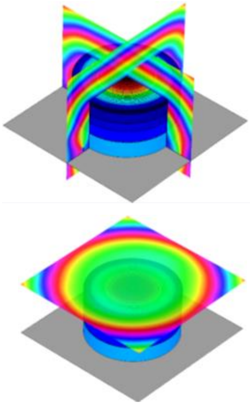

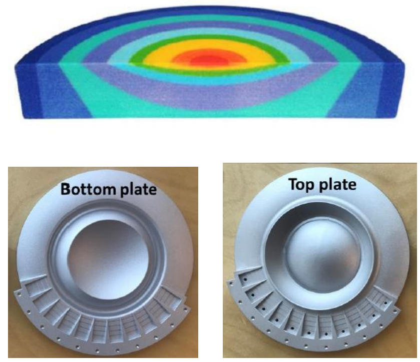

Transformation optics and its applications to antennas

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KTH Royal Institute of Technology

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1

Outline

- Theory:
  - Transformation optics concept.
  - Types:
    - Analytical transformation.
    - Quasi-conformal transformation.
    - Non-Euclidean transformation.
- Practice:
  - Lens design.
    - Compressed lenses.
    - Planar Lenses.
    - Collimated lenses.
    - Bespoke lenses.
  - Surface propagation.
    - Cloaking.
    - Surface waves lensing.
- Conclusions.

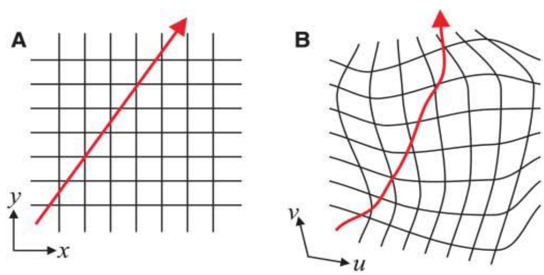
2

Transformation Optics Concept

- In 2006 two pioneering papers were published in *Science* defining the concept of **transformation optics:**
  - According to the theory, any given electromagnetic device can be transformed into an infinite number of new ones with same electromagnetic responses.
- This tool has incredible possibilities to redesign classic devices.

Smith et al., *Science*, 2006

Leonhardt, *Science*, 2006



$$\varepsilon' = \frac{J\varepsilon J^T}{|J|}$$

$$\mu' = \frac{J\mu J^T}{|J|}$$

Outline

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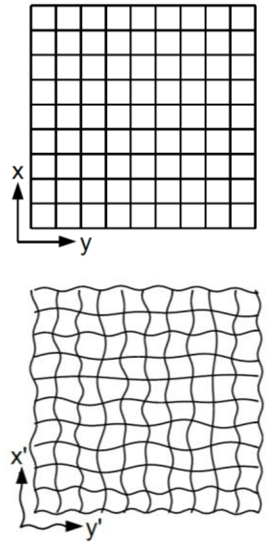
- Conclusions.

1) Analytical Transformation

- To make an analytical transformation taking into account all the components in Maxwell's equations.
- No approximations:
  - The physical space has the same response as the original virtual space.
- In practice, this idea is unaffordable:
  - Dispersive materials.
  - Anisotropic materials.



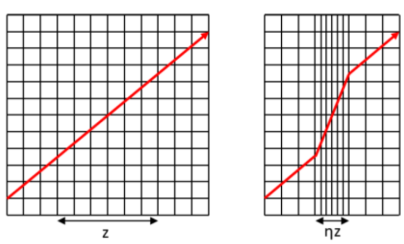
5

1) Analytical Transformation: Dispersive materials and anisotropy

- Lets assume the simplest transformation:
  - Compression in one of coordinate axes.

D. A. Roberts, N. Kundtz, and D. R. Smith, *Opt. Express*, 2009.

$$x'(x) = \begin{cases} ax + c, & l_1 < x < l_2 \\ l_1' + (x - l_1), & x \le l_1 \\ l_2' + (x - l_2), & x \ge l_2 \end{cases}$$



- The new permittivity and permeability maps will be:

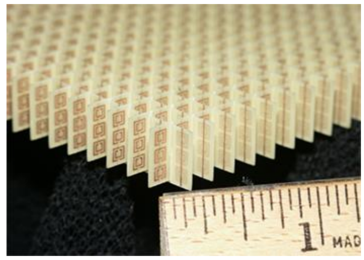
$$\varepsilon' = \varepsilon \begin{Bmatrix} a & 0 & 0 \\ 0 & 1/a & 0 \\ 0 & 0 & 1/a \end{Bmatrix}$$

$$\mu' = \mu \begin{Bmatrix} a & 0 & 0 \\ 0 & 1/a & 0 \\ 0 & 0 & 1/a \end{Bmatrix}$$

6

Dispersive materials

- Materials with refractive indexes lower than 1 can be only obtained with the use of metamaterials.
- Metamarials are strongly dispersive:
  - Very limited bandwidth of operation.



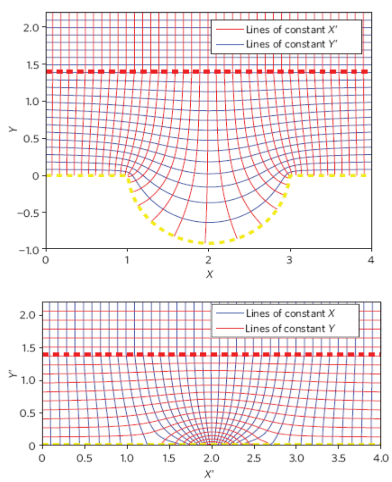
$$\varepsilon_r(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}$$

- To avoid the use of these materials is always an advantage for practical applications.

2) Discrete Transformation

N. Kundtz and D.R. Smith, *Nature Materials*, 2010.

- To make a transformation based on graphical coordinates.
- Importance of the coordinate lines to be orthogonal to the metallic boundaries.
- Transformation based on areas (not in shapes).
  - It does not take into consideration non-linear effects.

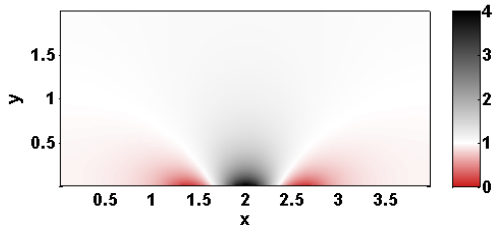


$$n' = n_0 \sqrt{\frac{\Delta x_0 \Delta y_0}{\Delta x_0' \Delta y_0'}}$$

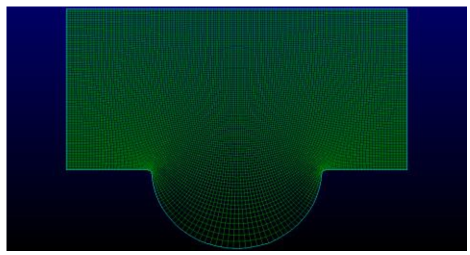
2) Discrete Transformation: Dispersive materials (I)

- Depending on the geometry, the required refractive index for the new map will have some lower than one index regions.
  - Lower than 1 refractive indexes require metamaterials implementations.
  - Dispersive materials and narrow band.

Physical Space



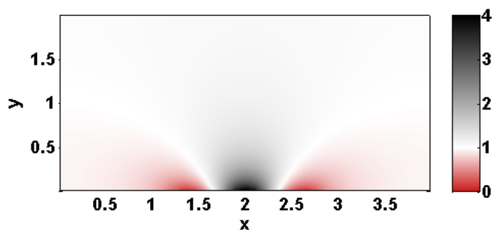
Virtual Space

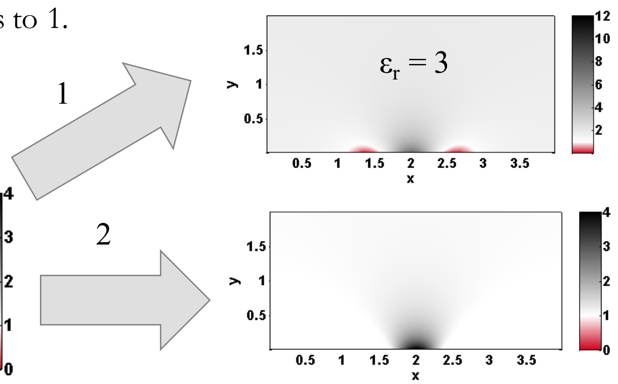


2) Discrete Transformation: Dispersive materials (II)

- Two possible solutions:
  1. To develop the transformation over an original dense material.
  2. To approximate these values to 1.

Physical Space

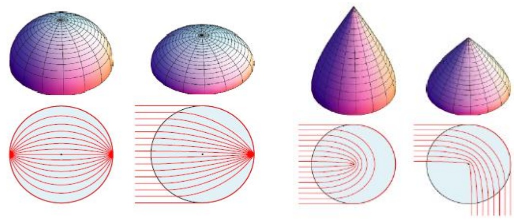




3) Non-Euclidean transformation

- To analyse the ray paths in a surface and to obtain the equivalent 2D plane which remains the same properties.

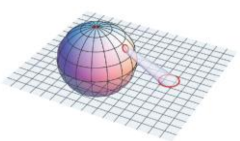
Maxwell Fish Eye | Luneburg | Eaton | 90º rotation

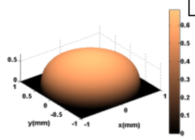


M.Sarbort and T. Tyc, *Journal of Optics*, 2012

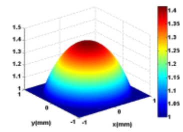
- One method: Stereographic projection

U. Leonhardt and T. G. Philbin, *Geometry and Light: The Science of Invisibility* 2010.

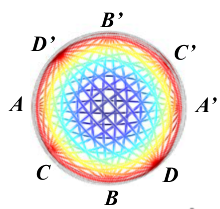




$$dS_1 = n \cdot dS_2$$

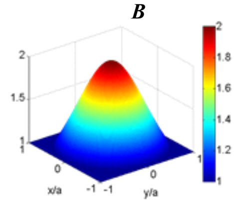


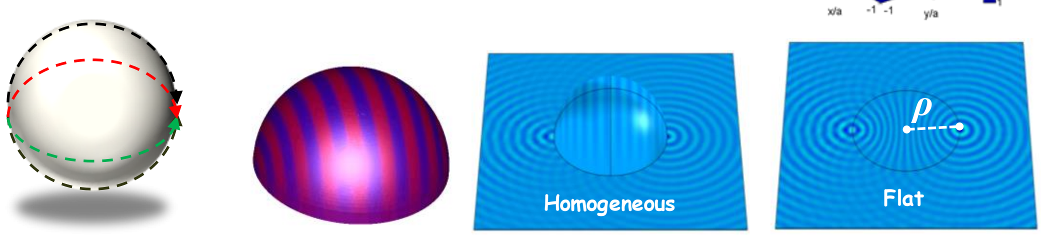
Maxwell Fish Eye Lens



- It is a lens in which a source in any excited point of the circle surface will converge exactly at the opposite size of the circle.
- It is a rotationally symmetric lens.
- Equivalent to an homogeneous sphere.

$$n(\rho) = \frac{2n_0}{1+\left(\frac{\rho}{a}\right)^2}$$





R. C. Mitchell–Thomas, O. Quevedo-Teruel, T.M. McManus, S.A.R. Horsley, Y. Hao, *Optics Letters*, 2014.

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Compressed lenses: Transformation optics

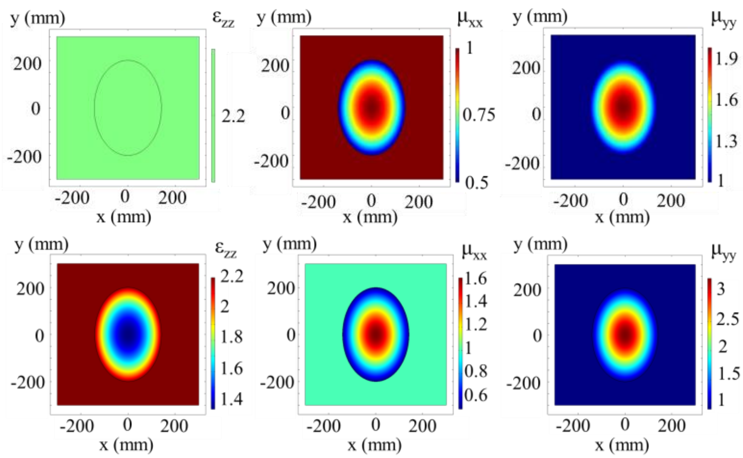
- Using transformation optics, we can compress the space:

$$\overline{\overline{\varepsilon'}} = \varepsilon \begin{bmatrix} 1/\alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \alpha \end{bmatrix}$$

$$\overline{\overline{\mu'}} = \mu \begin{bmatrix} 1/\alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \alpha \end{bmatrix}$$

$$\varepsilon = \varepsilon_0$$

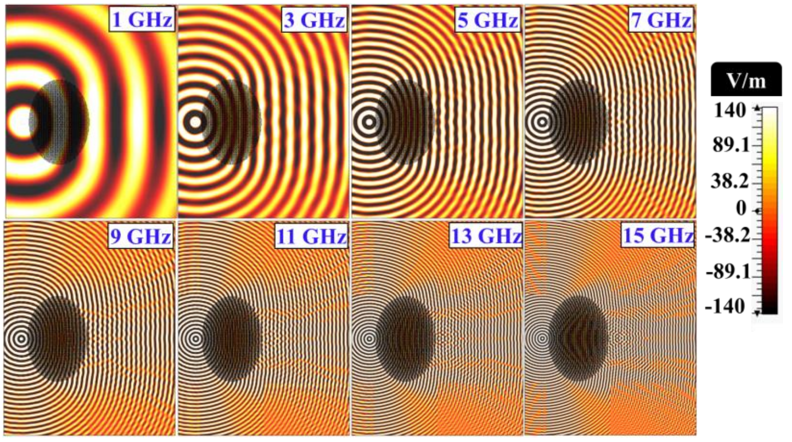
$$\mu = \mu_0 \left(2 - \frac{(\alpha x')^2 + {y'}^2}{R^2}\right)$$



M. Ebrahimpouri, O. Quevedo-Teruel, "Ultra-wideband Anisotropic Glide-symmetric Metasurfaces", *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1547-1551, Aug. 2019.

Compressed Luneburg lens

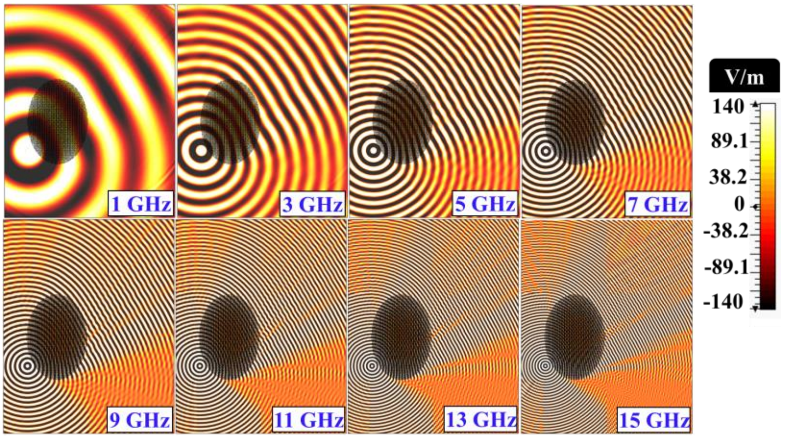
- Main direction:



M. Ebrahimpouri, O. Quevedo-Teruel, "Ultra-wideband Anisotropic Glide-symmetric Metasurfaces", *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1547-1551, Aug. 2019.

Compressed Luneburg lens

- Oblique radiation pattern:

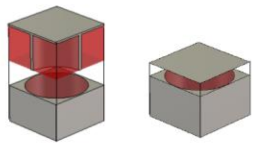


M. Ebrahimpouri, O. Quevedo-Teruel, "Ultra-wideband Anisotropic Glide-symmetric Metasurfaces", *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1547-1551, Aug. 2019.

Mode-matching: Anisotropy

- Lens compression:

$n^{MAX}_{\text{Glide}} = 2.86 \Rightarrow \beta^{MAX}_{\text{Glide}} = 43\%$

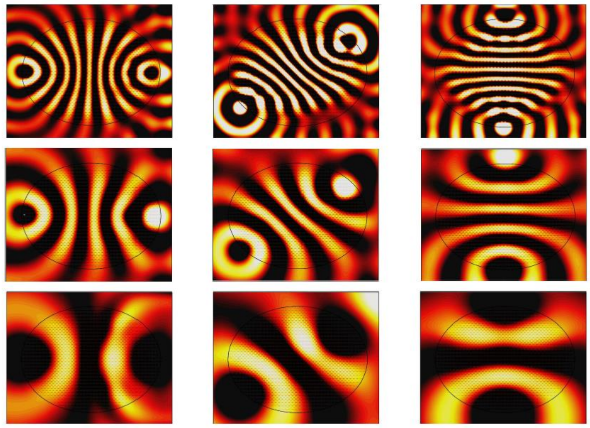


$n^{MAX}_{\text{Non-Glide}} = 2.05 \Rightarrow \beta^{MAX}_{\text{Non-Glide}} = 3.5\%$

10 GHz

5 GHz

2.5 GHz

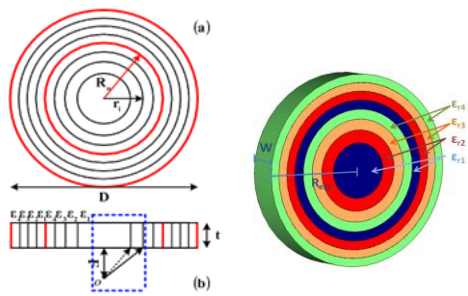


- A. Alex-Amor, F. Ghasemifard, G. Valerio, P. Padilla, J. M. Fernandez-Gonzalez, O. Quevedo-Teruel, "Glide-Symmetric Metallic Structures with Elliptical Holes", *submitted to IEEE Transactions on Microwave Theory and Techniques.*

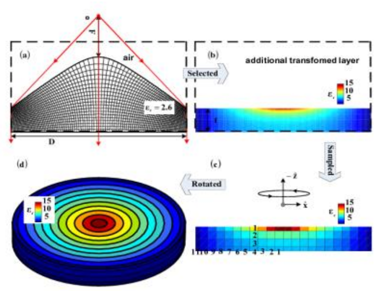
Planar lenses

- Option 1:
  - Fresnel Lenses
    - Single frequency of operation

A. Petosa, et al. *IEE Proc., Microw. Antennas Propag.* 2006.



- Option 2:
  - Transformation Electromagnetics
    - UWB solution.

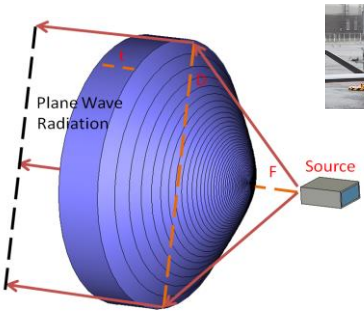


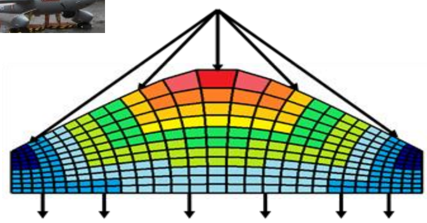
Design Process

- Quasi-conformal Transformation Optics.
- A discretization for the manufacturing process is required.

BAE SYSTEMS

O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

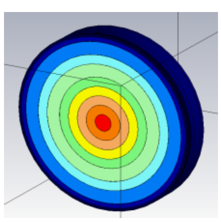


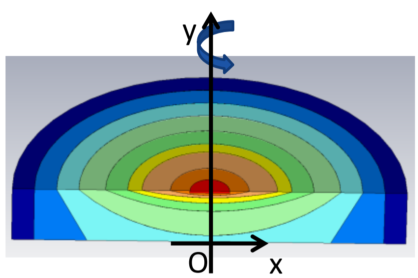


O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

Discretization process

- Spheres/Ellipsoids:
  - Ellipsoidal/spherical discretization along the iso-permittivity lines.
  - Zones of different permittivities:
    - $2<\varepsilon_r<14.5$
  - 10-15 zones

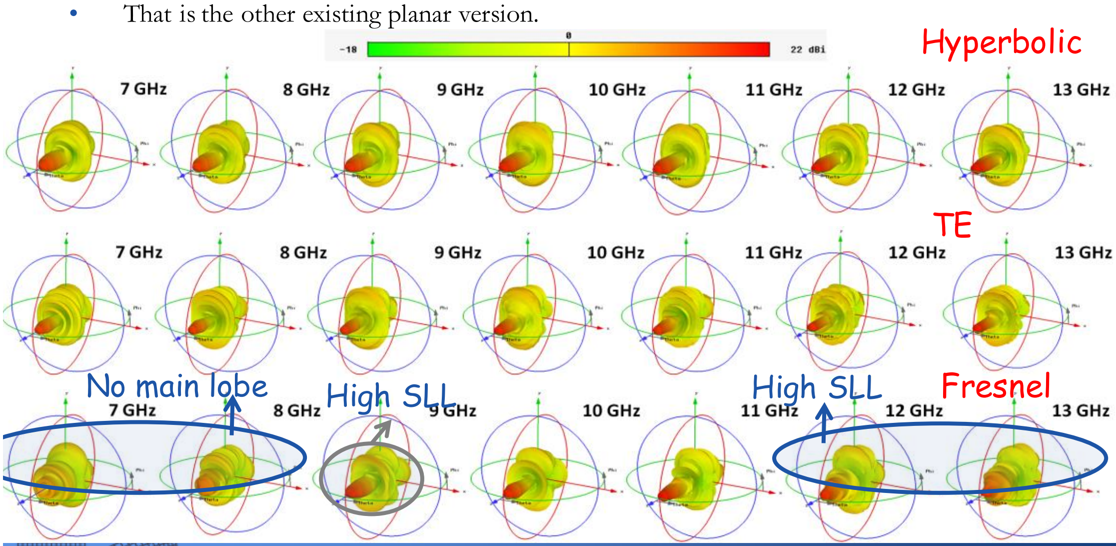




O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

Comparison with Fresnel lens

- Our solution overcomes Fresnel lenses in Bandwidth.
  - That is the other existing planar version.

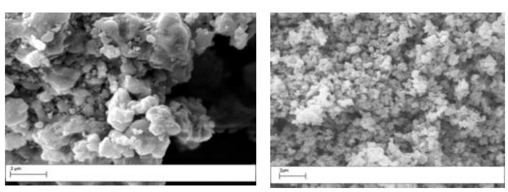


O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

Manufacturing

- Alternative permittivity regions have been produced through a combination of tailoring:
  1. Particle size.
  2. Dispersion and volume fraction of materials.
- The particle sizes where obtained using particle size reduction methods such as milling to achieve the distribution of sizes required, and these varied from nano- to micron size.

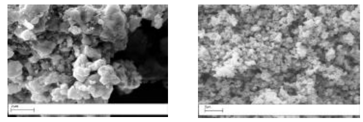
BAE SYSTEMS

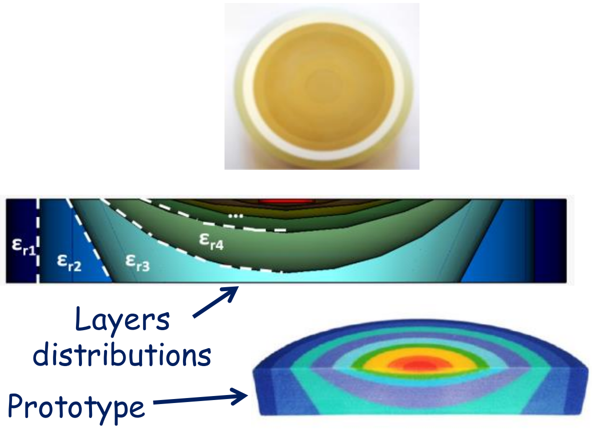


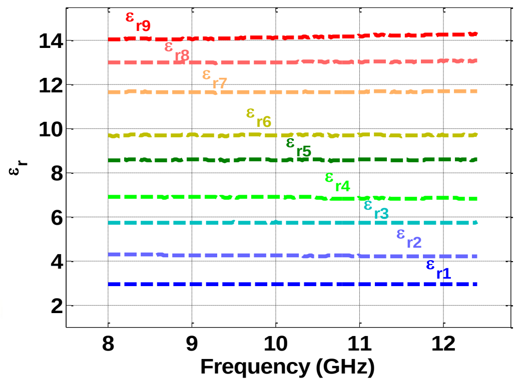
O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

Stability with Frequency

- The materials have a constant response with frequency (from 8GHz to 13GHz).



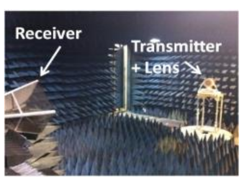


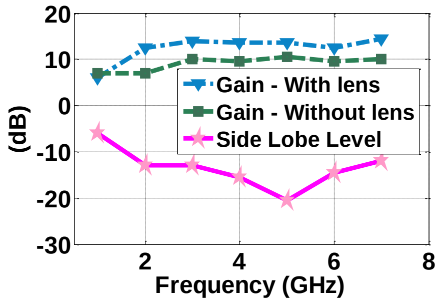


O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

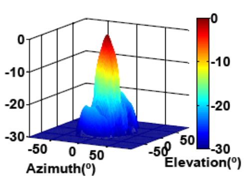
Measurements

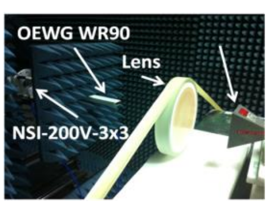
- Low frequency (1-7GHz):
  - Anechoic chamber.

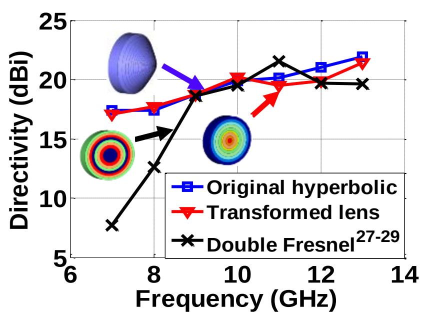




- High frequency (7-14GHz):
  - Near Field Scanner
    - NSI-200V-3x3

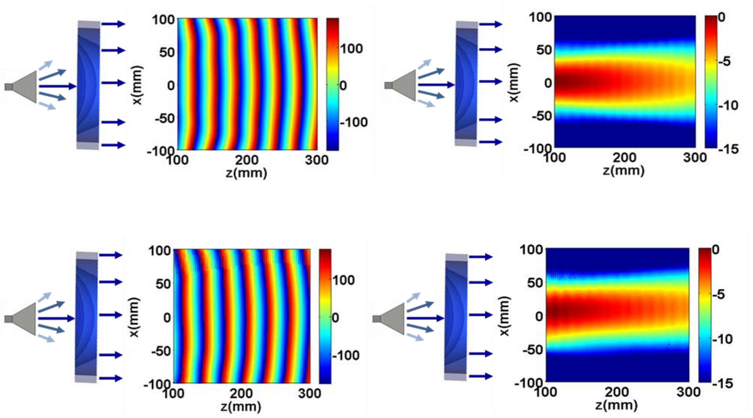






Simulation vs Measurements

- Good agreement in terms of phase and amplitude (10 GHz)



Simulation

O. Quevedo-Teruel, et al., *Scientific Reports,* 2013.

Measurement

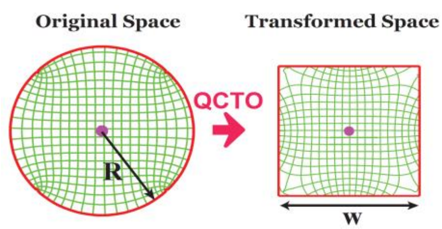
Phase (°)

Amplitude (dB)

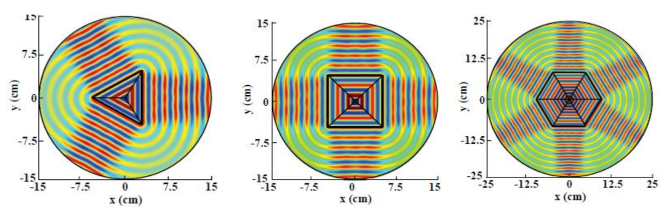
25

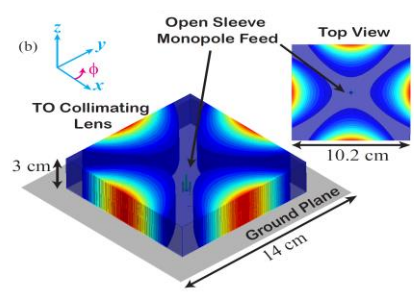
Collimated lenses

- Quasi-conformal transformation to obtain collimated lenses: multi-beams.



Q. Wu, Z. H. Jiang, O. Quevedo-Teruel, J. P. Turpin, W. Tang, Y. Hao, D. H. Werner, *IEEE Transactions on Antennas and Propagation,* vol.61, no.12, pp.5910-5922, Dec. 2013.

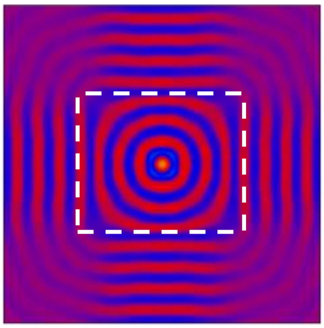


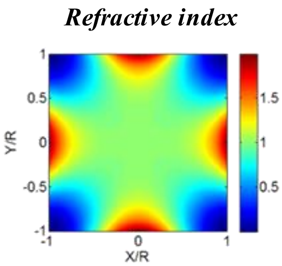


26

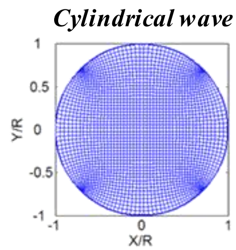
From cylindrical to squared waves

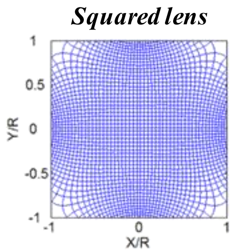
- Optical transformations can be used to create completely new type of lenses.
  - Transformation of a cylindrical wave in four directive beams.





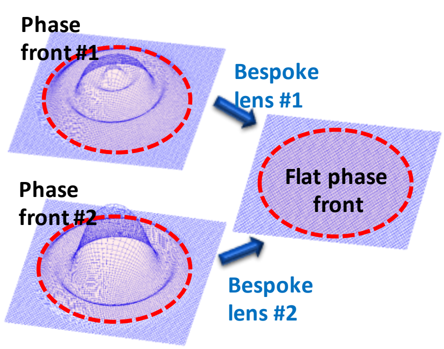
R. C. Mitchell-Thomas, M. Ebrahimpouri and O. Quevedo-Teruel, *Eucap 2015*.

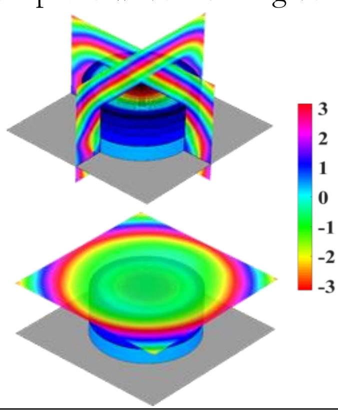


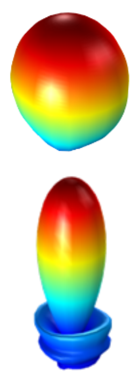


Bespoke lenses

- To produce ad-hoc lens for practical feedings.
- Most common situation is to produce a plane wave from a given radiator:
  - To increase the directivity.



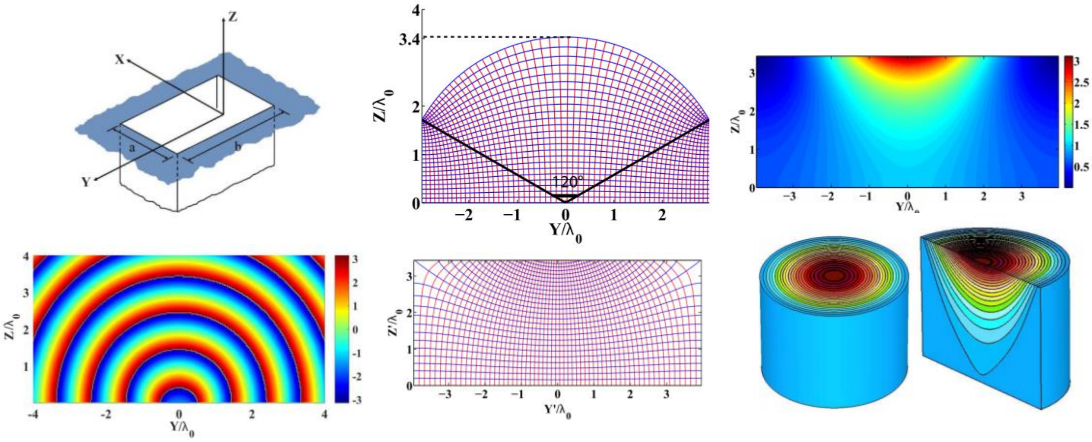




M. McCall, J. Pendry, V. Galdi, Y. Lai, S. Horsley, J. Li, J. Zhu, R. C. Mitchell-Thomas, O. Quevedo-Teruel, P. Tassin, V. Ginis, E. Martini, G. Minatti, S. Maci, M. Ebrahimpouri, Y. Hao, P. Kinsler, J. Gratus, J. Lukens, A. M. Weiner, U. Leonhardt, I. Smolyaninov, V. Smolyaninova, R. Thompson, M. Wegener, M. Kadic, S. Cummer, "Roadmap on transformation optics", Journal of Optics, Volume 20, Number 6, May 2018.

Bespoke lenses: Aperture antenna (I)

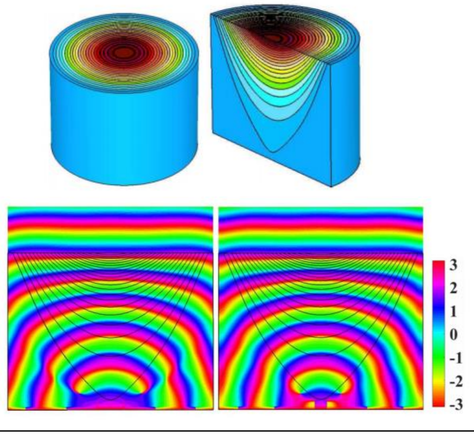
- Technique: Obtaining the map for the lens.

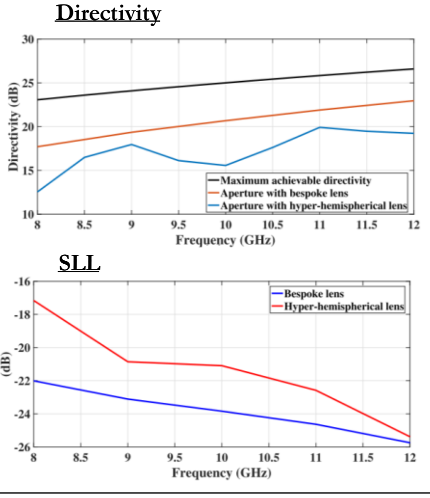


M. Ebrahimpouri, O. Quevedo-Teruel, "Bespoke Lenses Based on Quasi Conformal Transformation Optics Technique", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2256-2264, May 2017.

Bespoke lenses: Aperture Antenna (II)

- Technique: Final design and results.

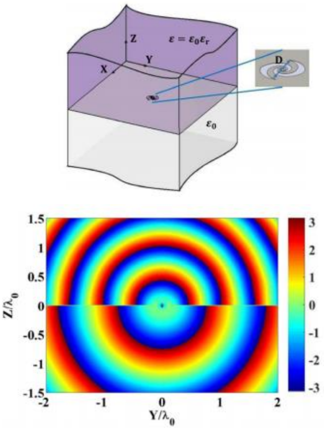


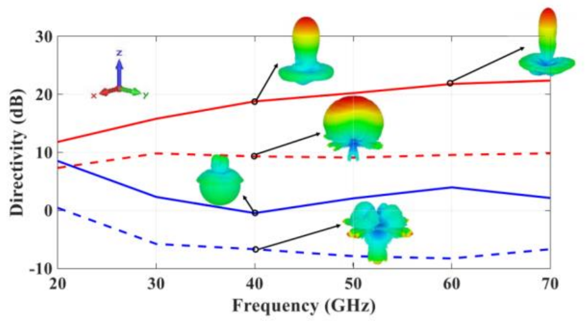


M. Ebrahimpouri, O. Quevedo-Teruel, "Bespoke Lenses Based on Quasi Conformal Transformation Optics Technique", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2256-2264, May 2017.

Bespoke lenses: Spiral antenna

- The lens is not limited in bandwidth and it applies to both polarizations:

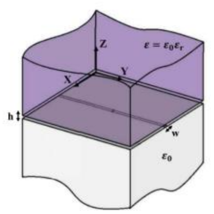


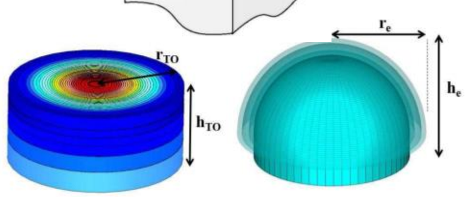


M. Ebrahimpouri, O. Quevedo-Teruel, "Bespoke Lenses Based on Quasi Conformal Transformation Optics Technique", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2256-2264, May 2017.

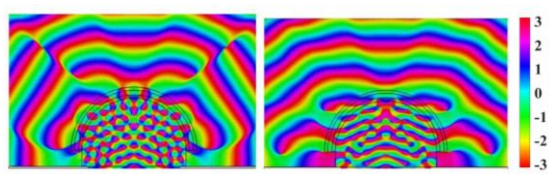
Bespoke lenses: Slot lines

- The lens is not limited in bandwidth.

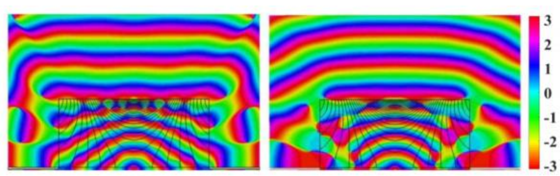




Conventional lens



Bespoke lens



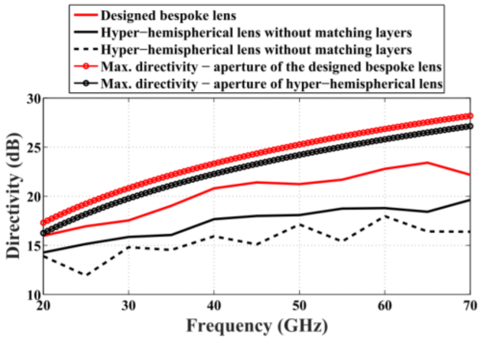
M. Ebrahimpouri, O. Quevedo-Teruel, "Bespoke Lenses Based on Quasi Conformal Transformation Optics Technique", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2256-2264, May 2017.

A. Neto, "UWB, non dispersive radiation from the Planarly fed leaky lens antenna—Part 1: Theory and design," IEEE Trans. Antennas Propag., vol. 58, no. 7, pp. 2238–2247, Jul. 2010.

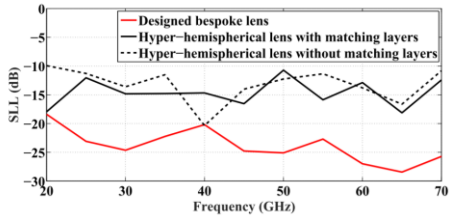
Bespoke lenses: Slot lines

- Figures of merit.

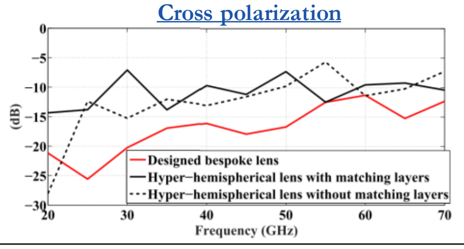
Directivity



SLL



Cross polarization



M. Ebrahimpouri, O. Quevedo-Teruel, "Bespoke Lenses Based on Quasi Conformal Transformation Optics Technique", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2256-2264, May 2017.

A. Neto, "UWB, non dispersive radiation from the Planarly fed leaky lens antenna—Part 1: Theory and design," IEEE Trans. Antennas Propag., vol. 58, no. 7, pp. 2238–2247, Jul. 2010.

Outline

- Theory:
  - Transformation optics concept.
  - Types:
    - Analytical transformation.
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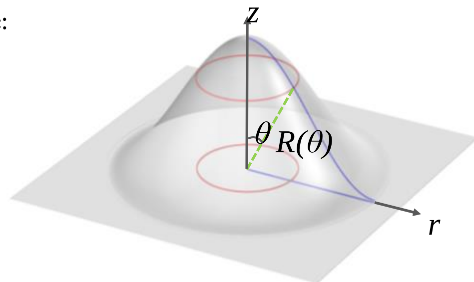
    - Non-Euclidean transformation.
- Practice:
  - Lens design.
    - Conformal lenses.
    - Compressed lenses.
    - Planar Lenses.
    - Collimated lenses.
    - Bespoke lenses.
  - Surface propagation.
    - Cloaking.
    - Surface waves lensing.
- Conclusions.

Theory

- The refractive index distribution of a rotationally symmetric curved surface can mimic a equivalent a flat homogeneous surface:



$$\int_0^{\pi/2} n(\theta)\sqrt{R(\theta)^2 + R'(\theta)^2}\, d\theta = \int_0^a dr$$

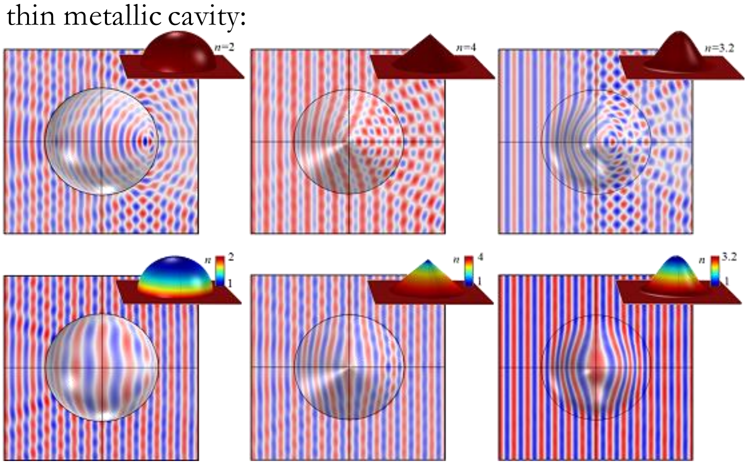
$$2\pi R(\theta)\sin(\theta)\, n(\theta) = 2\pi r$$

$$\Rightarrow \quad \frac{n'(\theta)}{n(\theta)} = \frac{\sqrt{R(\theta)^2 + R'(\theta)^2} - R'(\theta)\sin\theta - R(\theta)\cos\theta}{R(\theta)\sin\theta}$$

R. C. Mitchell-Thomas, T.M. McManus, O. Quevedo-Teruel, S.A.R. Horsley, Y. Hao, "Perfect Surface Wave Cloaks", *Physical Review Letters*, vol. 111, p. 213901, Nov 2013.

Results

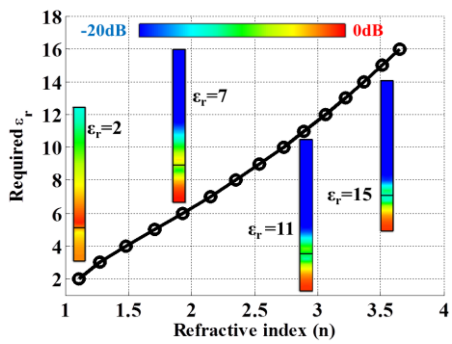
- Cloaking in a thin metallic cavity:

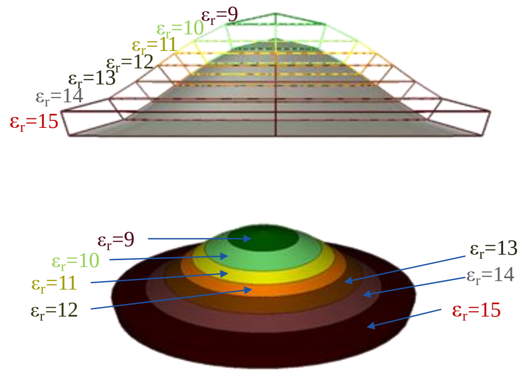


R. C. Mitchell-Thomas, T.M. McManus, O. Quevedo-Teruel, S.A.R. Horsley, Y. Hao, "Perfect Surface Wave Cloaks", *Physical Review Letters*, vol. 111, p. 213901, Nov 2013.

Surface waves implementation

- Slabs of different dielectric constants with constant thickness.



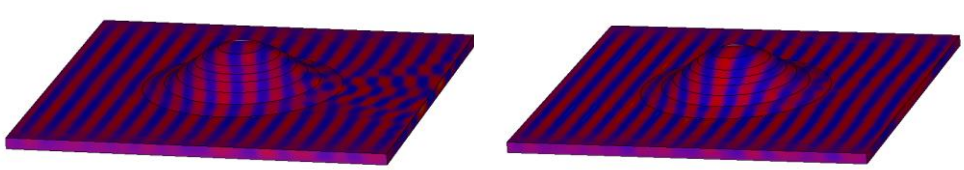


R. C. Mitchell-Thomas, T.M. McManus, O. Quevedo-Teruel, S.A.R. Horsley, Y. Hao, "Perfect Surface Wave Cloaks", *Physical Review Letters*, vol. 111, p. 213901, Nov 2013.

Surface waves results

- Very robust design.
- Only 7 layers have been used.
- Small deviations in the manufacturing process would not seriously influence the performance.

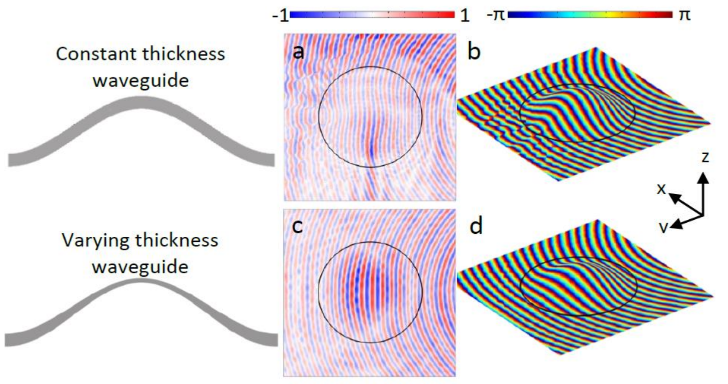
Uniform material | After cloaking



R. C. Mitchell-Thomas, T.M. McManus, O. Quevedo-Teruel, S.A.R. Horsley, Y. Hao, "Perfect Surface Wave Cloaks", *Physical Review Letters*, vol. 111, p. 213901, Nov 2013.

Experimental results

- Implementation with a single dielectric slab which changes the with the position to achieve different equivalent refractive indexes.



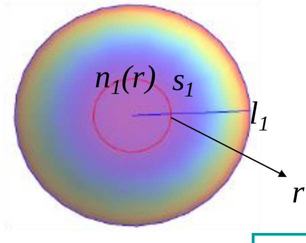
R. Mitchell-Thomas, O. Quevedo-Teruel, J. R. Sambles, A. P. Hibbins, "Omnidirectional surface wave cloak using an isotropic homogeneous dielectric coating" *Scientific Reports*, vol. 6, article number 30984, 2016.

Non-Euclidian mapping

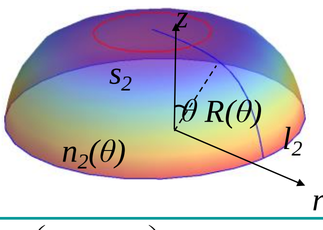
- By equating optical path lengths, it is possible to calculate the refractive index of a lens on a curved surface.

R.C. Mitchell-Thomas, O. Quevedo-Teruel, T.M. McManus, S.A.R. Horsley, and Y. Hao, "Lenses on Curved Surfaces", *Optics Letters*, vol. 39, pp. 3551-3554, 2014.

Flat space



Arbitrarily curved space



$$\int_0^{\pi/2} n_2(\theta)\sqrt{R(\theta)^2+R'(\theta)^2}\,d\theta = \int_0^a n_1(r)dr$$

$$2\pi\cdot R(\theta)\cdot n_2(\theta)\sin(\theta) = 2\pi\cdot r\cdot n_1(r)$$

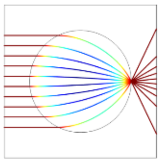
$$s_1 = 2\pi n_1(r)$$

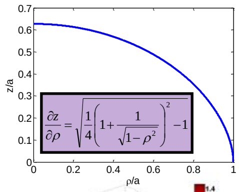
$$l_1 = \int_0^a n_1(r)dr$$

$$\frac{n_2'(\theta)}{n_2(\theta)} = \frac{\left(1+\frac{n_1'(r)}{n_1(r)}\right)\sqrt{R(\theta)^2+R'(\theta)^2} - R'(\theta)\sin(\theta) - R(\theta)\cos(\theta)}{R(\theta)\sin(\theta)}$$

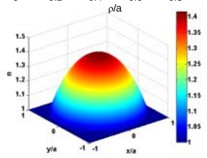
Luneburg lens examples

M. Sarbort and T. Tyc, Journal of Optics, 2012.

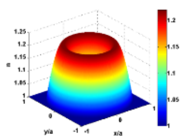


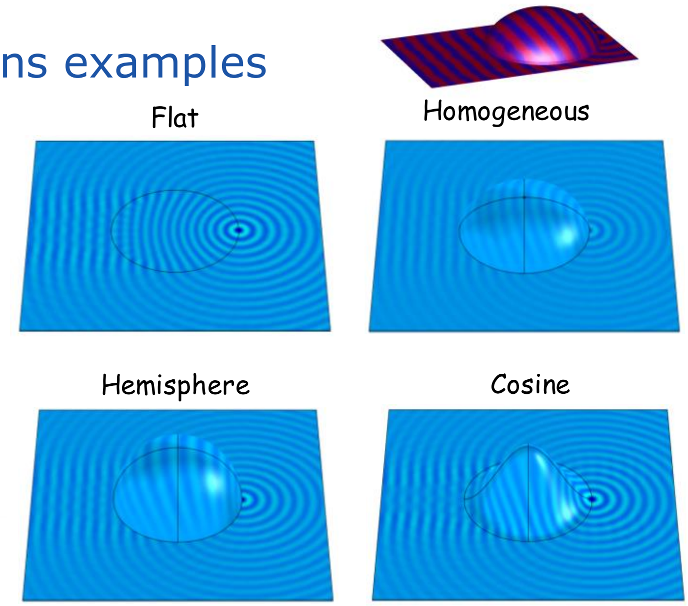


$$n(r)=\sqrt{2-\left(\frac{\rho}{a}\right)^2}$$



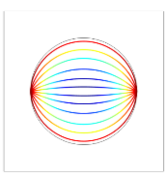
$$n(\theta)=\frac{\sqrt{1+3\cos(\theta)}}{(1+\cos(\theta))^{3/2}}$$



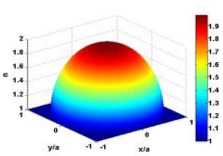


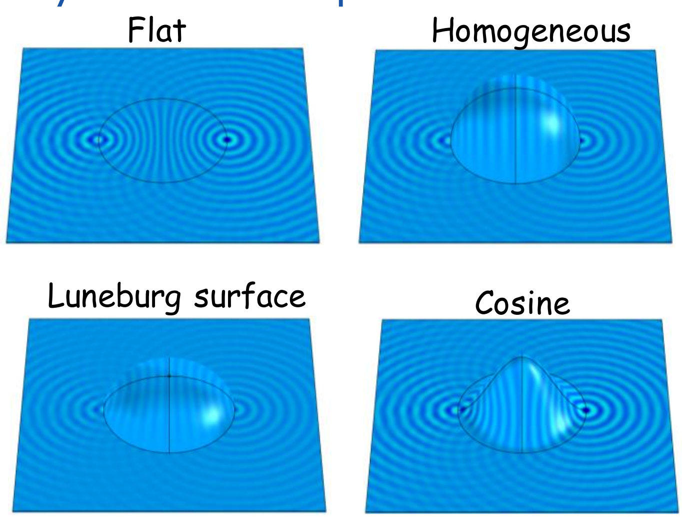
R.C. Mitchell-Thomas, O. Quevedo-Teruel, T.M. McManus, S.A.R. Horsley, and Y. Hao, "Lenses on Curved Surfaces", *Optics Letters*, vol. 39, pp. 3551-3554, 2014.

Maxwell fish eye lens examples



$$n(r)=\frac{n_0}{1+r^2}$$

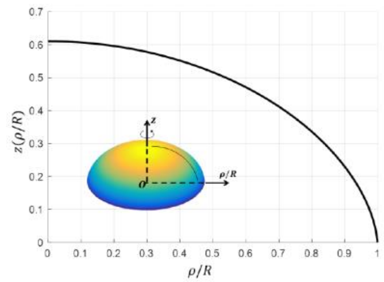


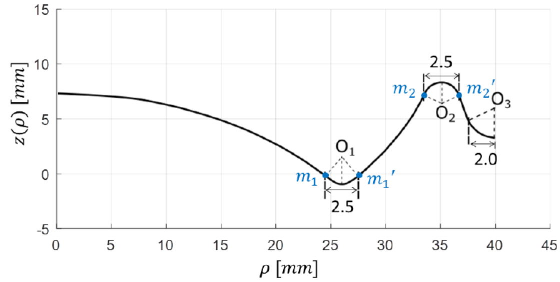


R.C. Mitchell-Thomas, O. Quevedo-Teruel, T.M. McManus, S.A.R. Horsley, and Y. Hao, "Lenses on Curved Surfaces", *Optics Letters*, vol. 39, pp. 3551-3554, 2014.

Lens implementation

- A Luneburg lens can be implemented with this technique.
- The surface can be bended to reduce the vertical dimension.

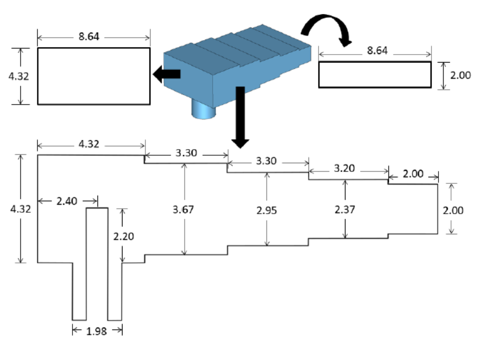


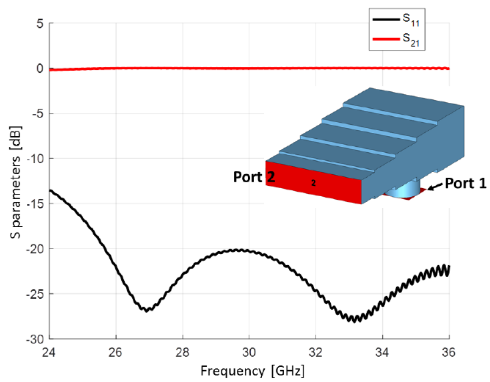


Q. Liao, N.J.G. Fonseca, O. Quevedo-Teruel, "Compact Multibeam Fully Metallic Geodesic Luneburg Lens Antenna Based on Non-Euclidean Transformation Optics", *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 7383-7388, Dec. 2018.

Antenna design

- Waveguides as connectors.
- Optimized flare design.





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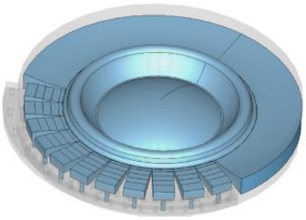
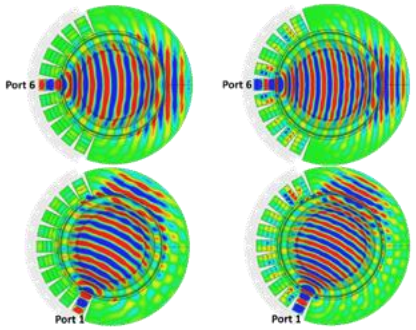
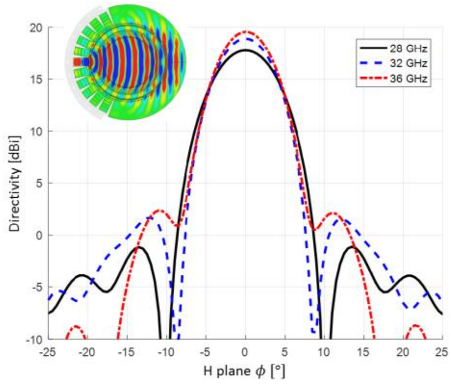
Luneburg lens antenna



- The antenna is fed with coaxial ports.
- Each port excitation produces a different beam.

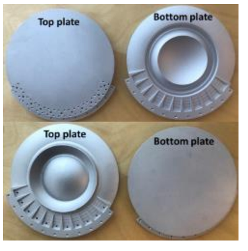


28 GHz 36 GHz



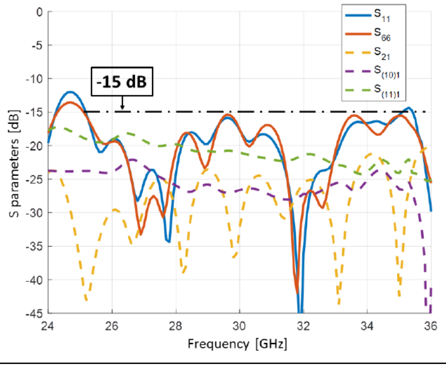
Q. Liao, N.J.G. Fonseca, O. Quevedo-Teruel, "Compact Multibeam Fully Metallic Geodesic Luneburg Lens Antenna Based on Non-Euclidean Transformation Optics", *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 7383-7388, Dec. 2018.

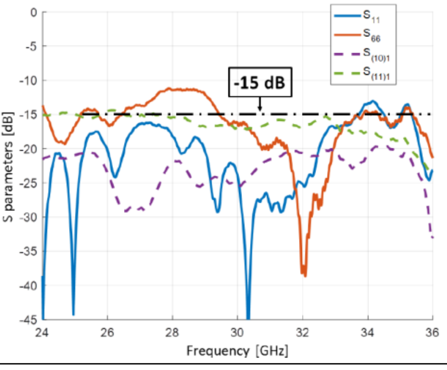
Matching



- Slightly higher mismatch in measurements

Simulations **Measurements**





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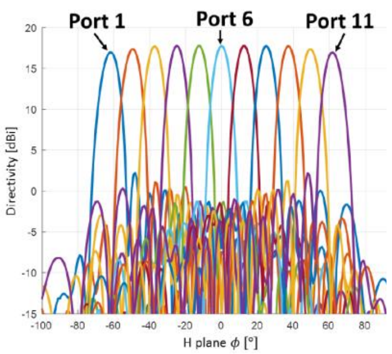
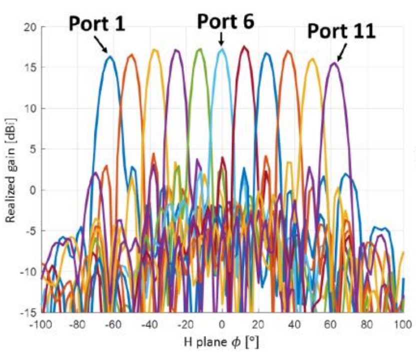
Radiation patterns

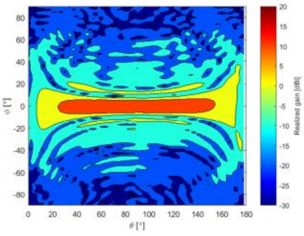
- Good agreement with simulations

Simulations



Measurements





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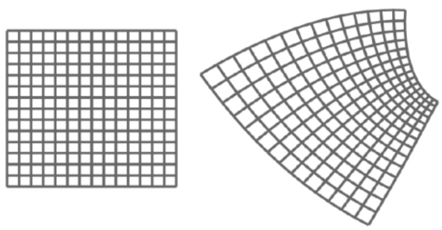
    - Compressed lenses.
    - Planar Lenses.
    - Collimated lenses.
    - Bespoke lenses.
  - Surface propagation.
    - Cloaking.
    - Surface waves lensing.
- Conclusions.

Conclusions

- The concept of Transformation Optics has been introduced.
- Three possible methodologies: Euclidean (analytical and discrete) and non-Euclidean have been drawn, and their advantages and disadvantages have been summarized.
- Few examples of design has been introduced:
  1. Conformal lenses:
     - They can be used to design lenses which bespoke surfaces.
  2. Planar lenses:
     - The use of metamaterials is not necessary for this design.
     - Measurements corroborate the original results.
  3. Surface propagation:
     - Cloaking has been demonstrating to be obtain with only full dielectric materials.
     - This technique can be employed to produce lenses conformal to surfaces and to eliminate singularities of lenses.



Transformation optics and its applications to antennas

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