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.

• 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.


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


Aperture fields and subwavelength focal patterns

Spatial spectrum of aperture fields and focal patterns

Spatial Form

Focal Pattern

Aperture Field

Spectral Form

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.


Frequency 1.027 GHz
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.


Airy profile

\[ E_{z}^{focal}(\rho) = \frac{J_1(k_{\text{max}}\rho)}{k_{\text{max}}\rho} \]

\[ k_{\text{max}} = 12.11k \]

Design parameters:

\[ f = 1.0GHz, \; N = 6, \; L = \lambda / 15 = 2cm, \; R = 42mm, \; w = 0.4mm, \; s = 6mm = \lambda / 50 \]

Bessel profile

\[ E_{z}^{focal}(\rho) = Ae^{(-\rho^2/2\sigma^2)}e^{(-\sqrt{q^2-k^2L})}J_0(q\rho) \]

\[ q = 7.6k, \sigma = 23mm \]

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

Airy pattern NFP

\[
\begin{align*}
\lambda/30 & \quad \lambda/5 \\
\lambda/30 & \quad \lambda/5
\end{align*}
\]
The measured electric field along each z=z' plane is normalized w.r.t. its maximum value.

- Measured beams in the reactive near field (1 GHz)

**Measured FWHM**

- Bessel beam NFP
- Airy pattern NFP
- Unloaded plate

**Bessel beam NFP**

**Airy pattern NFP**

**Coaxial probe**
Leaky-wave excitation of propagating Bessel beams

Planar Bessel beam launcher


Measured TM polarized Bessel beams (10 GHz)

Beam pattern

|E_z| [V/m]

Fourier transform

k_y [1/m]

k_x [1/m]

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

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

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

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

\[ \mathbf{S} \]

\[ \mathbf{J}_s = \hat{n} \times (\mathbf{H}_2 - \mathbf{H}_1) \]

\[ \mathbf{M}_s = -\hat{n} \times (\mathbf{E}_2 - \mathbf{E}_1) \]

• 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.

\[ \mathbf{J}_s = \hat{n} \times (\mathbf{H}_2 - \mathbf{H}_1) \]

\[ \mathbf{M}_s = -\hat{n} \times (\mathbf{E}_2 - \mathbf{E}_1) \]

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

\[ \mathbf{J}_s = j \omega \alpha_{es} \cdot \mathbf{E}_{t,av} \big|_S \]

\[ \mathbf{M}_s = j \omega \alpha_{ms} \cdot \mathbf{H}_{t,av} \big|_S \]

\[ \mathbf{J}_s = \overline{Y}_{es} \cdot \mathbf{E}_{t,av} \big|_S \]

\[ \mathbf{M}_s = \overline{Z}_{ms} \cdot \mathbf{H}_{t,av} \big|_S \]

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).

Sheet impedance realization

- 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.

Representative unit cell

Period of the Huygens’ surface
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**

![Measured near field plot]

**Simulated near field**

![Simulated near field plot]

**Measured far field**

![Measured far field plot]

**Simulated far field**

![Simulated far field plot]
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:

\[ E_z^2 = 2.04 J_0 (0.3ky) \exp \left( -\frac{y^2}{(8.33\lambda)^2} \right) \]
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.
Permeability tensor

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

Permittivity scalar

\[\varepsilon_z\]

Impedance tensor

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

Admittance scalar

\[Y\]

Equivalence between material and circuit parameters

\( \mathbf{\mu} = \begin{bmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{bmatrix} \)

\( \varepsilon = \varepsilon_z \)

\[ j \omega d \begin{pmatrix} \mu_{yy} & -\mu_{xy} \\ -\mu_{yx} & \mu_{xx} \end{pmatrix} \leftrightarrow \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \]

\[ \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} = \begin{pmatrix} \frac{1}{2Z_2} + \frac{1}{2Z_3} & \frac{1}{2Z_2} \\ \frac{1}{2Z_2} & \frac{1}{2Z_1} + \frac{1}{2Z_2} \end{pmatrix}^{-1} \]

\[ j \omega d \varepsilon_z \leftrightarrow Y \]
Medium

\[ \mu = \begin{bmatrix} 0.98 & 0.52 \\ 0.52 & 2.07 \end{bmatrix} \]

\[ \varepsilon = 6.72 \]

The figure shows the tensor transmission line with L1 = 6.0 nH, L2 = 18.0 nH, L3 = 20.0 nH, C = 0.5 pF.

\[ Z_1 = j\omega L_1 \quad Z_2 = j\omega L_2 \quad Z_3 = j\omega L_3 \]

\[ Y = j\omega C \]

Tilt Angle = -21.8°
Microstrip implementation

Dispersion curves

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

\[ L_1 = 3 \, nH \quad L_2 = 3.6 \, nH \]
\[ L_3 = 7.0 \, nH \quad C = 1.82 \, pF \]


• 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.

Beam-shifting slab: a transformations device

Transformation

\[
x' = x \quad y' = y + bx \quad z' = z
\]

Material Parameters

\[
\begin{pmatrix}
1 & b \\
b & 1 + b^2
\end{pmatrix} \mu_0, \quad \varepsilon_z = \varepsilon_0
\]

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

Point source radiation in the presence of a beam shifting slab


Anisotropic slab is 8 unit cells thick

\[
\begin{bmatrix}
\mu_{xx} & \mu_{xy} \\
\mu_{yx} & \mu_{yy}
\end{bmatrix} = 4.90 \begin{bmatrix} 1 & 0.66 \\ 0.66 & 1.45 \end{bmatrix} \mu_0
\]

\[\varepsilon_z = 2.215 \varepsilon_0\]

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)

Analytically derive dispersion equation for a tensor sheet over grounded dielectric

Printed-circuit tensor impedance surface (PCTIS)

Extract sheet admittance of patterned cladding

Analytically predict dispersion properties of PCTIS

Comparing the PCTIS to the TIBC

Transverse resonance condition for TIBC

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

Transverse resonance condition for PCTIS

\[
\begin{pmatrix}
Y^s_{xx} & Y^s_{xy} \\
Y^s_{yx} & Y^s_{yy}
\end{pmatrix}
+ R^T(-\theta)
\begin{pmatrix}
\frac{1}{j\eta_1\left(\frac{k_1}{k}ight)\tan(kz_1d)} & 0 \\
0 & \frac{1}{j\eta_1\left(\frac{k_1}{k}ight)\tan(kz_1d)}
\end{pmatrix}
R(-\theta)
\]

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

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


RO3010 grounded substrate, thickness \( d = 1.27 \text{ mm} \), \( \varepsilon_{r1} = 10.2 \)

unit cell length, \( a = 3\text{ mm} \)

\[\eta_{\text{sheet}} = j \begin{pmatrix} -97.5405 & -47.7295 \\ -47.8137 & -176.397 \end{pmatrix} \Omega\]

Comparison: analytical vs. full-wave simulation

Full-wave: white dots
PCTIS beam-shifter results

Simulation:
- Gaussian beam illumination
- Substrate: 1.27mm, $\varepsilon_r=10.2$ (R03010)
- Beamshift angle: -13.93 degrees

Isotropic:

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

Anisotropic

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

This work is supported by a Presidential Early Career Award for Scientists and Engineers (FA9550-09-1-0696), a NSF Faculty Early Career Development Award (ECCS-0747623) and the NSF Materials Research Science and Engineering Center program DMR 1120923 (Center for Photonics and Multiscale Nanomaterials at the University of Michigan).