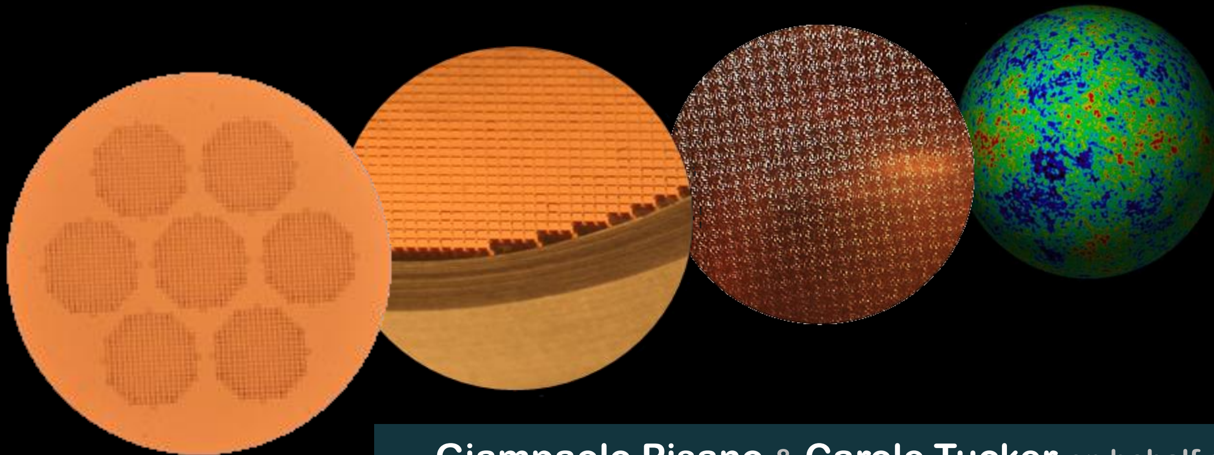
Metamaterials and quasi-optical components for space applications



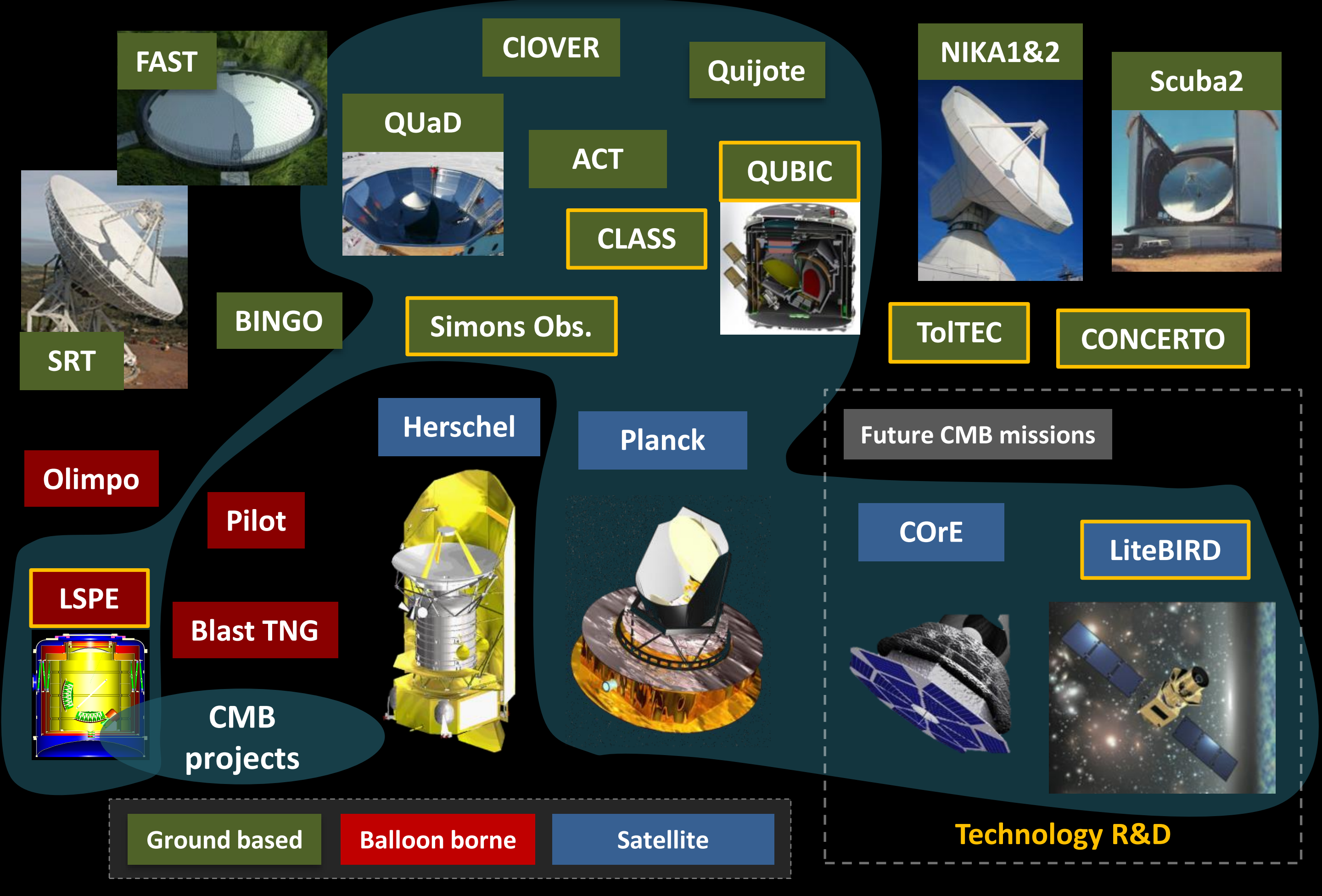
Giampaolo Pisano & **Carole Tucker** on behalf of

Gruppo di Cosmologia Sperimentale - Dipartimento di Fisica - Sapienza Università di Roma

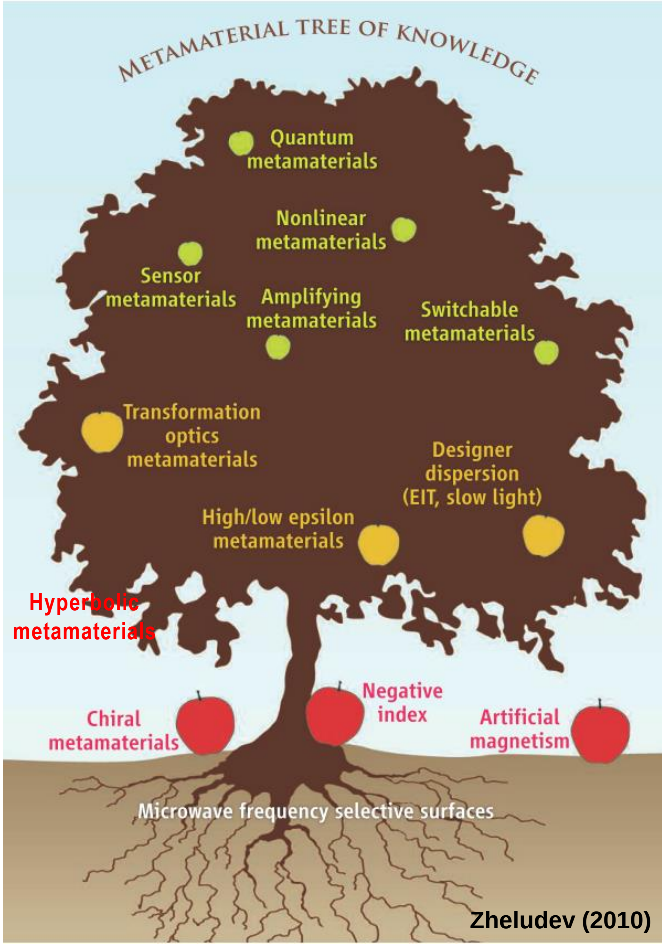
Astronomy Instrumentation Group - School of Physics & Astronomy - Cardiff University

CMB Day 2 - Agenzia Spaziale Italiana (ASI) - Roma, 17th October 2023

Development of instrumentation for mm and sub-mm astronomy



Why metamaterials? Where are we on the Metamaterial Tree ?



'Green' Metamaterials

Quantum metamaterials

- Array of split rings, magnetic field quantisation ??
- Array of SQUIDs, KIDs (meta-atoms) ??

Switchable/Tunable metamaterials

- Quasi-optical intensity switches
- Quasi-optical phase switches
- Switchable retarders
- Nonlinear devices

'Less Mature' Metamaterials

Transformation optics

- GRIN lenses, mesh-lenses, mesh-lens arrays, mesh prisms

High/Low epsilon metamaterials

- High epsilon artificial dielectrics

'Mature' Metamaterials

Negative index

- Pancharatnam mesh half wave plates

Artificial magnetism

- Artificial Magnetic Conductors (AMCs)

Orbital Angular Momentum

- Dielectric Spiral Phase Plates (SPPs) & Q-Plates (QPs)

'Roots' - Frequency Selective Surfaces (FSSs)

Frequency selection

- Mesh filters, thermal blockers

Amplitude and polarisation division

- Beam splitters, polarisers, polarisation splitters

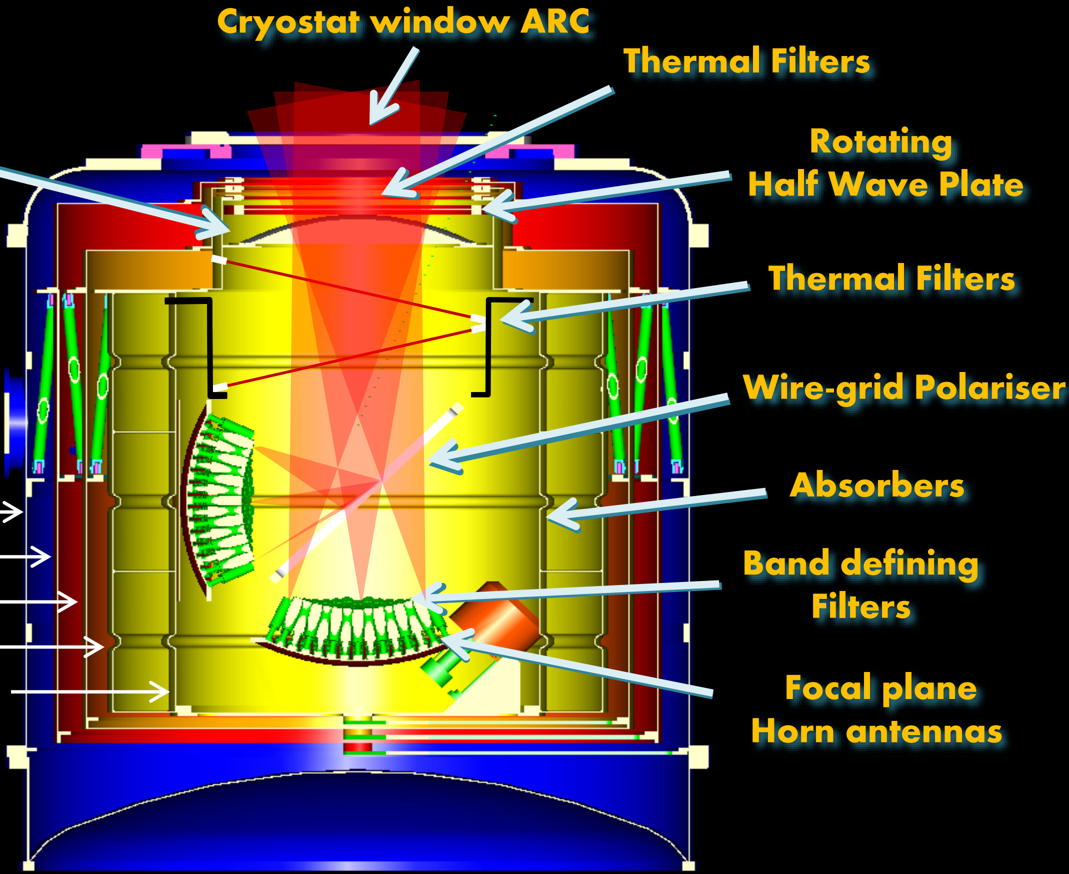
Retarders

- Mesh half wave plates, quarter wave plates

Summary

- Metamaterials for mm-wave telescopes
- More exotic metamaterial components
- Metamaterial telescopes

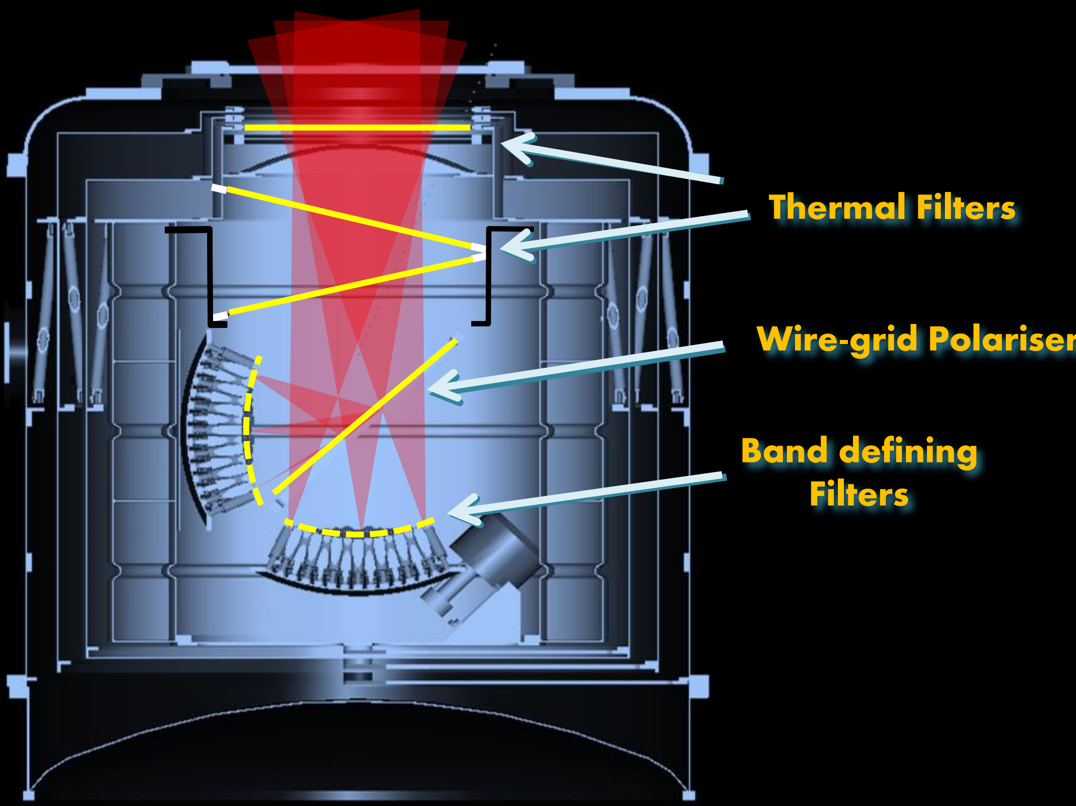
CMB instrument example: SWIPE instrument on LSPE



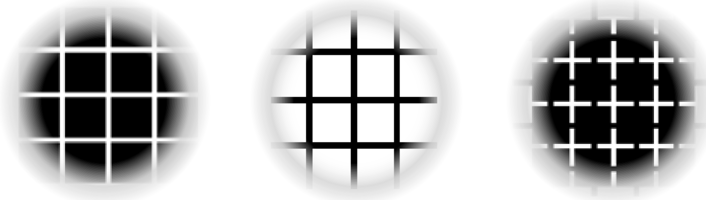
P. de Bernardis et al., *Proc. SPIE* **v.8452** (2012)

→ All the highlighted items can be realised with Metamaterials

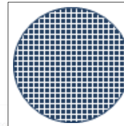
CMB instrument example: SWIPE instrument on LSPE



Spectral filtering: Mesh filters

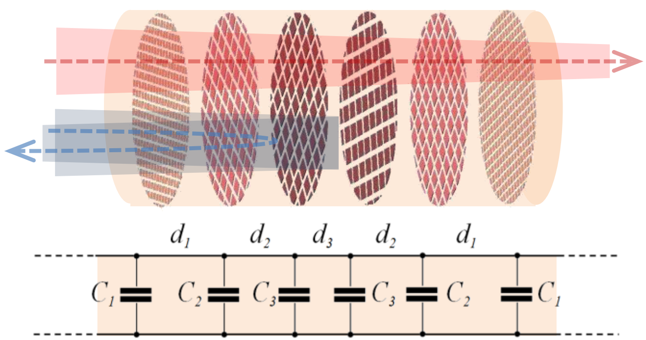


Capacitive	Inductive	Resonant
(Low-pass)	(High-pass)	(Band-pass)



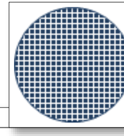
Homogeneous grids

Dielectrically Embedded multi-layer filters



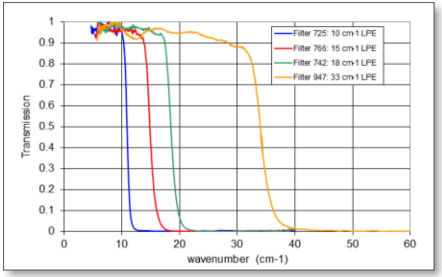
- Very robust and very light devices
- Can be cooled cryogenically
- Space qualified for small diameters (Cassini, Planck, Herschel, etc.)

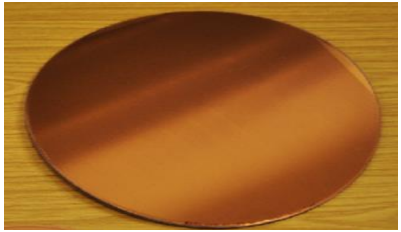
Mesh technology: Quasi-optical components

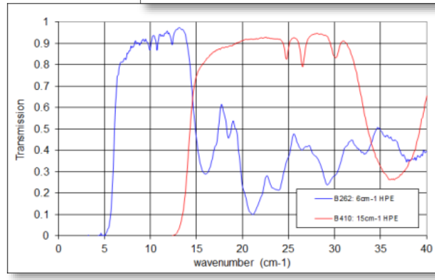


Homogeneous grids

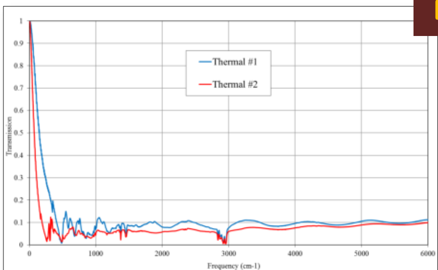
Band defining Filters

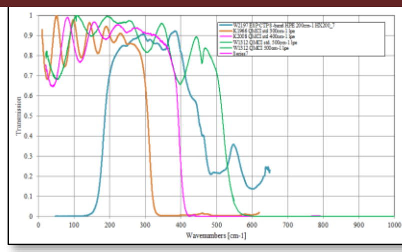


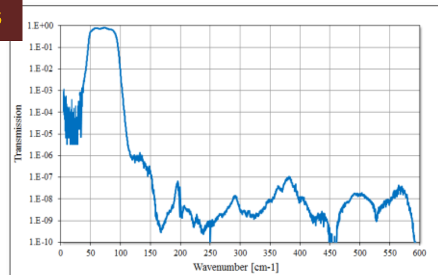




Blocking Filters and Filter Chains

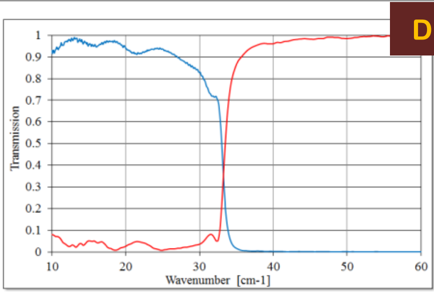


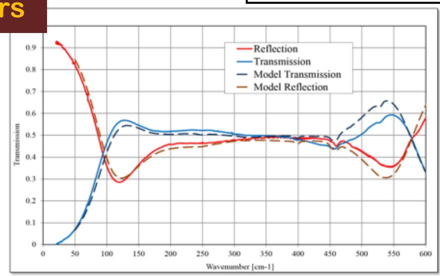




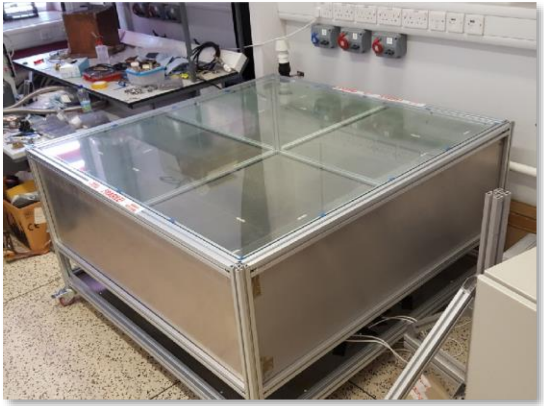
P. Ade, C. Tucker

Dichroics, Polarisers, Beam dividers





Mesh technology: Large diameter device manufacture facilities

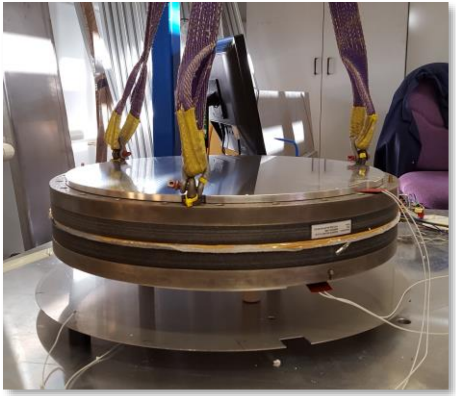


UV exposure box for photolithographic processes

Partially funded by esa

TRP
"Large radii HWP development"

Large hot-press oven



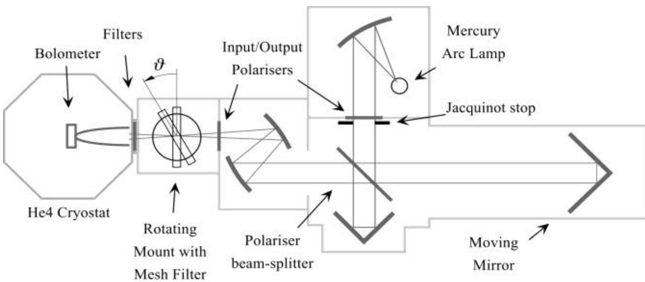
'50 cm' press plates

- **Large diameter mesh-devices development:**
  - **Cardiff - Rome MoU for R&D**
  - **Novel designs and testing @ Rome**
  - **Production of 50-80cm ∅ devices @ Cardiff**

Testing facilities: Coherent and incoherent sources

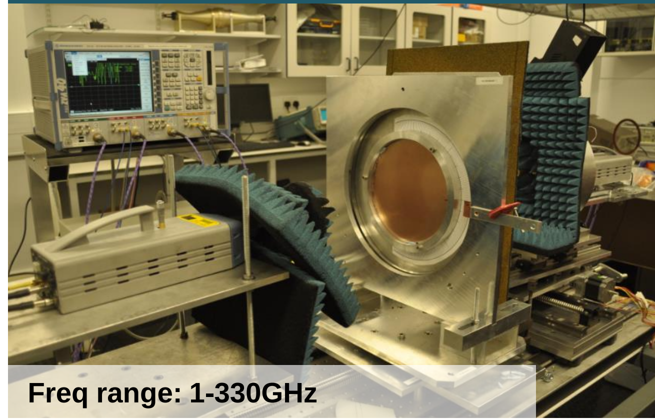
Fourier Transform Spectrometers (FTSs)

Martin-Puplett



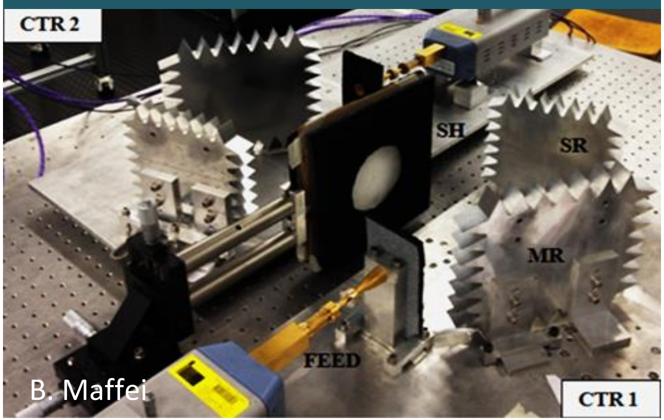
Freq range: 100GHz to many THz

Vector Network Analysers (VNAs)

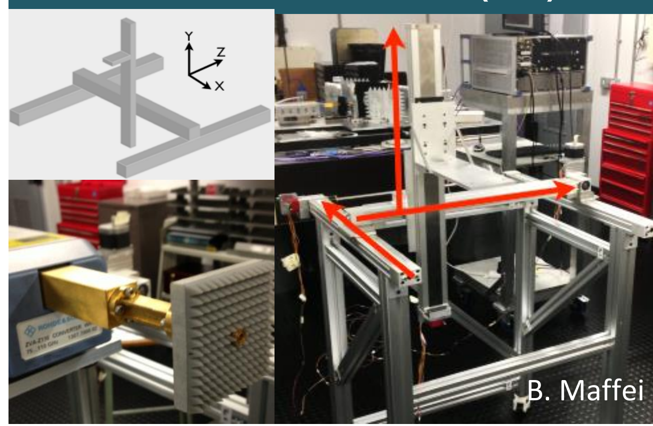


Freq range: 1-330GHz

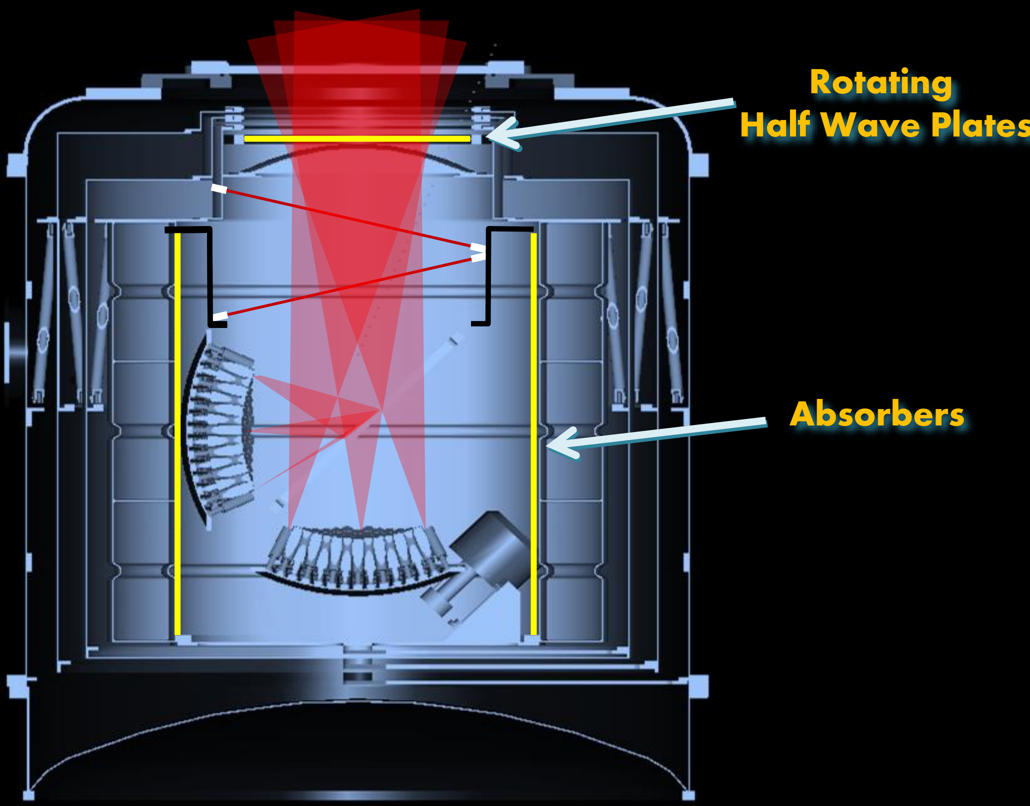
VNA free space S-parameters test bench



VNA near field 3D scanner (VNA)

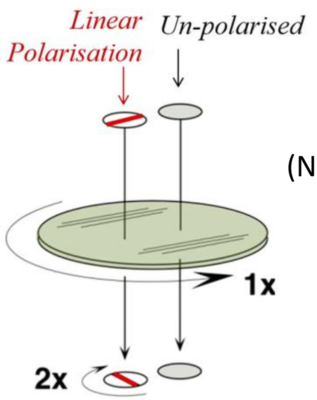


CMB instrument example: SWIPE instrument on LSPE



Polarisation modulators: Crystal-based HWP

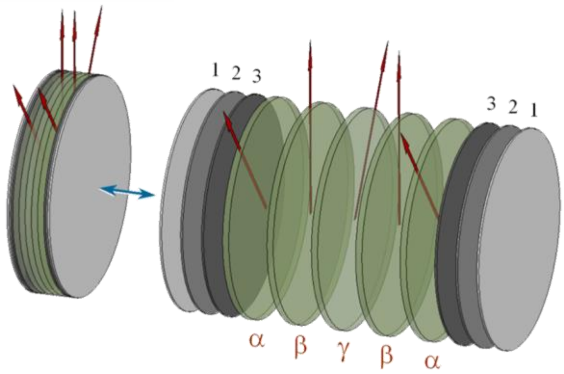
G. Pisano et al., Appl. Optics (2006)
G. Savini et al., Appl. Optics (2006)



Polarisation modulation

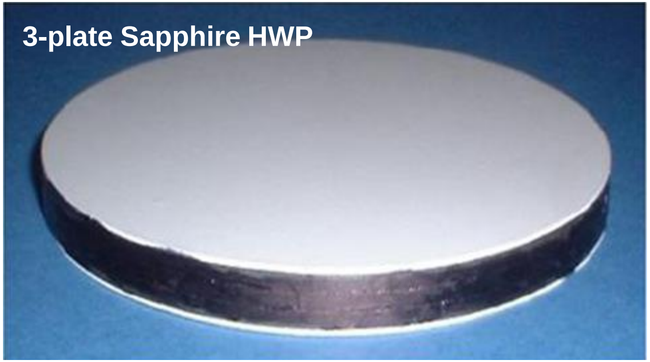
Single plate

(Narrow bandwidth)

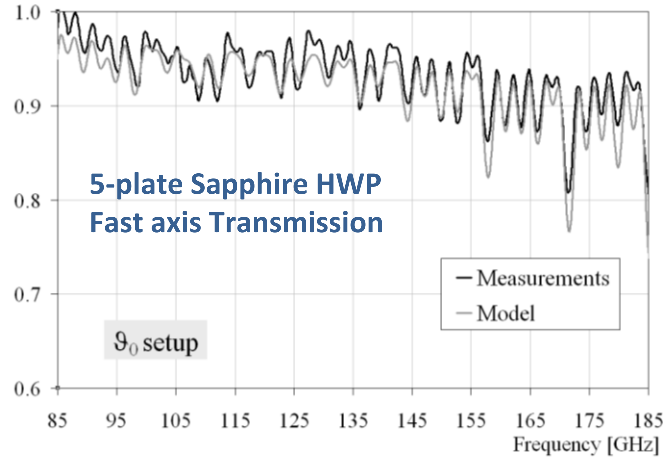


Pancharatnam multi-plate designs

(Large bandwidths)

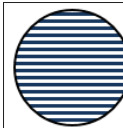


- **Challenging** development of **AR-coatings** operating at cryogenic temperatures

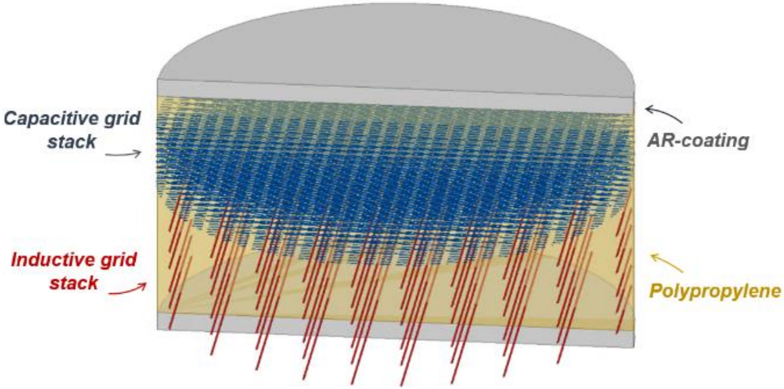


Polarisation modulators: Mesh HWP

G. Pisano et al
A&A (2022)

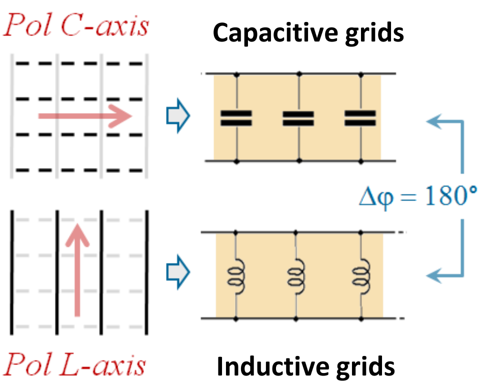


MHWP FEA model

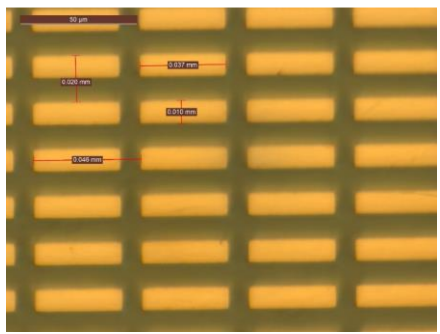


NIKA2 MHWP prototype
(~100 GHz - 300 GHz, 200mm ∅, 4mm, 120g)

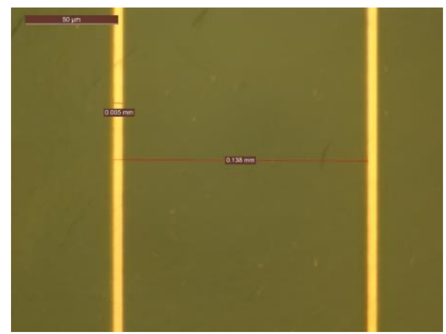
Blast TNG
(500 GHz - 1.4 THz)



Capacitive grid



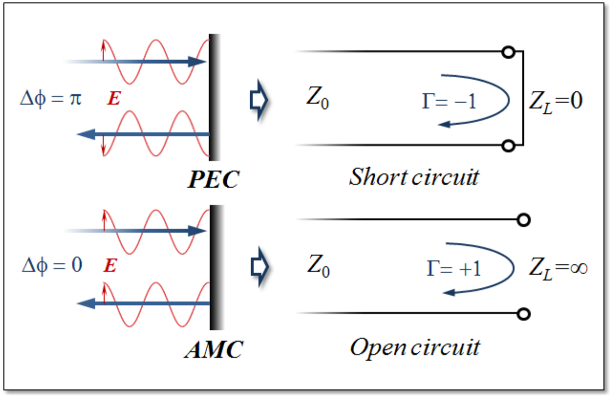
Inductive grid

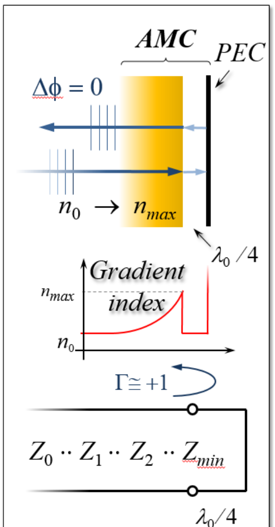


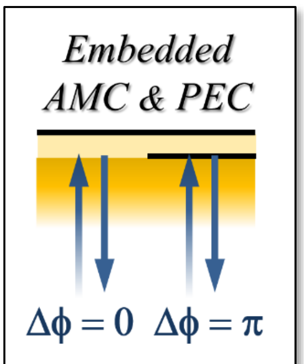
- Mesh-HWPs are the baseline design for the **LiteBIRD MFT** and **HFT** instruments - Funded by esa

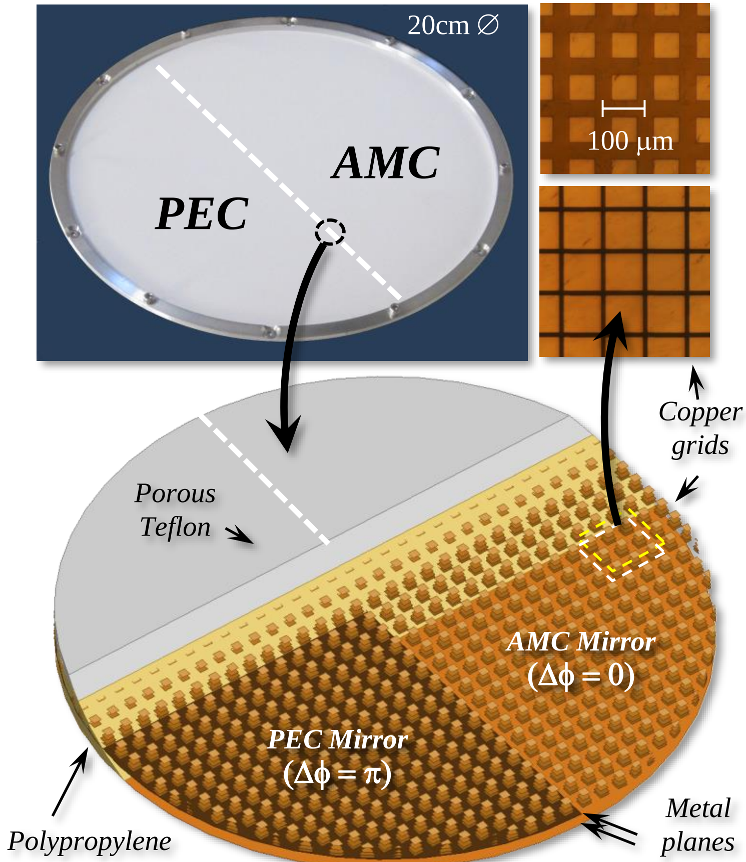
Artificial Magnetic Conductor: Design & realisation

G. Pisano et al.
Applied Optics (2016)



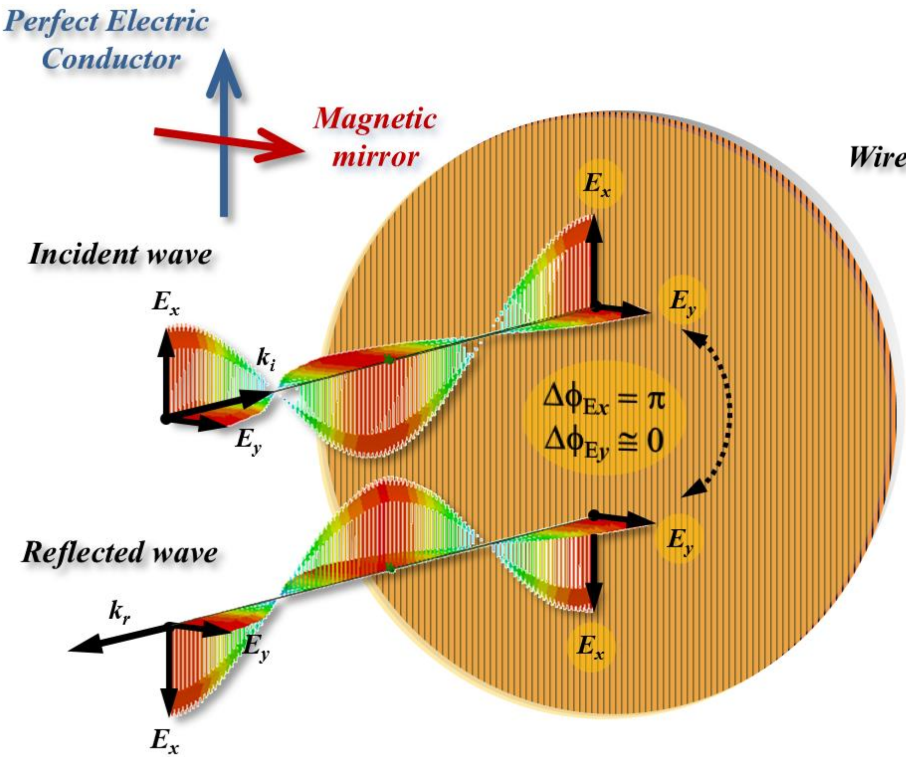


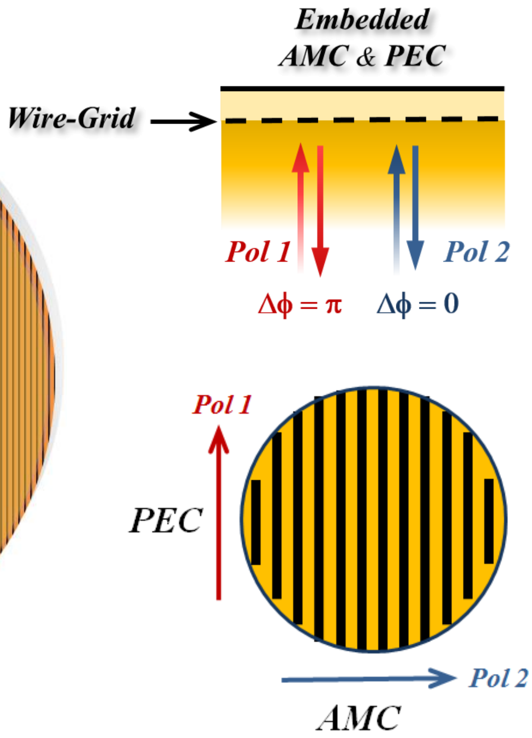




- Prototype with both **PEC** and **AMC** surfaces

Polarisation modulators: Embedded Reflective HWP

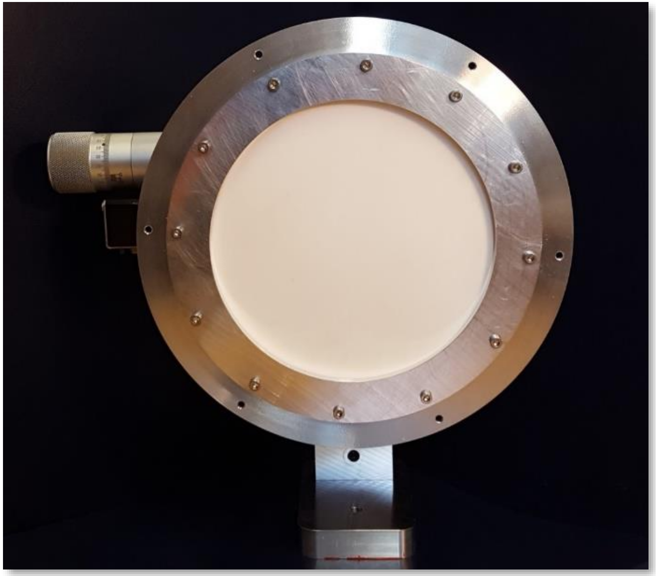


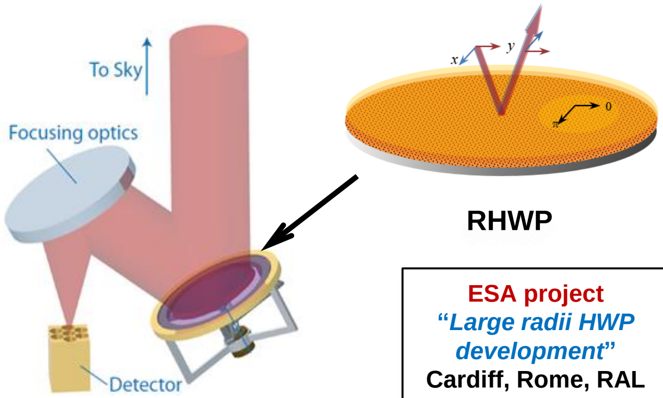


- Working principle based on artificial magnetic surface (AMC)
- Works off-axis up to more than 45°

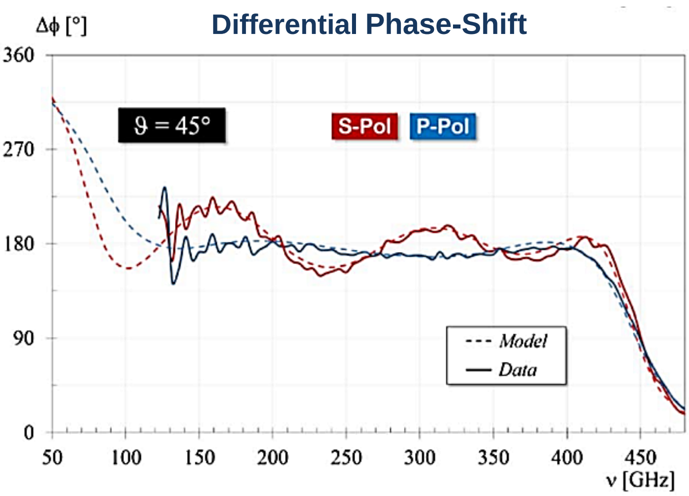
G.Pisano et al.
Applied Optics (2016)

Polarisation modulators: Embedded Reflective HWP





ESA project
"Large radii HWP development"
Cardiff, Rome, RAL

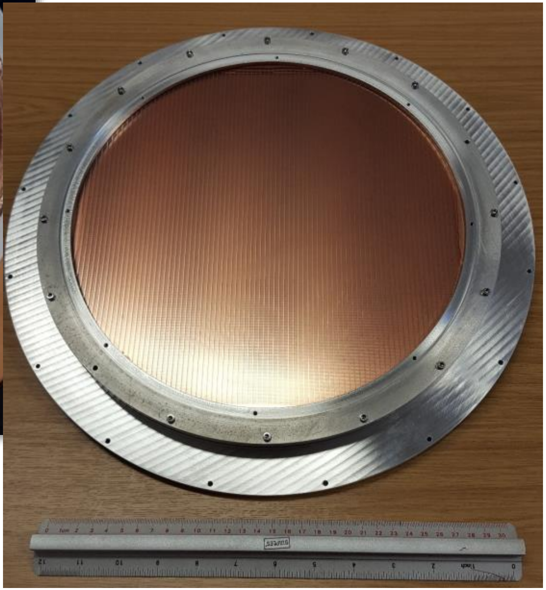


- Demonstrated bandwidth of **~4.5:1 ratio**
- Very large bandwidths achievable: **8:1 ratio** (3 octaves)
- Very thin device: **750 um**
- This was the original baseline for the **LiteBIRD MHFT** instrument

Large diameter Mesh HWPs: Device manufacture

- Large diameter devices manufactured at Cardiff

- **ER-HWP** devices: 450 mm & 650 mm Ø

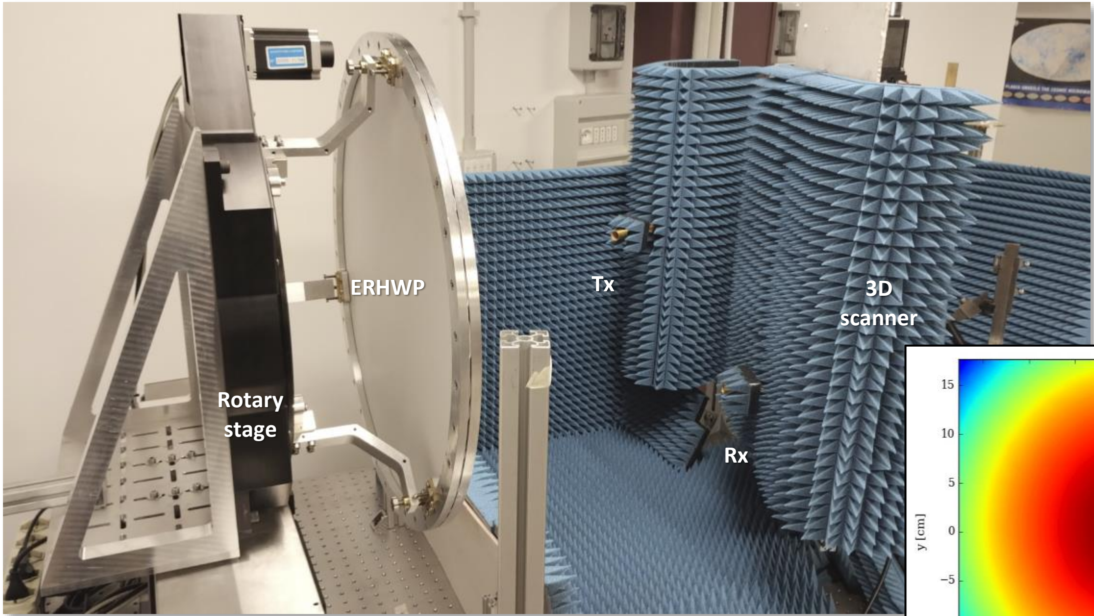


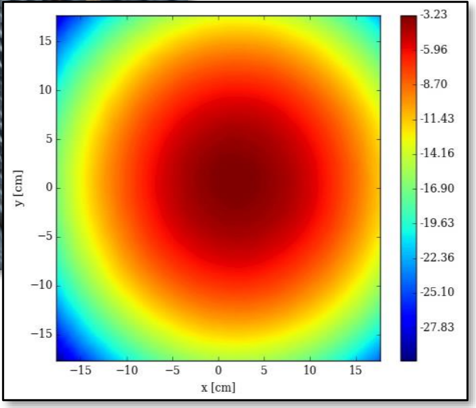
- **Mesh-QWP**: 300 mm Ø (CLASS)

Embedded Reflective HWP: RF characterisation

- **Ongoing tests on large diameter ER-HWP**

(Andrea Occhiuzzi)



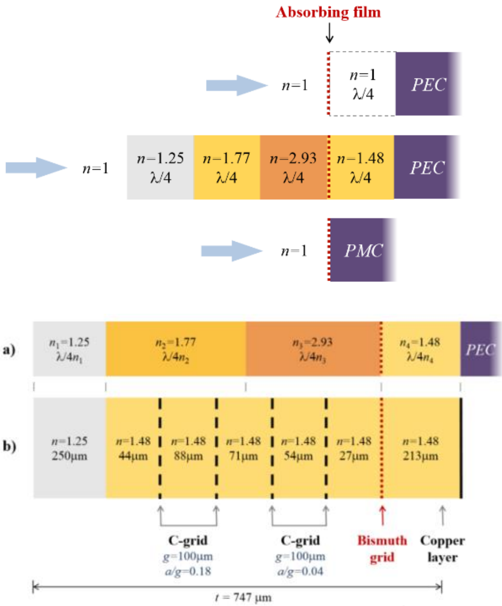


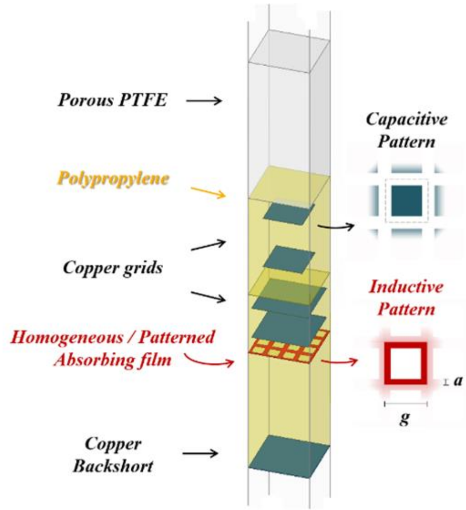
W-band corrugated horn co-polar beam reflection measurements off the ER-HWP back side

- **RF tests of 65 cm ∅ Embedded-Reflective-HWP**
  (90-450 GHz bandwidth)
- Acquiring **VNA** for tests between **20 - 500 GHz**
  (Ateneo Sapienza & ESA funds)

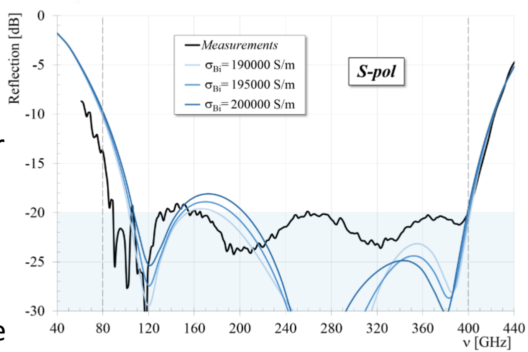
Radiation absorbers: Mesh-Absorber

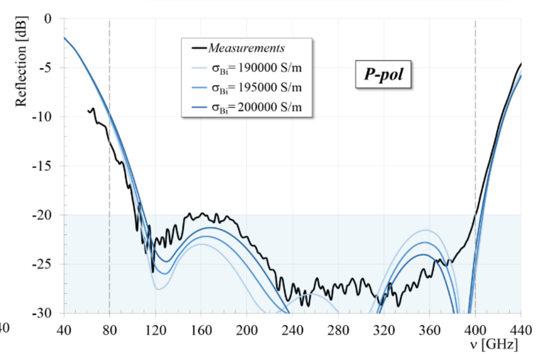
G. Pisano et al. *Appl Optics* (2023)



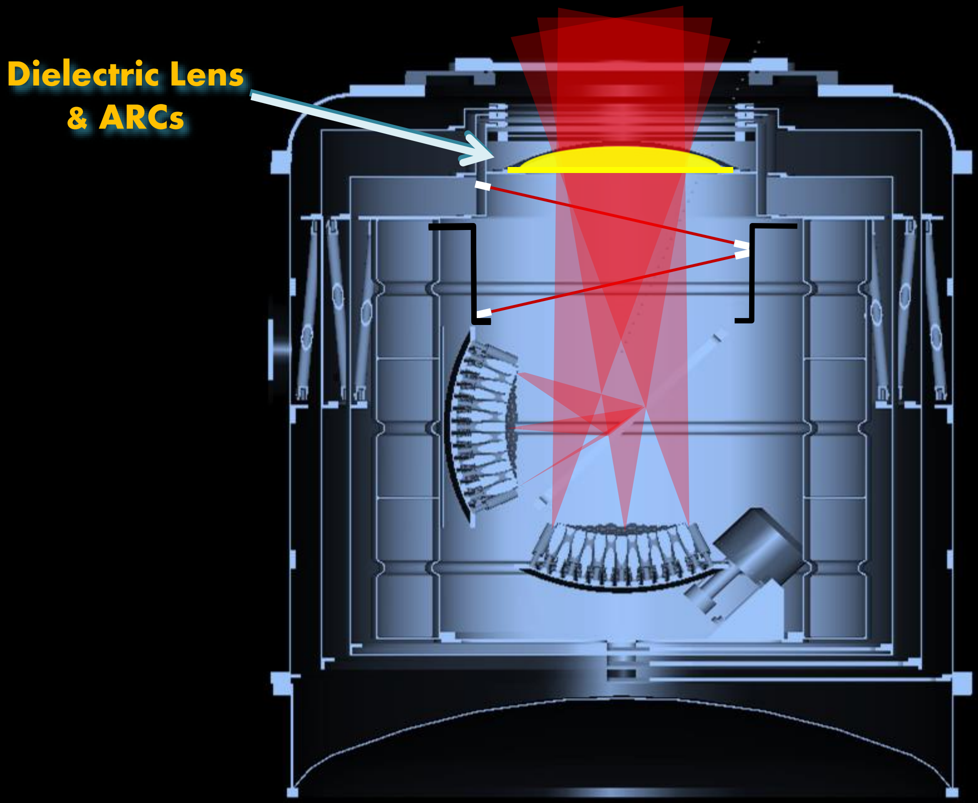


- Multi-octave thin absorber (0.75mm) working in the range **100-400 GHz**
- Thin device: **750 um**
- Good off-axis performance

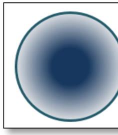


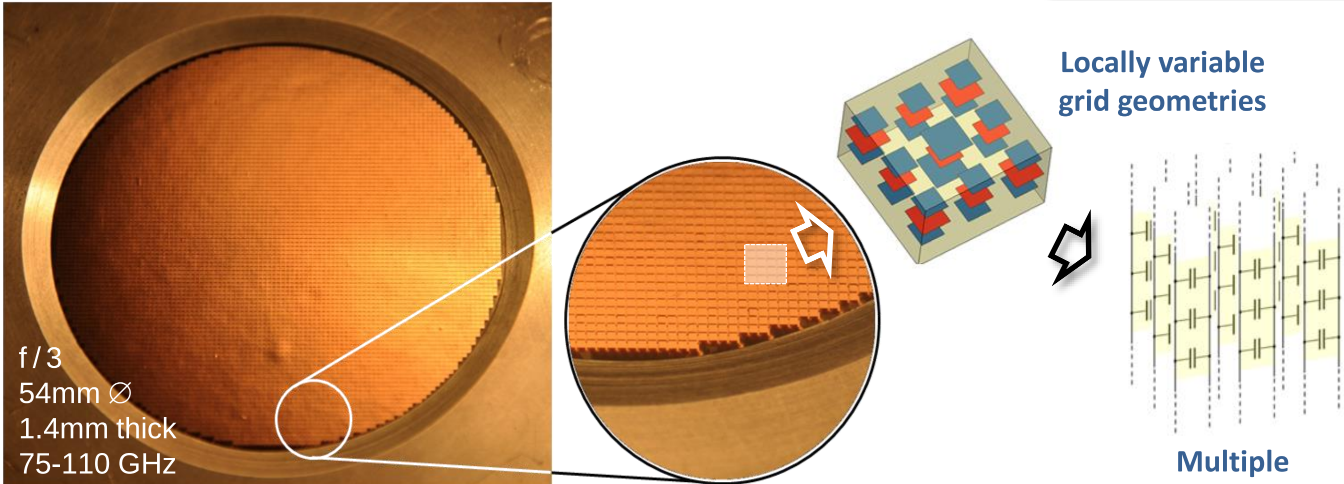


CMB instrument example: SWIPE instrument on LSPE



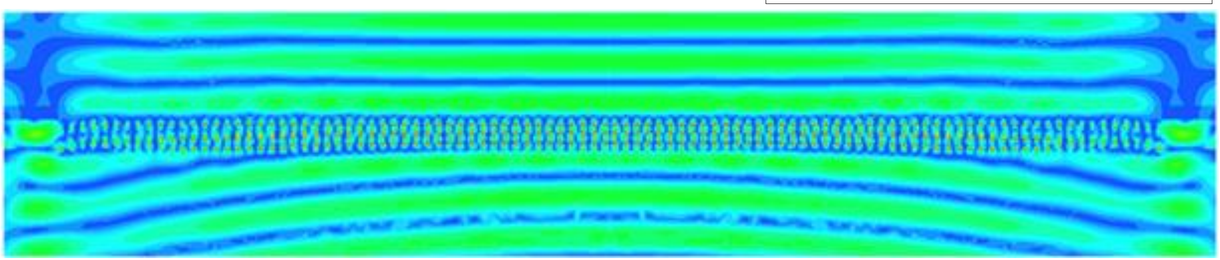
Mesh Lenses: Inhomogeneous phase delays





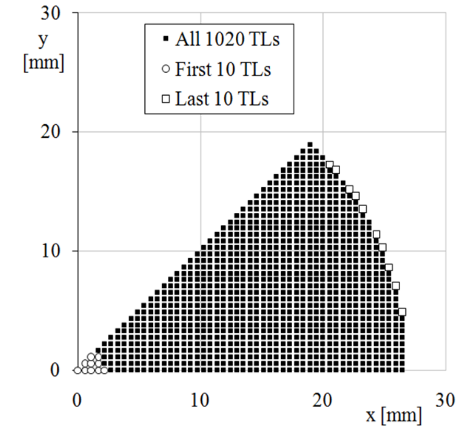
W-Band f/3 lens

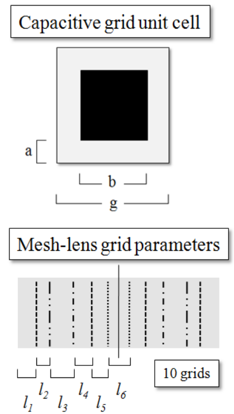
G. Pisano et al, *Applied Optics* (2013)



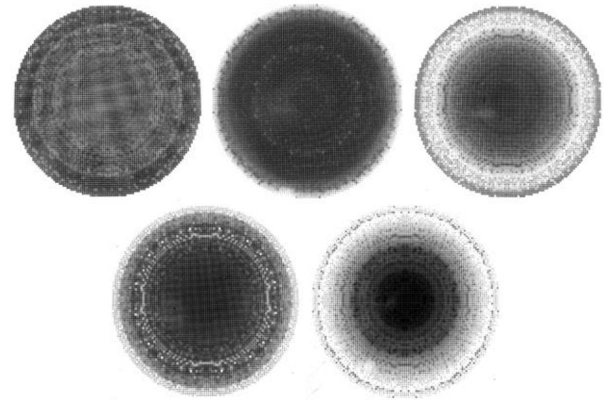
- Finite-element simulations showing the conversion of a spherical wavefront into a planar one

Mesh Lenses: Design and tests

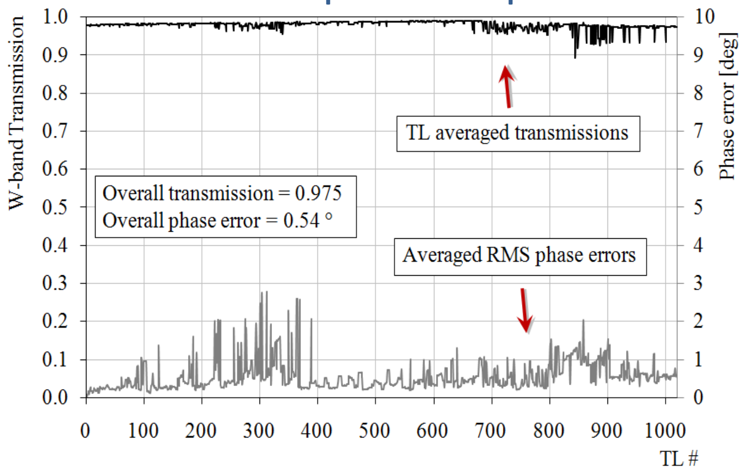




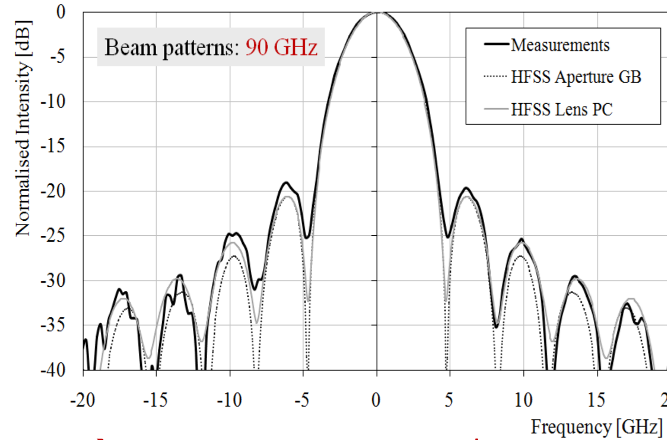
Optimised inhomogeneous grids



Transmissions & phase shifts optimisation



Beam measurements

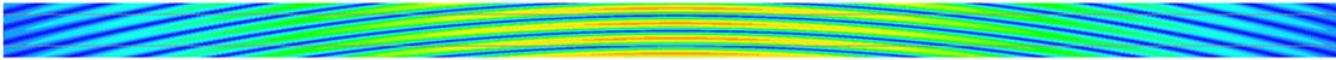


→ Agreement down to the 4th side lobes

Large diameter Mesh Lens: FEA simulations and mask example

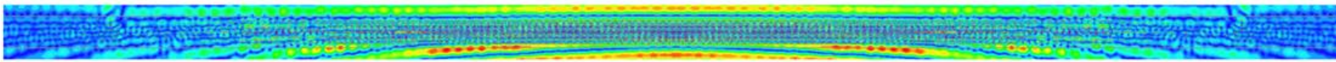
Mesh lens (Phase-delay type)

FEA simulation at 90 GHz



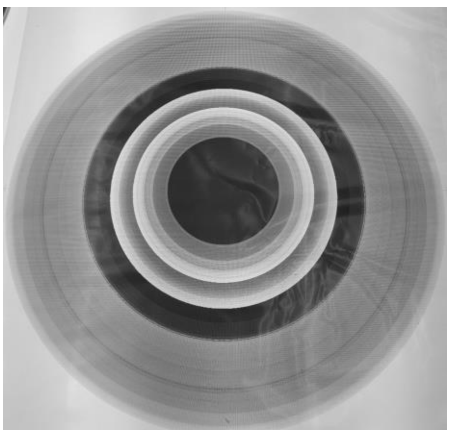
300mm ∅ - f/4 - ν_0= 125GHz

Incident fields ↑



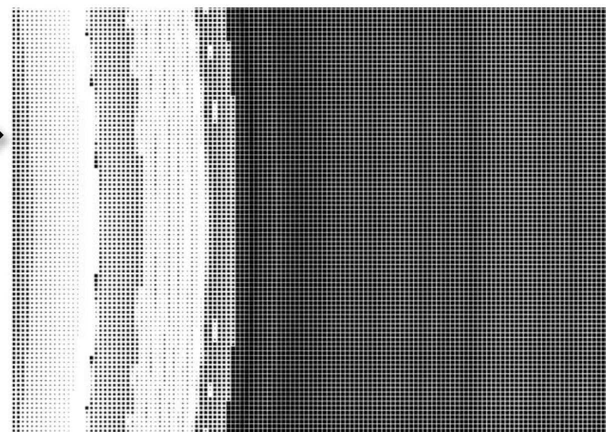
Fields with lens ↑

↑ **24 grids side view**



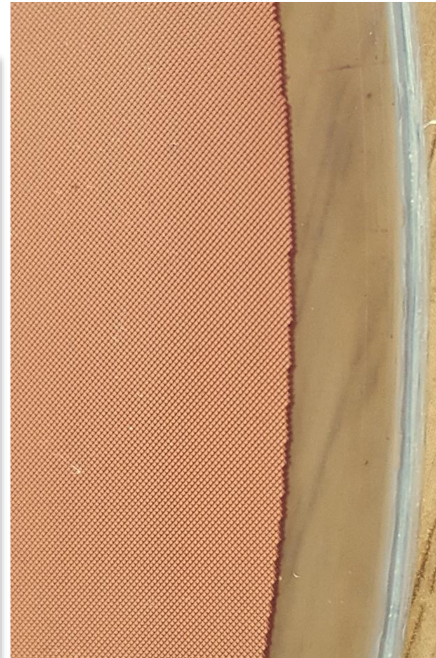
← **Mask example**

Pattern example →
~800k pixels
across surface



Large diameter Mesh Lens: Prototype

G. Pisano et al.
SPIE (2018)

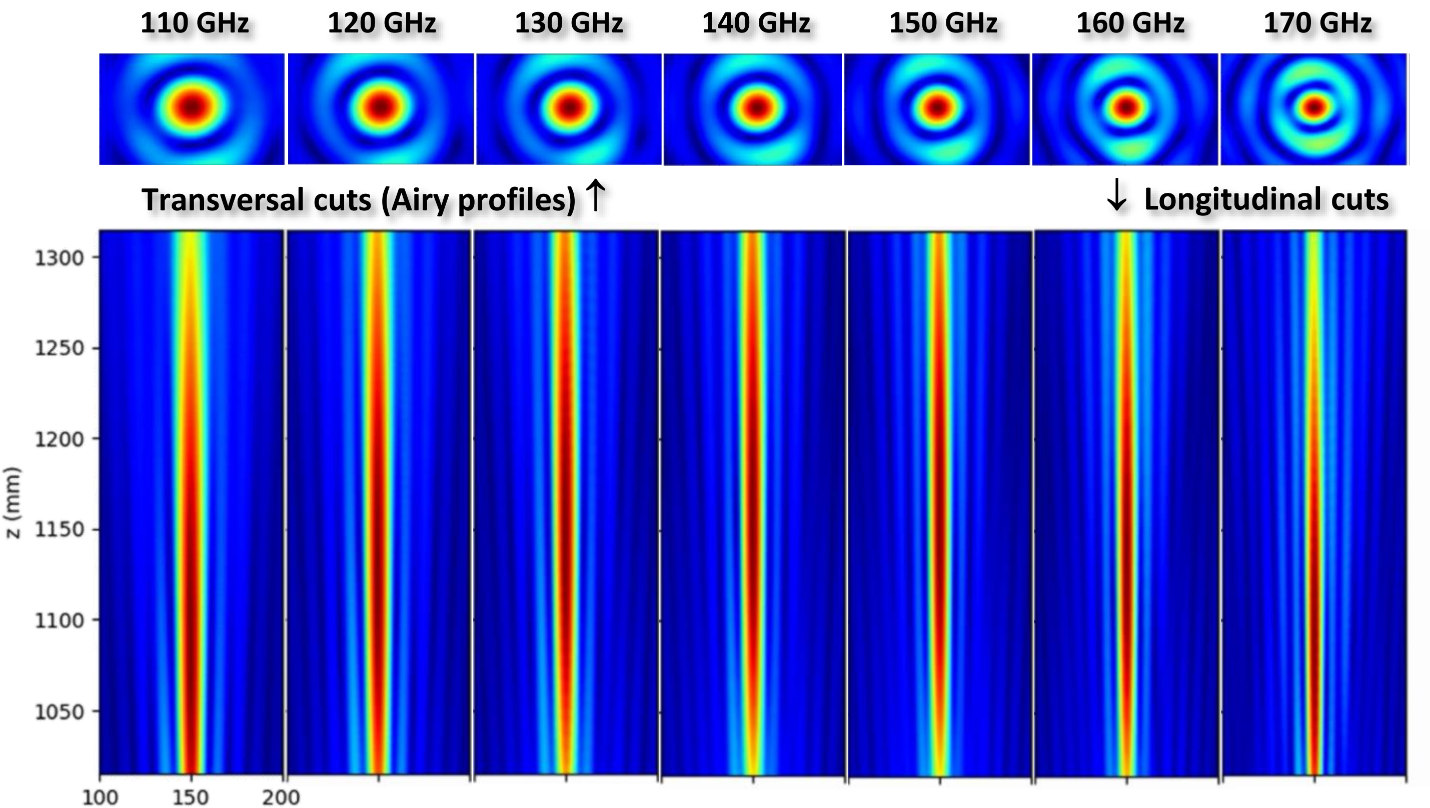


24-grid hot pressed grids (no ARC)

Details

- Diameter: 288 mm
- Thickness: 3.6 mm
- f-number: f/4
- Frequency range: 75-175 GHz
- Design: Phase-delay type

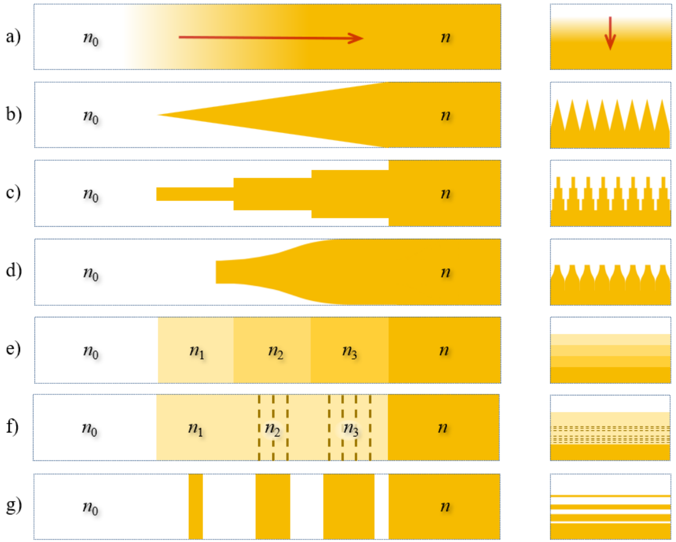
Large diameter Mesh Lens: Experimental characterisation (VNA)

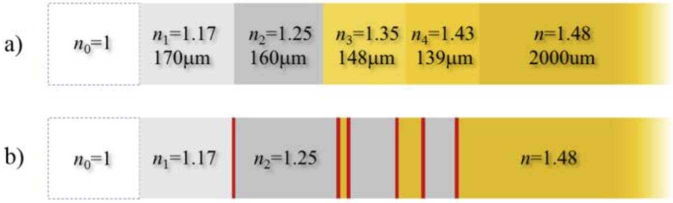


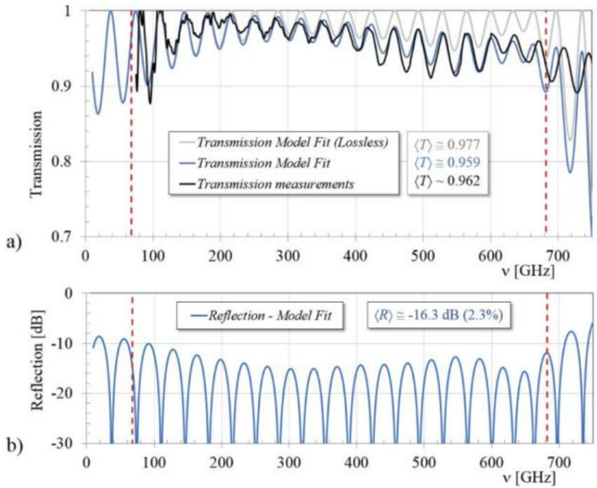
- The device **behaves like a lens across a large frequency range**
- The focus position moves slightly with the frequency

Anti Reflection Coatings: Multi-octave BW

Homogeneous layers



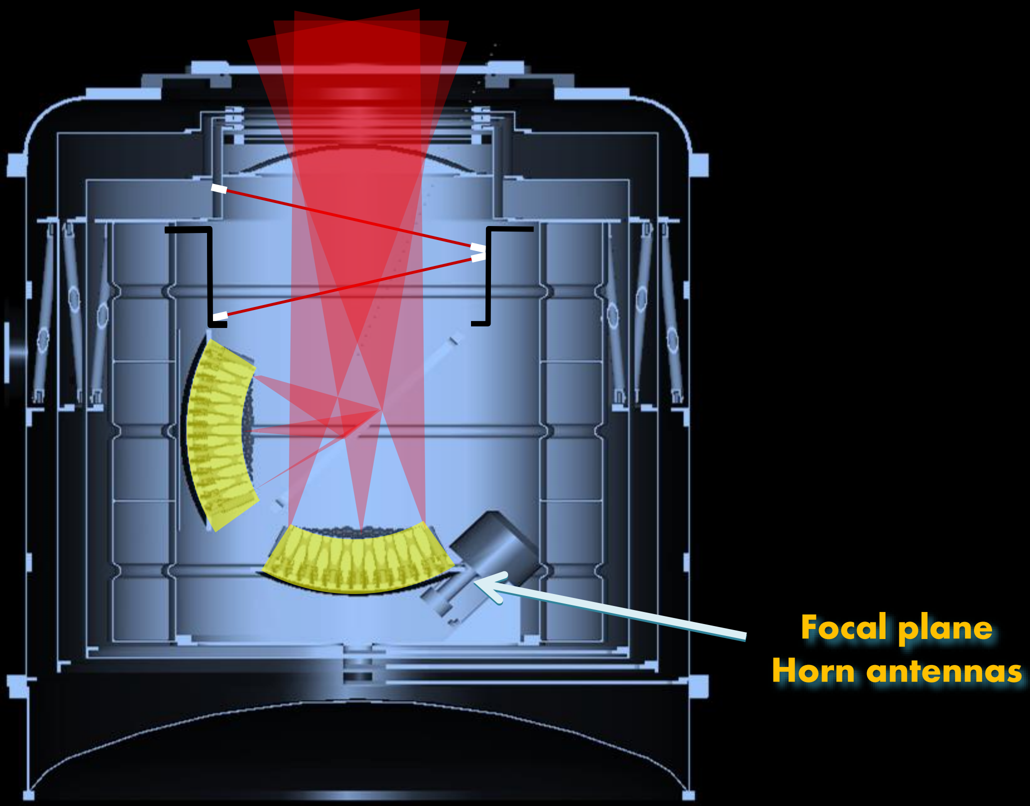




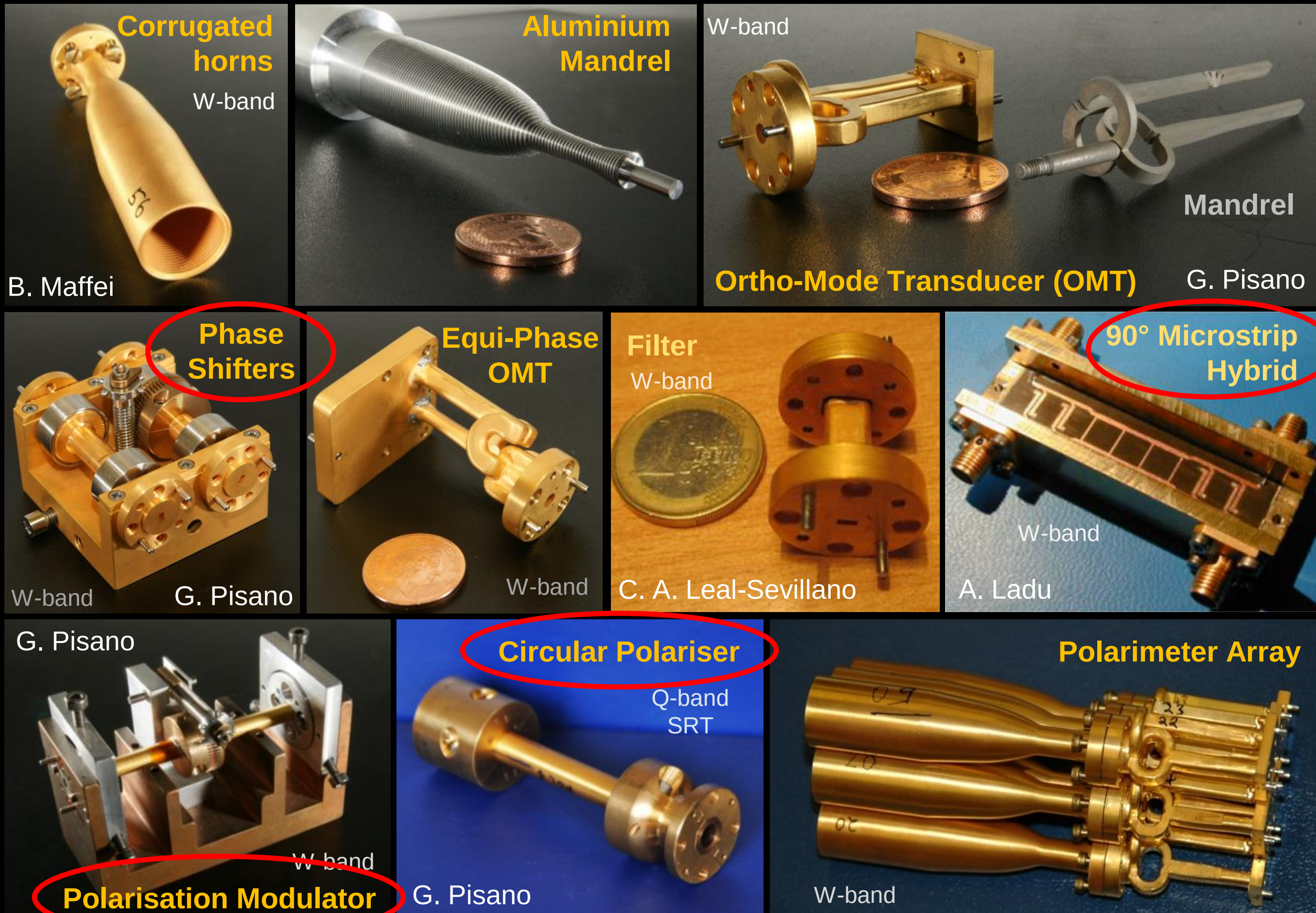
- We used this technique to design few-layer ARCs for the **LiteBIRD MHFT** PP lenses

G. Pisano et al. *Proc SPIE* (2018)

CMB instrument example: SWIPE instrument on LSPE

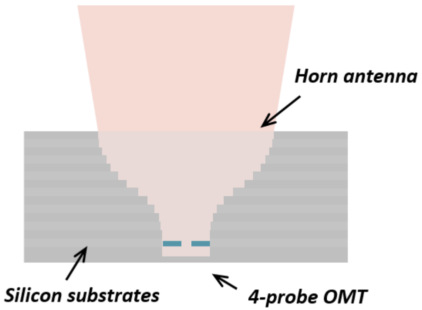


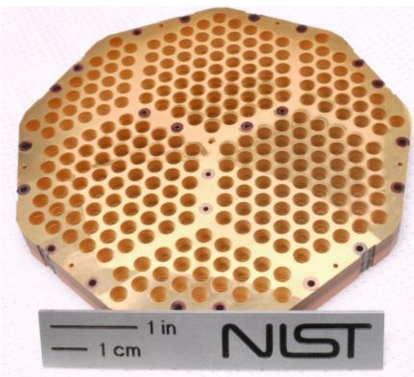
Focal plane developments: waveguide and planar components



Focal plane arrays: Available technologies

Si platelet feedhorn

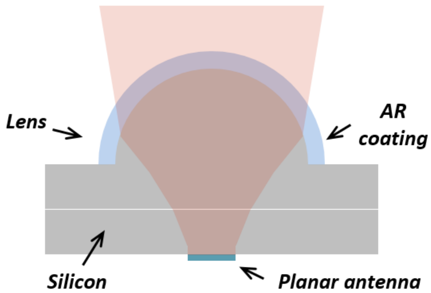




Si platelet feedhorn array

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

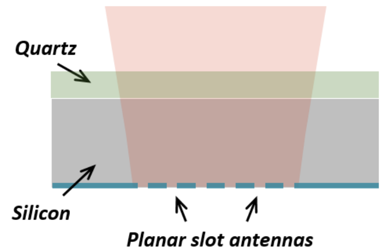
Si hemispherical lenslet

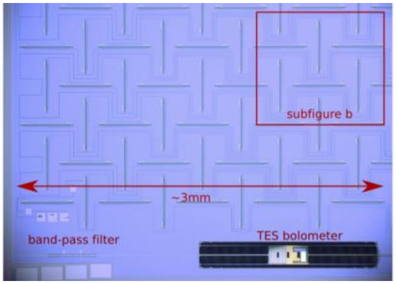


Si hemispherical lenslet array

Aritoki Suzuki et al. (2012)

Phase-array planar antennas

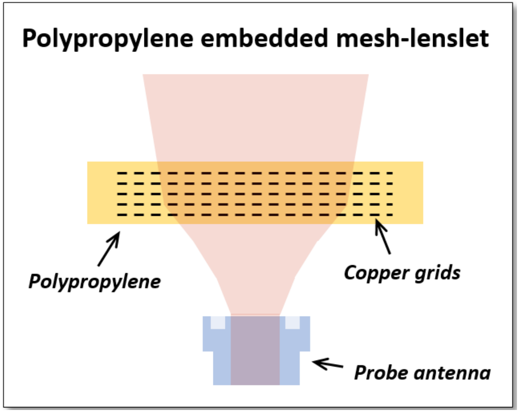




¼ detector element

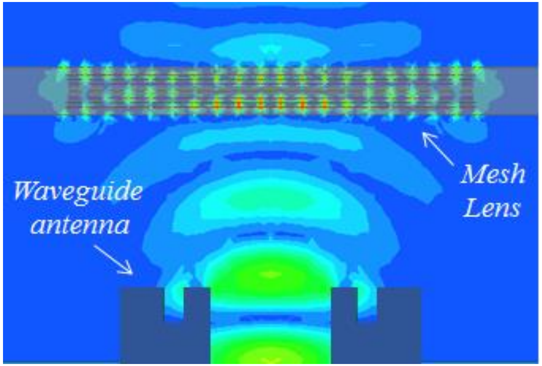
C. L. Kuo et al (2009)
R. C. O'Brient et al. (2012)

Polypropylene embedded mesh-lenslet: Design & tests



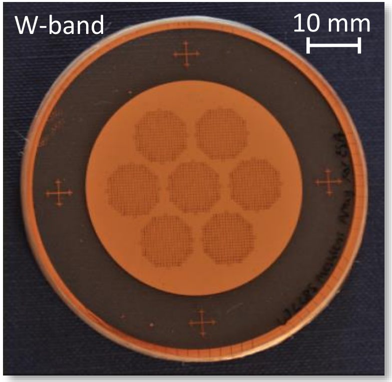
esa

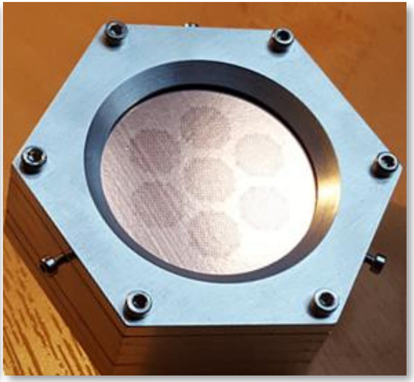
Maynooth (PI), Manchester, Cardiff, Rome, Paris APC & Chalmers



FEA simulation (HFSS)

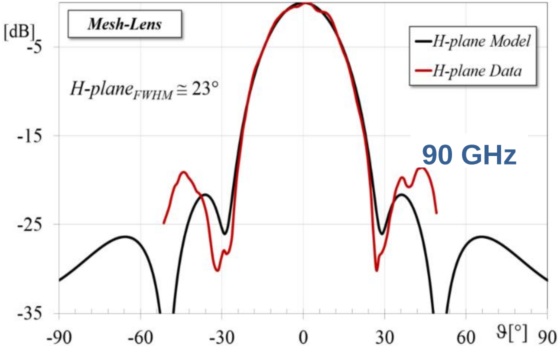
Working principle: Local 'transmission-line' phase-delays





PP mesh-lens array + cavities & probe antennas

Mesh Lens beam



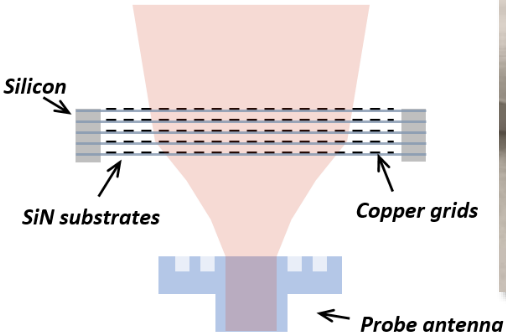
G. Pisano, IRMMW-THz (2016)

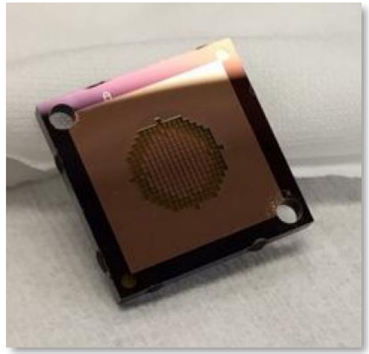
Si-based mesh-lenslet: Developments

PI

NASA | Boulder | NIST | Cardiff University / Prifysgol Caerdydd | Berkeley Lab

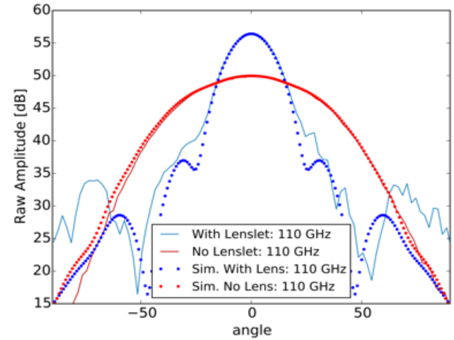
SiN air-gap mesh-lenslet





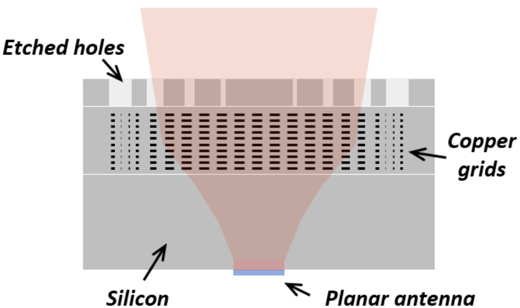
Single pixel prototype

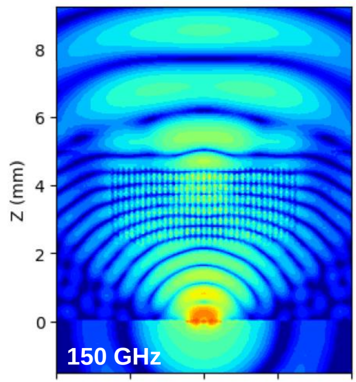
Antenna vs Lens beams



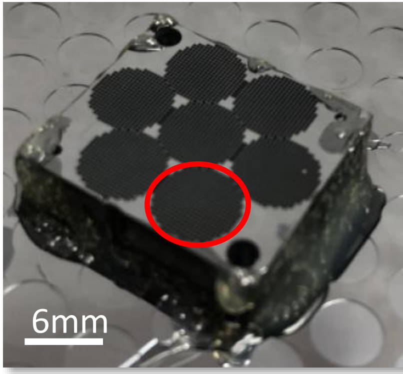
G. Pisano, JLTP (2019)

Si embedded mesh GRIN lenslet





FEA simulation



7-pixel array prototype

Summary

- Metamaterials for mm-wave telescopes
- ⇨ More exotic metamaterial components
- Metamaterial telescopes

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
- Artificial Magnetic Conductors (AMCs)
- Mesh Absorbers

… → More 'exotic' devices

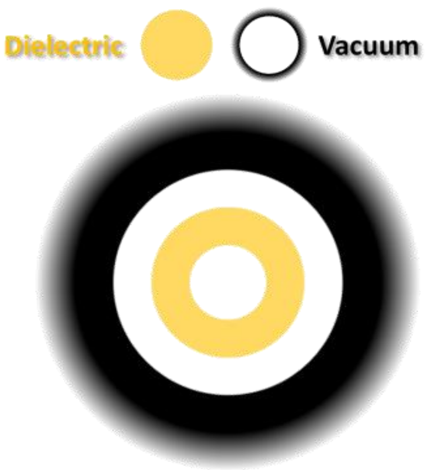
Dimensions

- 30, 50, 80 cm ∅ hot-pressed devices

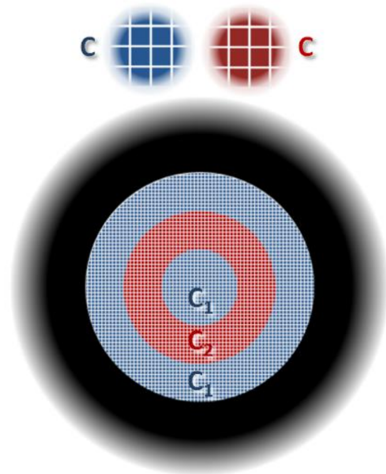
Metamaterial Toraldo Pupils: Different options

G. Pisano et al.
SPIE (2018)

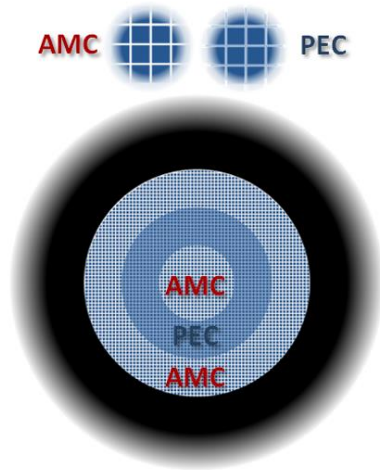
- The angular resolution of an optical imaging system can go beyond the classical diffraction limit (G. Toraldo di Francia, 1952)



Original design
(Dielectric rings)



Different capacitive filters
(Mesh-Lens)



PEC and AMC surfaces
(Reflective-HWP)

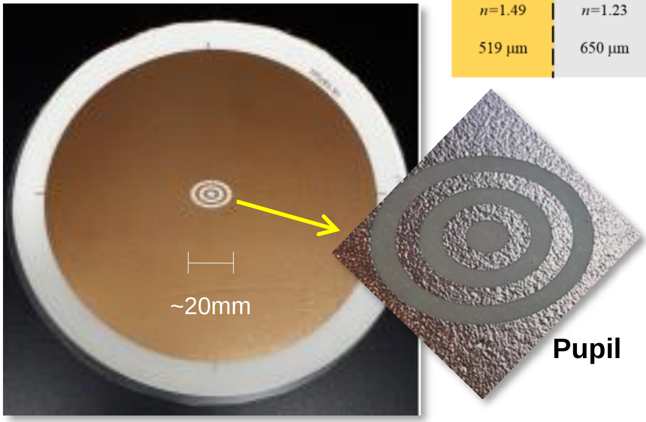
- We can introduce **180° phase-shifts** in different ways using metamaterials:

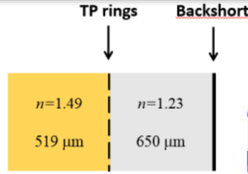
  - **The last two are flat devices produced with the same mesh-technology**

Toraldo Pupils: Reflective TP design and tests

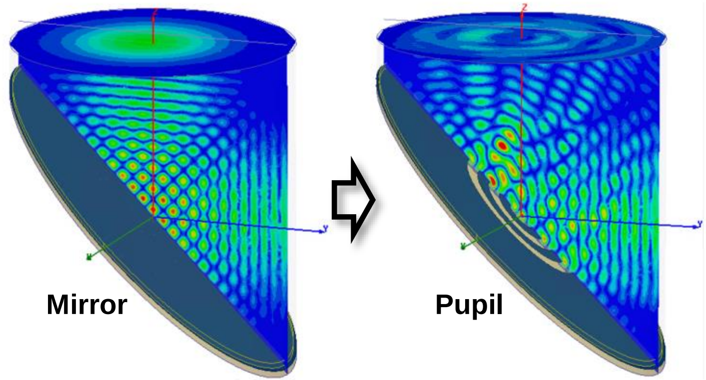
Cardiff University
INAF-OAA, Firenze
INAF-IRA, Medicina
ICVBC-CNR, Firenze
IFAC-CNR, Firenze
DIIN, Salerno
INAF-OAC, Cagliari
IAS, Paris

- AMC-based TP prototype

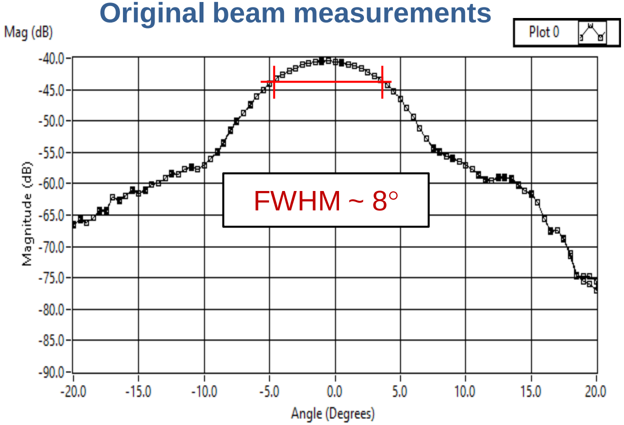




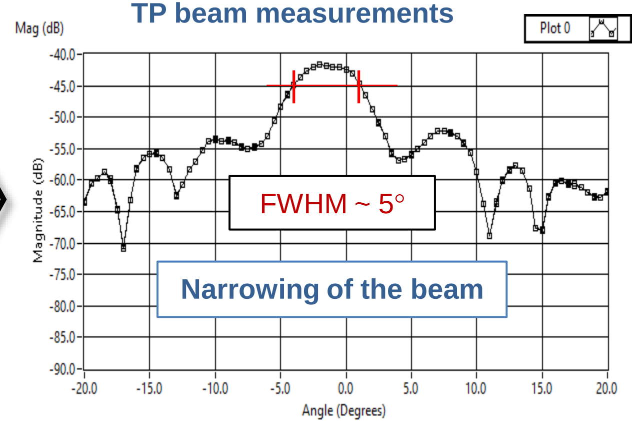
FEA modelling



Original beam measurements

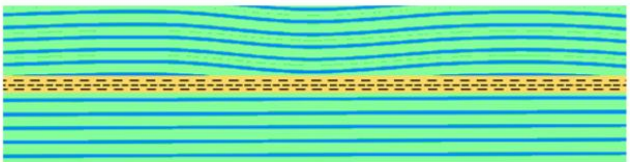


TP beam measurements

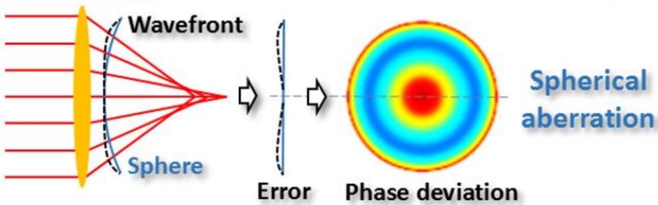


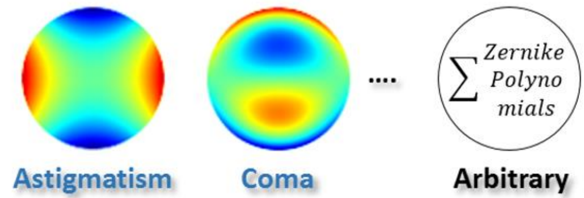
Optical systematics: Aberrations

Phase correcting surfaces (PC-Σ)



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





- Aberrations have specific associated wavefront distortion patterns that can be mathematically described using the Zernike polynomials

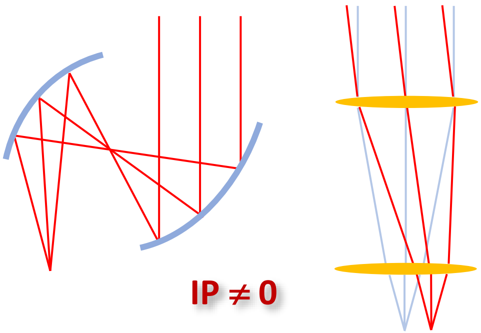
- We can experimentally quantify the phase errors by sampling the radiation wavefront

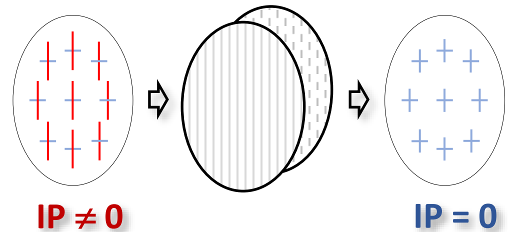
- The data will be a linear combination of different aberrations, including their frequency dependence

- With local arbitrary phase manipulations, we can design a **complex surface able correct and compensate those phase deviations**

Optical systematics: Instrumental Polarisation

Instrumental polarisation nulling surfaces (IP-Σ)



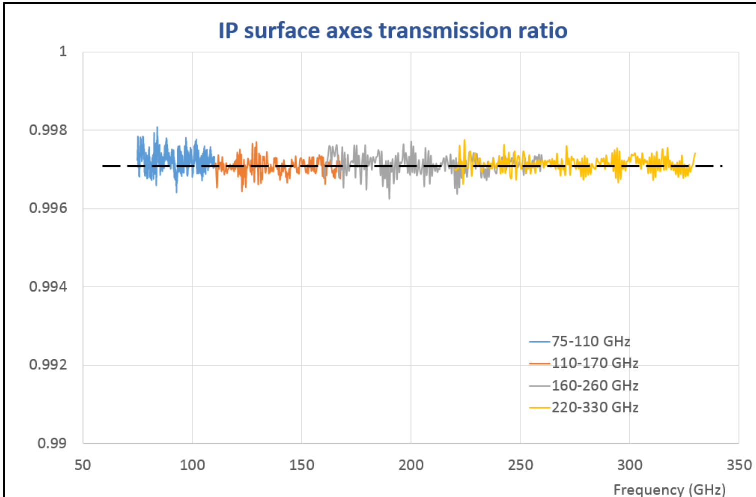


- IP can be mitigated at instrument level by adding a **slightly absorbing anisotropic surface**.

- **Instrumental polarisation (IP)** is generated in off-axis optical configurations

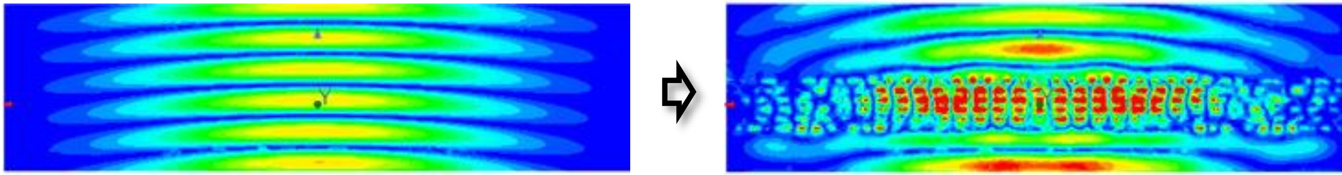
IP surface prototype tests →

(Designed to correct IP ~ 3×10^{-3})



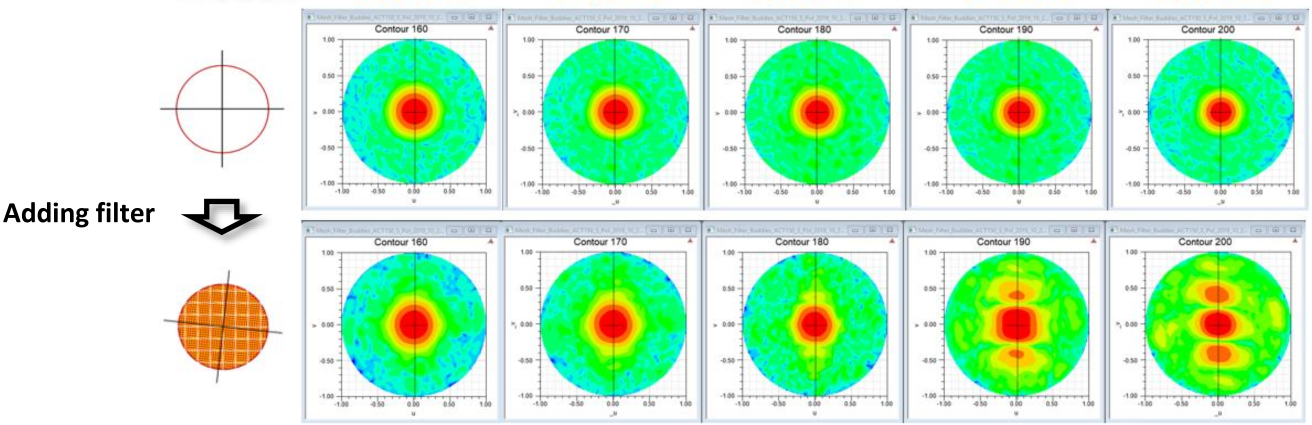
Optical systematics: Mesh-filters systematics

- **Perform 'critical' systematics studies:**
  - Mesh devices can introduce very subtle systematics
  - Instrumental polarisation, cross-polarisation, Wood's and Moirè pattern anomalies



Adding filter **FEA simulations**

Models 160 GHz 170GHz 180GHz 190GHz 200GHz



- **Theoretical** and **experimental** studies of impact on the beam

Summary

Metamaterials for mm-wave telescopes

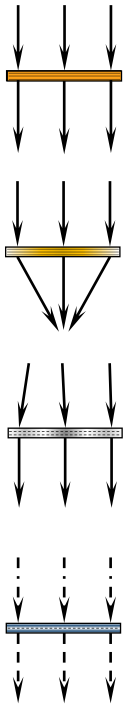
More exotic metamaterial components

Metamaterial telescopes

Metamaterial telescopes: Low systematics designs

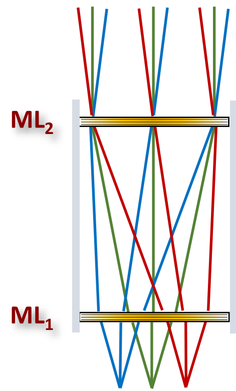
- In principle we could design and build metamaterial telescopes using a step-by-step design and test approach

Metamaterial devices



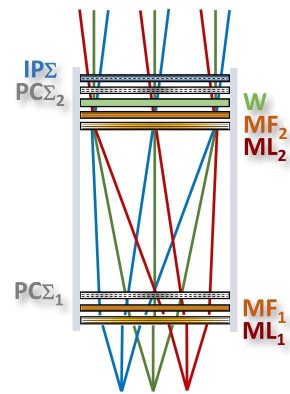
- Mesh Filters (MF)
- Flat mesh lenses (ML)
- Phase correcting surfaces (PCΣ)
- Instrumental polarisation surfaces (IPΣ)

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

Mesh devices with Silicon technology

- **Last decades**:
  - The **mesh**-technology has been very successful in providing passive **quasi-optical devices** for mm and sub-mm instrumentation, also for space applications.
  - Recent developments have led to large variety of **new exotic mesh devices**.

- **Today:**
  - In principle, it is possible to replace almost all the optical elements of a mm-wave telescope with mesh-devices and build "**metamaterial telescopes**".
  - The optical and polarization systematics of these systems could be studied and mitigated using additional **correcting surfaces**.

- **Near future**:
  - We would like to design to develop **tunable of quasi-optical components** able to switch their status electronically to avoid mechanical motion and allow general modulation of the radiation passing through them.
  - We should investigate the possibility to transfer our mesh-technology developments into the **Silicon technology**.
  - Not last, we seek to apply our techniques and our ideas to **other research fields**.

Grazie!