CEOI 5th and 6th Open Calls
Final Review

AGLeD

Advanced GRIN Lens Design for mm-wave Radiometer Systems

Graham Maxwell-Cox and Michael Notter
Astrium Ltd, Portsmouth

BMA House, Tavistock Square, London

20 March 2013

AGLeD Introduction

- AGLeD is a Seedcorn Project to investigate the methodology in the design of a Metamaterial GRIN Lens for mm-wave radiometer systems
  - Work follows on from the CEOI Metamaterial Study 2011-2012
  - Application to Eumetsat MetOp MWS Radiometer

- Key objectives
  - Develop the design methodology for metamaterial lenses
  - Manufacture and Test of a trial metamaterial lens (change from original proposal)

- Project partners
  - **Astrium Ltd, Portsmouth**
    - Dr Graham Maxwell-Cox — Project Management and Quasi-Optical Design
    - Dr Michael Notter — Metamaterial Lens design
  - **STFC – RAL**
    - Dr Manju Henry and Anup Mistry — MM-wave Test Facilities

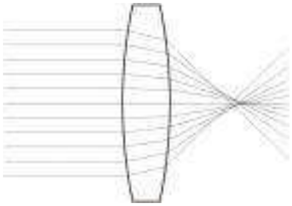
Technical Report on work

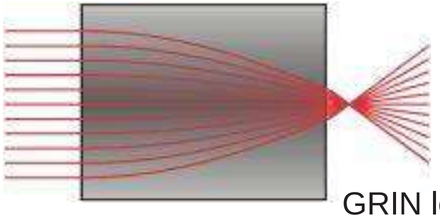
- **Dr Mike Notter Presents**:
- Some details of Advanced Gradient Index Lens (AGLeD) using metamaterials
  - Methodology
  - Design of lens
  - Lens construction
  - QO Testing

GRADIENT- INDEX (GRIN) LENS PROPERTIES

CYLINDRICAL GRIN LENS CONSTRUCTION

- Refractive index varies radially from optical axis
- Can be made in the form of a uniaxially anisotropic medium using stacked dielectric layers with metallic loading. Each layer is usually identical. The number of layers determines the focal length





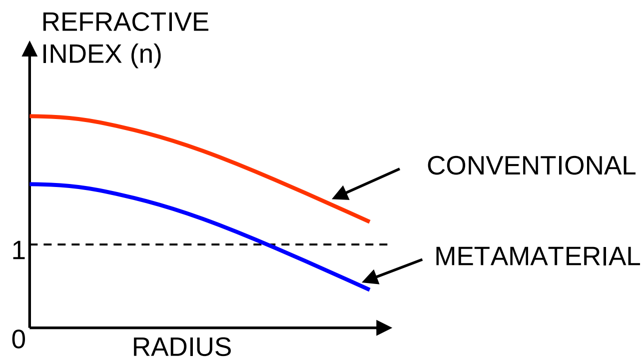
POTENTIAL BENEFITS OFFERED :

- Performance is largely unaffected by the (external) dielectric medium in which the lens operates
- Lens focal length can be changed (for a given design) by extending or reducing the length of the lens.
- Designer has greater control over ray trajectory within the body of the lens and can minimise aberrations for a given function
- Flat front and rear surfaces make the attachment or modification of matching layers straightforward
- Surface accuracy is less important than in a conventional lens.

APPLICATIONS

- Quasi-optical beam waveguide (e.g. as in MWS).
- Millimetre-wave antenna

NEW LENS DESIGN APPROACH USING 'METAMATERIALS'



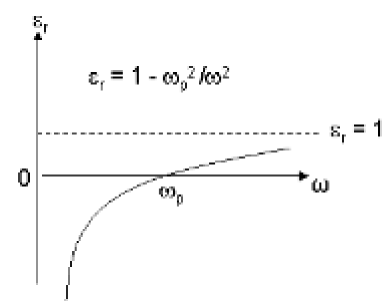
Refractive index = n = $\sqrt{\varepsilon_r \mu_r}$

- μ_r is fixed at around unity in practice, so only ε_r is varied to change 'n'
- Wave impedance = $\sqrt{\mu_r / \varepsilon_r}$

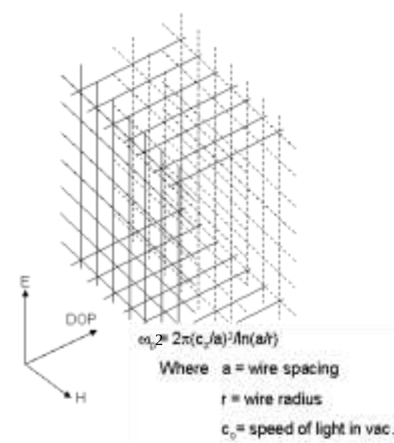
$\Rightarrow$ Mismatch at lens surface for $\varepsilon_r \neq 1$

Allowing values of 'n' <1 reduces the mismatch in wave impedances at the lens surface, and hence the reflection level.

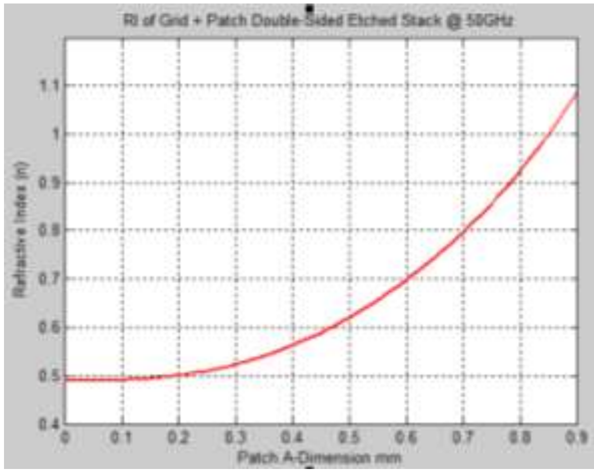
New metamaterial lens medium combines a wire grid with metal patch loading elements to provide a range of refractive index values from 0.5 to 1.4 @ 50GHz

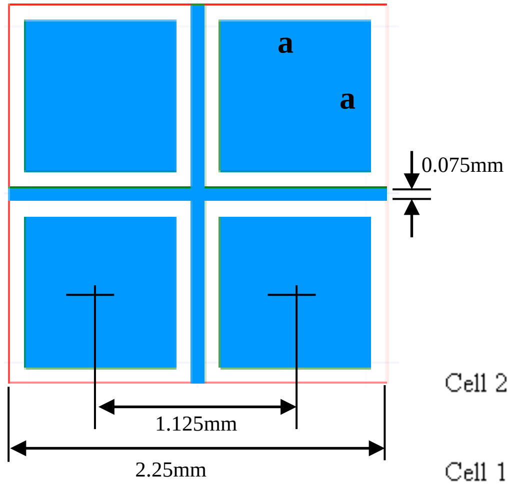


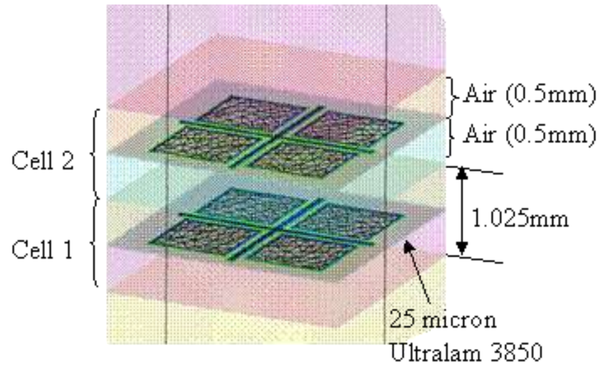
Wire grid response

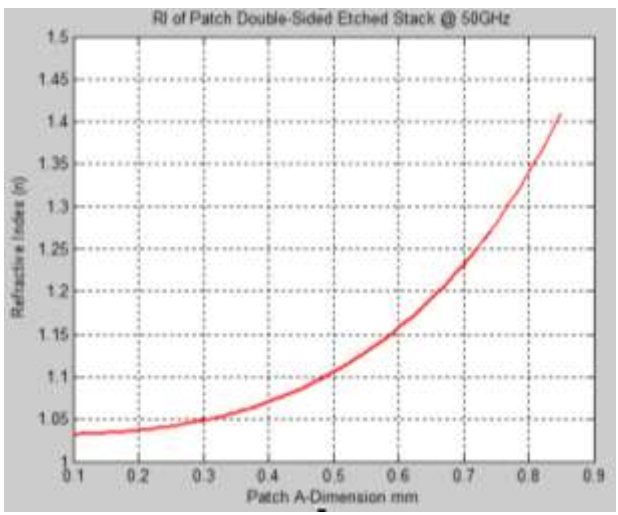


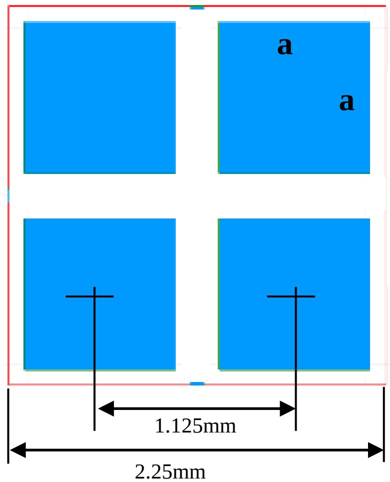
LENS MEDIUM CONSTRUCTION AND RF PROPERTIES @ 50GHz







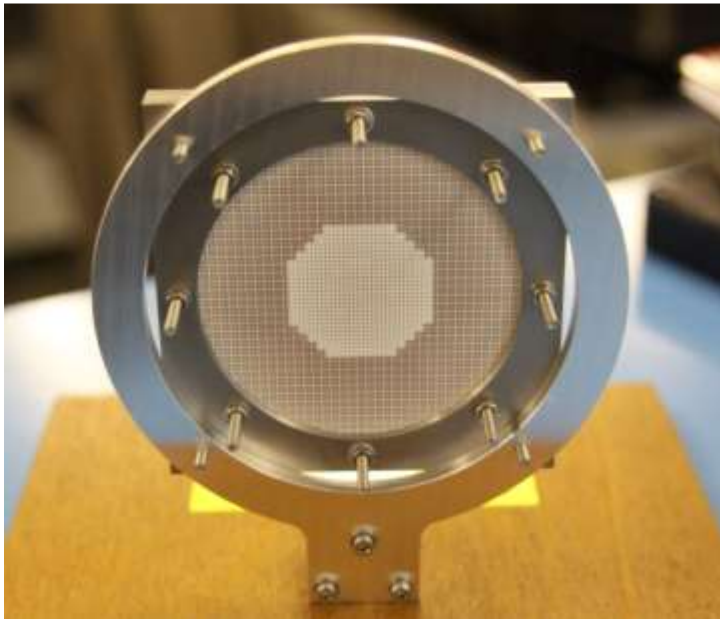


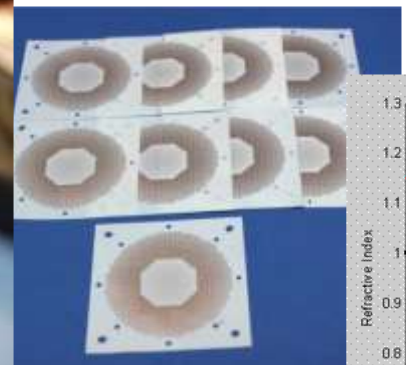


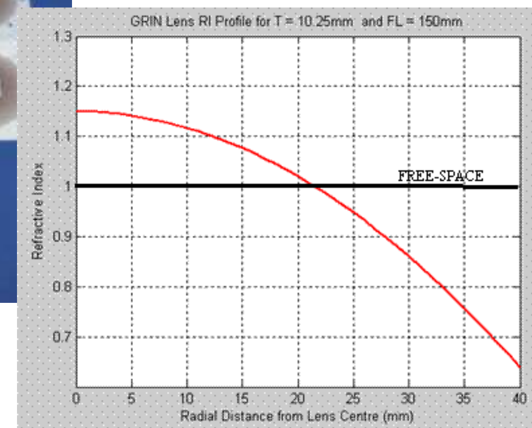
<u>Parameters:-</u>

- Lateral cell size: 2.25mm x 2.25mm
- Substrate: 25micron Ultralam 3850
- Substrate spacing: 1.025mm (= vertical cell size)
- Double-sided (0.5 oz) copper trace
- 50GHz design frequency

Breadboard Lens







REQUIRED REFRACTIVE INDEX PROFILE

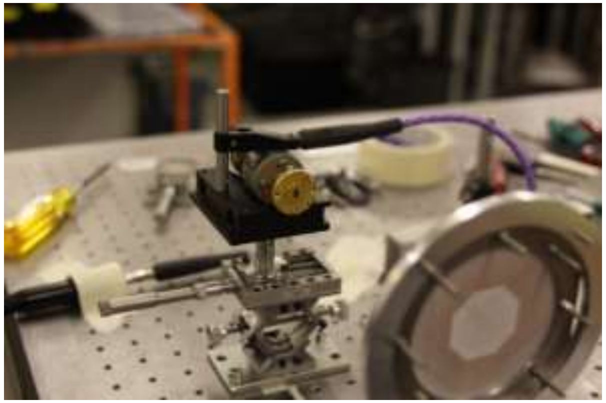
LENS DESIGN PARAMETERS

- Diameter: 80mm
- Number of layers: 10-off (9-off in practice)
- Focal length: 150mm (166mm with 9 layers)
- Design Frequency: 50GHz

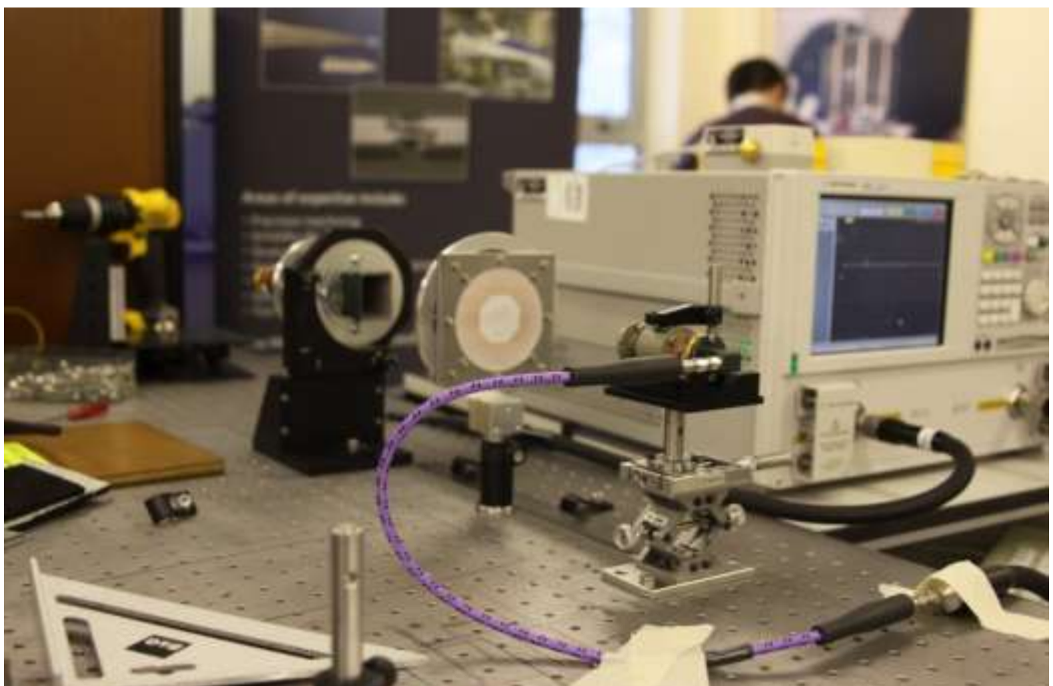
Expected beam waist diameters at 50GHz:-

- 27.5mm for uniform lens illumination
- 36.7mm for (1-r^2) amplitude taper across lens

Test Setup

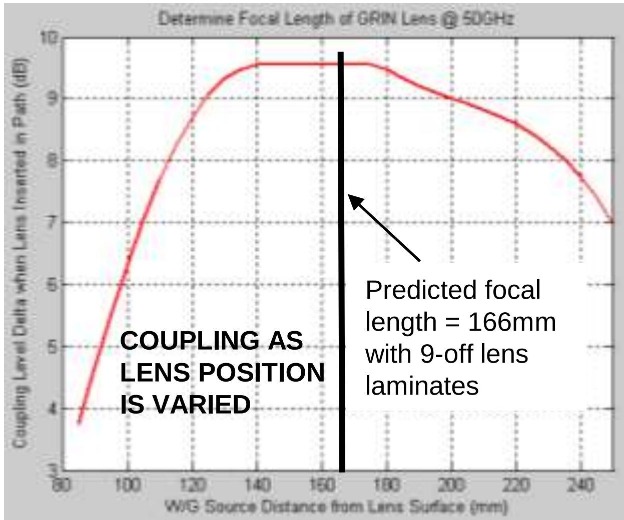


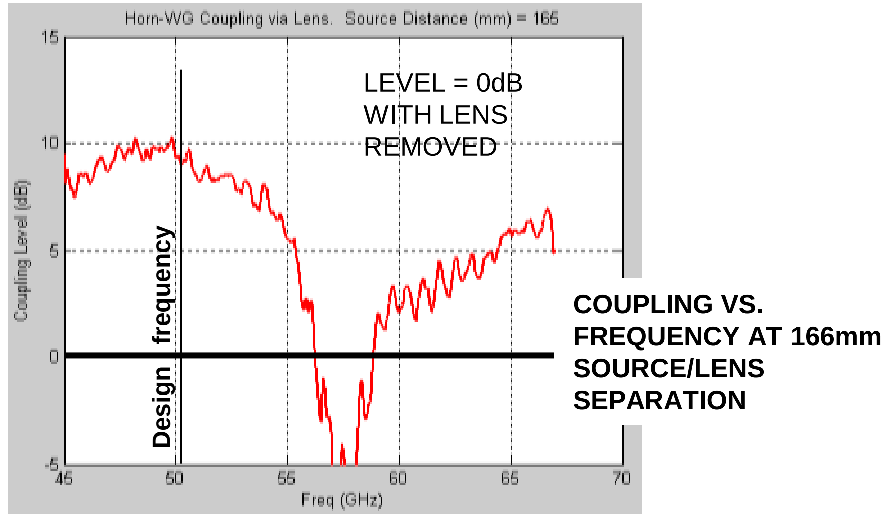
Source orientation to maximise measurement resolution and to minimise spurious illumination of table surface

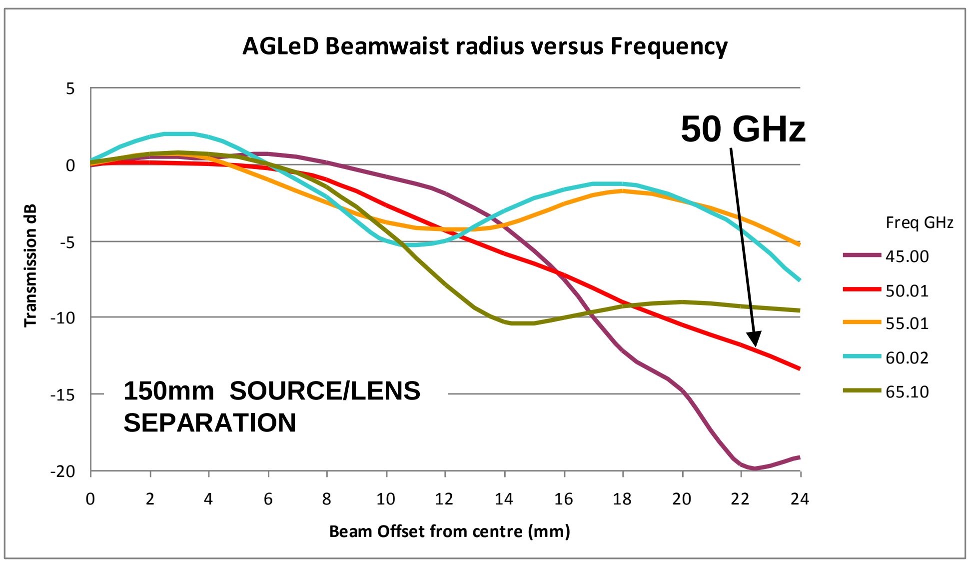


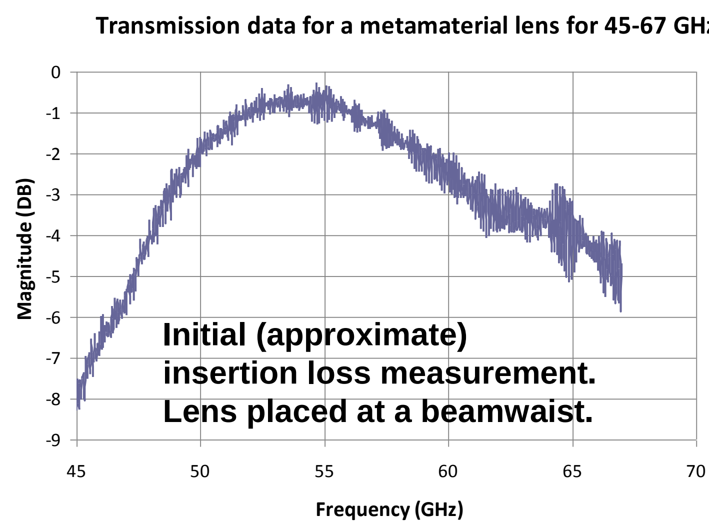
- Open-ended W/G source port
- Flann SGH (40 x x30 mm aperture) used on test-port to improve dynamic range (about 25dB with averaging).
- Separation between source W/G and horn aperture = 343mm
- Source- lens distance which gave maximum coupling was assumed to equal focal length.
- Beam waist diameter measured at 150mm distance from lens surface, using open-ended WG.

Initial Measured Results





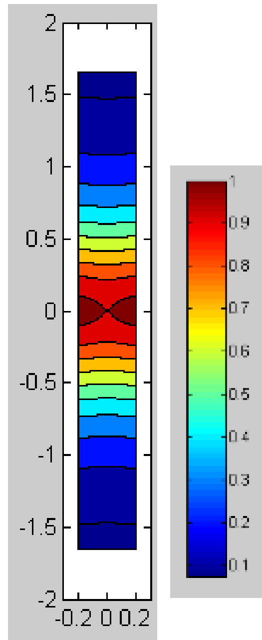




GRIN Lens Design using Transformational Optics (TO)

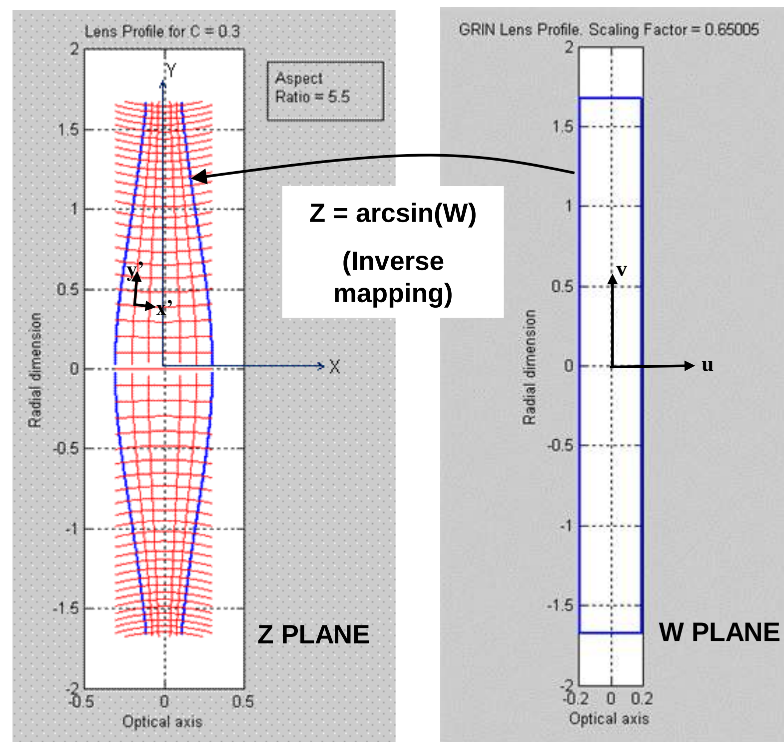
Use of conformal mapping to derive a suitable mapping from convex lens shape to cylinder

Required εr distribution in equivalent GRIN lens (normalised)

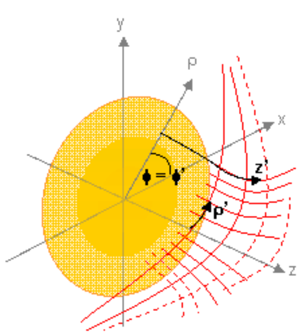


TO equations (J = Jacobean of the mapping):-

$\mu' = (\mathbf{J}\, \boldsymbol{\mu}\, \mathbf{J}^{T}) / \mathrm{Det}(\mathbf{J})$ $\varepsilon' = (\mathbf{J}\, \boldsymbol{\varepsilon}\, \mathbf{J}^{T}) / \mathrm{Det}(\mathbf{J})$



2D Version



DOMAIN (convex lens)

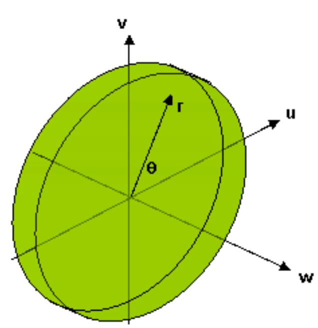
3D mapping

$r = \cos(z)\sinh(\rho)$

$\theta = \phi$

$w = \sin(z)\cosh(\rho)$

Extension to 3D



CO-DOMAIN (cylindrical GRIN lens)

Summary and Proposed Further Work

- The prototype MTM lens performance has yet to be fully characterised, but appears to have:
    - The correct focal length
    - Reasonably low loss
    - Around 10% bandwidth
- Etching misalignment error is up to ~25µm on double-sided lens substrate layers. Worst-case dimensional error is ~4%. Effect on lens performance is under assessment.
- A GRIN lens design has been derived analytically using a combination of Transformation Optics and conformal mapping. Awaiting ZEMAX modelling.
- Performance of lens with single-side lens substrate layers remains to be measured.
- Further lens measurements planned: (a) repeat of insertion loss (b) surface reflection level (c) aperture field probing

- **FURTHER WORK:**
- Design and integration of lens matching layers (if required)
- Rework of lens design to optimise performance
- The design of Transformation Optics software to assist with GRIN lens design for specialized applications

Achievements against goals

The programme has achieved the following so far:

- Investigated Design methodologies for GRIN lens including Transformational Optics
- Designed a GRIN lens at 50 GHz using constructed metamaterials
- Manufactured a metamaterial lens using PCB multilayer technology
- Tested the lens at STFC- RAL using Quasi-Optical bench
  - performed in the context the of the TSB BB MWS Radiometer work (Astrium / RAL 2012)
- Zemax analysis of the QO Test System (further zemax modelling to be performed)

Issues and problems encountered

Major issues resolved

- Programmatic
  - Personnel loading at Astrium and RAL due to support to:
    - MWS Phase a study and Phase B Bid
    - TSB MWS radiometer breadboard work
    - Overload on QO test facilities at RAL (MWS D1 dichroic work)
- Design, Manufacture and Test
  - PCB manufacturing accuracy for metamaterial laminates
- Any unresolved issues:
  - There is always more to do !

Positioning achieved

- Presentations and Publications
  - Poster Paper CEOI Workshop Nottingham Sept 2012
  - Paper presented at the CEOI Training Workshop at RAL on Quasi-Optical Design (Nov 2012)
  - Poster Paper provided at the CEOI Innovations in Remote Sensing Event in London on Metamaterials and QO components (Jan 2013)

- Patents
  - None specific to AGLeD yet !
  - *But …US patent for MM-wave QO Beam Splitter (Straw Cutter, CEOI Project 2007) – Graham Maxwell-Cox – March 2013 - At Last!*

- Leverage achieved
  - UK QO design capability in lenses for mm-wave radiometer (Applicable to MetOp MWS Radiometer)

- Collaborations forged
  - TSB BB Team for MWS Radiometer (MetOp)
  - STFC RAL MM-wave Test Facilities and Measurement Team
  - MetOp MWS Radiometer Systems team

Other Achievements

- Training and knowledge exchange
  - 6 months Support to Queens University London from previous CEOI Metamaterial study (Astrium QMUL) to March 2013

- UK Capability enhancement

  Benefits to UK Space

  - Design and test capability in **advanced lens design** for mm-and sub-mm-wave applications
  - Development of **practical metamaterial systems**
  - Development of **Non-sequential Ray Tracing** techniques for QO design and analysis

Roadmap

- Missions/exploitation route
  - MetOp MWS Radiometer (awarded Astrium UK 2013)
  - Risk mitigation for lens coupled QO systems (53 and 89 GHz)
  - QO modelling of radiometer systems using non-sequential ray tracing

- Future steps
  - Technology development required

- Design and integration of lens matching layers
- Rework of lens design to optimise performance
- Further QO testing required developing measurement techniques
- The design of Transformation Optics software to assist with GRIN lens design for specialized applications

  - Issues to be resolved

Manufacturing techniques for scaling to shorter wavelengths