PLANAR NEGATIVE REFRACTIVE INDEX METAMATERIALS BASED ON PERIODICALLY L-C LOADED TRANSMISSION LINES

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METAMATERIALS

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

TYPE#1:
ARTIFICIAL DIELECTRICS SYNTHESIZED BY PERIODICALLY LOADING A HOST TRANSMISSION-LINE MEDIUM WITH R,L,C ELEMENTS (lumped or distributed):
PERIODICITY << λ

TYPE#2:
DIELECTRIC OR METALLIC PHOTONIC-BANDGAP-MATERIALS (PBGs) FOR WHICH PERIODICITY ~ λ.

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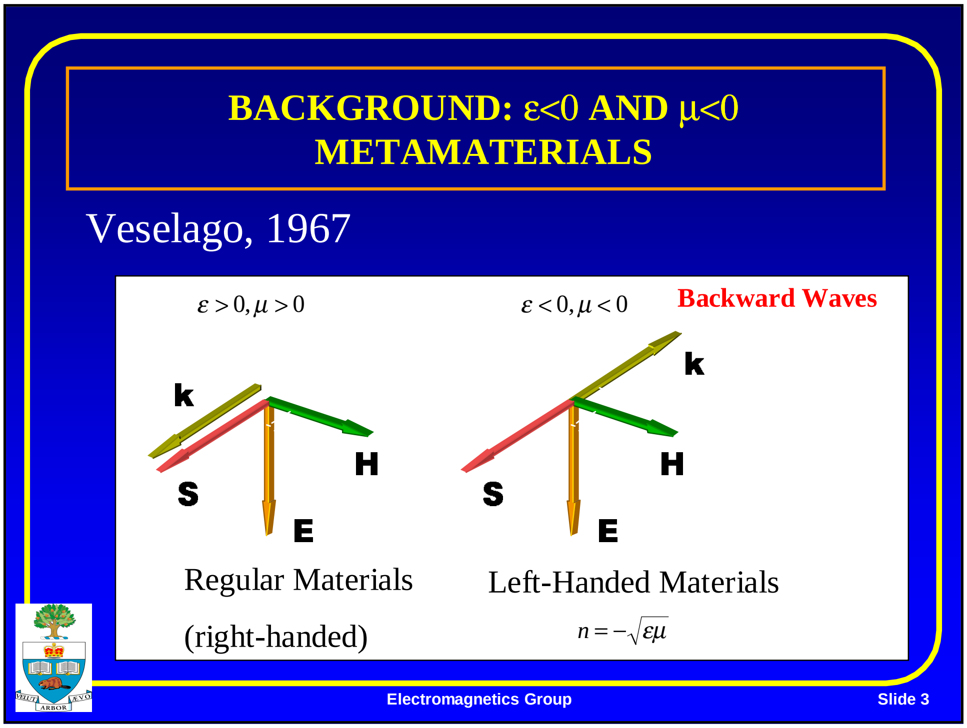
BACKGROUND: ε<0 AND μ<0
METAMATERIALS
Veselago, 1967
$\varepsilon > 0, \mu > 0$
$\varepsilon < 0, \mu < 0$
Backward Waves
k
S
E
H
k
S
E
H
Regular Materials
(right-handed)
Left-Handed Materials
$n = -\sqrt{\varepsilon\mu}$
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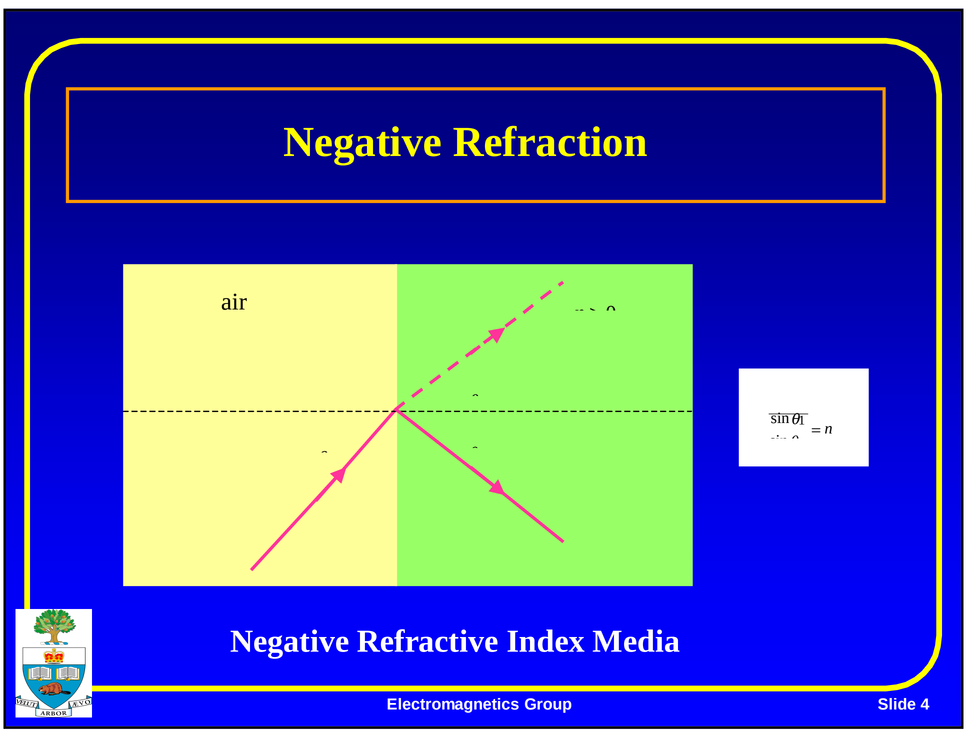
Negative Refraction
air
Negative Refractive Index Media
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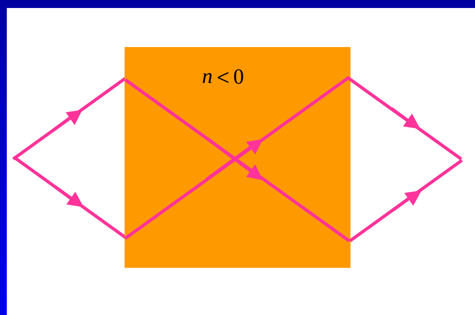
Focusing from Planar n<0 Slabs



- Flat but homogeneous lens
- Point-to-point focusing
- Unlike any other lens it offer sub-wavelength resolution!

Pendry 2000

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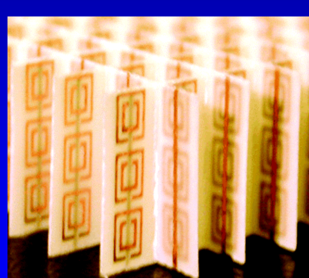
HOW CAN ONE MAKE ε<0 AND μ<0 METAMATERIALS?

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

Bulky: 3-D structure

Distributed cells: Large for usage at RF frequencies

Operates around resonances: Narrowband

Unit cells not connected: Difficult System Integration

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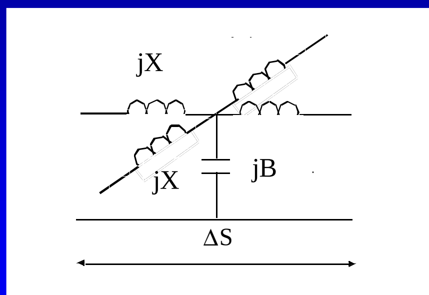
RECONCEPTUALIZING ε<0 AND μ<0 METAMATERIALS

Start from the transmission line representation of normal dielectrics:



$$j\omega\mu = \frac{jX}{\Delta S} = \frac{j\omega L}{\Delta S} \Rightarrow \mu = \frac{L}{\Delta S}$$

$$j\omega\varepsilon = \frac{jB}{\Delta S} = \frac{j\omega C}{\Delta S} \Rightarrow \varepsilon = \frac{C}{\Delta S}$$

How to synthesize ε<0, μ<0?

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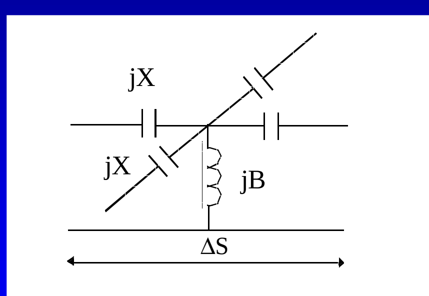
Simply: Make the series reactance X and shunt susceptance B both negative!



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

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

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.

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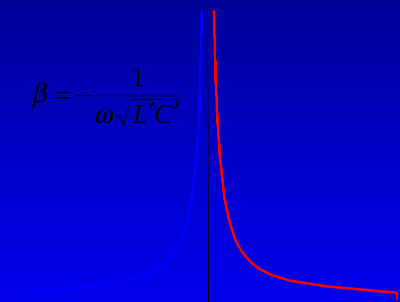
CONTINUOUS LIMIT

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



Backward Waves Supported

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

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

This practically yields a <u>very large</u> bandwidth over which n<0

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PERIODICALLY L-C LOADED TRANSMISSION LINES

Backward Wave

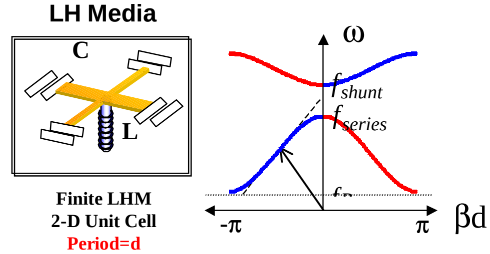
$v_p v_g < 0$

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

$$\varepsilon_{eff} \cong \varepsilon_o - \frac{1}{2\ldots}$$

$$\mu_{eff} \cong \mu_o - \frac{1}{2\ldots}$$

LH Media



$$f_{series} = \frac{1}{2\pi\sqrt{C(\ldots d)}}$$

$$f_{shunt} = \frac{1}{2\pi\sqrt{L(\ldots)}}$$

$$f_{Bragg} = \frac{1}{4\pi\sqrt{LC}}$$

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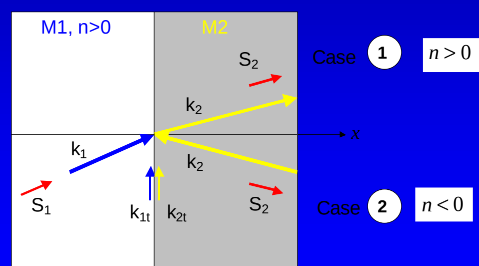
Negative Refraction

Such “Dual” L-C Networks Support Backward Waves

Explaining Negative Refraction (Key is phase matching)



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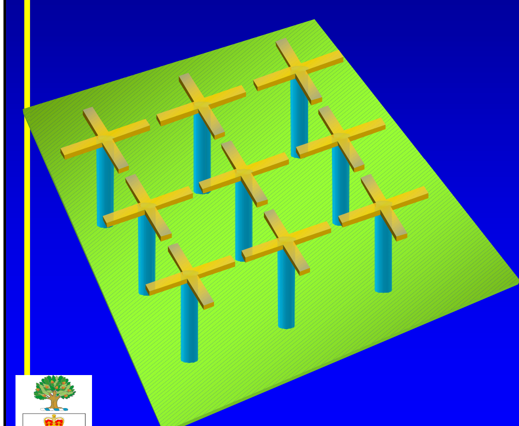
2-D Microstrip Implementation of $\varepsilon<0$ AND $\mu<0$ Metamaterials



The blue wires represent inductors, and the gaps capacitors

2-D (coplanar) propagation

The gaps can be loaded with chip capacitors and the vias with chip inductors to lower the operating frequency

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ADVANTAGES/UNIQUE FEATURES

Low profile 2-D operation

Connected unit cells/Easy system integration

Broadband n<0 bandwidth

By inserting lumped L-C elements, the operating frequency can be lowered for RF applications/Scalability

By using variable L-C elements and/or switches, controllable materials can be synthesized/Tunability

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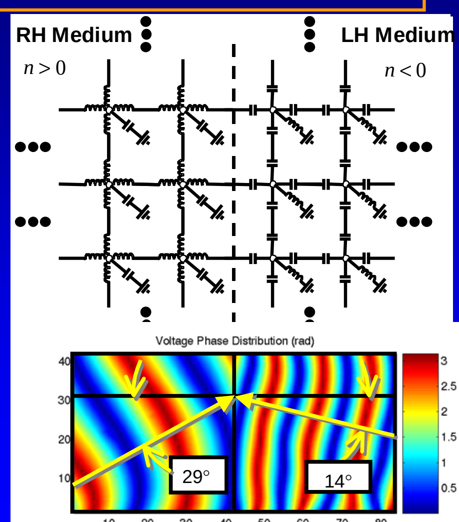
SIMULATION RESULTS

Negative Refraction

Microwave circuit simulation

Negative refraction observed at interface

Snell's Law verified for n<0 $\sin\theta_{RHM}/\sin\theta_{LHM} = n_{LHM}/n_{RHM} < 0$



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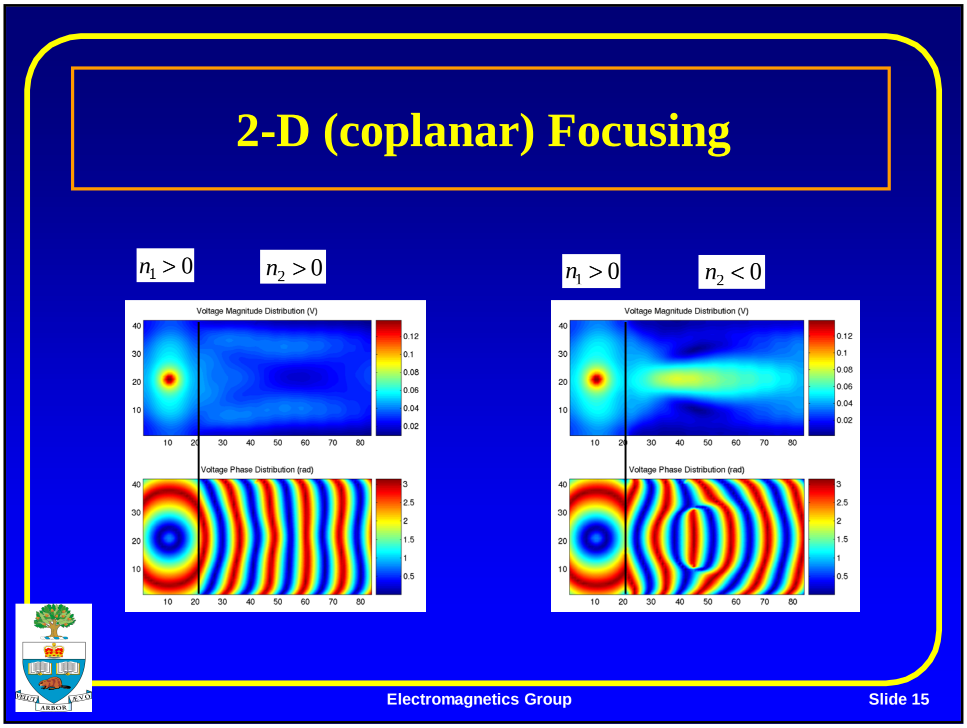
2-D (coplanar) Focusing
$n_1 > 0$
$n_2 > 0$
$n_1 > 0$
$n_2 < 0$
Voltage Magnitude Distribution (V)
Voltage Phase Distribution (rad)
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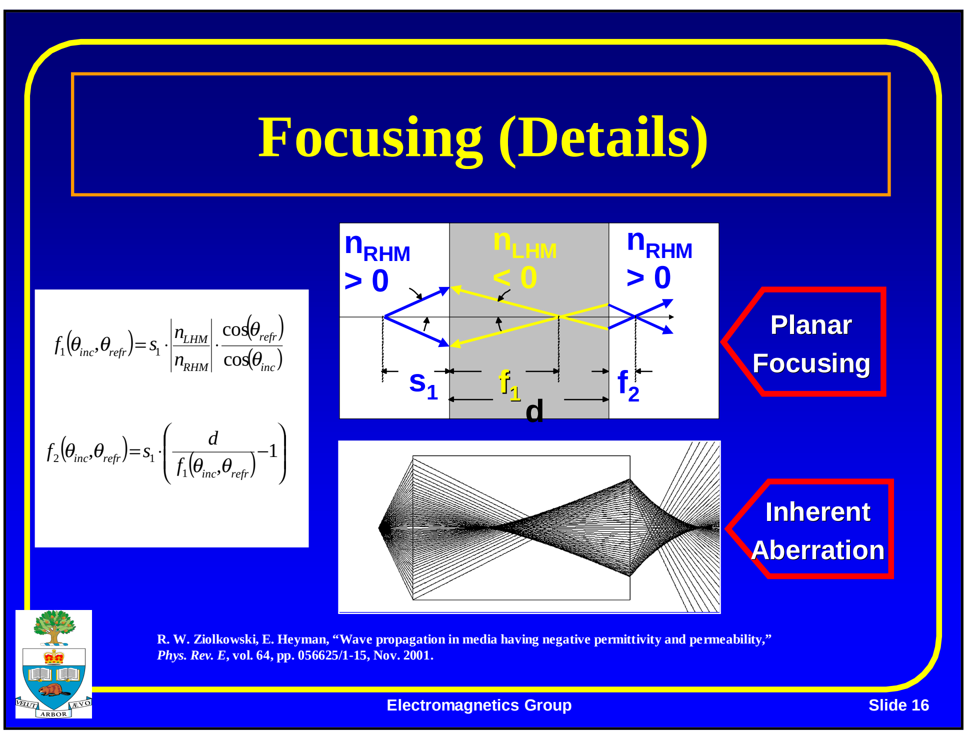
Focusing (Details)
$f_1(\theta_{inc},\theta_{refr}) = s_1 \cdot \left|\frac{n_{LHM}}{n_{RHM}}\right| \cdot \frac{\cos(\theta_{refr})}{\cos(\theta_{inc})}$
$f_2(\theta_{inc},\theta_{refr}) = s_1 \cdot \left(\frac{d}{f_1(\theta_{inc},\theta_{refr})} - 1\right)$
n_{RHM} > 0
n_{LHM} < 0
n_{RHM} > 0
s_1
f_1
f_2
d
Planar Focusing
Inherent Aberration
R. W. Ziolkowski, E. Heyman, "Wave propagation in media having negative permittivity and permeability," Phys. Rev. E, vol. 64, pp. 056625/1-15, Nov. 2001.
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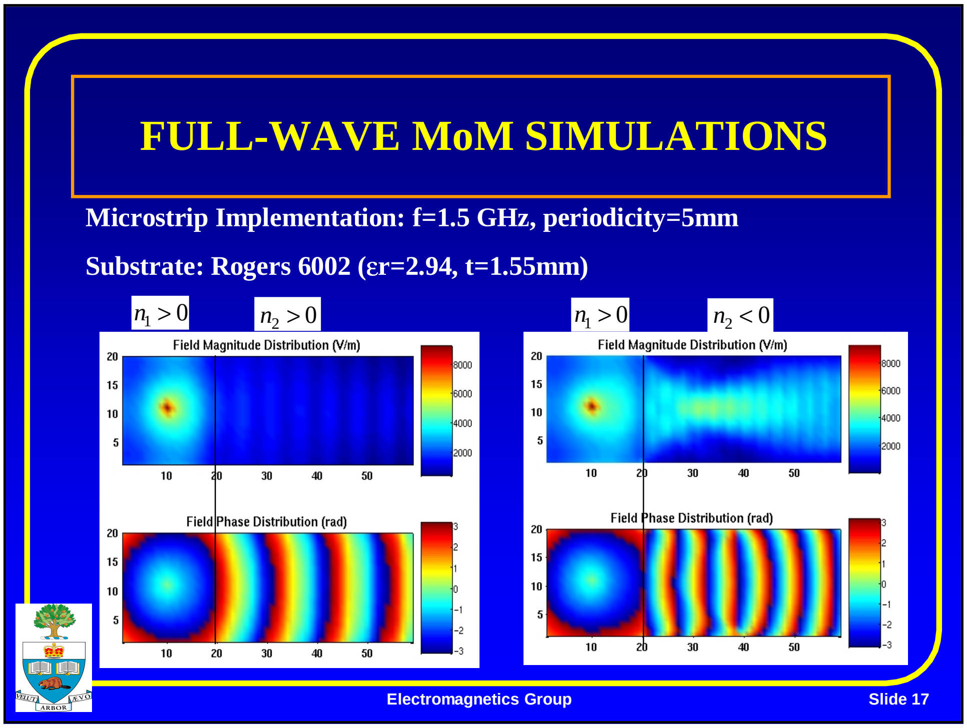
FULL-WAVE MoM SIMULATIONS
Microstrip Implementation: f=1.5 GHz, periodicity=5mm
Substrate: Rogers 6002 (εr=2.94, t=1.55mm)
$n_1 > 0$
$n_2 > 0$
$n_1 > 0$
$n_2 < 0$
Field Magnitude Distribution (V/m)
Field Phase Distribution (rad)
Field Magnitude Distribution (V/m)
Field Phase Distribution (rad)
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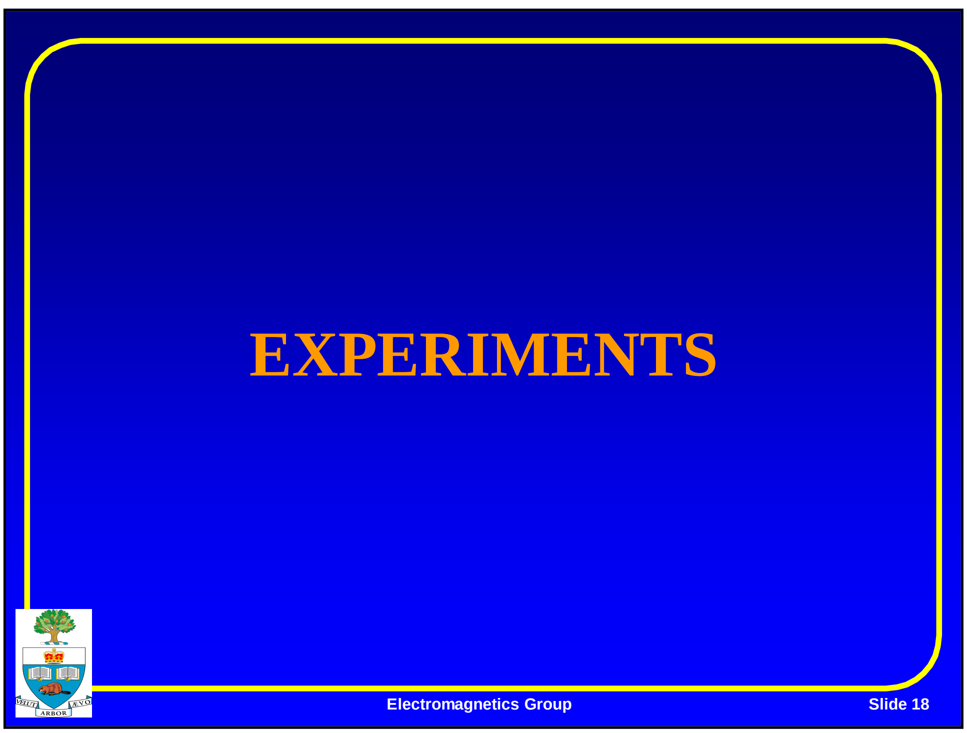
EXPERIMENTS
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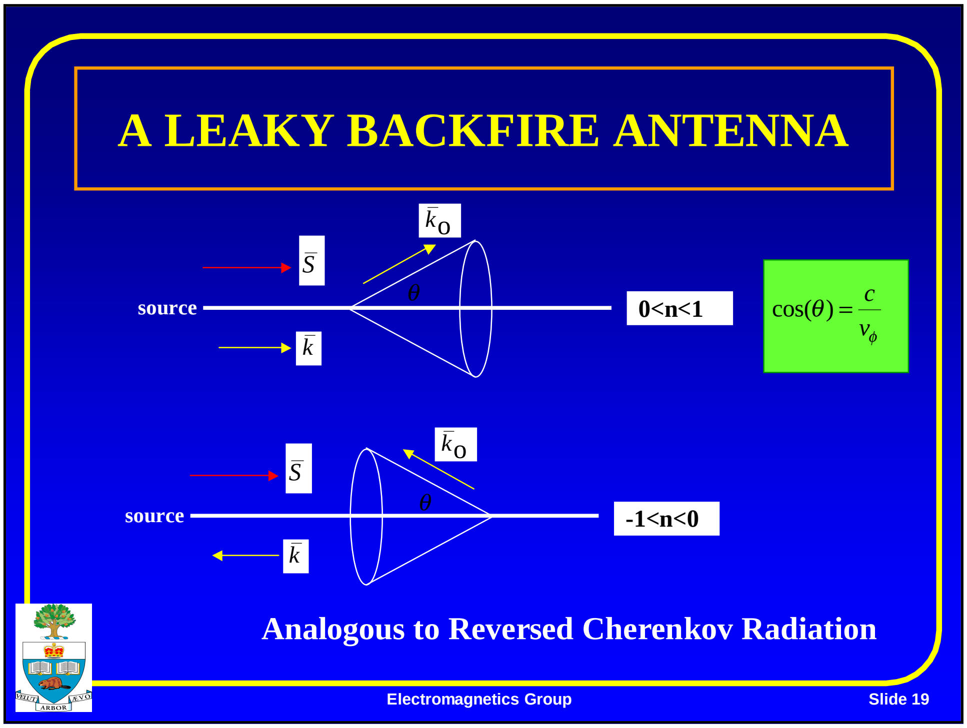
A LEAKY BACKFIRE ANTENNA
$\bar{k}_o$
$\bar{S}$
θ
source
0<n<1
$\bar{k}$
$\cos(\theta) = \frac{c}{v_\phi}$
$\bar{k}_o$
$\bar{S}$
θ
source
-1<n<0
$\bar{k}$
Analogous to Reversed Cherenkov Radiation
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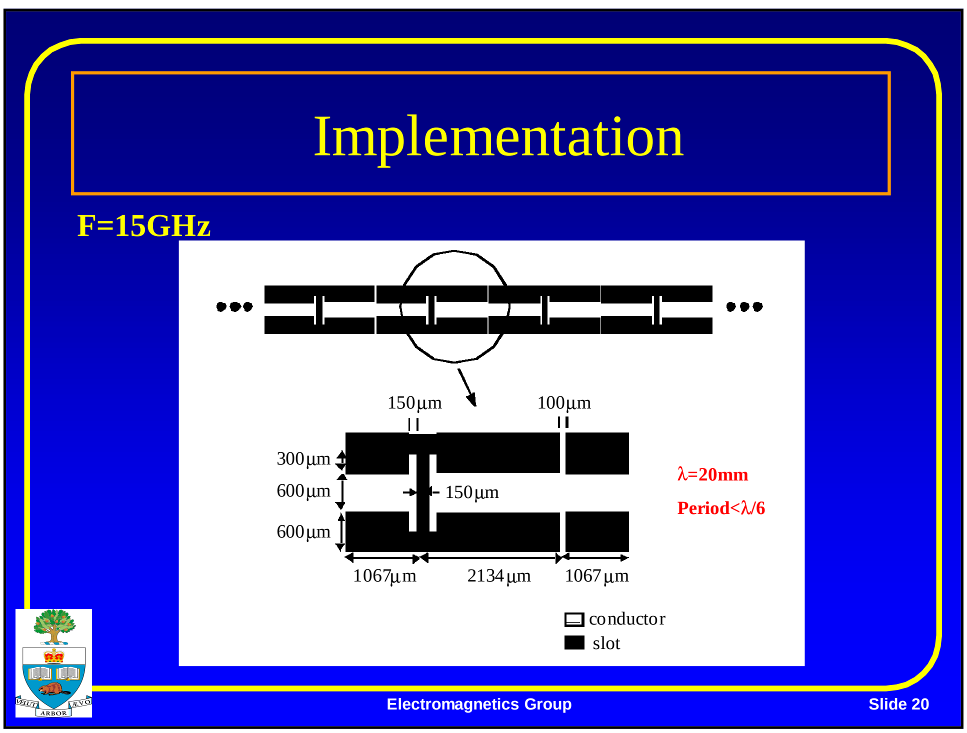
Implementation
F=15GHz
150μm
100μm
300μm
600μm
150μm
600μm
1067μm
2134μm
1067μm
λ=20mm
Period<λ/6
conductor
slot
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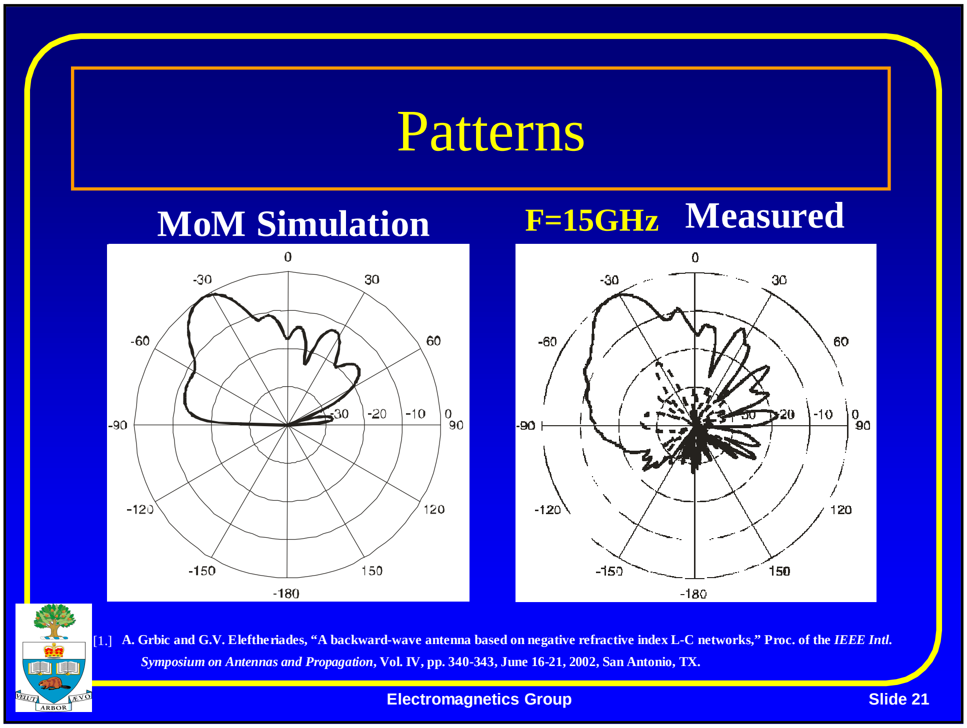
Patterns
MoM Simulation
F=15GHz
Measured
[1.] A. Grbic and G.V. Eleftheriades, “A backward-wave antenna based on negative refractive index L-C networks,” Proc. of the IEEE Intl. Symposium on Antennas and Propagation, Vol. IV, pp. 340-343, June 16-21, 2002, San Antonio, TX.
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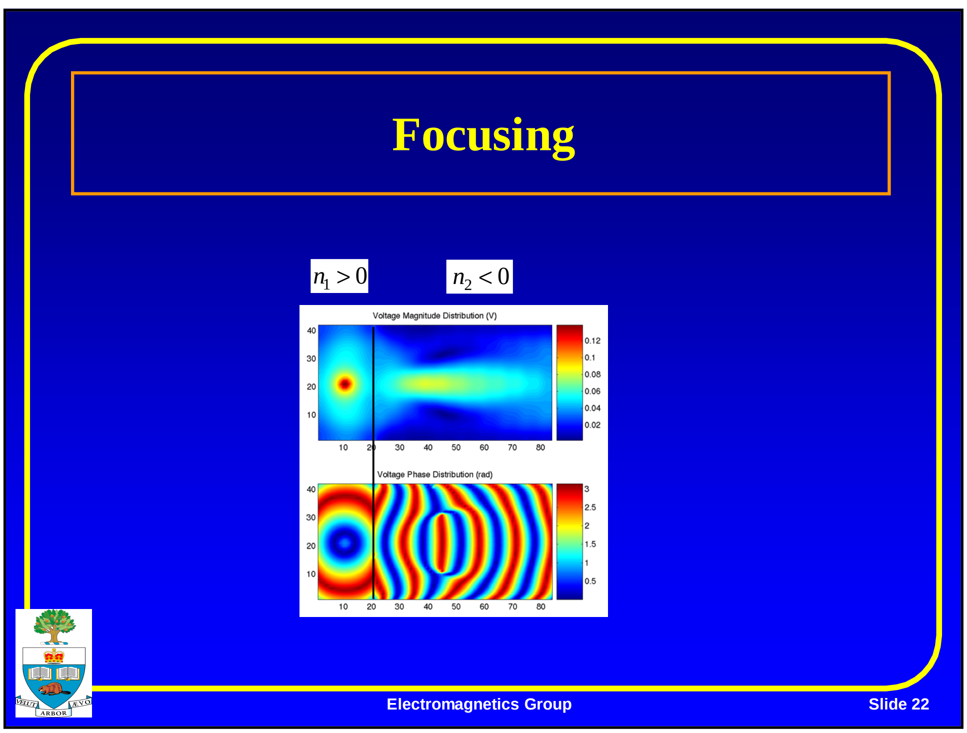
Focusing
$n_1 > 0$
$n_2 < 0$
Voltage Magnitude Distribution (V)
Voltage Phase Distribution (rad)
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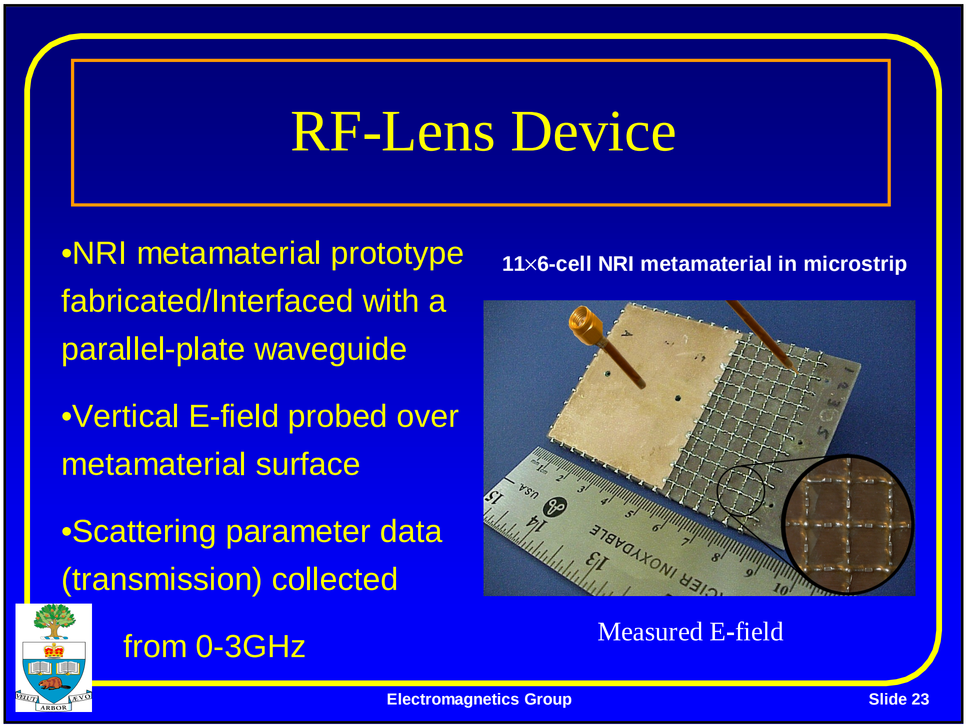
RF-Lens Device
•NRI metamaterial prototype fabricated/Interfaced with a parallel-plate waveguide
•Vertical E-field probed over metamaterial surface
•Scattering parameter data (transmission) collected from 0-3GHz
11×6-cell NRI metamaterial in microstrip
Measured E-field
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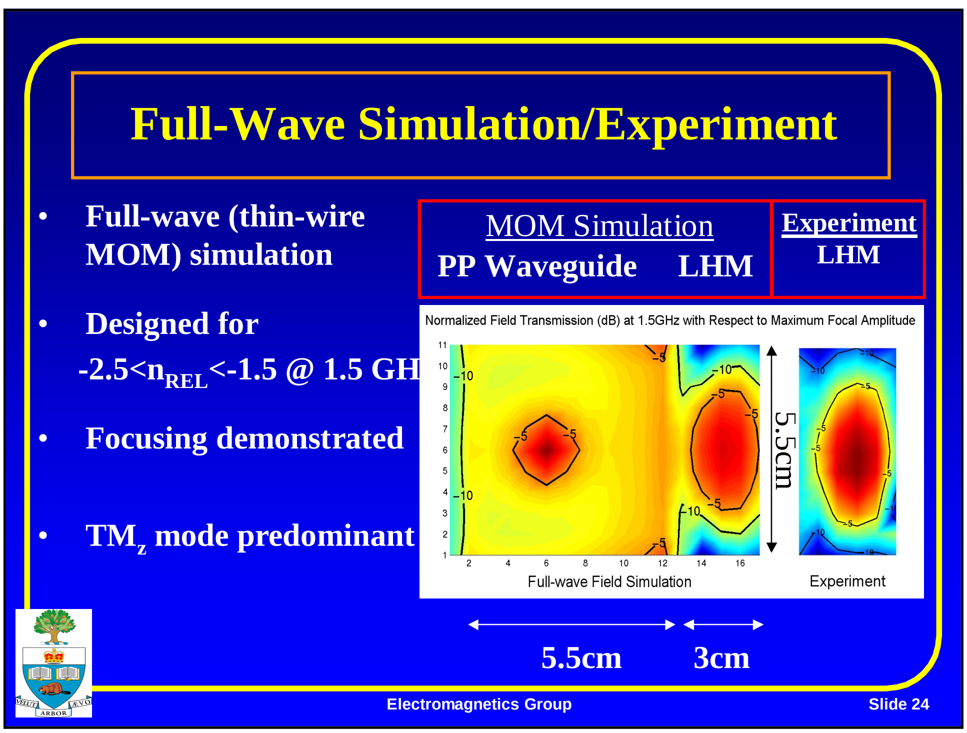
Full-Wave Simulation/Experiment
• Full-wave (thin-wire MOM) simulation
• Designed for -2.5<n_REL<-1.5 @ 1.5 GH
• Focusing demonstrated
• TM_z mode predominant
MOM Simulation
PP Waveguide LHM
Experiment
LHM
Normalized Field Transmission (dB) at 1.5GHz with Respect to Maximum Focal Amplitude
5.5cm
Full-wave Field Simulation
Experiment
5.5cm 3cm
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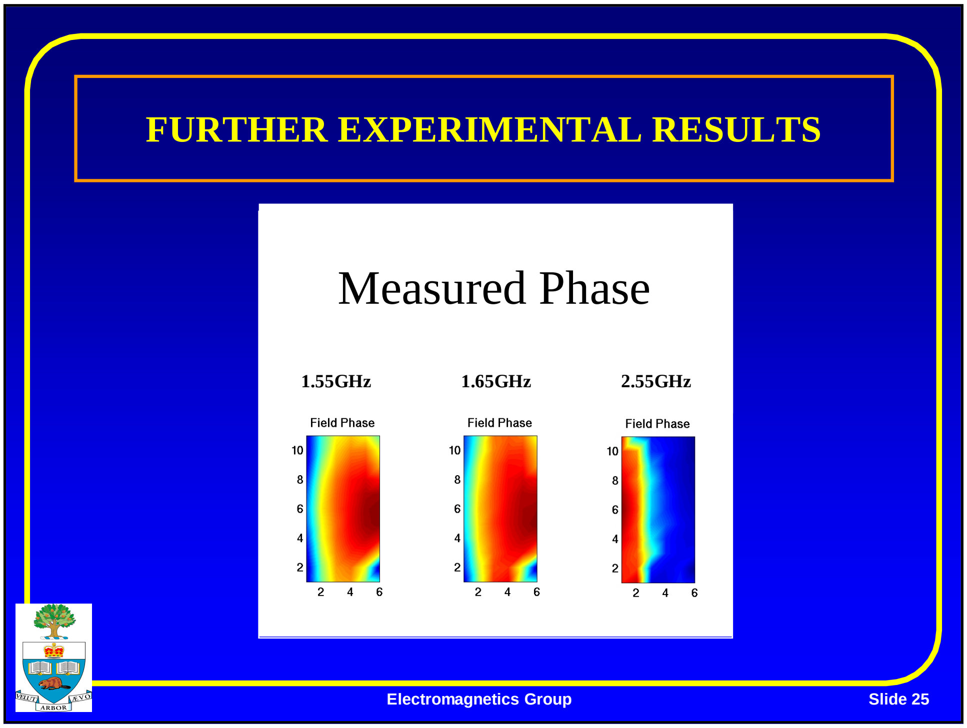
FURTHER EXPERIMENTAL RESULTS
Measured Phase
1.55GHz
1.65GHz
2.55GHz
Field Phase
Field Phase
Field Phase
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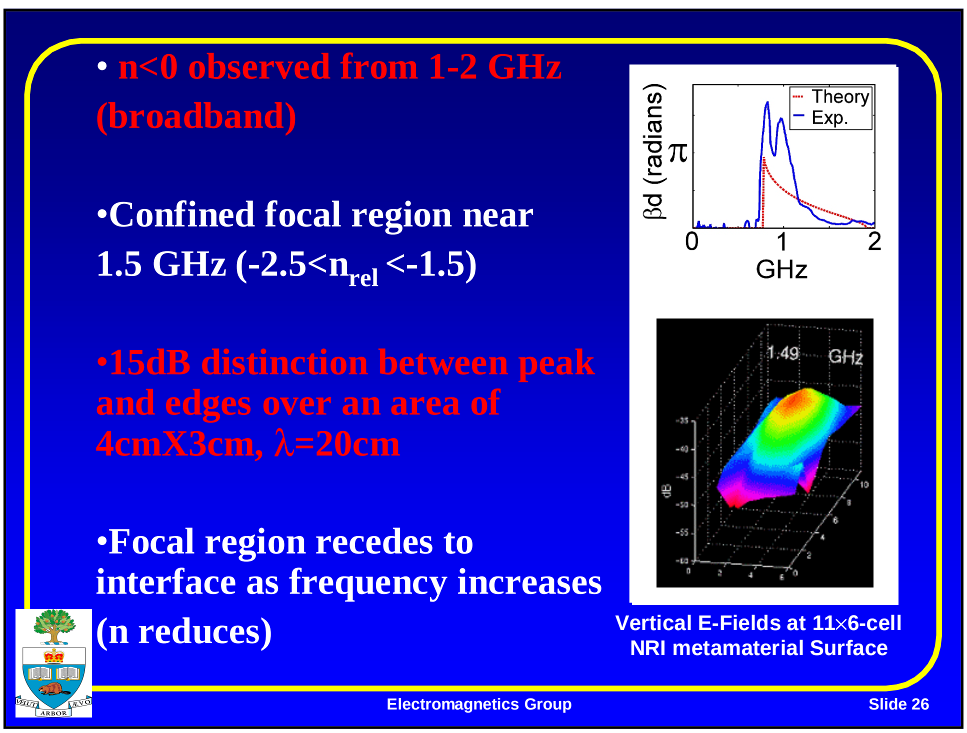
• n<0 observed from 1-2 GHz (broadband)
•Confined focal region near 1.5 GHz (-2.5<n_rel <-1.5)
•15dB distinction between peak and edges over an area of 4cmX3cm, λ=20cm
•Focal region recedes to interface as frequency increases (n reduces)
Theory
Exp.
βd (radians)
π
0
1
2
GHz
1.49 GHz
Vertical E-Fields at 11×6-cell NRI metamaterial Surface
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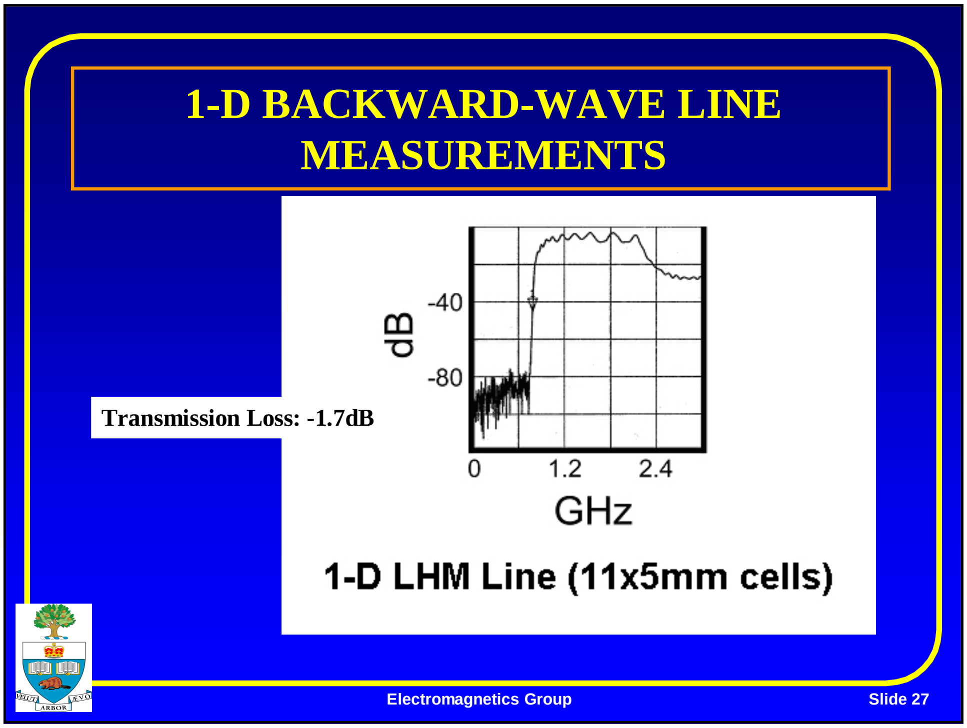
1-D BACKWARD-WAVE LINE MEASUREMENTS
Transmission Loss: -1.7dB
dB
-40
-80
0
1.2
2.4
GHz
1-D LHM Line (11x5mm cells)
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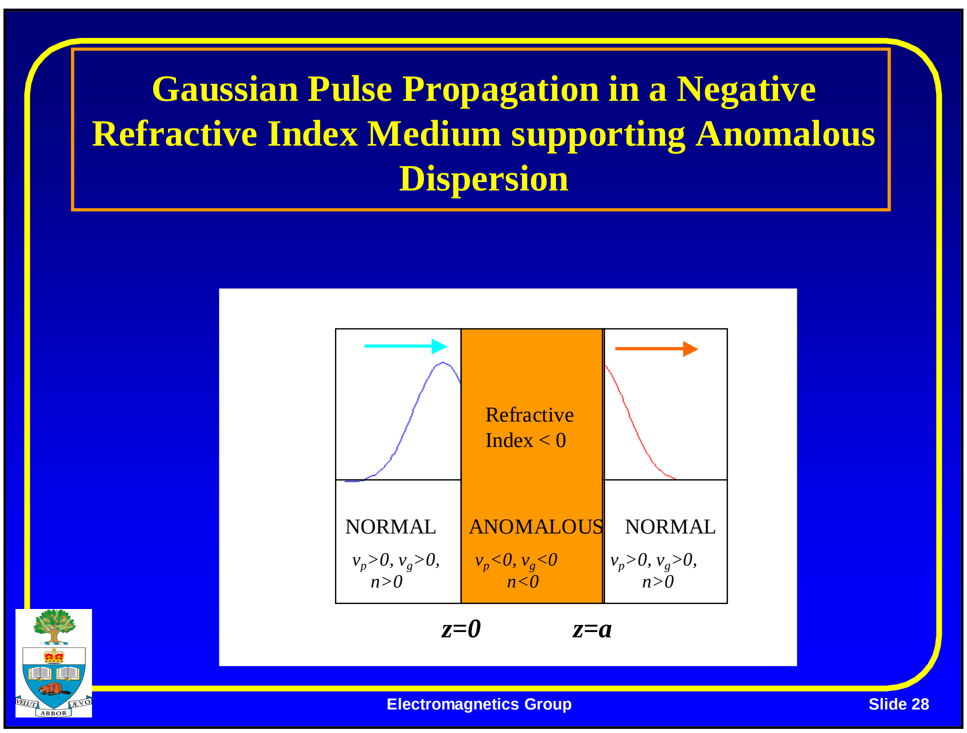
Gaussian Pulse Propagation in a Negative Refractive Index Medium supporting Anomalous Dispersion
Refractive Index < 0
NORMAL
$v_p>0, v_g>0, n>0$
ANOMALOUS
$v_p<0, v_g<0$ $n<0$
NORMAL
$v_p>0, v_g>0, n>0$
z=0
z=a
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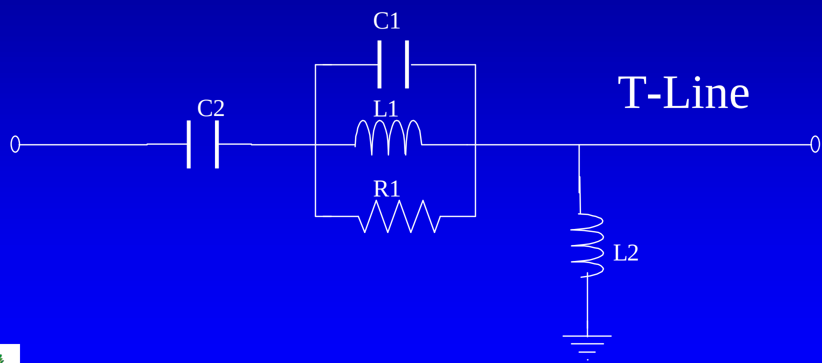
Negative Group Velocity Unit Cell



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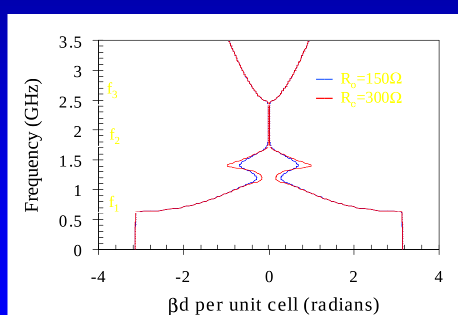
Negative Refractive Index Media With Anomalous Dispersion



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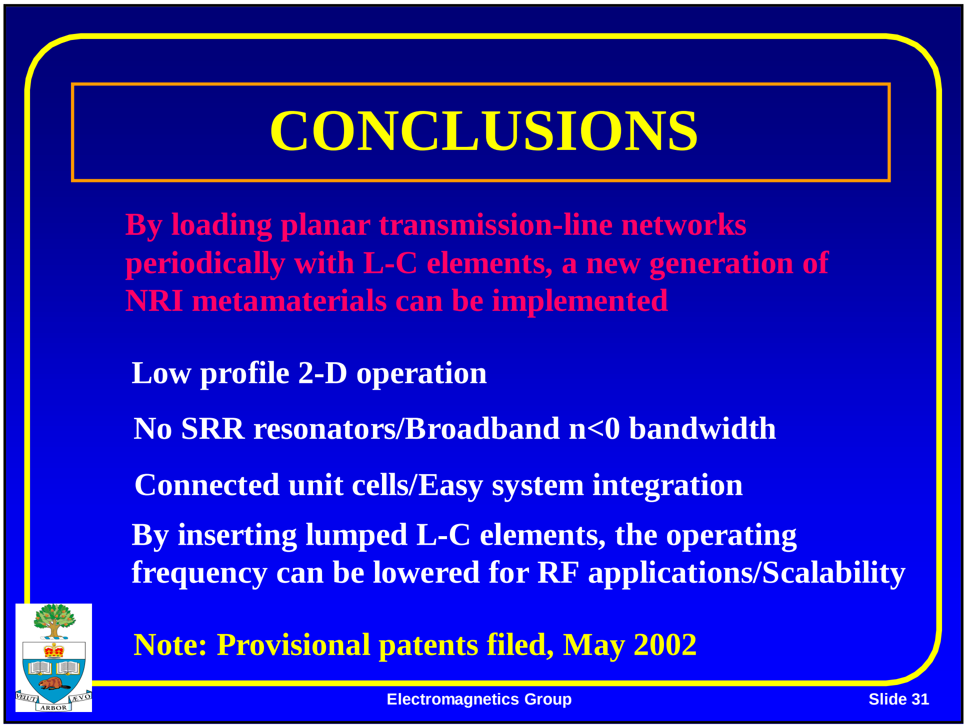
CONCLUSIONS
By loading planar transmission-line networks periodically with L-C elements, a new generation of NRI metamaterials can be implemented
Low profile 2-D operation
No SRR resonators/Broadband n<0 bandwidth
Connected unit cells/Easy system integration
By inserting lumped L-C elements, the operating frequency can be lowered for RF applications/Scalability
Note: Provisional patents filed, May 2002
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