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

George V. Eleftheriades

Department of Electrical and Computer Engineering

The University of Toronto

CANADA

METAMATERIALS

META="BEYOND" IN GREEK
Materials with unusual EM properties, not encountered in nature

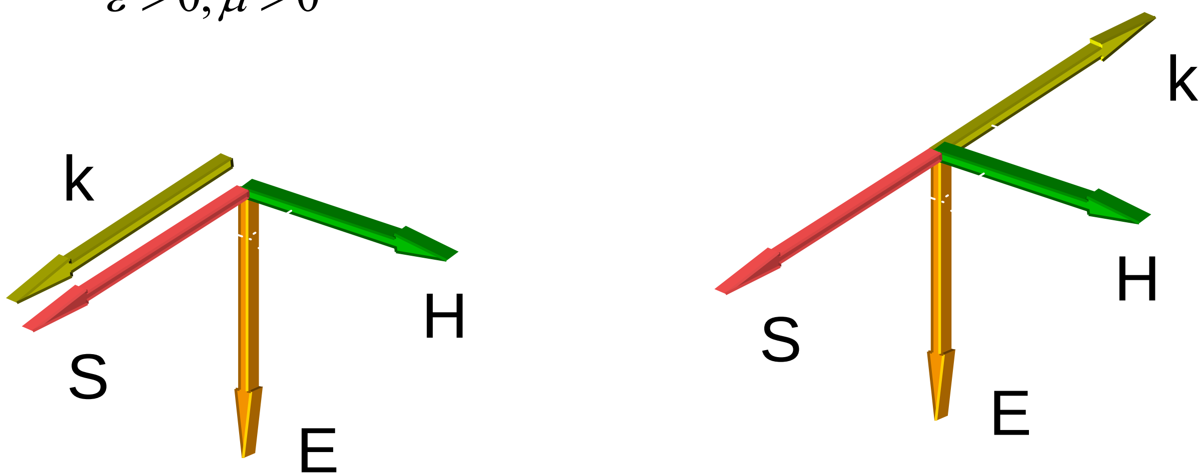
TRANSMISSION-LINE METAMATERIALS:

ARTIFICIAL DIELECTRICS SYNTHESIZED BY PERIODICALLY LOADING A HOST TRANSMISSION-LINE MEDIUM WITH R,L,C ELEMENTS (lumped or printed):
PERIODICITY $\ll \lambda$

LEFT-HANDED ε<0 AND μ<0 METAMATERIALS

Veselago, 1960s

$\varepsilon > 0, \mu > 0$ $\varepsilon < 0, \mu < 0$ **Backward Waves**



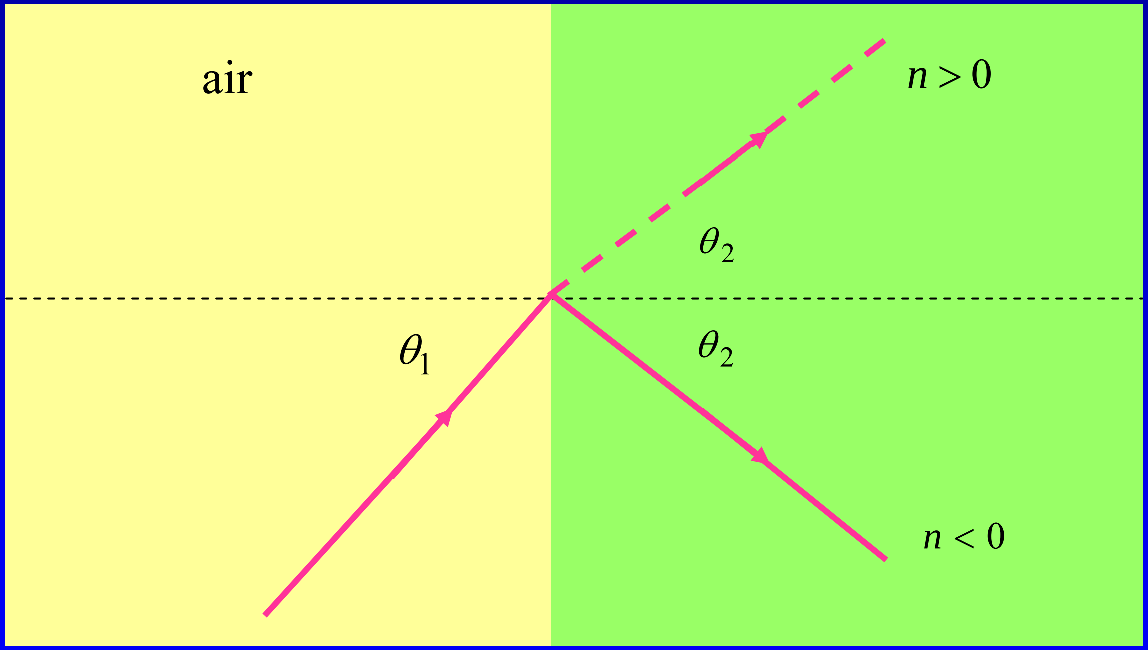
Regular Materials (right-handed)

Left-Handed Materials

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

Negative-Refractive-Index (NRI) Materials

NEGATIVE REFRACTION

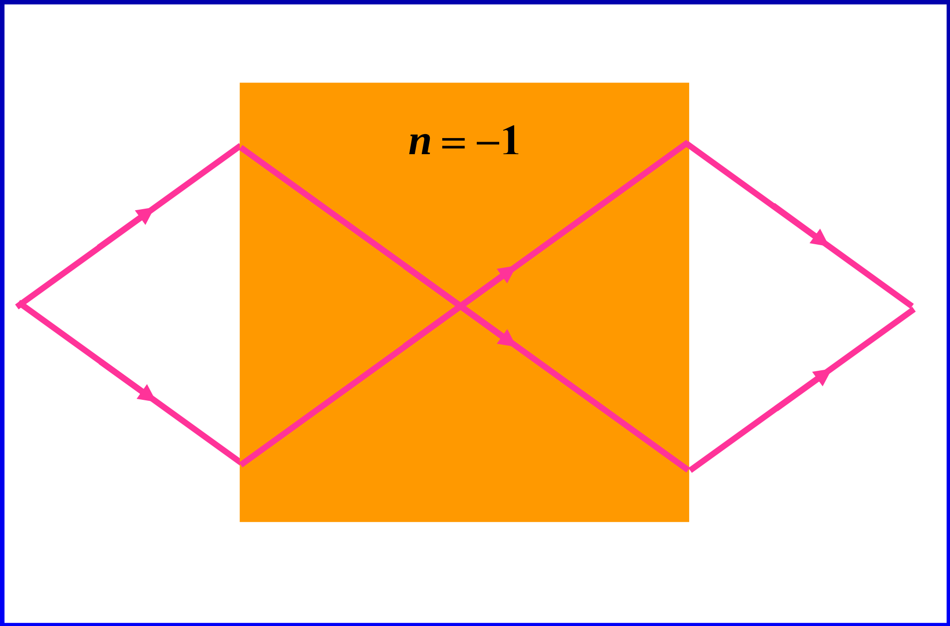


$$\frac{\sin\theta_1}{\sin\theta_2} = n$$

Negative-Refractive-Index (NRI) Media

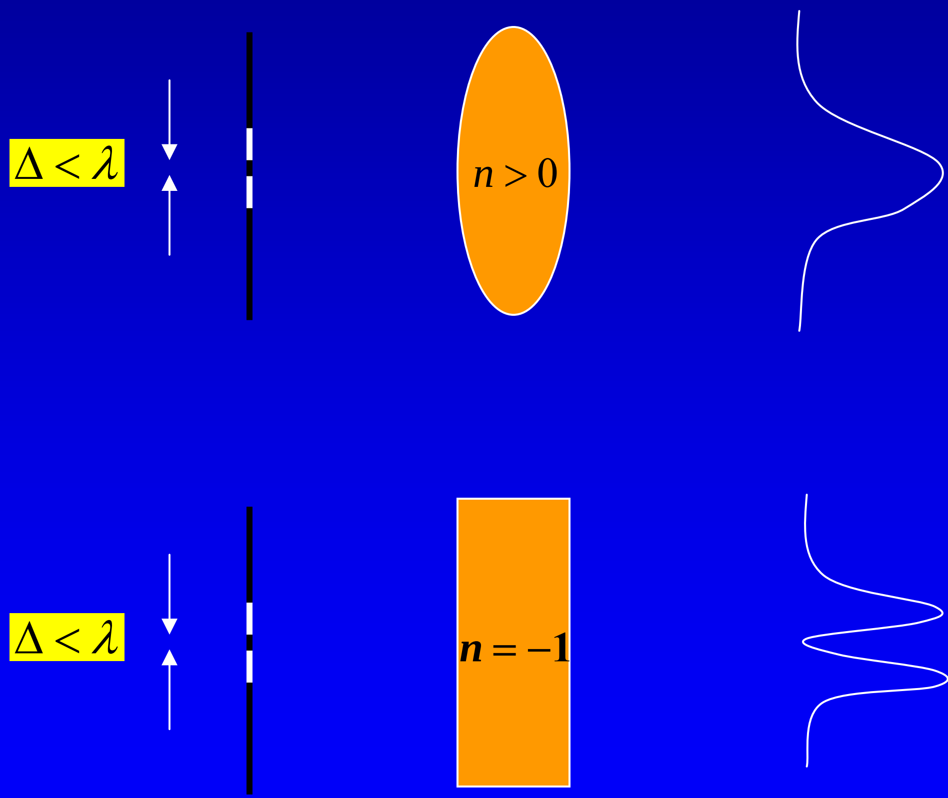
Focusing from Planar n<0 Slabs

Veselago's Lens



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

Sub-Wavelength Resolution



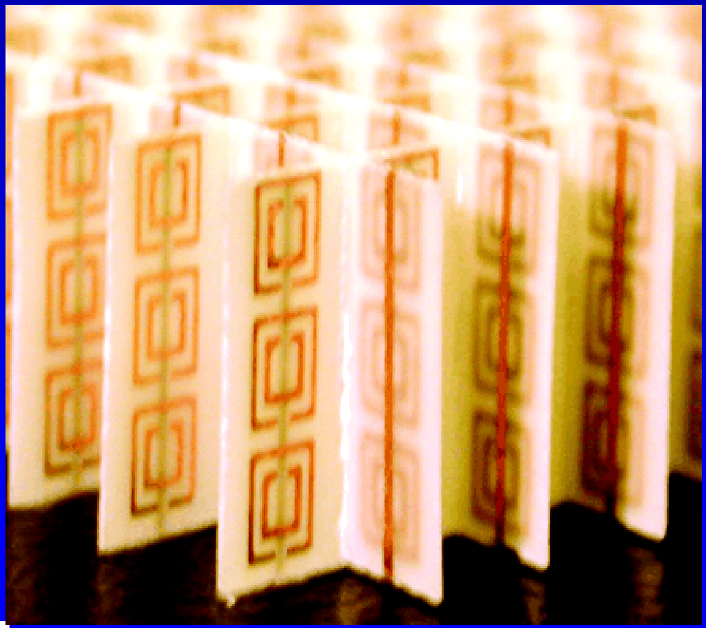
•Unlike any other lens it may offer <u>sub-wavelength resolution</u>!

John Pendry PRL 2000

Sub-wavelength resolution is a result of restoring the evanescent portion of the Fourier spectrum

HOW CAN ONE MAKE ε<0 AND μ<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

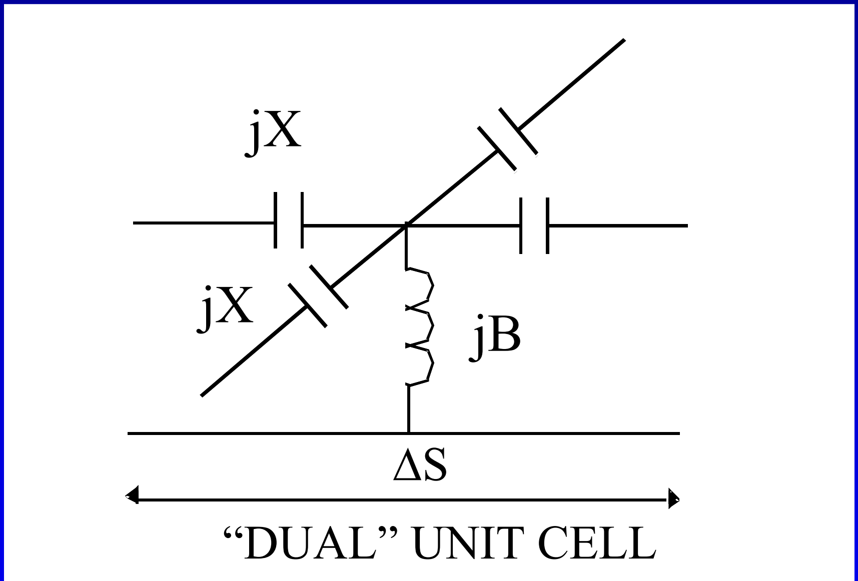
Operates around resonances: Narrowband/Lossy

Bulky: 3-D structure

Distributed cells: Large for usage at RF frequencies

Negative-Refractive-Index

Tranmission-Line 2D Metamaterials



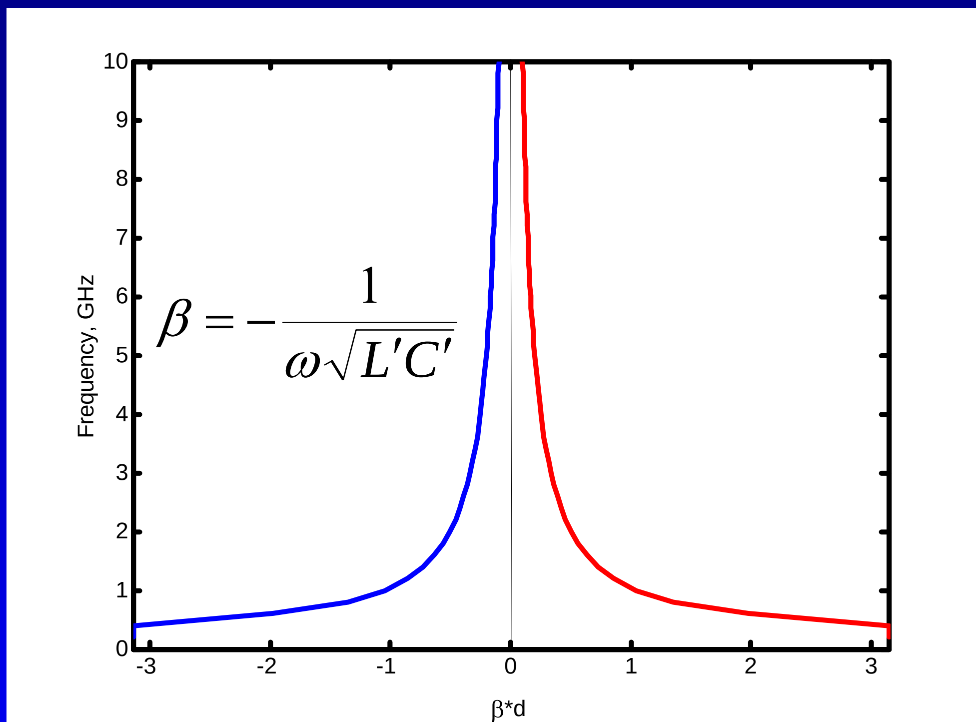
$$j\omega\varepsilon = \frac{jB}{\Delta S} = \frac{j(-1/\omega L)}{\Delta S} \Rightarrow \varepsilon = -\frac{1}{\omega^2 L \Delta S}$$

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

A.K. Iyer and G.V. Eleftheriades, "Negative Refractive Index Metamaterielas Supporting 2-D Waves," ***IEEE MTT-S Intl. Microwave Symposium Digest*****, (Seattle, WA), vol. 2, pp. 1067-1070, June 2-7, 2002.**

G.V. Eleftheriades, A.K. Iyer and P.C. Kremer, "Planar negative refractive index media using periodically L-C loaded transmission lines," ***IEEE Trans. on Microwave Theory and Techniques*****, vol. 50, no. 12, pp. 2702-2712, Dec. 2002.**

1D CONTINUOUS LIMIT



Backward Waves Supported

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

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

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

G.V. Eleftheriades, O. Siddiqui, and A.K. Iyer, "Transmission line models for negative refractive index media and associated implementations without excess resonators." *IEEE Microwave and Wireless Components Letters,* vol. 13, no. 2, pp. 51-53, Feb. 2003.

PERIODICALLY L-C LOADED TRANSMISSION LINES

Backward Wave

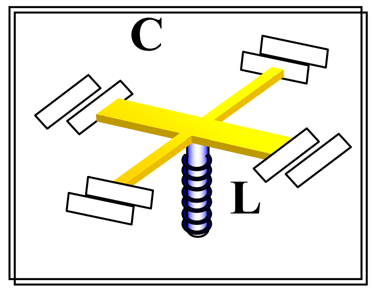
$v_p v_g < 0$

For short interconnecting lines kd<<1 and small phase-shifts per-unit-cell βd<<1

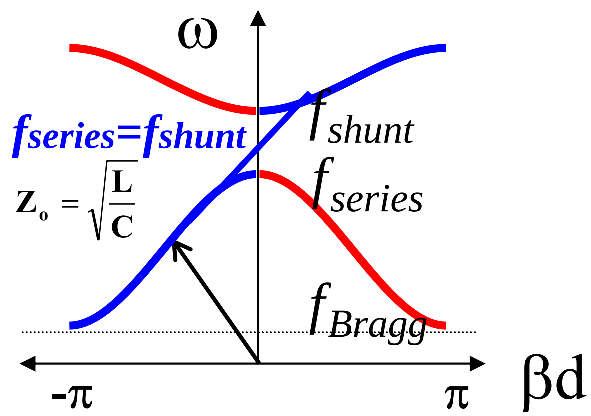
$$\varepsilon_{eff} \cong \varepsilon_o - \frac{1}{\omega^2 L d}$$

$$\mu_{eff} \cong \mu_o - \frac{1}{\omega^2 C d}$$

LH Media



Finite LHM
2-D Unit Cell
Period=d



$$f_{series} = \frac{1}{2\pi\sqrt{C(\mu_o d)}} \qquad (\mu = 0)$$

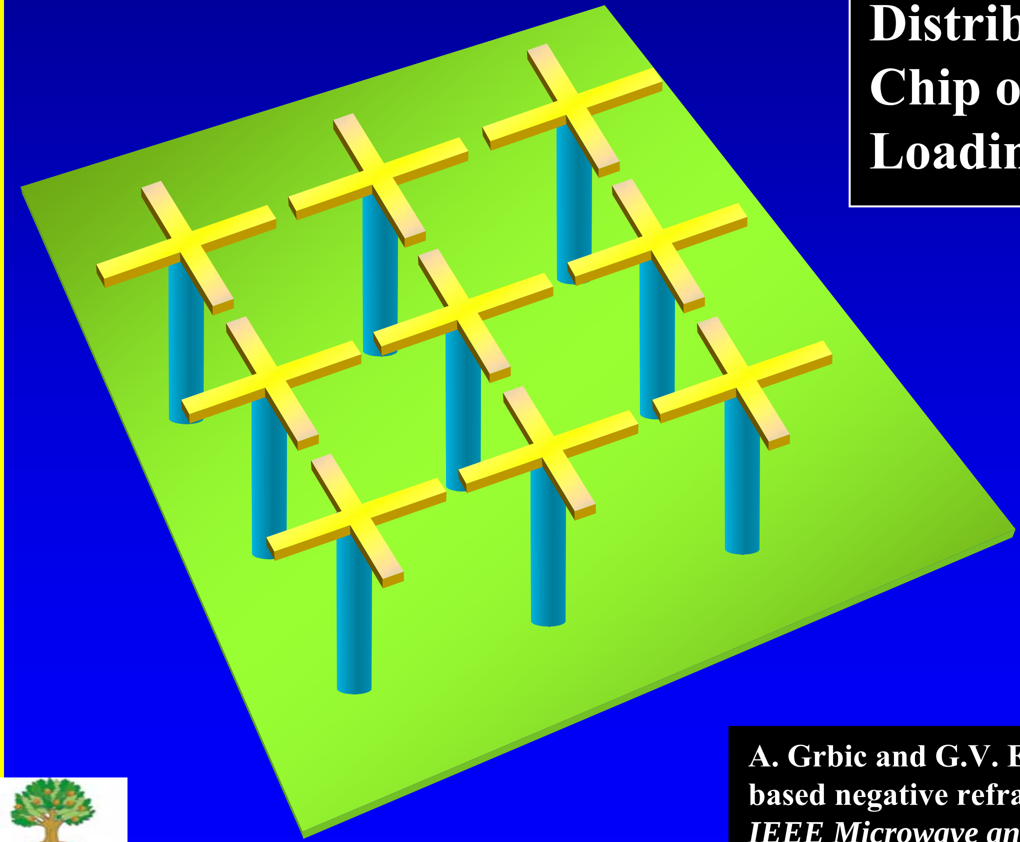
$$f_{shunt} = \frac{1}{2\pi\sqrt{L(\varepsilon_o d)}} \qquad (\varepsilon = 0)$$

$$f_{Bragg} = \frac{1}{4\pi\sqrt{L\,C}}$$

G.V.Eleftheriades et al., *IEEE T-MTT* vol. 50, no. 12, pp. 2702-2712, Dec. 2002.

Small period d: Large NRI bandwidth

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



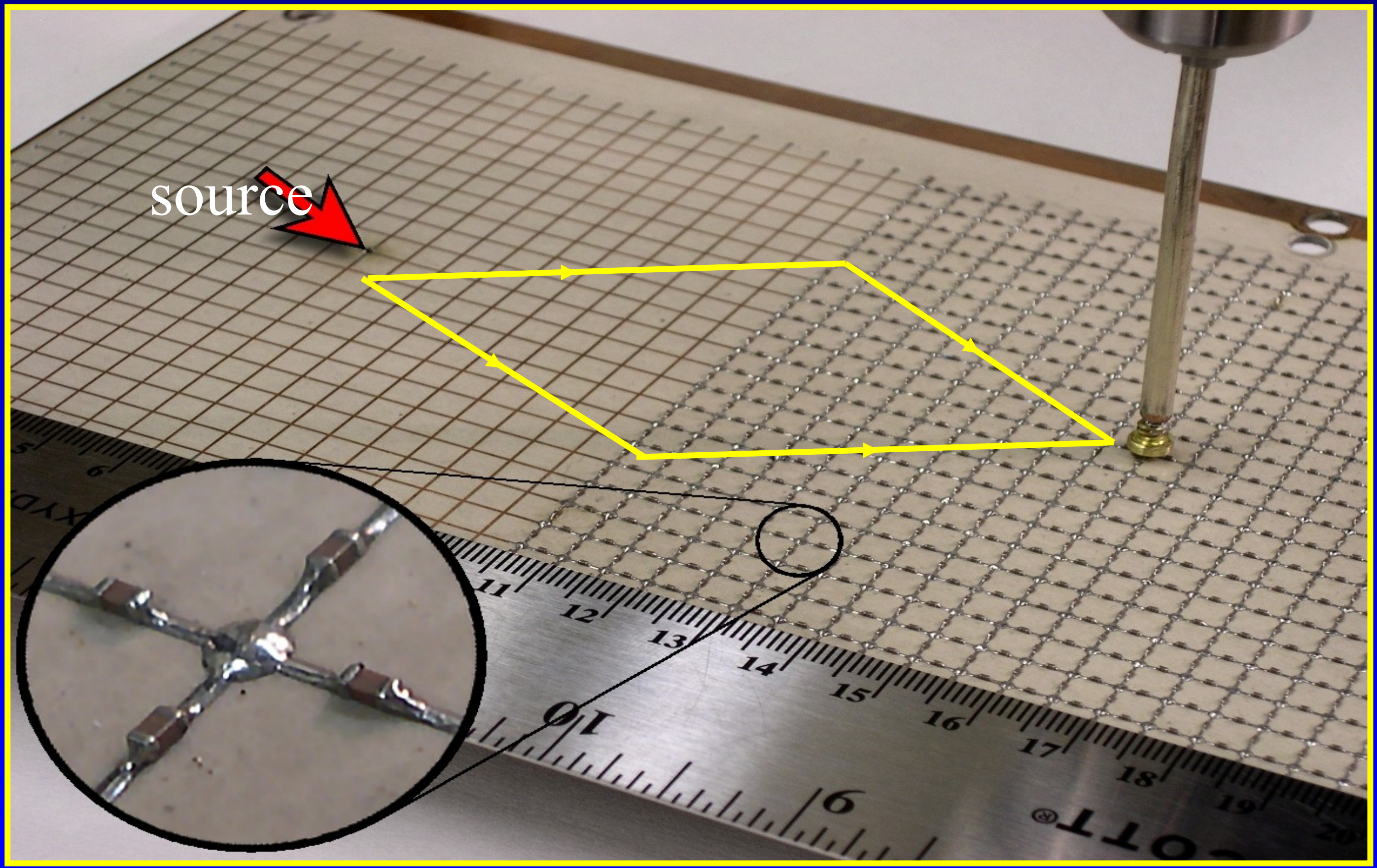
Distributed TL Network With Chip or Printed (gaps and vias) Loading Lumped Elements

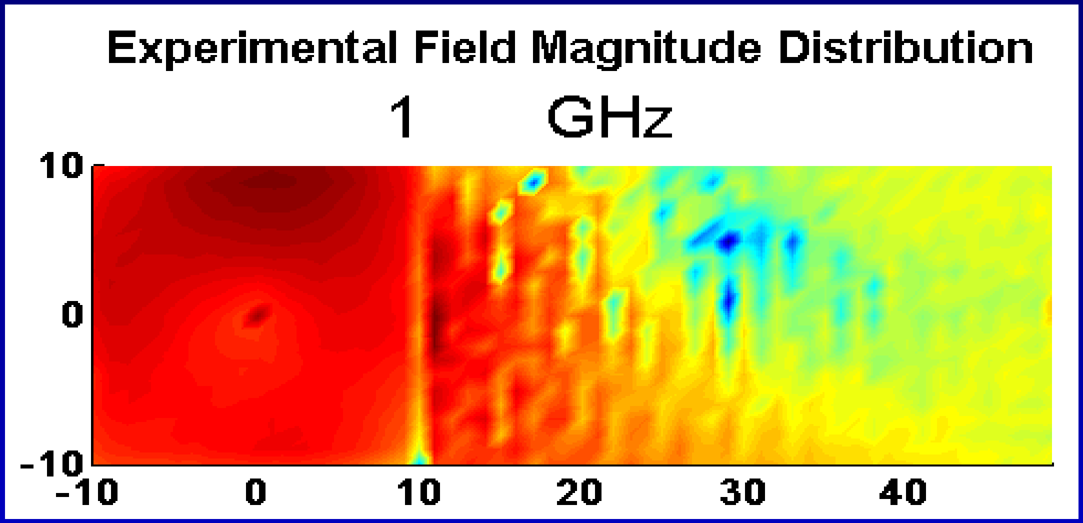
The electric field along the vias induces vertical electric dipole moments

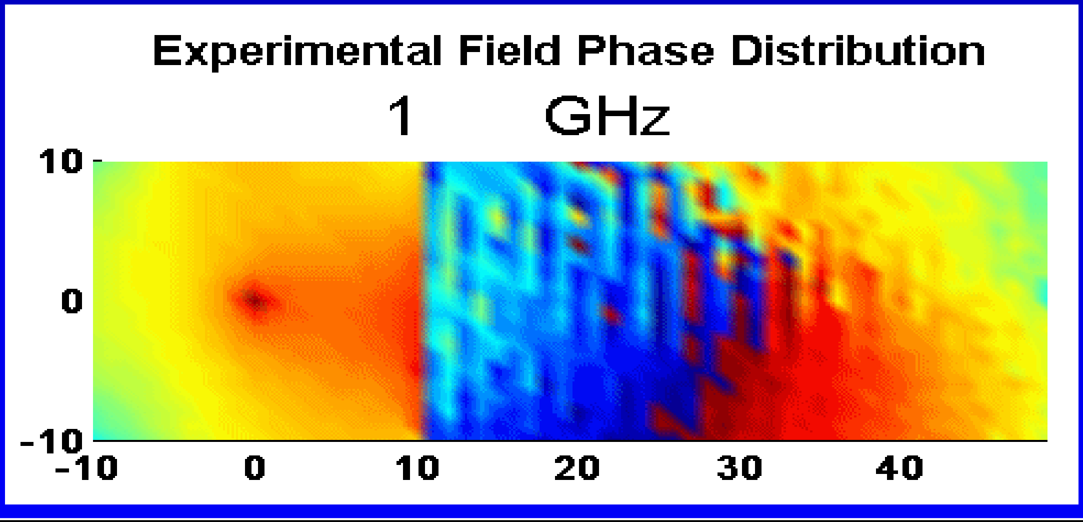
The magnetic field in the gaps induces horizontal magnetic dipole moments

A. Grbic and G.V. Eleftheriades, "Dispersion analysis of a microstrip based negative refractive index periodic structure."
IEEE Microwave and Wireless Components Letters,
vol. 13, no. 4, pp. 155-157, April 2003.

NEGATIVE-REFRACTIVE-INDEX (NRI) LENS

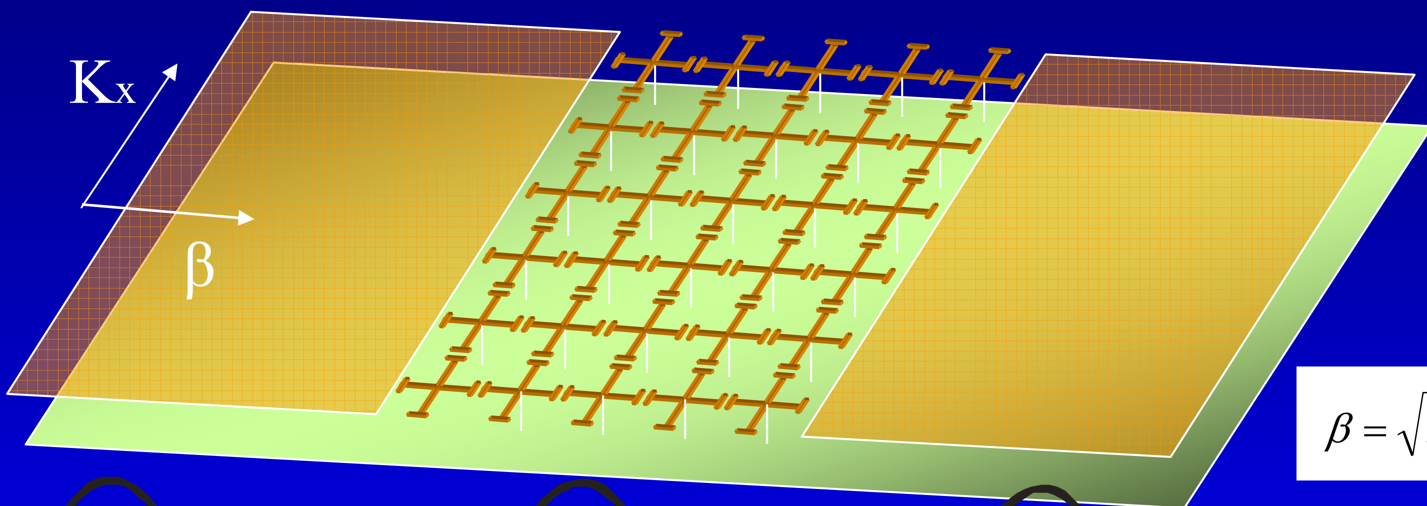






A.K. Iyer, P.C. Kremer and G.V. Eleftheriades, "Experimental and theoretical verification of focusing in a large, periodically loaded transmission line negative refractive index metamaterial." *Optics Express,* 11, pp. 696-708, April 07, 2003

Overcoming the Diffraction Limit?



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

Propagating Waves $K_x < K$

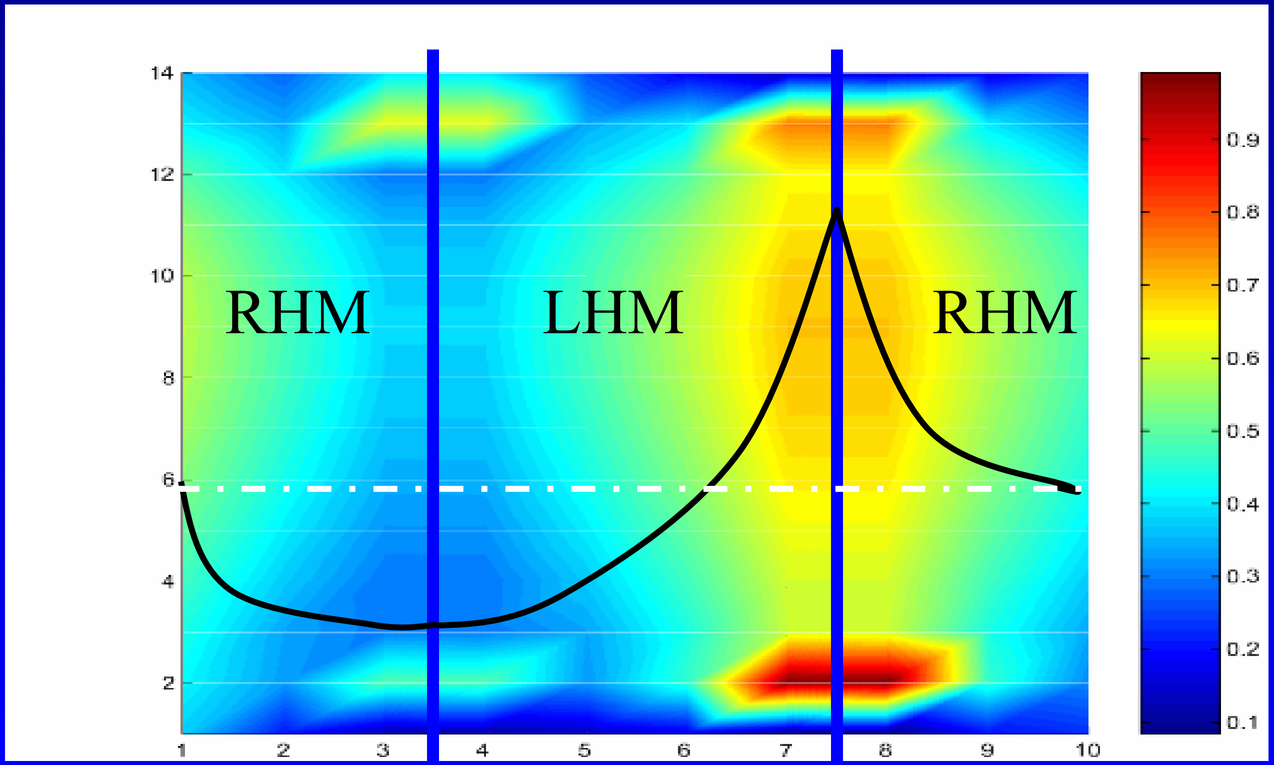
Evanescent Waves $K_x > K$

Phase Restoration

Amplitude Restoration

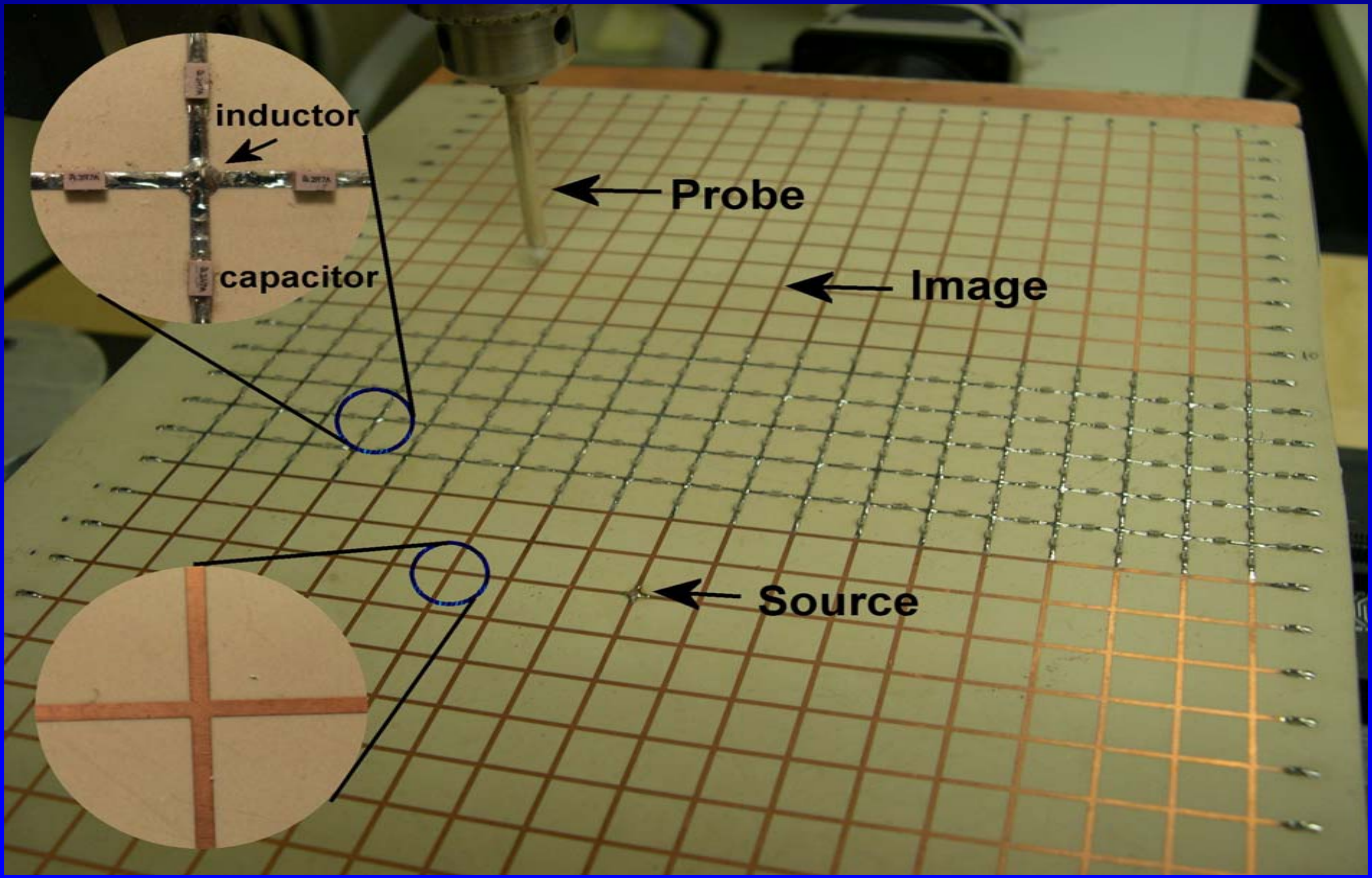
Growing Evanescent Waves

“Plasmon” Excitation On the Exit Interface



A. Grbic and G.V. Eleftheriades, “Growing Evanescent Waves in Negative - Refractive -Index Transmission-Line Media,” *Applied Physics Letters*, vol. 82, no. 12, pp. 1815-1817, March 24, 2003.

Transmission-Line NRI Super-Resolving Lens



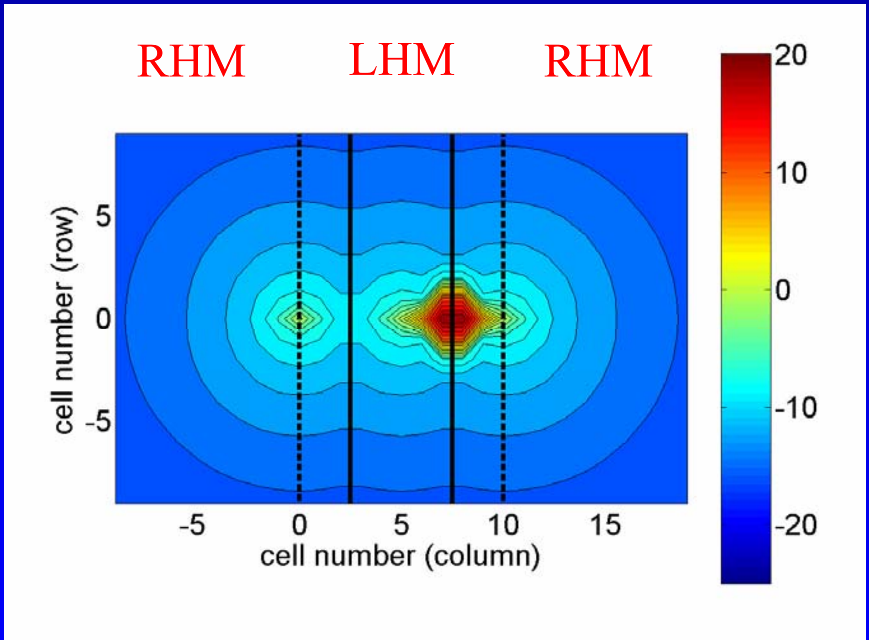
Left-handed Region: A 5 X 19 grid of unit-cell size 8.4mm X 8.4mm

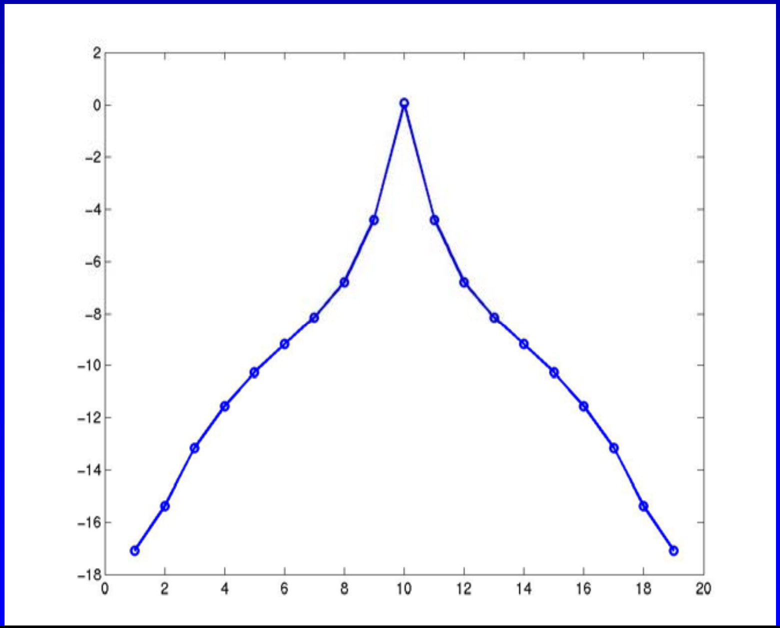
"Perfect" Imaging?

Analytical Theory

Solid Line=Source Profile

Dotted Line=Image Profile

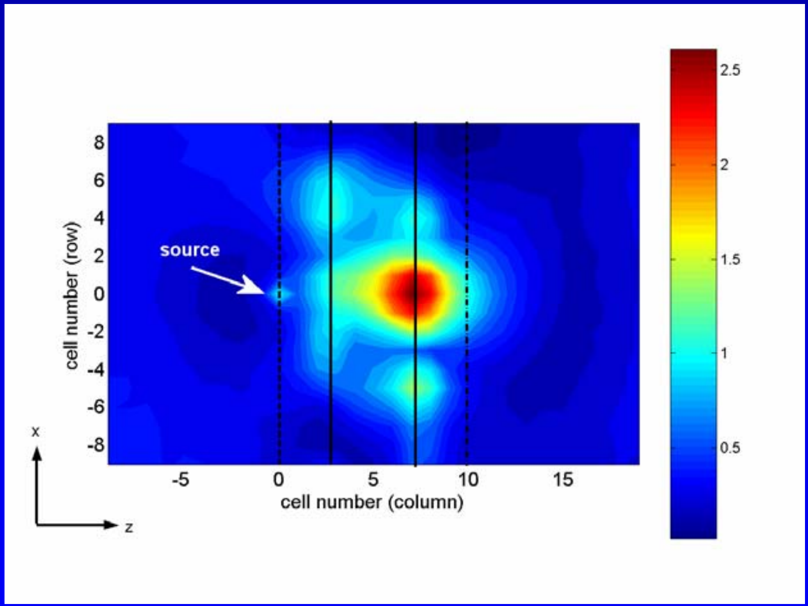


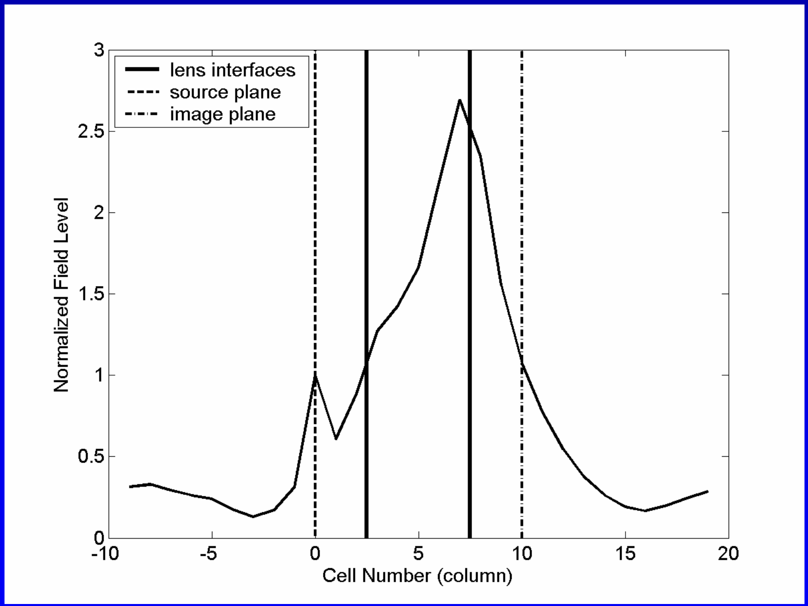


A. Grbic and G.V. Eleftheriades, "Negative refraction, growing evanescent waves and sub-diffraction imaging in loaded-transmission-line metamaterials." *IEEE Trans. on Microwave Theory and Techniques*, vol. 51, no. 12., pp. 2297- 2305, Dec. 2003.

Experimental Results

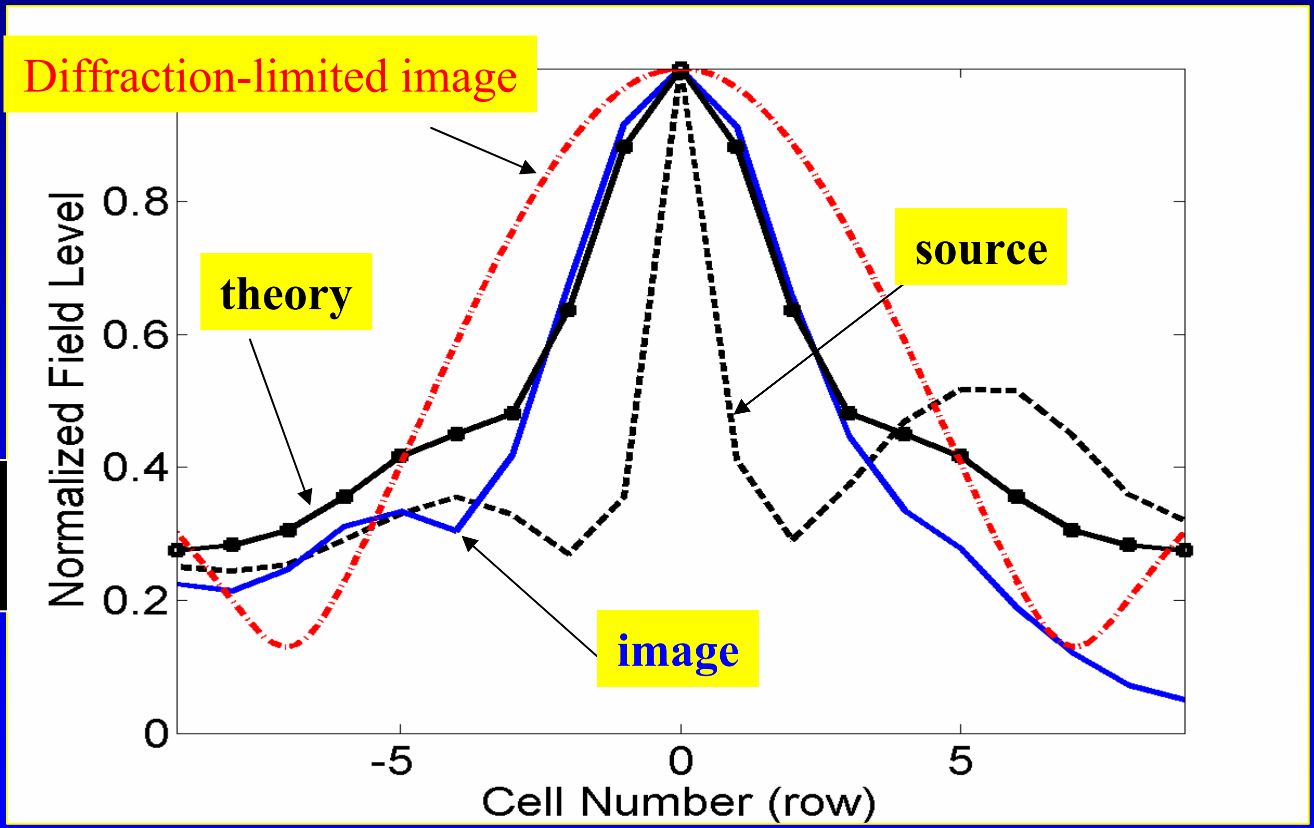
F=1.056GHz





Growing Evanescent Waves!

Measured Beamwidth at Focal Plane



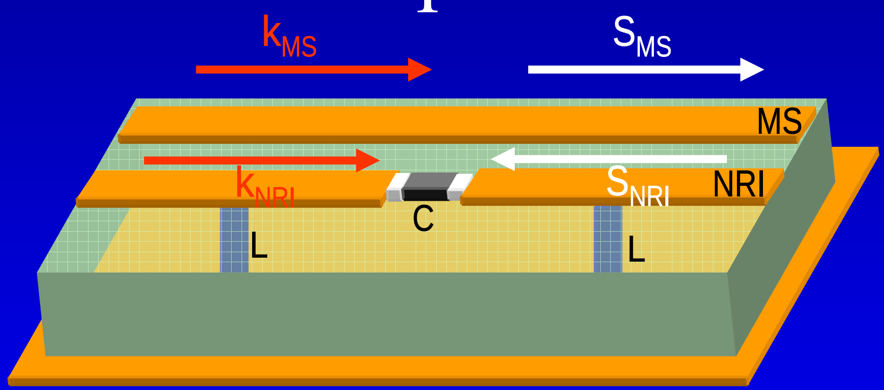
Low Loss:
Im(n)=0.06

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

A. Grbic and G.V. Eleftheriades, "Overcoming the diffraction limit with a planar left-handed transmission-line lens." *Physical Review Letters*, vol. 92, no. 11,pp. 117403 , March 19, 2004 .

High-Directivity Coupled-Line Coupler

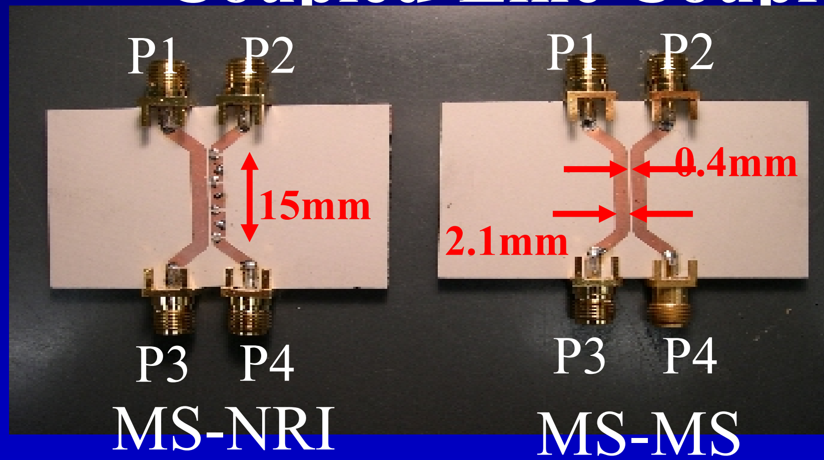
Coupled Microstrip/NRI Lines:



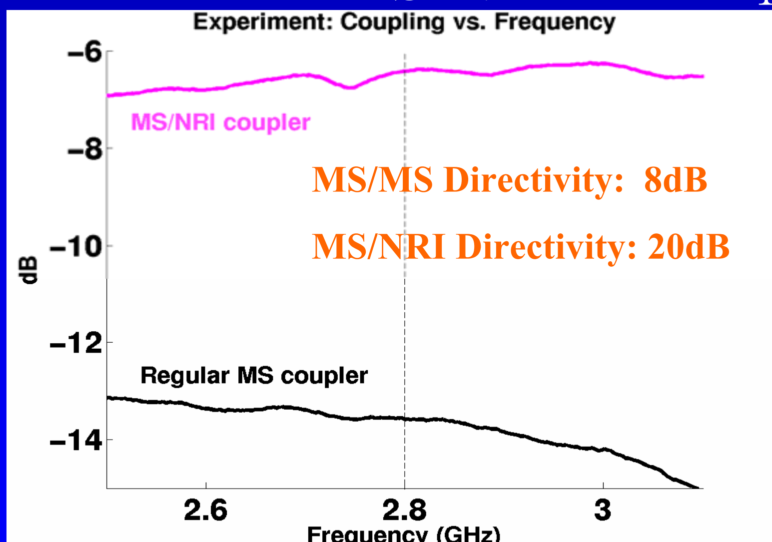
Co-directional phase flow but contra-directional power flow!

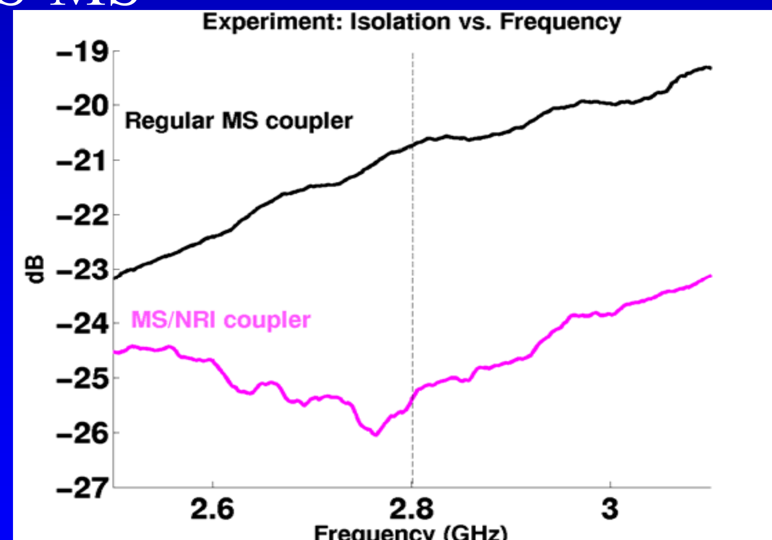
R. Islam and G.V. Eleftheriades, "A planar metamaterial co-directional coupler that couples power backwards." 2003 IEEE Itnl. Microwave Symposium Digest, Philadelphia, June 8-13, pp. 321-324, 2003.

Conventional Microstrip vs. MS/NRI Coupled-Line Coupler



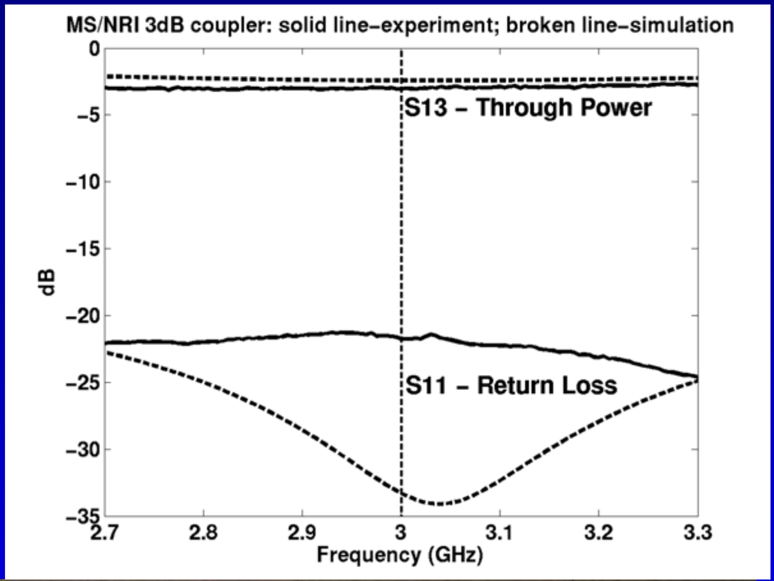
- Equal length
- Equal line spacing
- Equal propagation constant

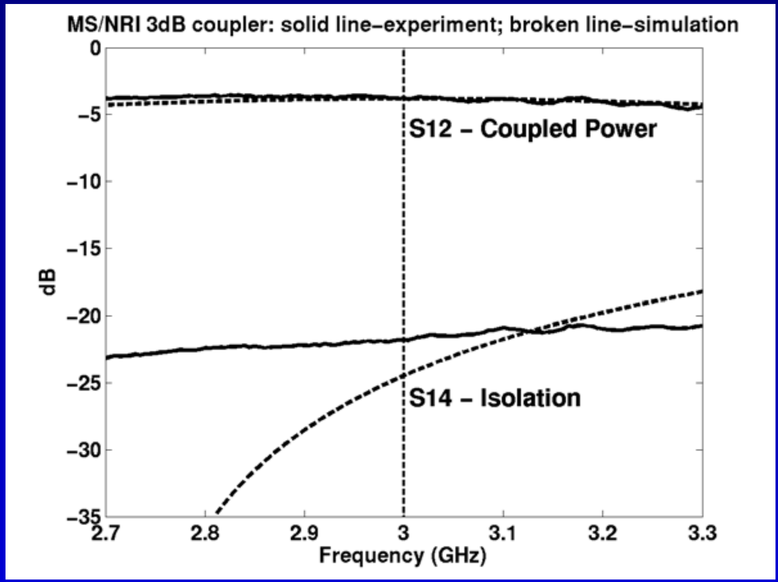


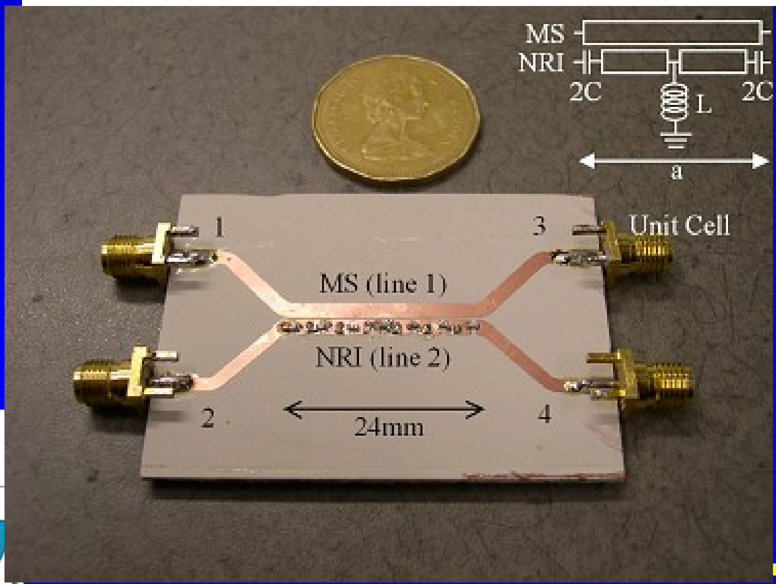


R. Islam and G.V. Eleftheriades, "A planar metamaterial co-directional coupler that couples power backwards." 2003 IEEE Itnl. Microwave Symposium Digest, Philadelphia, June 8-13, pp. 321-324, 2003.

3dB Coupler: Experimental Results



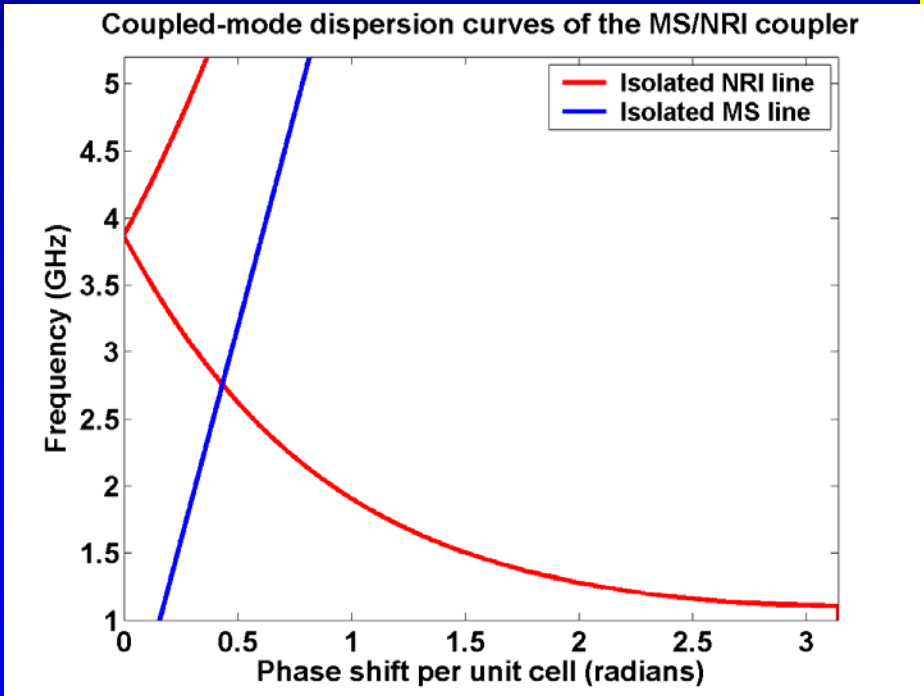




- Operating frequency – 3GHz
- Cell size – 4mm
- Line width – 2.34mm
- C - 1.3pF, L - 3.3nH
- #of unit cells – 6

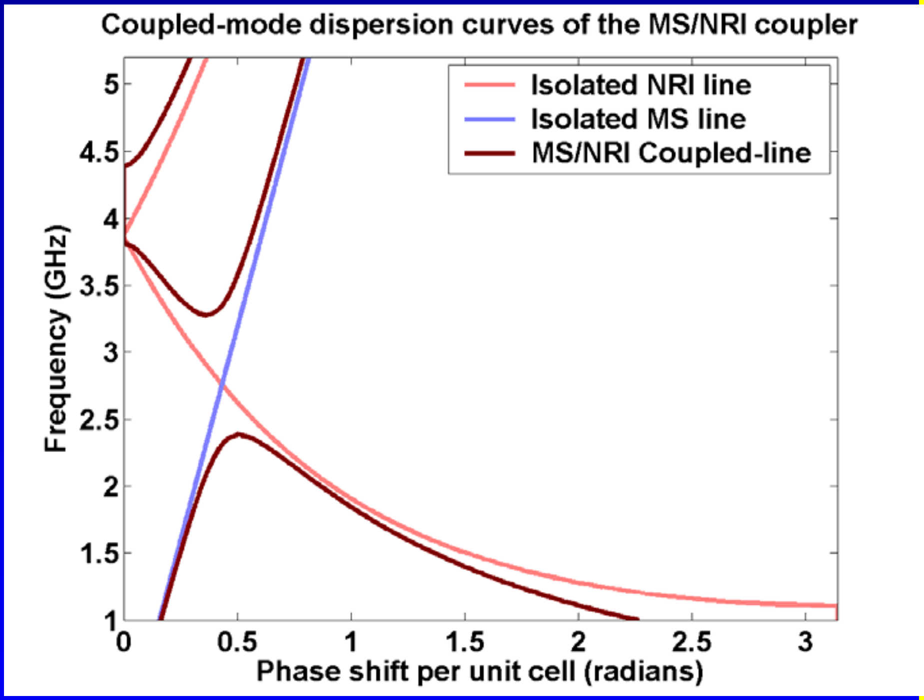
Metamaterial MS/NRI 3dB Coupler

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



Metamaterial MS/NRI 3dB Coupler

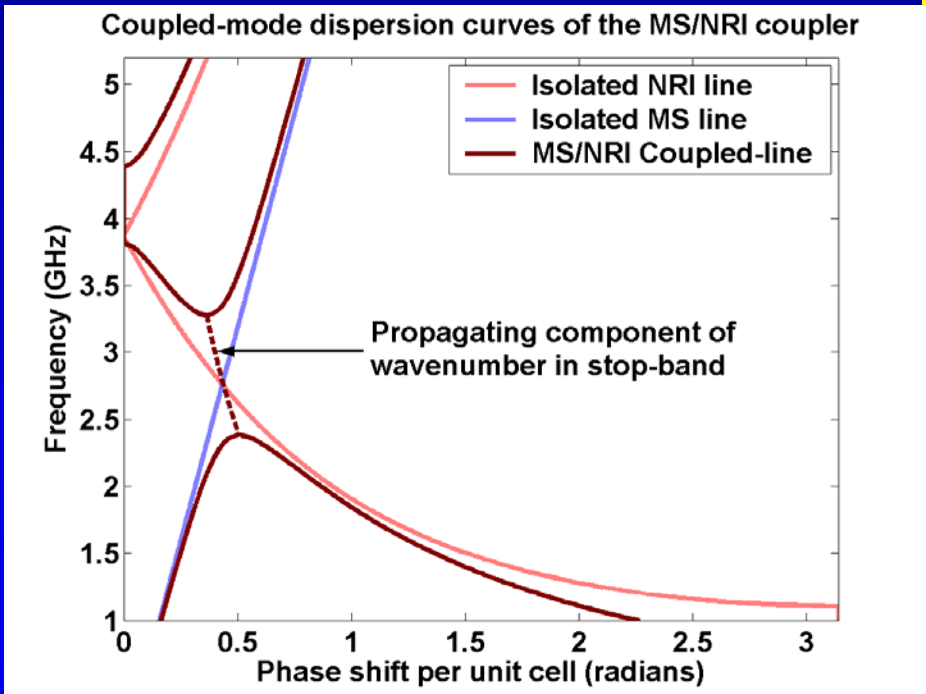
- Operates in coupled mode stop band
- Arbitrary coupling levels by increasing coupler length



Metamaterial MS/NRI 3dB Coupler

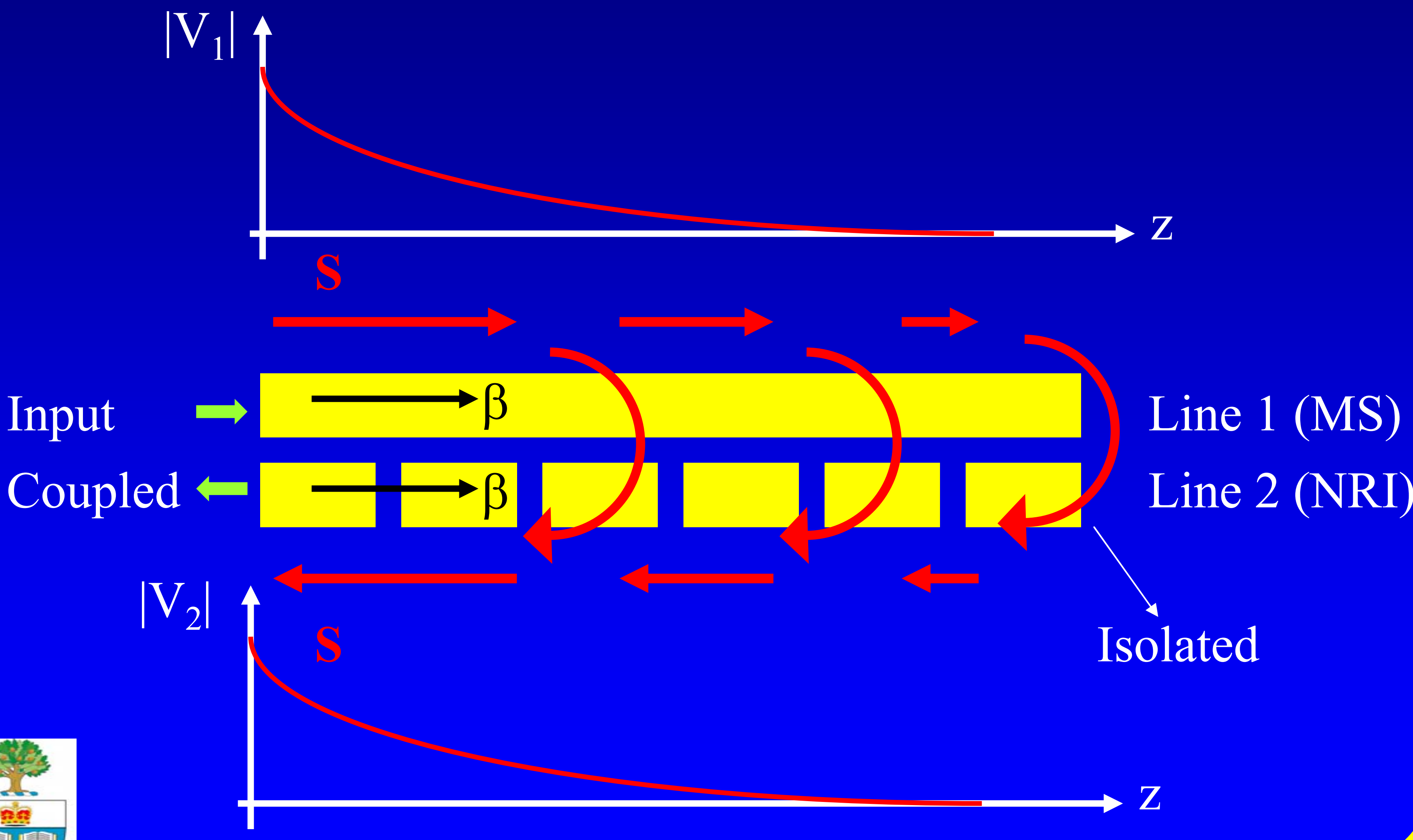
- Operates in coupled mode stop band
- Arbitrary coupling levels by increasing coupler length

Phase Progression With Exponential Field Variation

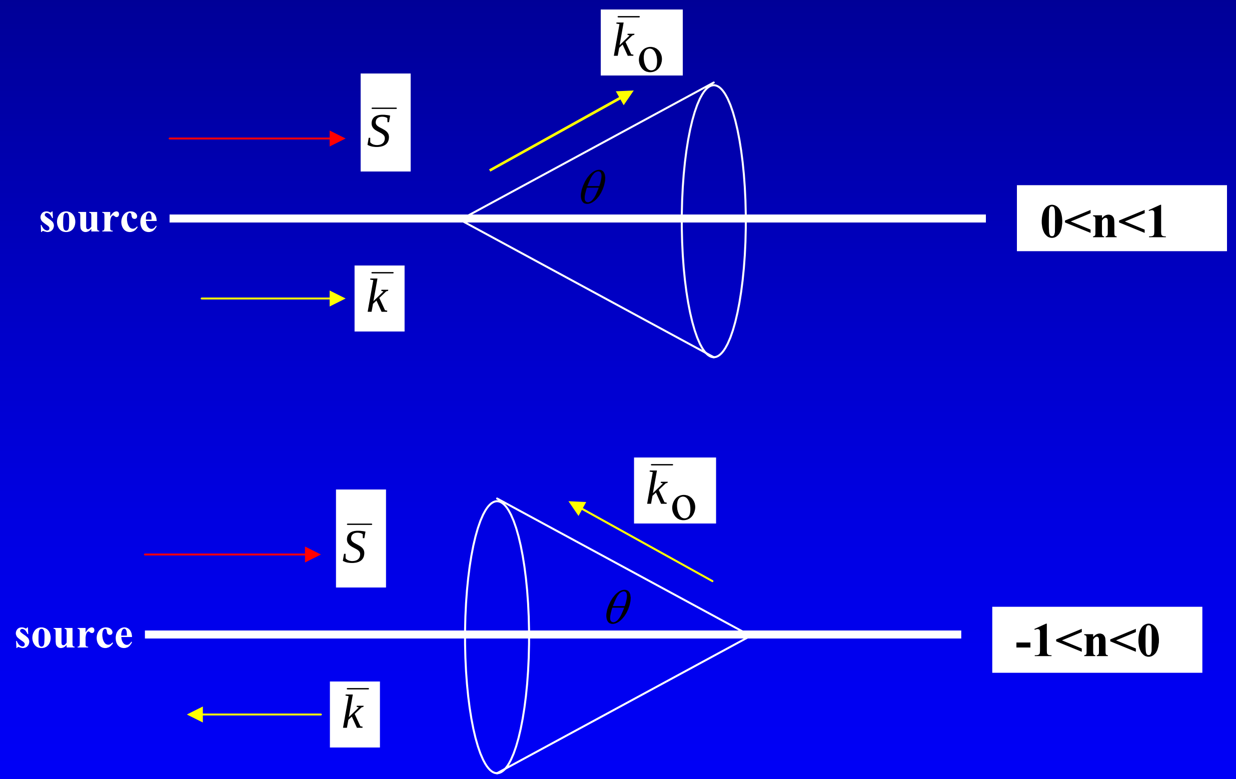


R. Islam, F. Elek and G.V. Eleftheriades, "A coupled-line metamaterial coupler having co- directional phase but contra-directional power flow." *Electronics Letters,* vol. 40, no. 5, March 04, 2004.

Operation in Coupled-Mode Stop Band



A LEAKY BACKWARD-WAVE ANTENNA

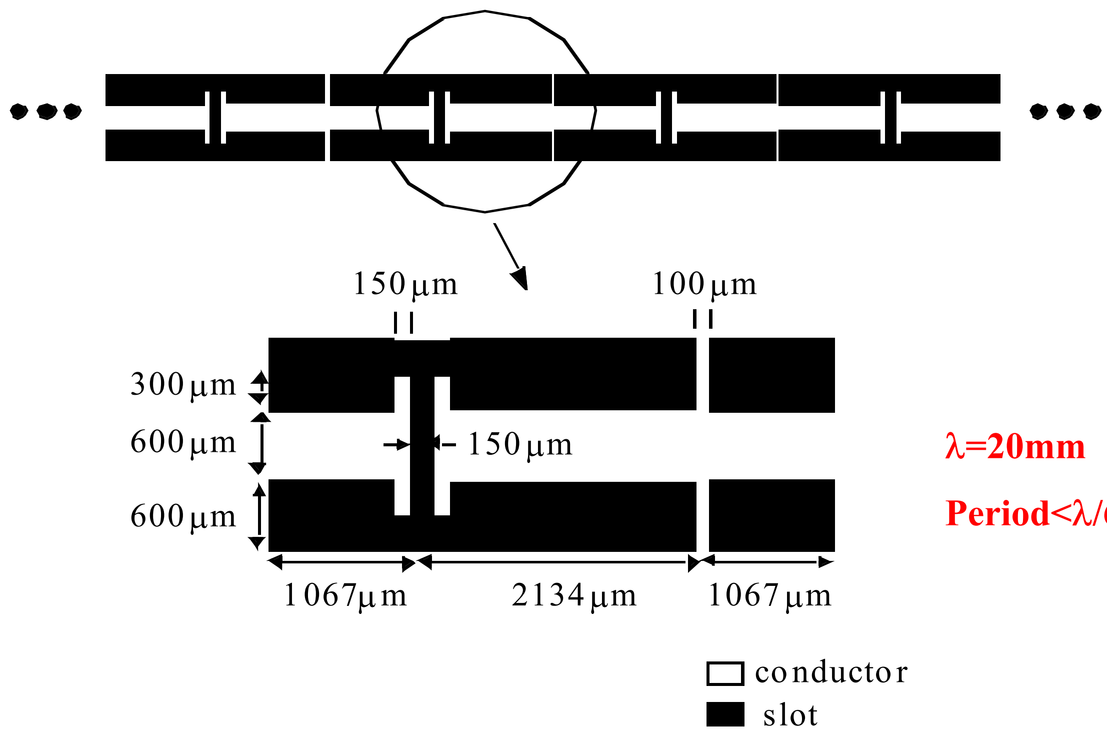


$$\cos(\theta) = \frac{c}{v_\phi}$$

Analogous to Reversed Cerenkov Radiation

Implementation

F=15GHz: Completely Printed Structure



A. Grbic and G.V. Eleftheriades, "A backward-wave antenna based on negative refractive index L-C networks," Proc. of the *IEEE Intl. Symposium on Antennas and Propagation*, Vol. IV, pp. 340-343, June 16-21, 2002, San Antonio, TX.

λ=20mm

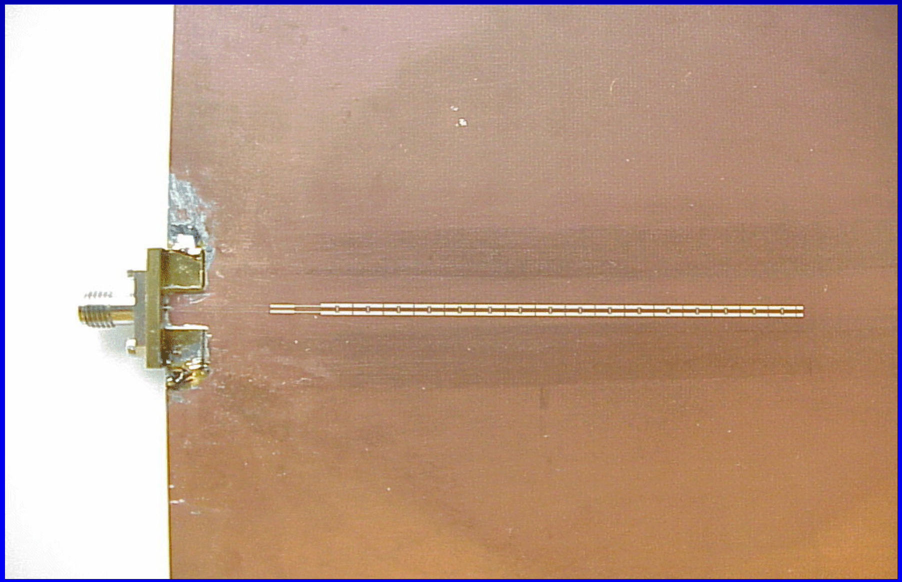
Period<λ/6

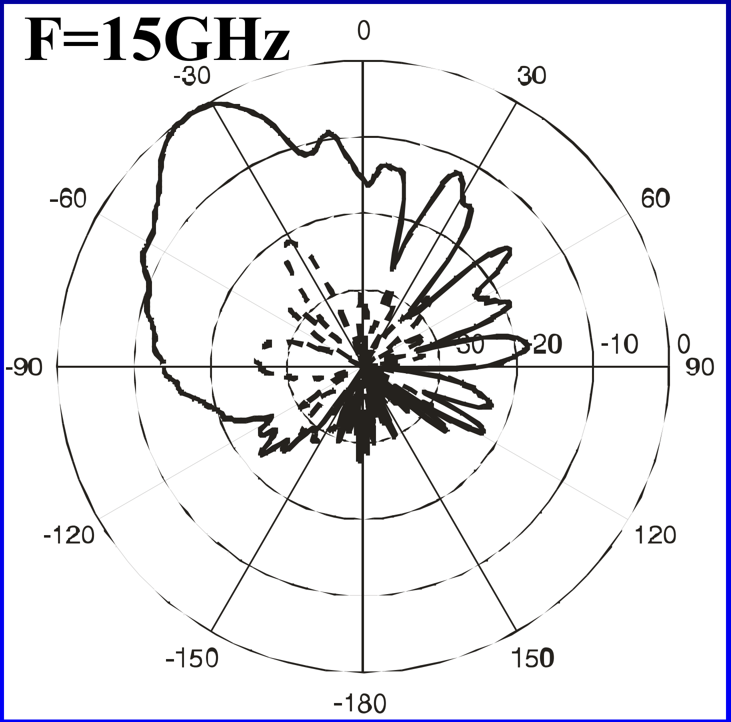
Shorted stubs are used to make shunt inductors

Gaps are used to make series capacitors

A LEAKY BACKWARD-WAVE ANTENNA (fan beam)

BACKWARD Radiation from the FUNDAMENTAL Spatial harmonic

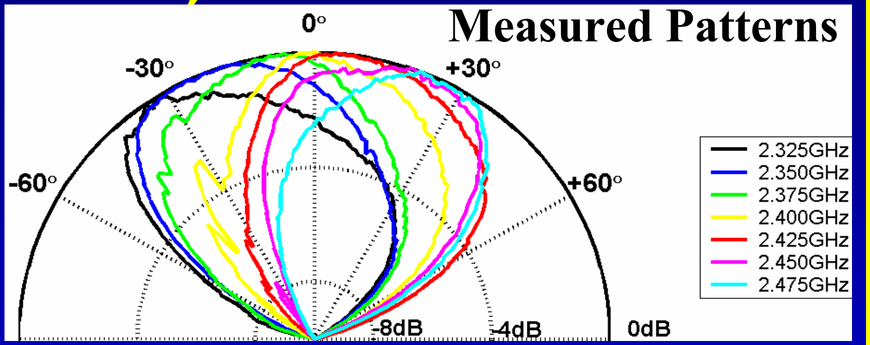




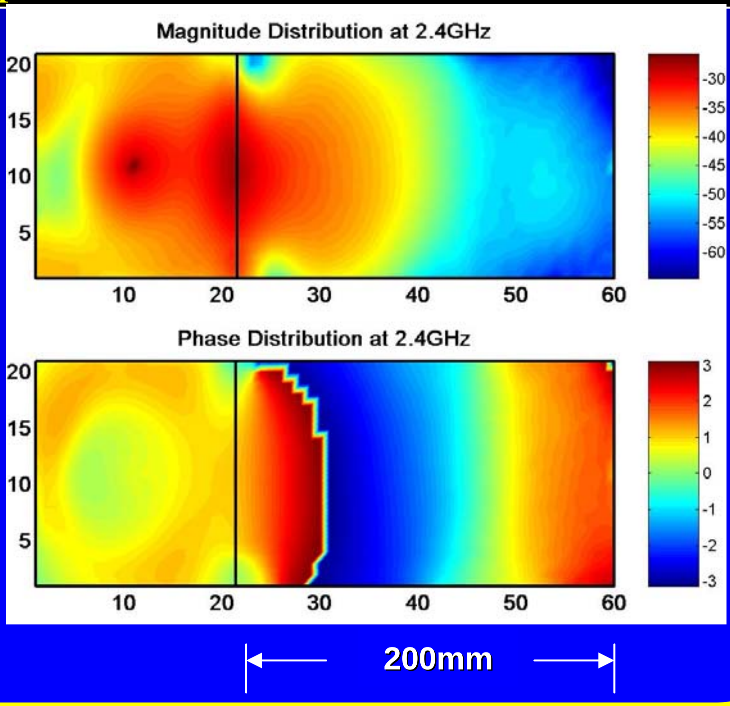
A.Grbic and G.V. Eleftheriades, "Experimental verification of backward-wave radiation from a negative refractive index metamaterial." *Journal of Applied Physics*, *vol. 92, pp. 5930-5935, Nov. 2002*.

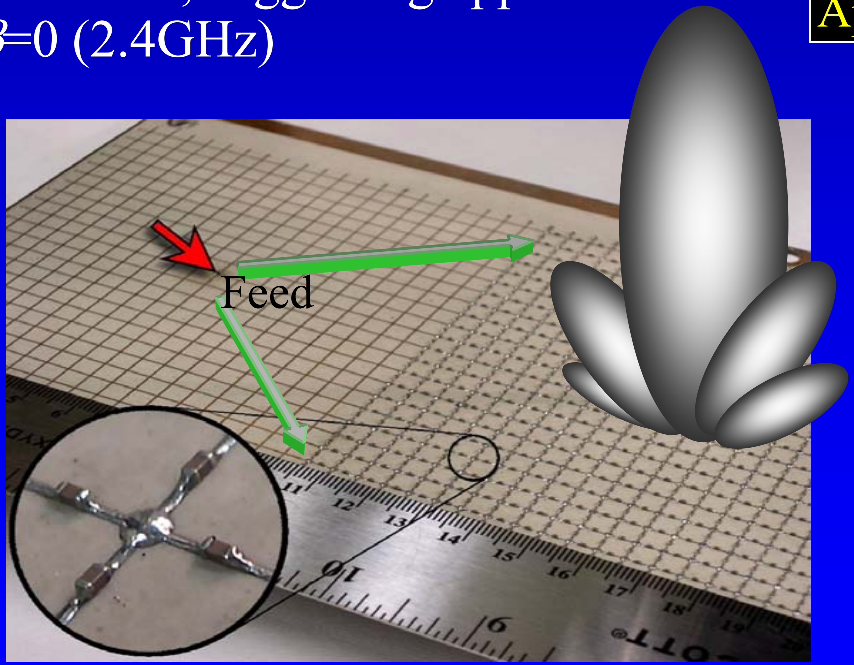
2-D Leaky-Wave Antenna (pencil beam)

- Beam scans from approx. -30° to +30° through broadside over a 150MHz range
- Phase profile nearly flat near broadside, suggesting approach to β=0 (2.4GHz)



Aperture Field Distribution at Broadside:



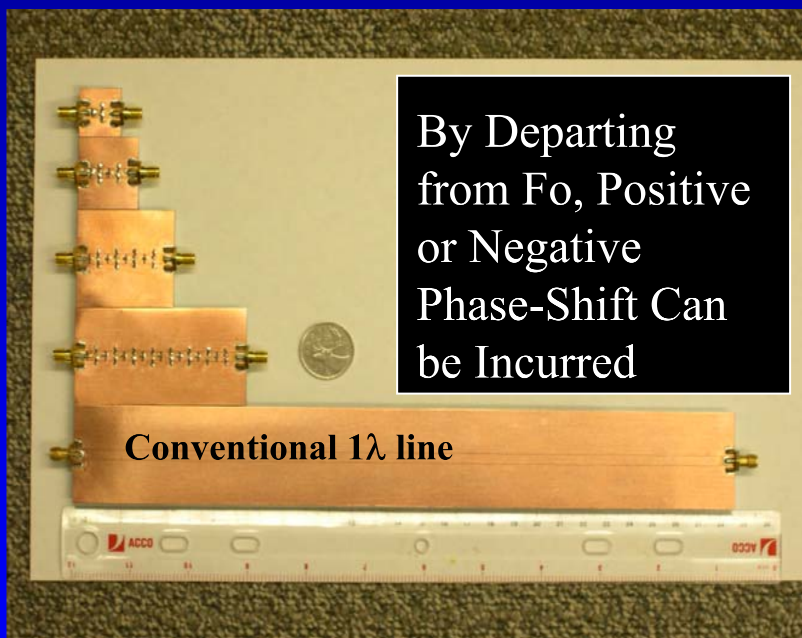


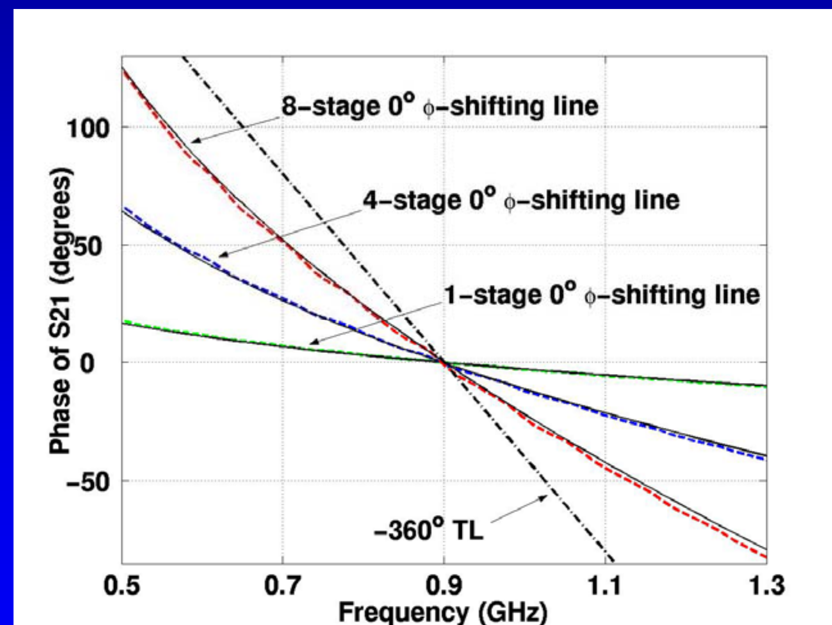
Zero-Degree Phase-Shifting Lines

Phase Compensation with RHM/LHM Lines

$-\phi$	$+\phi$

Measured vs. Simulated



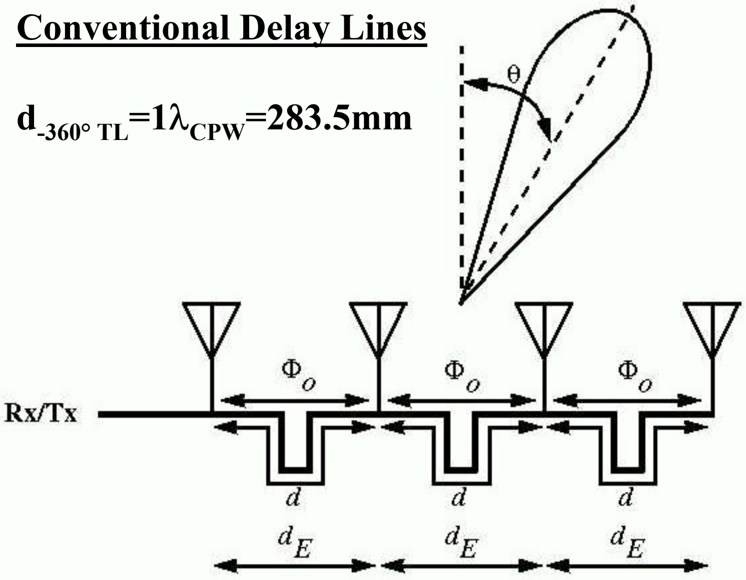


M. Antoniades and G.V. Eleftheriades, "Compact, Linear, Lead/Lag Metamaterial Phase Shifters for Broadband Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 2, issue 7, pp. 103-106, July 2003.

Series-Fed Linear Array

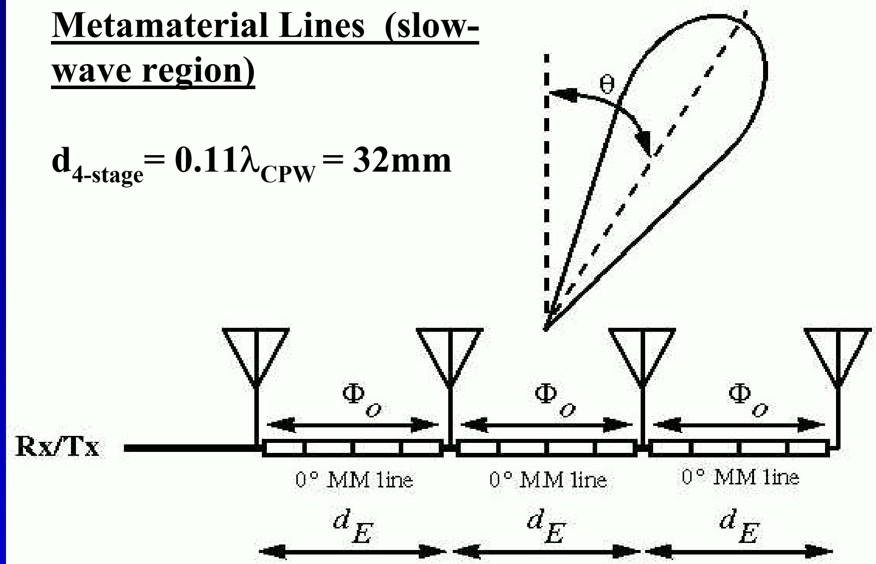
Conventional Delay Lines

$d_{-360° \, TL} = 1\lambda_{CPW} = 283.5mm$



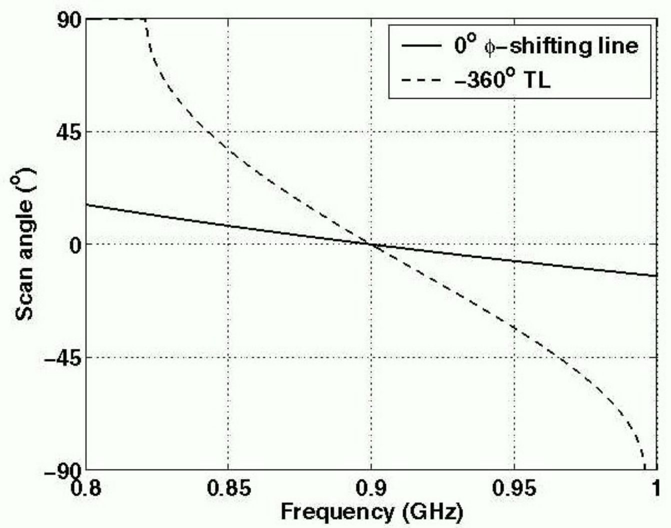
Metamaterial Lines (slow-wave region)

$d_{4\text{-}stage} = 0.11\lambda_{CPW} = 32mm$



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

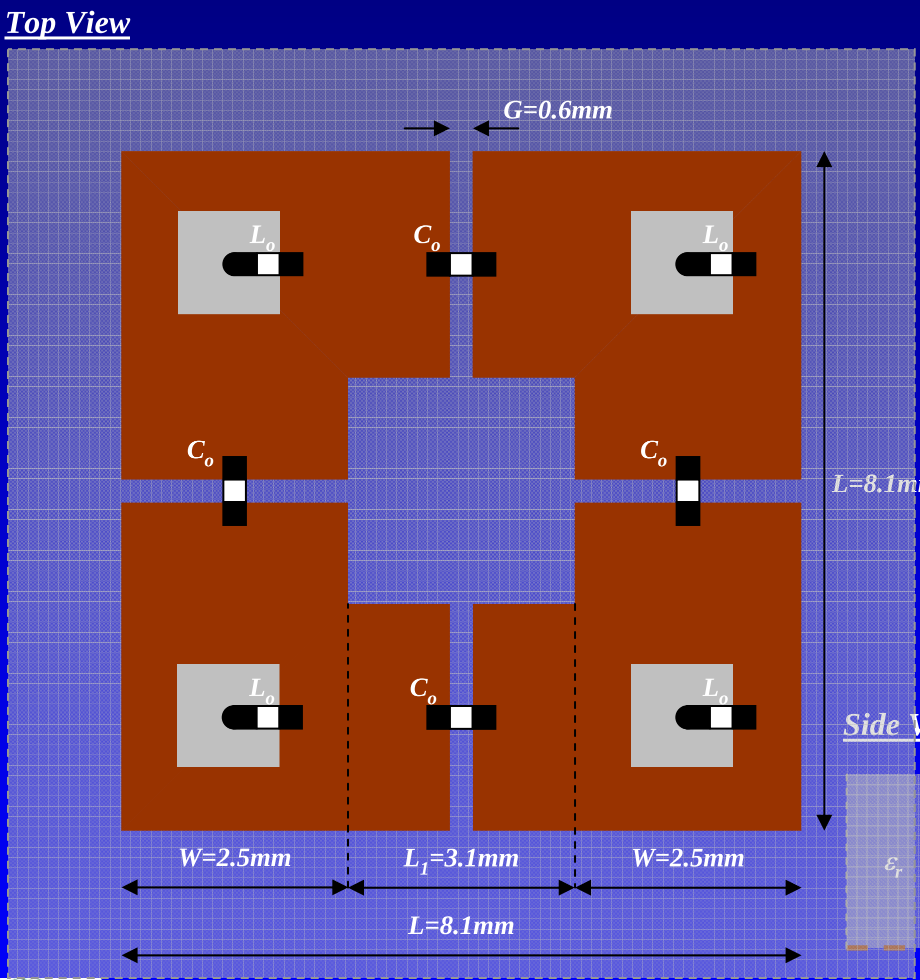
360° TL

Squint = 180°

0° MM line

Squint = 24.3°

COMPACT METAMATERIAL RING ANTENNA

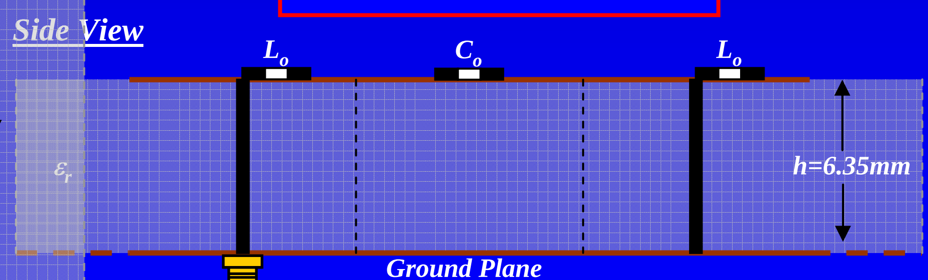


- 4 unit cell metamaterial ring antenna
- Implemented in microstrip at 1.52 GHz
- Fed by a standard 50 Ω coaxial connector

Rogers RT5880 Substrate
ε_r = 2.2, h = 6.35mm

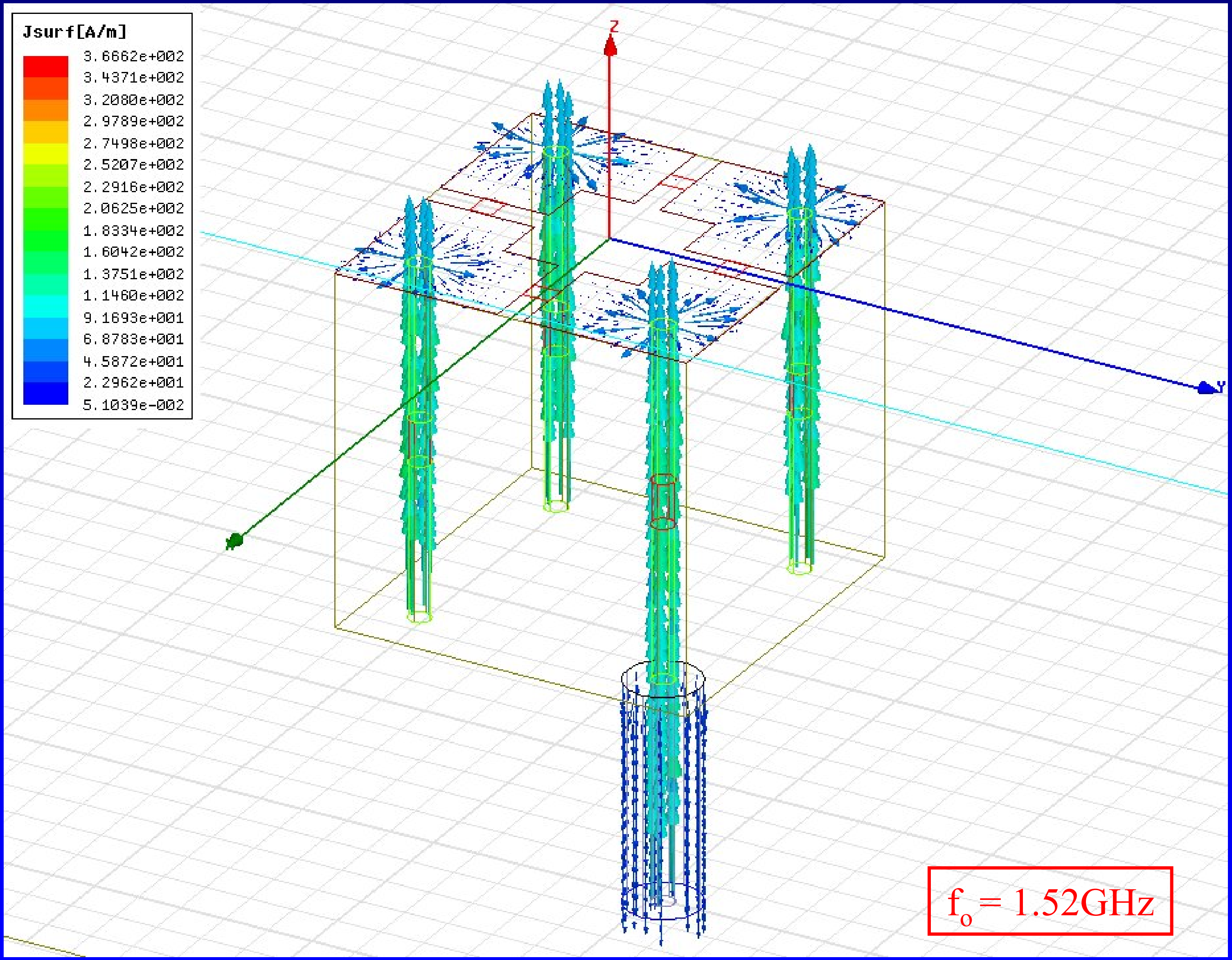
At 1.52 GHz:
λ_o=200mm
λ_{ms}=150mm

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



G.V. Eleftheriades, A. Grbic, M. Antoniades, "Negative-Refractive-Index Transmission-Line Metamaterials and Enabling Electromagnetic Applications," 2004 *IEEE Antennas and Propagation Society International Symposium Digest*, pp. 1399-1402, Monterey, CA, USA, June 20-25, 2004.

PLOT OF THE IN-PHASE RADIATING CURRENTS IN THE VIAS

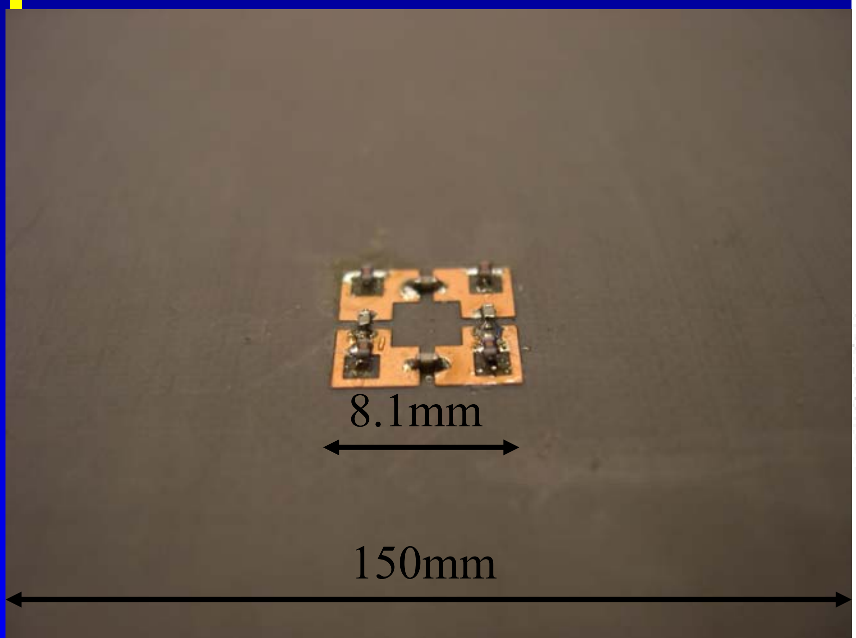


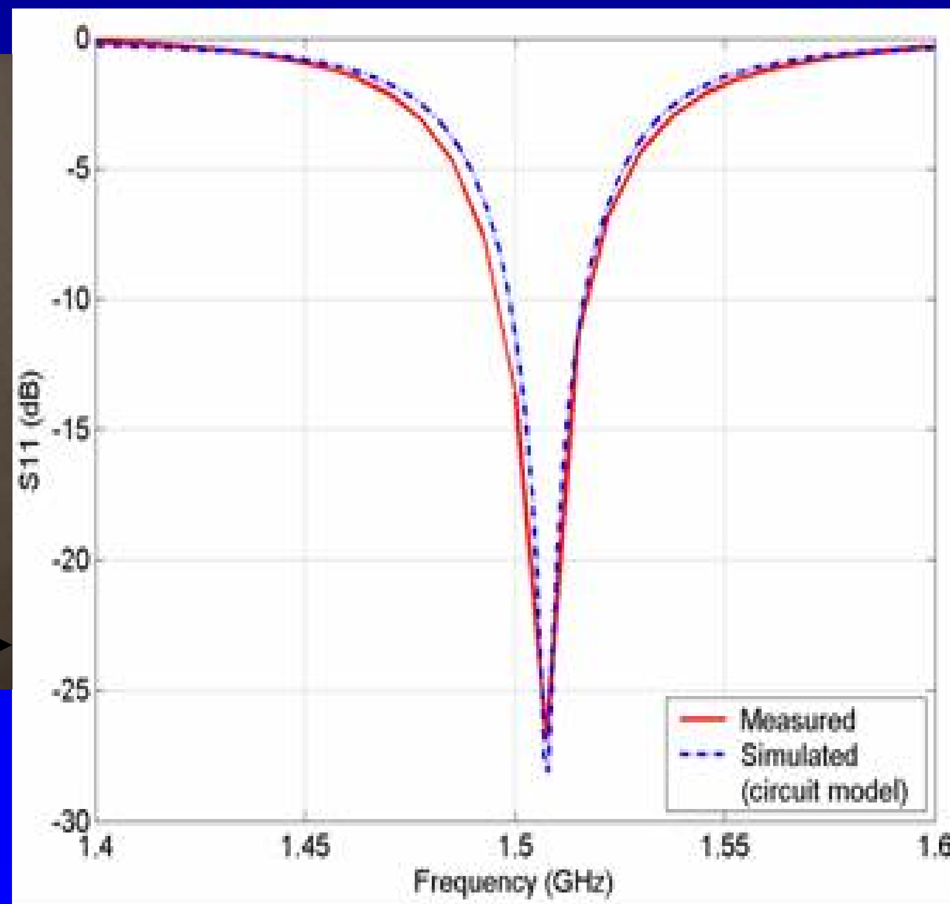
$f_o = 1.52\text{GHz}$

MEASURED Vs. SIMULATED RETURN LOSS

f_o=1.52GHz

S_{11} BW (<-10dB) = 2%

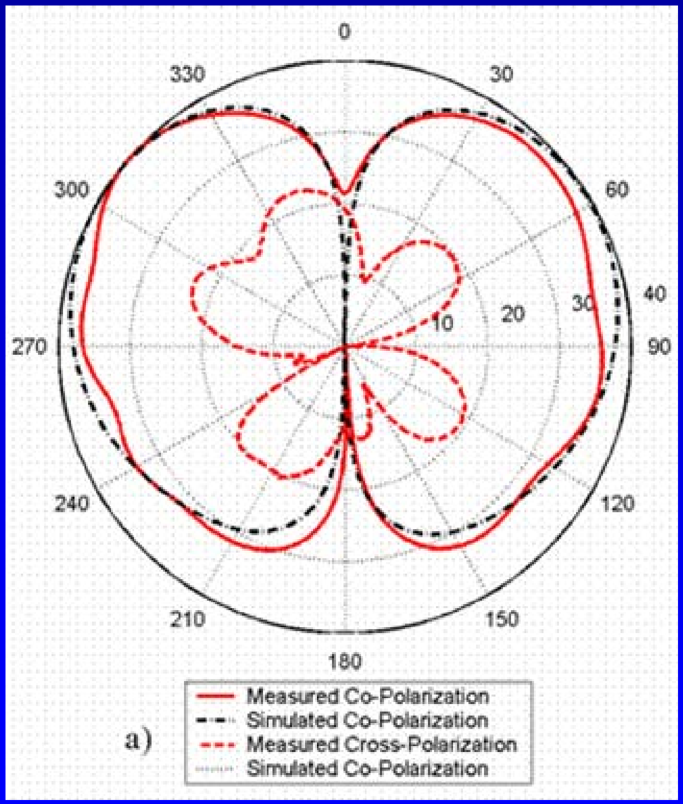




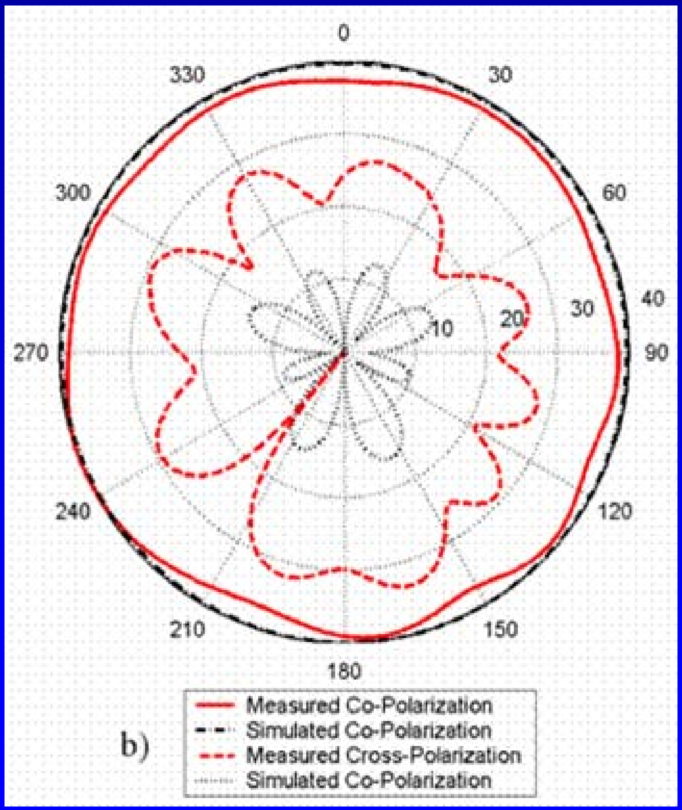
MEASURED RADIATION PATTERNS at F=1.52GHz

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

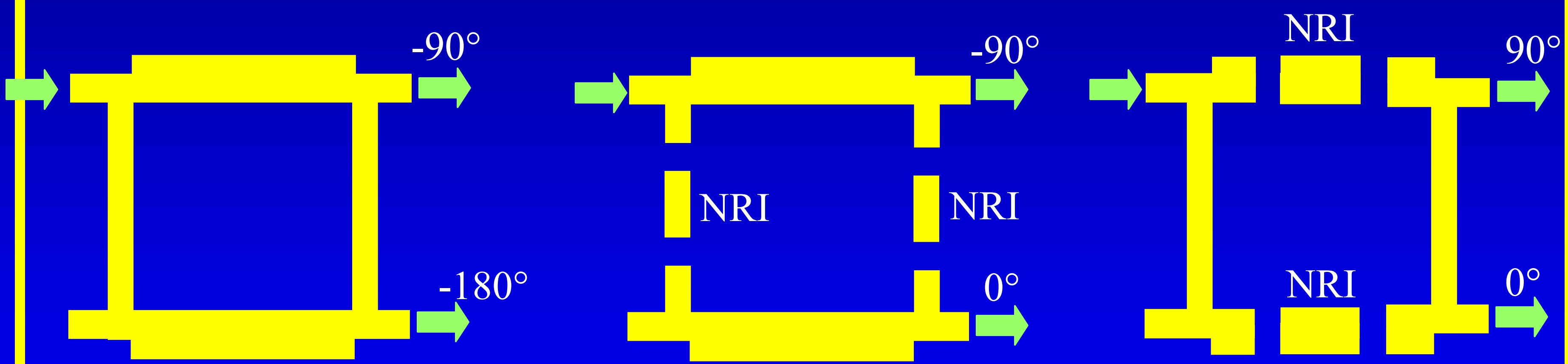
E-plane



H-plane



Phase-Agile MS/NRI Branch-Line Couplers



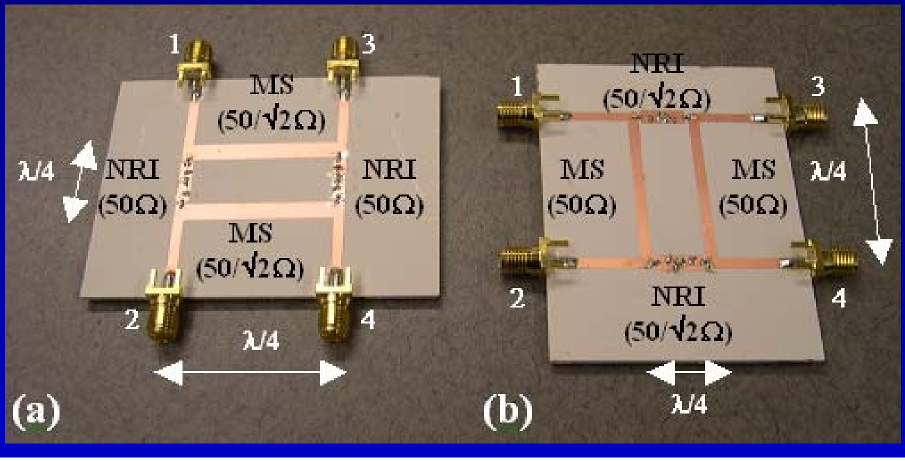
Regular Branch-line coupler

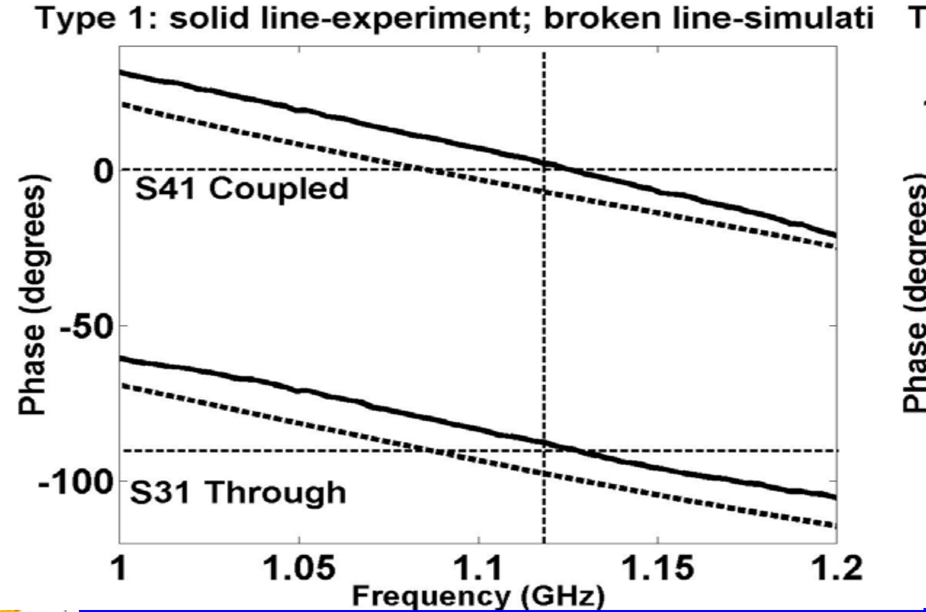
Type-1 MS/NRI Branch-line coupler

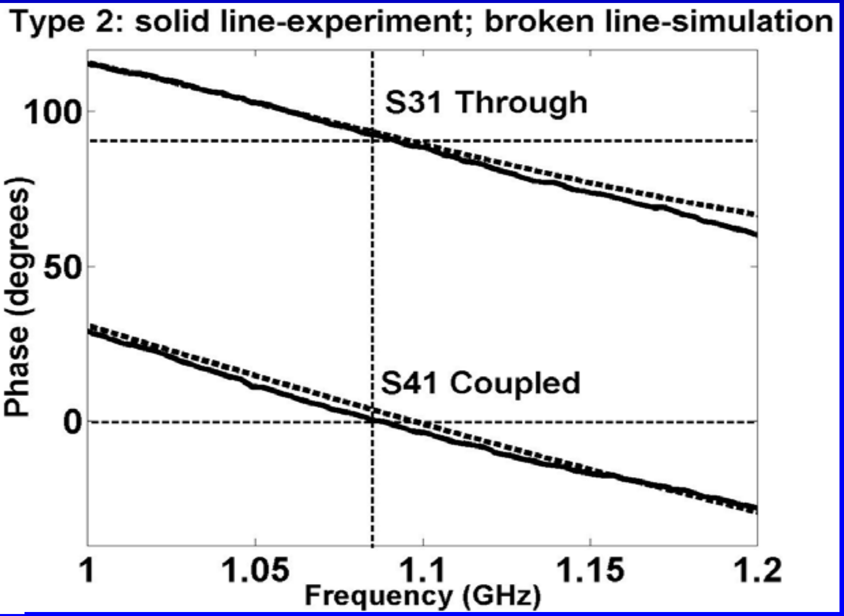
Type-2 MS/NRI Branch-line coupler

R. Islam and G.V. Eleftheriades, "Phase-agile branch-line couplers using metamaterial lines."
IEEE Microwave and Wireless Components Letters. , vol. 14, no. 7, pp. 340-342, July 2004.

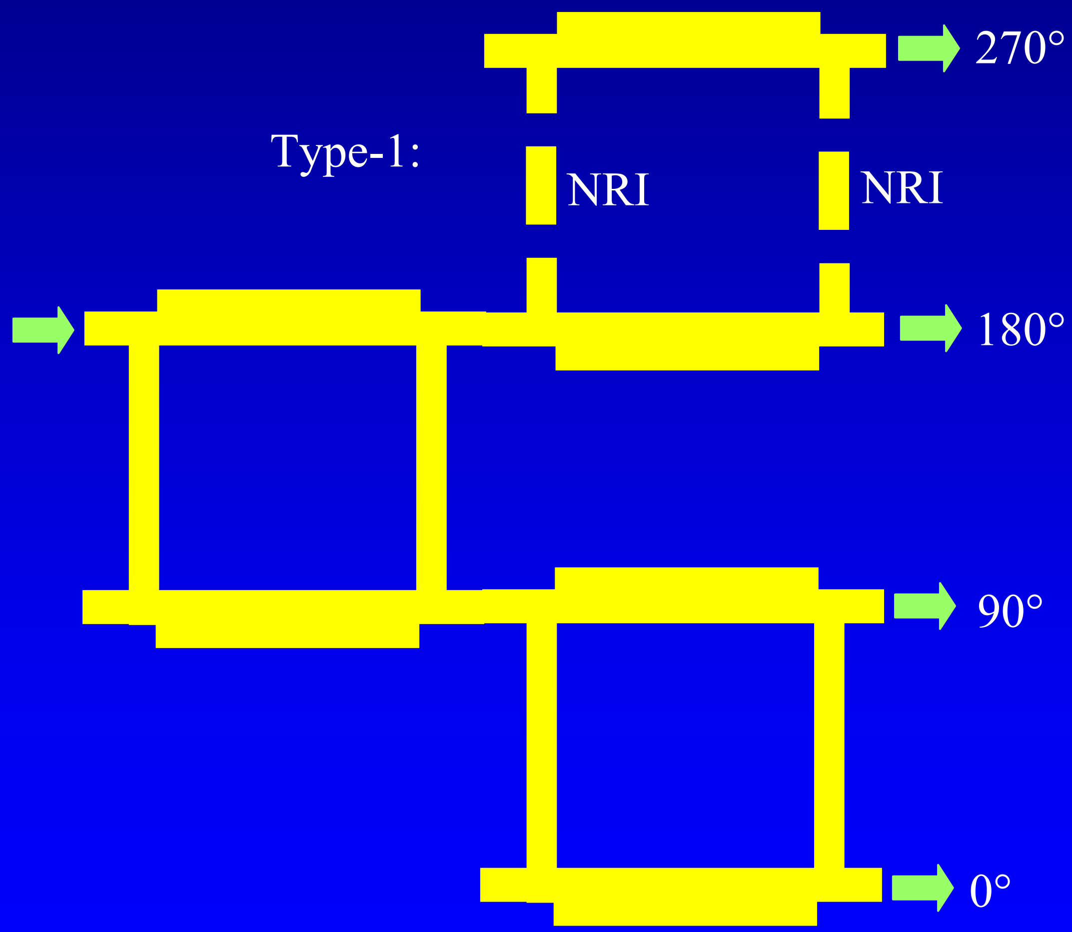
Experimental Results







Antenna Beamforming Networks



Acknowledgements

Graduate Students

Anthony Grbic
Ashwin Iyer
Marco Antoniades
Rubaiyat Islam
Omar Siddiqui

Technologist: Peter C. Kremer
Lab. Manager: Gerald Dubois
Colleagues: Keith G. Balmain, Mo Mojahedi, Costas Sarris, S. Aitchison