Metamaterial Surfaces for Near and Far-Field Applications

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Metamaterials

•Metamaterials are engineered materials with tailored electromagnetic properties. They derive their properties from their subwavelength texture.

•Extreme control over electromagnetic fields can be achieved with metamaterials.

•Progress in metamaterials has enabled a myriad of devices: superlenses, invisibility cloaks, novel antennas and microwave/optical devices.

•However, the notable thickness of volumetric metamaterials can lead to bulky devices, fabrication challenges and even added losses.

•These concerns have driven the development of metamaterial surfaces: metasurfaces.

Metasurfaces

•Metasurfaces: two dimensional equivalents of metamaterials.

•Metasurfaces are textured at a subwavelength scale much like bulk metamaterials exhibit subwavelength granularity.

•They can be described macroscopically in terms electric and magnetic polarizabilities, just as bulk metamaterials are described using effective material parameters: permittivity and permeability.

•Alternatively, metasurfaces can be described in terms of electric and magnetic surface impedances / admittances.

C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, *IEEE Antennas and Propagation Magazine,* Vol. 54, pp. 10-35, April 2012.

A. Grbic, R. Merlin, E.M. Thomas, M.F. Imani, *Proceedings of the IEEE*, vol. 99, pp. 1806-1815, October 2011.

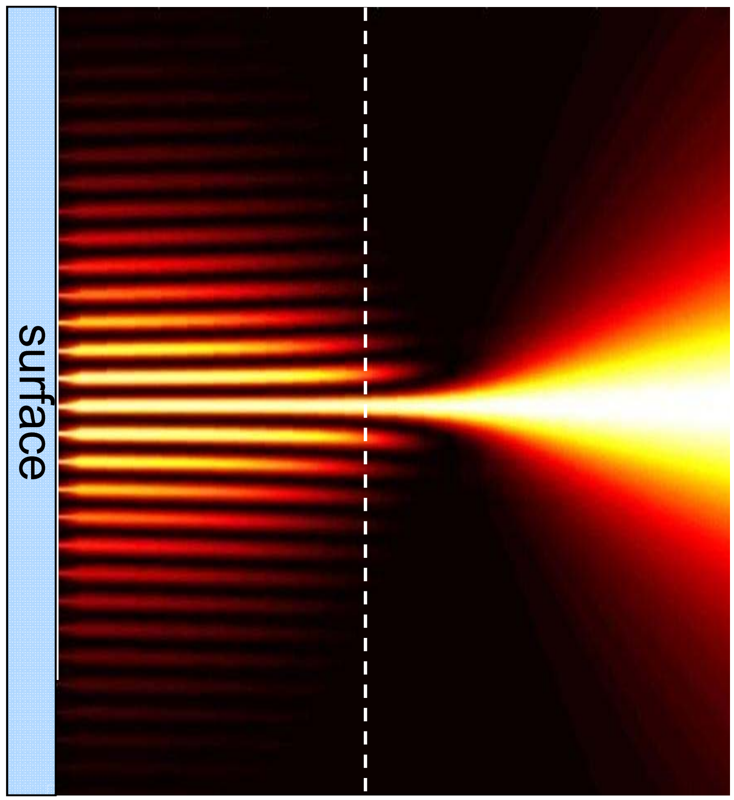
Outline

•Metasurfaces for near-field manipulation will be presented: near-field plates (non-periodic metasurfaces) for subwavelength focusing and detection, and leaky radial waveguides (periodic metasurfaces) for the generation of propagating Bessel beams.

•Reflectionless metasurfaces based on the Huygens' principle / surface equivalence principle that can tailor electromagnetic wavefronts will be introduced. These surfaces provide new beam shaping, steering, and focusing capabilities.

•Planar metamaterials for the design of transformation electromagnetics devices will be reviewed and their operation explained. These circuit-based metamaterials can possess tensorial effective material parameters.

Metamaterial surfaces for manipulating the near field



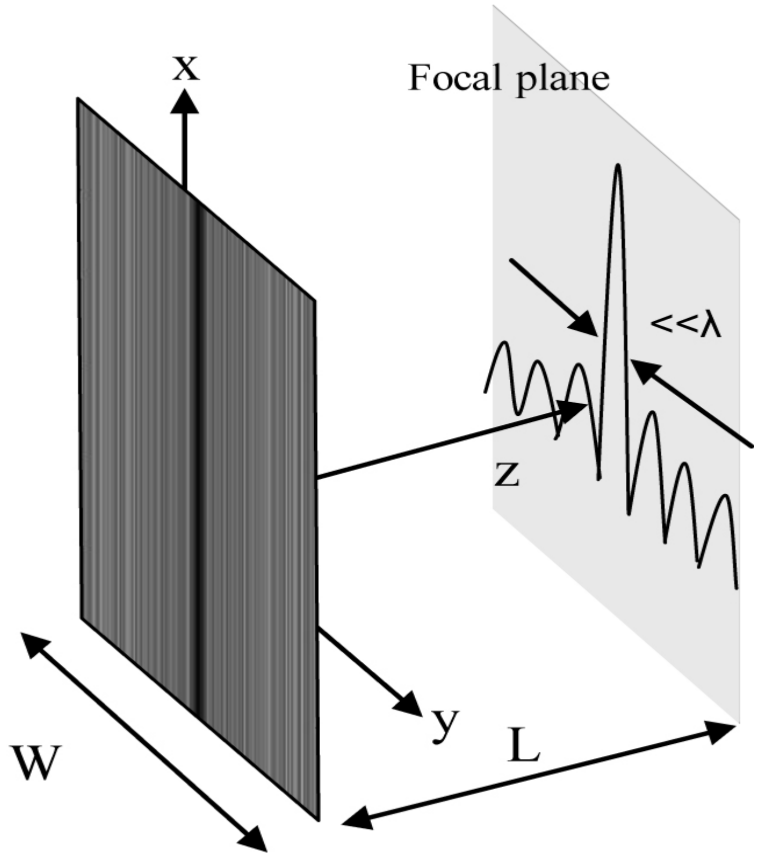
Near-field plates

- A few years ago, a new method of subwavelength focusing was proposed.

  A general class of aperture fields was proposed that can form a near-field focus.

  R. Merlin, "Radiationless electromagnetic interference: evanescent-field lenses and perfect focusing," *Science*, **317**, pp. 927-929, August 2007.

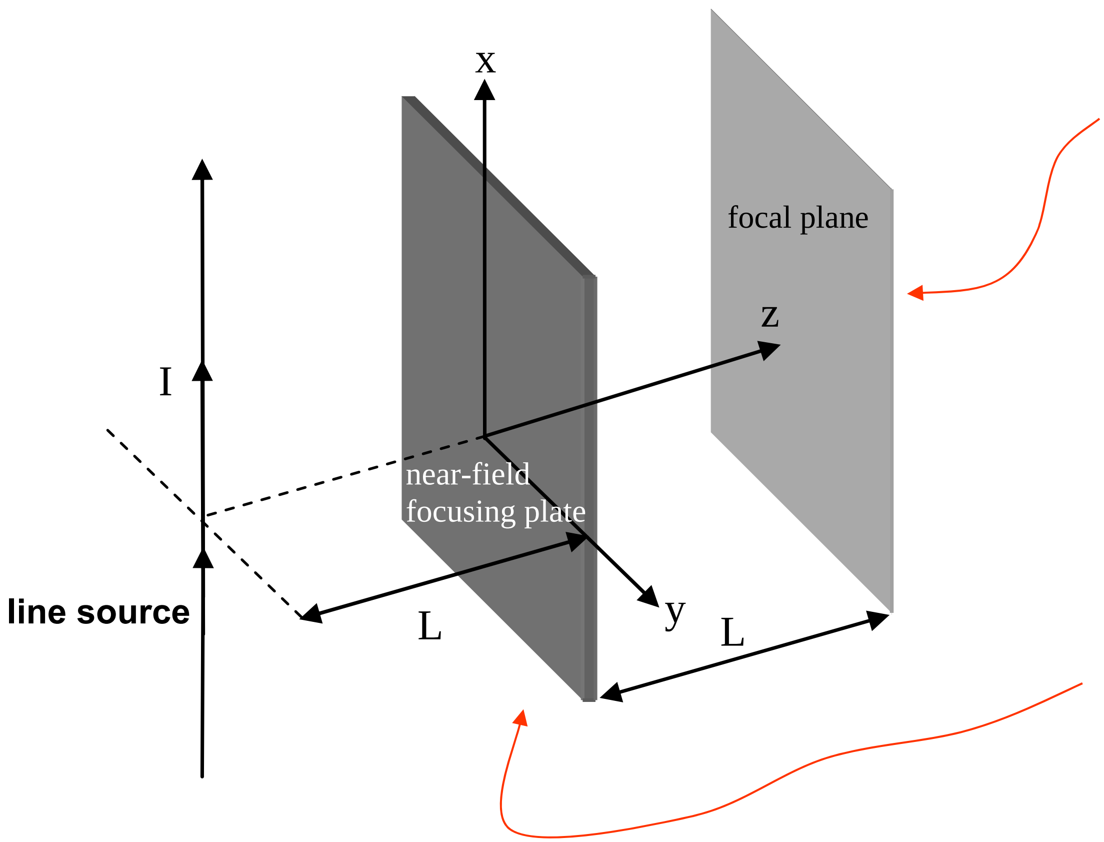
- A near-field plate is a non-periodic patterned, grating-like surface that can focus electromagnetic waves to subwavelength dimensions.



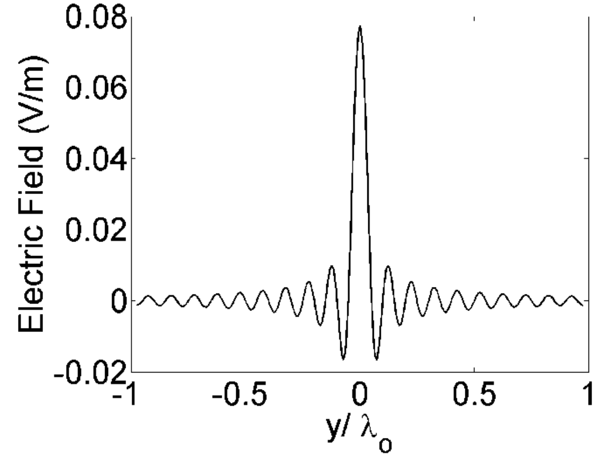
A. Grbic and R. Merlin, “Near-field focusing plates and their design”, *IEEE Transactions on Antennas and Propagation*, **56**, pp. 3159-3165, October 2008.

A. Grbic, L. Jiang, and R. Merlin, “Near-Field Plates: Subdiffraction focusing with patterned surfaces,” *Science*, **320**, April 2008.

Aperture fields and subwavelength focal patterns

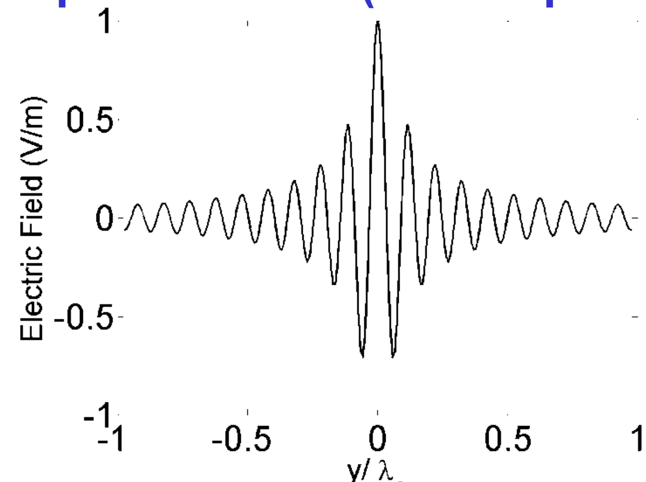


Desired Focal Pattern



$$E_x(y, z = L) \approx e^{-q_o L} q_o L \sin c(q_o y)$$

Aperture Field (field at plate)



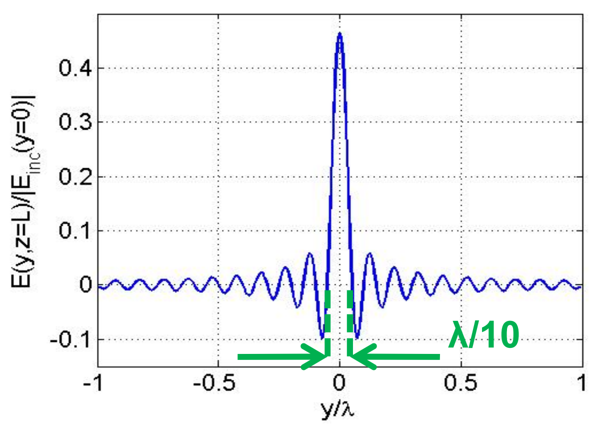
$$E_{total}(y) = E_x(y, z = 0) \approx \frac{L[L\cos(q_o y) + y\sin(q_o y)]}{L^2 + y^2}$$

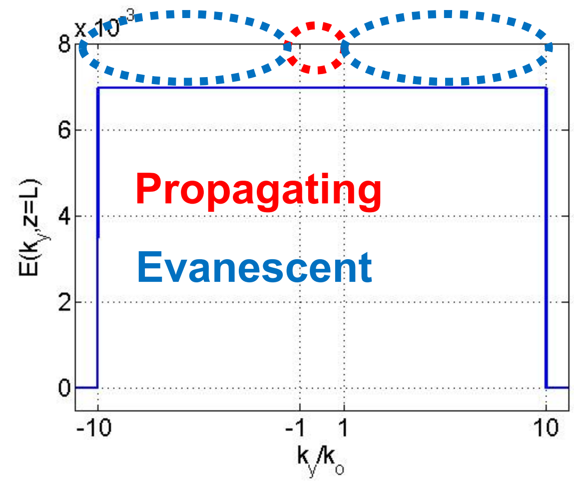
A. Grbic, R. Merlin, E.M. Thomas, M.F. Imani, "Near-field plates: metamaterial surfaces / arrays for subwavelength focusing and probing," *Proceedings of the IEEE*, vol. 99, pp. 1806-1815, Oct. 2011.

Spatial spectrum of aperture fields and focal patterns

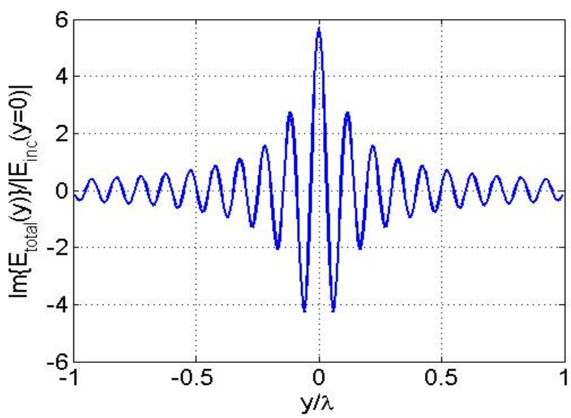
Spatial Form | **Spectral Form**

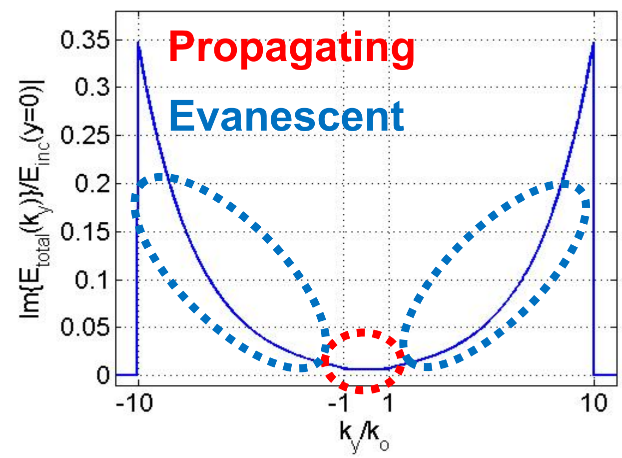
Focal Pattern





Aperture Field

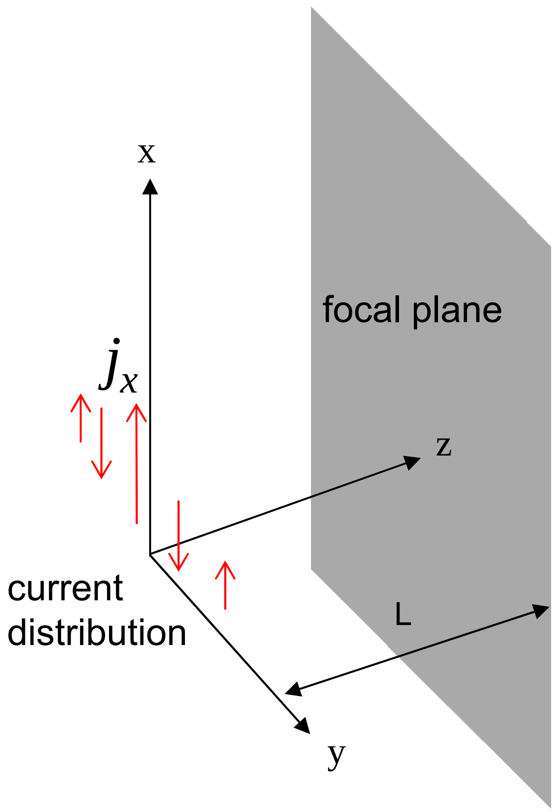


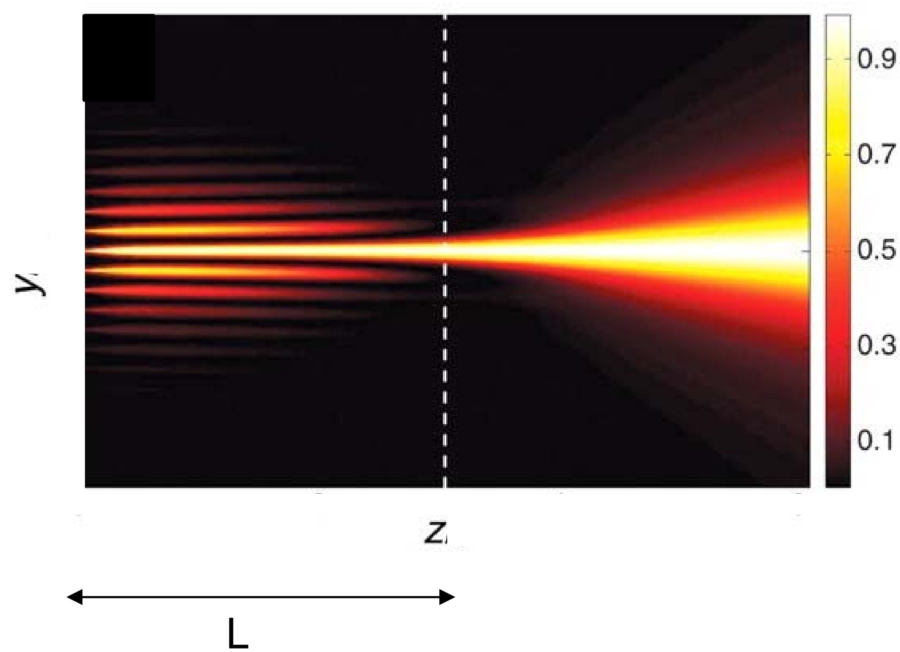


A. Grbic, R. Merlin, E.M. Thomas, M.F. Imani, "Near-field plates: metamaterial surfaces / arrays for subwavelength focusing and probing," *Proceedings of the IEEE*, vol. 99, pp. 1806-1815, Oct. 2011.

Contour plot of the electromagnetic field

The near-field plate supports a highly oscillatory current distribution (aperture field) that focuses the electromagnetic near field to a subwavelength focus.





Design procedure for near-field plates

1) The current density needed to produce the focal pattern is computed.

2) The tangential field at the surface of the plate is found.

3) The surface impedance is calculated from the ratio of the current density to tangential field.

4) The surface is discretized into subwavelength elements. Each surface element is textured in order to realize the required impedance profile.

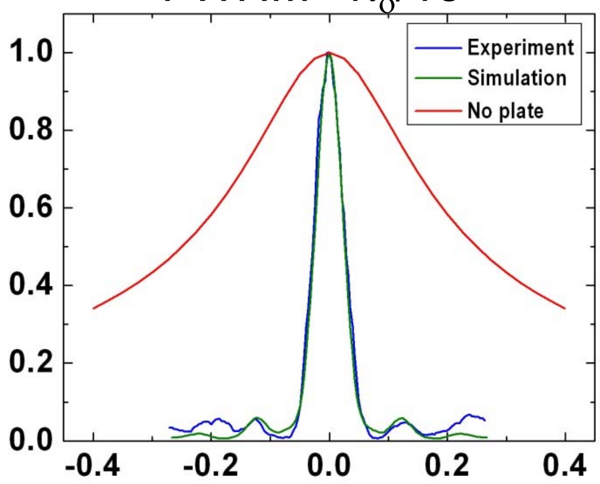
Initial near-field plate implementation

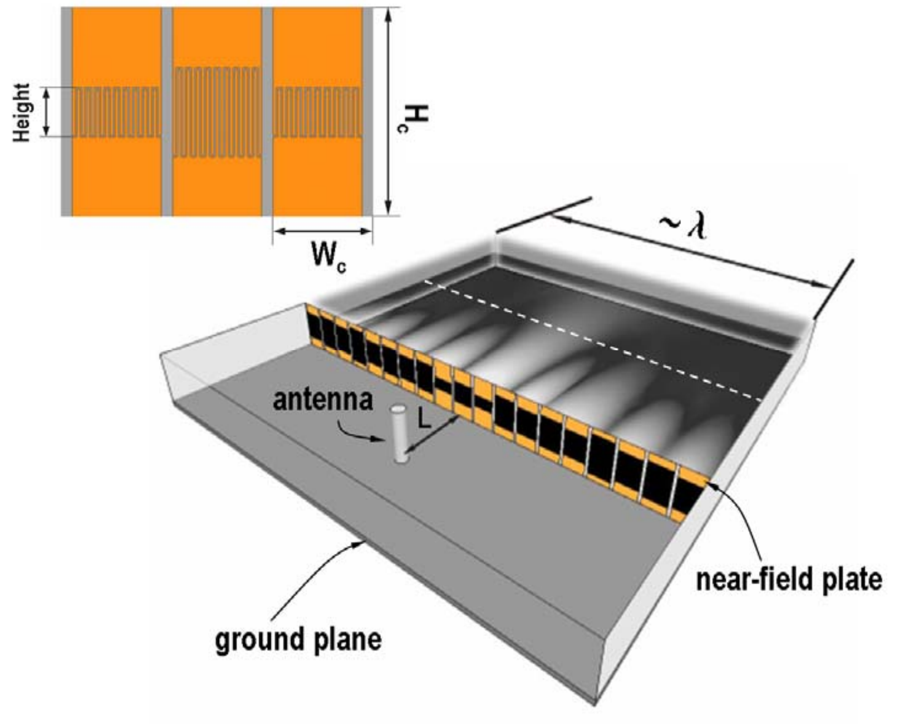
- This design procedure has been used to implement a near-field plate at microwave frequencies.

A. Grbic, L. Jiang, R. Merlin, "Near-field plates: subdiffraction focusing with patterned surfaces," *Science*, **320**, pp. 511-513, Apr. 25, 2008.

Frequency 1.027 GHz

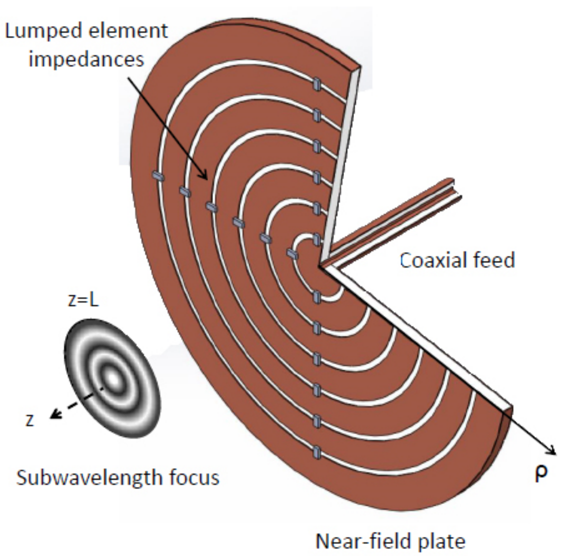
FWHM= $\lambda_o/18$

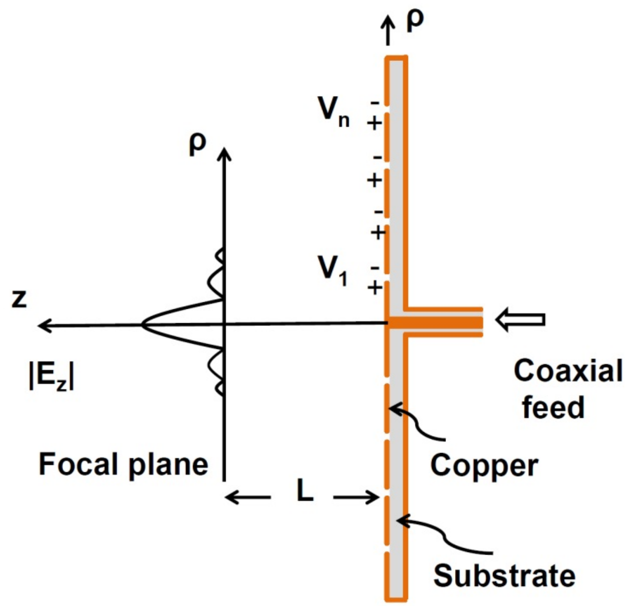




Printed, concentric near-field plates

- Printed near-field plates (NFPs) consist of concentric annular slots, loaded with reactive elements, over a grounded dielectric substrate. The slots are non-periodically loaded to achieve a desired subwavelength focal pattern.





M.F. Imani and A. Grbic, “Design of a planar near-field plate”, *IEEE International Symposium on Antennas and Propagation*, 2 pages, Chicago IL, July 8-14, 2012.
M.F. Imani and A. Grbic, “Planar near-field plates,” *IEEE Trans. on Antennas and Propagation*, submitted Jan. 2013.

Design parameters for printed near-field plates

Airy profile

$$E_z^{focal}(\rho) = \frac{J_1(k_{\max}\rho)}{k_{\max}\rho}$$

$$k_{\max} = 12.11k$$

Bessel profile

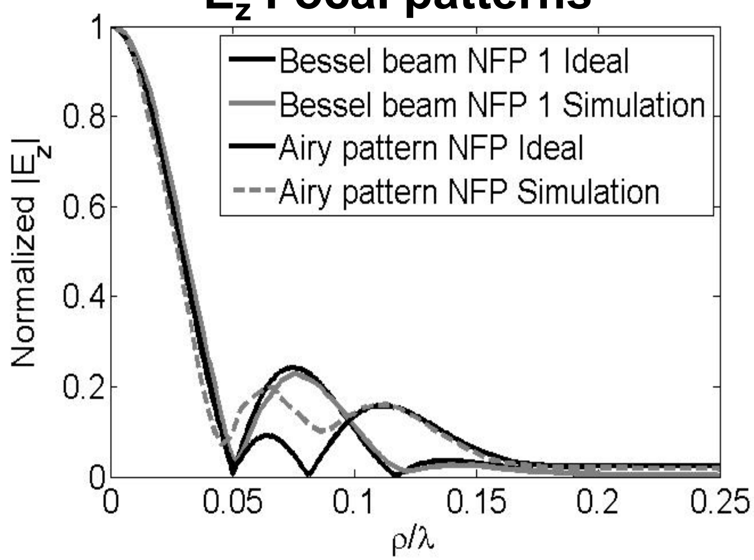
$$E_z^{focal}(\rho) = Ae^{(-\rho^2/2\sigma^2)}e^{(-\sqrt{q^2-k^2}L)}J_0(q\rho)$$

$$q = 7.6k, \sigma = 23\text{mm}$$

Design parameters:

$$f = 1.0GHz,\ N = 6,\ L = \lambda/15 = 2cm, R = 42\text{mm}, w = 0.4\text{mm}, s = 6\text{mm} = \lambda/50$$

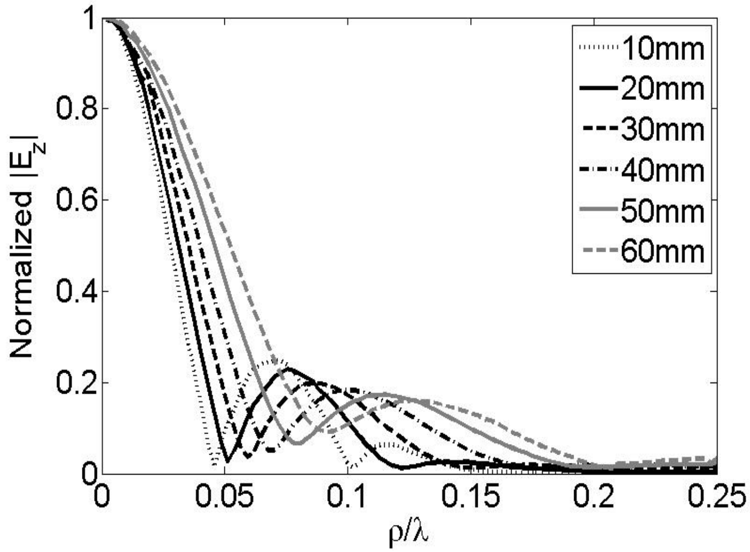
E_z Focal patterns



•Bessel beams are solutions to Maxwell equations which do not undergo diffraction and retain their transverse pattern as they propagate in free space.

Simulated near-field plate performances

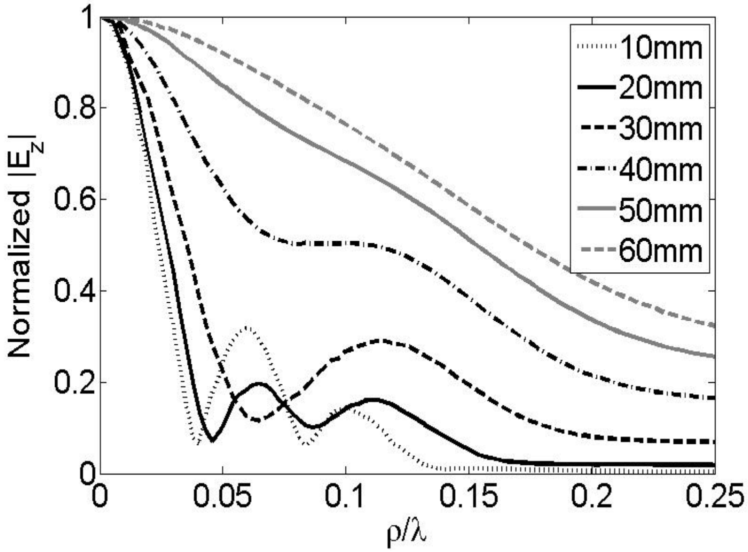
Bessel beam NFP



λ/30

λ/5

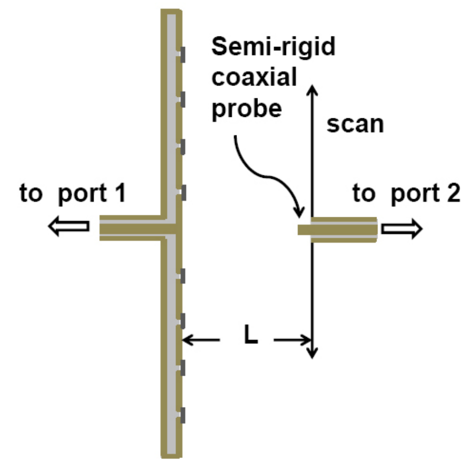
Airy pattern NFP

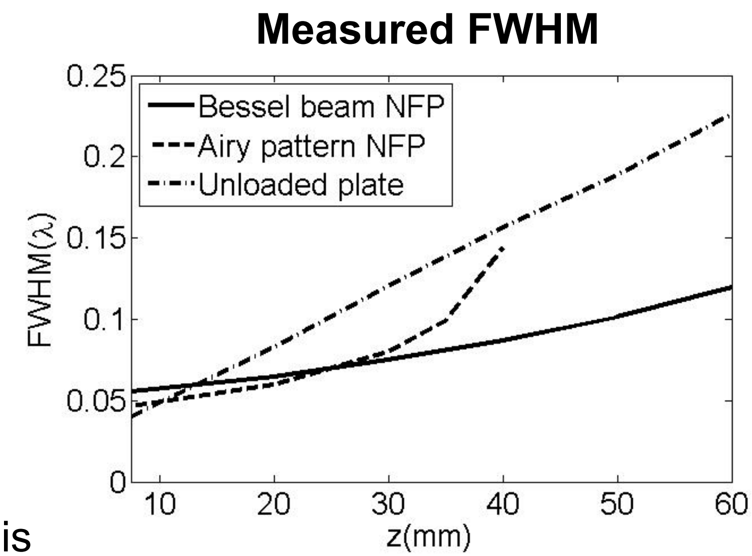


λ/30

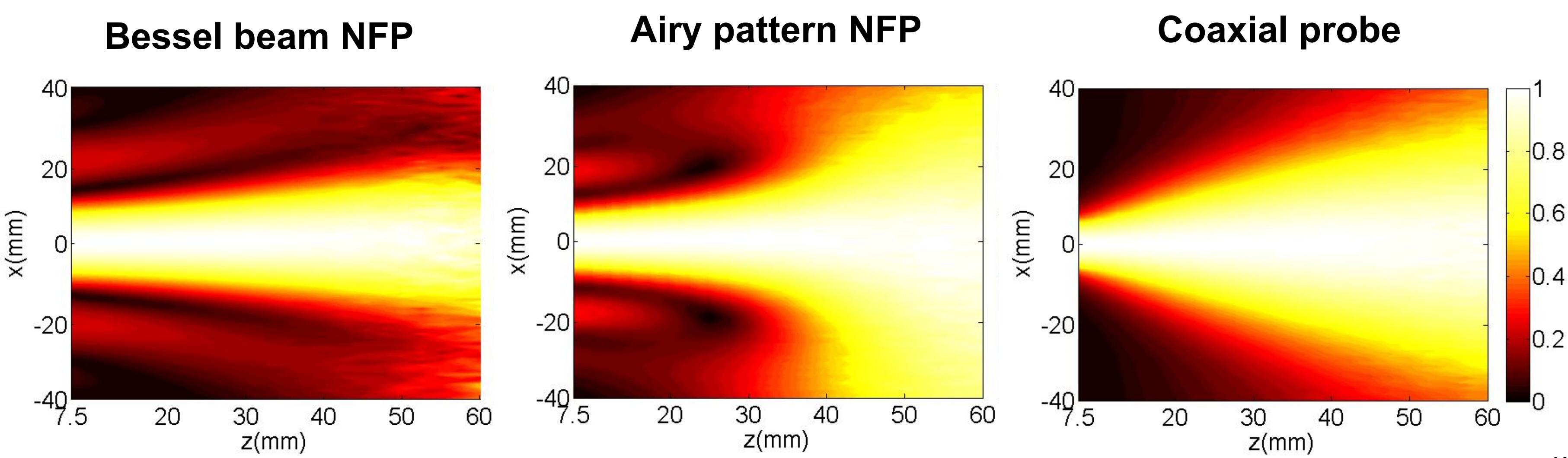
λ/5

Measured beams in the reactive near field (1 GHz)



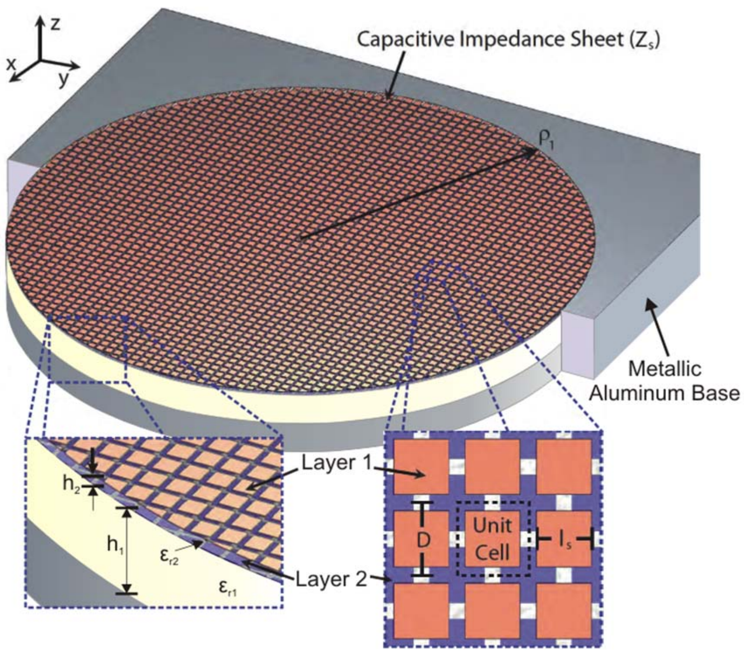


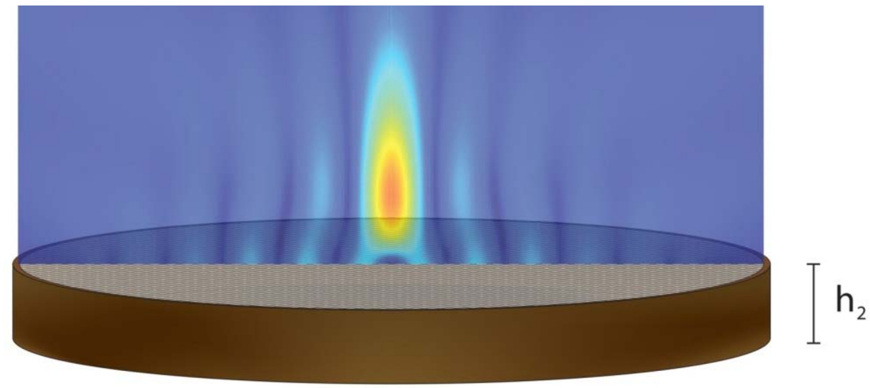
- The measured electric field along each z=z' plane is normalized w.r.t. its maximum value.



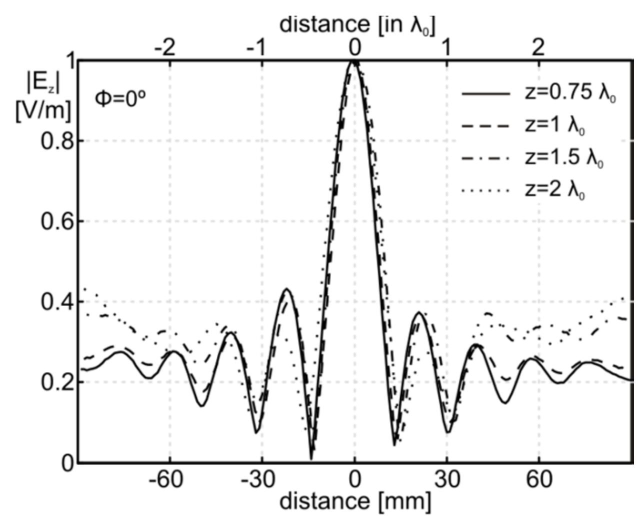
Leaky-wave excitation of propagating Bessel beams

Planar Bessel beam launcher





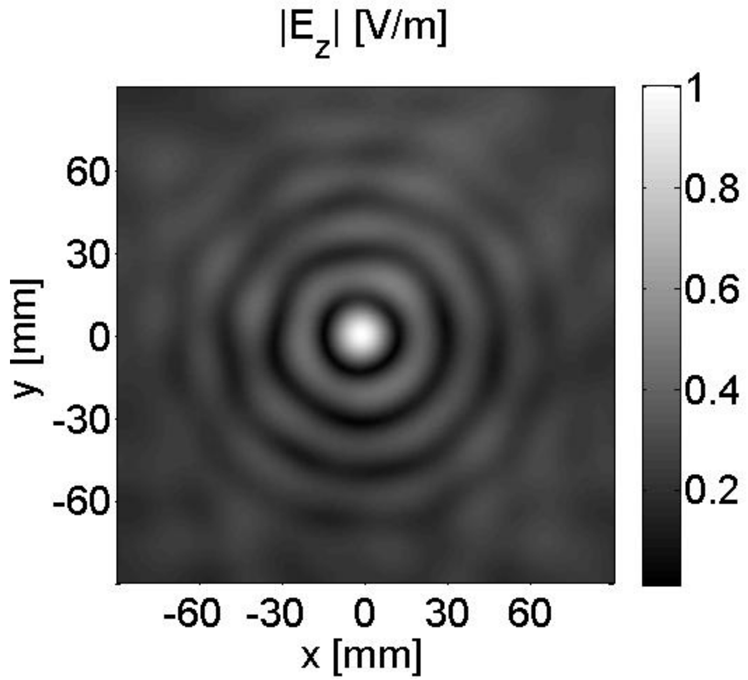
Experiment



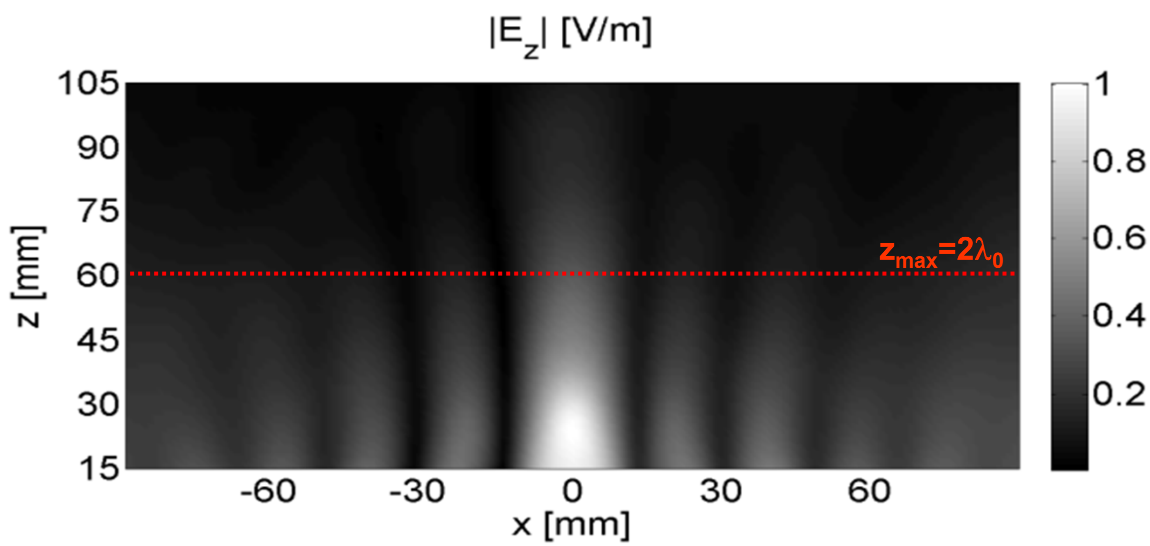
M. Ettorre and A. Grbic, "Generation of propagating Bessel beams using leaky-wave modes," *IEEE Trans. on Antennas and Propagation*, vol. 60, pp. 3605 – 3613, Aug. 2012

M. Ettorre and A. Grbic, "Generation of propagating Bessel beams using leaky-wave modes: experimental validation," *IEEE Trans. on Antennas and Propagation*, vol. 60, pp. 2645 – 2653, Jun. 2012.

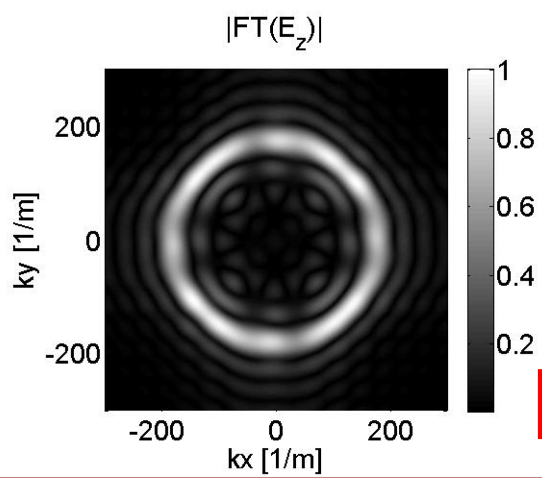
Measured TM polarized Bessel beams (10 GHz)



Beam pattern



Fourier transform



$z=0.75\lambda_0=22.5\text{mm}$

Applications

Microwave frequencies:

At microwave frequencies, metasurfaces that manipulate the near field will find a number of applications:

- Probing devices for non-contact sensing.
- Targeting devices for medical devices.
- Wireless power transfer receivers and transmitters.

THz and optical frequencies:

Nanostructured implementations at these frequencies hold promise for:

- Microscopy
- Near-field optical data storage
- Lithography

Metamaterial Huygens surfaces

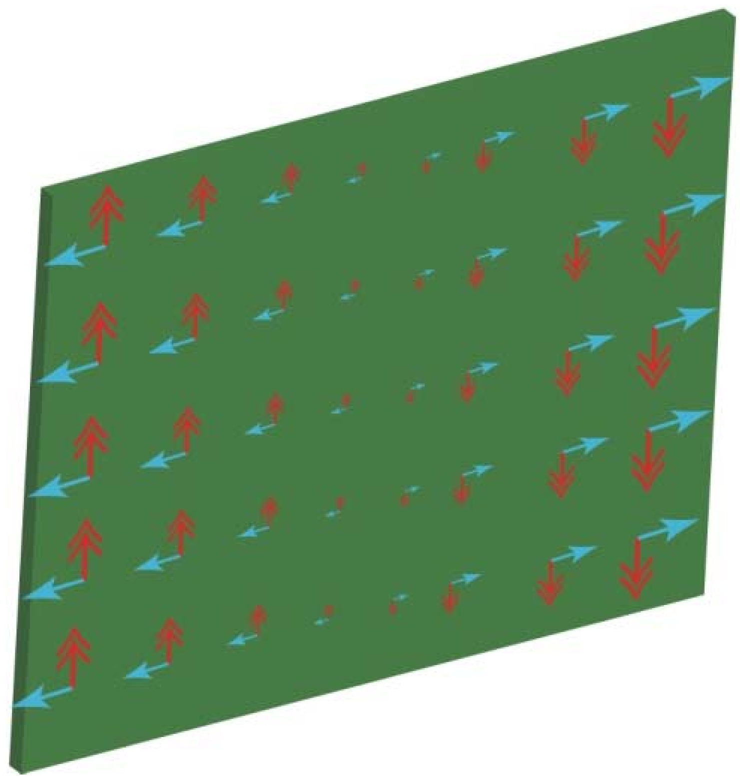
Approach: employ the Surface Equivalence Principle (a rigorous form of Huygens' Principle) to design metamaterial surfaces.

Characteristics:

- textured at a subwavelength scale.
- spatially non-periodic.
- exhibit both electric and magnetic responses.

Advantages:

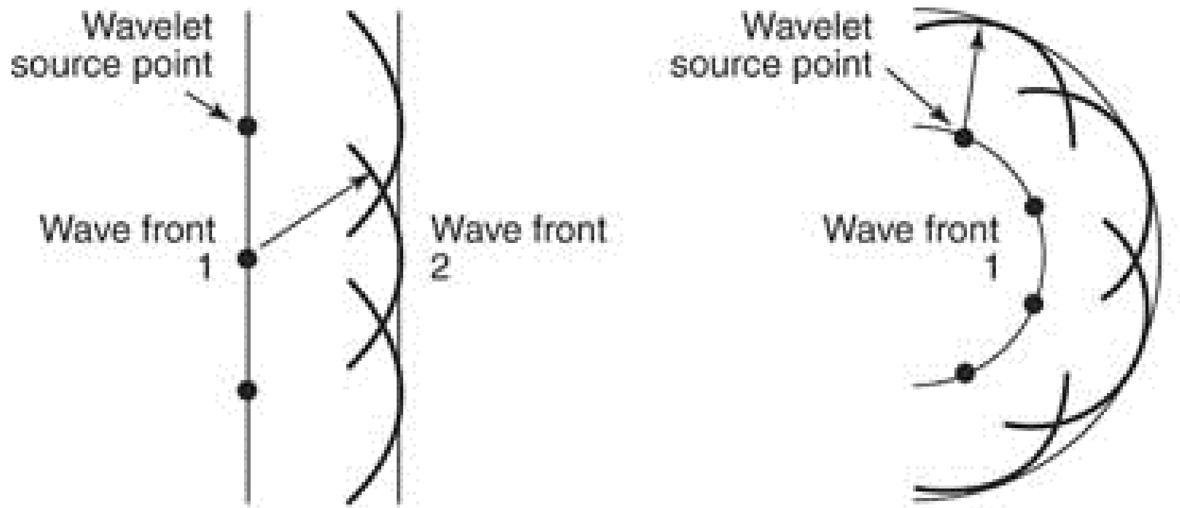
- reflectionless.
- can fully manipulate co- and cross-polarized radiation.
- Can re-direct a beam with nearly 100% efficiency into a refracted beam.



N. Yu, P. Genevet, M. Kats, F. Aieta, J. Tetienne, F. Capasso, and Z. Gaburro, "Light propagation with phase discontinuities: generalized laws of reflection and refraction," *Science*, vol. 334, pp. 333-3337, Oct. 2011.

Huygens' Principle

1678: Christiaan Huygens' proposed that each point on a wavefront acts as a secondary source of outgoing waves [10].



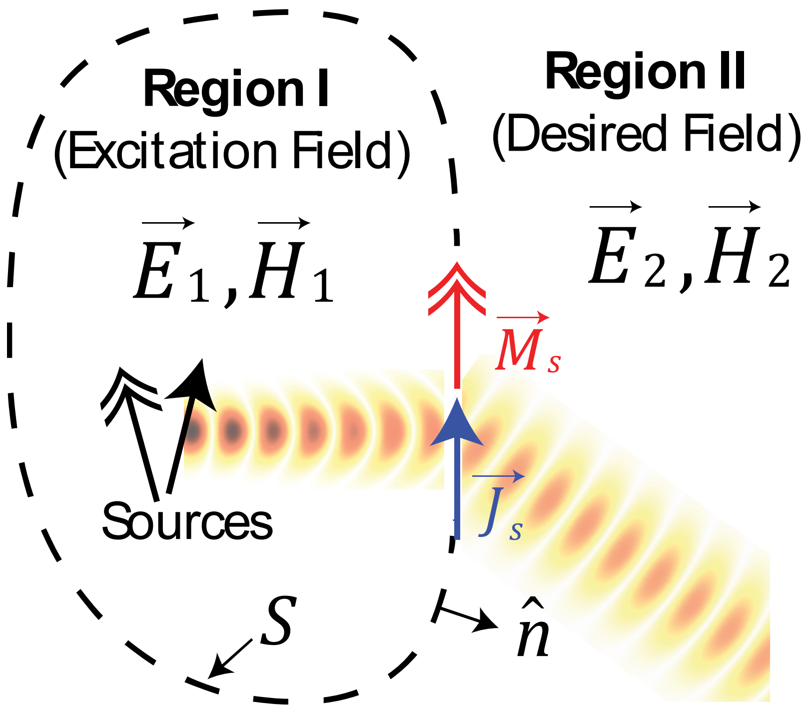
1936: Sergei A. Schelkunoff introduced a rigorous form of the Huygens' principle based on Maxwell's equations: the Surface Equivalence Principle [11].

- Secondary sources are specified in terms of well defined, fictitious electric and magnetic currents.

C. Huygens, *Traite de la Lumiere,* Leyden, 1690. English translation by S. P. Thompson, London, 1912.
S. Schelkunoff, *Bell System Technical Journal*, vol. 15, pp. 92-112, Jan. 1936.

Surface Equivalence Principle

•Employed in the analysis of aperture antennas, diffraction problems, and computational electromagnetics formulations. Here, we use it to design metasurfaces.



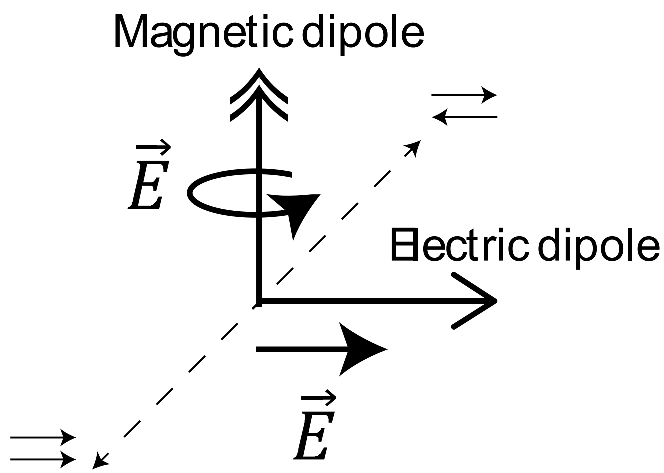
$$\vec{J}_s = \hat{n} \times \left(\vec{H}_2 - \vec{H}_1 \right)$$

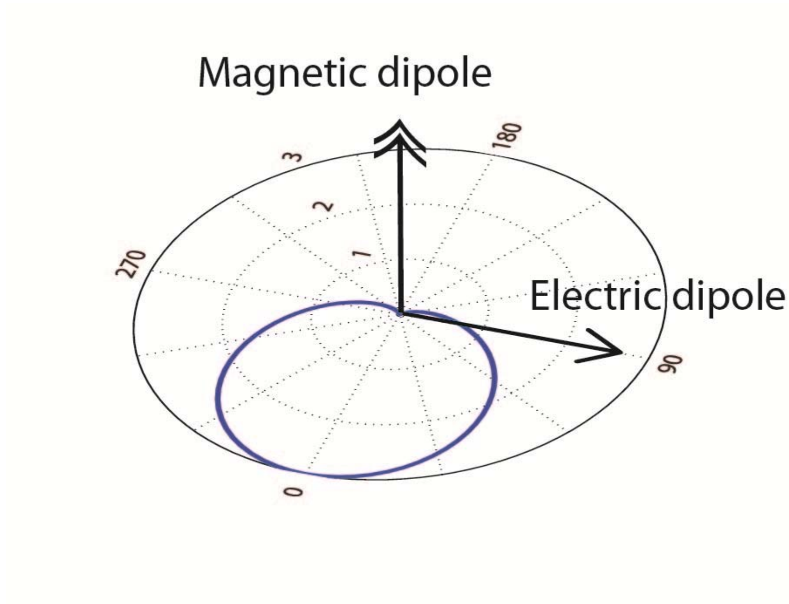
$$\vec{M}_s = -\hat{n} \times \left(\vec{E}_2 - \vec{E}_1 \right)$$

- Using the Surface Equivalence Principle, fictitious electric and magnetic surface currents are derived that produce a null field in the backward direction (zero reflection) and a stipulated field in the forward direction.

Huygens' source

- Simplest example: a Huygens' source (two orthogonal electric and magnetic currents) produces a unidirectional radiation pattern.





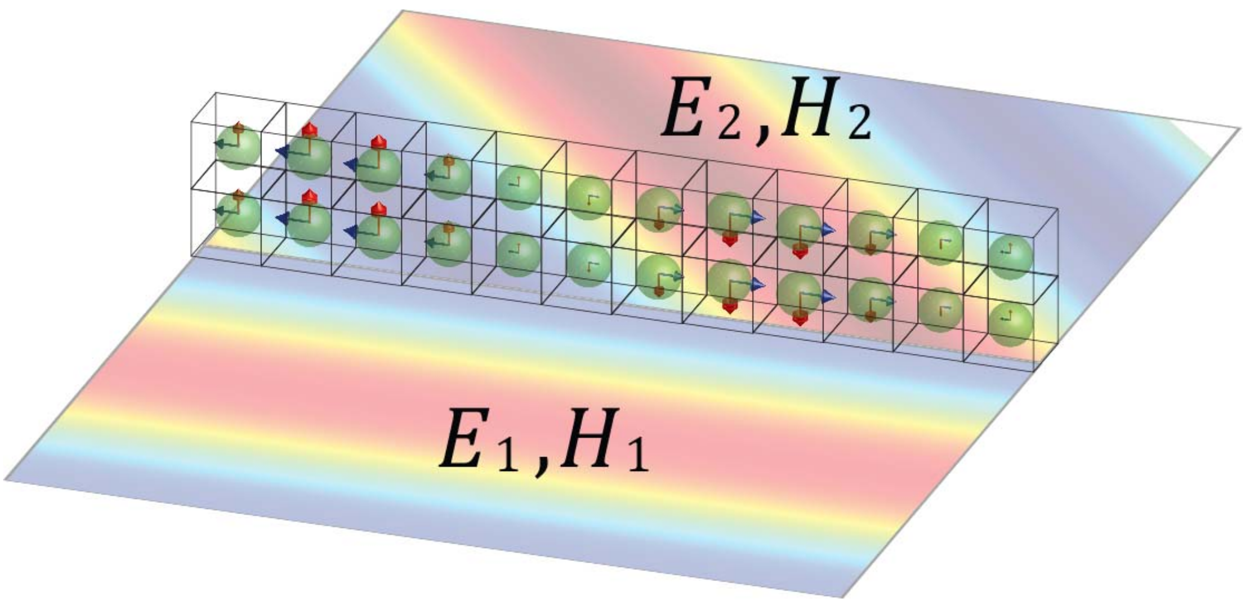
Design procedure

•Schelkunoff's fictitious currents are treated as polarization currents that create a unidirectional scattered field.

$$\vec{J}_s = \hat{n} \times \left(\vec{H}_2 - \vec{H}_1 \right)$$

$$\vec{M}_s = -\hat{n} \times \left(\vec{E}_2 - \vec{E}_1 \right)$$

•The ratios of the current to the local tangential field determine the necessary surface polarizabilities or equivalently sheet impedances.



$$\vec{J}_s = j\omega \overline{\overline{\alpha}}_{es} \cdot \vec{E}_{t,av}\Big|_S$$

$$\vec{M}_s = j\omega \overline{\overline{\alpha}}_{ms} \cdot \vec{H}_{t,av}\Big|_S$$

$$\vec{J}_s = \overline{\overline{Y}}_{es} \cdot \vec{E}_{t,av}\Big|_S$$

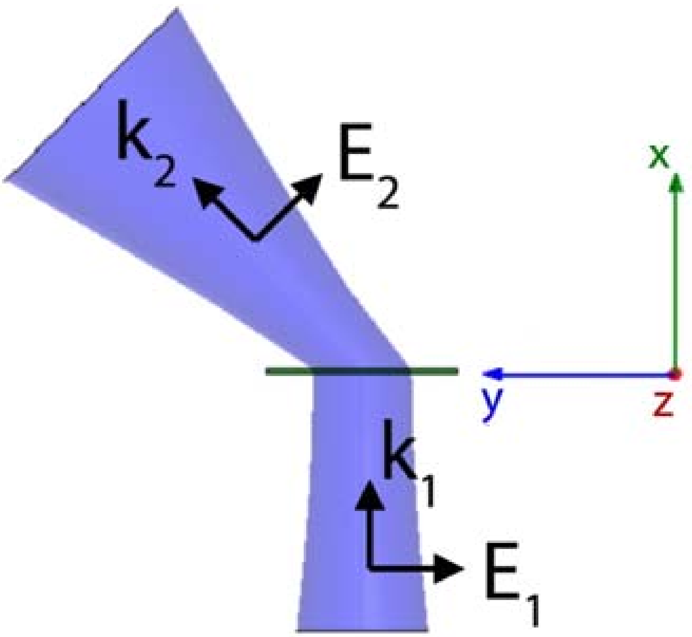
$$\vec{M}_s = \overline{\overline{Z}}_{ms} \cdot \vec{H}_{t,av}\Big|_S$$

C. Pfeiffer and A. Grbic, "Metamaterial Huygens' surfaces: tailoring wavefronts with reflectionless sheets", *Physical Review Letters*, 110, 197401, May 2013.

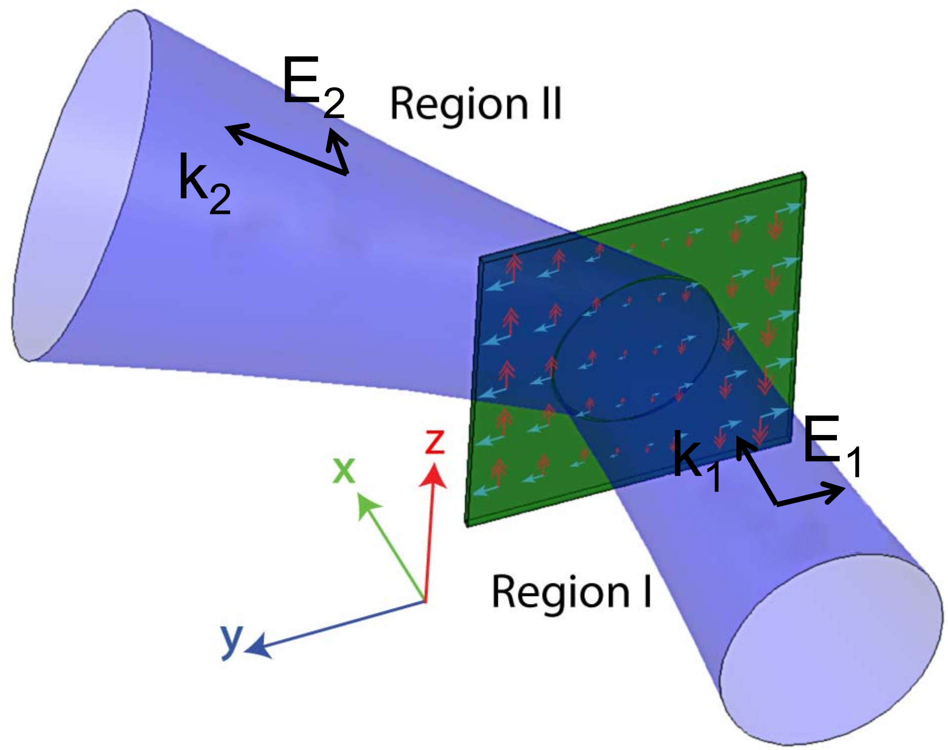
Example: a beam deflecting surface

- Normally incident plane wave is refracted/deflected to an angle $\phi=45^{\circ}$.
- Electromagnetic field is TM-polarized (magnetic field is z-directed).

Top view



Perspective view



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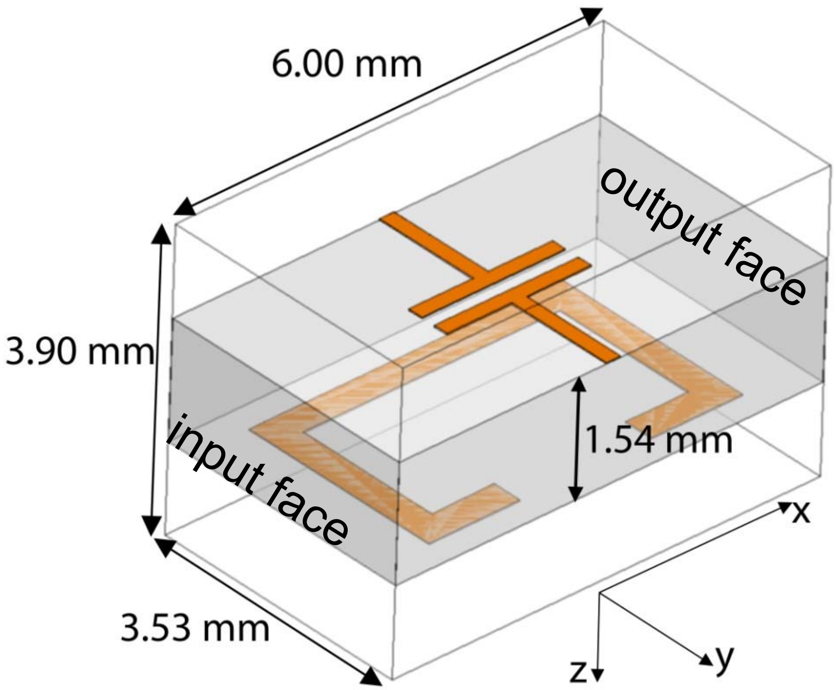
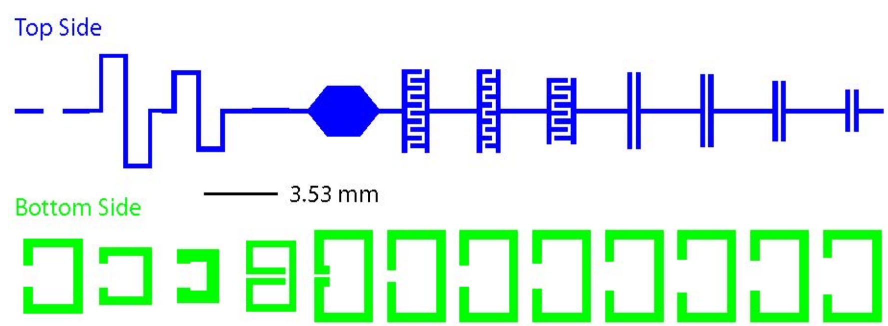
Sheet impedance realization

Representative unit cell



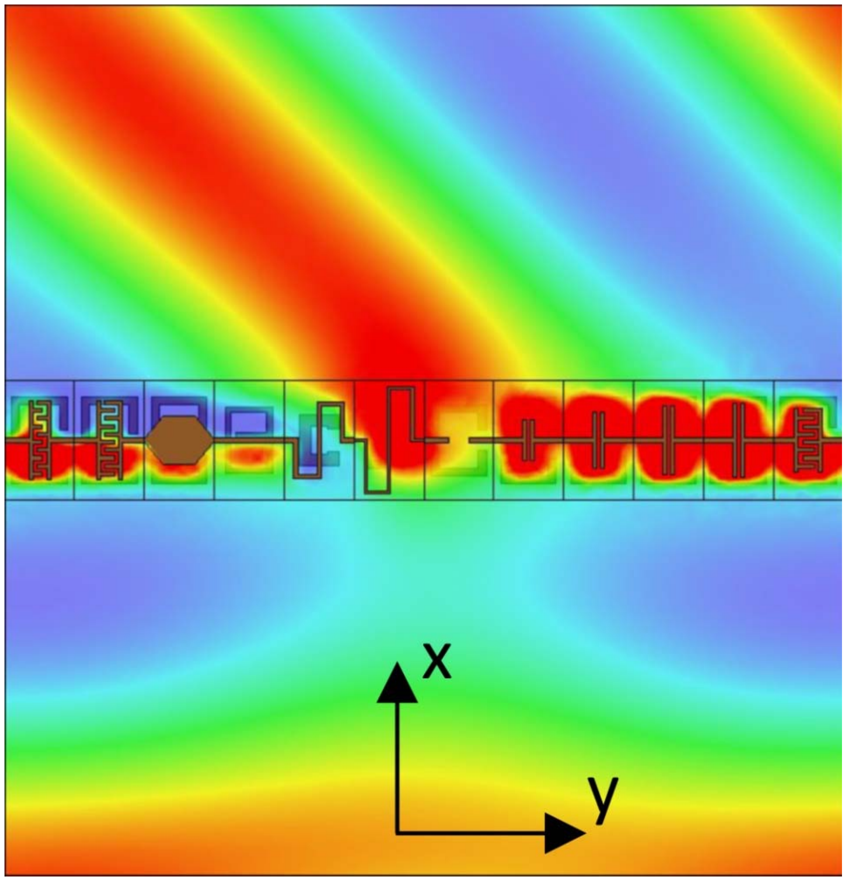
Period of the Huygens' surface



- Electric sheet impedances are realized with loaded traces on top of the substrate.
- Magnetic sheet impedances are realized with split-ring-resonators on the bottom of the substrate.

Simulated beam refraction

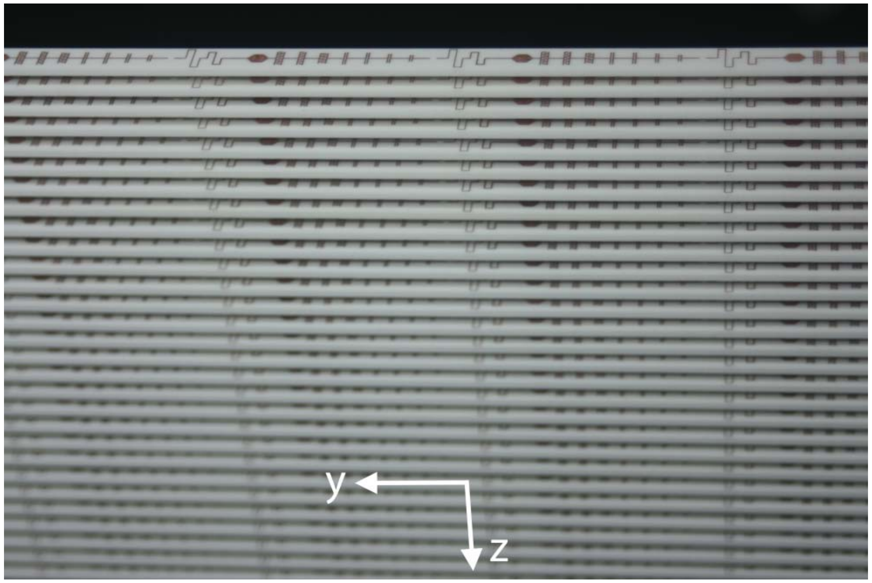
Top view of Huygens' surface



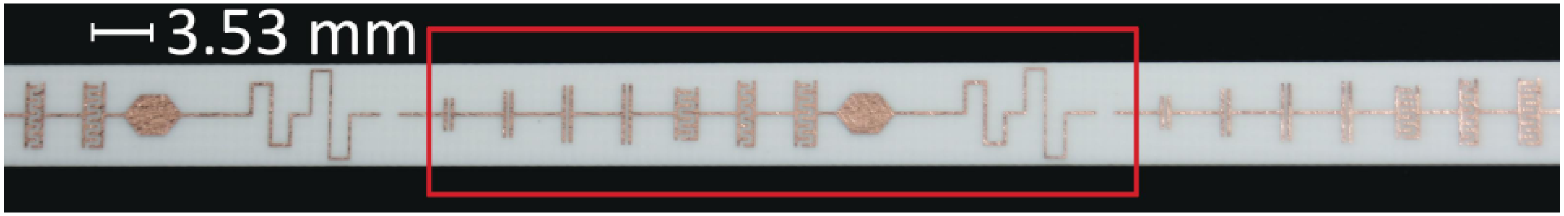
- A normally incident plane wave is steered to 45°.

Experimental Huygens' surface

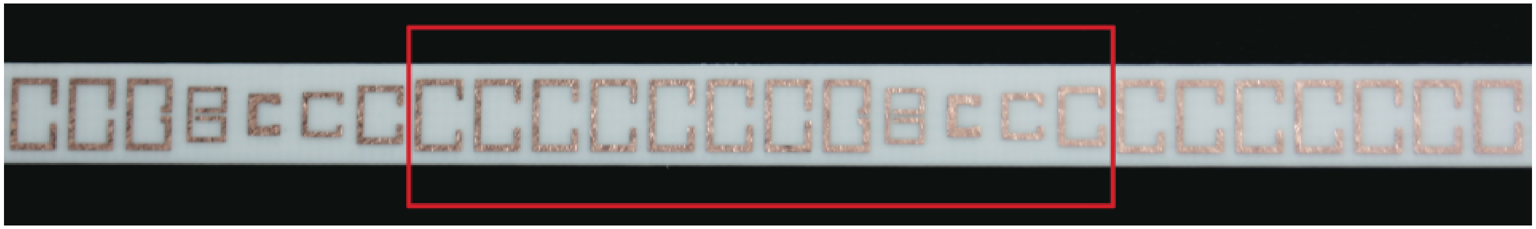
- Incident electric field is polarized in the y-direction.



Top side (electric response)

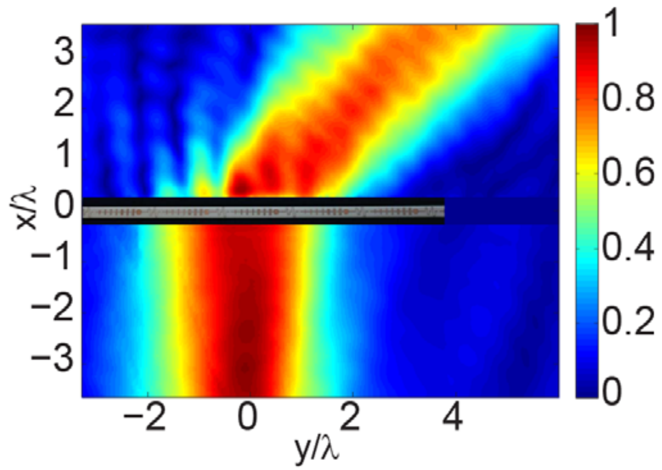


Bottom side (magnetic response)

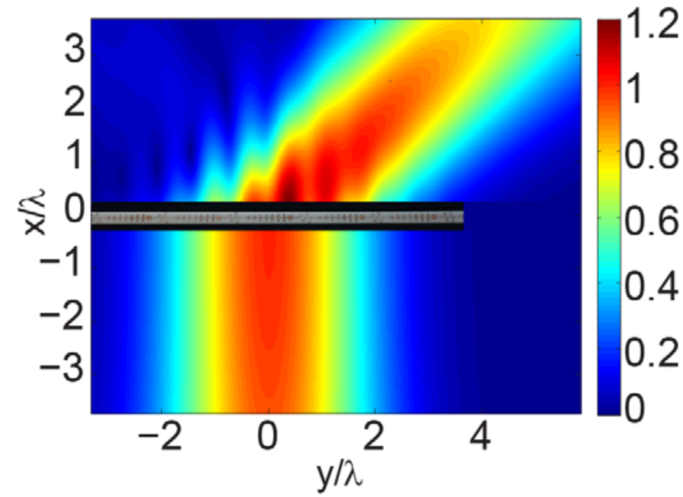


Measurement results

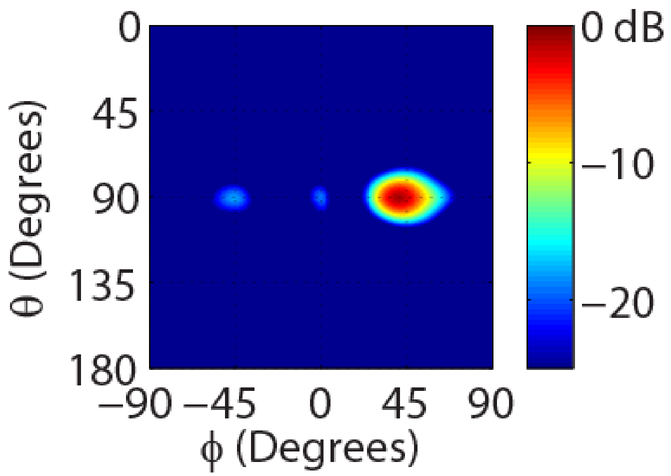
Measured near field



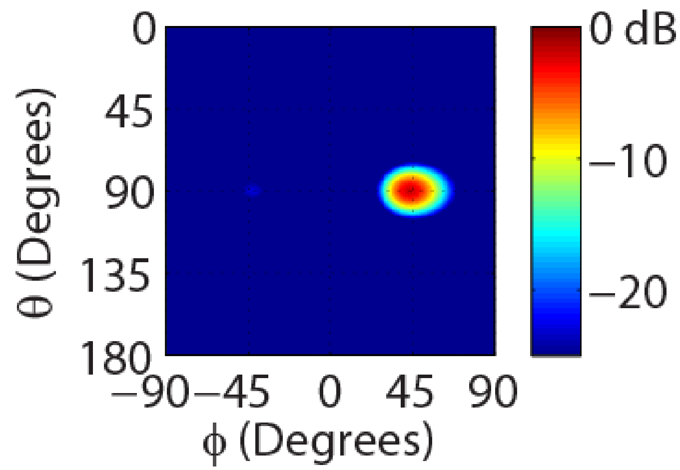
Simulated near field



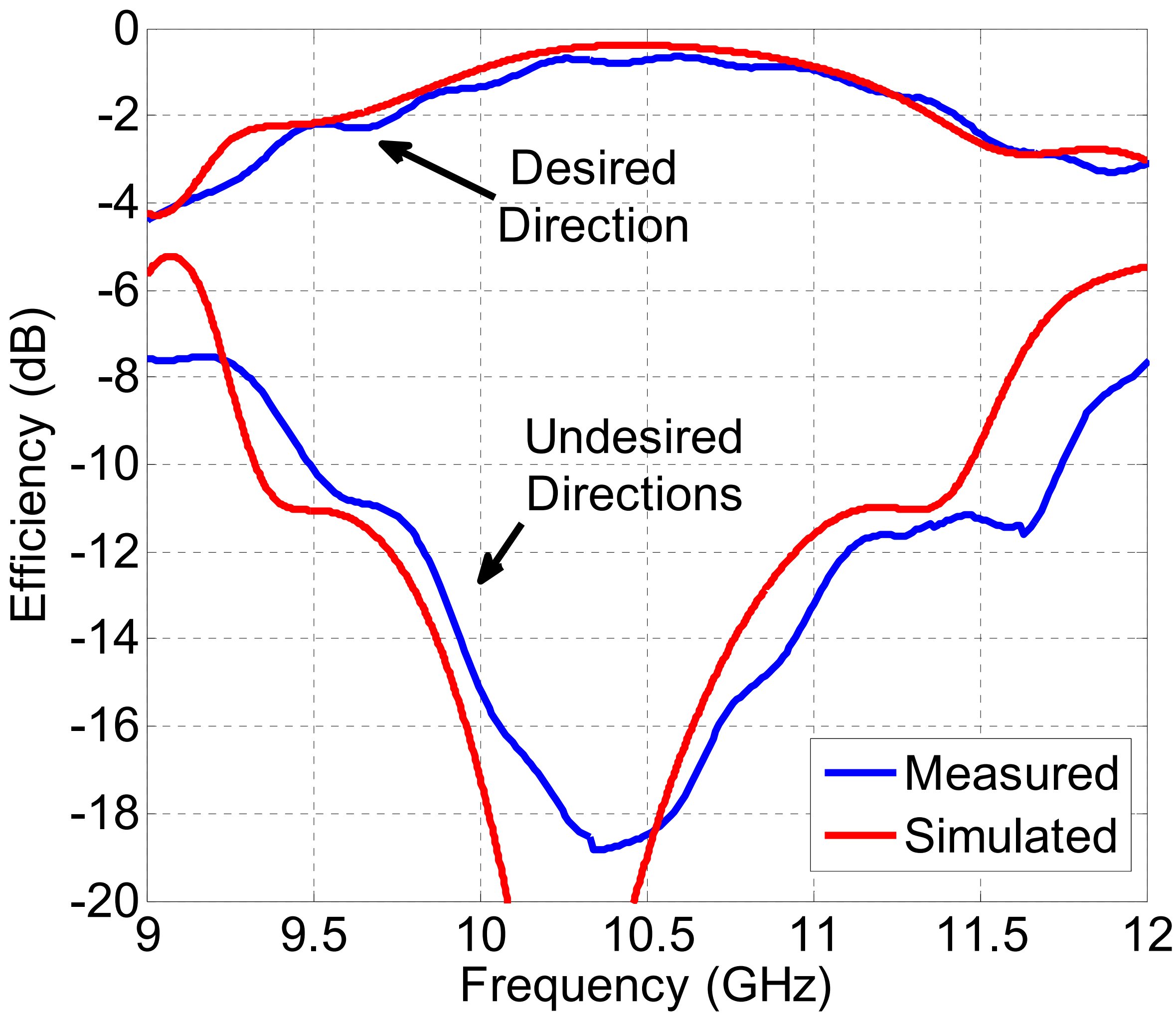
Measured far field



Simulated far field



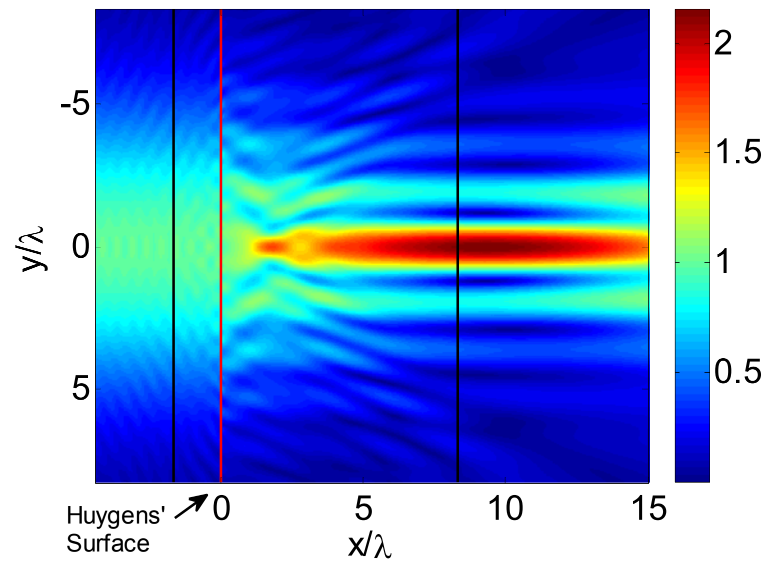
Efficiency



C. Pfeiffer and A. Grbic, “Metamaterial Huygens' surfaces: tailoring wavefronts with reflectionless sheets”, *Physical Review Letters,* 110, 197401, May 2013.

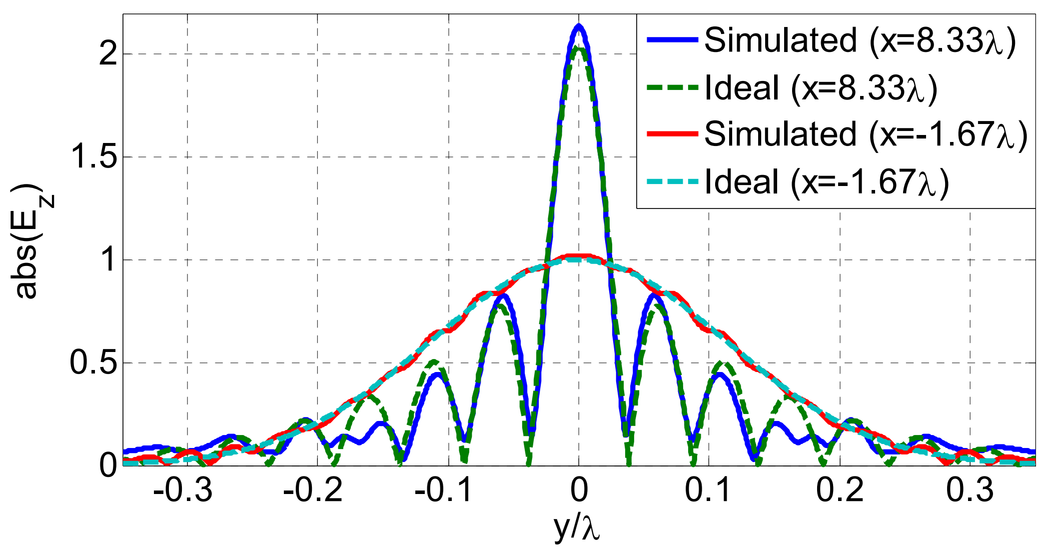
Gaussian-to-Bessel beam transformer

Incident field is a 2D Gaussian Beam and the transmitted field is a 2D Bessel beam.



Field in region I:

$$E_z^1 = \exp\left(\frac{-y^2}{(5.33\lambda)^2}\right)$$



Field in region II:

$$E_z^2 = 2.04 J_o(0.3ky)\exp\left(\frac{-y^2}{(8.33\lambda)^2}\right)$$

Summary and applications

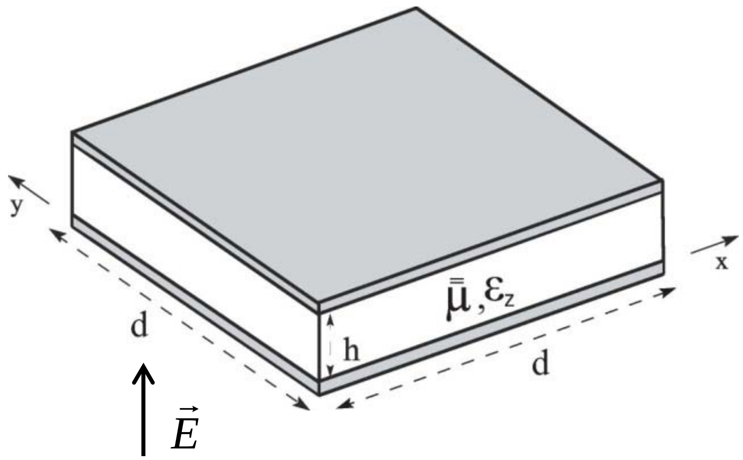
- The Huygens' principle / surface equivalence principle was used to develop reflectionless surfaces that allow extreme control of electromagnetic wavefronts, offering new beam shaping, steering, and focusing capabilities.

- Metamaterial Huygens' surfaces are realized as two-dimensional arrays of polarizable particles that provide both electric and magnetic polarization currents to generate prescribed wavefronts.

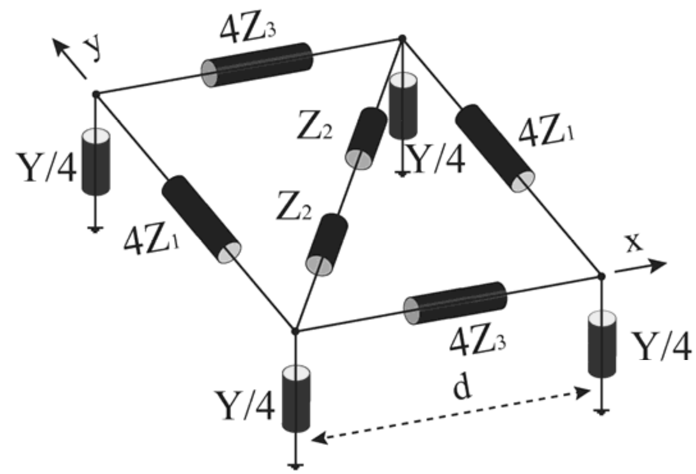
- A straightforward design methodology is demonstrated, and applied to develop a beam-refracting surface and a Gaussian-to-Bessel beam transformer.

- Applications include: single-surface lenses, polarization controlling devices, smart radomes.

Circuit-based tensor metamaterials



$\equiv$



Permeability tensor

$$\begin{pmatrix} \mu_{yy} & \mu_{xy} \\ \mu_{yx} & \mu_{xx} \end{pmatrix}$$

Impedance tensor

$$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

Permittivity scalar

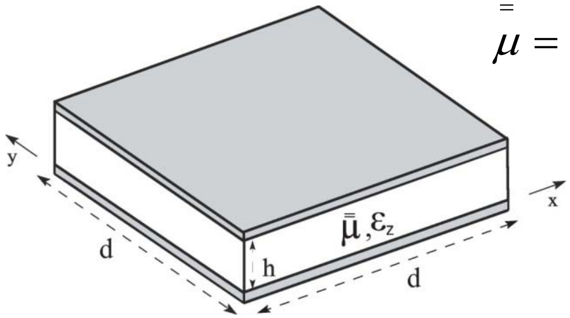
$$\varepsilon_z$$

Admittance scalar

$$Y$$

G. Gok and A. Grbic, "Tensor transmission-line metamaterials," *IEEE Trans. on Antennas and Propagation*, vol. 58, pp. 1559 – 1566, May 2010.

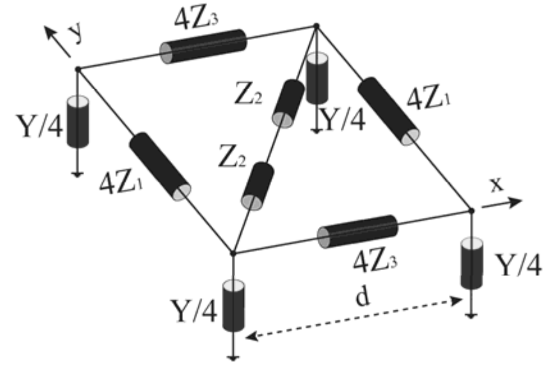
Equivalence between material and circuit parameters



$$\bar{\bar{\mu}} = \begin{bmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{bmatrix}$$

$$\varepsilon = \varepsilon_z$$

$$\equiv$$



Permeability tensor $\leftrightarrow$ **Impedance tensor**

$$j\omega d\begin{pmatrix} \mu_{yy} & -\mu_{xy} \\ -\mu_{yx} & \mu_{xx} \end{pmatrix} \leftrightarrow \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} = \begin{pmatrix} \dfrac{1}{2Z_2}+\dfrac{1}{2Z_3} & \dfrac{1}{2Z_2} \\ \dfrac{1}{2Z_2} & \dfrac{1}{2Z_1}+\dfrac{1}{2Z_2} \end{pmatrix}^{-1}$$

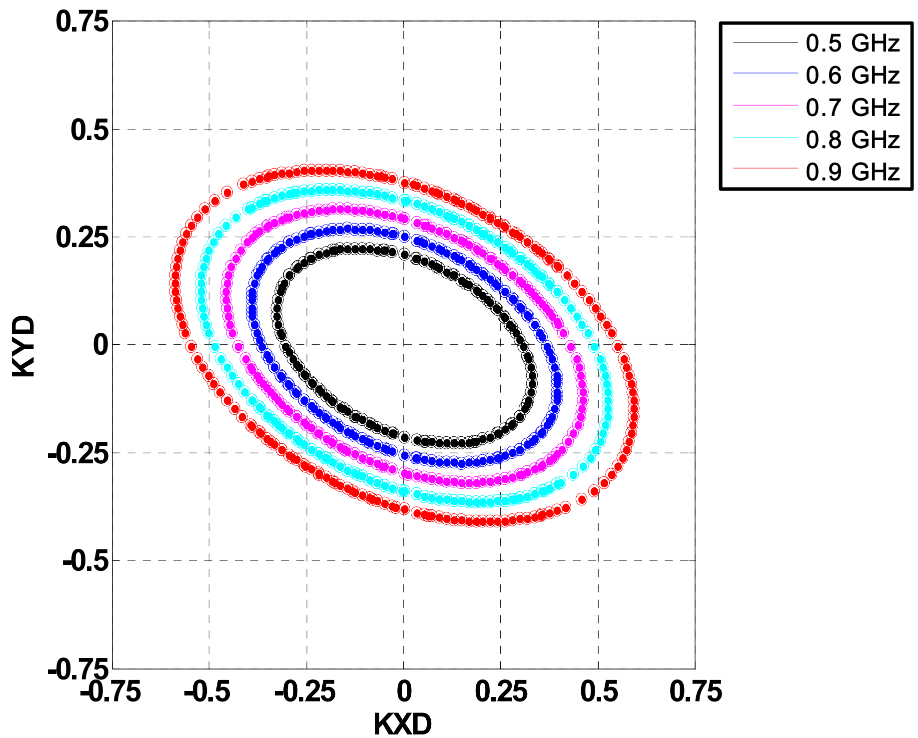
Permittivity scalar $\leftrightarrow$ **Admittance scalar**

$$j\omega d\varepsilon_z \leftrightarrow Y$$

Example

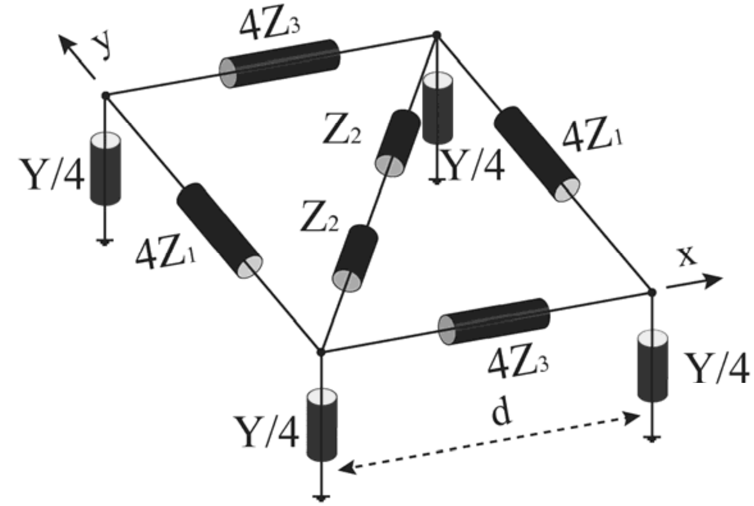
Medium

$$\bar{\bar{\mu}} = \begin{bmatrix} 0.98 & 0.52 \\ 0.52 & 2.07 \end{bmatrix} \qquad \varepsilon = 6.72$$



$$Tilt\,Angle = \text{-}21.8^\circ$$

Tensor transmission line



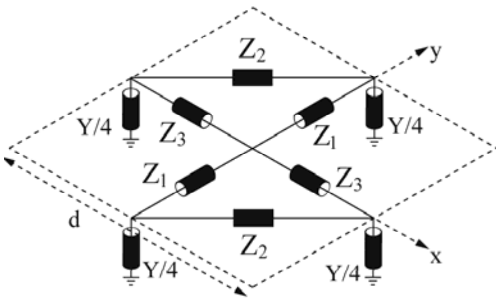
$L_1 = 6.0$ nH $\quad L_2 = 18.0$ nH $\quad L_3 = 20.0$ nH

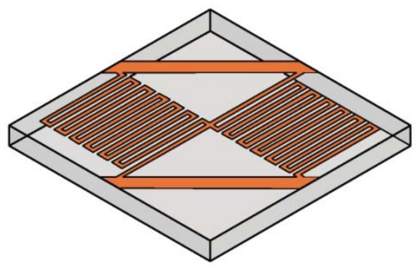
$C = 0.5$ pF

$$Z_1 = j\omega L_1 \qquad Z_2 = j\omega L_2 \qquad Z_3 = j\omega L_3$$

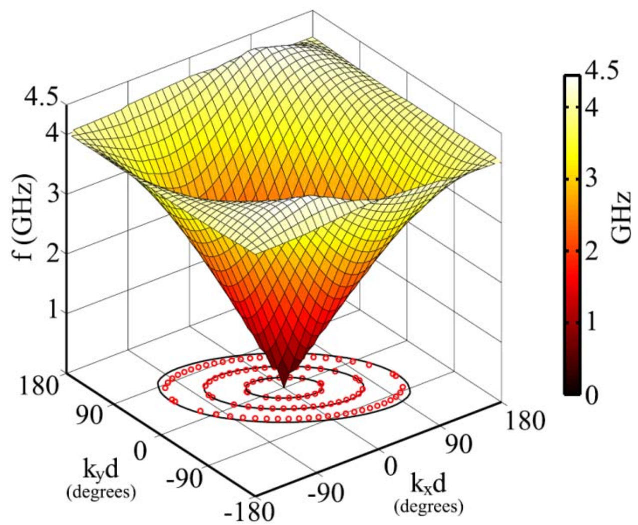
$$Y = j\omega C$$

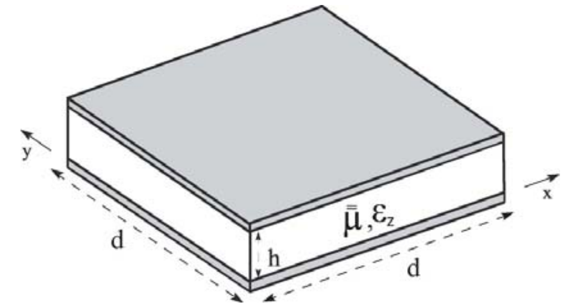
Microstrip implementation





Dispersion curves





$$\bar{\bar{\mu}} = \begin{pmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{pmatrix} = 4.90 \begin{pmatrix} 1 & 0.66 \\ 0.66 & 1.45 \end{pmatrix} \mu_o$$

$$\varepsilon_z = 2.215\varepsilon_o$$

$L_1 = 3\,nH \quad L_2 = 3.6\,nH$

$L_3 = 7.0\,nH \quad C = 1.82\,pF$

Full wave simulation (solid lines).
Homogenized Parallel-plate waveguide (dots).

G. Gok and A. Grbic, “Homogenization of tensor TL metamaterials,” *Metamaterials*, vol. 5, pp. 81-89, Jun.-Sep. 2011.

G. Gok and A. Grbic “A printed beam-shifting slab designed using tensor transmission-line metamaterials,“ *IEEE Trans on Antennas and Propagation*, vol. 61, pp. 728-734, Feb. 2013.

Relevance

•The ability to create metamaterials with arbitrary material tensors allows arbitrary control and manipulation of electromagnetic field.

•One way of exploiting this increased design flexibility is through transformation electromagnetics.

•In transformation electromagnetics, an initial field distribution is mapped to an desired field distribution through a coordinate transform. Due to the form invariance of Maxwell's equations, this coordinate transform directly translates to a change in the permittivity and permeability of the underlying medium. This new medium supports the desired field distribution.

•Transformation designed devices can consist of materials with full tensors that vary in space. Therefore, the ability to design anisotropic/tensor metamaterials is crucial to implementing transformation electromagnetics designs.

J.B. Pendry, D. Schurig, and D.R. Smith, "Controlling electromagnetic fields," *Science*, vol. 312, pp. 1780-1782, June 2006.

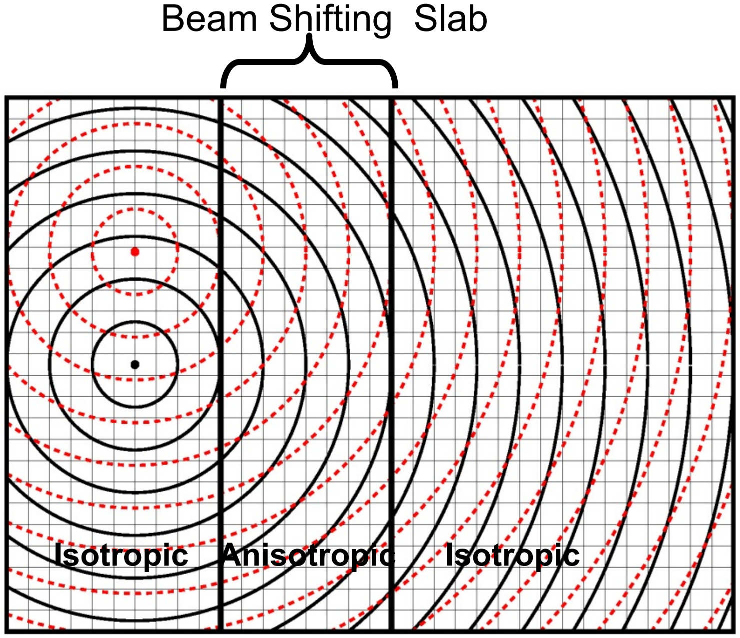
Beam-shifting slab: a transformations device

Transformation

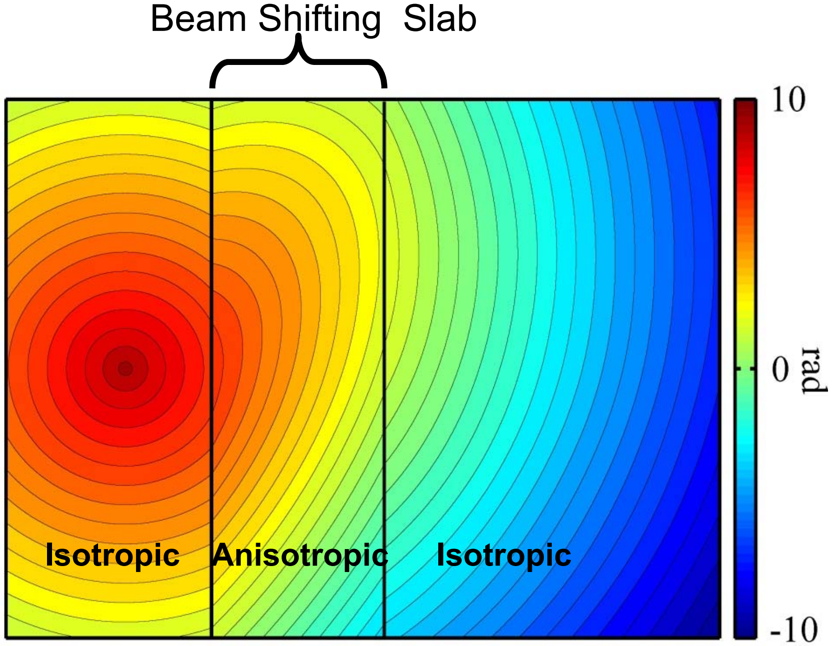
$$x' = x \quad y' = y + bx \quad z' = z$$

Material Parameters

$$\overline{\overline{\mu}} = \begin{pmatrix} 1 & b \\ b & 1+b^2 \end{pmatrix} \mu_o \quad \varepsilon_z = \varepsilon_o$$



Original source vs. shifted source
Shift amount = b times slab thickness

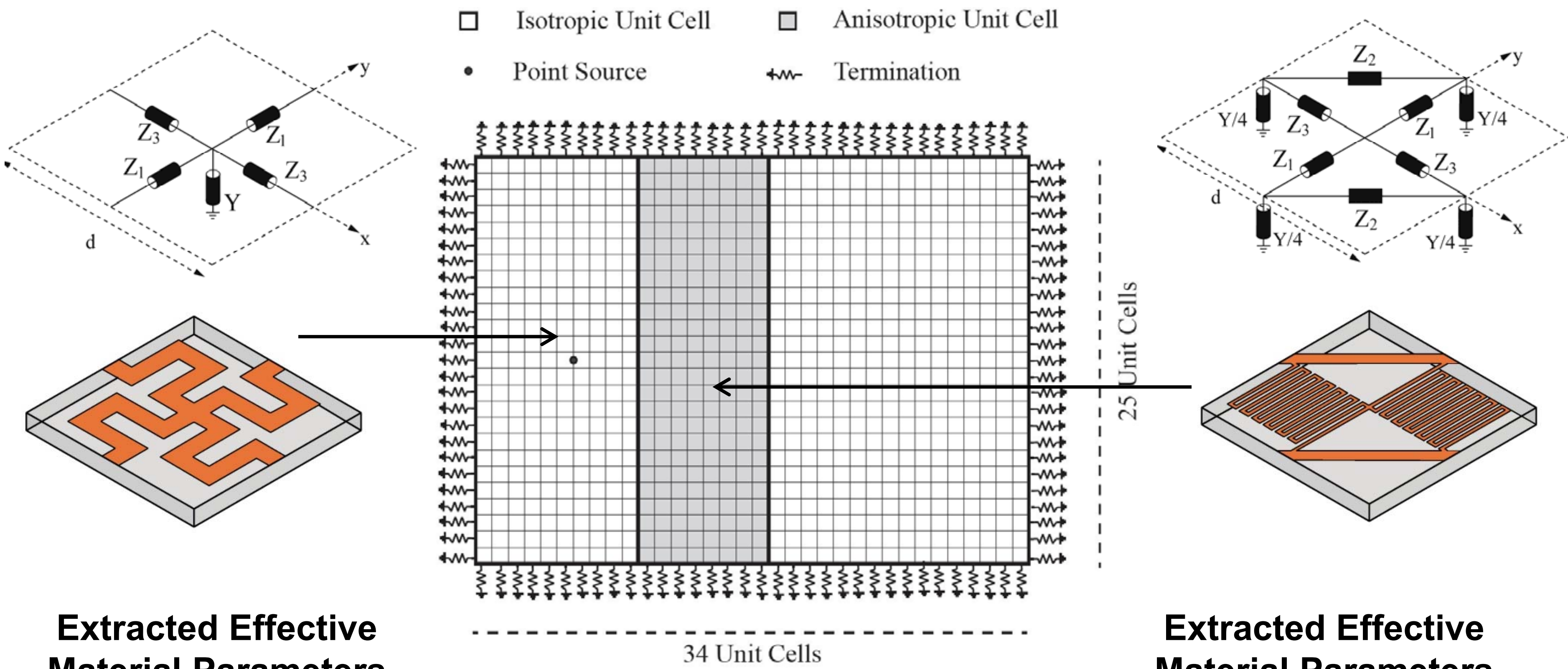


Point source radiation in the presence of a beam shifting slab

M. Rahm, S. A. Cummer, D. Schurig, J. B. Pendry, and D. R. Smith, "Optical design of reflectionless complex media by finite embedded coordinate transformations," *Physical Review Letters*, vol. 100, pp. 063903, Feb. 2008.

I. Gallina, G. Castaldi, V. Galdi, A. Alu, and N. Engheta, "General class of metamaterial transformation slabs," *Physical Review B*, vol. 81, pp. 125124, Mar. 2010.

Planar beam-shifting slab



Extracted Effective Material Parameters

$$\mu = 5.00\mu_o$$

$$\varepsilon_z = 2.205\varepsilon_o$$

Anisotropic slab is 8 unit cells thick

Extracted Effective Material Parameters

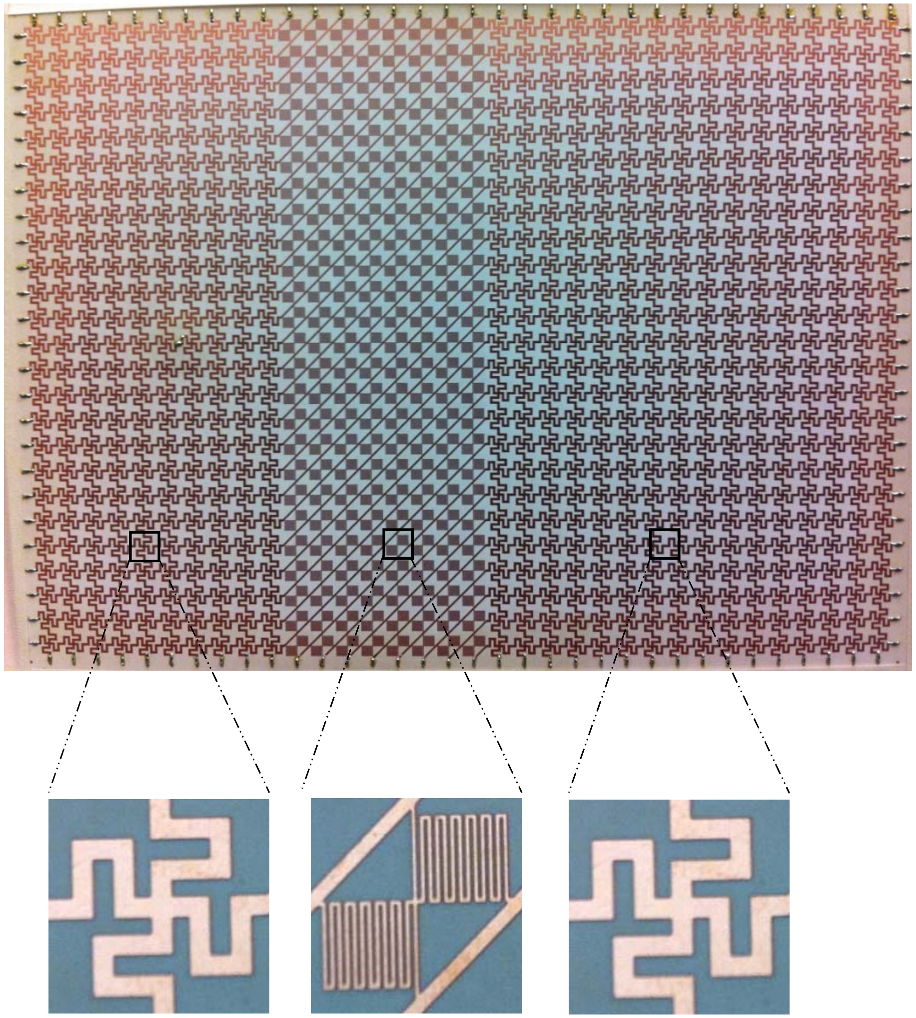
$$\bar{\bar{\mu}} = \begin{pmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{pmatrix} = 4.90 \begin{pmatrix} 1 & 0.66 \\ 0.66 & 1.45 \end{pmatrix} \mu_o$$

$$\varepsilon_z = 2.215\varepsilon_o$$

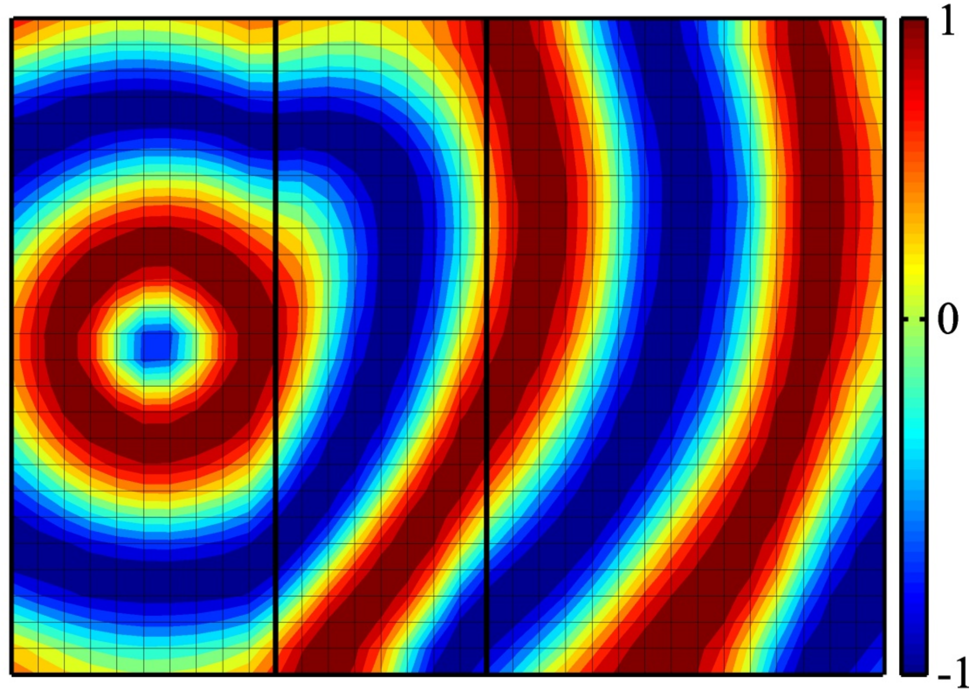
G. Gok and A. Grbic “A printed beam-shifting slab designed using tensor transmission-line metamaterials, “ I*EEE Trans on Antennas and Propagation*, vol. 61, pp. 728-734, Feb. 2013.

Experimental beam-shifting slab

Experimental structure



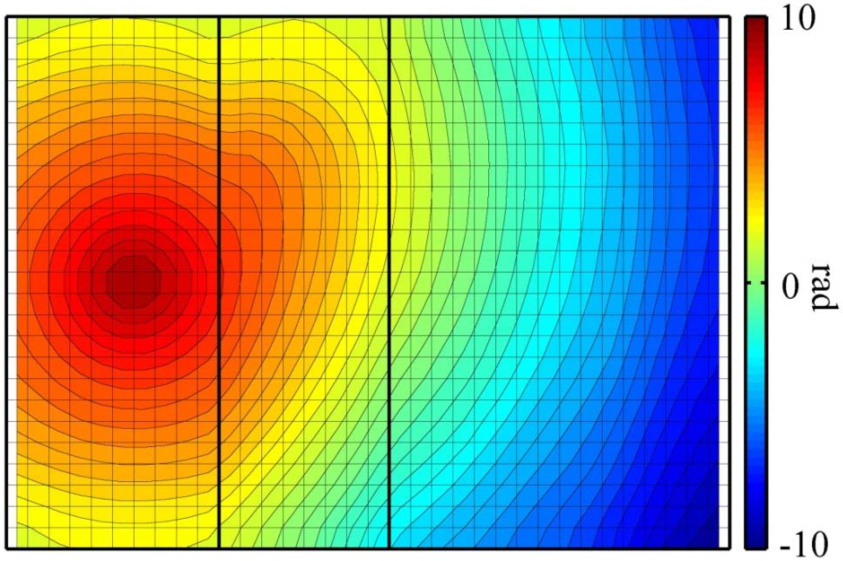
Measured phase of vertical E- field

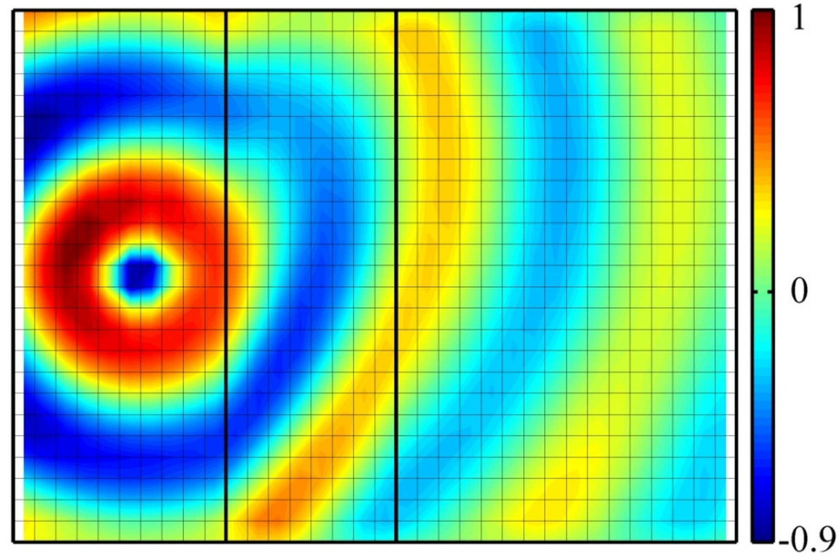


Unit Cells

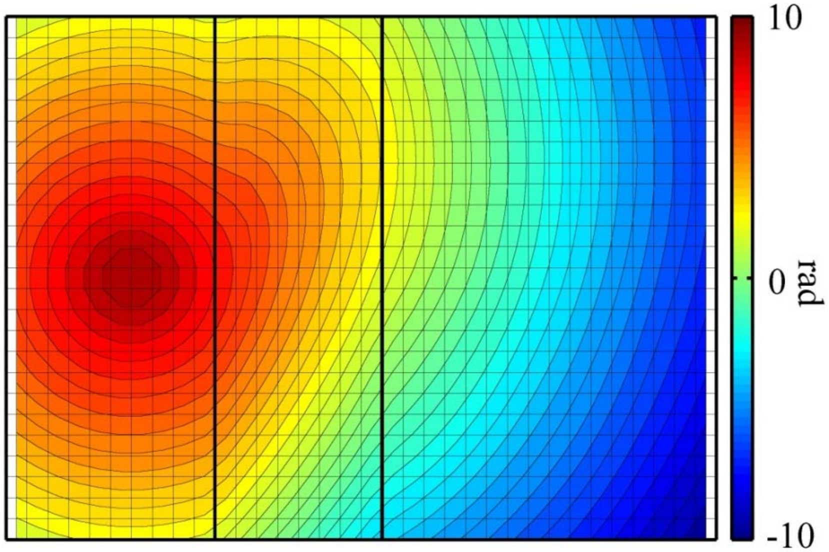
Measurement vs. simulation

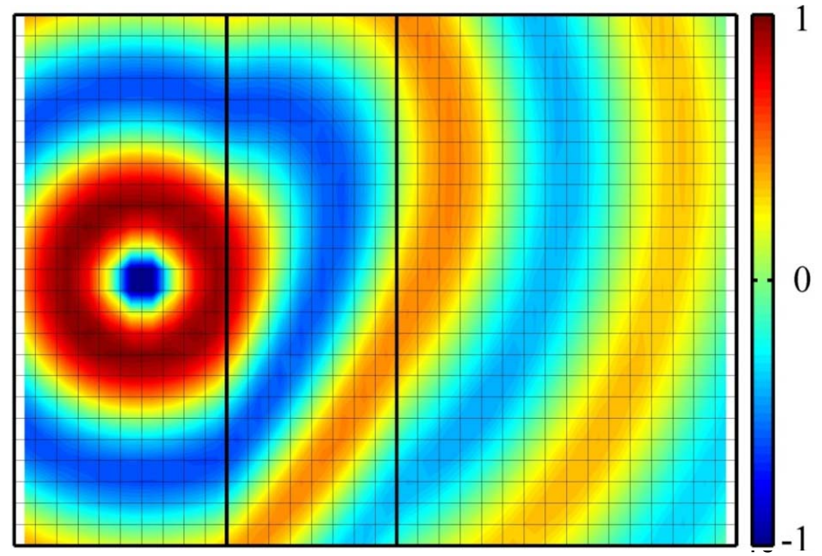
Phase **MEASUREMENT** **Steady-state time snapshot**





SIMULATION





Applications of tensor TL metamaterials

- Tensor metamaterials can be designed using loaded transmission-line grids, opening new opportunities to design microwave devices based on transformation electromagnetics.

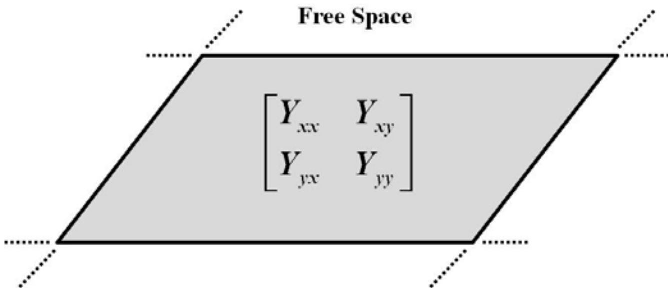
- These metamaterials provide a bridge between transformation electromagnetics and microwave network theory (circuit theory).

- Tensor transmission-line metamaterials allow extreme control of electromagnetic fields along a surface or radiating aperture.

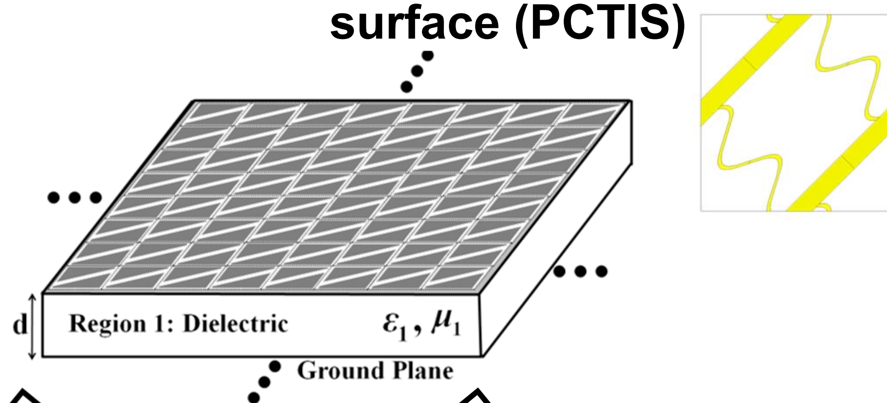
- They will find application in the design of microwave devices including antennas, antenna feeds, beamforming networks, power dividers and couplers.

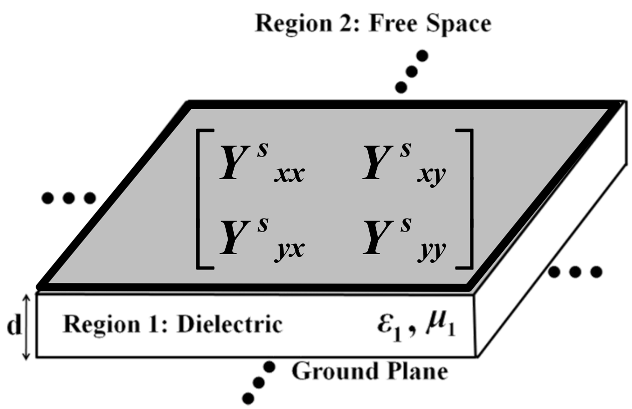
Tensor impedance surfaces

Tensor impedance boundary condition (TIBC)



Printed-circuit tensor impedance surface (PCTIS)





Extract sheet admittance of patterned cladding

Analytically derive dispersion equation for a tensor sheet over grounded dielectric

Analytically predict dispersion properties of PCTIS

B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, D. F. Sievenpiper, "Scalar and Tensor Holographic Artificial Impedance Surfaces," *IEEE Transactions on Antennas and Propagation* , vol.58, pp.3212-3221, Oct. 2010.

Comparing the PCTIS to the TIBC

Transverse resonance condition for TIBC

$$\begin{pmatrix} Y_{xx} & Y_{xy} \\ Y_{yx} & Y_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = R^T(-\theta) \begin{pmatrix} -\frac{1}{\eta_2 \frac{k_{z2}}{k_2}} & 0 \\ 0 & -\frac{1}{\eta_2 \frac{k_2}{k_{z2}}} \end{pmatrix} R(-\theta) \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

Transverse resonance condition for PCTIS

$$\left[\begin{pmatrix} Y^s_{xx} & Y^s_{xy} \\ Y^s_{yx} & Y^s_{yy} \end{pmatrix} + R^T(-\theta) \begin{pmatrix} \frac{1}{j\eta_1 \left(\frac{k_{z1}}{k_1}\right) \tan(k_{z1}d)} & 0 \\ 0 & \frac{1}{j\eta_1 \left(\frac{k_1}{k_{z1}}\right) \tan(k_{z1}d)} \end{pmatrix} R(-\theta) \right] \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

$$= R^T(-\theta) \begin{pmatrix} -\frac{1}{\eta_2 \frac{k_{z2}}{k_2}} & 0 \\ 0 & -\frac{1}{\eta_2 \frac{k_2}{k_{z2}}} \end{pmatrix} R(-\theta) \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

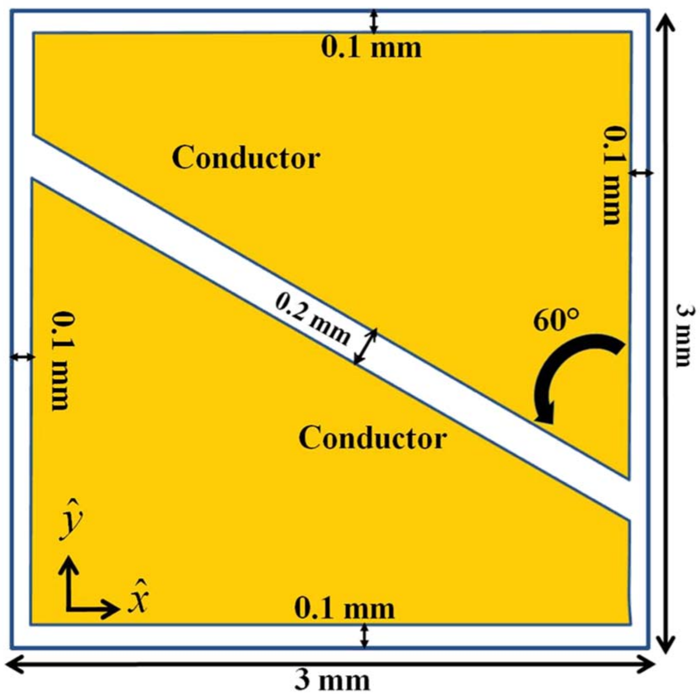
$$R(\theta) = \frac{1}{k_t} \begin{bmatrix} k_x & -k_y \\ k_y & k_x \end{bmatrix}$$

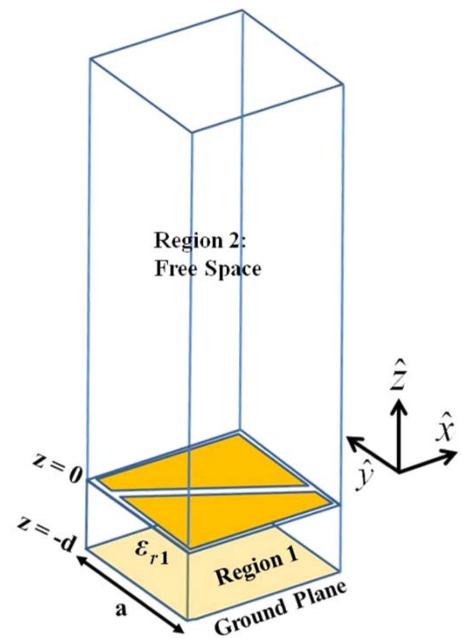
A. M. Patel, A. Grbic, "Modeling and analysis of printed-circuit tensor impedance surfaces," *IEEE Trans. on Antennas and Propagation,* vol. 61, pp.211-220, Jan. 2013

A. M. Patel and A. Grbic, “Effective surface impedance of a printed-circuit tensor impedance surface,” IEEE Trans. on Microwave Theory and Techniques, vol. 61, pp. 1403-1413, Apr. 2013.

Extraction example

RO3010 grounded substrate,
thickness d = 1.27 mm, ε_{r1} = 10.2
unit cell length, a= 3mm



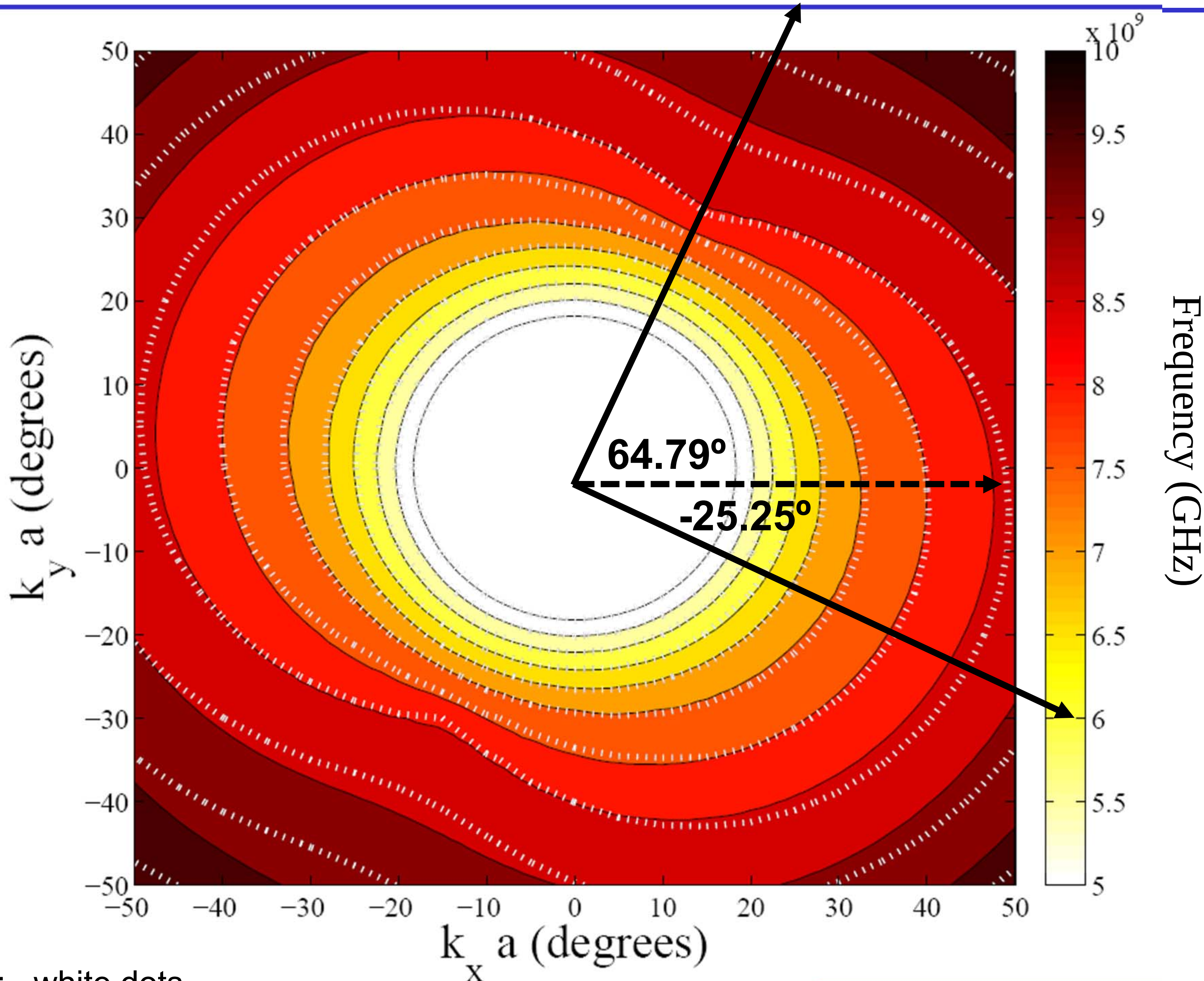


Extracted Sheet Impedance at 10 GHz:

$$\overline{\overline{\eta}}_{sheet} = j\begin{pmatrix} -97.5405 & -47.7295 \\ -47.8137 & -176.397 \end{pmatrix}\Omega$$

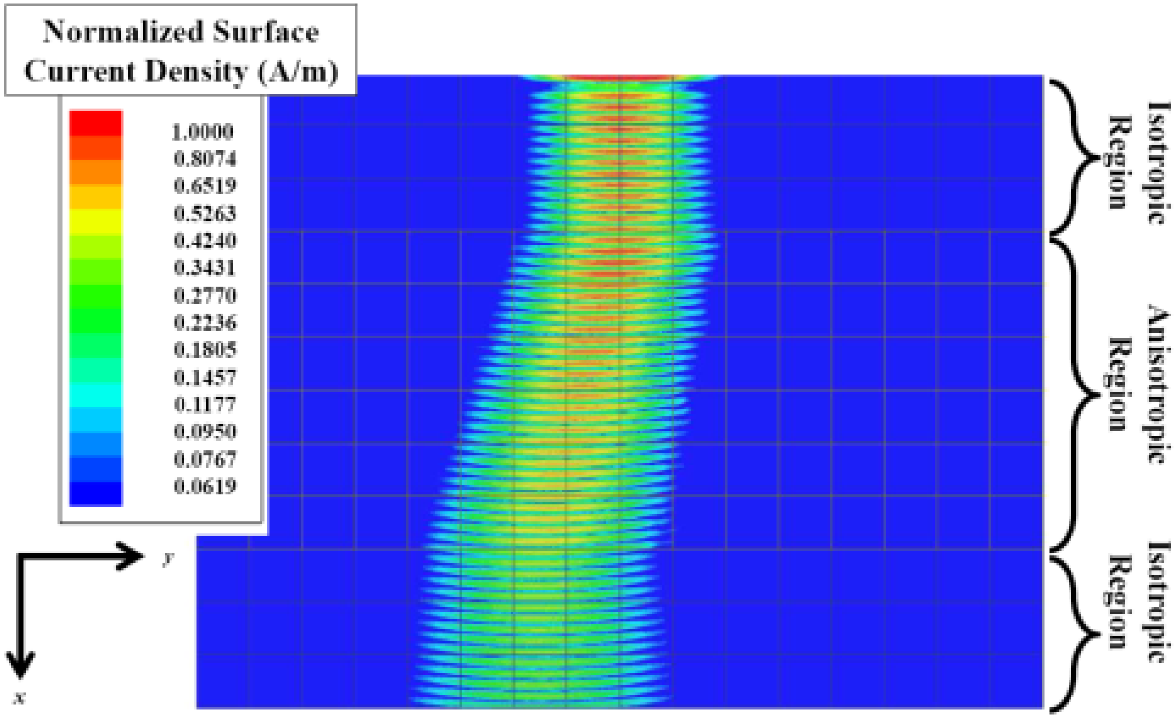
B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, D. F. Sievenpiper, ”Scalar and Tensor Holographic Artificial Impedance Surfaces,” *IEEE Transactions on Antennas and Propagation* , vol.58, pp.3212-3221, Oct. 2010.

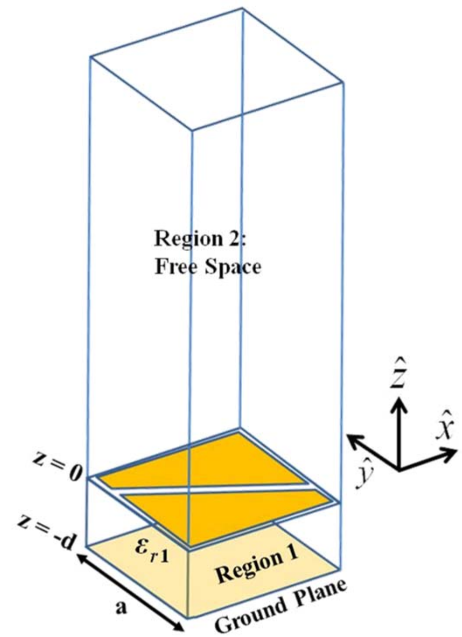
Comparison: analytical vs. full-wave simulation



Full-wave: white dots

PCTIS beam-shifter results





Isotropic:

$$\eta_{sheet}=Y_{sheet}^{-1}=j\begin{pmatrix}-199.33 & 0\\ 0 & -199.33\end{pmatrix}\Omega$$

Anisotropic

$$\eta''_{sheet}=(Y''_{sheet})^{-1}=j\begin{pmatrix}-288.09 & 82.59\\ 82.59 & -184.88\end{pmatrix}\Omega.$$

Simulation:

- Gaussian beam illumination
- Substrate:1.27mm, ε_r=10.2 (R03010)
- Beamshift angle: -13.93 degrees

Conclusion

•Metamaterial surfaces (near-field plates) for near-field manipulation were reviewed: near-field plates for subwavelength focusing and detection, and leaky radial waveguides for propagating Bessel beam generation.

•Reflectionless metasurfaces, referred to as metamaterial Huygens surfaces, for the manipulation of electromagnetic wavefronts were introduced. These surfaces can manipulate the amplitude, phase and polarization of transmitted fields.

•Tensor transmission-line metamaterials were introduced and their operation was explained.Tensor impedance surfaces were also covered. Their use in the design of planar transformation electromagnetics devices was demonstrated.

•Application areas for the proposed structures were identified.

Acknowledgments

Collaborator: Prof. Roberto Merlin, Physics Department., University of Michigan.

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