FORTH

Metamaterials:
Applications, Analysis
and Modeling
January 25 - 29, 2010

IPAM

Left-handed metamaterials behavior towards optical regime

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Left-handed metamaterials?

Veselago (1968)

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

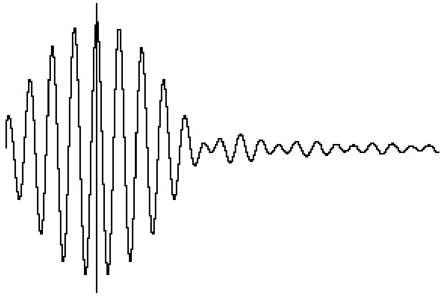
$$n = -\sqrt{\varepsilon\mu}$$

negative

Negative ε, μ, n ⇒ **Novel and unique propagation characteristics in those materials!**

Novel phenomena in left-handed materials (LHMs)

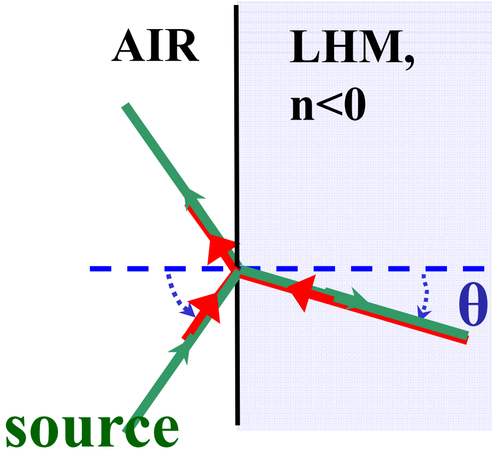
Backwards propagation
(opposite phase & energy velocity)



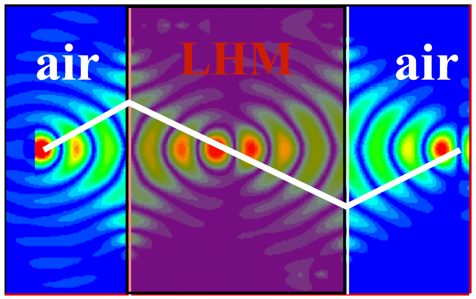
$$\mathbf{k}\times\mathbf{E}=\frac{\omega}{c}\mu\mathbf{H}$$

S=E×H

Negative refraction



Flat lenses - "Perfect" lenses
(subwavelength resolution)



- Opposite Doppler effect
- Opposite Cherenkov radiation
- ……

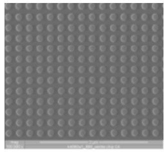
- **Interesting physical system**
- **New possibilities for light manipulation → important potential applications**

Why optical left-handed materials (LHMs)?

New solutions and possibilities in

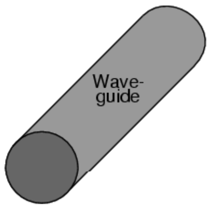
- **Imaging/microscopy**

- **Lithography**



- **Data storage**

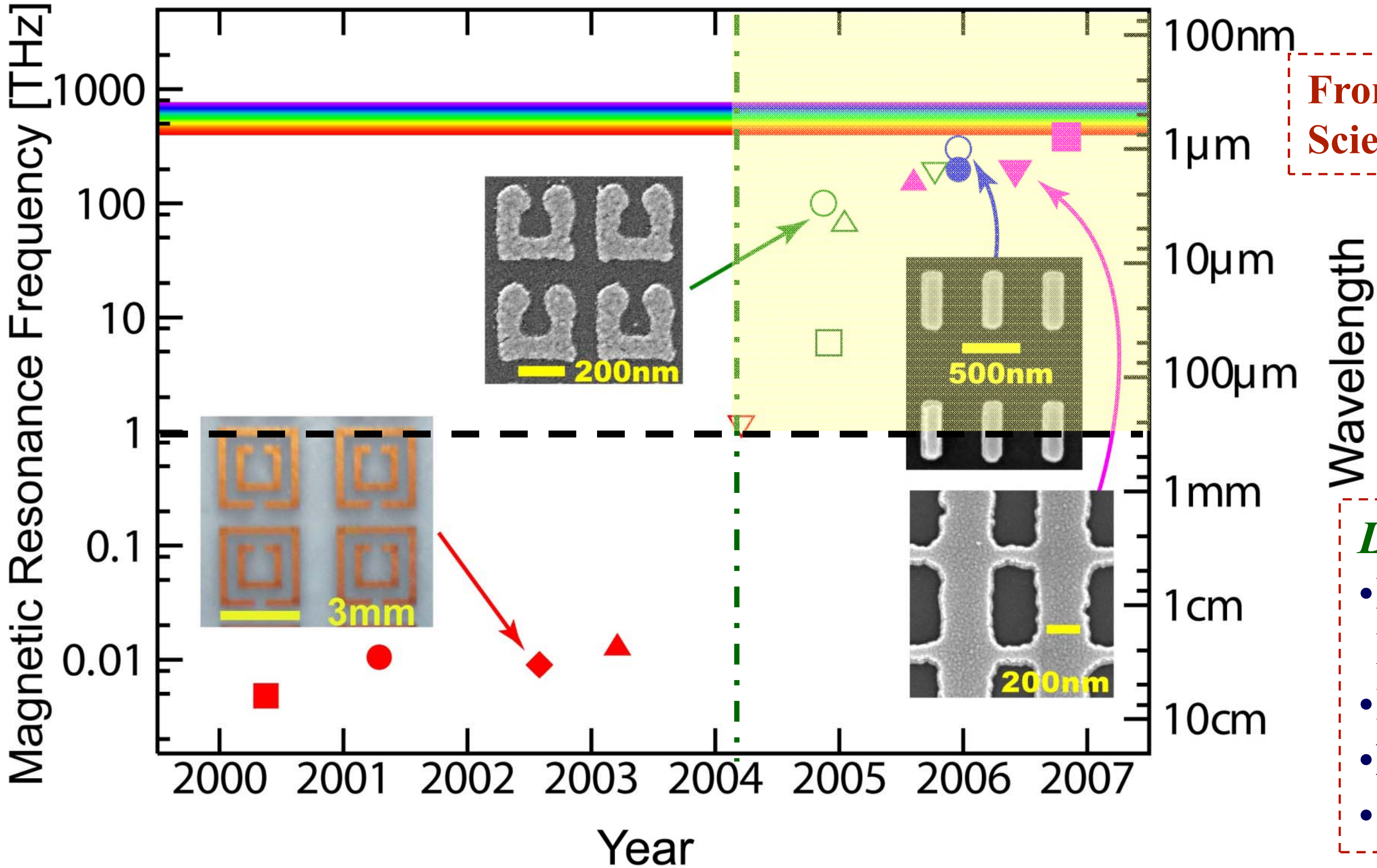
- **Optical communications and information processing**



- **….**

Exploiting the subwavelength resolution capabilities of LHMs

Going to IR and optical frequenices…



From Soukoulis et. al., Science 315, 47 (2007)

Leaders

- Karlsruhe and FORTH/ISU
- Purdue
- New Mexico
- Stuttgart

Solid symbol n<0

Open symbol μ<0

Orange: double-ring SRRs based structures

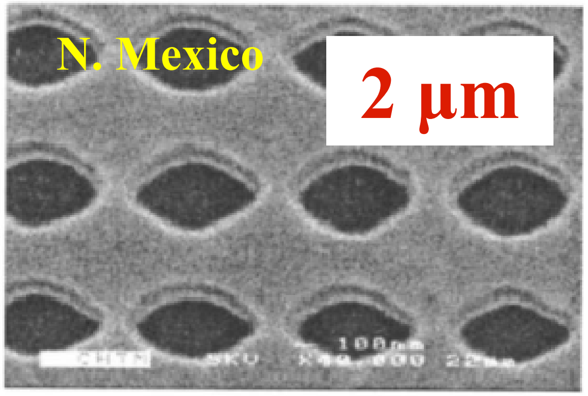
Green: single-ring SRR based structures

Blue: slab-pair-based structures

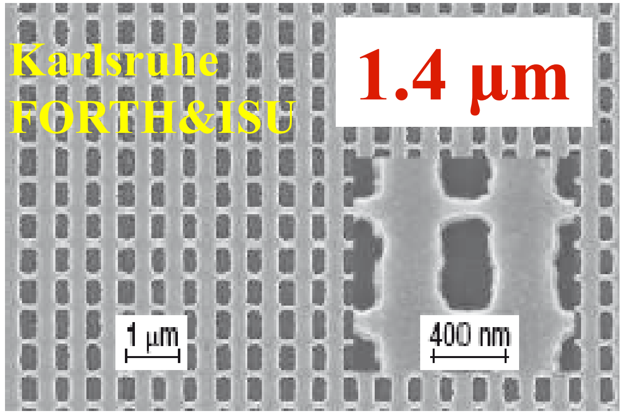
Pink: fishnet

Negative *n* towards optical regime

Fore review, see:
- Soukoulis et. al., Science 315 (2007)
- Shalaev, Nat. Mat. (2007)
- Boltasseva et. al., Metamaterials 2 (2008)

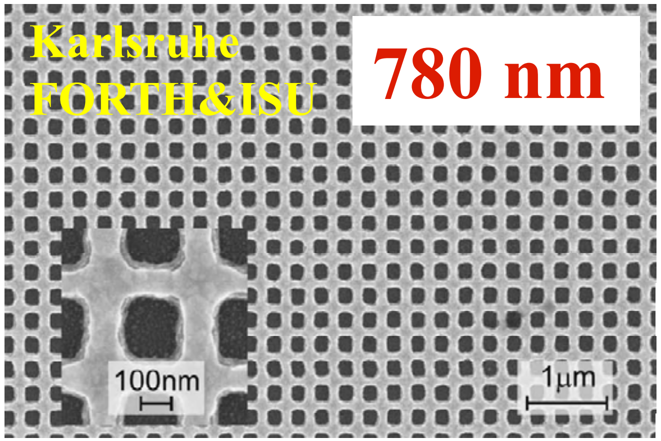


Zhang et. al., PRL 95, 137404 (2005)

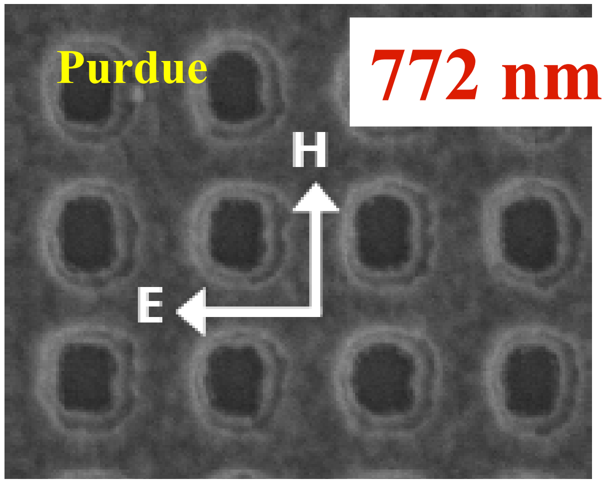


Dolling et. al., Opt. Lett. 31, 1800 (2006)

Lowest losses (FOM=3)



Dolling et. al., Opt. Lett. 32, 53 (2007)



Chettiar et. al., Opt. Lett. 32, 1671 (2007)

$$\mathrm{FOM} = \frac{|\mathrm{Re}(n)|}{\mathrm{Im}(n)}$$

Recently up to yellow! Purdue

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

⟷

- Design optimizations
- "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, adapted to fabrication capabilities

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↔

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↔

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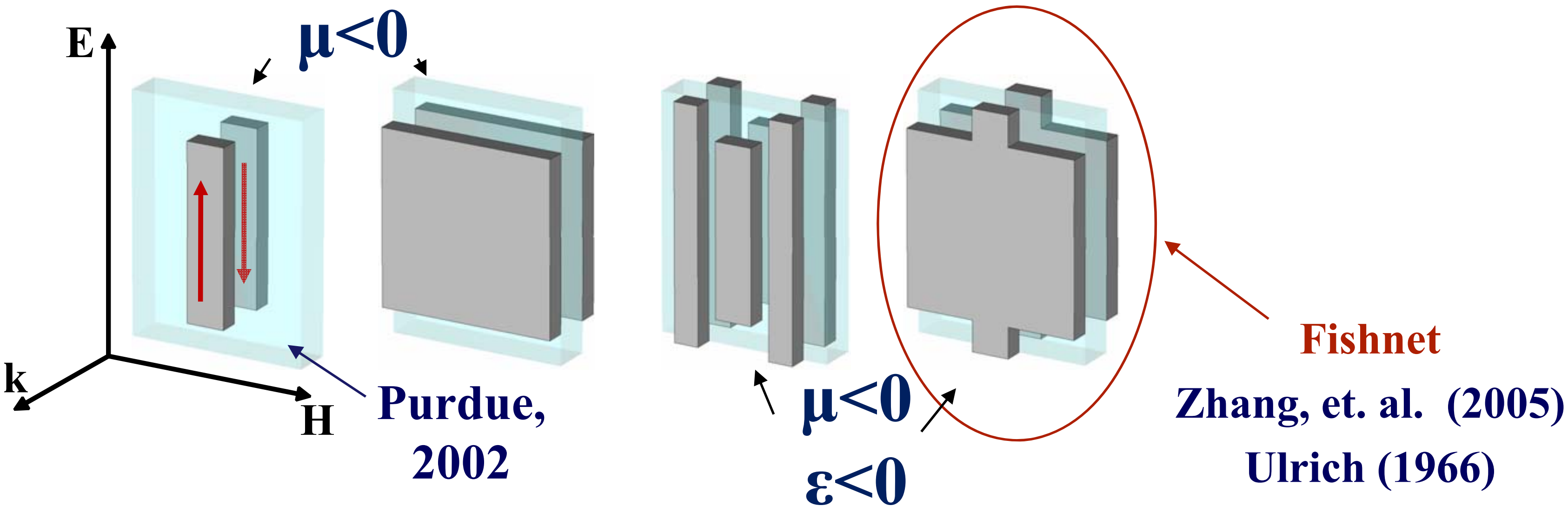
Designs discussed here

Unit cells

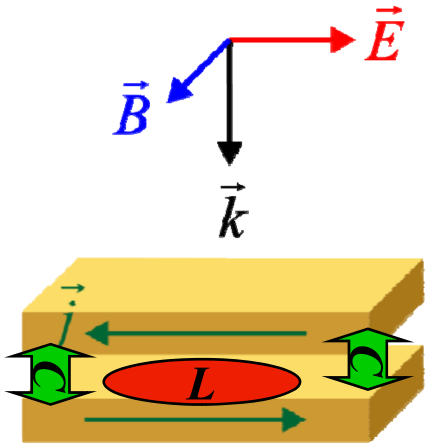


Aim

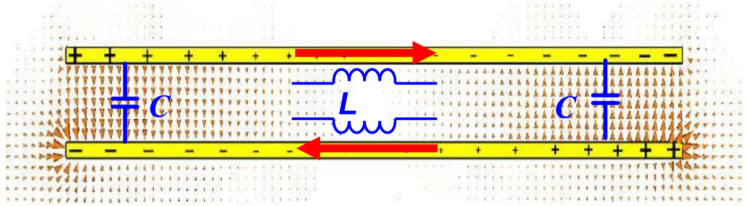
Examine the behavior of the designs as they are scaled down targeting optical negative index response

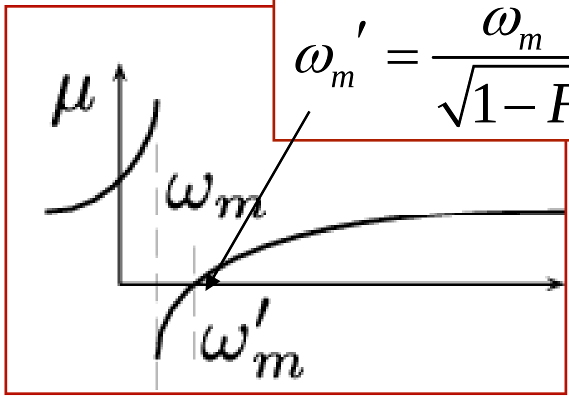
Seek for optimization rules

Slab-pair magnetic response



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





$$\omega_m' = \frac{\omega_m}{\sqrt{1-F}}$$

F **~ volume fraction of the resonator within unit cell**

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

F **determines:**

•Width of negative μ regime

•Strength of resonance

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

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

Loss factor γ **determines:**

•Strength of resonance

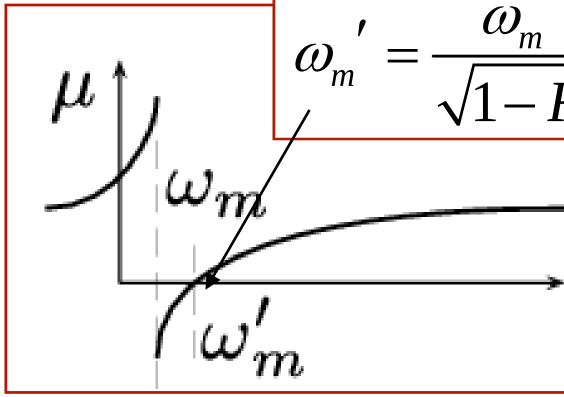
$L = \mu_0 lt / w$

Slab-pair uniform scaling

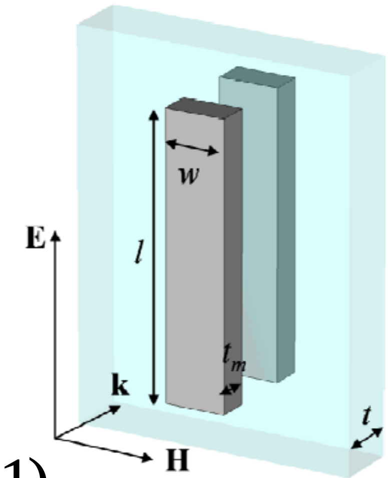
***F* ~ volume fraction of the resonator within unit cell**

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

$$\omega_m' = \frac{\omega_m}{\sqrt{1-F}}$$



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



For uniform scaling:

$$L \sim \mu_0 \frac{lt}{w} \propto a \qquad C \sim \varepsilon_b \varepsilon_0 \frac{lw}{t} \propto a$$

a: lattice constant

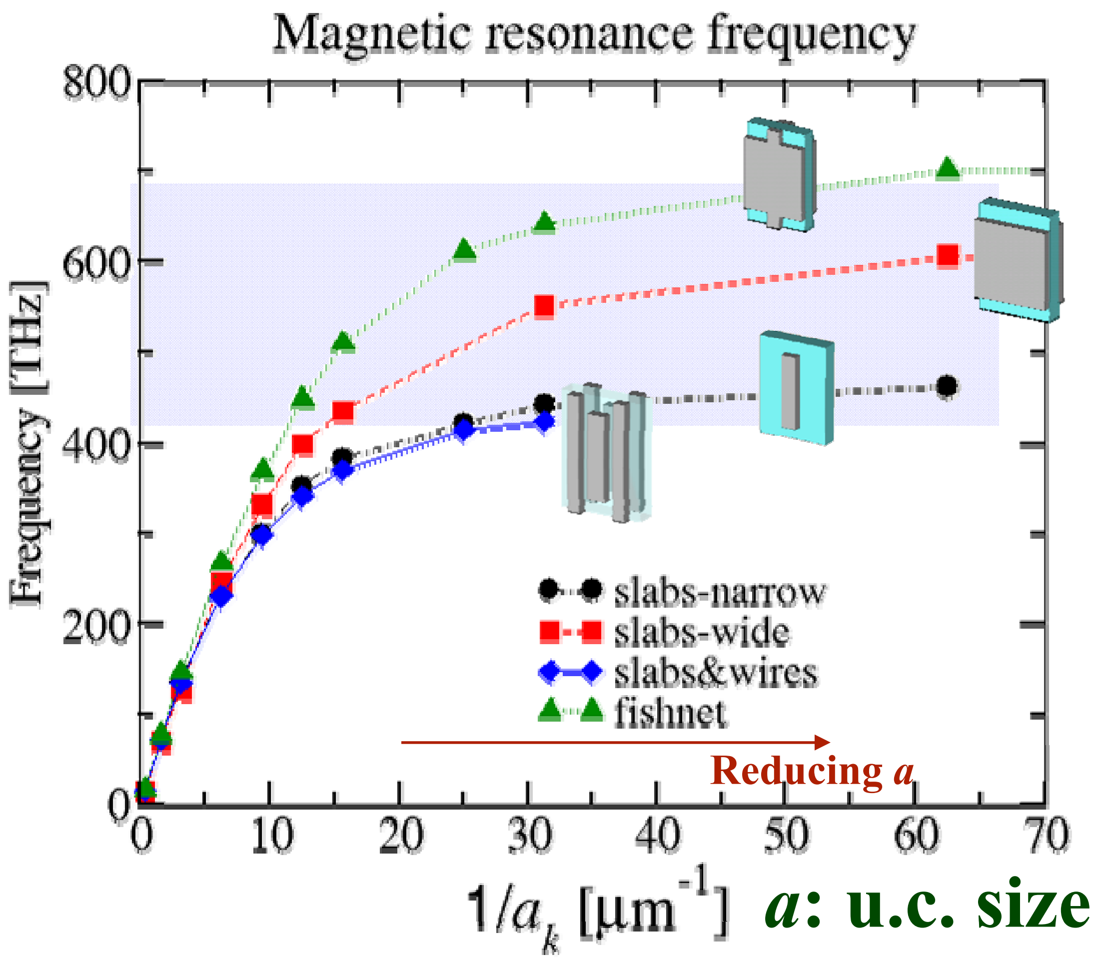
$$\Rightarrow \quad \omega_m = \frac{1}{\sqrt{LC}} \sim \frac{1}{a} \xrightarrow[a \to 0]{} \infty$$

Goes to infinity?!

$$\omega_m' - \omega_m = \omega_m \left(\frac{1}{\sqrt{1-F}} - 1\right)$$

Scale independent?!

Magnetic resonance frequency vs length scale



a: u.c. size

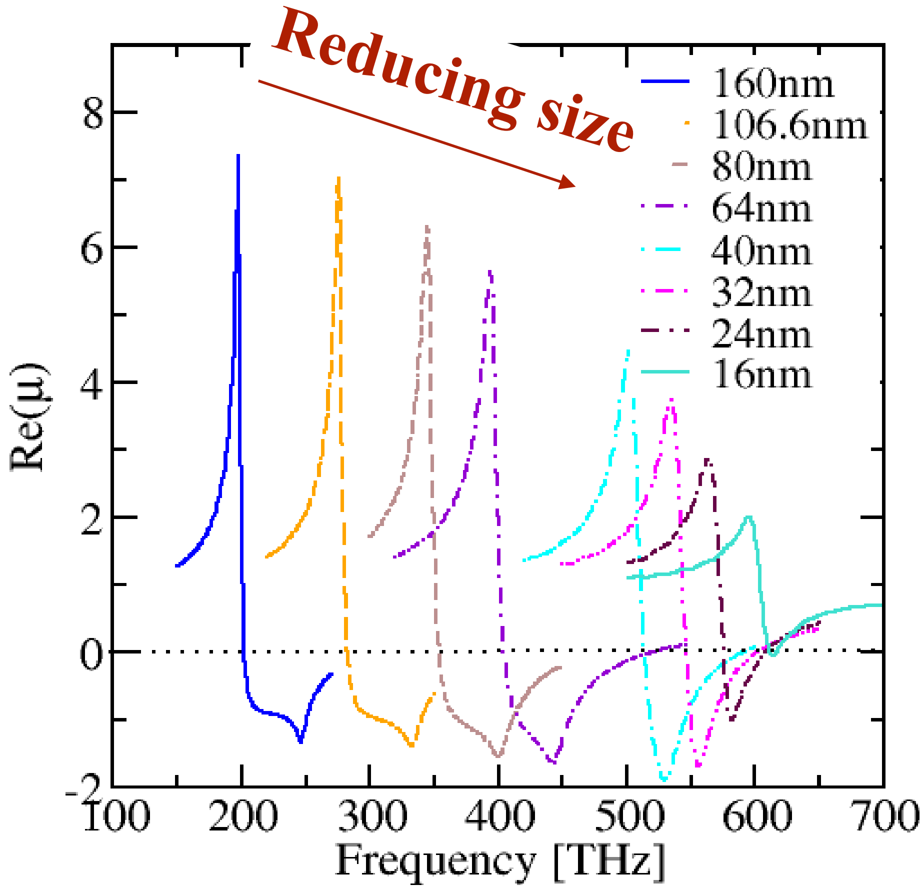
Al metal
Glass substrate

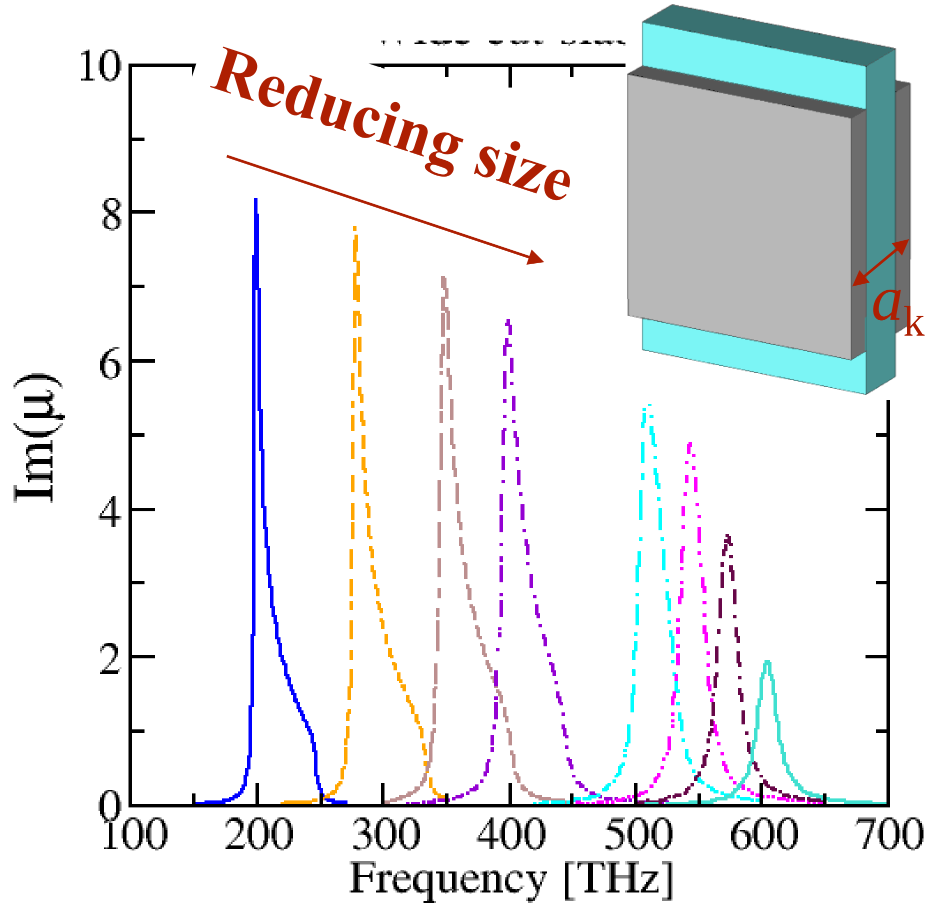
Saturation value depends on design

Fishnet: higher saturation value

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

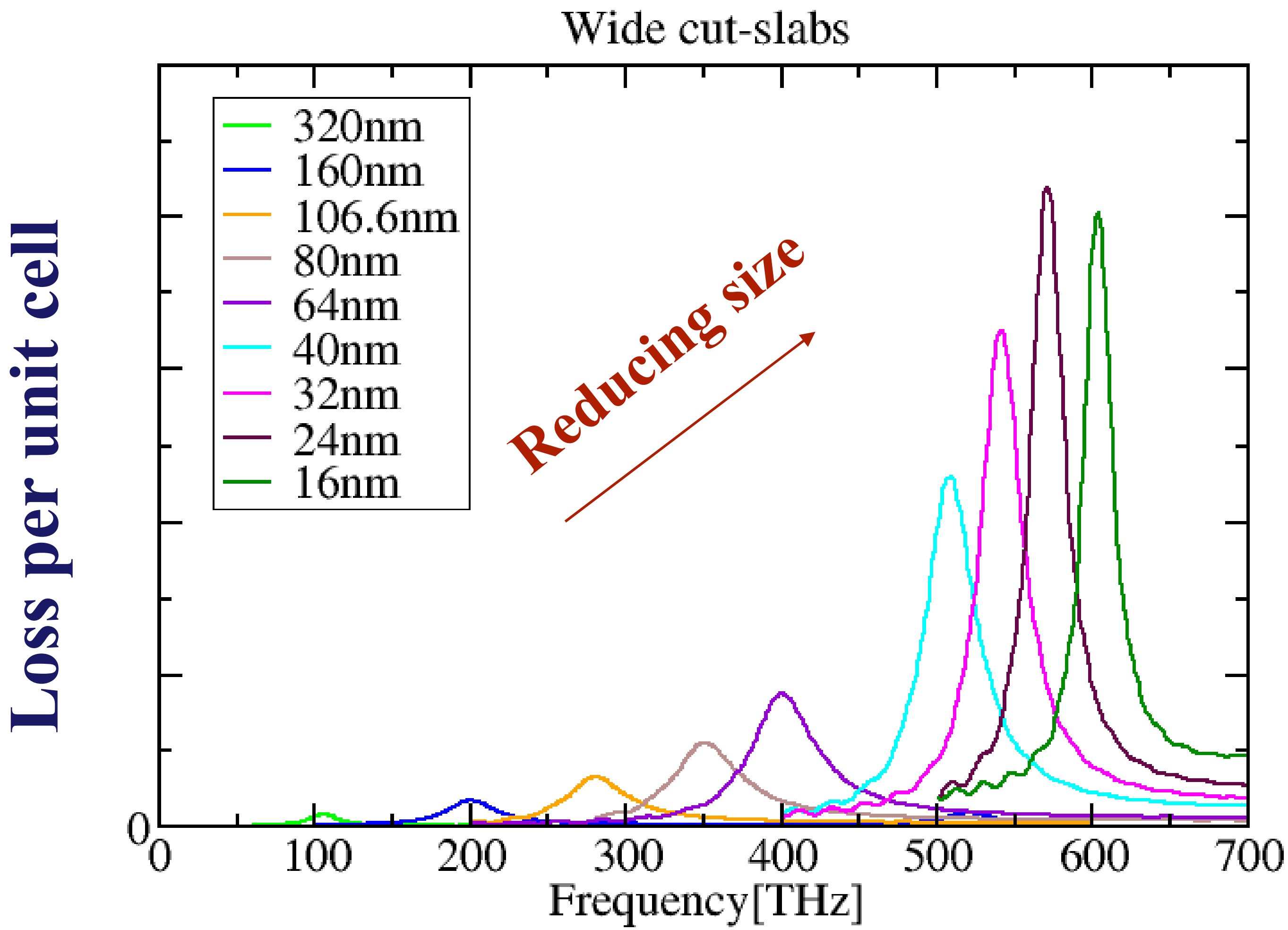
Magnetic permeability by scaling down the structures

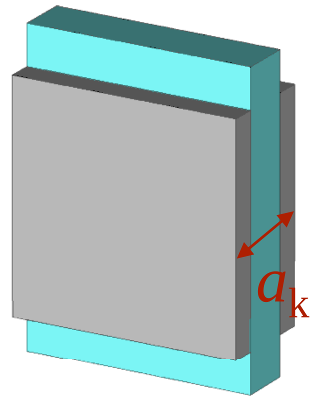




Weakening of magnetic resonance at small scales

Losses by scaling down the structures

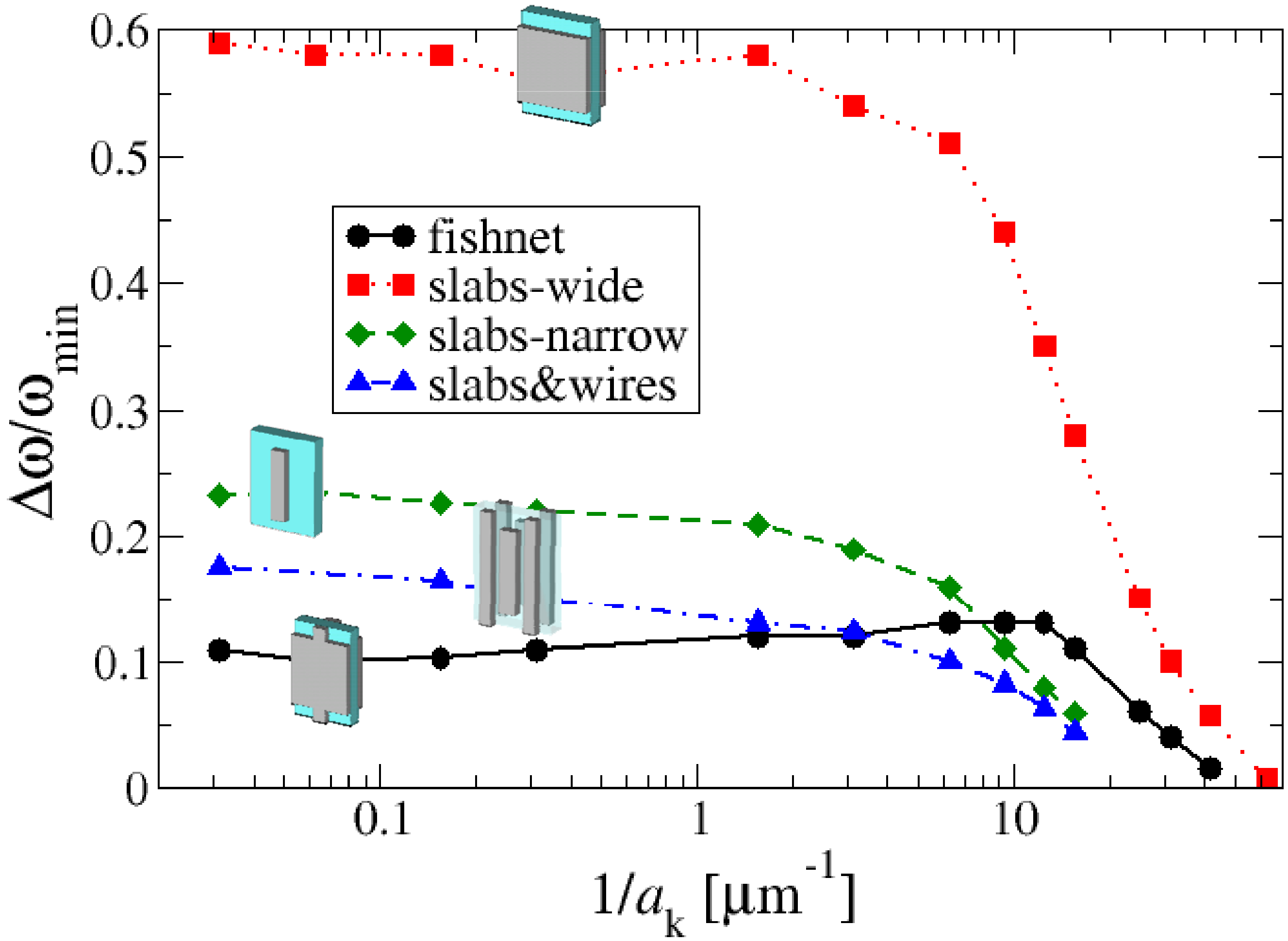




$$\text{Loss} = 1 - R - T$$

Increase of losses going to smaller scale

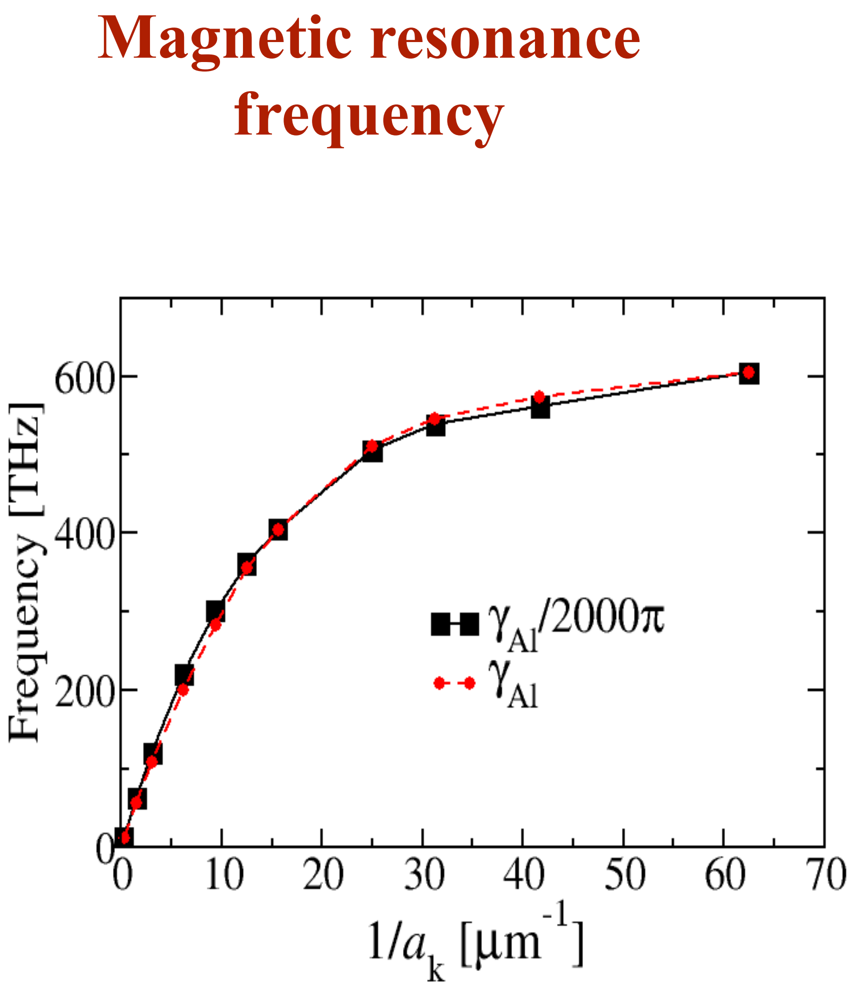
Spectral width of negative μ regime

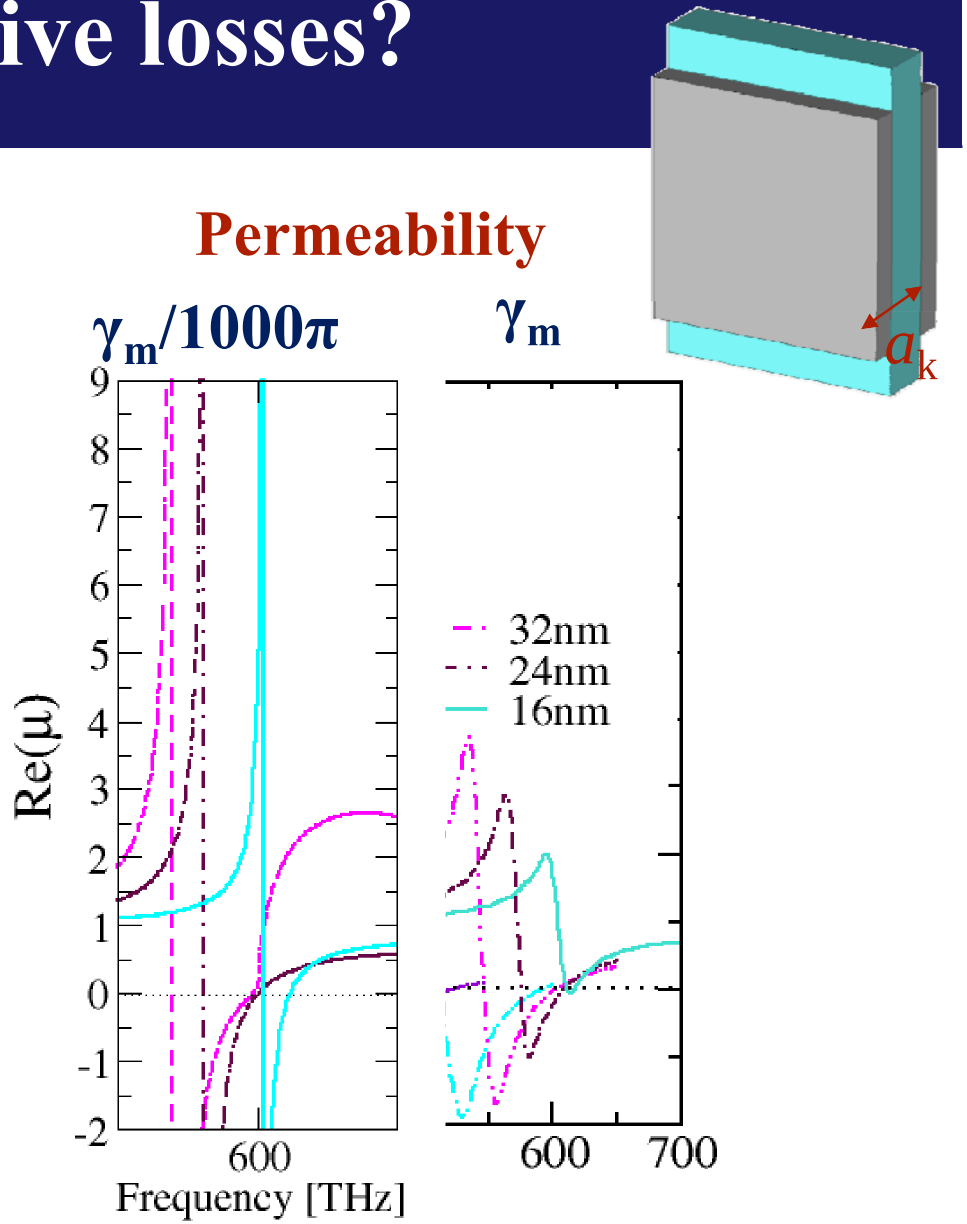


$\Delta\omega/\omega_{min}$: constant at larger scales

tends to zero for smaller scales

Effect of resistive losses?





Saturation is not affected by the metal loss

Negative permeability width slightly affected by metal loss

Explaining ω_m saturation and μ-strength reduction

Consideration of metal dispersive response in the conductivity:

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

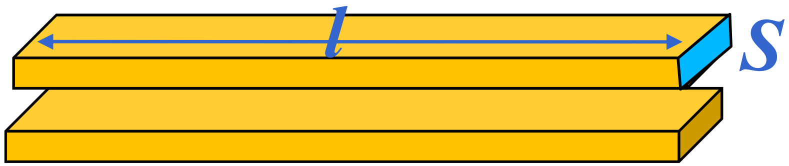
Zhou et. al., 2005
Shvets et. al., 2005
Tretyakov, 2007
Solymar, 1976

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

Inductive term (electrons inductance)
due to electrons inertia
("Difficulty" to accelerate finite mass particles with such high rates)

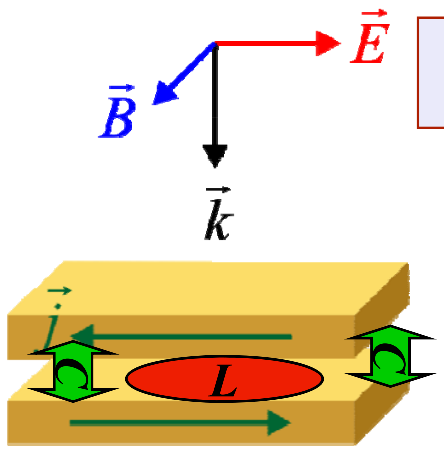
ω_p= metal plasma frequency

γ_m=metal collision frequency



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

Slab-pair effective permeability in sub-μm scale



L_e is added to L in the effective circuit equation

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

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

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

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

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

F ~ volume fraction of the resonator within unit cell

$$L_e=\frac{1}{\varepsilon_0\omega_p^2}\frac{l}{S}$$

$$R=\frac{\gamma_m}{\varepsilon_0\omega_p^2}\frac{l}{S}$$

For uniform scaling:

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

$$L\propto a\qquad C\propto a$$

a: lattice constant

Explaining the observed response

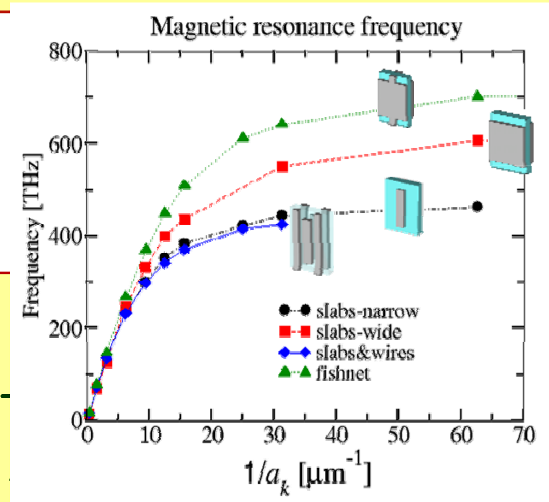
$\sigma = i\varepsilon_0 \frac{\omega_p^2}{\omega^2 + i\gamma_m}$

***a*: u.c. size**

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

$$\omega_m' = \frac{1}{\sqrt{(L+L_e)C}} \sim \frac{1}{\sqrt{c_1 a^2 + c_2}} \rightarrow \text{const.}$$

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

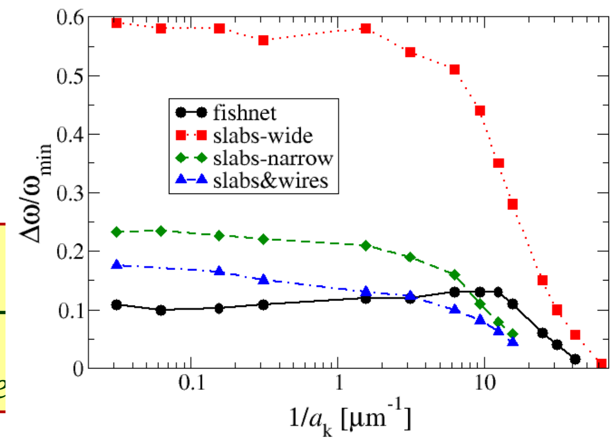


Strength parameter F' becomes proportional to area → Vanishing of negative μ regime <u>even if the absence of ohmic losses</u>

$$F' = F$$

Loss parameter increases for small length scales;
-γ´ depends on shape
-it saturates to metal collision frequency

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



For high frequency magnetic metamaterials

High

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

High

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

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

Low

$$\gamma' = \frac{\gamma_m}{1+L/L_e}$$

Requirements

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

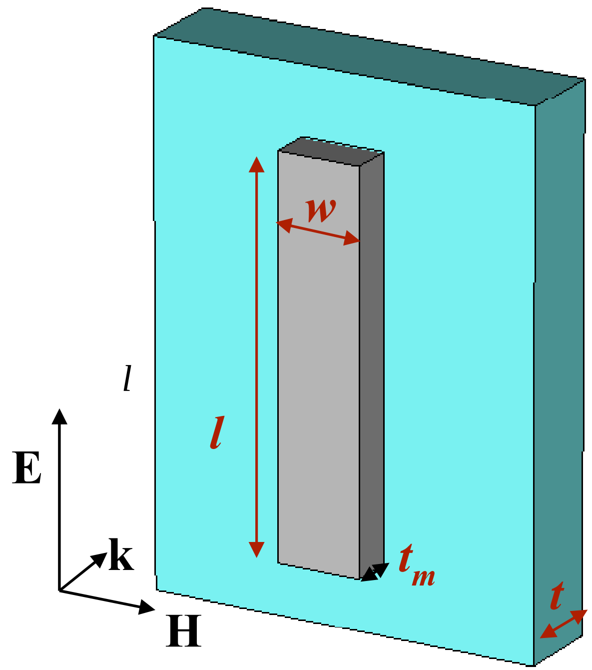
Optimizing the slab-pair

Maximizing

$$\omega_m^{\text{saturation}} = \omega_p \frac{\sqrt{t\,t_m}}{l}$$

$$F' = \frac{w\,t\,l}{V_{uc}} \frac{\omega_p^2 t_m t}{\omega_p^2 t_m t + c^2}$$

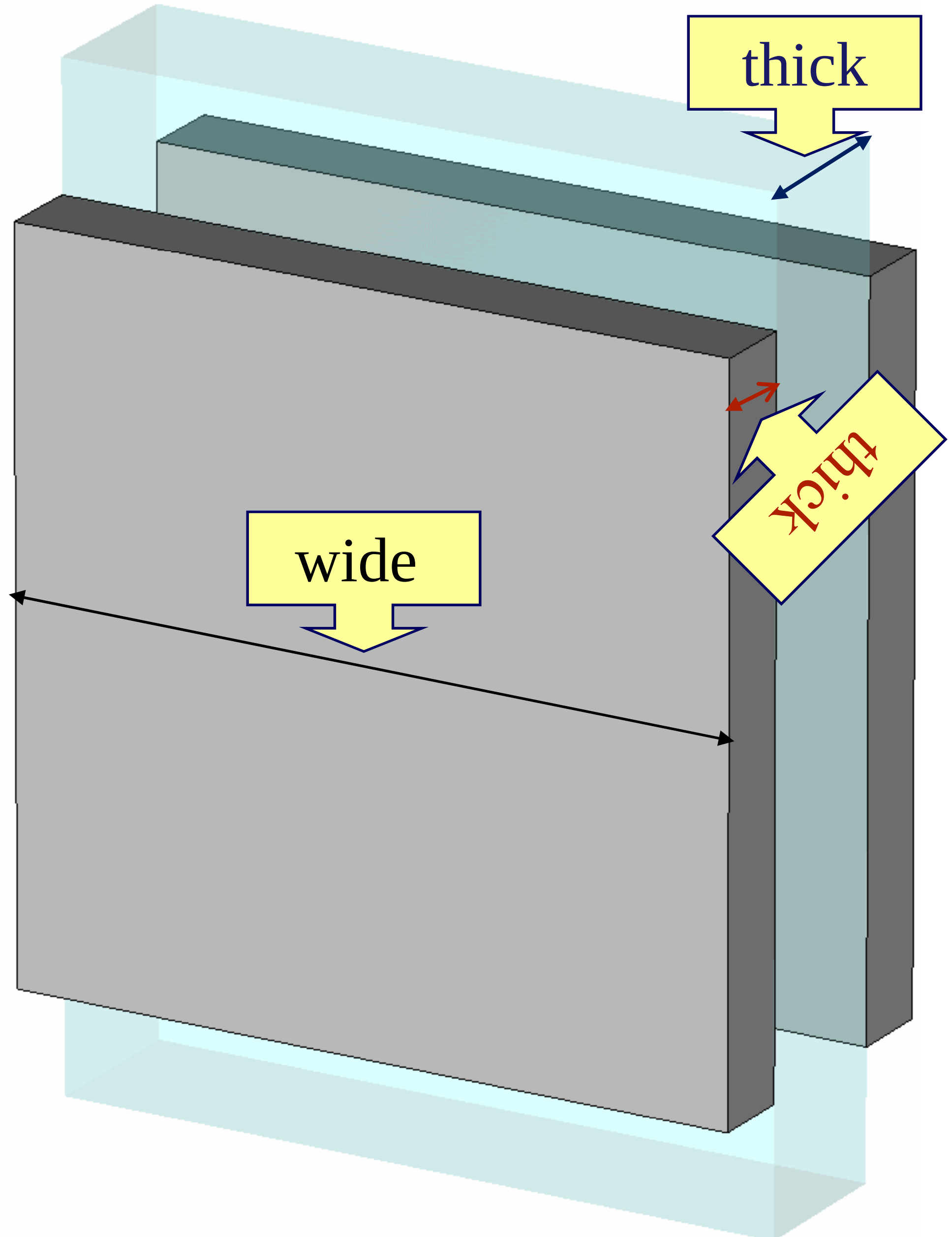
$$\frac{1}{\gamma'} = \frac{\omega_p^2 t_m t + c^2}{\gamma_m\, c^2}$$



Metals of high plasma frequency, low collision frequency

Wide slabs (*w*), thick metal (t_m), thick separation layer (*t*)

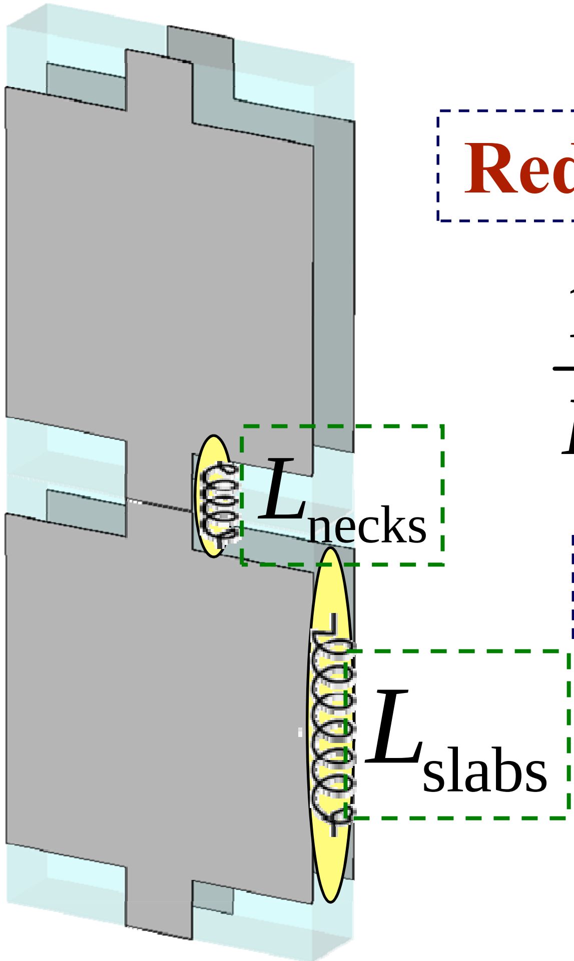
Optimizing slab-pair-based systems



Requirements

- Thick & wide slabs
- "Thick" separation layer
- Metal of high ω_p & low γ_m

Fishnet



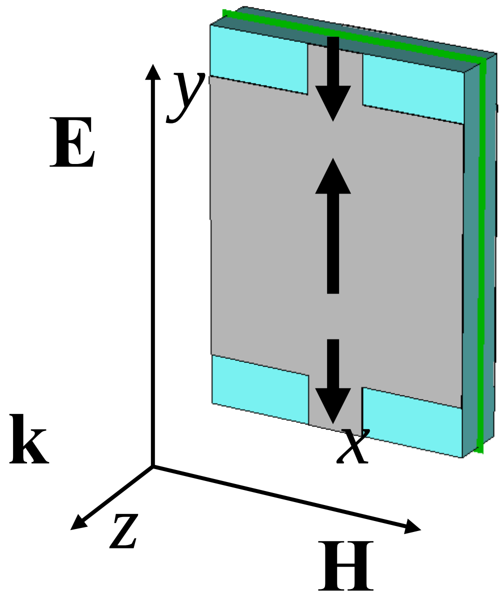
Reduced inductance compared to only slabs

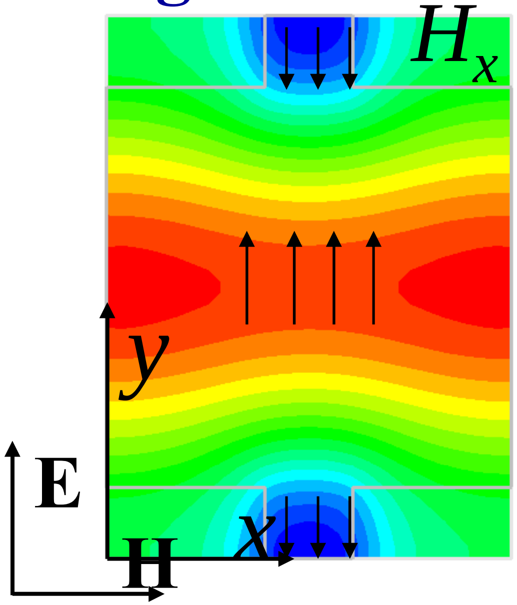
$$\frac{1}{L} = \frac{1}{L_{\text{slabs}}} + \frac{1}{L_{\text{necks}}}$$

→ **higher magnetic resonance frequency**

$$\omega_m^2 = \frac{1}{LC} = \frac{1}{L_{\text{slabs}}C} + \frac{1}{L_{\text{necks}}C}$$

Fishnet: Currents and fields at resonance





Antiparallel currents in slabs and necks → smaller induced magnetic moment compared to slabs-only case

Optical metamaterials: Facing the challenges

High losses
Electrons inductance

- Design optimizations
- "Good" constituent media
- Gain media?
- Novel approaches (anisotropic media, chiral media, EIT)

Limited fabrication capabilities

Current procedures:

- difficult/time-consuming
- expensive
- unable to produce
  - complicated patterns
  - large samples
  - 3D isotropic designs

- Advancement of fabrication procedures
- New fabrication methods (direct laser writing, nanoimprint lithography)
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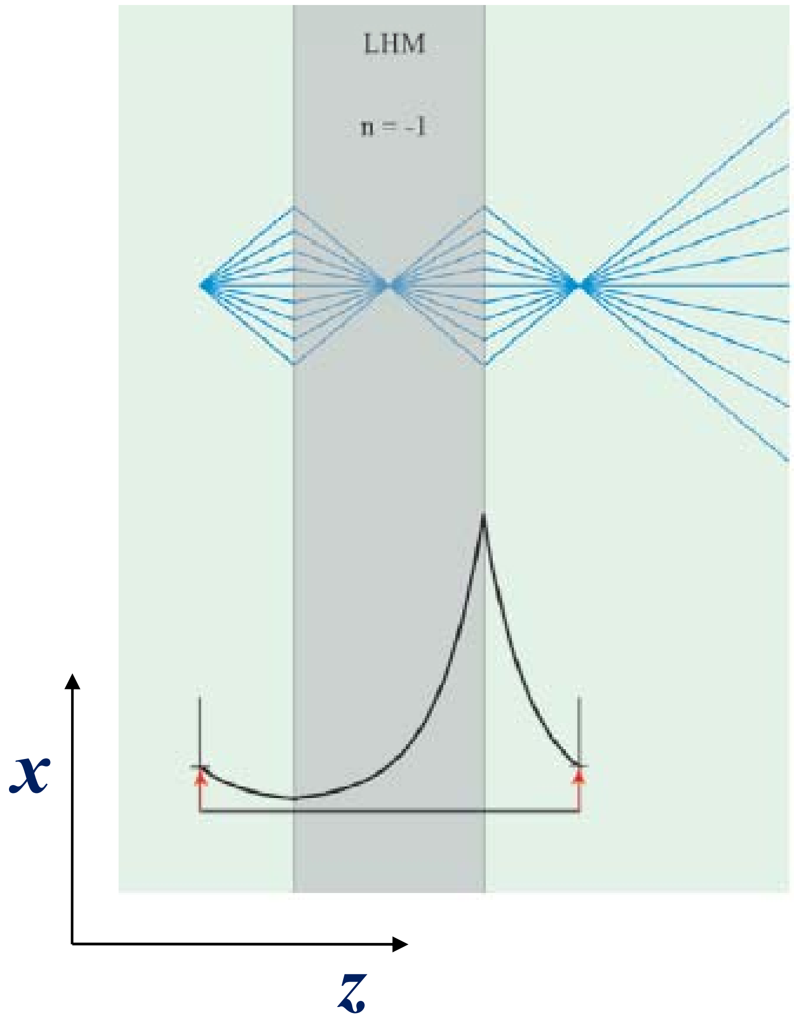
Examine superlensing possibility using anisotropic left-handed media

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

Work done by N.H. Shen

Most of the currently fabricated left-handed materials are anisotropic

Superlenses for anisotropic media?



Perfect lensing conditions:

Propagating components:

Omnidirectional total transmission

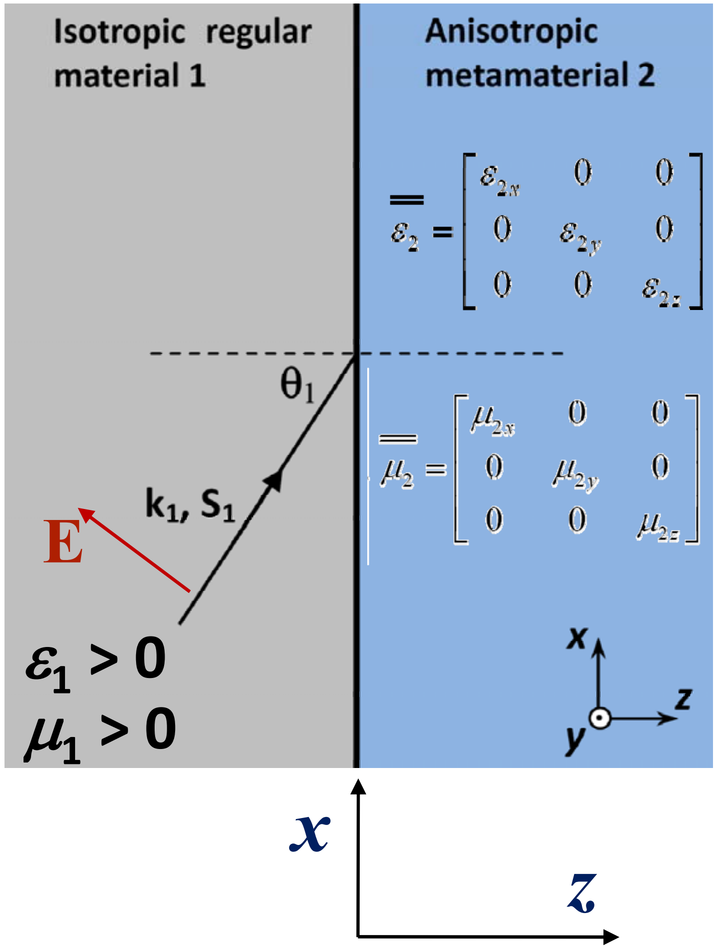
Evanescent components:

Excitation of dispersionless surface plasmon modes

$$\overline{\overline{\varepsilon}}_2 = \begin{bmatrix} \varepsilon_{2x} & 0 & 0 \\ 0 & \varepsilon_{2y} & 0 \\ 0 & 0 & \varepsilon_{2z} \end{bmatrix}, \overline{\overline{\mu}}_2 = \begin{bmatrix} \mu_{2x} & 0 & 0 \\ 0 & \mu_{2y} & 0 \\ 0 & 0 & \mu_{2z} \end{bmatrix}$$

Aim: Examine these conditions for anisotropic materials

Superlensing conditions for anisotropic media



For p-polarization

$$\frac{\varepsilon_{2x}}{\mu_{2y}} = \frac{\varepsilon_1}{\mu_1}$$

$$\varepsilon_{2x}\varepsilon_{2z} = \varepsilon_1^2$$

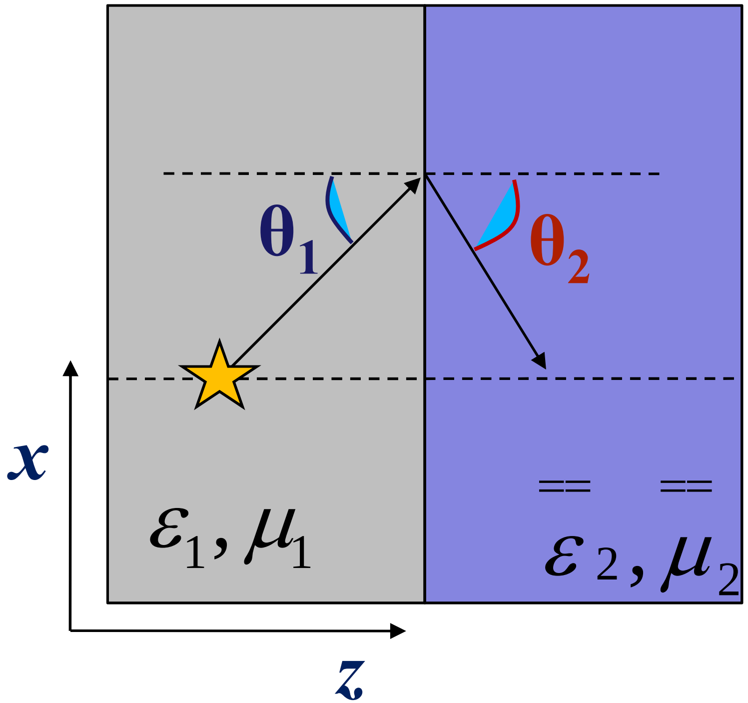
$$\varepsilon_{2x}, \varepsilon_{2z}, \mu_{2y} < 0$$

For isotropic media:

$$\varepsilon_2 = -\varepsilon_1, \ \mu_2 = -\mu_1$$

Easy to implement conditions with planar technologies

"Snell's" law for anisotropic double-negative media



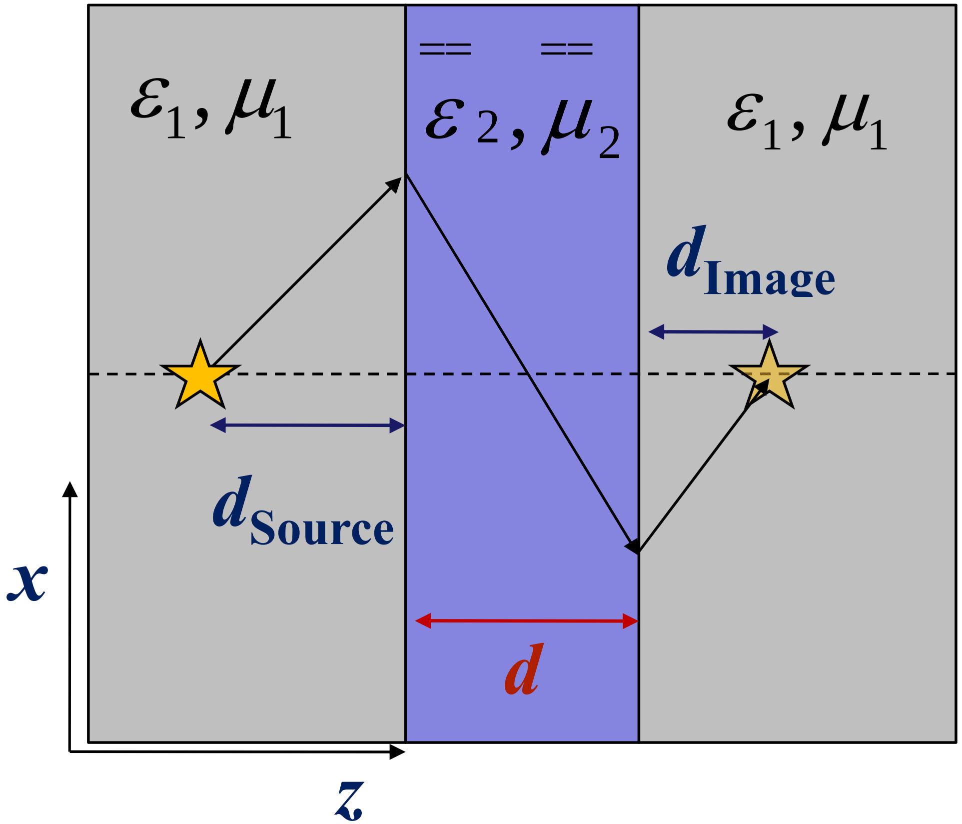
$$\tan\theta_2 / \tan\theta_1 = \varepsilon_1 / \varepsilon_{2z}$$

Refraction angle

Incidence angle

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

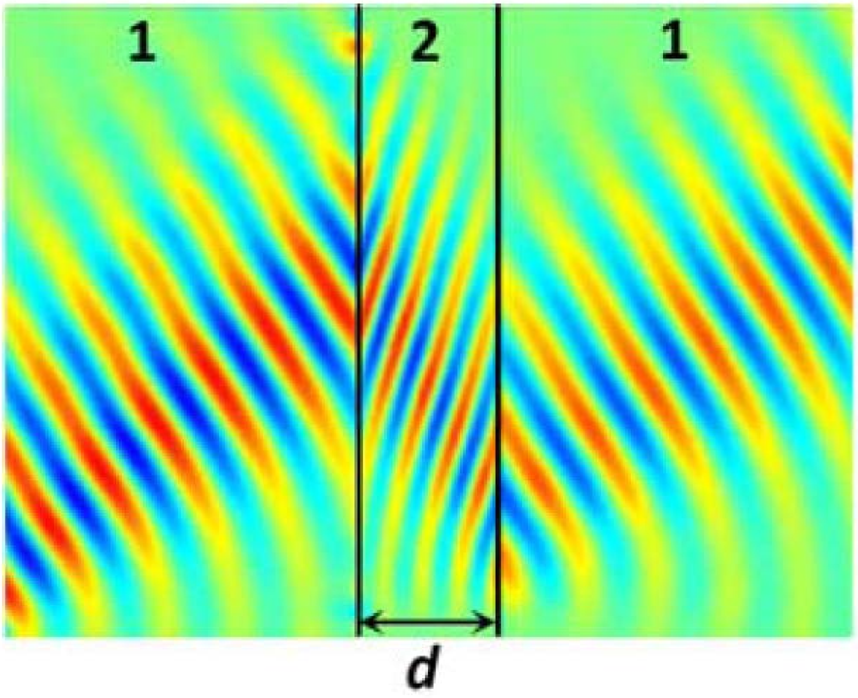
Isotropic lens: $d_{\text{Source}} + d_{\text{Image}} = d$



Possibility for thin lenses!
(less influenced by losses)

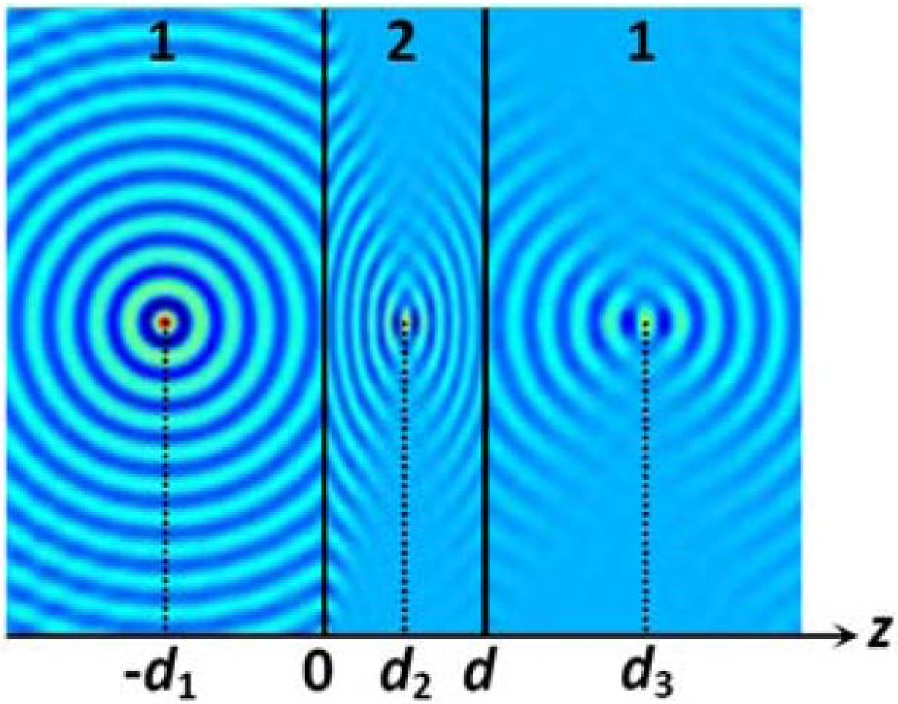
Anisotropic “perfect” lens: Negative refraction & focusing

Negative refraction by an anisotropic double negative slab



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

Focusing in an anisotropic double negative slab



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

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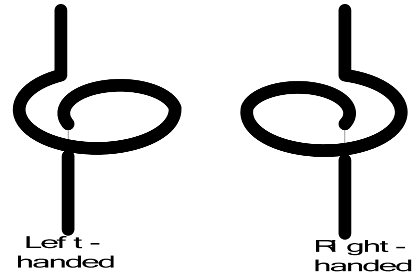
Negative refractive index in chiral media?

Chiral structure: not-identical to its mirror image



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

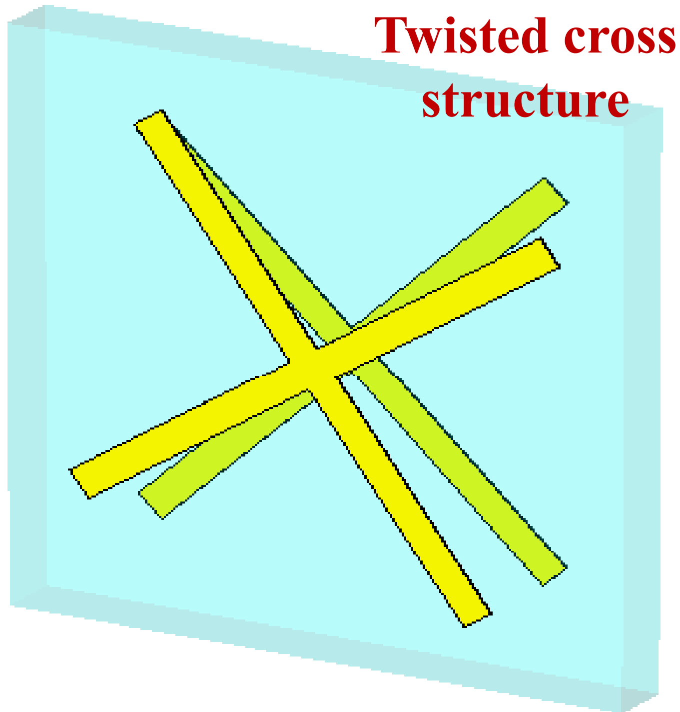
- Different index for left- and right-handed circularly polarized waves
- Alternative path to achieve negative index (Tretyakov, Pendry)

$$\boldsymbol{D} = \varepsilon\boldsymbol{E} + j\kappa\sqrt{\mu_0\varepsilon_0}\boldsymbol{H}$$
$$\boldsymbol{B} = \mu\boldsymbol{H} - j\kappa\sqrt{\mu_0\varepsilon_0}\boldsymbol{E}$$

Besides negative index:
- Polarization rotation
- Circular dichroism

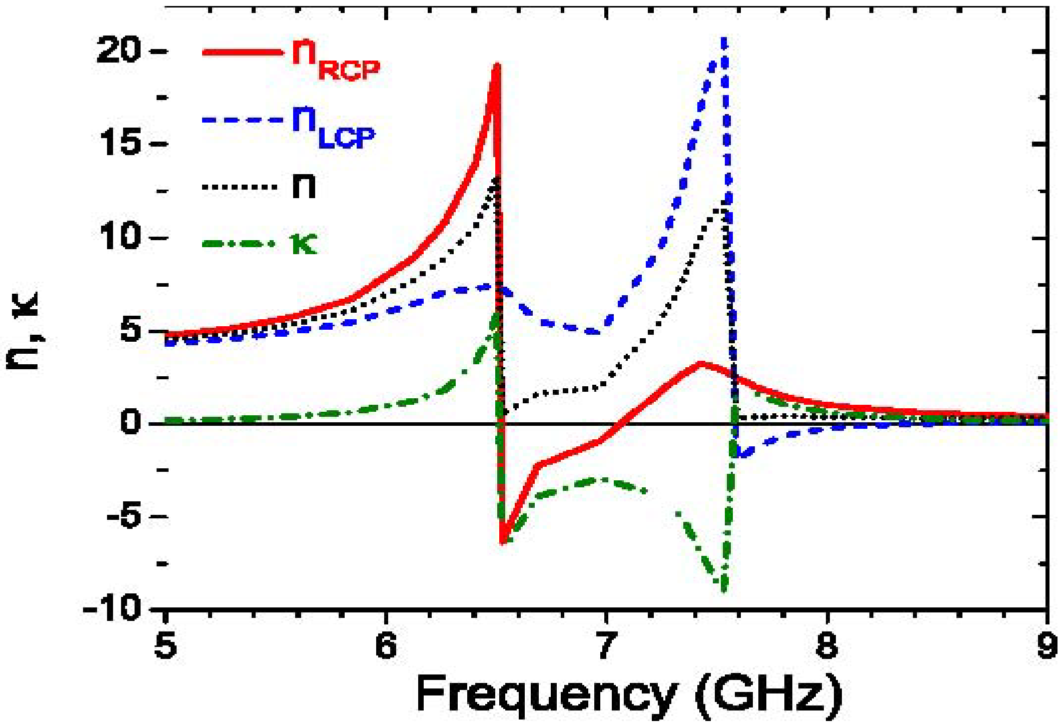
Negative index
Large polarization rotation
Large circular dichroism

Twisted cross structure

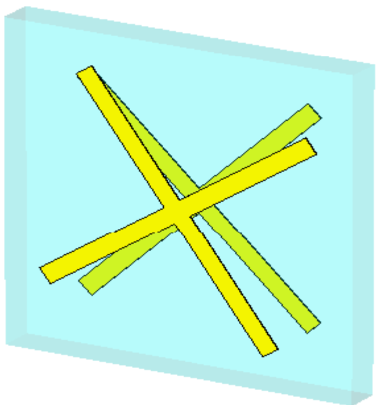


J. Zhou, J. Dong, B. Wang, et. al., PRB

Negative refractive index in chiral media



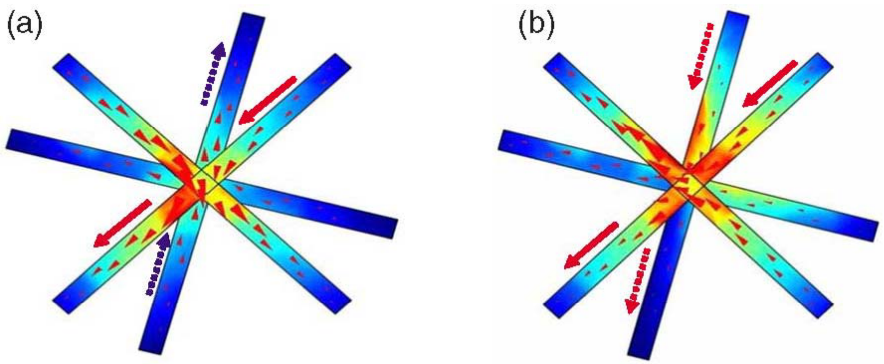
$$n_{\pm} = n \pm \kappa$$



Twist angle=15°

Unit cell = 15 mm

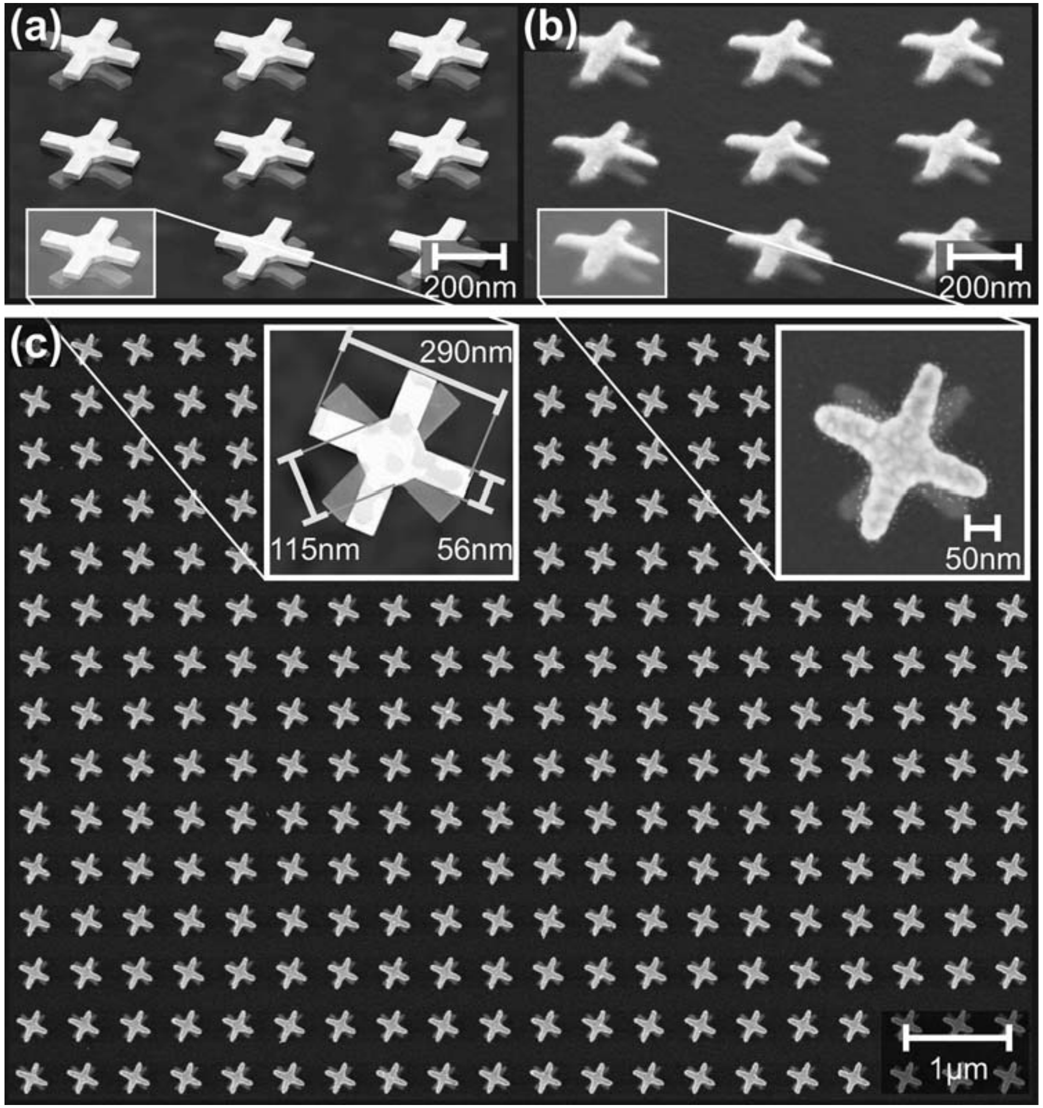
FR4 substrate



Negative index at the magnetic and electric resonance of the structure

Chiral optical structures

Twisted gold crosses



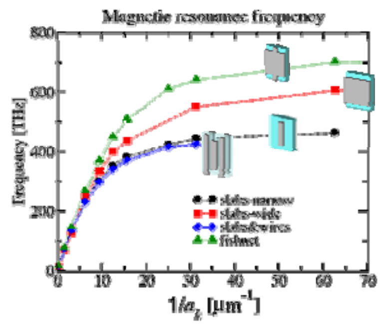
Response @ 1-2 µm

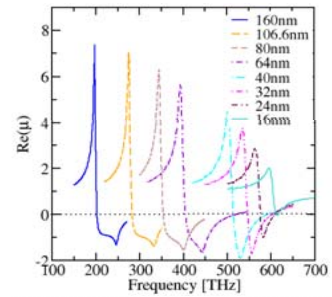
Large polarization rotation
Large circular dichroism

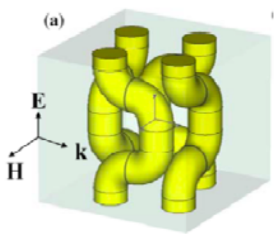
Wegener's group , Opt. Lett. 2009

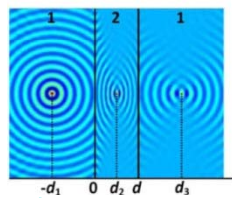
Summary/Conclusions

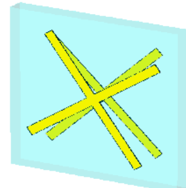
- **Magnetic metamaterial behaviour towards optical regime (nm scale):**
  - **magnetic resonance frequency saturates (higher attainable frequency for fishnet)**
  - **permeability resonance becomes weaker**
  - **losses increase (up to a saturation)**
  - **negative permeability regime vanishes**
- **Metal dispersive response can account for all the above effects and can lead to design rules for high frequency magnetic metamaterials**
- **Connected SRRs can give 2D isotropic negative index materials at ~ 1.5 μm**
- **Anisotropic double negative metamaterials can lead to thin-film superlensing**
- **Chiral structures can give new possibilities in optical metamaterials**











Work thanks to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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*, submitted to Phys. Rev. B. Also at http://xxx.lanl.gov/abs/1001.1073
- **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).