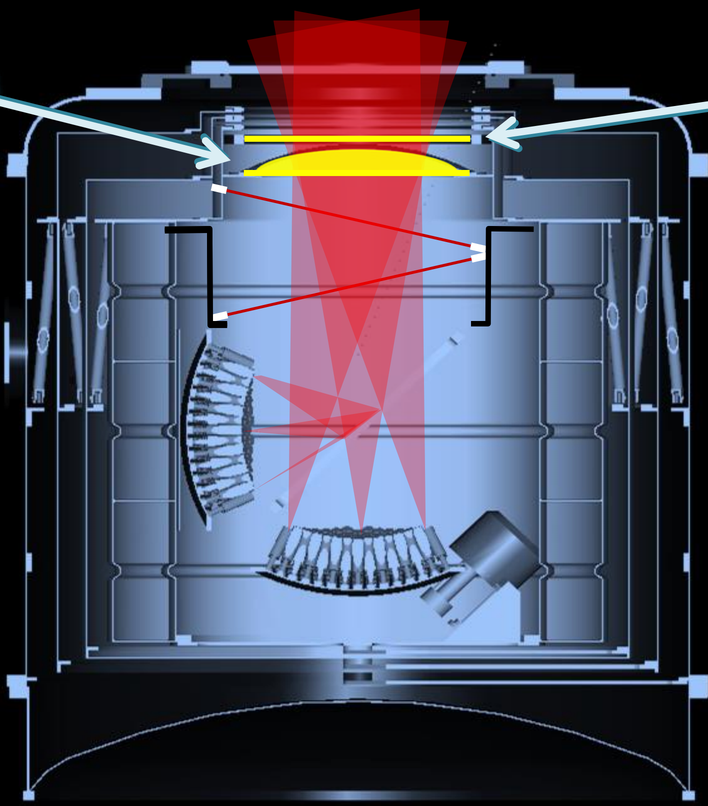
VNA free space S-parameters test bench



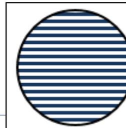
VNA near field 3D scanner (VNA)



CMB instrument example: SWIPE instrument on LSPE

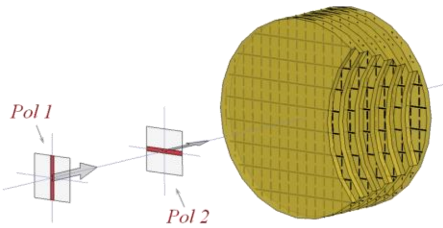


Mesh technology: Half Wave Plates

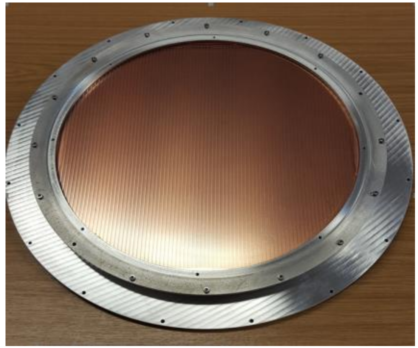


Homogeneous anisotropic grids

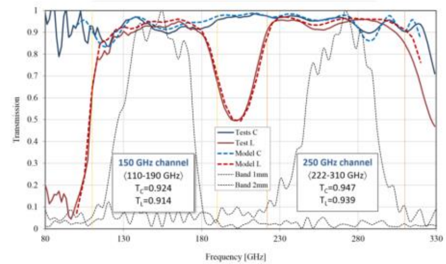
Transmissive Mesh HWPs



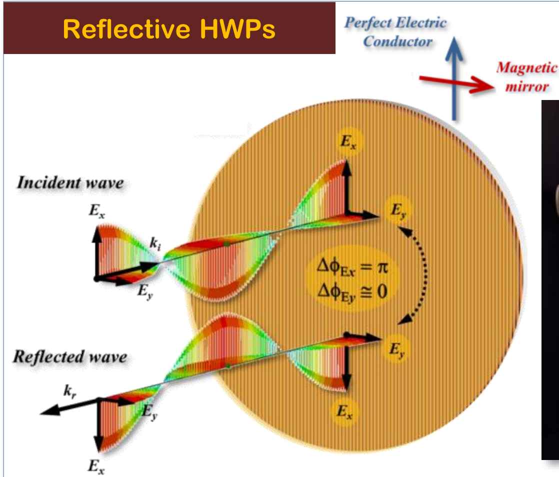
Capacitive & Inductive grids



Axes transmissions

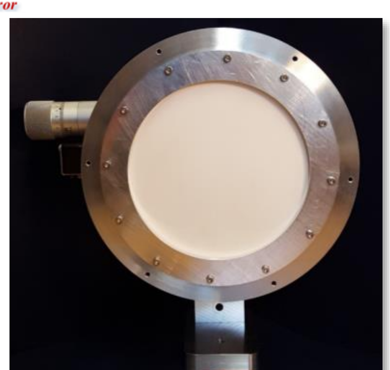


Reflective HWPs

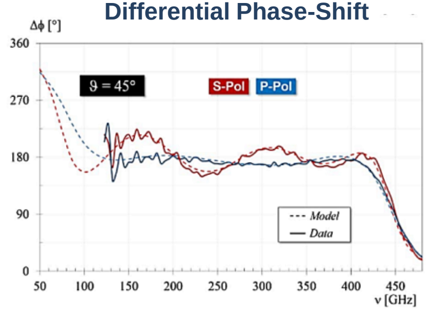


esa

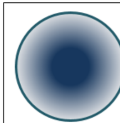
Cardiff (PI), RAL, Rome & Manchester



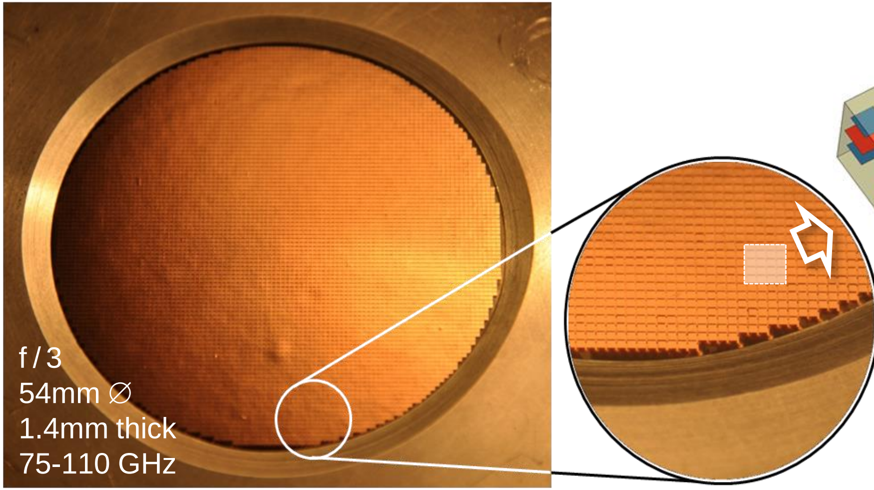
Differential Phase-Shift



Mesh Lenses: Inhomogeneous phase delays

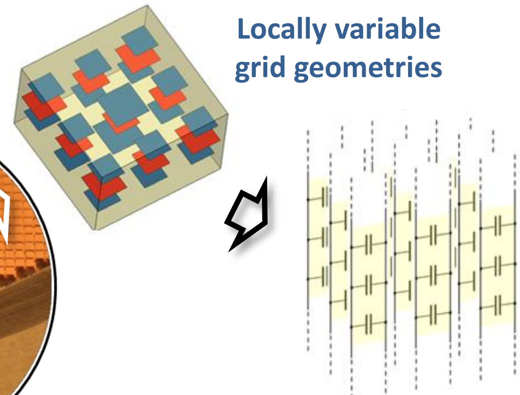


Inhomogeneous grids



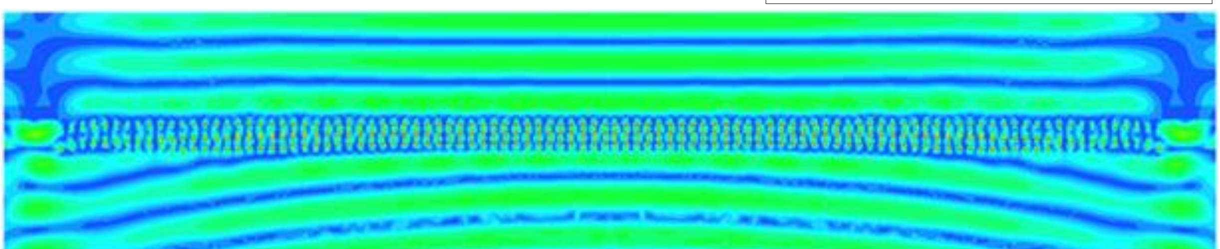
W-Band f/3 lens

Locally variable grid geometries



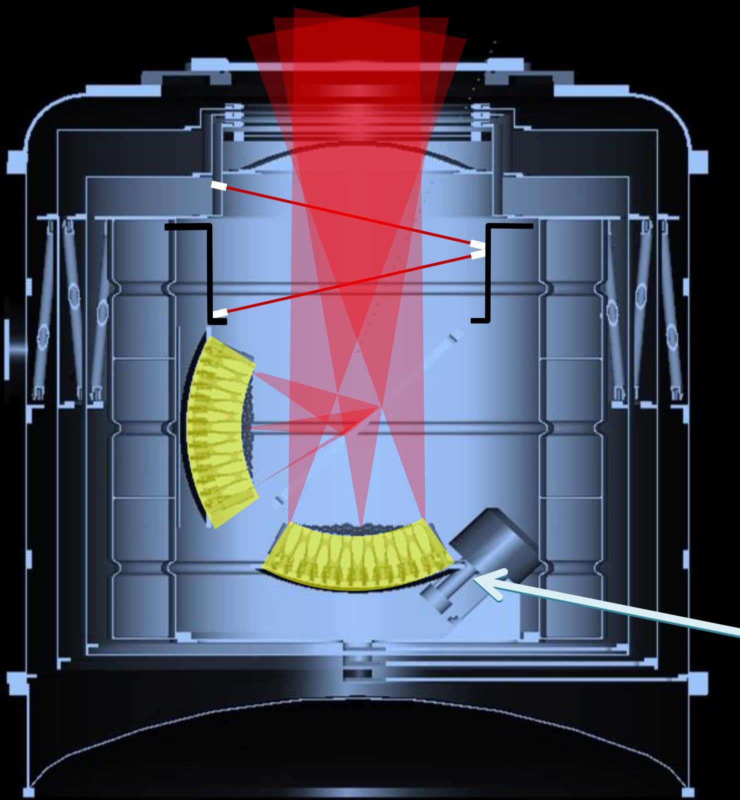
Multiple transmission lines

G. Pisano et al, *Applied Optics* (2013)

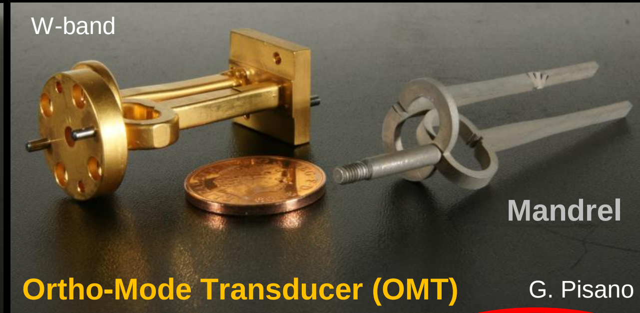


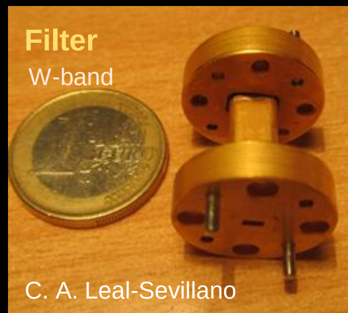
- Finite-element simulations showing the conversion of a spherical wavefront into a planar one

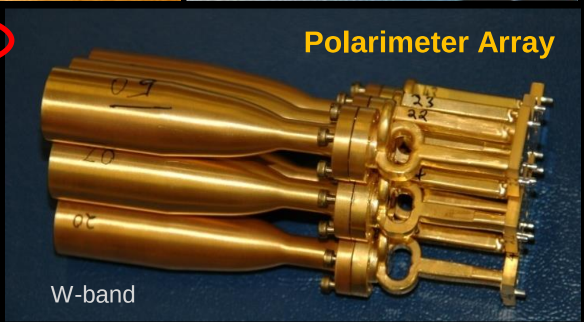
CMB instrument example: SWIPE instrument on LSPE



Focal plane developments: Waveguide and planar components

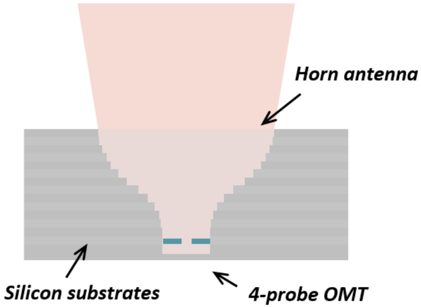


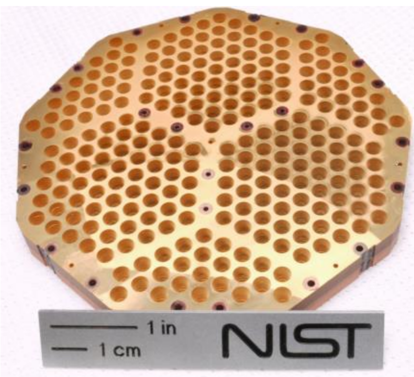




Focal plane arrays: Available technologies

Si platelet feedhorn

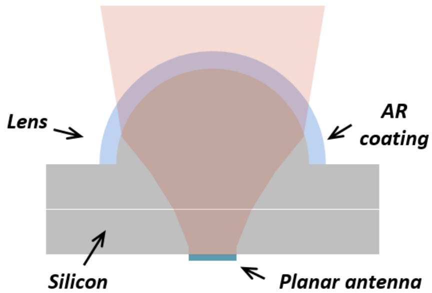




Si platelet feedhorn array

J. W. Britton et al. (2012)
J. P. Nibarger et al (2012)

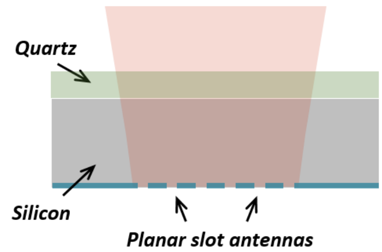
Si hemispherical lenslet

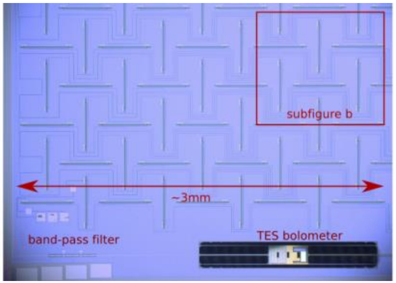


Si hemispherical lenslet array

Aritoki Suzuki et al. (2012)

Phase-array planar antennas

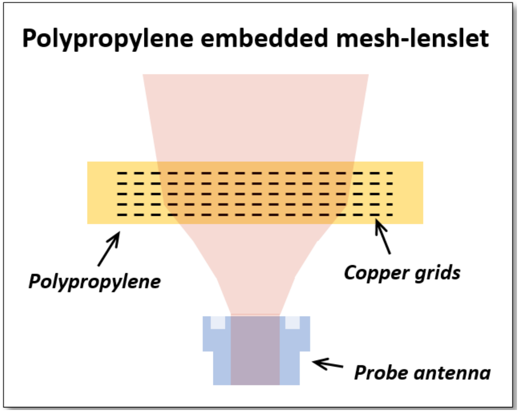




¼ detector element

C. L. Kuo et al (2009)
R. C. O'Brient et al. (2012)

Polypropylene embedded mesh-lenslet: Design & tests



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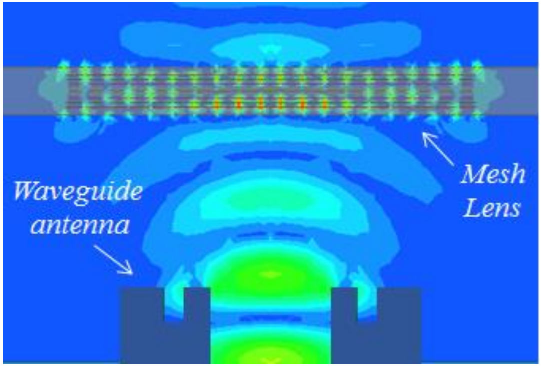
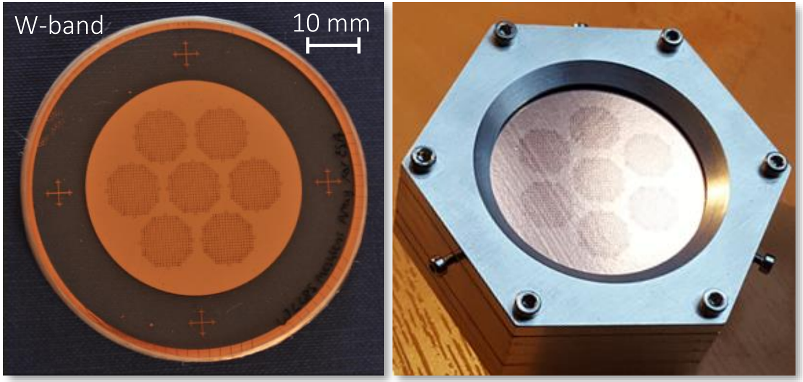
Maynooth (PI), Manchester, Cardiff, Rome, Paris APC & Chalmers



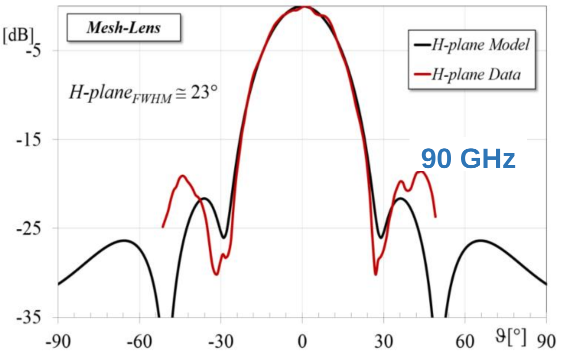
FEA simulation (HFSS)

Working principle: Local 'transmission-line' phase-delays



PP mesh-lens array + cavities & probe antennas

Mesh Lens beam



Mesh-technology: Components summary

Filters

- Low pass & high pass
- Band pass
- Blocking filters
- Neutral density

Retarders

- Mesh HWP
- Mesh QWP (circ.polariser)
- Reflective HWP
- Spiral Phase Plate

Flat lenses

- Graded index lens
- Mesh lens
- Mesh lens array
- Negative index lens

Dividers

- Beam divider
- Dichroic
- Polariser
- Polarisation splitter
- Mesh Prism

Metamaterials

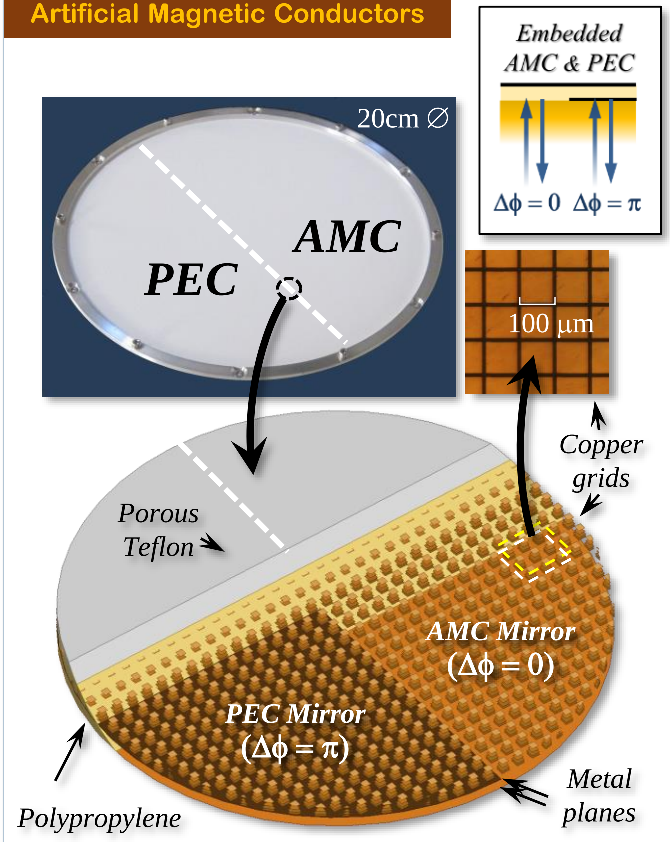
- Artificial dielectrics
- Artificial birefringent materials
- Anti-Reflection Coatings (ARCs)
- Negative Index metamaterials
- Mesh Absorbers

More 'exotic' devices

- Artificial Magnetic Conductors (AMCs)
- Toraldo pupils (super-resolution)
- Photon Orbital Angular Momentum SP- & Q-Plates
- Phase Correcting Surfaces
- Instrumental Polarisation Surfaces

'Exotic' devices: Development examples

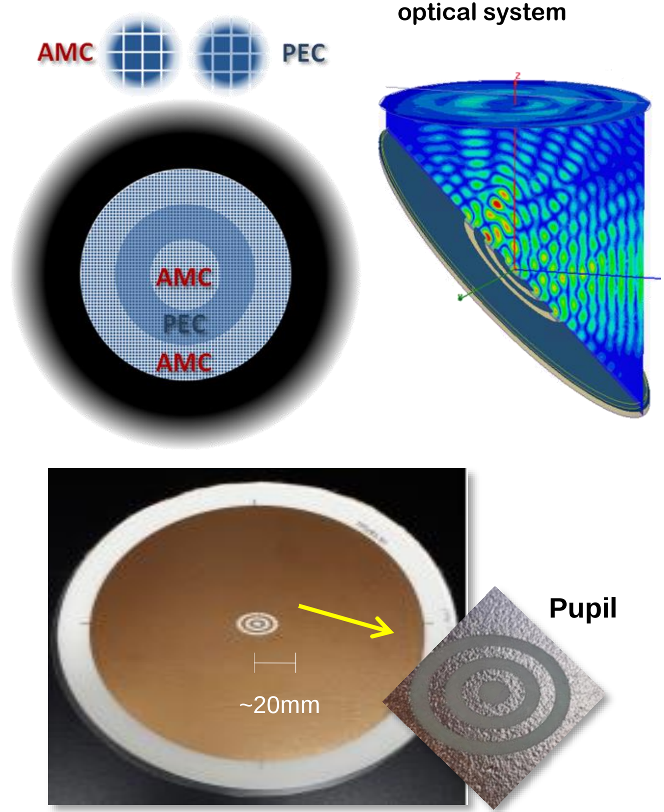
Artificial Magnetic Conductors



Prototype with both PEC and AMC surfaces

Toraldo Pupils

Increase angular resolution optical system

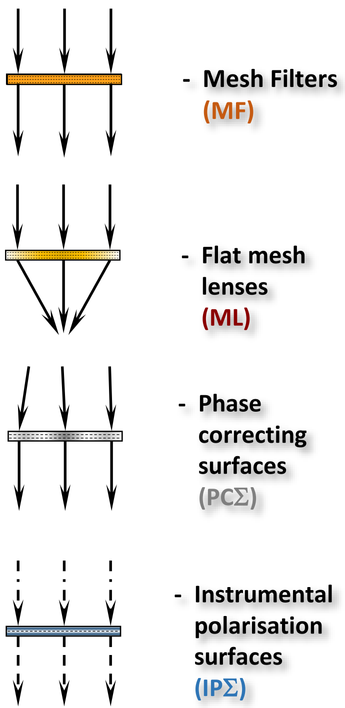


AMC/PEC based pupil

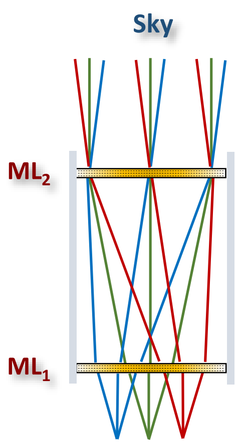
Metamaterial telescopes: Low systematics designs

- We are in position to build ‘metamaterial telescopes’ using a step-by-step design and test approach:

Metamaterial devices

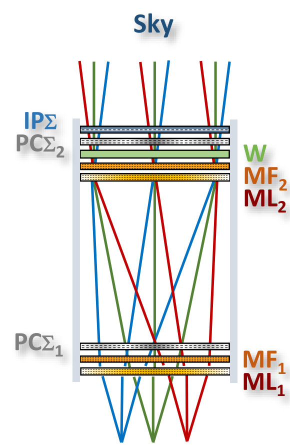


Metamaterial Telescopes



Metamaterial 2-lens telescope

CMB metamaterial telescopes



CMB metamaterial 2-lens telescope

Telescopes as stacks of planar devices

The optical systematics can be ‘cured’ at hardware level by introducing correcting surfaces

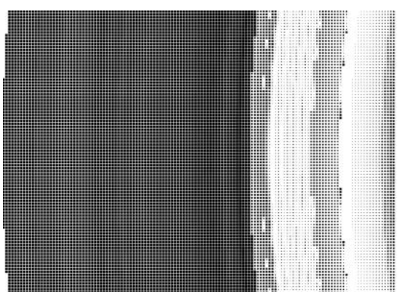
Conclusions

- **The AIG has developed technology and instruments for studies of the Early Universe, CMB science, Star Formation and Evolution**
- **The mesh-technology developed by the group enabled the realization of a large variety of novel quasi-optical components and metamaterials that have been employed in many astronomical instruments at mm and sub-mm waves**
- **The inherent flexibility of the metamaterial properties allows the development on novel components with ‘exotic behaviour’**
- **The working principles of these devices are applicable to other technologies and could be implemented in other astronomical instruments at higher frequencies**
- **We have started transferring the mesh-technology into the Silicon technology which allows much higher processing accuracy**
- **We are looking forward for new collaborations**

Mesh Lenses: Large diameter devices

G. Pisano et al. SPIE (2018)

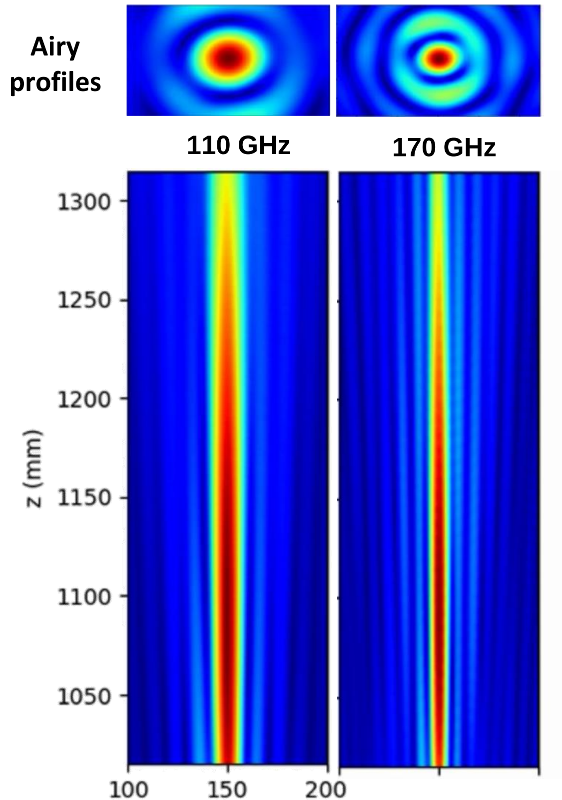
Large diameter hot-pressed mesh-lens



← Pattern example
~800k pixels
across surface

Mesh Lens 3D beam tests

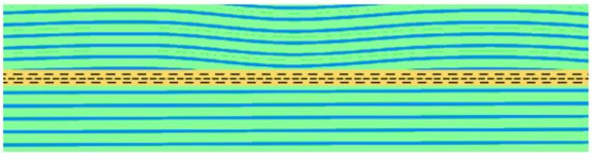
↓ Transversal cuts ↓

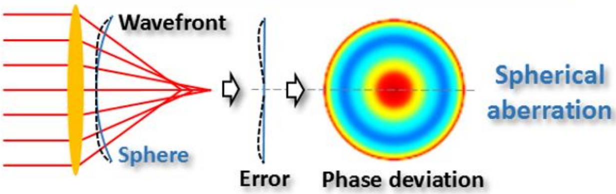


↑ Longitudinal cuts ↑

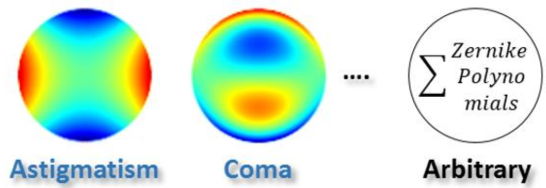
Optical systematics: Aberrations & Instrumental Polarisation

Phase correcting surfaces

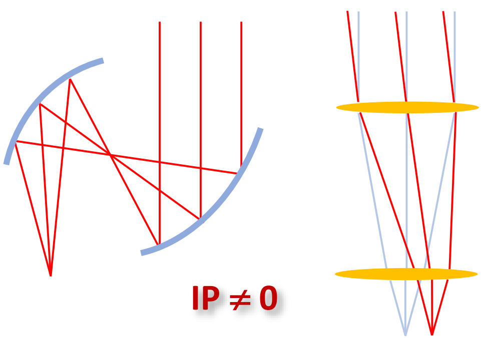


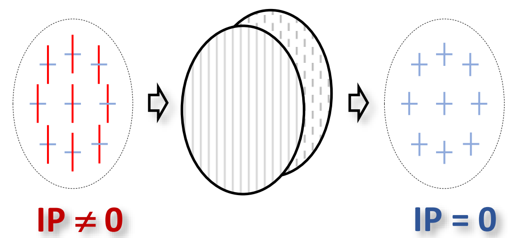


- Arbitrary wavefront error compensation
- Local phase correction
- Compensation of aberrations
- Reduction beam ellipticity and sidelobes



Instrumental polarisation nulling surfaces

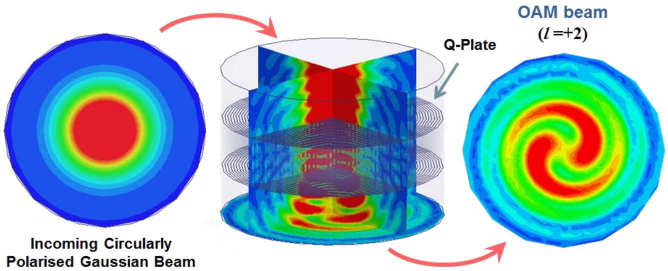


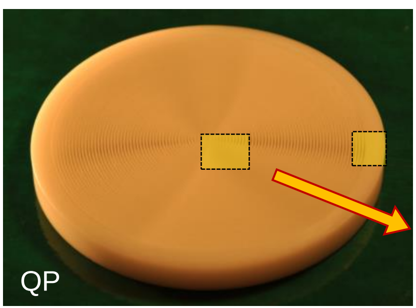


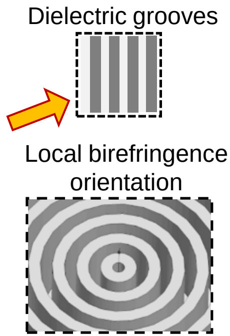
- **Slightly absorbing anisotropic surface**.

Photon Orbital Angular Momentum (OAM) : Generation & Manipulation

Dielectric Q-Plate (QP)



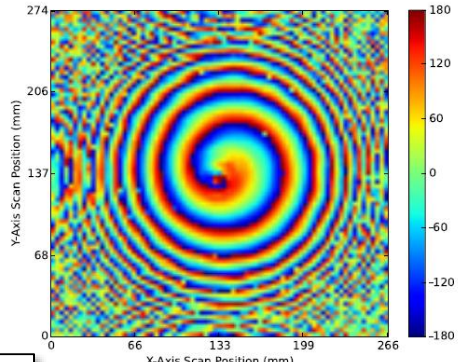




S. Maccalli, *Applied Optics* (2013)

Spiral Phase Plate (SPP)

100 GHz phase measurements

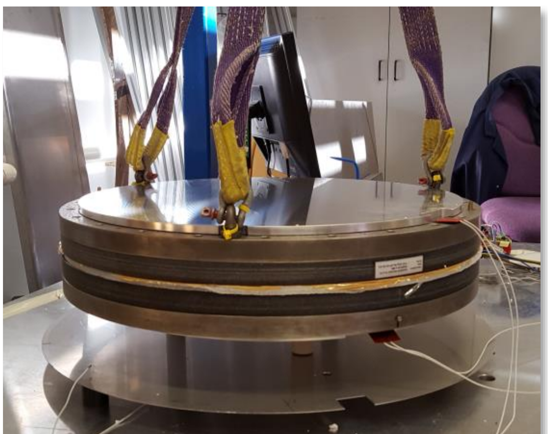


P. Schemmel *Optics Letters* (2014)

Can be built using the mesh technology

Mesh technology: Large diameter device manufacture facilities

UV exposure box for photolithographic processes



'50 cm' press plates

esa

TRP

"Large radii HWP development"

Large hot-press oven

- **Large diameter mesh-devices:**
  - **Production of 50cm ∅ devices**
  - **Upgrading for 70cm ∅ devices**