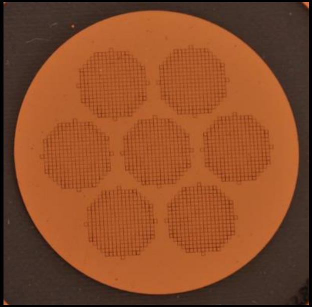
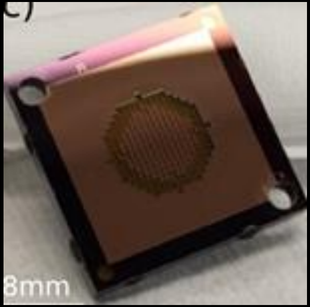
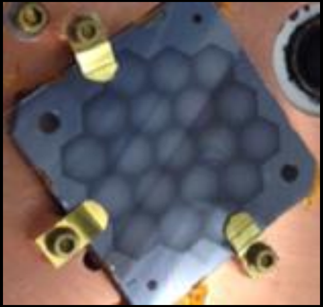
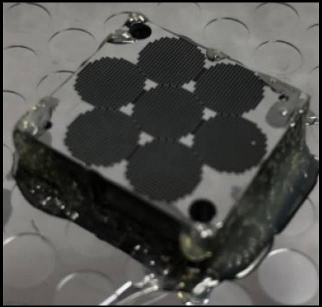
Development of flat Silicon-based mesh-lens arrays for millimetre and submillimetre wave astronomy









Giampaolo Pisano[1], Jay Austermann[2], James Beall[2], Nils Halverson[3], Johannes Hubmayr[2], Gregory Jaehnig[3], Christopher McKenney[3], Benjamin Raymond[3], Aritoki Suzuki[4]

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[2] National Institute of Standards and Technology
[3] University of Colorado - Boulder
[4] Lawrence Berkeley National Laboratory

Low Temperature Detectors, LTD-18, Milano, 24th July 2019

Millimetre and Sub-mm wave arrays: Context

Science:

- Cosmic Microwave Background (CMB) B-modes polarisation
- Next generation of CMB experiments will attempt to answer fascinating questions about fundamental physics and the Universe

Requirements:

- High sensitivities, large arrays of polarisation sensitive detectors
- Multichroic operation for polarised foreground removal
- Accurate control and knowledge of systematic effects

Current focal plane array coupling technologies:

- Silicon platelet horns
- Silicon hemispherical lenslets
- Antenna-coupled phased-arrays

(Require scalability, easy fabrication, large bandwidths,…)

Novel coupling solution (this work):

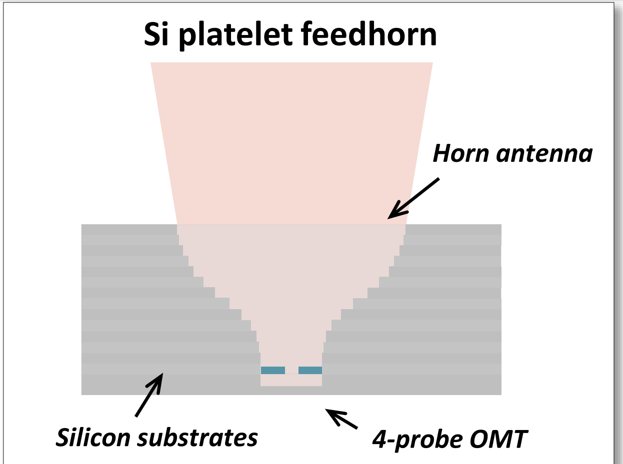
- Flat metamaterial lenslets

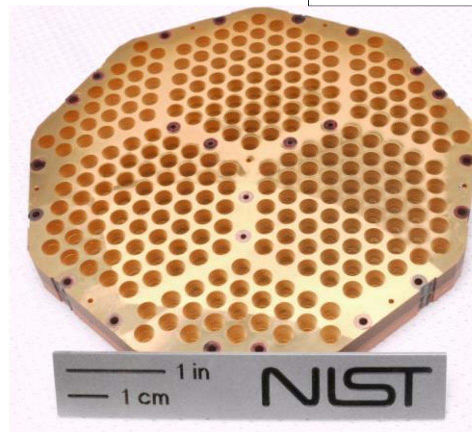
Summary

- Focal plane arrays coupling technologies
- Mesh-technology & mesh-lens array
- Silicon-based mesh-lenslet arrays
- Conclusions

Available technology: Silicon platelet horns

J. W. Britton et al. (2012)
J. P. Nibarger et al (2012)
J. Hubmayr et al (2015)





Si platelet feedhorn array

Working principle:

- Si platelet design of spline-profiled/corrugated horn antennas

Manufacture:

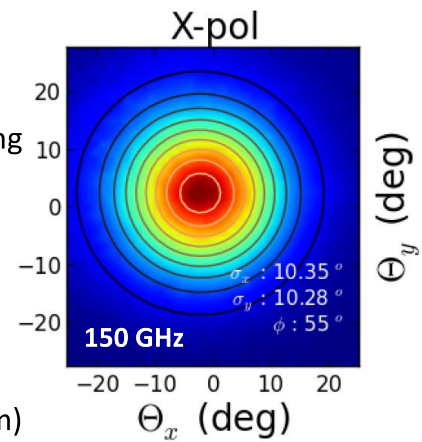
- Etching circular apertures on Silicon wafers, stacking and Cu/Au plating

Pros:

- Scalable, monolithic arrays (made 2k pixels), multi-chroic operation
- Accurate geometries achieved by photolithography
- High performance beams similar to electroformed horns
- Same thermal expansion of Si detector arrays
- Demonstrated in the field: **STP-Pol, ACT-Pol**

Cons: (~30-60, 254um)

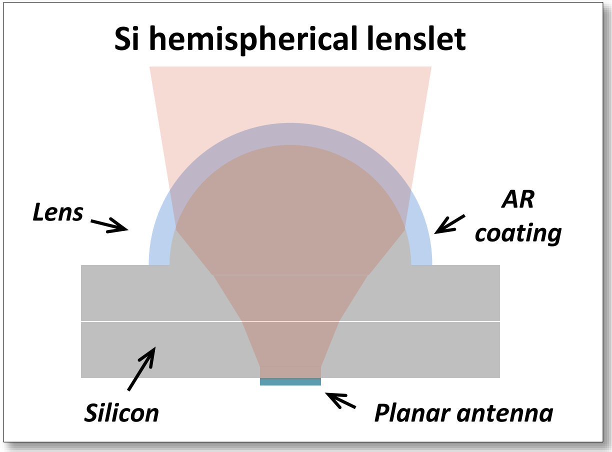
- Bandwidth limited by horn/OMT to ~80% (2.3:1); many layers required

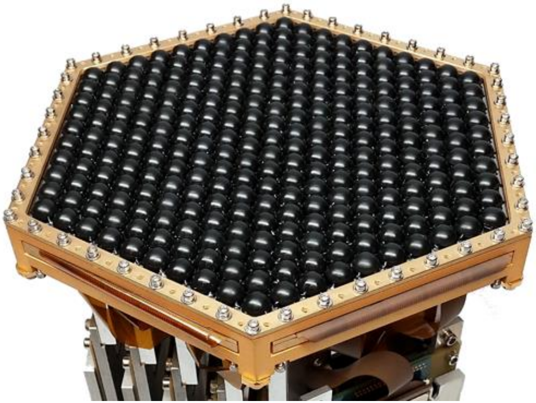


Beam tests example

Available technology: Hemispherical lenslets

Aritoki Suzuki et al. (2012)





Si hemispherical lenslet array

Working principle:

- Classical lens coupled to antenna (all within Silicon)

Manufacture:

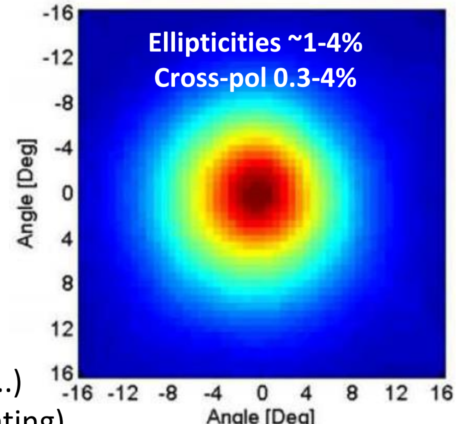
- Micromachined silicon lenses
- ARC manufactured using a mold then epoxied on the lens

Pros:

- Demonstrated tri-chroic operation with sinuous antennas
- Operated in the field: **POLARBEAR-1/2, SPT-3G, and DESHIMA**

Cons:

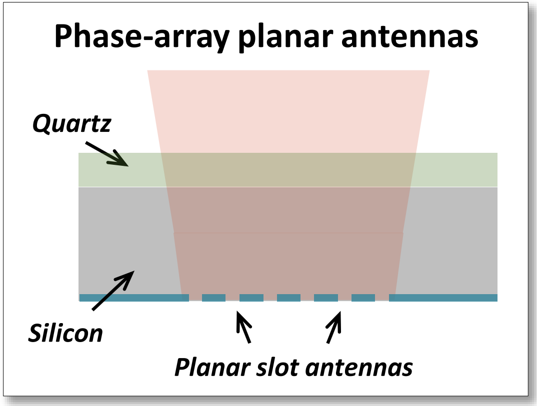
- Lenses produced individually then assembled (monolithic solutions..)
- CTE mismatch between 2-layer AR and Si lens (sometimes delaminating)
- Lower performance at high frequencies due to fabrication processes

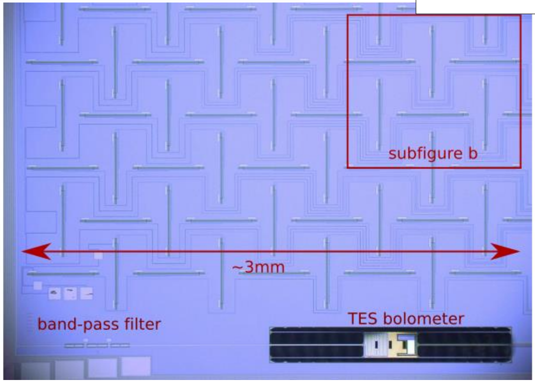


Beam tests example

Available technology: Phase-array antennas

C. L. Kuo et al (2009)
R. C. O'Brient et al. (2012)
P. Ade et al. (2015)





One quarter of detector element

Working principle:

- Synthesised beam with coherently fed slot-antennas
- Signals combined with T-junctions into a microstrip

Manufacture:

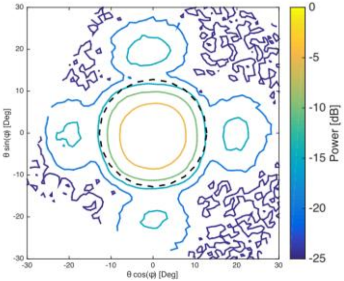
- All antennas fabricated via photolithographic processes
- Antennas as slots in superconducting Nb film, dual polarisation

Pros:

- Optics integrated with filters and detectors (no horns/lenses)
- Operated in the field: **BICEP, Keck Array, SPIDER**

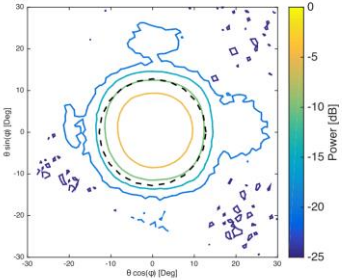
Cons:

- Beam side-lobe levels require controlled 4K aperture stop
- The antenna bandwidth limited to 30% by microstrip circuitry
- End-to-end optical efficiency ~40%



Beam tests with uniform illumination

Beam tests Gaussian illuminatior



Summary

- Focal plane arrays coupling technologies
- Mesh-technology & Mesh-lens array
- Silicon-based mesh-lenslet arrays
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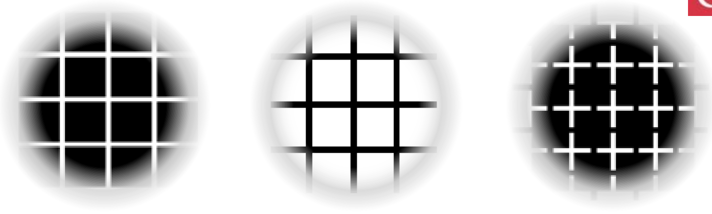
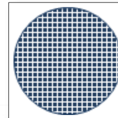
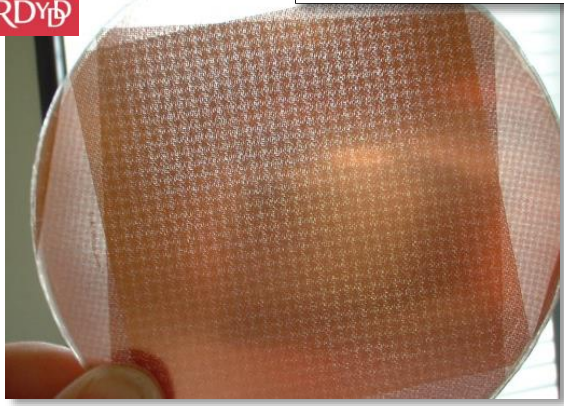
Spectral filtering: Mesh filters



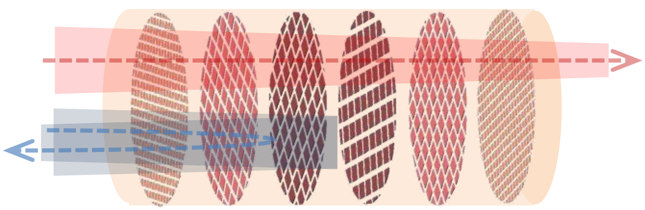
Capacitive (Low-pass) | **Inductive** (High-pass) | **Resonant** (Band-pass)

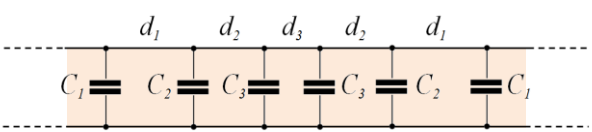


Homogeneous grids

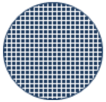


Dielectrically Embedded multi-layer filters



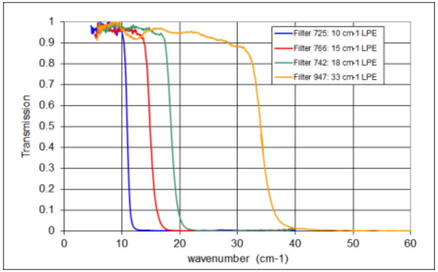


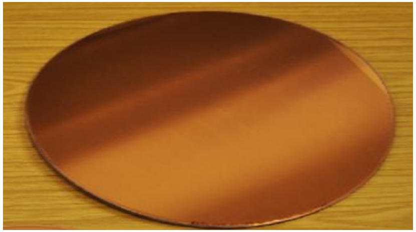
Mesh technology: QO components

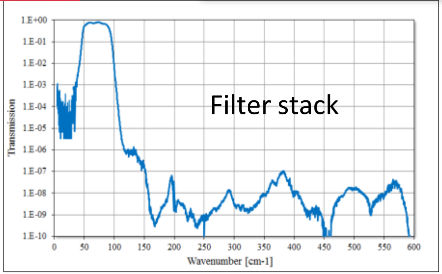


Homogeneous grids

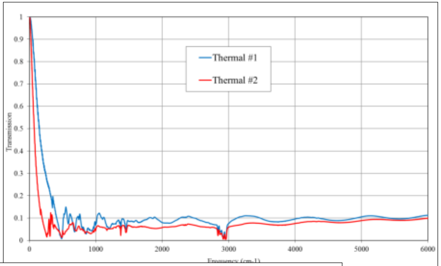
Band-defining Filters

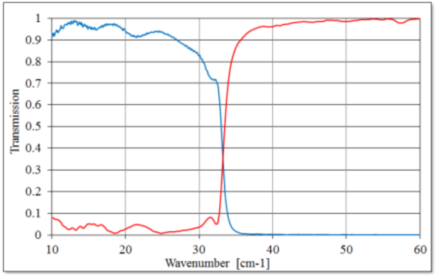






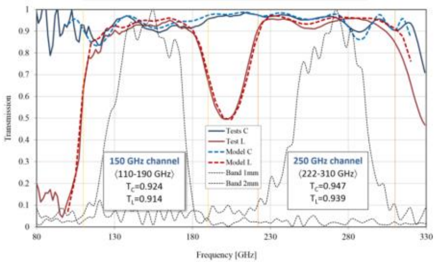
Thermals, Polarisers, Dichroics

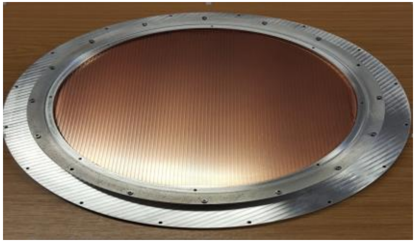


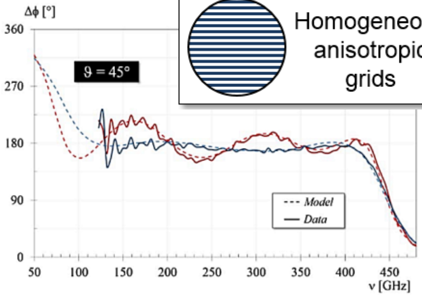


P. Ade, C. Tucker, G. Pisano

Transmissive & Reflective HWPs

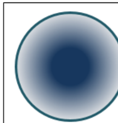




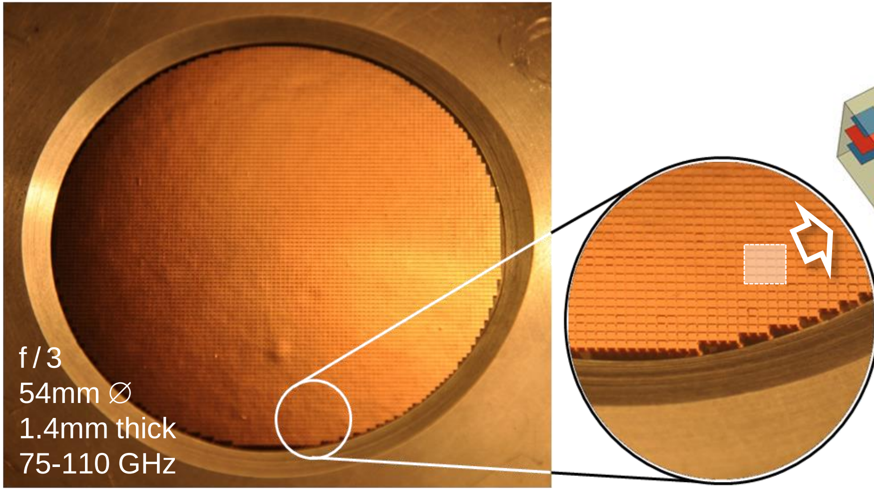


Homogeneous anisotropic grids

Mesh Lenses: Inhomogeneous phase delays

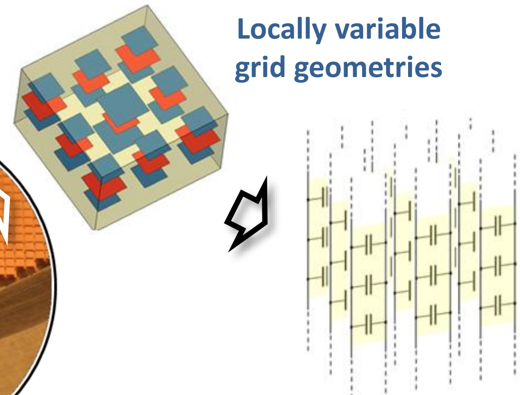


Inhomogeneous grids



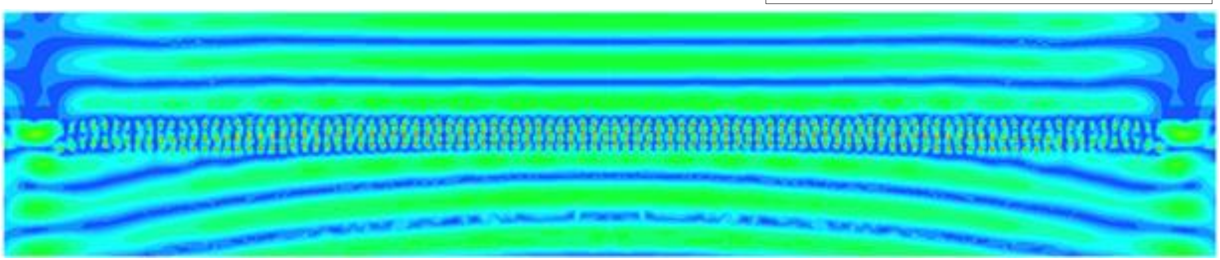
W-Band f/3 lens

Locally variable grid geometries



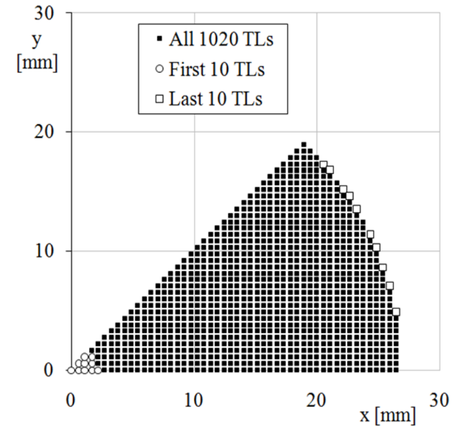
Multiple transmission lines

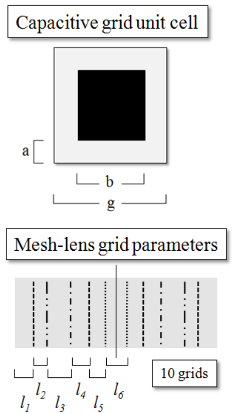
G. Pisano et al, *Applied Optics* (2013)



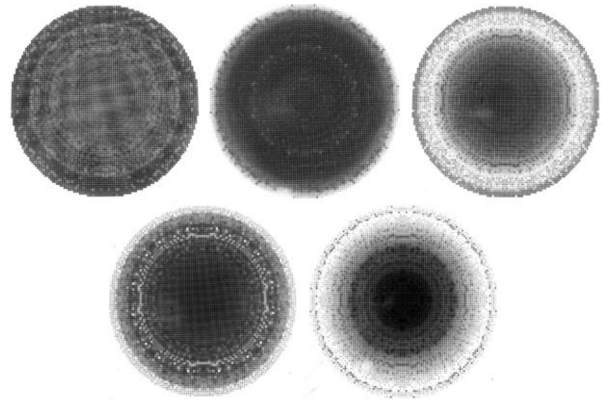
- **Finite-element simulations showing the conversion of a spherical wavefront into a planar one**

Mesh Lenses: Design and tests

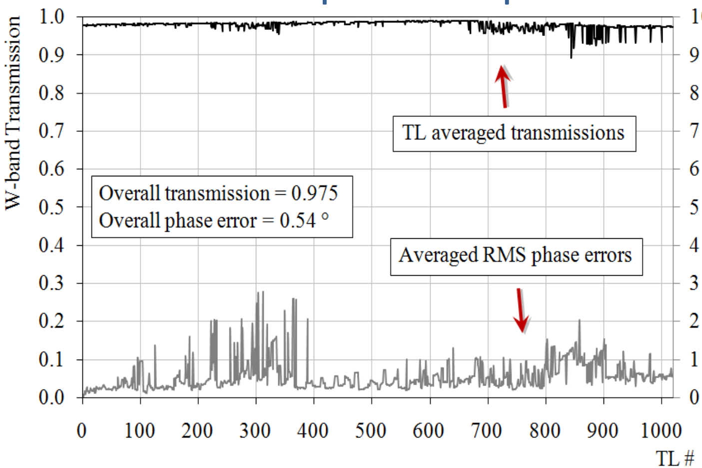




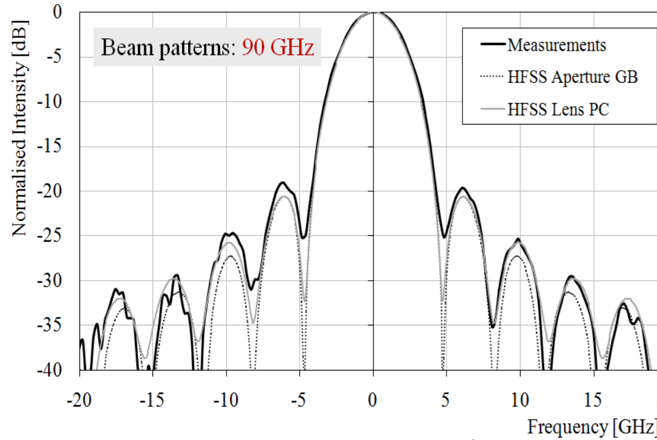
Optimised inhomogeneous grids



Transmissions & phase shifts optimisation



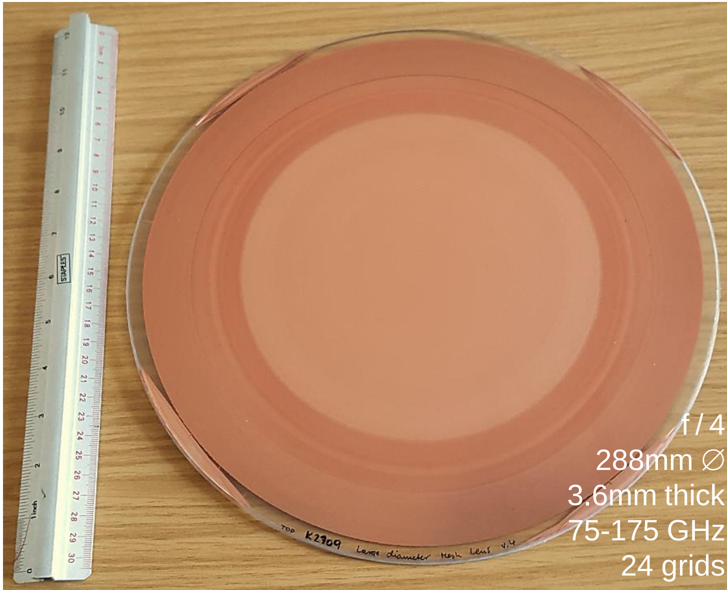
Beam measurements



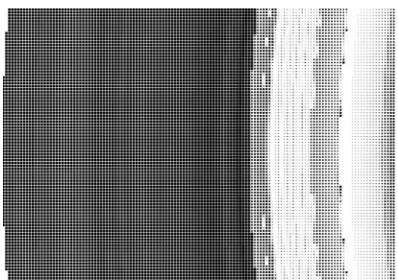
→ Agreement down to the 4th side lobes

Mesh Lenses: Large diameter devices

G. Pisano et al. SPIE (2018)



Large diameter hot-pressed mesh-lens

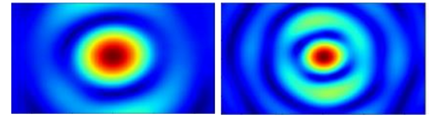


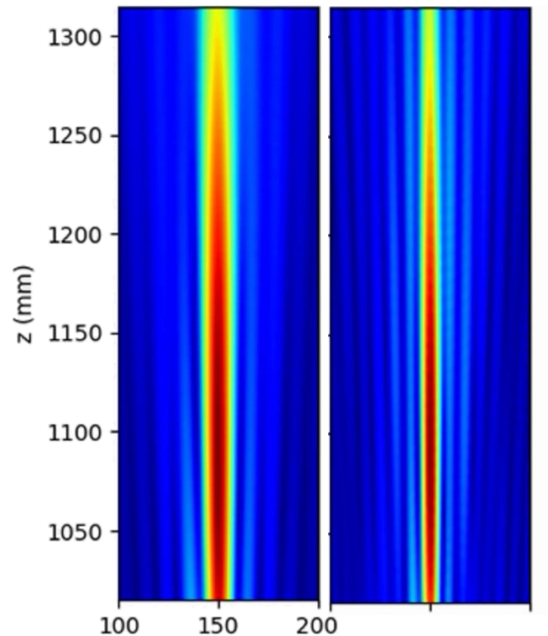
← Pattern example
~800k pixels
across surface

Mesh Lens 3D beam tests

↓ Transversal cuts ↓

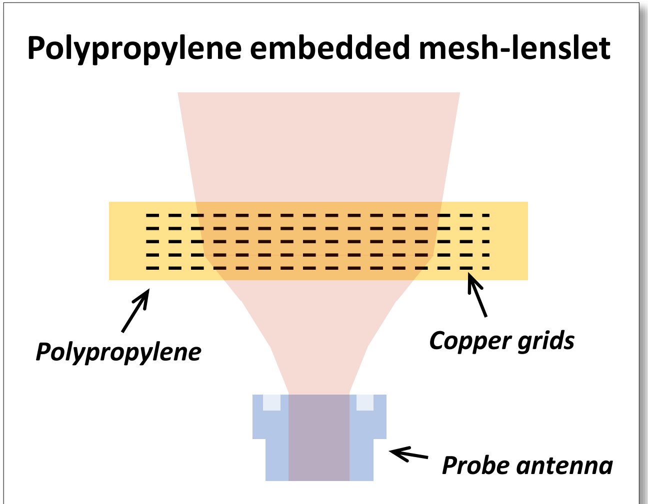
Airy profiles





↑ Longitudinal cuts ↑

Polypropylene embedded mesh-lenslet: Design

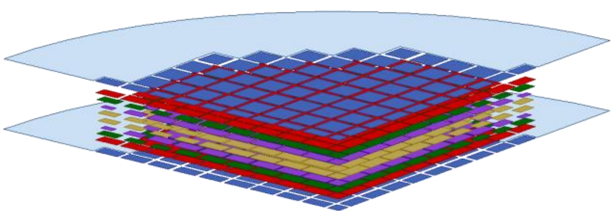


Working principle:

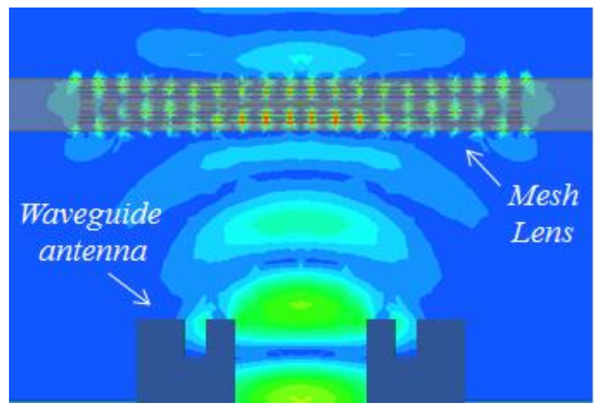
- Local 'transmission-line' phase-delays
- Each column as a mesh-filter
- Phase-shifts optimised to mimic lens behaviour

Manufacture:

- Copper evaporated on PP substrates
- Etching of the grids with variable pattern
- Hot bonding of the grids and PP spacers into a single device



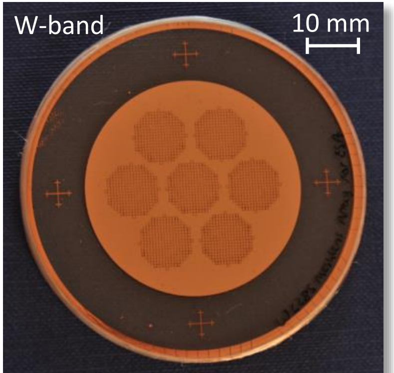
FEA model detail

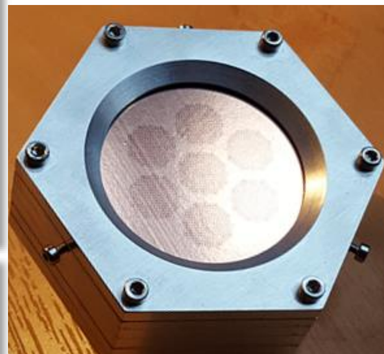


FEA simulation (HFSS)

Mesh Lens Array: Prototype tests

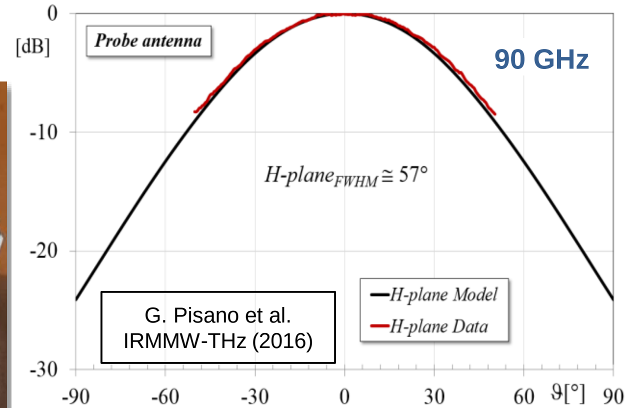
ESA project - "*Next Generation Sub-Millimetre Wave Focal Plane Array Coupling Concepts*" – Maynooth (PI), Manchester, Cardiff, Rome, Paris APC & Chalmers



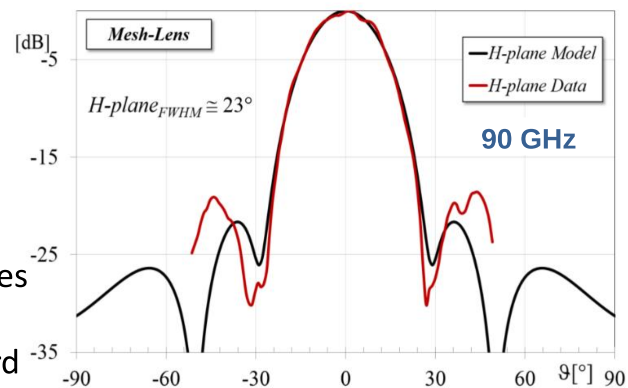


PP mesh-lens array + cavities & probe antennas

Probe antenna beam



Mesh Lens beam



Pros:

- Same photolithographic processes as mesh filters (only grids alignment needed)

Cons:

- Differential contractions at cryogenic temperatures to be taken into account
- Coupling to Si-based detectors not straightforward

Summary

- Focal plane arrays coupling technologies
- Mesh-technology & mesh-lens array
- Silicon-based mesh-lenslet arrays
- Conclusions

Silicon-based lenslet arrays: NASA APRA project

NASA APRA Project

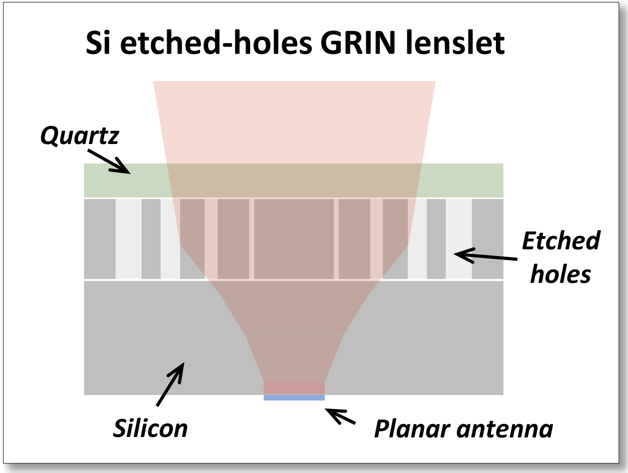
NNX17AE85G

**PLANAR SILICON METAMATERIAL LENSLET ARRAYS
FOR SPACEBORNE
MILLIMETER-WAVELENGTH IMAGING**

Principal Investigator
Nils W. Halverson
University of Colorado Boulder

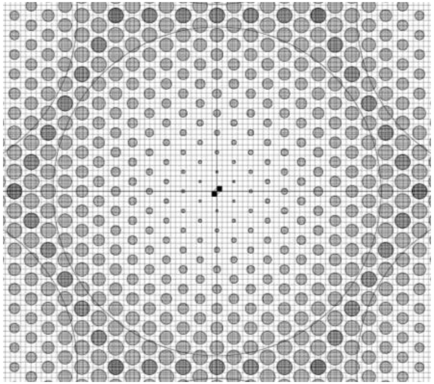
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD NIST Boulder BERKELEY LAB

Silicon etched-holes GRIN lenslet: Design

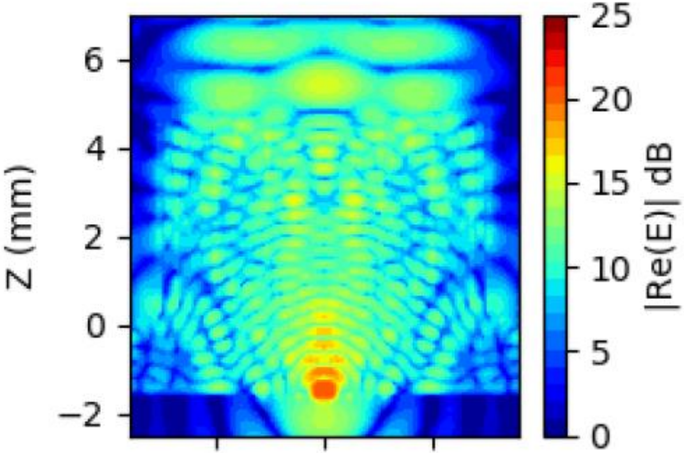


Working principle:
- Graded-index Silicon lens
- Subwavelength vacuum holes
- Variable lower indices obtained by varying the hole diameters

Manufacture:
- Etching of holes in Silicon wafers
- Possible to build ARC with larger etched holes

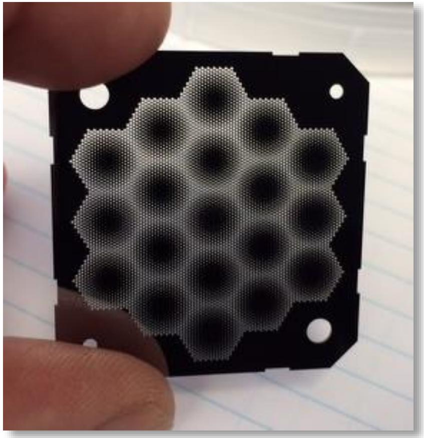


GRIN pattern example

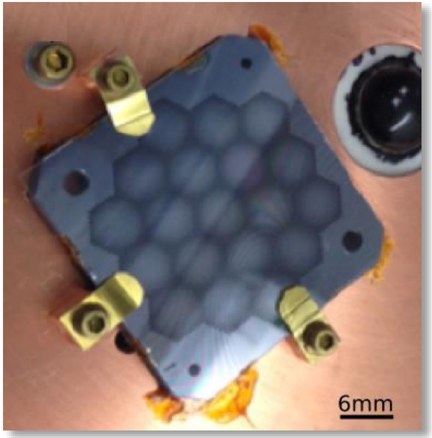


FEA simulation

Silicon etched-holes GRIN lenslet: Prototype tests



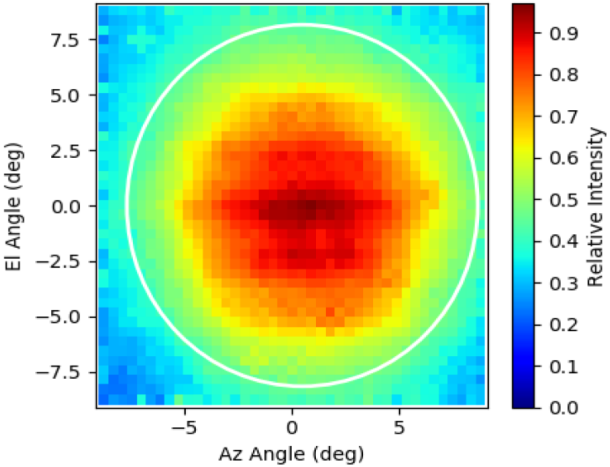
Etched-holes Si wafer (500um)



19-pixel array prototype

6D beam mapper

2D beam measurements



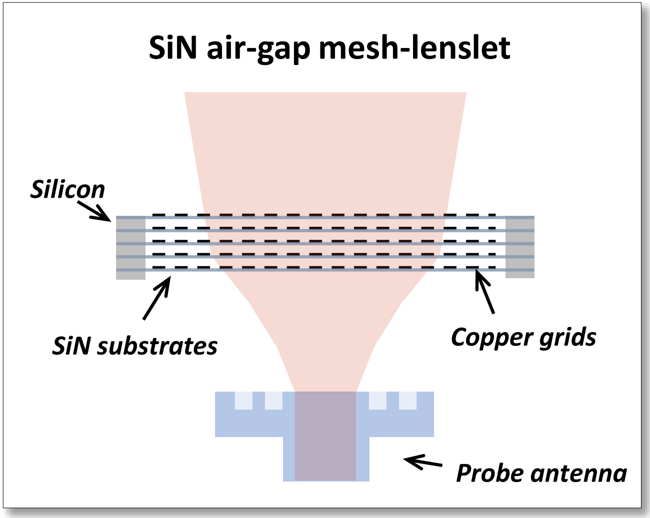
Pros:

- Naturally matched to Si-based detectors

Cons:

- Need ARC (Quartz or Si etched-hole layer)
- Smallest hole diameter limited by 10:1 aspect ratio of thickness-to-hole size
- Largest hole diameter limited by minimum thickness of the wall between the holes
- Above effects limit to frequencies up to ~170 GHz

SiN air-gap mesh-lenslet: Design

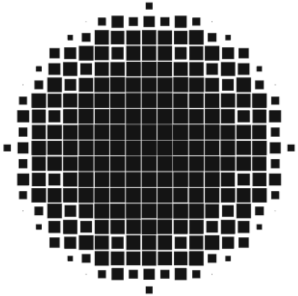


Working principle:

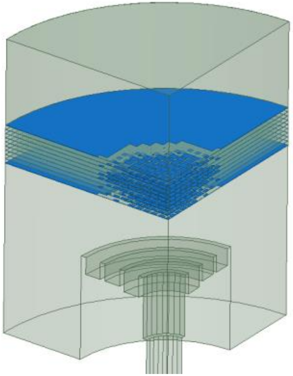
- Local 'transmission-line' phase-delays
- Each column behaves like a highly transmissive mesh-filter
- Phase-shifts optimised to mimic lens behaviour

Manufacture:

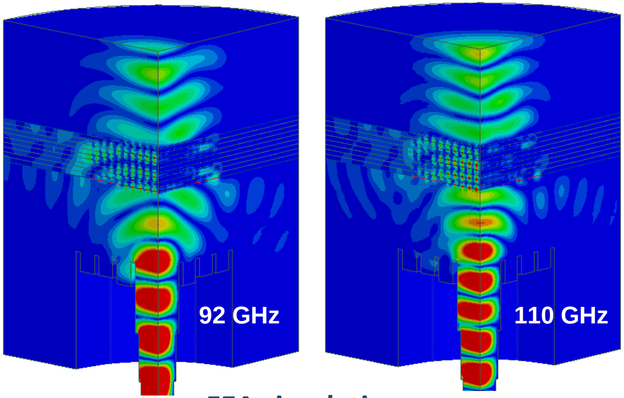
- SiN films on Silicon wafers
- Copper grids evaporated/etched on SiN films
- Silicon apertures etched in correspondence of the grids



Grid pattern example

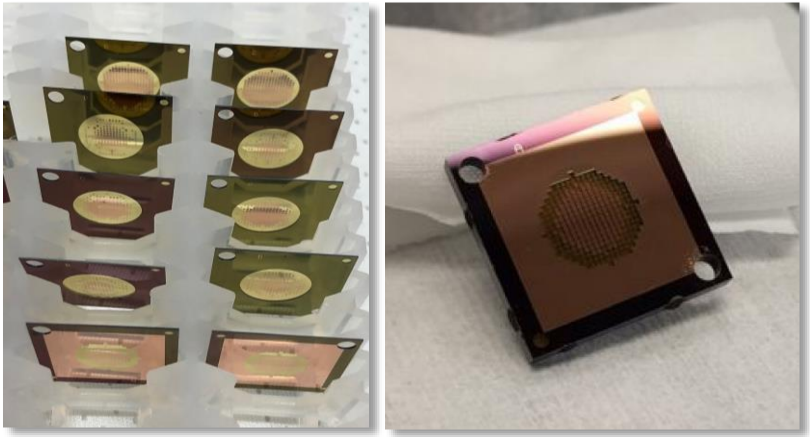


FEA model



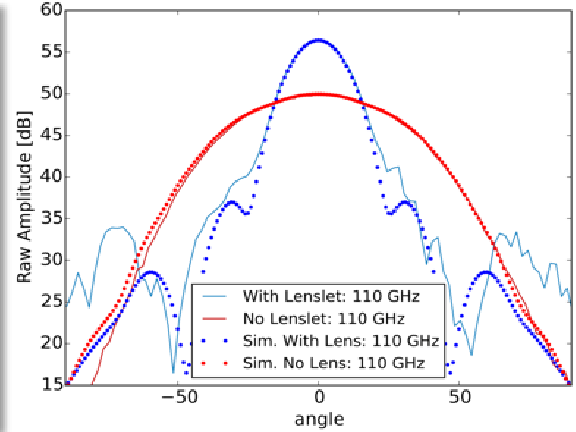
FEA simulations

SiN air-gap mesh-lenslet: Prototype tests



Individual layers and single pixel prototype

Antenna vs Lens beams



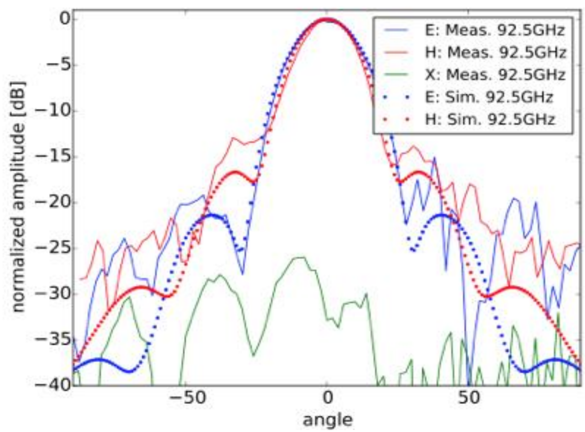
Pros:

- Can be designed to be coupled to any antenna (need phase profile at lens entrance)
- Relatively easy to manufacture
- No need for ARC for free-space application

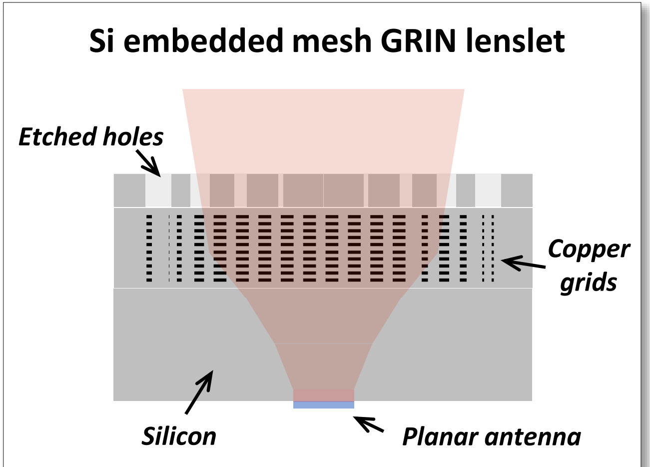
Cons:

- Coupled to free-space source
- Need ARC to be used with Si detectors
- Design/code iterations required for low f[#]

Lens Co-polar (E,H) & Cross-polar beams



Silicon embedded mesh GRIN lenslet: Working principle

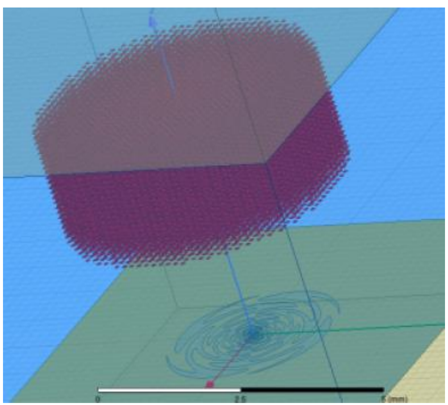


Working principle:

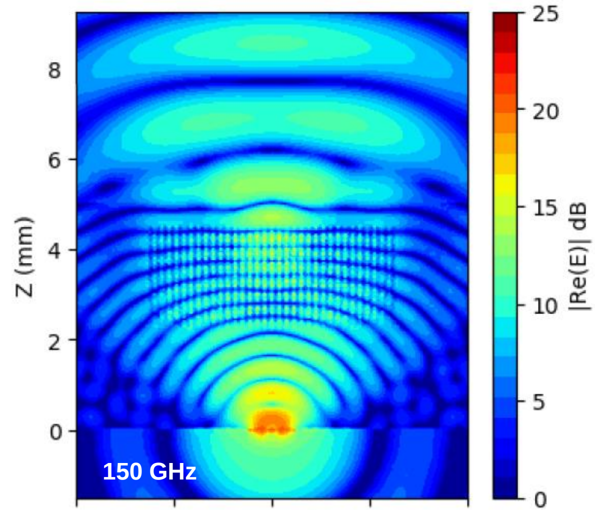
- Graded-index Silicon lens
- Copper grids embedded in Silicon
- Variable higher indices obtained by varying the sizes of the Copper patches

Manufacture:

- Copper grids evaporated on Si wafers
- Etched holes Silicon wafer for ARC layer

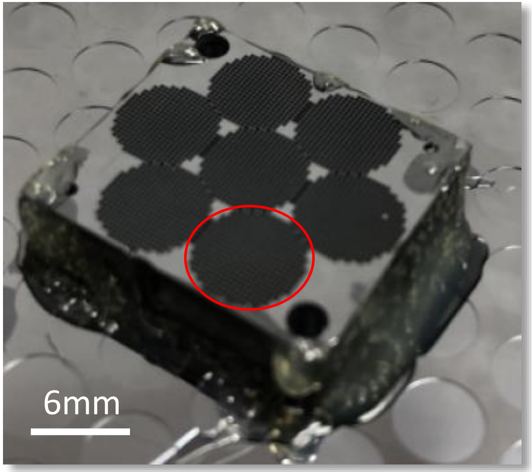


FEA model (with sinuous antenna)

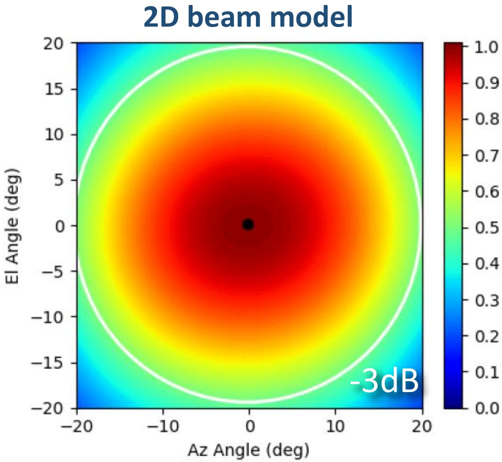


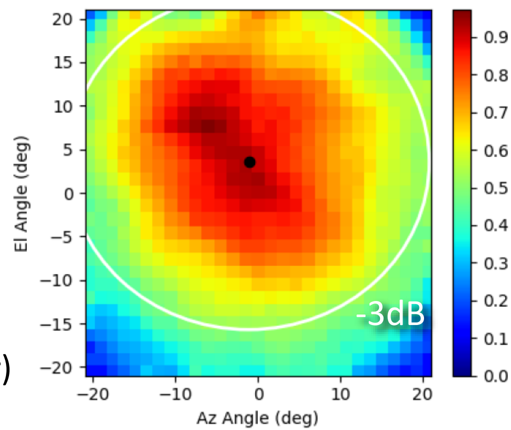
FEA simulation

Silicon embedded mesh GRIN lenslet: Prototype tests



7-pixel array prototype





Pros:

- Naturally coupled to Si-based detectors
- Simple metal deposition scalable to high frequencies
- No air-gaps, no back etching, mechanically more robust

Cons:

- Need ARC (Quartz or Si etched-hole layer)
- Large number of platelets (34) between 100-250 um thick

Note:

- Only tested edge-lenslet (unable to use central bolometer)
- Asymmetry likely due to vacuum on the side

Conclusions

- Investigating alternative solutions to current coupling technologies
- First attempt with etched-holes Si lenslets showed limits from the manufacture point of view
- Started to transfer the mesh-filters into the Silicon technology
- Successfully developed air-gap SiN mesh lenslet
- Very encouraging results from Si-embedded mesh-GRIN lenslet

What next?

- Design a Si-embedded mesh-lenslet to reduce the number of layers/grids
- More complex designs with arbitrary GRIN patterns with both transversal and longitudinal variability
- Mesh-GRIN hybrid solutions

Grazie!