Physics and Applications of Negatively Refracting Electromagnetic Materials

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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
\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \]

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

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

Flat 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 $\varepsilon$ and $\mu$

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

$\Rightarrow$ Negative index of refraction! Many optical properties are reversed!

**Propagating Waves**

- **RHM**
- **LHM**

**Non-propagating Waves**

**Ordinary Refraction**

**Negative Refraction**
Negative Refraction: Consequences

Left-Handed or Negative Index of Refraction Metamaterials

\[ \varepsilon < 0 \text{ AND } \mu < 0 \]  
\text{Veselago, 1967}

Propagating waves have index of refraction \( n < 0 \)

\[ \Rightarrow \text{Phase velocity is opposite to Poynting vector direction} \]

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)

Converging Lens → Diverging Lens
and vice-versa

Reverse Doppler Effect
Reversed Čerenkov Effect

Radiation Tension

Flat Lens Imaging

How to make a Negative Dielectric Constant

The dielectric constant is

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

\(\omega_p\) = plasma frequency

\(n_{\text{eff}}\) = electron concentration

\(\omega = \frac{n_{\text{eff}} e^2}{\varepsilon_0 m_{\text{eff}}}\)

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

Strategy to decrease the plasma frequency

⇒ Thin wire lattice
Decrease \(n_{\text{eff}}\) and increase \(m_{\text{eff}}\)

with \(a = 5\) mm and \(r = 1\) μm,

\(f_p = \frac{\omega_p}{2\pi} = 8.20\) GHz
Metamaterial vs Photonic Crystal

Create an “effective medium” with macroscopic $\varepsilon_{\text{eff}}$, $\mu_{\text{eff}}$, $n$ properties that are engineered

Use constructive and destructive interference to engineer properties of light $\rightarrow \omega(\vec{k})$
- band structure
- band gaps
- defect states
- negative group velocity …
How to Make Negative Permeability

Magnetic Permeability \( \mu = \mu_r \mu_0 \)

\[ \vec{M} = \chi_{\text{magnetic}} \vec{H} \]

\[ \mu = \mu_0(1 + \chi_{\text{magnetic}}) \]

A closed ring is diamagnetic (Lenz’s Law)

Enhance \( \chi_{\text{magnetic}} \) 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 $\mu_{\text{eff}} < 0$

SRR $\mu_{\text{eff}}$

region of $\mu_{\text{eff}} < 0$

Jelly Roll SRR

Resonance $\sim$21 MHz

Planar SRR

Resonance $\sim$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:
- $\varepsilon_{\text{eff}} < 0$ accomplished by Pendry, et al. (1998)
- $\mu_{\text{eff}} < 0$ accomplished by Pendry, et al. (1999)
  using split-ring resonators (SRR)
- $\varepsilon_{\text{eff}} < 0 \ AND \ \mu_{\text{eff}} < 0$ done by D. R. Smith, et al., PRL 84, 4184 (2000)
  using wires and SRRs

Applications: Now Emerging!
Metamaterials: Realizations


Refraction experiment from a prism

Teflon prism

LHM prism

normal

prism

incident beam

10.5 GHz
Evanescent Excitations

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

Optically less-dense material \[ \rightarrow \] Evanescent signal

Optically dense material

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 < \( \lambda \)

Parimi (2003)

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

Cubukcu (2003)

13.7 GHz

FWHM = \( \lambda/5 \)

with lens

w/o lens
Thin SubWavelength Cavity Resonators (Engheta, 2002)

For a resonance in the $z$-direction:

New possibility – zero net phase winding

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

$p = 0$ “zeroth order resonance”

$0^{th}$ resonance condition independent 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

Microstrip Resonators

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

Scher, et al., 2004
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
Super-Efficient Electrically-small Dipole Antenna ($\ell \ll \lambda$)

\[
\frac{X_{Ant}}{R_{Rad}} = \left( \frac{\lambda}{\pi \ell} \right)^3 + \frac{1}{2} \left( \frac{1}{\pi \ell} \right)^3
\]

LHM shell compensates $\text{Im}[Z_{Ant}]$

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

Ziolkowski (2003)

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

Wu, et al., 2003

Nano-Scale

Split Ring Resonators

$\mu_{\text{eff}} < 0$ for 81 – 87 THz

Linden, et al., 2004

$\mu_{\text{eff}} < 0$ for 180 THz (1.67 $\mu$m)

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)

Glass
Gold

n < 0 behavior washed out by high losses
Im[μ_eff] ~ 1

Demonstration of μ_eff > 1 in optics

Impedance Matching

An Important Limitation: Losses

Negative Permittivity

Operate just below $\omega_{\text{plasma}}$ to minimize loss

$$\frac{\varepsilon_{\text{eff}}}{\varepsilon_0} = 1 - \frac{\omega^2}{\omega(\omega + i\gamma)}$$

Transfer Function of a Flat Lens

$$\omega_0 = 2\pi 10 \text{GHz}$$
Superconducting Metamaterials

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

Holey X-Band Niobium Wires
Radius~.0125mm
10 Cells (50.8mm)

Nb film, ~200 nm thick

All-Nb X-band waveguide + couplers

Niobium Wires
Radius~.0125mm

Holey X-Band
Negative Index Passband with a Superconducting All-Nb Metamaterial
Elementary NIR Material:
Single SRR in a 5 x 7 Nb Wire Array

\[ |S_{21}| \text{ (dB)} \]

\[ \varepsilon < 0 \text{ and } \mu < 0 \]

Frequency (GHz)
Caveats and Some Issues to be Addressed

Negative Index behavior is limited to finite frequency ranges

\[
\frac{d(\omega n(\omega))}{d\omega} > 1
\]

Causality constraint: For \(\text{Im}[\varepsilon] \ll 1\), Smith, Kroll (2000)

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

Losses limit frequency range of \(\varepsilon_{\text{eff}} < 0\) and \(\mu_{\text{eff}} < 0\)

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

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