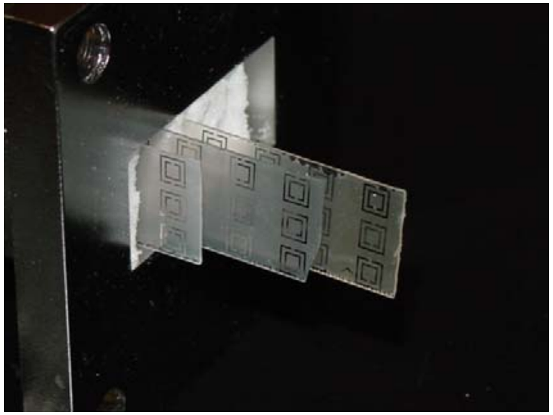
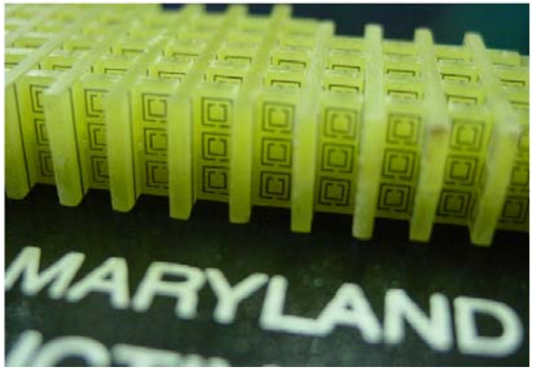
Physics and Applications of Negatively Refracting Electromagnetic Materials

Steven M. Anlage, Michael Ricci, Nathan Orloff



DEPARTMENT OF PHYSICS
UNIVERSITY OF MARYLAND

Center for Superconductivity Research



National Science Foundation
WHERE DISCOVERIES BEGIN

Work Funded by NSF/ECS-0322844

Outline

What are Negative Index of Refraction Metamaterials?

What novel properties do they have?

How are they made?

What new RF/microwave applications are emerging?

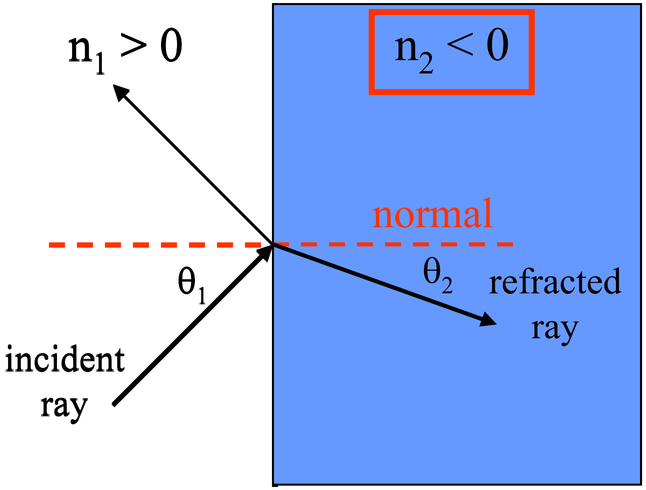
Superconducting Metamaterials

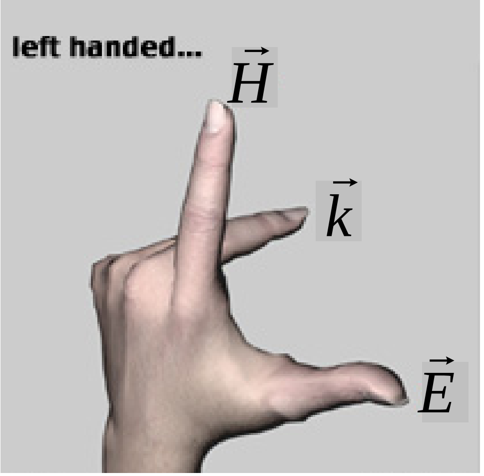
Caveats / Prospects for the future

Why Negative Refraction?

Snell's Law

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$





Negative Index of Refraction (NIR) = Left Handed Medium (LHM)

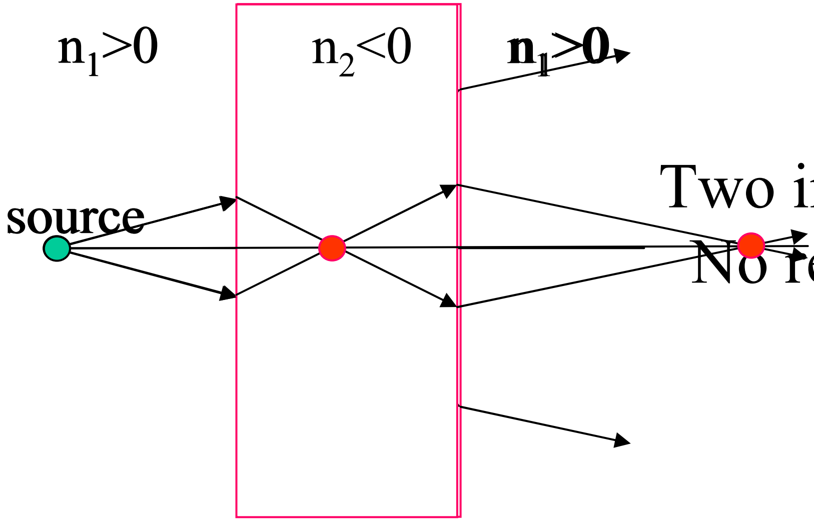
Positive Index of Refraction (PIR) = Right Handed Medium (RHM)

NIR / LHM

PIR / RHM

Flat Lens

"Lens"



Two images!

No real image

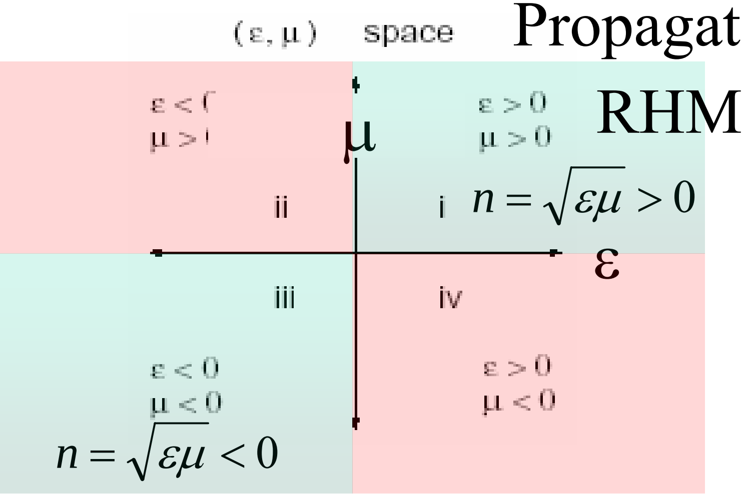
How can we make refractive index n < 0?

Use “Metamaterials”

Artificially prepared dielectric and conducting materials with negative values of both ε and μ

$$\vec{D} = \varepsilon \vec{E} \qquad \vec{B} = \mu \vec{H}$$

➔<u>Negative index of refraction</u>! Many optical properties are reversed!



Propagating Waves

RHM

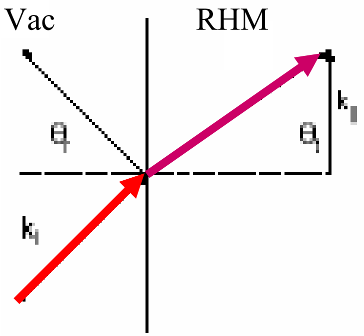
$n = \sqrt{\varepsilon\mu} > 0$

$n = \sqrt{\varepsilon\mu} < 0$

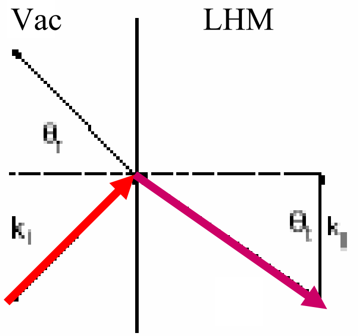
Propagating Waves!

LHM

Non-propagating Waves



Ordinary Refraction



Negative Refraction

Negative Refraction: Consequences

Left-Handed or Negative Index of Refraction Metamaterials

$\varepsilon < 0$ AND $\mu < 0$ Veselago, 1967

Propagating waves have index of refraction $n < 0$

$\Rightarrow$ Phase velocity is opposite to Poynting vector direction

Negative refraction in Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Flat lens with no optical axis

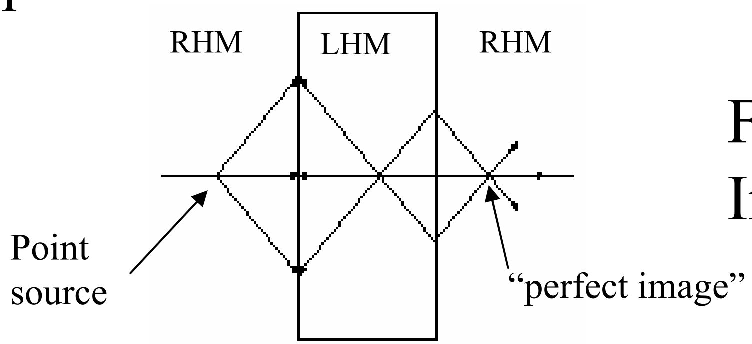
"Perfect" Lens (Pendry, 2000)

Reverse Doppler Effect

Radiation Tension

Converging Lens → Diverging Lens and *vice-versa*

Reversed Čerenkov Effect

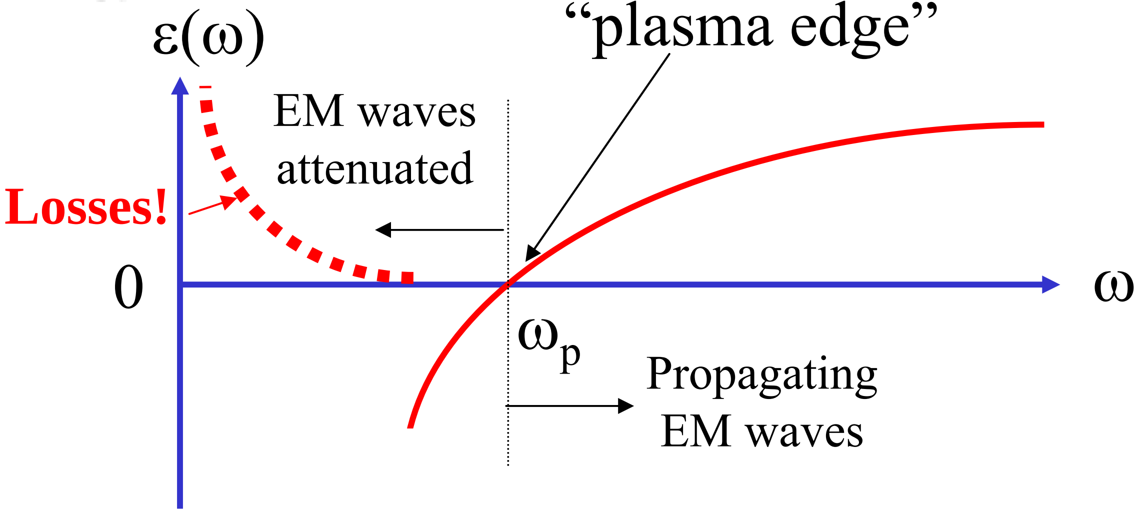


Flat Lens Imaging

V. G. Veselago, Usp. Fiz. Nauk 92, 517 (1967)

[Eng. Trans.: Sov. Phys. Uspekhi **10**, 509 (1968)]

How to make a Negative Dielectric Constant



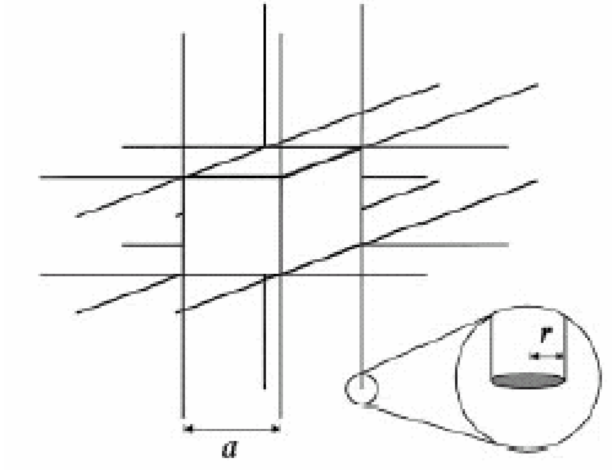
The dielectric constant is

$$\varepsilon_r(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

n_{eff} = electron concentration

$$\omega_p^2 = \frac{n_{eff} e^2}{\varepsilon_0 m_{eff}}$$

The plasma frequency for most metals is in the optical or UV spectral ranges



Strategy to decrease the plasma frequency

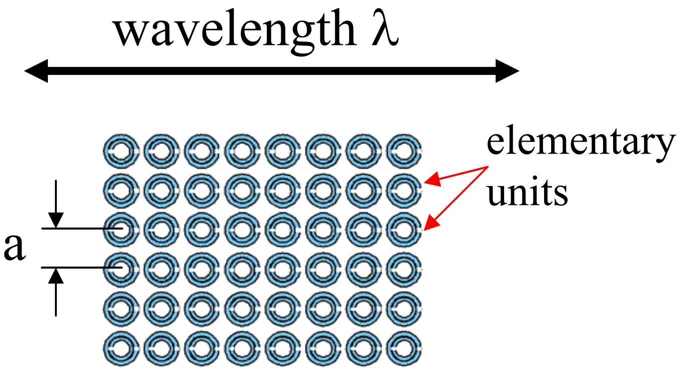
⇒ Thin wire lattice

Decrease n_{eff} and increase m_{eff}

with a = 5 mm and r = 1 μm,
$f_p = \omega_p/2\pi = 8.20$ GHz

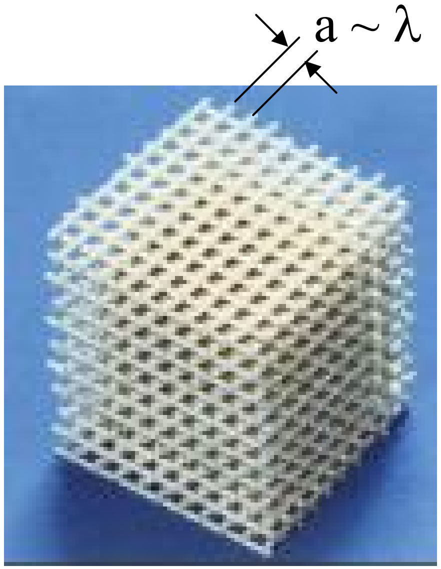
Metamaterial vs Photonic Crystal

Metamaterial



Create an “effective medium” with macroscopic ε_{eff}, μ_{eff}, n properties that are engineered

Photonic Crystal



Use constructive and destructive interference to engineer properties of light → $\omega(\vec{k})$

- band structure
- band gaps
- defect states
- negative group velocity …

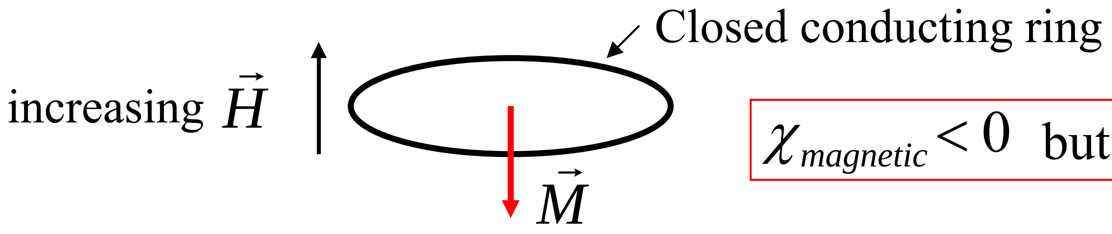
How to Make Negative Permeability

Magnetic Permeability $\mu = \mu_r\mu_0$

$$\vec{M} = \chi_{magnetic}\,\vec{H}$$

$$\mu = \mu_0\left(1 + \chi_{magnetic}\right)$$

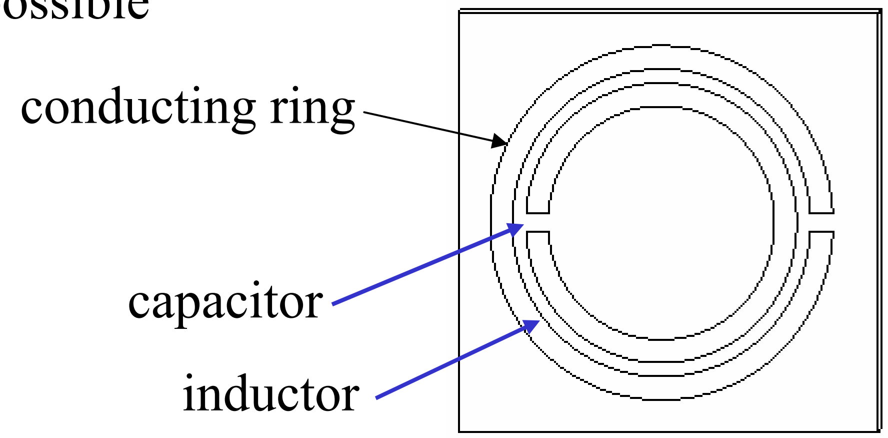
A closed ring is diamagnetic (Lenz’s Law)



$\chi_{magnetic} < 0$ but very small

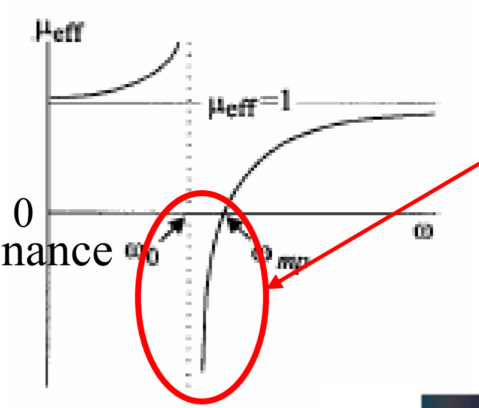
Enhance $\chi_{magnetic}$ with a resonance. Add a capacitor to make an LC oscillator
Screening current is enhanced and $\mu < 0$ is possible

Split-ring resonator (SRR)



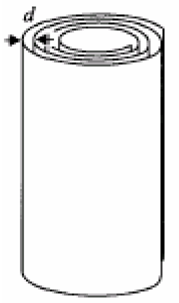
Some Ways to Make $\mu_{eff} < 0$

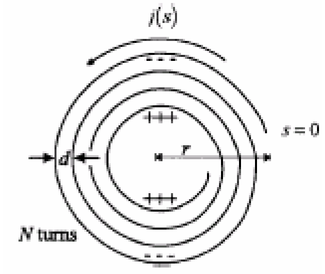
SRR μ_{eff}

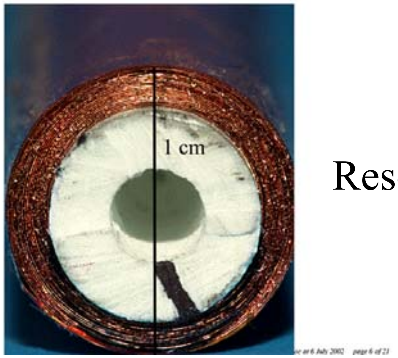


region of $\mu_{eff} < 0$

Jelly Roll SRR

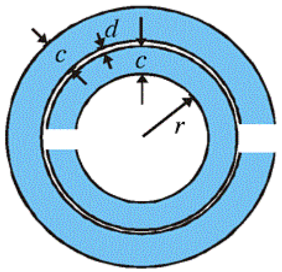


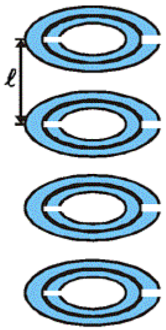


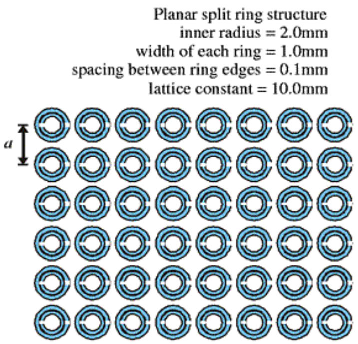


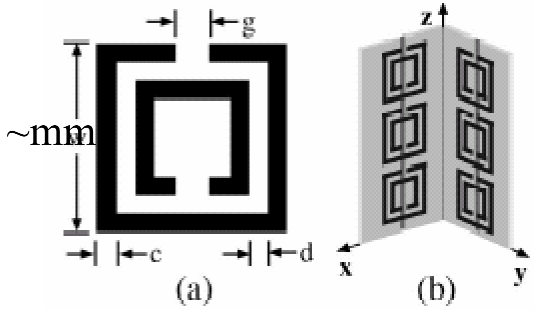
Resonance ~21 MHz

Planar SRR









Resonance ~10 GHz

Metamaterials: Realizations

One Strategy: Combine metamaterials so that frequency ranges of $\varepsilon < 0$ and $\mu < 0$ overlap to give $n < 0$

Left-Handed Materials Theory (Veselago, 1967)

Experiments:

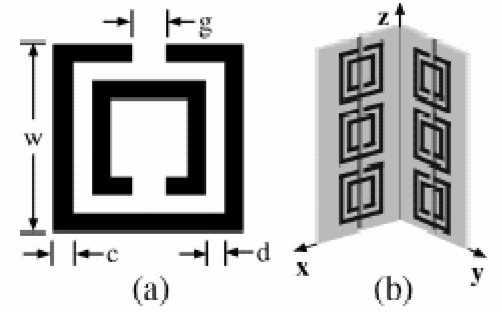
$\varepsilon_{\mathrm{eff}} < 0$ accomplished by Pendry, *et al*. (1998)
$\mu_{\mathrm{eff}} < 0$ accomplished by Pendry, *et al*. (1999)
using split-ring resonators (SRR)

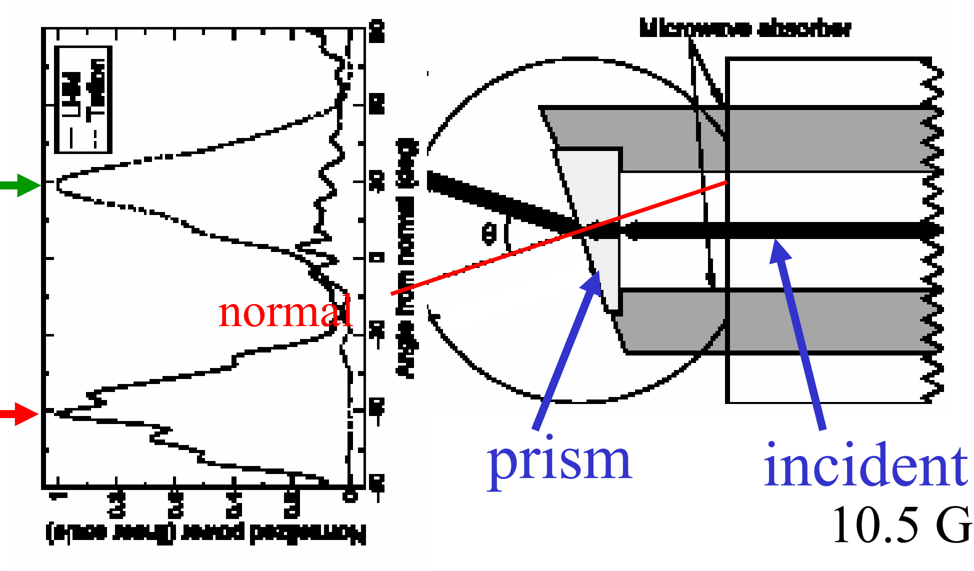
$\varepsilon_{\mathrm{eff}} < 0$ AND $\mu_{\mathrm{eff}} < 0$ done by D. R. Smith, *et al*., PRL 84, 4184 (2000)
using wires and SRRs

Applications: Now Emerging!

Metamaterials: Realizations

Left-Handed Materials, Negative Refraction: Science **292** 77 (2001)





Teflon prism

LHM prism

normal

prism

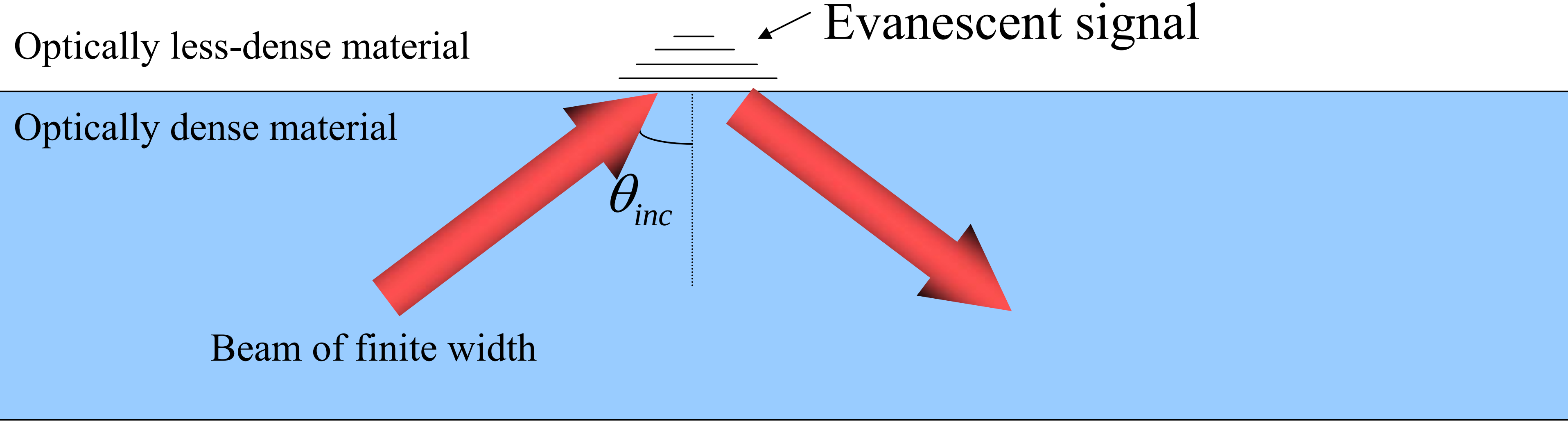
incident beam

10.5 GHz

Refraction experiment from a prism

Evanescent Excitations

Consider total internal reflection ($\theta_{inc} > \theta_{critical}$)



Evanescent signal

Optically less-dense material

Optically dense material

θ_{inc}

Beam of finite width

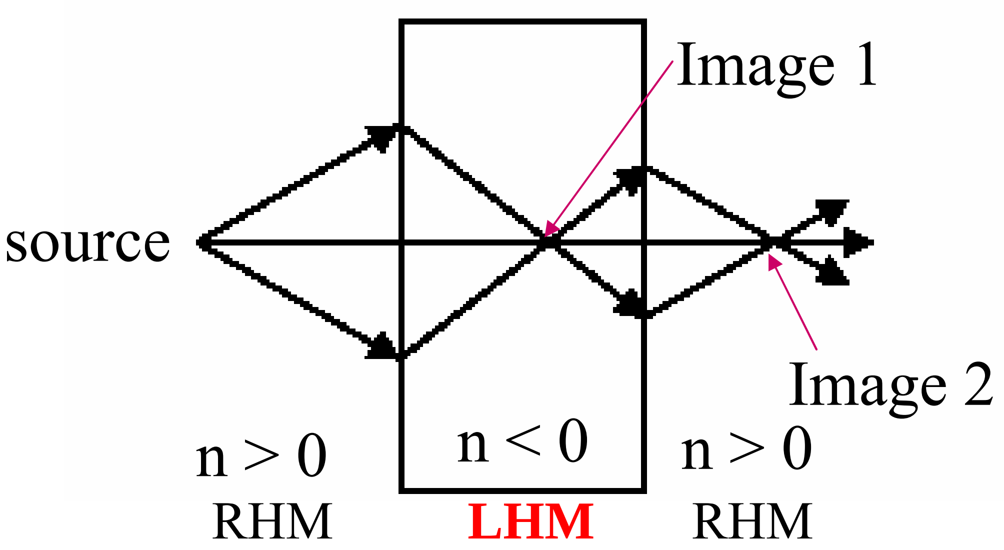
Other examples of Evanescent signals:

Excitation of a waveguide beyond cutoff

High spatial-frequency (k) non-propagating fields near a source (antenna)

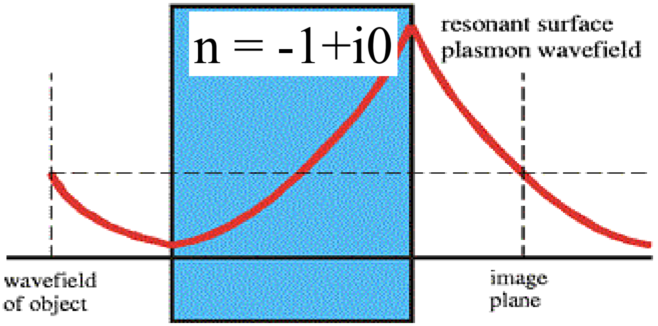
“Perfect” Flat Lens Imaging

n < 0 Flat Lens can be a Perfect Lens: Pendry PRL **85**, 3966 (2000)



High spatial frequency optical information is carried in evanescent fields
These waves are lost in normal “far-field” imaging. However,
it is possible to recover this information and make “super resolution” images using LHM lenses!

Source must be in the near-field of the lens to gather the evanescent waves

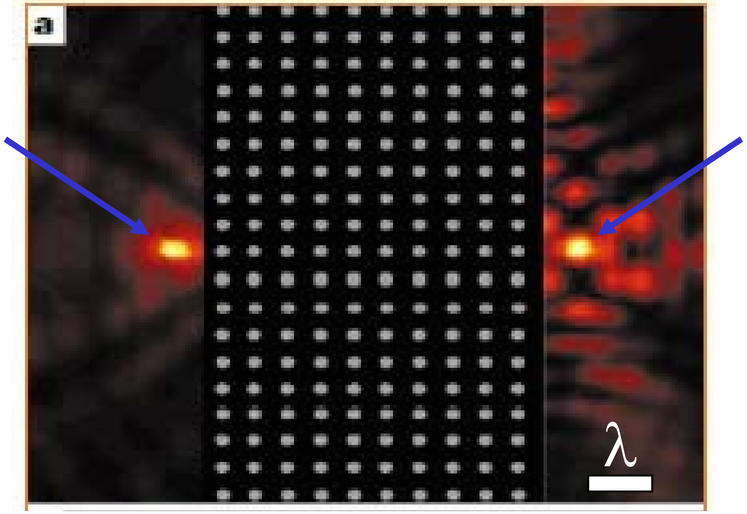


Losses and deviations from
n = -1 limit the range of
wavevectors that can be amplified!

Experimental Evidence for Super-Resolution Imaging

“n=-1” photonic crystal

Source

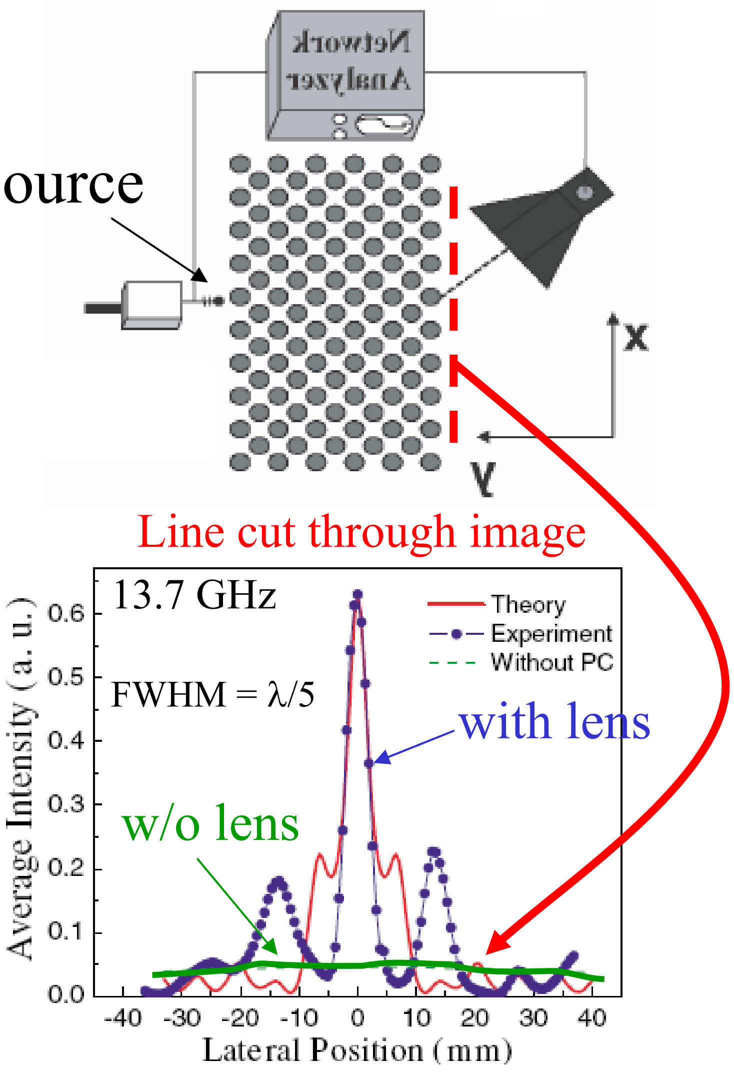


Image

9.3 GHz

image size ~ source size < λ

Parimi (2003)



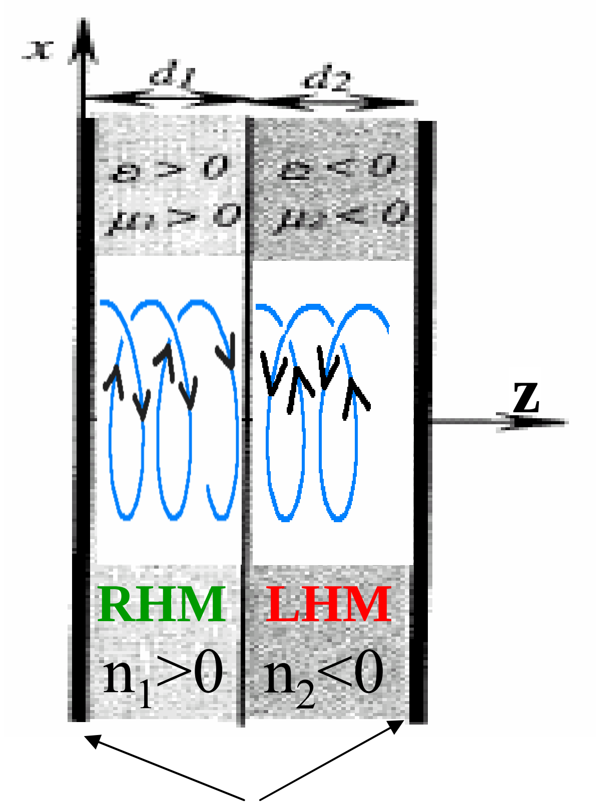
Line cut through image

Cubukcu (2003)

Losses and deviations from n = -1 limit the image quality

Metamaterials: Novel Applications

Thin SubWavelength Cavity Resonators (Engheta, 2002)



Conducting planes

For a resonance in the z-direction:
New possibility – zero net phase winding

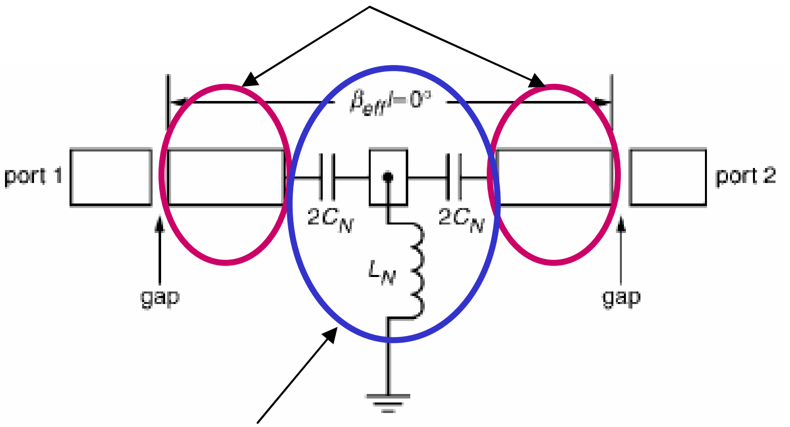
$$2\pi p = k_0(n_1 d_1 - |n_2| d_2) \qquad p = \text{integer}$$

$p = 0$ “zeroth order resonance”

0th resonance condition <u>independent</u> of $d_1 + d_2$
and depends only on d_1/d_2

$$\frac{d_1}{d_2} = \frac{|n_2|}{n_1}$$

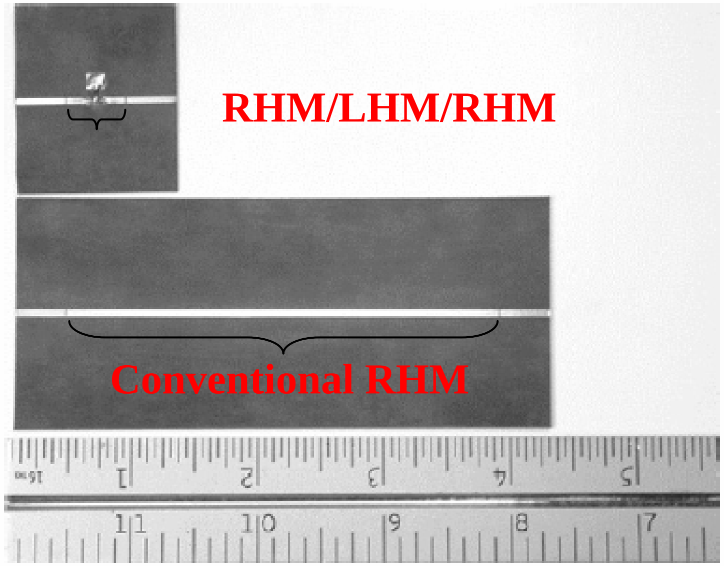
Implementation of an LHM Compact Resonator



RHM Transmission Lines

LHM Transmission Line
(Dual structure)

Microstrip Resonators

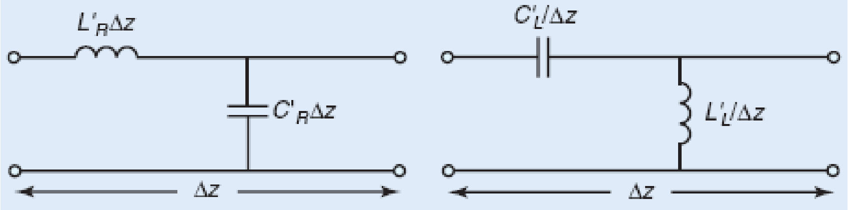


Both resonate at 1.2 GHz
RHM/LHM/RHM resonator is 86% smaller

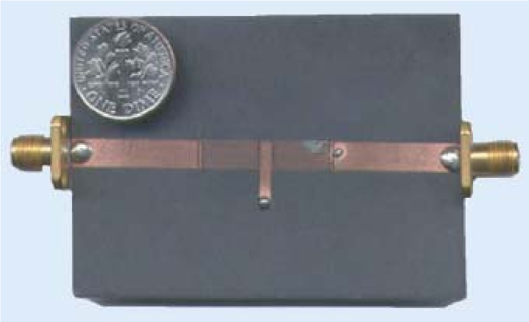
Scher, *et al.*, 2004

Negative Index Microwave Circuits

Dual Transmission Lines with NIR concepts are leading to a new class of microwave devices



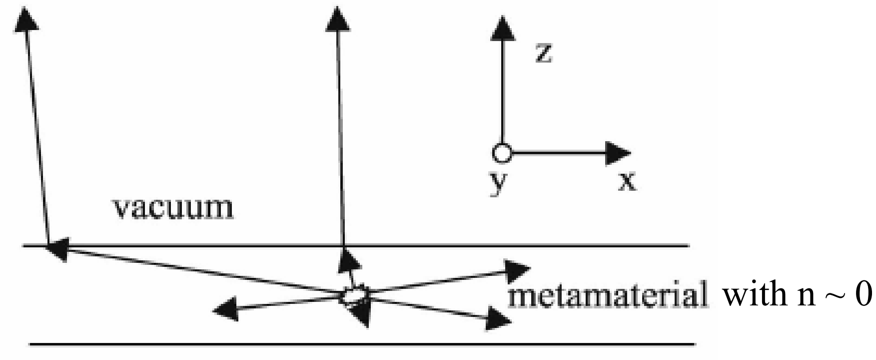
Compact couplers, resonators, antennas, phase shifters have been demonstrated



1.9 GHz 0th-order resonator
T. Itoh, *et al.*, UCLA

Metamaterials: Novel Antennas

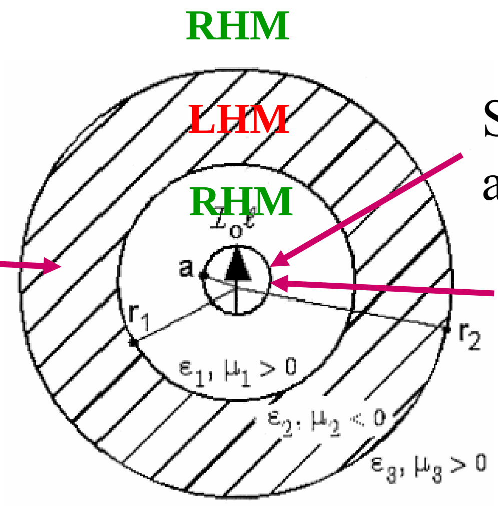
Directional Antenna



A point source embedded in a metamaterial with n~0 will produce a directed beam nearly normal to the metamaterial/vacuum interface. From [Enoch2002].

Super-Efficient Electrically-small Dipole Antenna (ℓ << λ)

$$\frac{X_{Ant}}{R_{Rad}} = +\left(\frac{\lambda}{\pi\ell}\right)^3$$



Small dipole antenna

$$\frac{X_{Ant}}{R_{Rad}} = -\left(\frac{\lambda}{\pi\ell}\right)^3$$

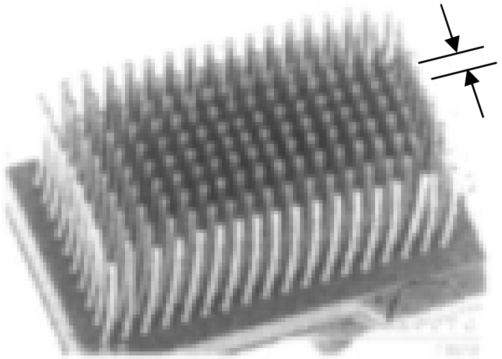
LHM shell compensates Im[Z_{Ant}]

Factor of 74 improvement in P_{Rad} at 10 GHz with λ/1000 antenna

Ziolkowski (2003)

Scaling LHM ($n < 0$) Behavior to THz Frequencies…

Micro- and Nano-Wire Arrays
gold wires
$\varepsilon < 0$ for $f < \omega_p/2\pi = 0.7$ THz

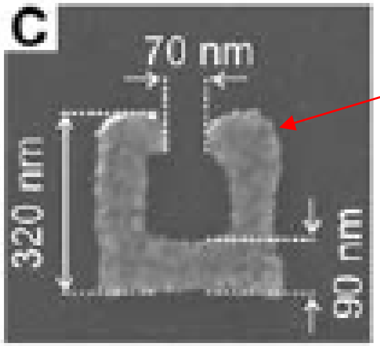


$a = 120\ \mu m$

$r = 15\ \mu m$

Wu, *et al*., 2003

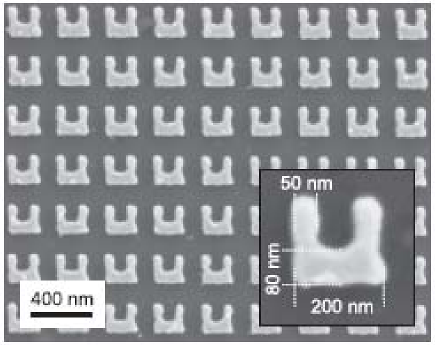
Nano-Scale
Split Ring Resonators
$\mu_{eff} < 0$ for 81 – 87 THz



20 nm-thick gold film

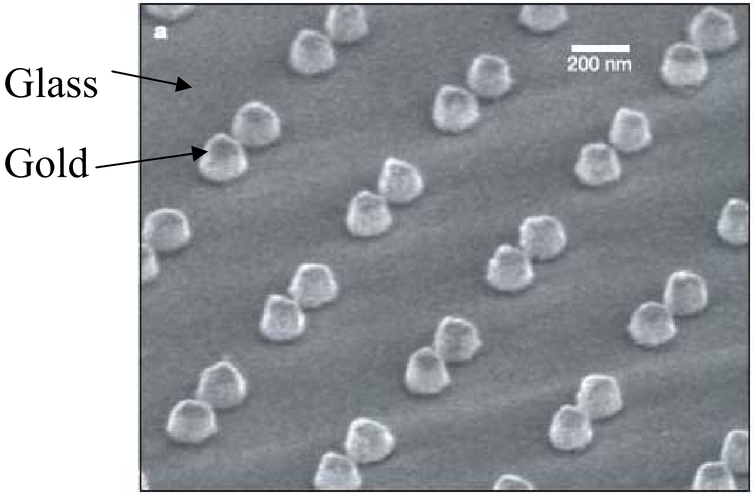
Linden, *et al*., 2004

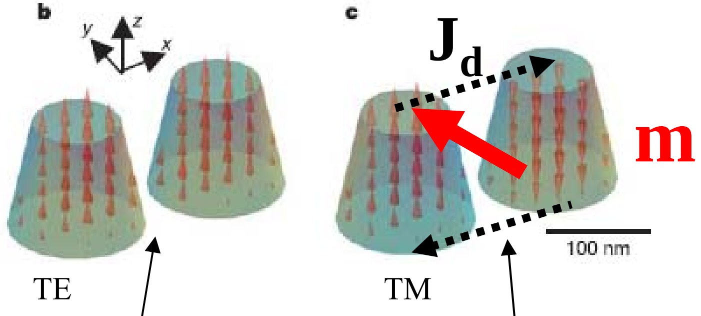
$\mu_{eff} < 0$ for 180 THz (1.67 μm)



Enkrich, *et al*., 2005

… and on to Infrared and Optical Frequencies

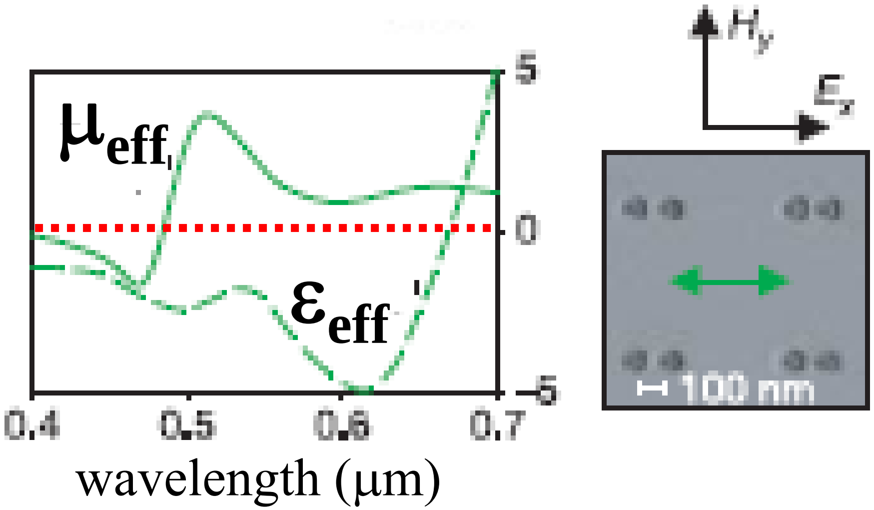




Symmetric electric dipole mode (670 nm, red)

Antisymmetric magnetic dipole mode (550 nm, green)

Grigorenko, *et al*. Nature 2005

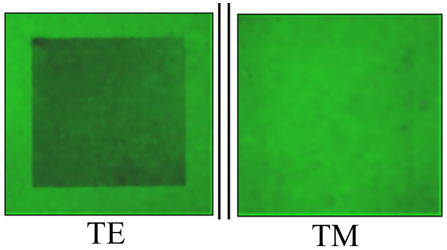


n < 0 behavior washed out by high losses

$\mathrm{Im}[\mu_{eff}] \sim 1$

Demonstration of $\mu_{eff} > 1$ in optics

Impedance Matching

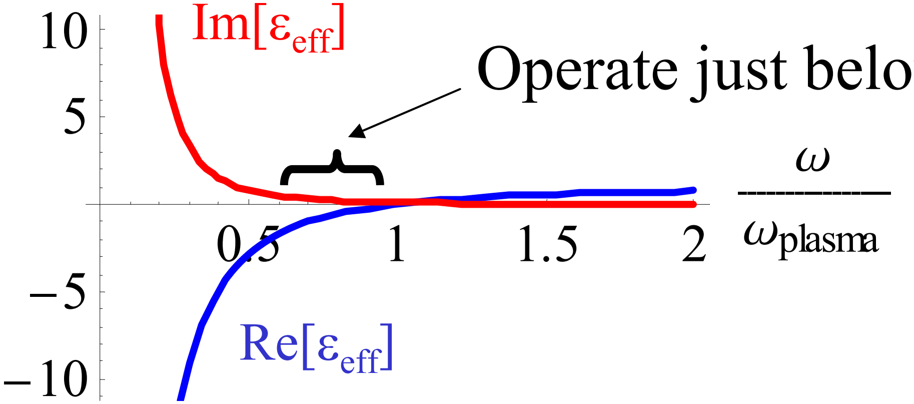


$$Z = \sqrt{\frac{\varepsilon_{eff}}{\mu_{eff}}}$$

An Important Limitation: Losses

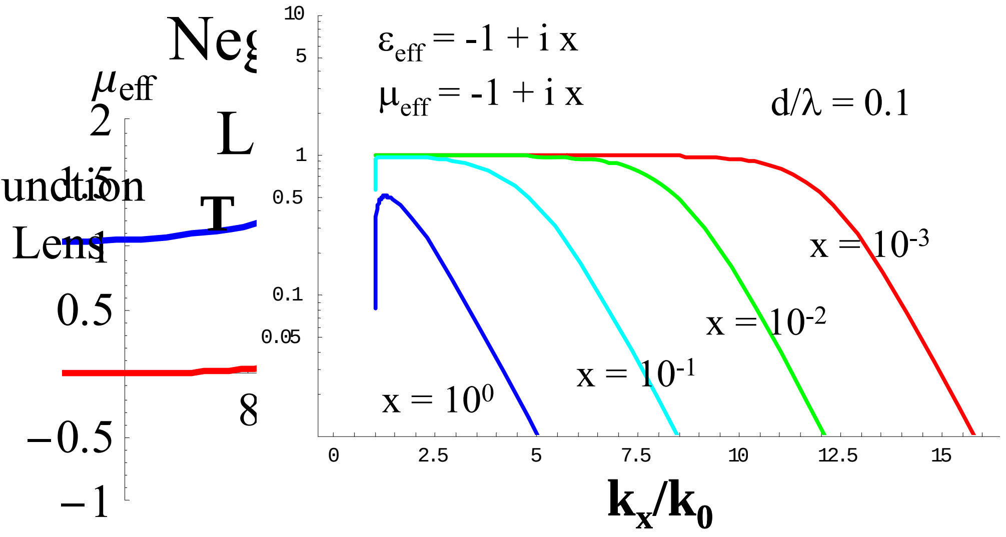
Negative Permittivity

Operate just below ω_{plasma} to minimize loss



$$\boxed{\varepsilon_{eff} / \varepsilon_0 = 1 - \frac{\omega_{plasma}^2}{\omega(\omega + i\gamma)}}$$

Transfer Function
of a Flat Lens

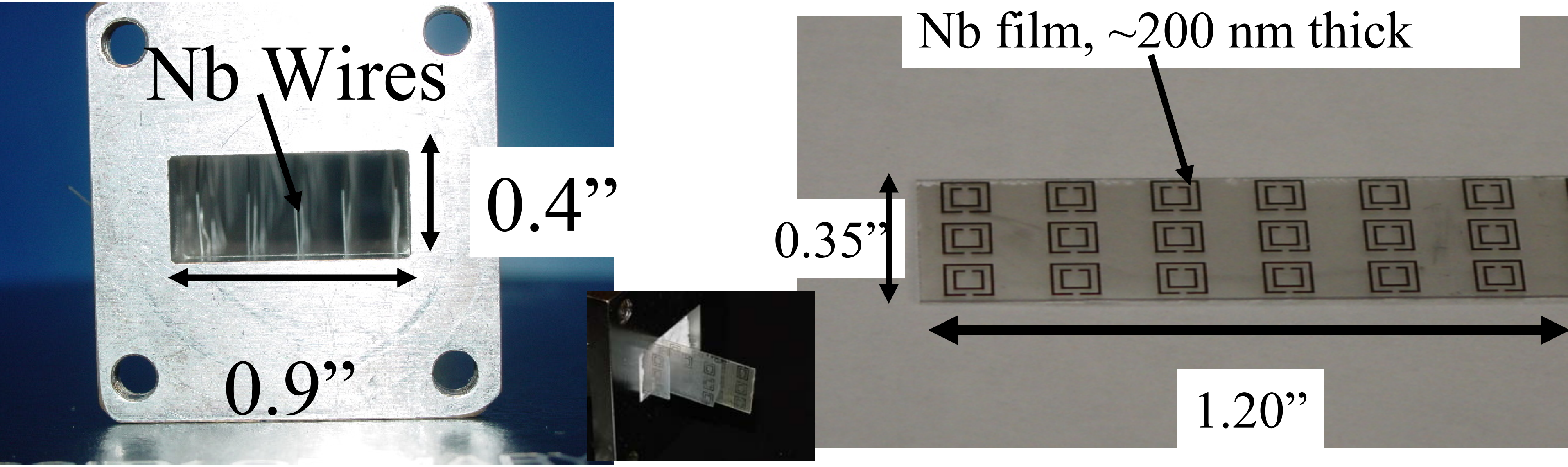


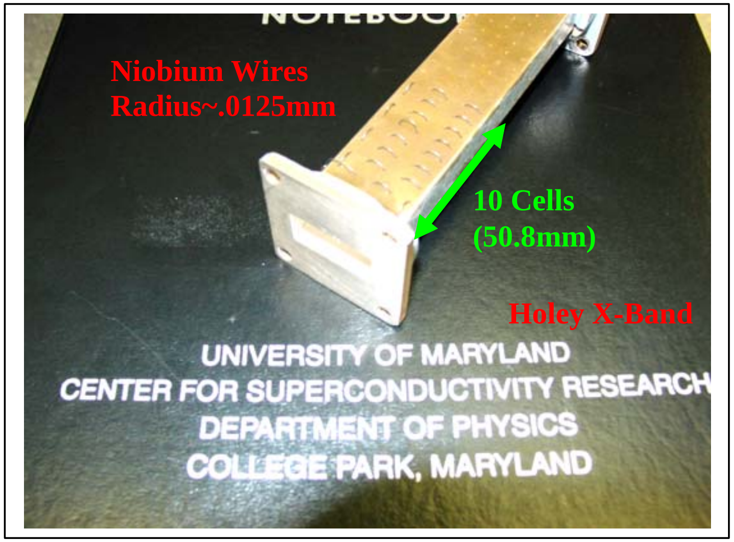
$\omega_0 = 2\pi\ 10\,GHz$

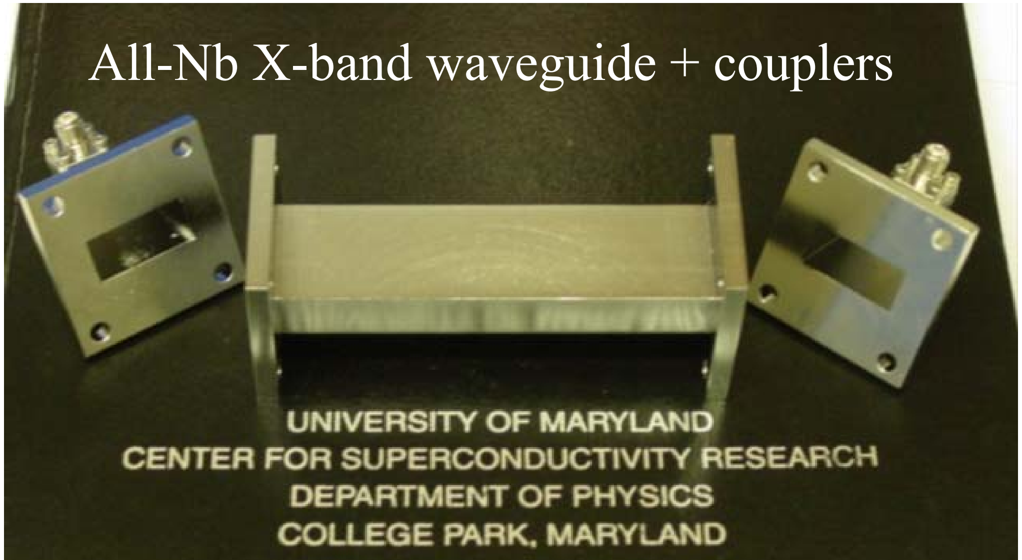
Lateral Wavenumber

Superconducting Metamaterials

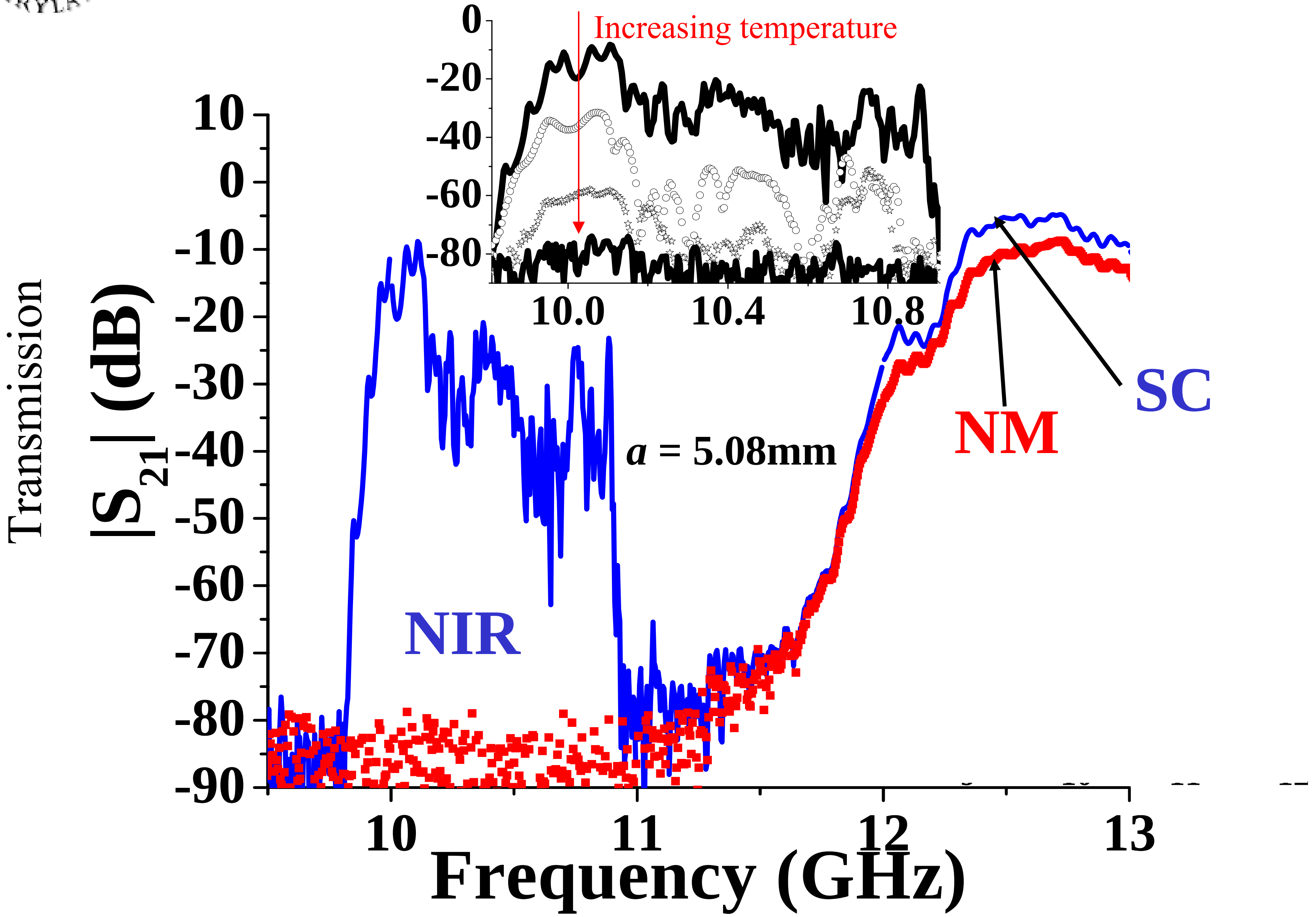
Perhaps the only way to demonstrate amplification
of evanescent waves (the key new physics)





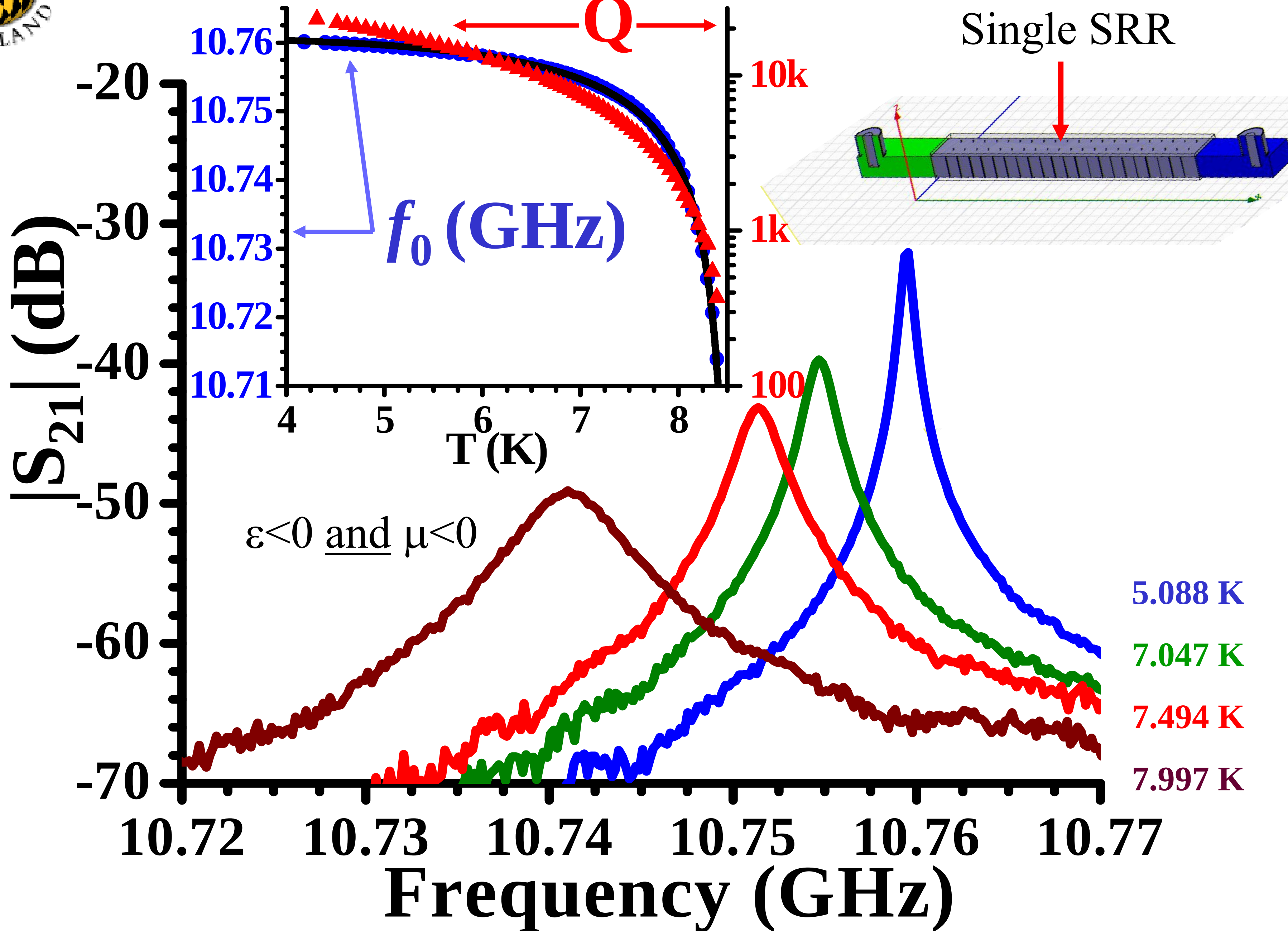


Negative Index Passband with a Superconducting All-Nb Metamaterial



Elementary NIR Material:

Single SRR in a 5 x 7 Nb Wire Array



Caveats and Some Issues to be Addressed

Negative Index behavior is limited to finite frequency ranges

Causality constraint: $$\frac{d(\omega n(\omega))}{d\omega} > 1$$ For Im[ε] << 1, Smith, Kroll (2000)

Dispersion in Re[$n(\omega)$] implies loss: Im[n] > 0

- Losses limit frequency range of $\varepsilon_{eff} < 0$ and $\mu_{eff} < 0$
- Decreased range of k_x/k_0 for evanescent wave amplification
  - Solution: superconductors, active media

Scaling to higher frequencies (decrease cell size *a*)

- Metal losses generally scale as 1/*a* or faster
  - Solution: active media, photonic crystals?

Conclusions

Negatively Refracting Metamaterials offer opportunities for a new kind of optics

Negative Index of Refraction
Flat Lens Imaging
Amplification of Evanescent Waves
“Super Lenses”

There are many new Emerging Applications
Compact (dual TL) structures with enhanced performance
Composite LHM/RHM materials with unique field structures
New antenna structures
Novel optics / NIR lithography

SC metamaterials papers: Appl. Phys. Lett. **87**, 034102 (2005)
and cond-mat/0512515
anlage@umd.edu