Optical metamaterials: Possibilities and limitations

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Metamaterials

Artificial, structured (in sub-wavelength scale) materials

Electromagnetic (EM) properties derive from shape and distribution of constituent units (artificial atoms)

EM properties not-encountered in natural materials

Possibility to engineer electromagnetic properties
Negative electrical permittivity ($\varepsilon$)
Negative magnetic permeability ($\mu$)

Veselago (1968): How a plane wave $e^{ikx}$ propagates in media with $\varepsilon<0$ & $\mu<0$?

$$k = \frac{\omega}{c} \sqrt{\varepsilon \mu}$$

$$n^2 = \varepsilon \mu \Rightarrow n = -\sqrt{\varepsilon \mu}$$

Novel and unique propagation characteristics in those materials!
Novel phenomena in left-handed materials

Backwards propagation (opposite phase & energy velocity)

\[ k \times E = \frac{\omega}{c} \mu H \]
\[ S = E \times H \]

Negative refraction

\[ \sin \theta_2 = \frac{n_1}{n_2} \sin \theta_1 \]

Flat lenses - “Perfect” lenses (subwavelength resolution)

- Zero-reflection possibility
- Opposite Doppler effect
- Opposite Cherenkov radiation
- ……

- Interesting physical system
- New possibilities for light manipulation → important potential applications
Application areas of left-handed materials

New solutions and possibilities in

- Imaging/microscopy
- Lithography
- Data storage
- Communications and information processing (subwavelength guides, optimized/miniatuized antennas & filters, improved transmission lines ...)

Exploiting the subwavelength resolution capabilities of LHMs

The “trapped rainbow”

Tsakmakidis et al., Nature 450, 397 (2007)
Metamaterials beyond negative index

- High index metamaterials
- Shrinkage of devices
- Low index metamaterials
- Cloaking
- Parallel beam formation

Pendry et. al., Science 312, 1781 (2006)
“Zero”-index metamaterials

Parallel beam formation

0 = n_1 \sin \theta_1 = n_2 \sin \theta_2

All the angles \theta_2 should be zero, and therefore perpendicular to the surface
Metamaterials beyond negative index

- High index metamaterials
- Shrinkage of devices
- Cloaking
- Low index metamaterials
- Parallel beam formation
- Indefinite media
- Hyperlensing
- Single-negative media
- Bi-anisotropic media

Pendry et. al., Science 312, 1781 (2006)
Most common approach: Merging structures of negative permittivity ($\varepsilon$) with structures of negative permeability ($\mu$)

Negative permeability: Structures of resonant loop-currents

Negative permittivity: Continuous wires

Split Ring Resonator (SRR), Pendry, 1999

Short-slabs-pair, Shalaev, 2002

$$\omega_m = \frac{1}{\sqrt{LC}}$$
• Analyze, understand, optimize and tailor metamaterial response
• Achieve optical metamaterials – reduce losses in metamaterials
• Achieve three-dimensional isotropic left-handed metamaterials
• Create switchable and tunable metamaterials
• Devise/analyze new designs and approaches for negative index behaviour (chiral or anisotropic metamaterials)
• To explore novel phenomena and possibilities in metamaterials
Main investigation aims/directions

- Analyze, understand, optimize and tailor metamaterial response

- **Achieve optical metamaterials – reduce losses in metamaterials**

- Achieve three-dimensional isotropic left-handed metamaterials

- Create switchable and tunable metamaterials

- Devise/analyze new designs and approaches for negative index behaviour (chiral or anisotropic metamaterials)

- To explore novel phenomena and possibilities in metamaterials
To achieve optical left-handed materials?

Scaling down of structures demonstrated initially in microwaves or THz

Metal response is not scalable up to optical regime

Examination mainly of the negative permeability components
Slab-pair: more suitable than SRR in sub-micron scale

- Magnetic response for normal incidence $\Rightarrow$ exploitation in “small” length scales
- Simplified and easy in fabrication

Examples of slab-pair based left-handed materials

Slabs & wires

Slabs & wires connected

Fishnet design

Fishnet (wide-slabs & connected with wires): Optimized design for left-handed behavior

Ulrich (1966)
Negative $n$ towards visible

Fore review, see:
• Soukoulis et al., Science 315 (2007)
• Shalaev, Nat. Mat. (2007)

Leading efforts by
• Karlsruhe
• Purdue
• Stuttgart
• Berkeley
• ....

Lowest losses
(Re($n$)/Im($n$)=3)

High losses
Single functional layer

Zhang et. al., PRL (2005)


Karlsruhe
1.4 μm

N. Mexico
2 μm


Chettiar et. al., MRS Bul. (2008)
Optical metamaterials: Problems/challenges

High losses

Limited fabrication capabilities

Current procedures:
• difficult/time-consuming
• expensive
• unable to produce
- complicated patterns
- large samples
- 3D isotropic designs
Optical metamaterials: Facing the challenges

High losses

• Analysis & design optimization
• “Good” constituent media
• Gain media?
• Novel approaches (anisotropic media, chiral media, EIT)

Limited fabrication capabilities

Current procedures:
• difficult/time-consuming
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• Advancement of fabrication procedures
• New fabrication methods (direct laser writing, nanoimprint lithography)
• New designs/approaches, adapted to fabrication capabilities
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- **High losses**

- **Analysis & design optimization**
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- **Limited fabrication capabilities**
  - **Current procedures:**
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- **Advancement of fabrication procedures**
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**Aim**

Examine the behavior of the designs as they are scaled down targeting **optical negative index response**

Seek for optimization rules
Slab-pair magnetic response

\[ L\dot{I} + \frac{1}{C} \int I dt + RI = -\dot{\phi} \]

\[ \mu(\omega) = 1 - \frac{F \omega^2}{\omega^2 - \omega_m^2 + i\omega\gamma} \]

\[ \omega_m = \frac{1}{\sqrt{LC}} \]

\[ \gamma = \frac{R}{L} \]

\[ \omega'_m = \frac{\omega_m}{\sqrt{1 - F}} \]

\[ F \sim \text{volume fraction of the resonator within unit cell} \]

\( F \) determines:
- Width of negative \( \mu \) regime
- Strength of resonance

\[ \gamma \text{ (loss factor) determines:} \]
- Strength of resonance \( \omega'_m = \frac{1}{\sqrt{LC}} \sim \frac{1}{a} \)

For uniform scaling:
\( C \propto a \quad L \propto a \)

\[ \frac{\omega'_m - \omega_m}{\omega_m} = \frac{1}{\sqrt{1 - F}} - 1 \]
Magnetic resonance frequency vs length scale

Al metal, Glass substrate

Saturation value independent of ohmic losses

Saturation value depends on design

Saturation of magnetic resonance frequency in small length scales ($a<500$ nm)

Magnetic permeability by scaling down the structures

Al metal
Glass substrate

Reducing size

Weakening of magnetic resonance at small scales
μ ultimately does not reach negative values

Spectral width of negative $\mu$ regime

$\frac{\Delta \omega}{\omega_{\text{min}}}$: constant at larger scales
tends to zero for smaller scales

Spectral width only slightly affected by metal loss

Losses by scaling down the structures

Loss per unit cell

Wide cut-slabs

320nm
160nm
106.6nm
80nm
64nm
40nm
32nm
24nm
16nm

Frequency[THz]

0 100 200 300 400 500 600 700

Reducing size

Loss = 1 − R − T

Increase of losses going to smaller scale

Explaining $\omega_m$ saturation and $\mu$-strength reduction

Consideration of metal dispersive response in the conductivity:

$$\sigma = i\varepsilon_0 \frac{\omega_p^2}{\omega + i\gamma_m}$$

$$R_{tot} = \frac{1}{\sigma} \frac{l}{S} = \frac{\gamma_m}{\varepsilon_0 \omega_p^2} \frac{l}{S} - i\omega \frac{1}{\varepsilon_0 \omega_p^2} \frac{l}{S} = R - i\omega L_e$$

$\omega_p =$ metal plasma frequency

$\gamma_m =$ metal collision frequency

Inductive term (electrons inductance) due to electrons inertia

("Difficulty" to accelerate finite mass particles with such high rates)

$$E_{\text{kinetic}} = \frac{1}{2} L_e I^2$$

$$m\frac{dv}{dt} + \gamma_m v = qE$$
Slab-pair effective permeability in sub-μm scale

$L_e$ is added to $L$ in the effective circuit equation:

$$(L + L_e)\dot{I} + (1/C)\int I dt + RI = -\phi$$

$$\mu(\omega) = 1 - \frac{F'\omega^2}{\omega^2 - \omega_m'^2 + i\omega\gamma'}$$

$F' \sim$ volume fraction of the resonator within unit cell

For uniform scaling:

$$L_e \sim \frac{1}{a} \quad R \sim \frac{1}{a}$$

$$L \sim a \quad C \sim a$$

$a$: lattice constant
Explaining the observed response

Magnetic resonance frequency saturates to $\omega_{m\text{-max}}$
- dependent on shape
- independent of ohmic losses
- proportional to metal plasma frequency

Strength parameter $F'$ becomes proportional to area $\rightarrow$ Vanishing of negative $\mu$ regime even if the absence of ohmic losses

Loss parameter increases for small length scales;
- $\gamma'$ depends on shape
- it saturates to metal collision frequency

\[
L \propto a, \quad C \propto a, \quad L_e \propto 1/a, \quad R \propto 1/a
\]
\[
a: \text{ u.c. size}
\]
\[
\omega'_m = \frac{1}{\sqrt{(L+L_e)C}} \sim \frac{1}{\sqrt{a^2 + c_1}} \rightarrow \text{const.}
\]
\[
F' = F \frac{L}{L + L_e} \rightarrow F \frac{a^2}{a^2 + 1}
\]
\[
\gamma' = \frac{R}{L + L_e} = \frac{\gamma_m}{1 + L / L_e} \rightarrow \frac{\gamma_m}{1 + a^2}
\]

For high frequency magnetic metamaterials

For high frequency magnetic metamaterials

\[ F' = F \frac{1}{1 + L_e / L} \]

\[ \omega_m = \frac{1}{\sqrt{(L + L_e)C}} \]

\[ \mu = \mu_0 [1 - \frac{F' \omega^2}{\omega^2 - \omega_m^2 + i \omega \gamma'}] \]

Requirements

- Small capacitance, \( C \)
- Small \( L_e \)
- Large metal plasma frequency – small collision frequency
- \( L? \): opposite role in \( \omega_m \) and \( \mu \)

Electrons inductance at the electric dipole resonance: Resonance frequency

\[ \varepsilon(\omega) = 1 - \frac{\omega^2_{pe}}{\omega^2 - \omega^2_e + i\omega\gamma} \]

\[ \omega_e = \frac{1}{\sqrt{(L+L_e)C}} \sim \frac{1}{\sqrt{a^2 + c_1}} \rightarrow \text{const.} \]

\[ C, L \sim a, \quad R, L_e \sim 1/a \]
Electrons inductance at the electric dipole resonance: Resonance strength

\[ \varepsilon(\omega) = 1 - \frac{\omega^2_{pe}}{\omega^2 - \omega^2_e + i\omega\gamma} \]

\[ \omega^2_{pe} = \frac{l^2}{\varepsilon_0 V_{uc}} \frac{1}{L + L_e} \sim \frac{1}{a^2 + c^2} \rightarrow \text{const.} \neq 0 \]

No vanishing resonance strength

\[ C, L \sim a, \quad R, L_e \sim 1/a \]

\[ (L + L_e) \frac{d^2 Q}{dt^2} + \frac{Q}{C} + R \frac{dQ}{dt} = E_0 e^{-i\omega t} \]
Electrons inductance at the electric dipole resonance features?

\[
(\mathcal{L} + L_e) \frac{d^2 Q}{dt^2} + \frac{Q}{C} + R \frac{dQ}{dt} = E_0 l e^{-i\omega t}
\]

\[
\varepsilon(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_e^2 + i\omega\gamma}
\]

\[
\omega_e = \frac{1}{\sqrt{(\mathcal{L} + L_e)C}} \sim \frac{1}{\sqrt{a^2 + c_1}} \rightarrow \text{const.}
\]

Saturation

No vanishing resonance strength

\[
\omega_{pe}^2 = \frac{l^2}{\varepsilon_0 V_{uc}} \frac{1}{L + L_e} \sim \frac{1}{a^2 + c_2} \rightarrow \text{const.} \neq 0
\]

Spectral width of negative \( \varepsilon \): independent of \( L_e \) and length-scale
Optical metamaterials: Facing the challenges

High losses

• Analysis & design optimization
• “Good” constituent media
• Gain media?
• Novel approaches (anisotropic media, chiral media, EIT)

Limited fabrication capabilities

Current procedures:
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• New designs/approaches, adapted to fabrication capabilities
“Connected” structures for direct laser writing

Gold in polyimide

\[
\text{Re}(n) / \text{Im}(n) \mid_{n=-1} = 5
\]

Double negative @ ~200 THz (1.5 μm)

Calculations by D. Guney

“Connected” structure realization

M.Wegener’s group, Karlsruhe
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Negative refractive index in chiral media

Chiral structure: not-identical to its mirror image

- Different index for left- and right-handed circularly polarized waves

\[ n_{\pm} = \sqrt{\varepsilon \mu \pm \kappa} \]

- Alternative path to achieve negative index (Pendry, Tretyakov)

\[ D = \varepsilon E + i\kappa H \]
\[ B = \mu H - i\kappa E \]

Besides negative index:
- Polarization rotation
- Circular dichroism


Negative index
Large polarization rotation
Large circular dichroism
Chiral optical structures

Twisted gold crosses

Response @ 1-2 μm

Large polarization rotation
Large circular dichroism

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**Superlenses for anisotropic media?**

**Perfect lensing conditions:**

**Propagating components:**
Omnidirectional total transmission

**Evanescent components:**
Excitation of dispersionless surface plasmon modes

**Aim:** Examine these conditions for anisotropic materials

\[
\varepsilon_2 = \begin{bmatrix}
\varepsilon_{2x} & 0 & 0 \\
0 & \varepsilon_{2y} & 0 \\
0 & 0 & \varepsilon_{2z}
\end{bmatrix},
\mu_2 = \begin{bmatrix}
\mu_{2x} & 0 & 0 \\
0 & \mu_{2y} & 0 \\
0 & 0 & \mu_{2z}
\end{bmatrix}
\]

Work done by N.H. Shen
Superlensing conditions for anisotropic media

For p-polarization

\[
\frac{\mathcal{E}_{2x}}{\mathcal{E}_{1}} = \frac{\mathcal{E}_{1}}{\mathcal{E}_{1}}
\]

\[
\frac{\mathcal{\mu}_{2y}}{\mathcal{\mu}_{1}} = \frac{\mathcal{\mu}_{1}}{\mathcal{\mu}_{1}}
\]

For isotropic media:

\[
\mathcal{E}_{2x}\mathcal{E}_{2z} = \mathcal{E}_{1}^{2}
\]

\[
\mathcal{E}_{2} = -\mathcal{E}_{1}, \quad \mathcal{\mu}_{2} = -\mathcal{\mu}_{1}
\]

\[
\mathcal{E}_{2x}, \mathcal{E}_{2z}, \mathcal{\mu}_{2y} < 0
\]

Easy to implement conditions with planar technologies
Lens formula for anisotropic lenses

\[ d_{\text{Source}} + d_{\text{Image}} = \left( \frac{\varepsilon_{2x}}{\varepsilon_1} \right) d \]

Isotropic lens: \[ d_{\text{Source}} + d_{\text{Image}} = d \]

Possibility for thin lenses! (less influenced by losses)
Anisotropic “perfect” lens: Negative refraction & focusing

Negative refraction by an anisotropic double negative slab

Focusing in an anisotropic double negative slab

\[ \varepsilon_{2x} = \mu_{2y} = -2 + 0.01i, \quad \varepsilon_{2z} = -0.5 + 0.01i \]

\[ d = 0.2\lambda \quad \text{resolution} = \lambda / 5 \]
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High losses

Limited fabrication capabilities

A research field of many exciting possibilities

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Relevant publications


