Optical metamaterials: Possibilities and limitations

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*Mesosopic Physics
in Complex Media
Cargese, July 2010*

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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

EM properties

ϵ

**Electrical
permittivity**

μ

**Magnetic
permeability**

Possibility to engineer electromagnetic properties

Left-handed metamaterials

Negative electrical permittivity (ϵ)
Negative magnetic permeability (μ)

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

Sov. Phys. Usp. 10, 509 (1968)

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

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

Negative ϵ , μ , n

**Novel and unique propagation
characteristics in those materials!**

Novel phenomena in left-handed materials

Backwards propagation
(opposite phase & energy velocity)

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/miniaturized 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

Pendry et. al., Science 312, 1781 (2006)

Parallel beam formation

“Zero”-index metamaterials

Parallel beam formation

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

All the angles θ_2 should be zero, and therefore perpendicular to the surface

Metamaterials beyond negative index

High index metamaterials

Shrinkage of devices

Low index metamaterials

Cloaking

Pendry et. al., Science 312, 1781 (2006)

Parallel beam formation

Indefinite media

Hyperlensing

Single-negative media

Bi-anisotropic media

Designing left-handed metamaterials

Most common approach: Merging structures of negative permittivity (ϵ) with structures of negative permeability (μ)

Negative permeability:
Structures of resonant loop-currents

Negative permittivity:
Continuous wires

Split Ring Resonator (SRR), Pendry, 1999

Short-slabs-pair, Shalaev, 2002

$$\omega_m = 1 / \sqrt{LC}$$

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**

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

Shalaev et. al., Opt. Lett. **30**, 3356 (2005)

Examples of slab-pair based left-handed materials

Slabs & wires

Slabs & wires
connected

Fishnet design

Zhang, et. al., Opt. Expr. (2005)

Ulrich (1966)

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

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

($\text{Re}(n)/\text{Im}(n)=3$)

Zhang et. al., PRL (2005)

Illing et. al., Opt. Lett. (2006)

et. al., Opt. Lett. (2007)

Chettiar et. al., Opt. Lett. (2007)

Chettiar et. al., MRS Bul. (2008)

ω

High losses
Single functional layer

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:

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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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Designs discussed here

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

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

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

F determines:

- Width of negative μ regime
- Strength of resonance

$$\omega_m = \frac{1}{\sqrt{LC}}$$

$$\gamma = \frac{R}{L}$$

γ (loss factor) determines:

- Strength of resonance $\omega_m = \frac{1}{\sqrt{LC}} \sim \frac{1}{a}$

For uniform scaling: $C \propto a$ $L \propto a \Rightarrow \frac{\omega'_m - \omega_m}{\omega_m} = \frac{1}{\sqrt{1-F}} - 1$

a : lattice constant

Magnetic resonance frequency vs length scale

Al metal, Glass substrate

Saturation value
independent of
ohmic losses

Saturation value
depends on design

Penciu et. al., Phys. Rev. B 81, 235111 (2010)

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

Magnetic permeability by scaling down the structures

Al metal
Glass substrate

Penciu et. al., Phys. Rev. B 81, 235111 (2010)

Weakening of magnetic resonance at small scales

μ ultimately does not reach negative values

Spectral width of negative μ regime

Al metal

Glass substrate

Penciu et. al., Phys. Rev. B 81,
235111 (2010)

Spectral width only
slightly affected by
metal loss

$\Delta\omega/\omega_{\min}$: constant at larger scales

tends to zero for smaller scales

Losses by scaling down the structures

Increase of losses going to smaller scale

$$\sigma = i\epsilon_0 \frac{\omega_p^2}{\omega^2 + i\gamma_m}$$

Explaining ω_m saturation and μ -strength reduction

Consideration of metal dispersive response in the conductivity:

$$\sigma = i\epsilon_0 \frac{\omega_p^2}{\omega + i\gamma_m}$$

Zhou et. al., 2005

Tretyakov, 2007

Solymar, 1976

Shvets et. al., 2005

$$R_{tot} = \frac{1}{\sigma} \frac{l}{S} = \frac{\gamma_m}{\epsilon_0 \omega_p^2} \frac{l}{S} - i\omega \frac{1}{\epsilon_0 \omega_p^2} \frac{l}{S} = R - i\omega L_e$$

ω_p = metal plasma frequency

γ_m = metal collision frequency

Inductive term (electrons inductance)

due to electrons inertia

(*“Difficulty” to accelerate finite mass particles with such high rates*)

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

$$m \frac{d\mathbf{v}}{dt} + \gamma_m \mathbf{v} = q\mathbf{E}$$

Slab-pair effective permeability in sub- μm scale

L_e is added to L in the effective circuit equation

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

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

$$\omega_m' = \frac{1}{\sqrt{(L + L_e)C}}$$

$$F' = F \frac{L}{L + L_e}$$

$$\gamma' = \frac{R}{L + L_e}$$

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

$$L_e = \frac{1}{\epsilon_0 \omega_p^2} \frac{l}{S}$$

$$R = \frac{\gamma_m}{\epsilon_0 \omega_p^2} \frac{l}{S}$$

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

$$\sigma = i\epsilon_0 \frac{\omega_p^2}{\omega^2 + i\gamma_m}$$

Explaining the observed response

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

$$L \propto a, C \propto a, L_e \propto 1/a, R \propto 1/a$$

a : u.c. size

$$\omega'_m = \frac{1}{\sqrt{(L + L_e)C}} \sim \frac{1}{\sqrt{a^2 + c_1}} \rightarrow \text{const.}$$

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

$$F' = F \frac{L}{L + L_e} \rightarrow F \frac{a^2}{a^2 + 1}$$

Loss parameter increases for small length scales;

- γ' depends on shape

-it saturates to metal collision frequency

$$\gamma' = \frac{R}{L + L_e} = \frac{\gamma_m}{1 + L / L_e} \rightarrow \frac{\gamma_m}{1 + a^2}$$

Penciu et. al., Phys. Rev. B 81, 235111 (2010)

For high frequency magnetic metamaterials

High $\omega_m = \frac{1}{\sqrt{(L + L_e)C}}$

for High operation frequency
Broad-band
Low-loss

High $F' = F \frac{1}{1 + L_e / L}$

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

Requirements

NOT $\gamma' = \frac{\gamma_m}{1 + L / L_e}$

- Small capacitance, C
- Small L_e
- Large metal plasma frequency – small collision frequency
- $L?$: opposite role in ω_m and μ

Electrons inductance at the electric dipole resonance: Resonance frequency

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

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

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

Saturation

$$C, L \sim a, \quad R, L_e \sim 1/a$$

Electrons inductance at the electric dipole resonance: Resonance strength

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

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

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

**No vanishing
resonance strength**

$$C, L \sim a, \quad R, L_e \sim 1/a$$

Electrons inductance at the electric dipole resonance features?

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

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Saturation

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**No vanishing
resonance strength**

Spectral width of negative ε : 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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“Connected” structures for direct laser writing

1D

Gold in
polyimide

$$\text{Re}(n)/\text{Im}(n)|_{n=-1} = 5$$

Double negative @
~200 THz (1.5 μm)

2D

Double negative @
~160 THz

Calculations by
D. Guney

D. Guney et.al., Opt. Lett. 34, 506 (2009)

“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

$$n_{\pm} = \sqrt{\varepsilon\mu} (\pm \kappa)$$

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

Twisted cross

Zhou et. al., Phys. Rev. B
79, 121104R (2009)

Negative index
Large polarization rotation
Large circular dichroism

Chiral optical structures

Twisted gold crosses

Response @ 1-2 μm

**Large polarization rotation
Large circular dichroism**

M. Wegener's group , Opt. Lett. (2009)

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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

$$\underline{\underline{\varepsilon_2}} = \begin{bmatrix} \varepsilon_{2x} & 0 & 0 \\ 0 & \varepsilon_{2y} & 0 \\ 0 & 0 & \varepsilon_{2z} \end{bmatrix}, \quad \underline{\underline{\mu_2}} = \begin{bmatrix} \mu_{2x} & 0 & 0 \\ 0 & \mu_{2y} & 0 \\ 0 & 0 & \mu_{2z} \end{bmatrix}$$

Work done by N.H. Shen

Superlensing conditions for anisotropic media

For p-polarization

$$\frac{\epsilon_{2x}}{\mu_{2y}} = \frac{\epsilon_1}{\mu_1}$$

$$\epsilon_{2x} \epsilon_{2z} = \epsilon_1^2$$

$$\epsilon_{2x}, \epsilon_{2z}, \mu_{2y} < 0$$

For isotropic media:

$$\epsilon_2 = -\epsilon_1, \mu_2 = -\mu_1$$

**Easy to implement
conditions with planar
technologies**

Lens formula for anisotropic lenses

$$d_{\text{Source}} + d_{\text{Image}} = (\varepsilon_{2x} / \varepsilon_1) d$$

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

$$\epsilon_{2x} = \mu_{2y} = -2 + 0.01i, \quad \epsilon_{2z} = -0.5 + 0.01i$$

Focusing in an
anisotropic double
negative slab

$$d = 0.2\lambda \quad \text{resolution} = \lambda/5$$

Optical metamaterials: Facing the challenges

High losses

Limited
capa

- exp
- unabl
- complic
- large samp
- 3D isotropic designs

**A research
field of many
exciting
possibilities**

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Work thanks to

PHUME

NIMNIL

ECONAM

COST

C. Soukoulis

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S. Foteinopoulou

D. Guney

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B. Wang

N.H. Shen

M. Wegener's group at Karlsruhe

Thank you!

Relevant publications

- R. S. Penciu, M. Kafesaki, Th. Koschny, E. N. Economou, and C. M. Soukoulis, *Magnetic response of nanoscale left-handed metamaterials*, Phys. Rev. B (2010).
- D. Guney, Th. Koschny, M. Kafesaki, and C. M. Soukoulis, *Connected bulk negative index photonic metamaterials*, Opt. Lett. **34**, 506 (2009).
- N. H. Shen, S. Foteinopoulou, M. Kafesaki, Th. Koschny, E. Ozbay, E. N. Economou, and C. M. Soukoulis, *Compact planar far-field superlens based on anisotropic left-handed metamaterials*, Phys. Rev. B **80**, 115123 (2009).
- J. Zhou, J. Dong, B. Wang, Th. Koschny, M. Kafesaki, and C. M. Soukoulis, *Negative refractive index due to chirality*, Phys. Rev. B **79**, 121104(R) (2009).