NEGATIVE-REFRACTIVE-INDEX
TRANSMISSION-LINE
METAMATERIALS AND ENABLING
MICROWAVE DEVICES

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CANADA
META=“BEYOND” IN GREEK
Materials with unusual EM properties, not encountered in nature

TRANSMISSION-LINE METAMATERIALS:

ARTIFICIAL DIELECTRICS SYNTHESIZED BY PERIODICALLY LOADING A HOST TRANSMISSION-LINE MEDIUM WITH R,L,C ELEMENTS (lumped or printed):
PERIODICITY $<< \lambda$
LEFT-HANDED $\varepsilon < 0$ AND $\mu < 0$
METAMATERIALS

Veselago, 1960s

$\varepsilon > 0, \mu > 0$

Regular Materials
(right-handed)

$\varepsilon < 0, \mu < 0$

Left-Handed Materials

Backward Waves

Negative-Refractive-Index (NRI) Materials

$n = -\sqrt{\varepsilon \mu}$
NEGATIVE REFRACTION

Negative-Refractive-Index (NRI) Media

\[ \frac{\sin \theta_1}{\sin \theta_2} = n \]
Focusing from Planar $n<0$ Slabs

Veselago’s Lens

- Flat but homogeneous lens
- Point-to-point focusing
- No optical axis
Sub-Wavelength Resolution

Sub-wavelength resolution is a result of restoring the evanescent portion of the Fourier spectrum. Unlike any other lens it may offer sub-wavelength resolution!

John Pendry PRL 2000

Sub-wavelength resolution is a result of restoring the evanescent portion of the Fourier spectrum.
HOW CAN ONE MAKE $\varepsilon < 0$ AND $\mu < 0$ METAMATERIALS?

3-D Arrangement of Split-Ring Resonators (SRR) and Straight Wires

R. A. Shelby, D.R. Smith, S. Schultz
Science, 2001 Demonstrated Negative Refraction at Microwave Frequencies

Operates around resonances:
Narrowband/Lossy

Bulky: 3-D structure

Distributed cells: Large for usage at RF frequencies
Negative-Refractive-Index
Transmission-Line 2D Metamaterials

\[ j \omega \varepsilon = \frac{jB}{\Delta S} = \frac{j(-1/\omega L)}{\Delta S} \Rightarrow \varepsilon = -\frac{1}{\omega^2 L \Delta S} \]

\[ j \omega \mu = \frac{jX}{\Delta S} = \frac{j(-1/\omega C)}{\Delta S} \Rightarrow \mu = -\frac{1}{\omega^2 C \Delta S} \]


No Resonant Elements: This practically yields a very large bandwidth over which $n<0$ (blue curve)

$$\beta = -\frac{1}{\omega \sqrt{L'C'}}$$

$$\nu_\phi = -\omega^2 \sqrt{L'C'}$$

$$\nu_g = \omega^2 \sqrt{L'C'}$$

PERIODICALLY L-C LOADED TRANSMISSION LINES

Backward Wave \( v_p v_g < 0 \)

For short interconnecting lines \( kd << 1 \) and small phase-shifts per-unit-cell \( \beta d << 1 \)

\[
\varepsilon_{\text{eff}} \approx \varepsilon_0 - \frac{1}{\omega^2 Ld}
\]

\[
\mu_{\text{eff}} \approx \mu_0 - \frac{1}{\omega^2 Cd}
\]

Finite LHM 2-D Unit Cell
Period = \( d \)

\[
f_{\text{series}} = \frac{1}{2\pi \sqrt{C(\mu_0 d)}} \quad (\mu = 0)
\]

\[
f_{\text{shunt}} = \frac{1}{2\pi \sqrt{L(\varepsilon_0 d)}} \quad (\varepsilon = 0)
\]

\[
f_{\text{Bragg}} = \frac{1}{4\pi \sqrt{L C}} \quad \text{Small period } d: \text{ Large NRI bandwidth}
\]

2D Microstrip Implementation of $\varepsilon<0$ AND $\mu<0$ Metamaterials

Distributed TL Network With Chip or Printed (gaps and vias) Loading Lumped Elements

The electric field along the vias induces vertical electric dipole moments

The magnetic field in the gaps induces horizontal magnetic dipole moments

NEGATIVE-REFRACTIVE-INDEX (NRI) LENS
Overcoming the Diffraction Limit?

Amplitude Restoration

Evanescent Waves $K_x > K$

Phase Restoration

Propagating Waves $K_x < K$

$\beta = \sqrt{K^2 - K_x^2}$
Growing Evanescent Waves

“Plasmon” Excitation On the Exit Interface

Transmission-Line NRI
Super-Resolving Lens

Left-handed Region: A 5 X 19 grid of unit-cell size 8.4mm X 8.4mm
“Perfect” Imaging?

Analytical Theory

Solid Line=Source Profile
Dotted Line=Image Profile

Experimental Results

F=1.056GHz

Growing Evanescent Waves!
Measured Beamwidth at Focal Plane

- Diffraction-limited peak-null beamwidth: \( \lambda/2 \)
- Measured peak-null beamwidth: \( \lambda/6 \)

Low Loss: \( \text{Im}(n) = 0.06 \)
High-Directivity Coupled-Line Coupler

Coupled Microstrip/NRI Lines:

Co-directional phase flow but contra-directional power flow!

Conventional Microstrip vs. MS/NRI Coupled-Line Coupler

- Equal length
- Equal line spacing
- Equal propagation constant

MS-MS Directivity: 8dB
MS/NRI Directivity: 20dB

3dB Coupler: Experimental Results

- Operating frequency – 3GHz
- Cell size – 4mm
- Line width – 2.34mm
- C - 1.3pF, L - 3.3nH
- #of unit cells – 6
Metamaterial MS/NRI 3dB Coupler

- Operates in coupled mode stop band
- Arbitrary coupling levels by increasing coupler length
Metamaterial MS/NRI 3dB Coupler

Operates in coupled mode stop band
Arbitrary coupling levels by increasing coupler length
Metamaterial MS/NRI 3dB Coupler

Operates in coupled mode stop band
Arbitrary coupling levels by increasing coupler length

Phase Progression With Exponential Field Variation

Operation in Coupled-Mode Stop Band

\[ |V_1| \]
\[ |V_2| \]

Input
Coupled
Isolated

Line 1 (MS)
Line 2 (NRI)

\[ S \]
\[ \beta \]
A LEAKY BACKWARD-WAVE ANTENNA

Analogous to Reversed Cerenkov Radiation

\[ n > 0 \Rightarrow \cos(\theta) = \frac{c}{v_\phi} \]

\[ n < 0 \Rightarrow \cos(\theta) = \frac{c}{v_\phi} \]
Implementation

F=15GHz: Completely Printed Structure

Shorted stubs are used to make shunt inductors

Gaps are used to make series capacitors

A LEAKY BACKWARD-WAVE ANTENNA (fan beam)

2-D Leaky-Wave Antenna (pencil beam)

- Beam scans from approx. -30° to +30° through broadside over a 150MHz range
- Phase profile nearly flat near broadside, suggesting approach to $\beta=0$ (2.4GHz)
Zero-Degree Phase-Shifting Lines

Phase Compensation with RHM/LHM Lines

By Departing from Fo, Positive or Negative Phase-Shift Can be Incurred

**Series-Fed Linear Array**

**Conventional Delay Lines**

\[ d_{360^\circ \text{TL}} = 1\lambda_{\text{CPW}} = 283.5\, \text{mm} \]

**Metamaterial Lines (slow-wave region)**

\[ d_{4\text{-stage}} = 0.11\lambda_{\text{CPW}} = 32\, \text{mm} \]

**Advantages of replacing the conventional delay lines with metamaterial phase-shifting lines:**

1. More compact
2. More broadband
3. Less beam squint

**Freq. Range:**

0.82-1.00 GHz

**360° TL**

Squint = 180°

**0° MM line**

Squint = 24.3°
• 4 unit cell metamaterial ring antenna
• Implemented in microstrip at 1.52 GHz
• Fed by a standard 50 $\Omega$ coaxial connector

Rogers RT5880 Substrate
$\varepsilon_r = 2.2, \ h = 6.35\text{mm}$

At 1.52 GHz:
$\lambda_o = 200\text{mm}$
$\lambda_{ms} = 150\text{mm}$

$L = \lambda_o/25, \ h = \lambda_o/32$

PLOT OF THE IN-PHASE RADIATING CURRENTS IN THE VIAS

$J_{surf} [A/m]$:
- 3.666e+002
- 3.4571e+002
- 3.2086e+002
- 2.9785e+002
- 2.7495e+002
- 2.5397e+002
- 2.3515e+002
- 2.2625e+002
- 2.1834e+002
- 2.042e+002
- 2.0092e+002
- 1.9595e+002
- 1.8751e+002
- 1.6442e+002
- 1.3775e+002
- 1.1860e+002
- 9.1599e+001
- 6.9703e+001
- 5.8726e+001
- 2.562e+001
- 5.2696e-002

$f_o = 1.52$ GHz
MEASURED Vs. SIMULATED RETURN LOSS

\( f_0 = 1.52\text{GHz} \quad S_{11} \text{ BW } (<-10\text{dB}) = 2\% \)

8.1mm

150mm
MEASURED RADIATION PATTERNS at $F=1.52\,\text{GHz}$

- The radiation patterns resemble those of a vertical dipole
- There is back-radiation due to the finite ground plane

E-plane

H-plane
Phase-Agile MS/NRI Branch-Line Couplers

Regular Branch-line coupler

Type-1 MS/NRI Branch-line coupler

Type-2 MS/NRI Branch-line coupler

Experimental Results

(a) Type 1: solid line-experiment; broken line-simulation

(b) Type 2: solid line-experiment; broken line-simulation
Antenna Beamforming Networks

Type-1:

NRI

NRI

270°

180°

90°

0°
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