Metamaterials: Giving Light the Second Hand

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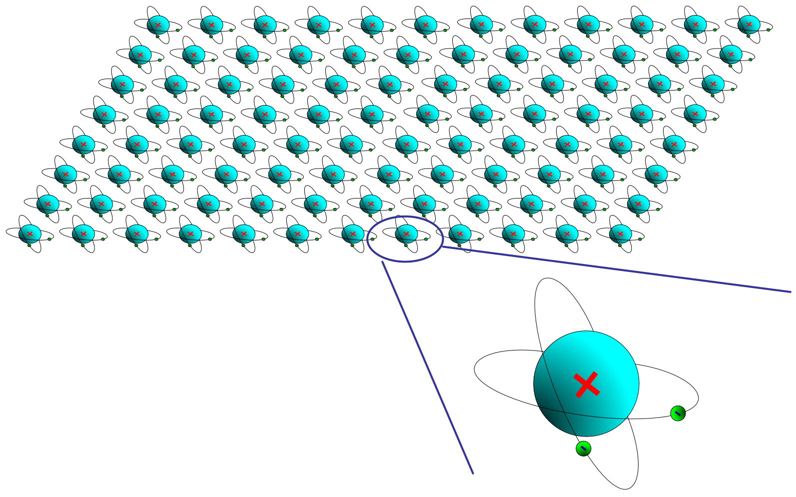
Outline

- What are metamaterials?
- Electrical metamaterials
- Magnetic metamaterials
- Negative-index metamaterials
- Perfect lens and superlens
- Optical cloaking - intro

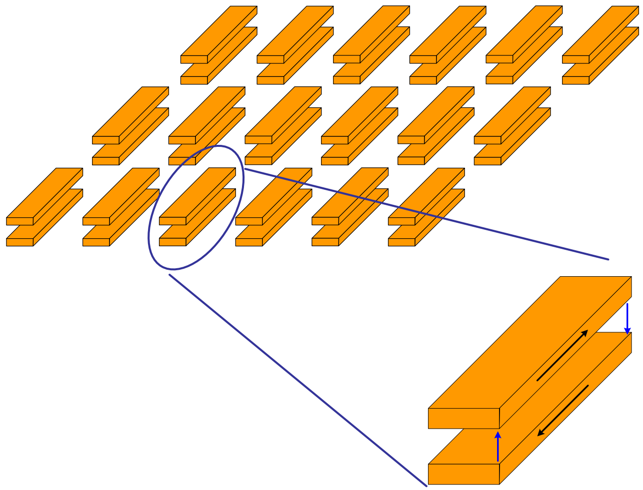
What is a metamaterial?

Metamaterials are engineered composites tailored for specific electromagnetic properties that are not found in nature and not observed in the constituent materials

$\mu\varepsilon\tau\alpha$ = meta = beyond (Greek)



A natural material with its atoms



A metamaterial with artificially structured “atoms”

Electromagnetic properties v.s. characteristic sizes

a<<λ.
Effective medium description using Maxwell equations with μ, ε, n, Z

Example:
Optical crystals
Metamaterials

a~λ.
Structure dominates. Properties determined by diffraction and interference

Example:
Photonics crystals
Phased array radar
X-ray diffraction optics

a>>λ.
Properties described using geometrical optics and ray tracing

Example:
Lens system
Shadows

PC-"metamaterials" are not considered

Natural Crystals

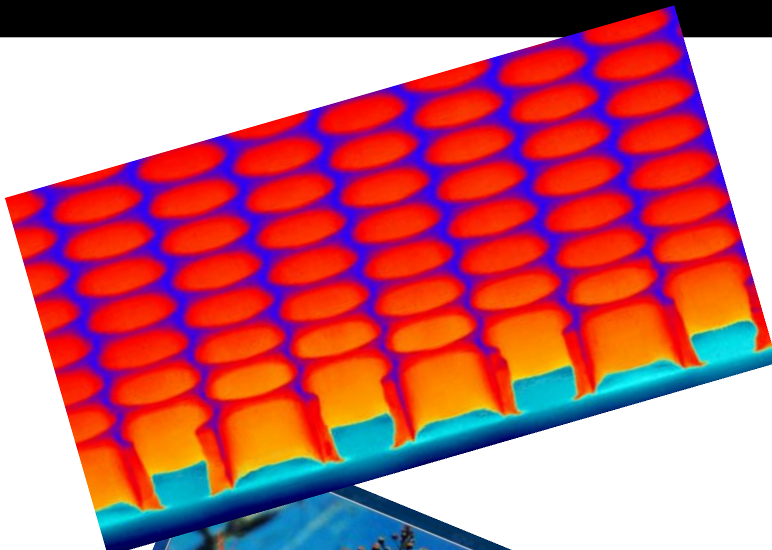
… have lattice constants much smaller than light wavelengths: $a << \lambda$

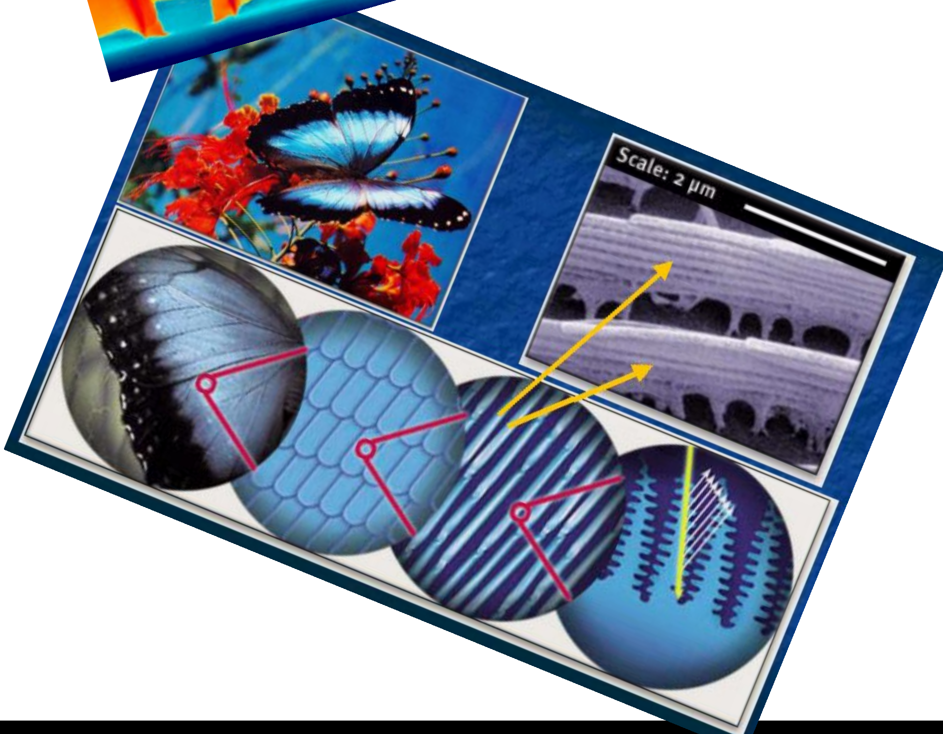
… are treated as homogeneous media with parameters ε, μ, n, Z **(tensors in anisotropic crystals)**

… have a positive refractive index: $n > 1$

… show no magnetic response at optical wavelengths: $\mu = 1$

Photonic crystals





... **have lattice constants comparable to light wavelengths:** $a \sim \lambda$

... **can be artificial or natural**

... **have properties governed by the diffraction of the periodic structures**

... **may exhibit a bandgap for photons**

... **typically are *not* well described using effective parameters** ε, μ, n, Z

... **often behave like but they are *not* true metamaterials**

Why need metamaterials?

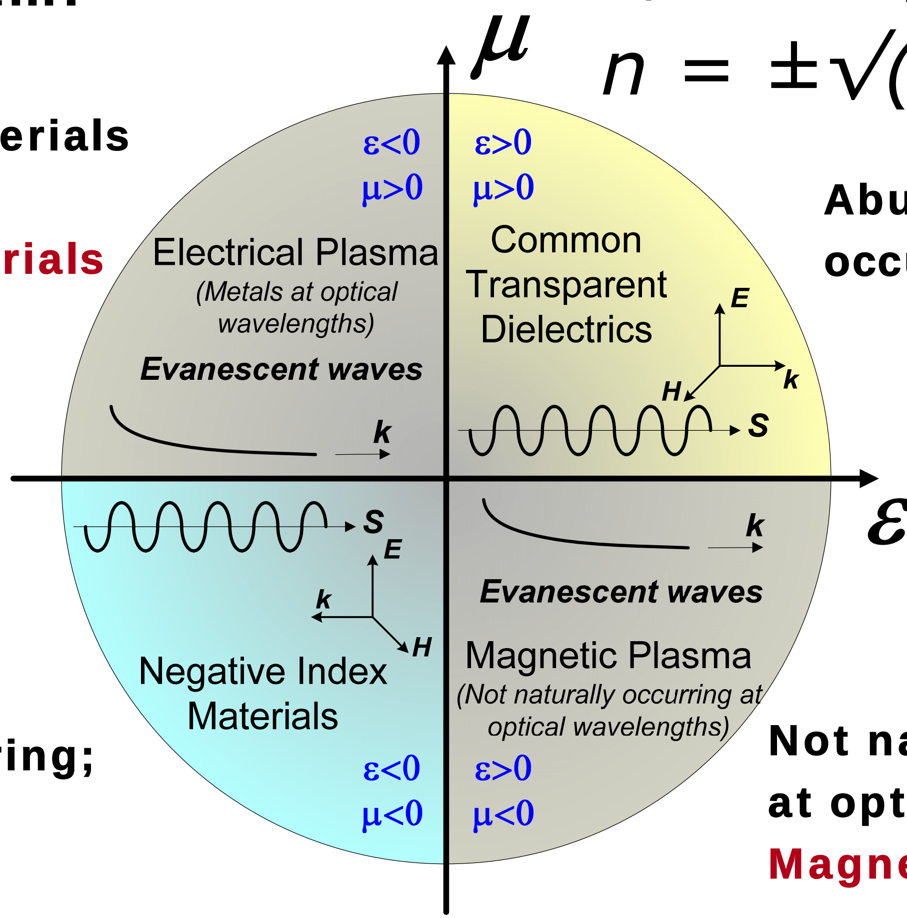
$$E,H \sim \exp[in(\omega/c)z]$$

$$n = \pm\sqrt{(\varepsilon\mu)}$$

ε, μ diagram:

Limited natural materials like noble metals;
Electrical metamaterials

Abundant naturally-occurring materials

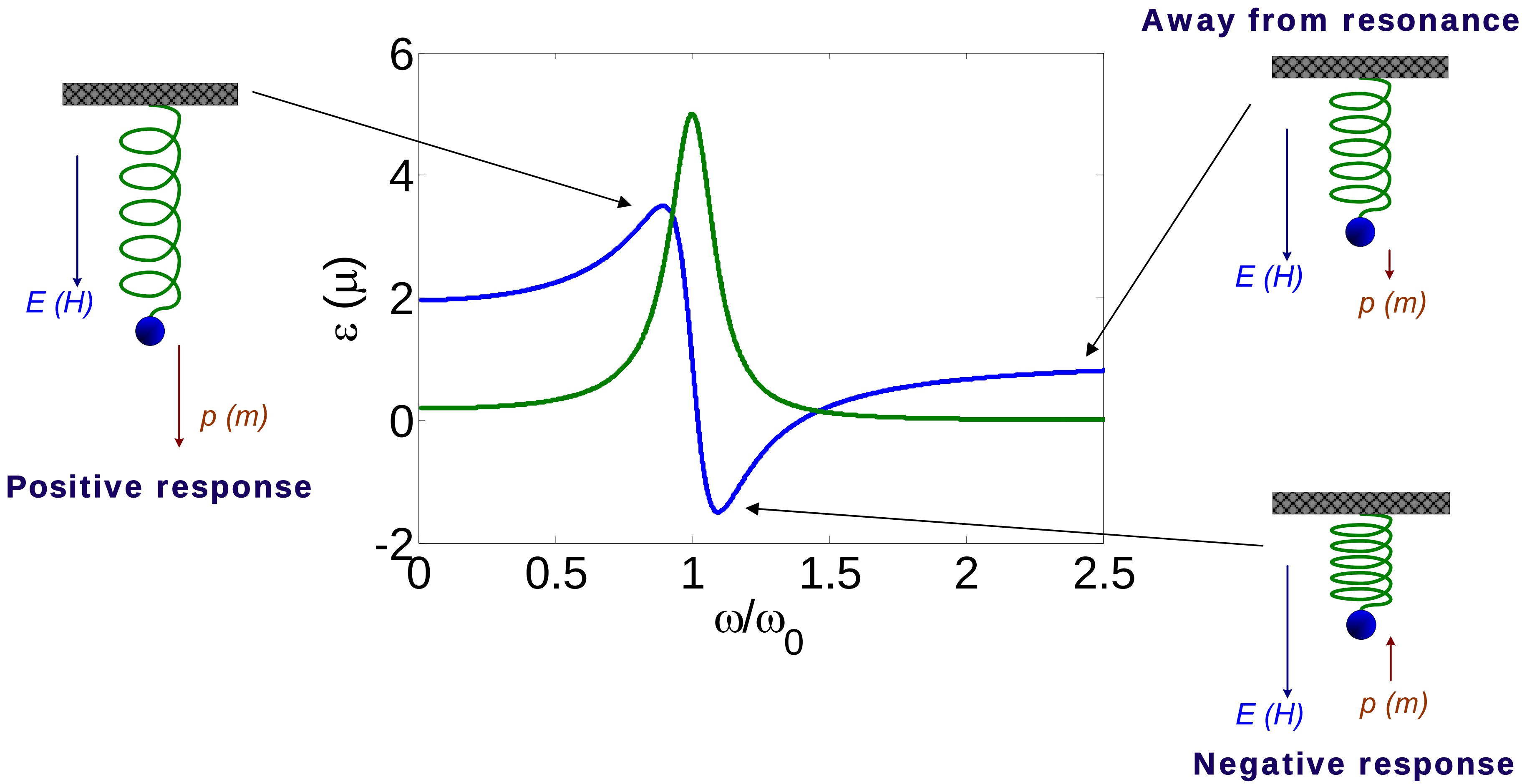


Not naturally occurring;
Negative-index metamaterials

Not naturally occurring at optical frequencies;
Magnetic metamaterials

General properties of electromagnetic resonances

Resonance described by Lorentz line shape



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Drude model for noble metal: negative ε in nature

Drude model for permittivity:

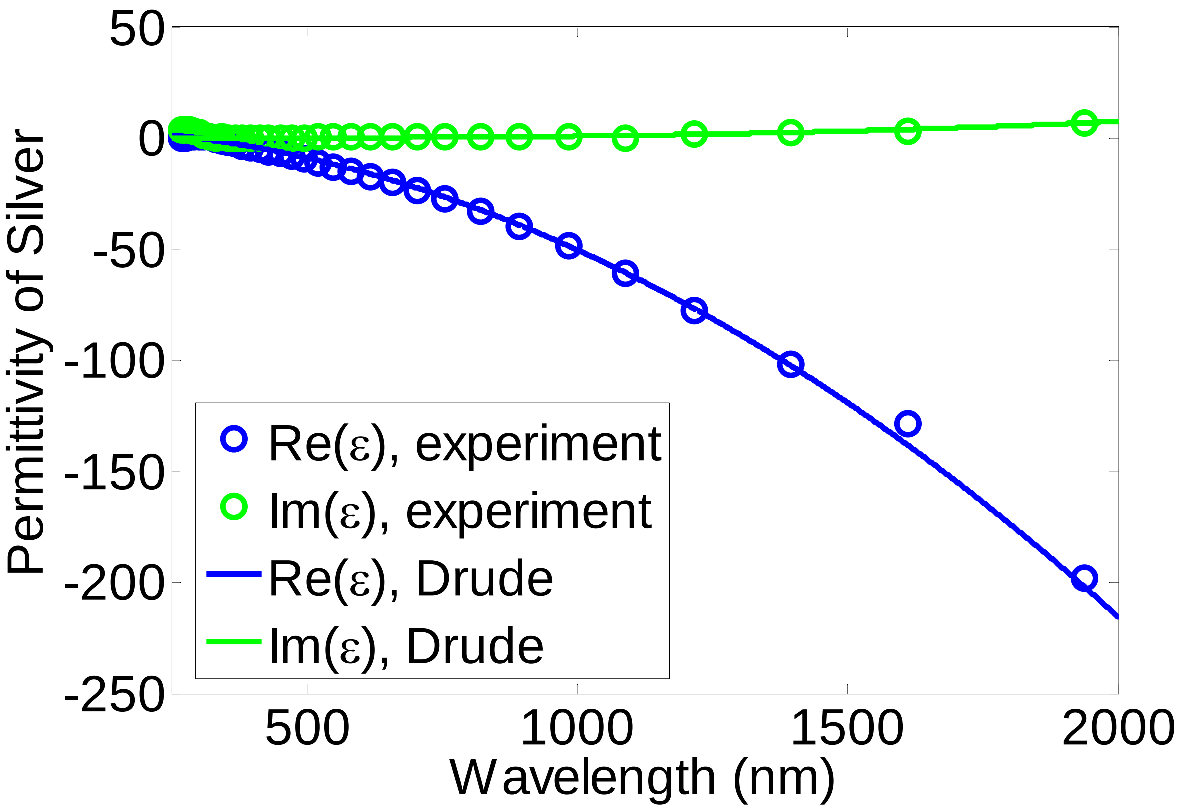
$$\varepsilon(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$$

Silver parameters:

$\varepsilon_0 = 5.0$

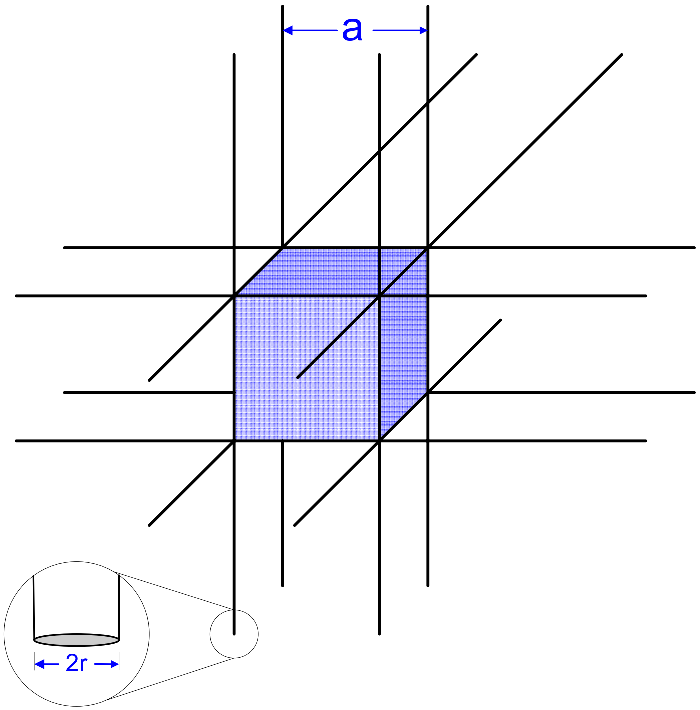
$\omega_p = 9.216 \quad eV$

$\Gamma = 0.0212 \quad eV$



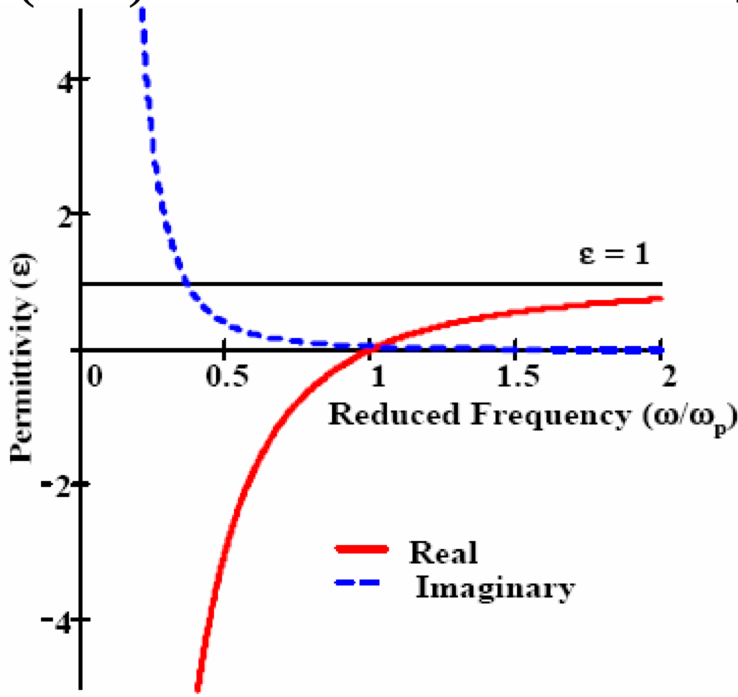
Experimental data from Johnson & Christy, PRB, 1972

Example of electrical metamaterials: *metal wires arrays*



$$\varepsilon = \varepsilon' + i\varepsilon'' = 1 - \frac{\omega_p^2}{\omega(\omega + i\varepsilon_0 a^2 \omega_p^2 / \pi r^2 \sigma)}$$

$$\omega_p^2 = \frac{2\pi c^2}{a^2 \ln(a/r)}$$



A periodic array of thin metal wires with r<<a<<λ acts as a low frequency plasma

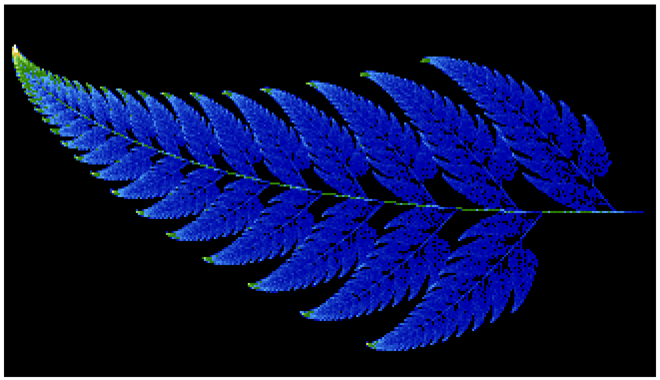
The effective ε is described with modified ω_p

Plasma frequency depends on geometry rather than on material properties

Pendry, PRL (1996)

Random electrical metamaterials

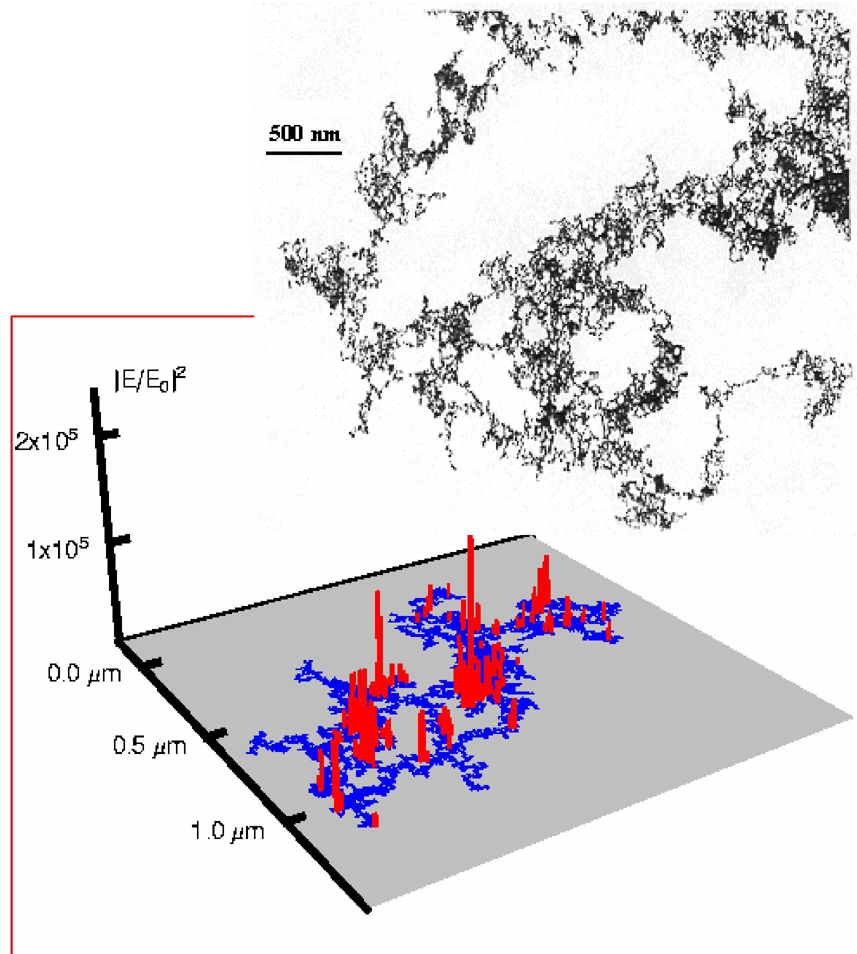
Self-similar structures in nature



Fern leaves

Colorado river delta, ***National Geographic, Oct. 05***

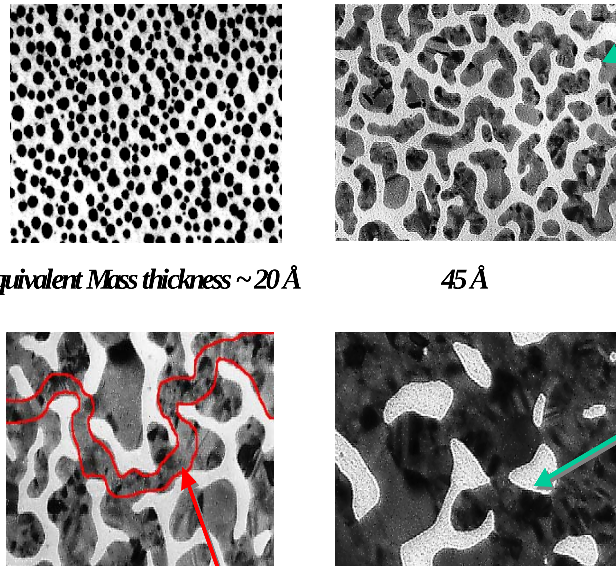
"Hot-spots" in fractals



Shalaev, Nonlinear Optics of Random Media, Springer, 2000

Giant local field enhancement in percolating films

TEM:

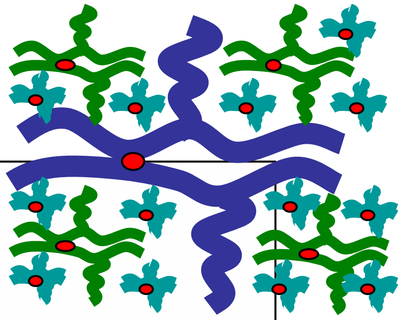


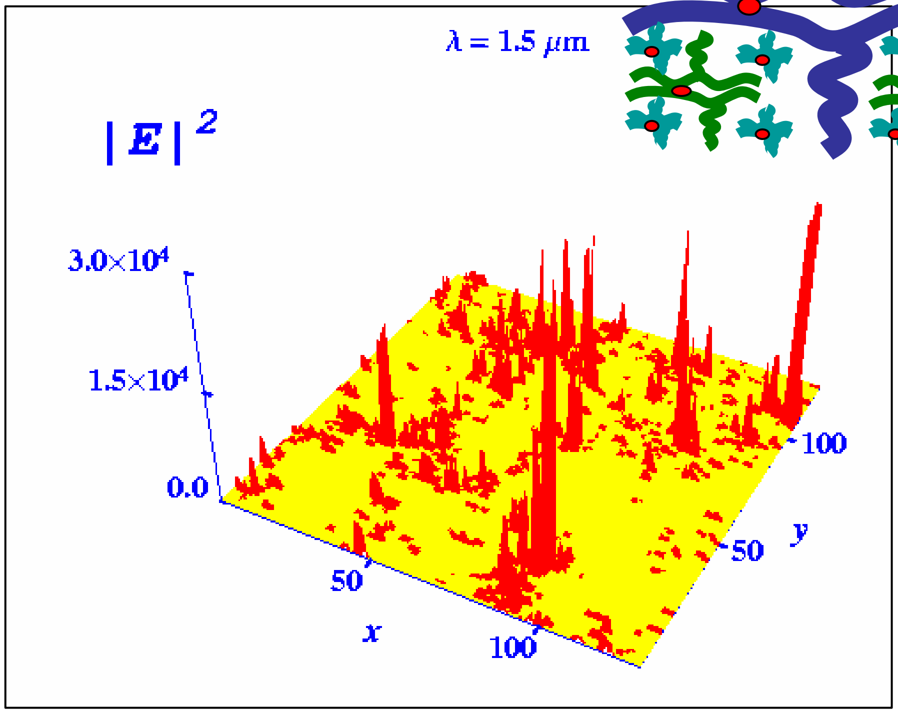
Equivalent Mass thickness ~ 20 Å | *45 Å* | *65 Å* | *106 Å*

gold | *glass* | 50 nm

⇒ *Percolation threshold* $p = p_c$

$$L \sim l \qquad C \sim l \qquad \omega_r = \frac{1}{\sqrt{LC}} \propto \frac{1}{l}$$





Sarychev and Shalaev, Phys. Reports, 2000

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Optical magnetic response: *a missing hand of light in nature*

Natural magnetic responses (Ferromagnetic / Ferrimagnetic / Antiferromagnetic resonances) typically occur at lower than a few GHz

There are no free magnetic monopoles; therefore no magnetic plasma

All conventional optics (lenses, mirrors, crystals, …) essentially have nothing to do with magnetic fields

Magnetic coupling to an atom: ~ $\mu_B = e\hbar / 2m_e c = \alpha e a_0$ ***(Bohr magneton)***

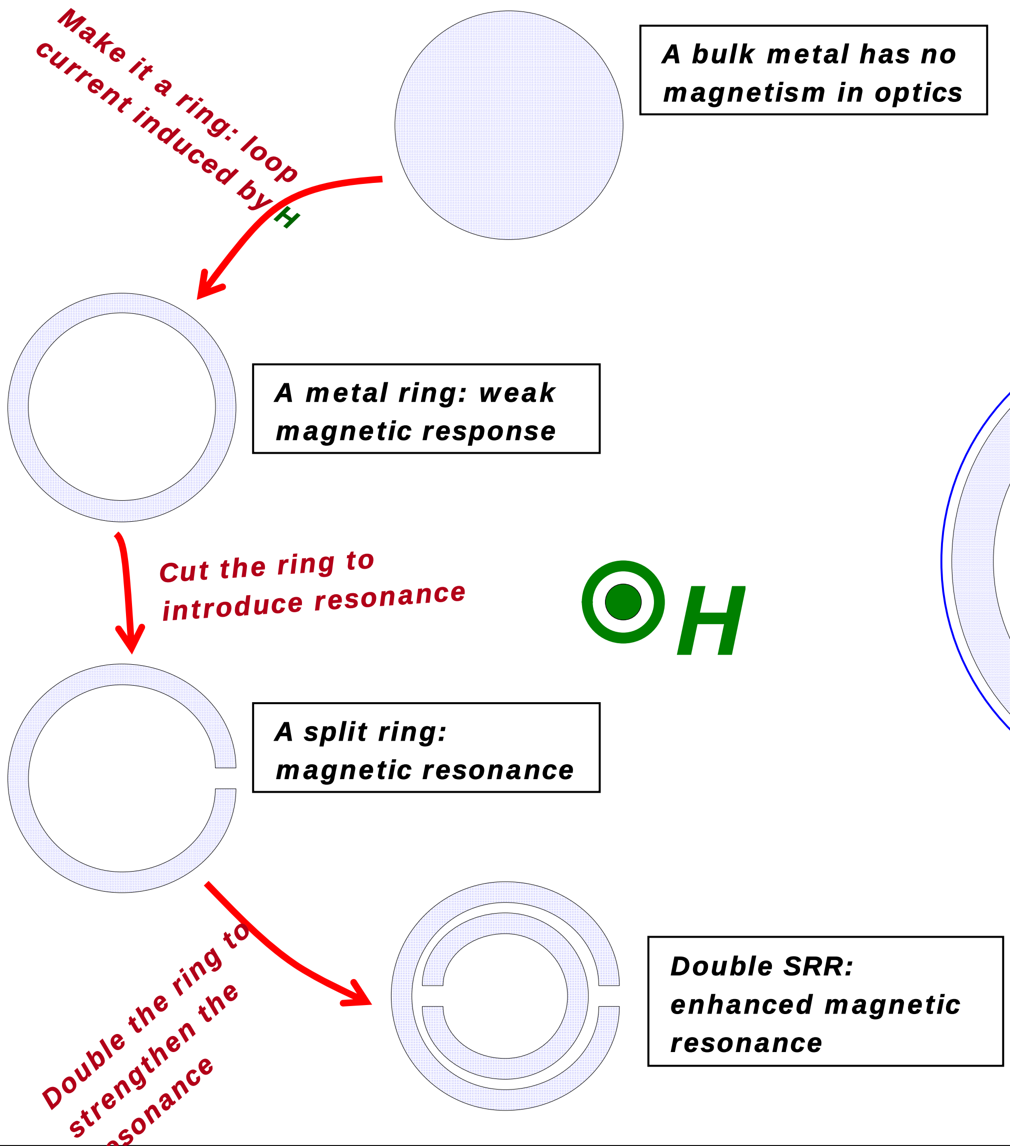
Electric coupling to an atom: ~ $e a_0$

Magnetic effect / electric effect $\approx \alpha^2 \approx (1/137)^2$

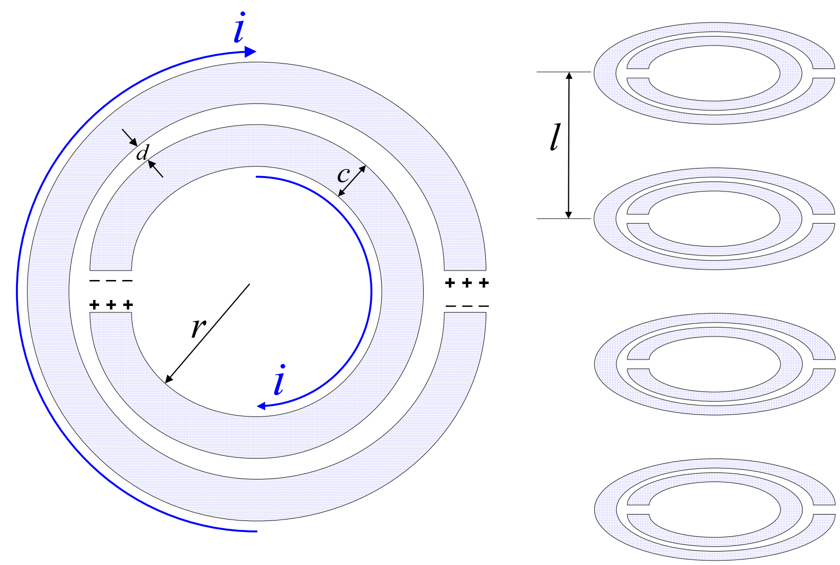
"… the magnetic permeability μ(ω) ceases to have any physical meaning at relatively low frequencies…there is certainly no meaning in using the magnetic susceptibility from optical frequencies onwards, and in discussion of such phenomena we must put μ=1."

Landau and Lifshitz, ECM, Chapter 79.

SRR: the first magnetic metamaterials



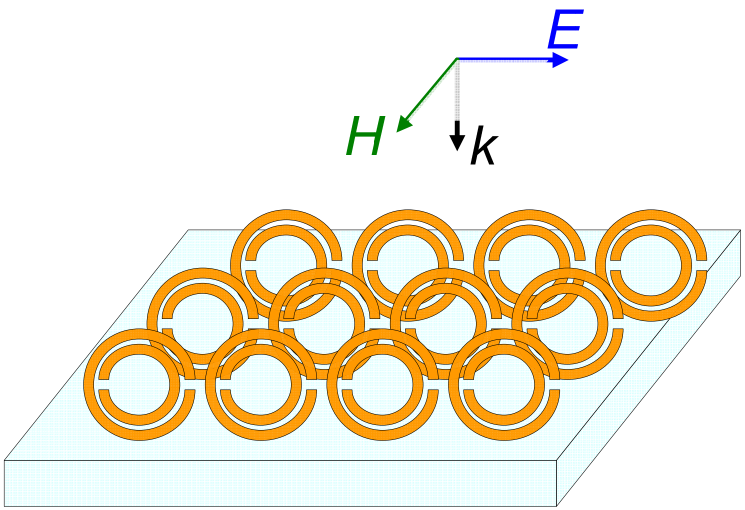
Split-ring resonator (SRR)



Theory: Pendry et al., 1999.

Experiment: Smith et al., 2000.

SRR towards high frequency



The standard configuration of SRR

Fabrication for microwave: Printed circuit board (PCB)

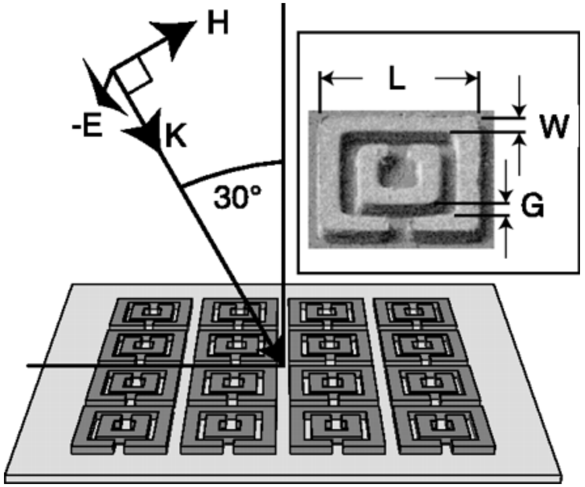
Fabrication for optics: not feasible by lithography (a layer by layer fashion)

Attempt #1 of SRR towards optics:

Planar SRR and inclined incidence

A small portion of H penetrates the SRRs

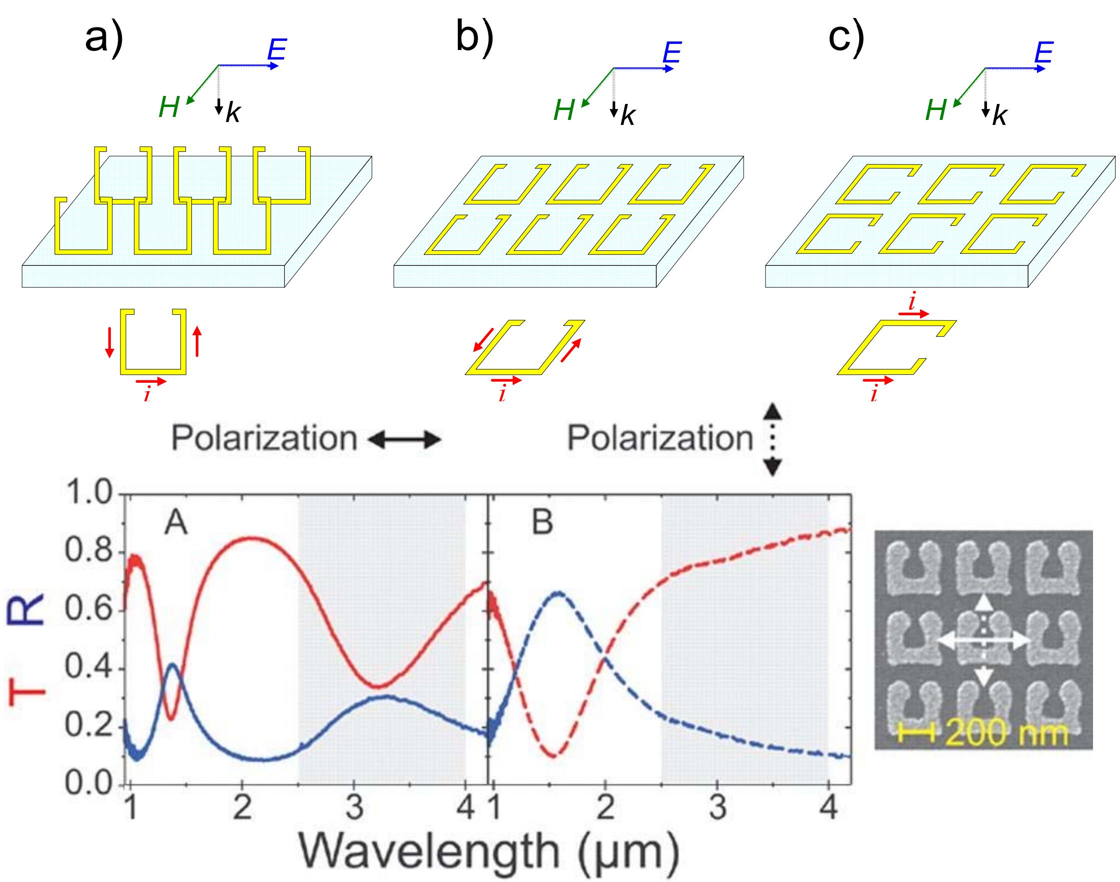
Yen et al., 1 THz magnetism, 2004



Magnetic effect from electrical field

Attempt #2 of SRR towards optics:

Electric coupling to magnetic resonance in planar SRR at normal incidence



(a) Standard SRR with $H \perp$ SRR
Pendry et al., proposed in 1999

(b) Electric coupling to magnetic resonance in plane SRR
Soukoulis et al., proposed in 2004

(c) No magnetic resonance

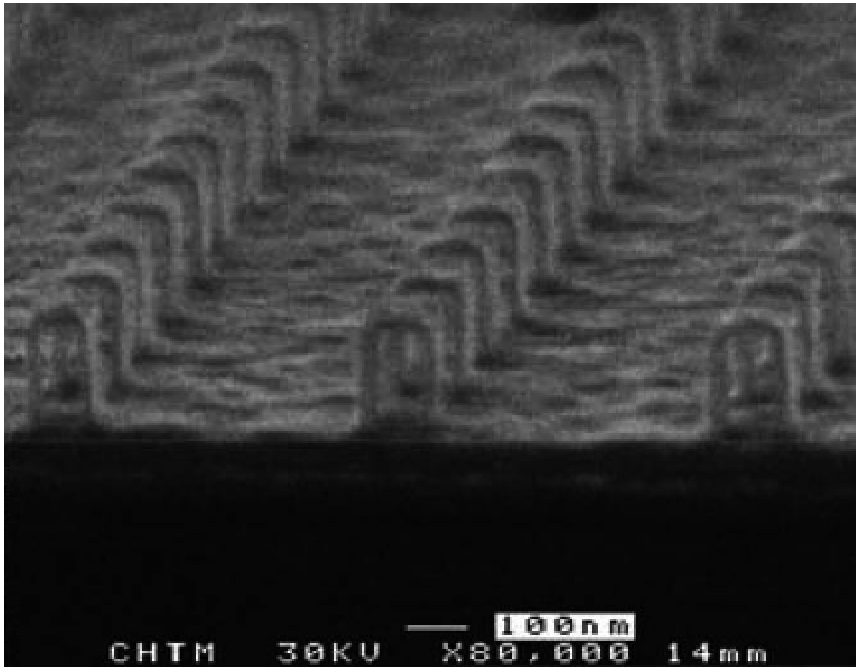
The magnetic response is relatively weak due to indirect excitation.

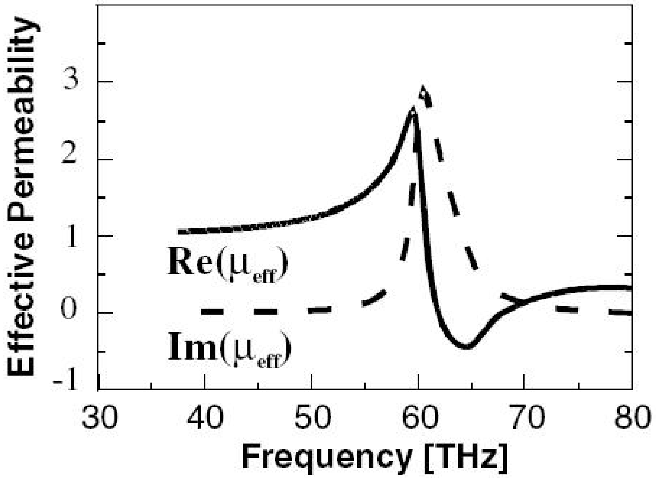
Linden et al., ~ 100 THz magnetism, 2004
Enkrich et al., ~ 200 THz magnetism, 2005 (u-shaped)

"Magnetic staples"

Attempt #3 of SRR towards optics:

Advanced technique to fabricate "standing" structure similar to SRR (H-excited)





Structures stand on substrate.

Zhang et al., U. New Mexico, 65 THz magnetism, 2005

Limits of size scaling in SRRs

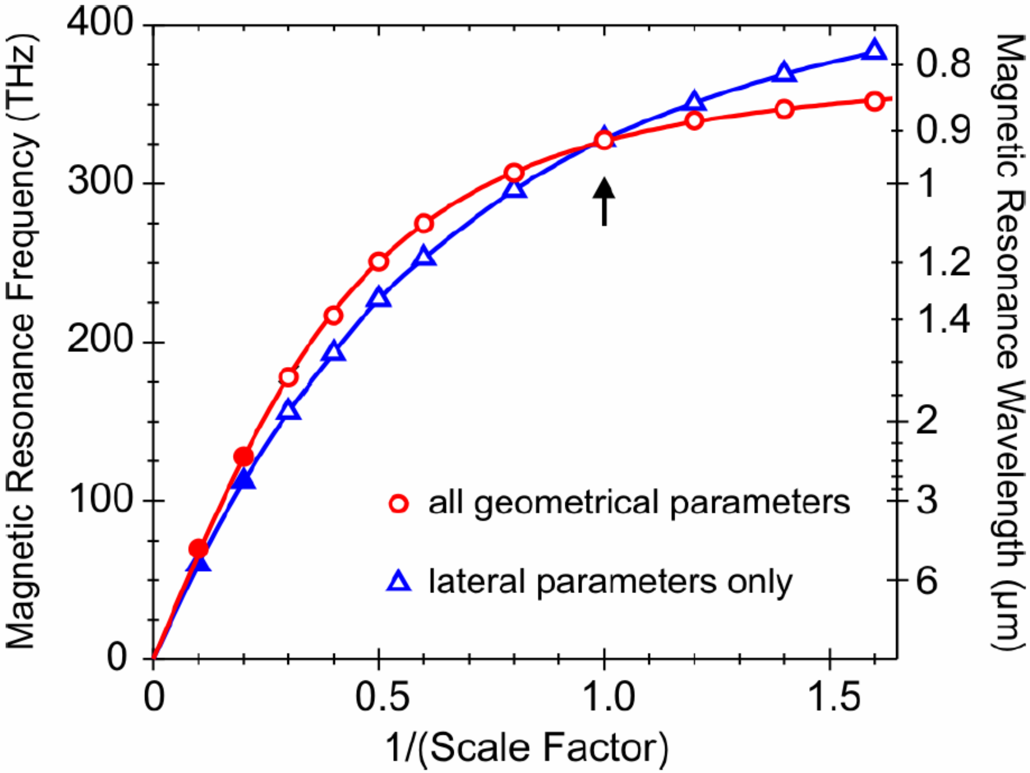
Direct scaling-down the SRR dimensions doesn't help much…

Loss in metal gives kinetic inductance

$$L_{coil} \propto size \qquad L_{kinetic} \propto \frac{1}{size}$$

$$L_{total} = L_{coil} + L_{kinetic}$$

$$C_{total} \propto size$$

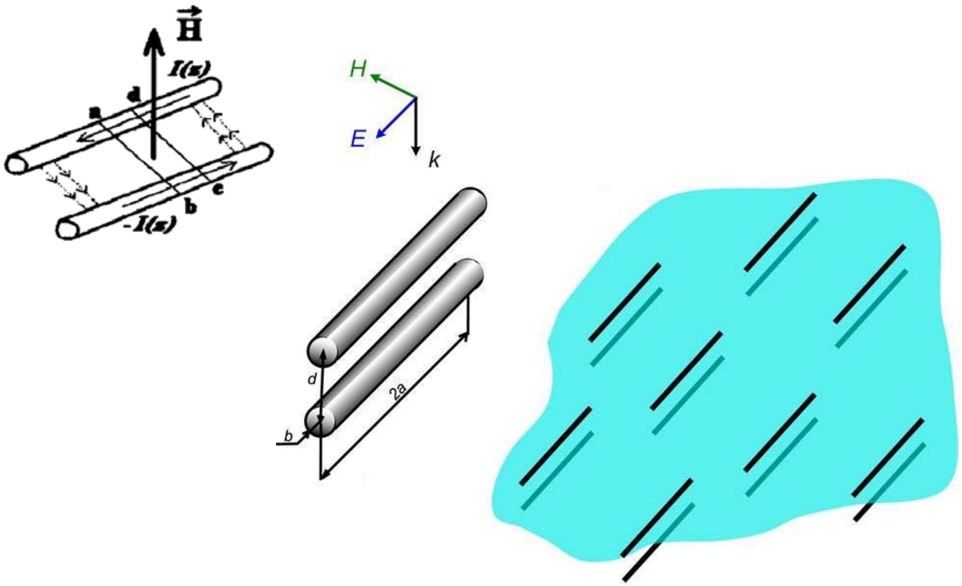


$$\omega_{res} \propto \frac{1}{\sqrt{L_{total} \times C_{total}}} = \frac{1}{\sqrt{(A \cdot size + B / size) \cdot (C \cdot size)}} \propto \frac{1}{\sqrt{size^2 + const.}}$$

Saturation

Klein, et al., OL, 2006

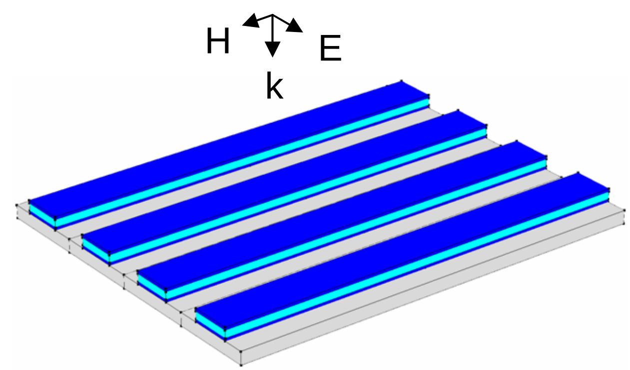
Design of optical magnetic metamaterial
excited by H field directly



Paired nanorods:

Currents in a pair of rods excited by an external magnetic field H. The displacement currents "closes" the loop in the rods.

Proposed by Podolskiy, Sarychev, & Shalaev, 2002



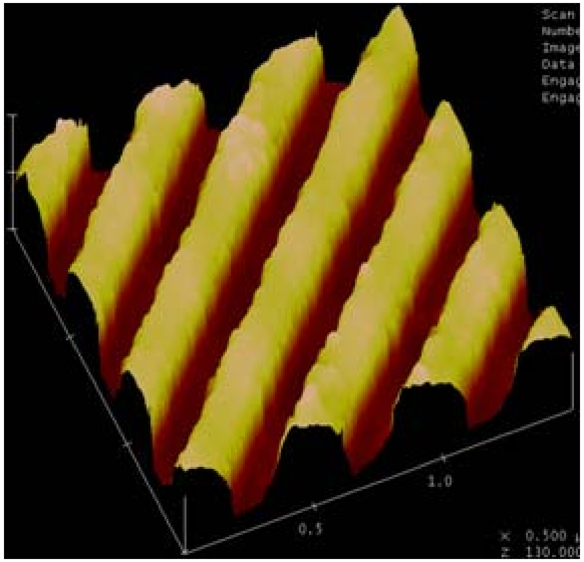
Paired nano-strips:

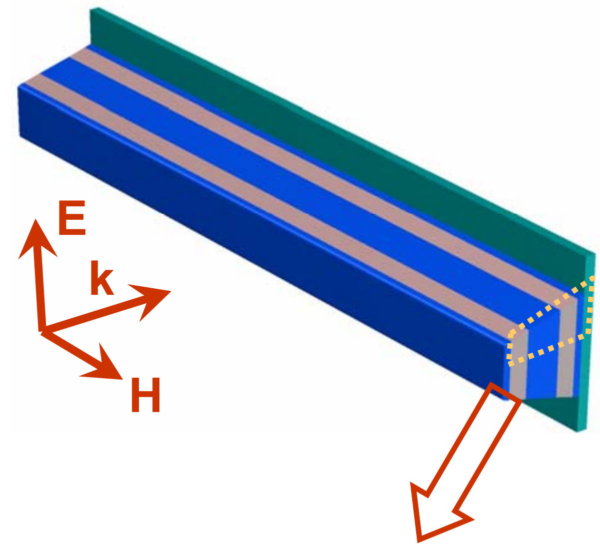
The two-dimensional version of the nanorods system.

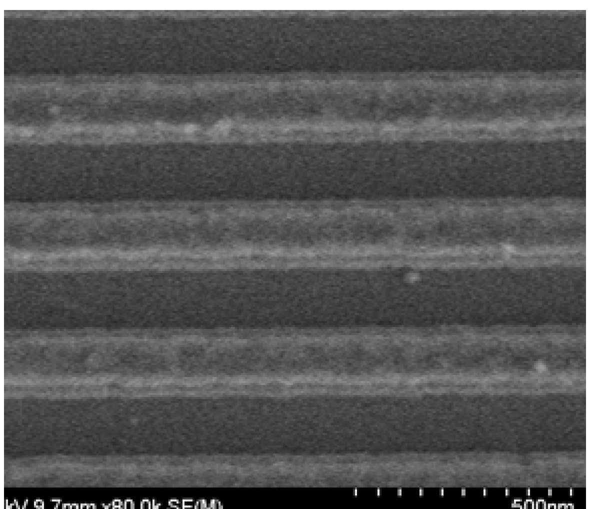
Proposed by Kildishev, et al., Purdue Group, 2005

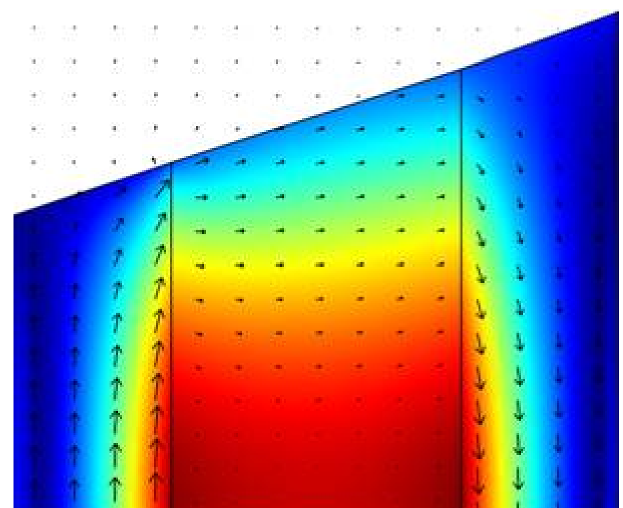
Note: these two systems can support both electrical resonance and magnetic resonance, which may result in a negative n with relatively low magnitude (but there are some difficulties)

Paired nano-strips: a close look

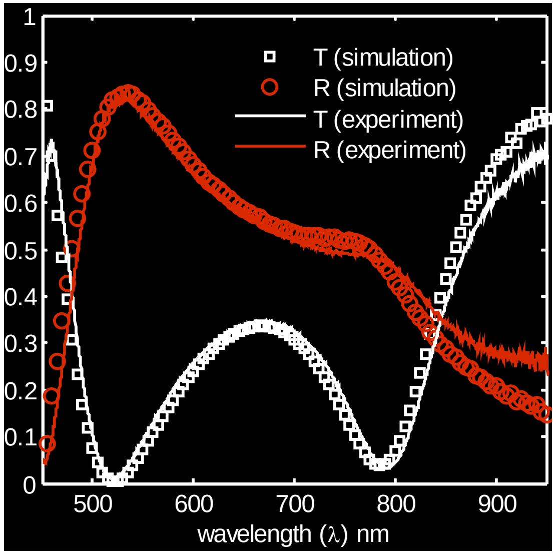


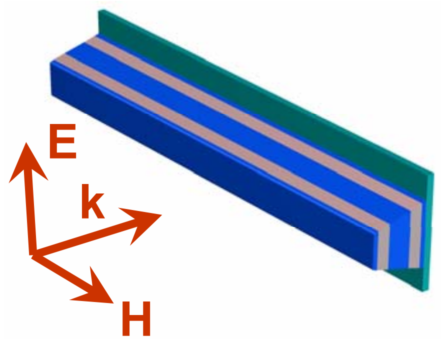




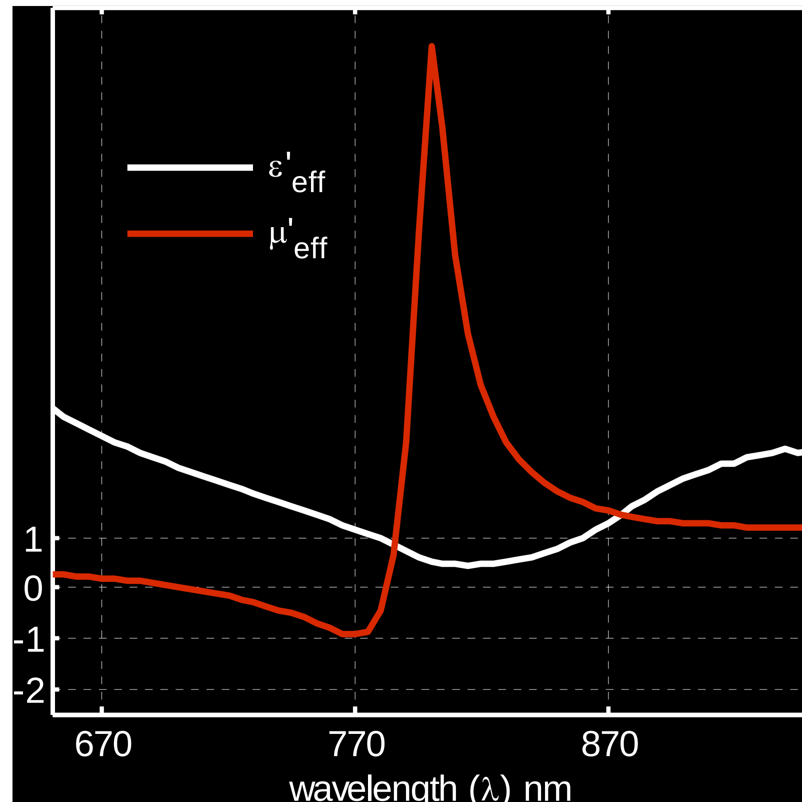


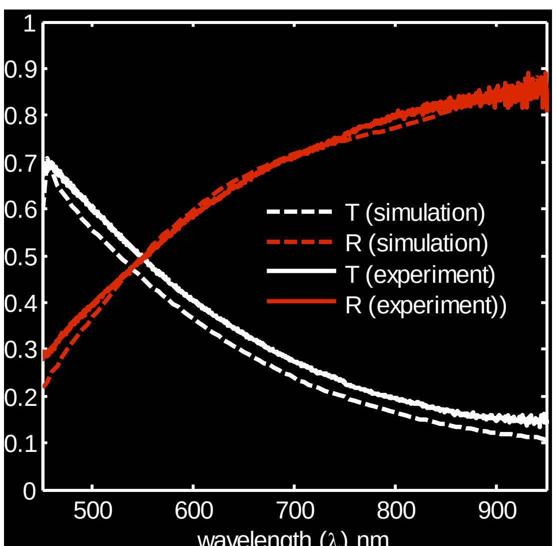
Negative magnetism in the visible

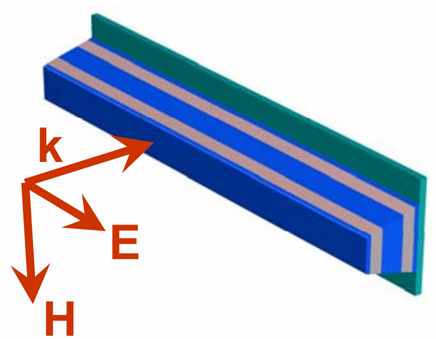




$\mu' = -1$, $\lambda = 770$ nm







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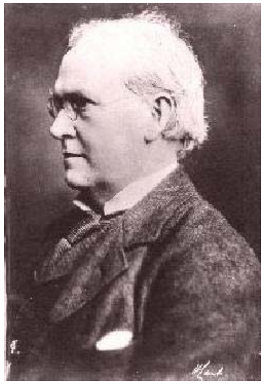
Negative refractive index: A historical review


Sir Arthur Schuster


Sir Horace Lamb

… energy can be carried forward at the group velocity but in a direction that is anti-parallel to the phase velocity…
Schuster, 1904

Negative refraction and backward propagation of waves
Mandel'stam, 1945


L. I. Mandel'stam


V. G. Veselago

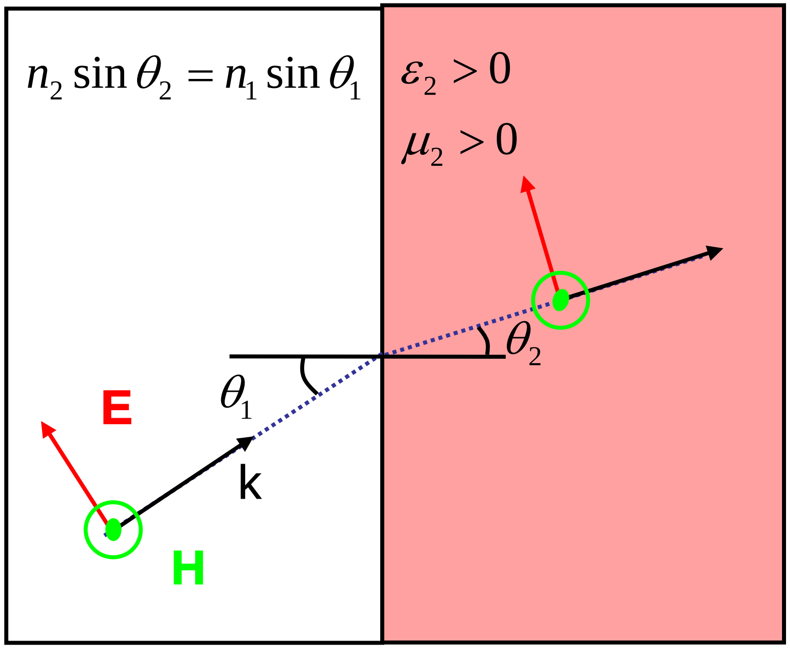
Left-handed materials: the electrodynamics of substances with simultaneously negative values of ε and μ
Veselago, 1968

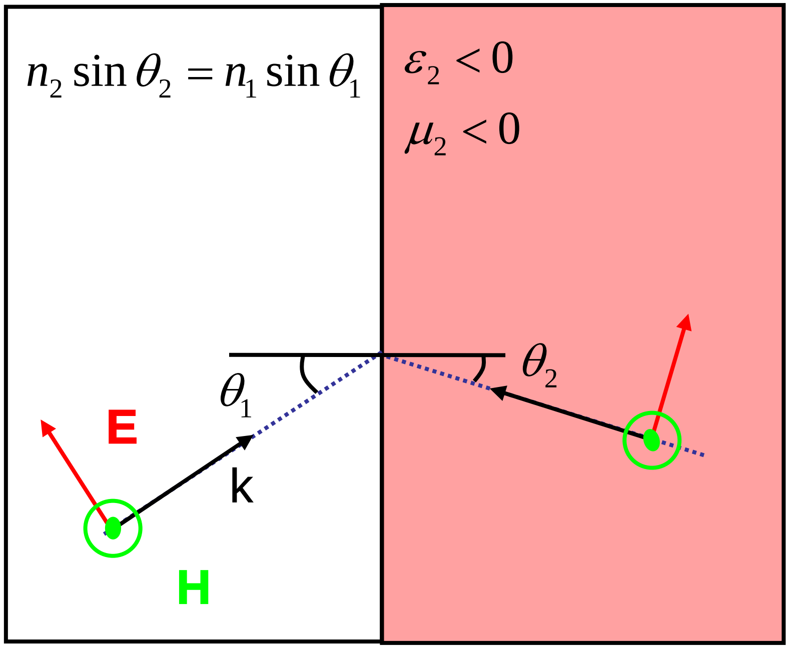
Pendry, the one who whipped up the recent boom of NIM researches

Low frequency plasmonic structure (1996)
High frequency magnetic structure (1999)
Perfect lens (2000)
Optical cloaking (2006)


Sir John Pendry

Refraction in Right and Left-Handed Media



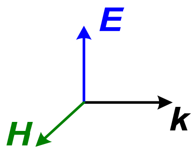


Energy propagation $\qquad \mathbf{S} = \frac{c}{4\pi}[\mathbf{EH}] \qquad$ **Energy propagation**

$$\begin{cases} \vec{k} \times \vec{H} = -\omega\varepsilon_0\varepsilon\vec{E} \\ \vec{k} \times \vec{E} = \omega\mu_0\mu\vec{H} \end{cases}$$

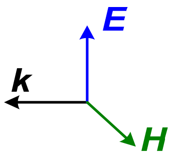
$$n = \pm\sqrt{\varepsilon\,\mu}$$

PIM



→ $S = E \times H$

NIM

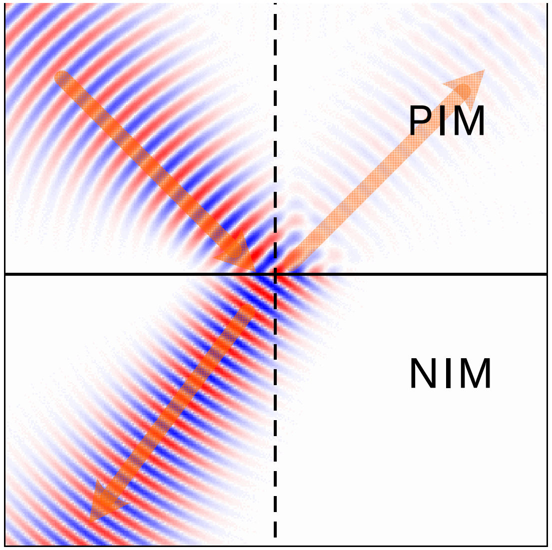


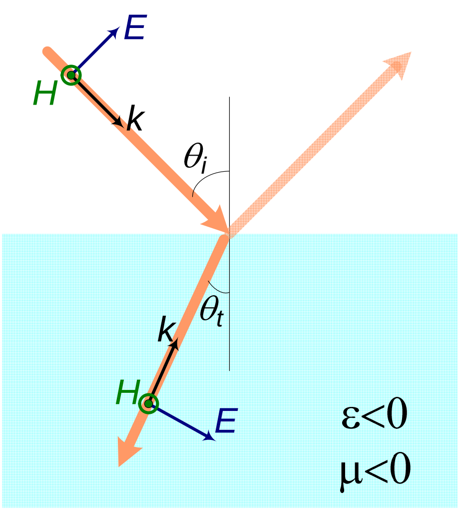
→ $S = E \times H$

- **Inverse Doppler effect**
- **Inverse Snell law**
- **Inverse Cerenkov effect**
- **Inverse Light pressure**
- **…**

Physics of Negative Index Materials

Phase reversal in NIMs





Dispersion and dissipation in NIMs

Energy density:

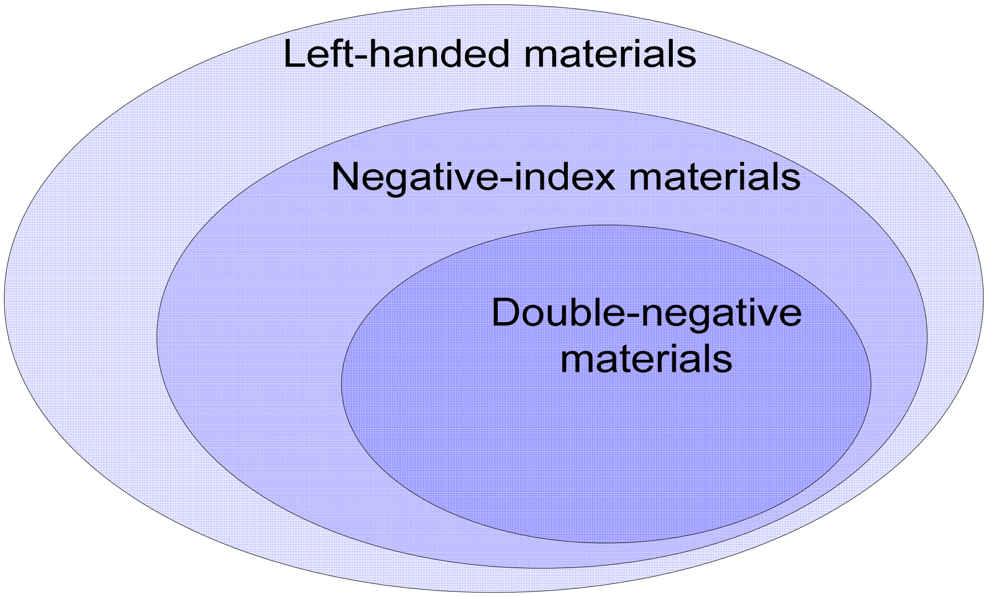
$$W = \frac{\partial(\varepsilon\omega)}{\partial\omega} E^2 + \frac{\partial(\mu\omega)}{\partial\omega} H^2$$

Therefore

$$\frac{\partial(\varepsilon\omega)}{\partial\omega} > 0\,; \qquad \frac{\partial(\mu\omega)}{\partial\omega} > 0$$

NIM is always dispersive and dissipative

Terminology — Similar names



$$\varepsilon = \varepsilon' + i\varepsilon'' \qquad \mu = \mu' + i\mu''$$

$$n = n' + in'' = \sqrt{\varepsilon\mu}$$

$$\varepsilon'|\mu| + \mu'|\varepsilon| < 0 \longrightarrow n' < 0$$

Left-handed material (LHM): *the anti-parallel relation between k and S. This may happen in photonic crystals or waveguide structures where the properties are typically not described by n (also could be confused with "chiral" optics)*

Negative-index material (NIM): *the negative value of refractive index.*

Double-negative material (DNM): *both ε' and μ' are negative. This is the sufficient (not necessary) condition for a NIM.*