Bending Back Light: The Science of Negative Index Materials

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AMES LABORATORY FORTH IOWA STATE UNIVERSITY OF SCIENCE AND TECHNOLOGY

Left-Handed Materials

AMES LABORATORY

History:

- Permittivity ε, permeability μ and index of refraction *n* negative
- Reversal of Snell's Law, perfect focusing, flat lenses, etc.
- Impedance match $z=\sqrt{\mu/\varepsilon}$ and $n = -1$, zero reflection
- $\lambda >> a$ in LHM, while $\lambda = a$ in PBG

Both PBG and LHM exhibit properties not found in naturally materials

Vision:

- Understanding the physics and the exotic properties of LHMs
- Perfect Lens. Near-field optical microscopy, nano-lithography
- Wireless and optical communications. RF sensing.
- Antenna and microwave device miniaturization

✓ Breakthroughs and new concepts in materials processing at nanoscale

✓ Search for new materials that exhibit $n < 0$ at THz or optical regime

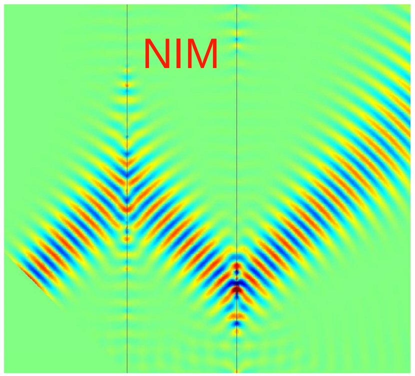
Some reviews articles from our group

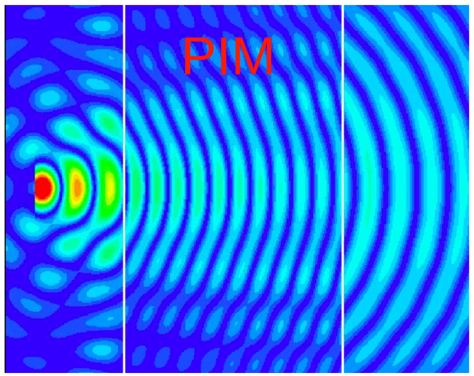
1) Bending Back Light: The Science of Negative Index Materials
   Optics and Photonics News, June 2006

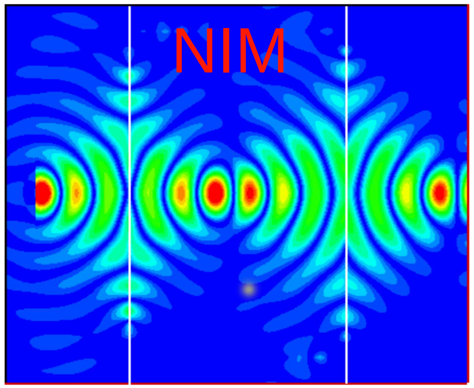
2) Negative index materials: New frontiers in optics,
   Adv. Mater. **18**, 1941 (2006)

3) Photonic metamaterials: Magnetism at optical frequencies,
   IEEE J. of Selected Topics in Quant. Electr. **12**, 1097 (2006)

4) Negative Refractive Index at Optical Wavelengths
   Science **315**, 47 (2007)







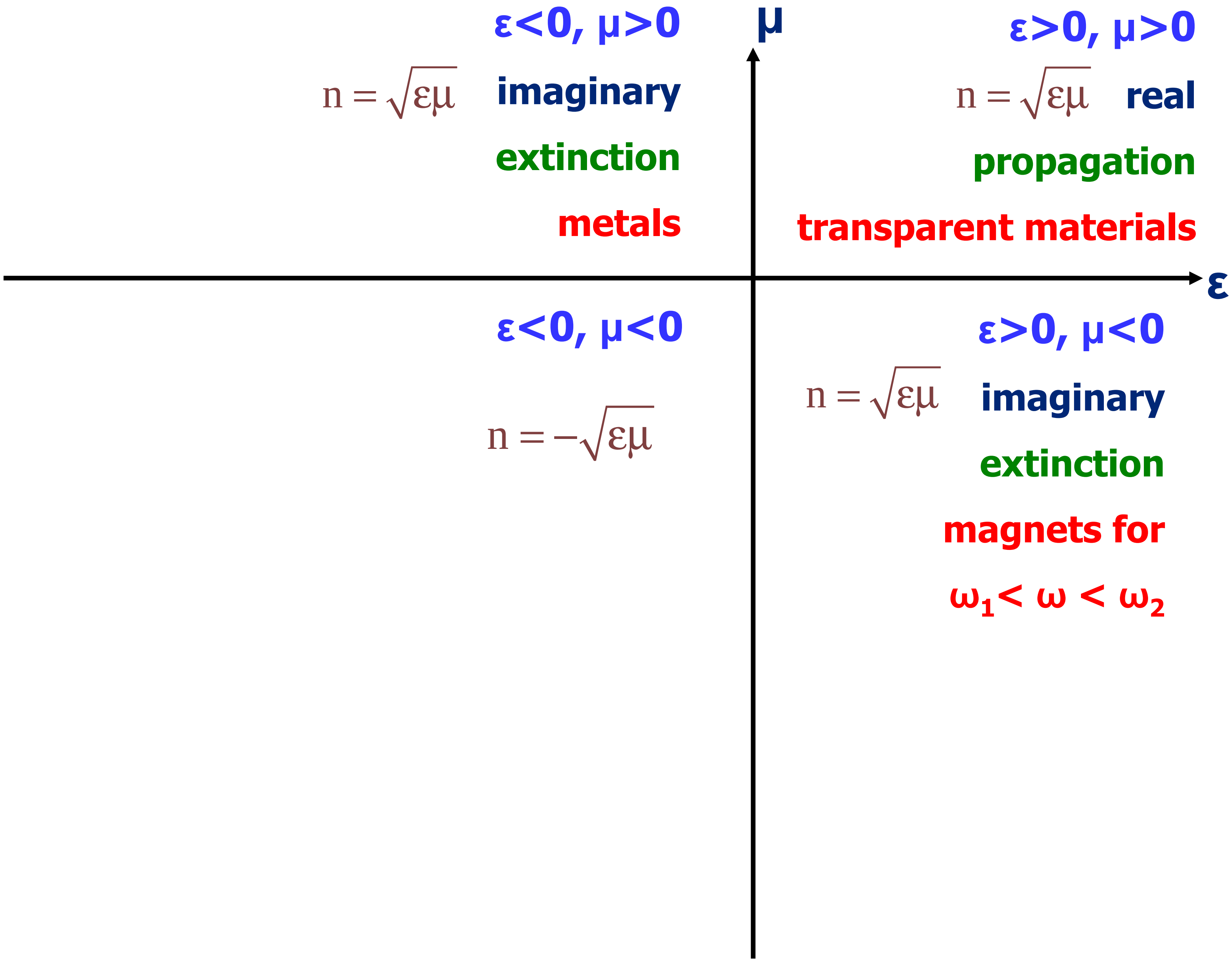
Collaborators

P. Markos (Ames & Slovakia), Th. Koschny (Crete & Ames)
E. N. Economou, M. Kafesaki, N. Katsarakis (Crete, Greece)
S. Foteinopoulou (Crete & Ames)
E. Ozbay's group (Bilkent, Turkey)
Lei Zhang, J. Zhou, R. Moussa & G. Tuttle (Ames, USA)
D. R. Smith (Duke, USA); J. B. Pendry (Imperial, UK)
V. Sandoghdar (ETH, Zurich)
M. Wegener's group, S. Linden (Karlsruhe, Germany)
Boeing's group (Seattle, USA)

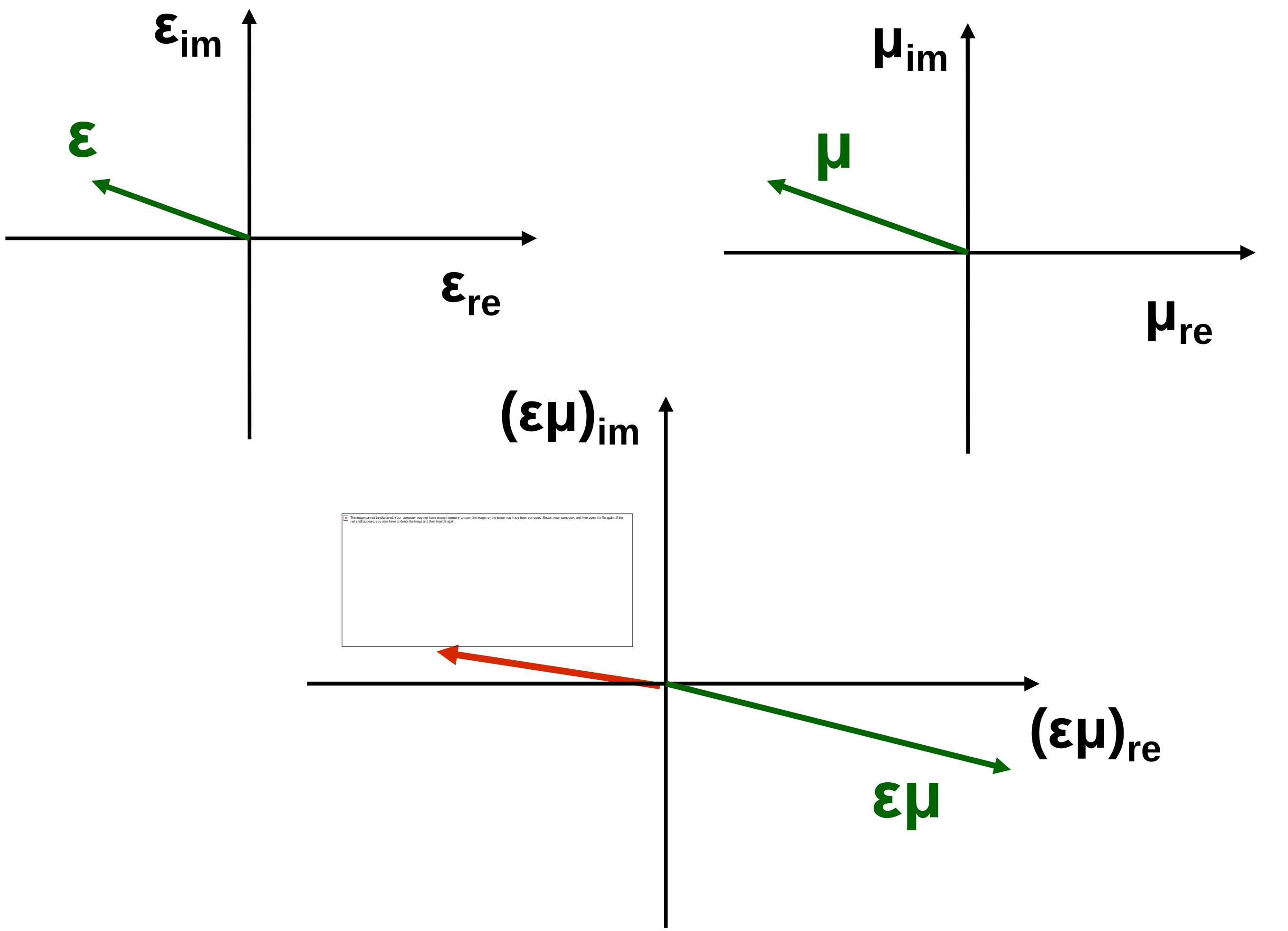
http://cmpweb.ameslab.gov/personnel/soukoulis

Outline of Talk

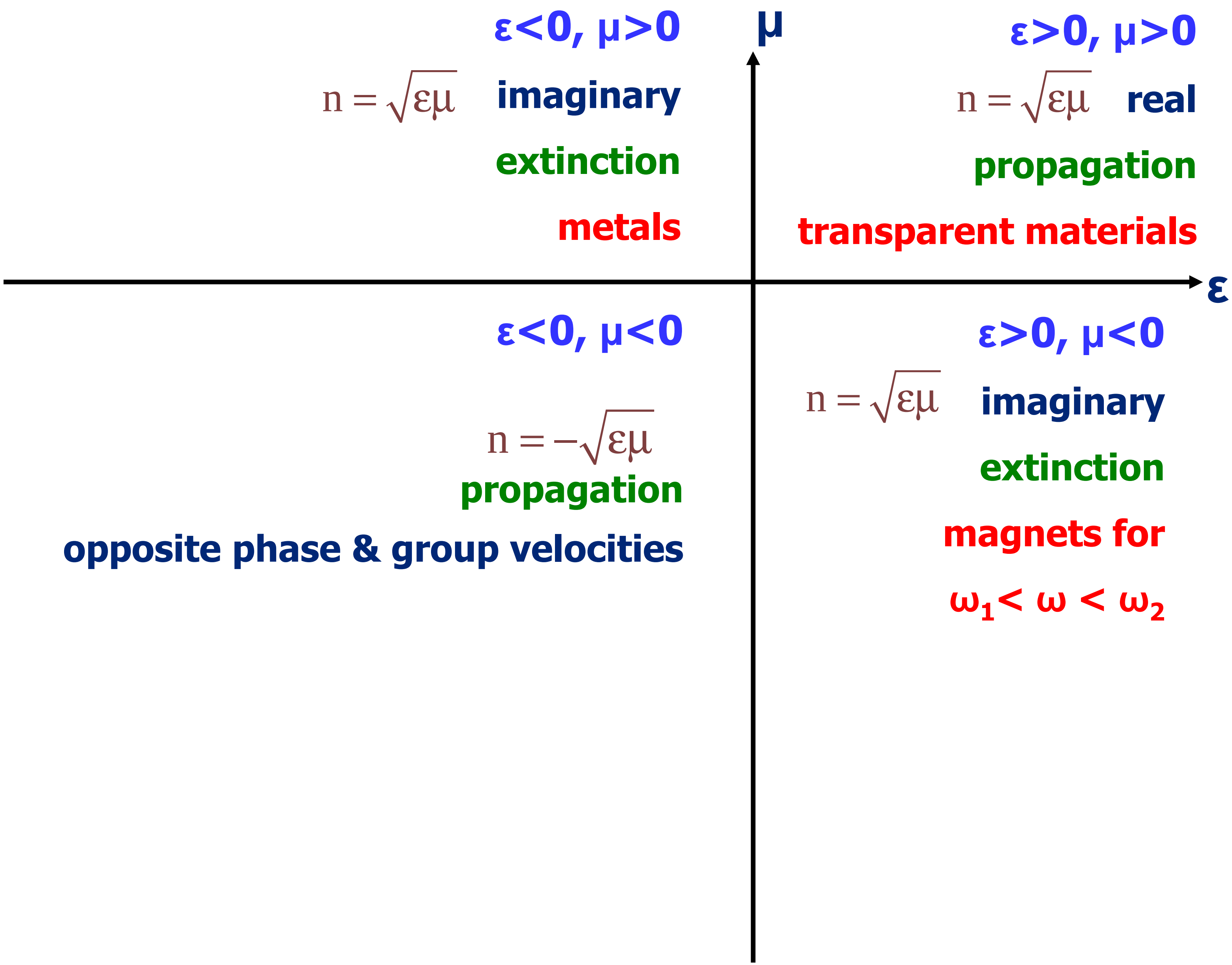
- **Brief history of left-handed materials**
- Electric and Magnetic Response of SRRs and LHMs
- 6, 100 and 200 THz response of SRRs (Karlsruhe, Crete, Ames)
- Upper limits of the SRRs? Simulation results and their interpretation by a LC model. Experiments.
- Breaking of scaling. Top-down approach does not work.
- Diamagnetic response and current density.
- LHM by Double Layer Cut - Wires. Negative n at optical frequencies.
- Negative group and phase velocities in NIMs!
- No negative n with only cut wires.
- Losses can give a negative n, without LH propagation.
- Concluding Remarks (EIT, Chiral, Losses, 3d structures with DLW)


μ
ε
ε<0, μ>0
$n=\sqrt{\varepsilon\mu}$ imaginary
extinction
metals
ε>0, μ>0
$n=\sqrt{\varepsilon\mu}$ real
propagation
transparent materials
ε<0, μ<0
$n=-\sqrt{\varepsilon\mu}$
ε>0, μ<0
$n=\sqrt{\varepsilon\mu}$ imaginary
extinction
magnets for
$\omega_1 < \omega < \omega_2$

Negative ε and μ lead to negative n



Causality requires Im(n)>0 ⇒ Re(n) <0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opposite phase & group velocities
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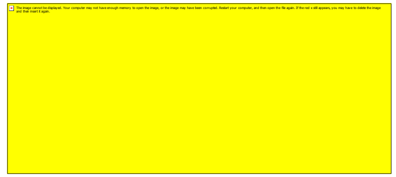
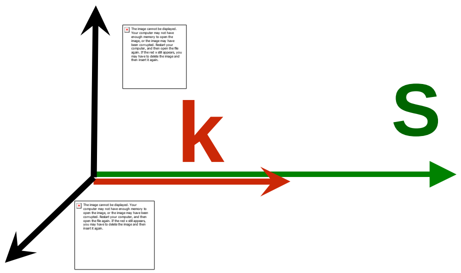
Group vs phase velocity

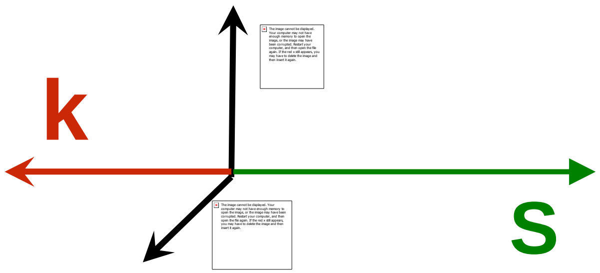


- For ε>0, μ>0 ⇒ (k, E, H) right-handed set



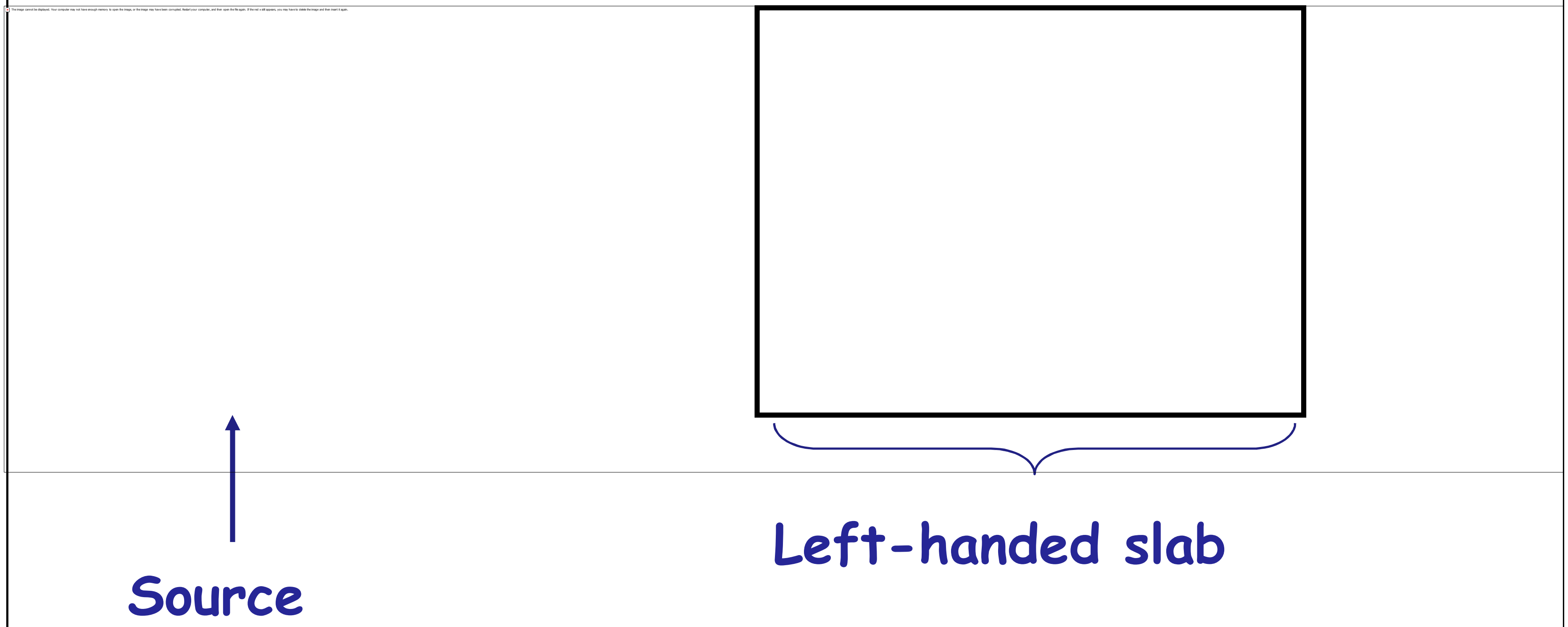
$$\mathbf{S}=\frac{c}{4\pi}\mathbf{E}\times\mathbf{H}=\langle u\rangle\,\mathbf{v}_g$$

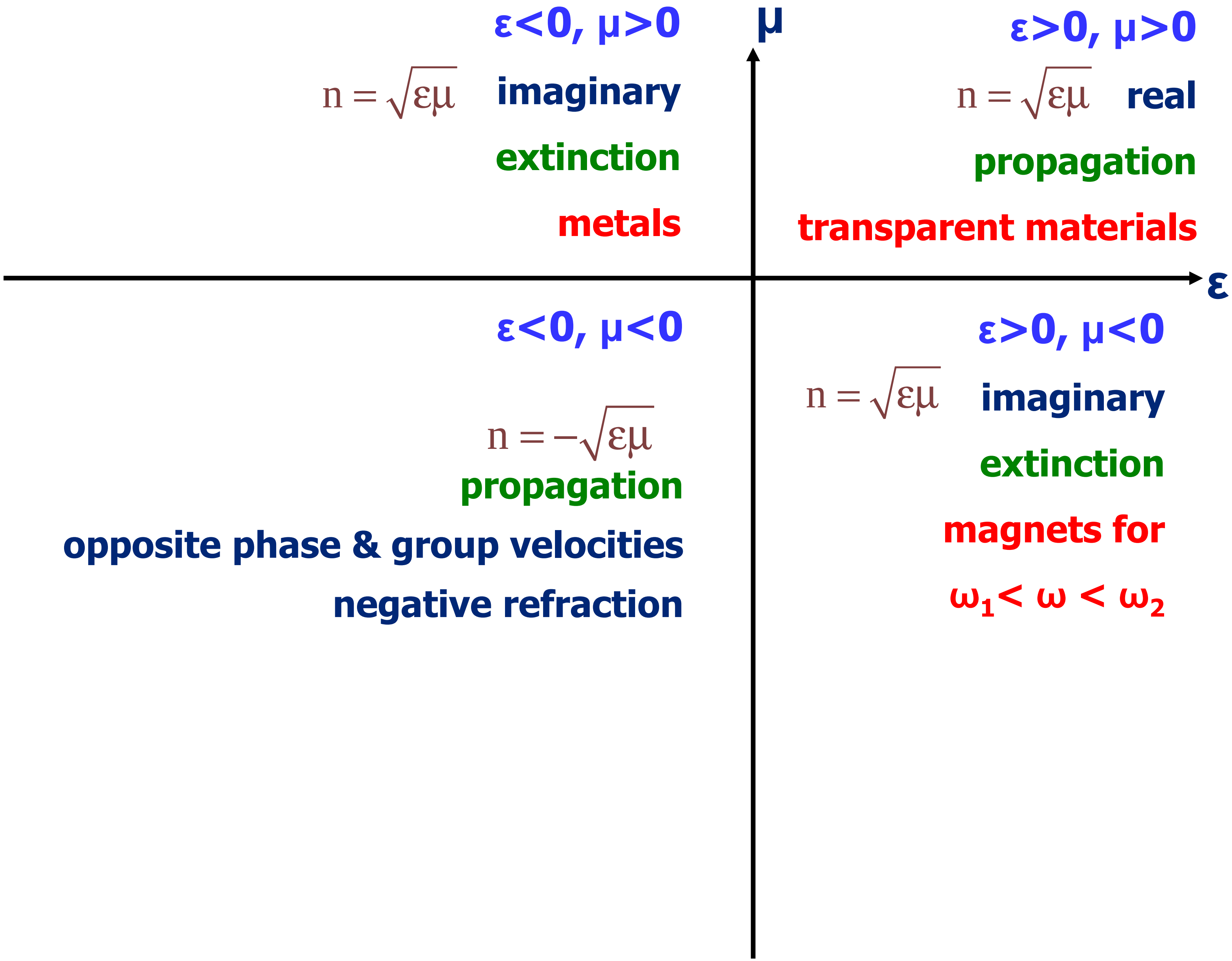
- For ε<0, μ<0 ⇒ (k, E, H) left-handed set



$$\mathbf{v}_g \uparrow\downarrow \mathbf{v}_{ph}$$

Opposite phase and group velocities !!

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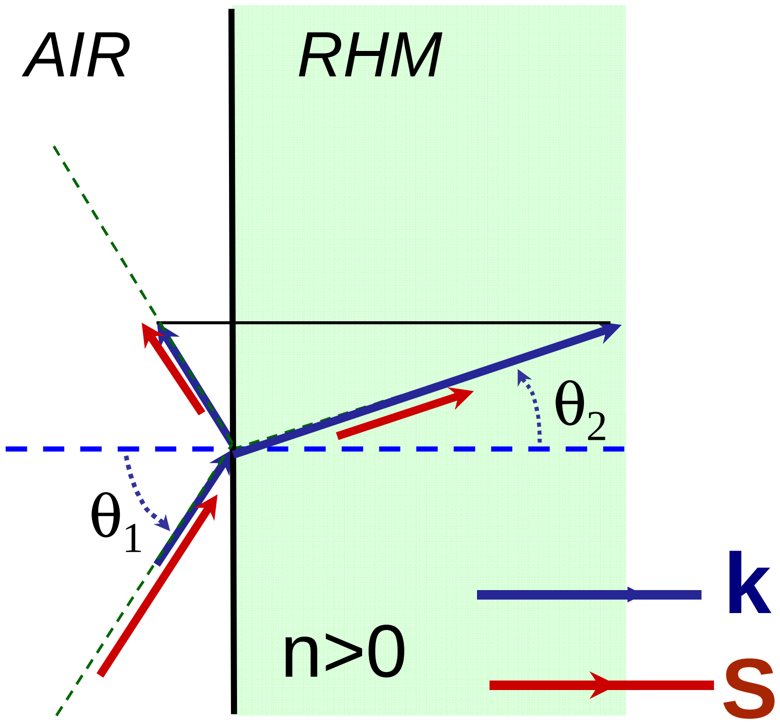
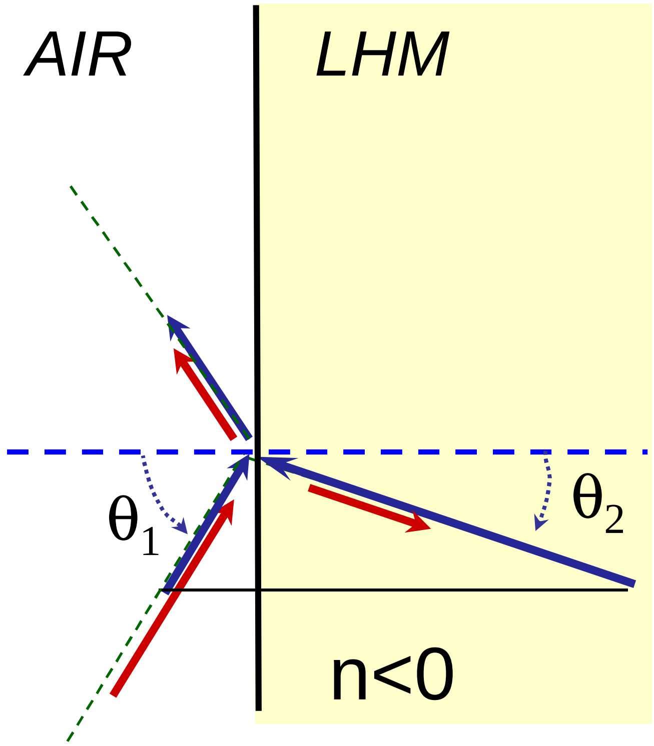
propagation
opposite phase & group velocities
negative refraction
ε>0, μ<0
$n = \sqrt{\varepsilon\mu}$ imaginary
extinction
magnets for
$\omega_1 < \omega < \omega_2$

Negative refraction - Snell's law reversion

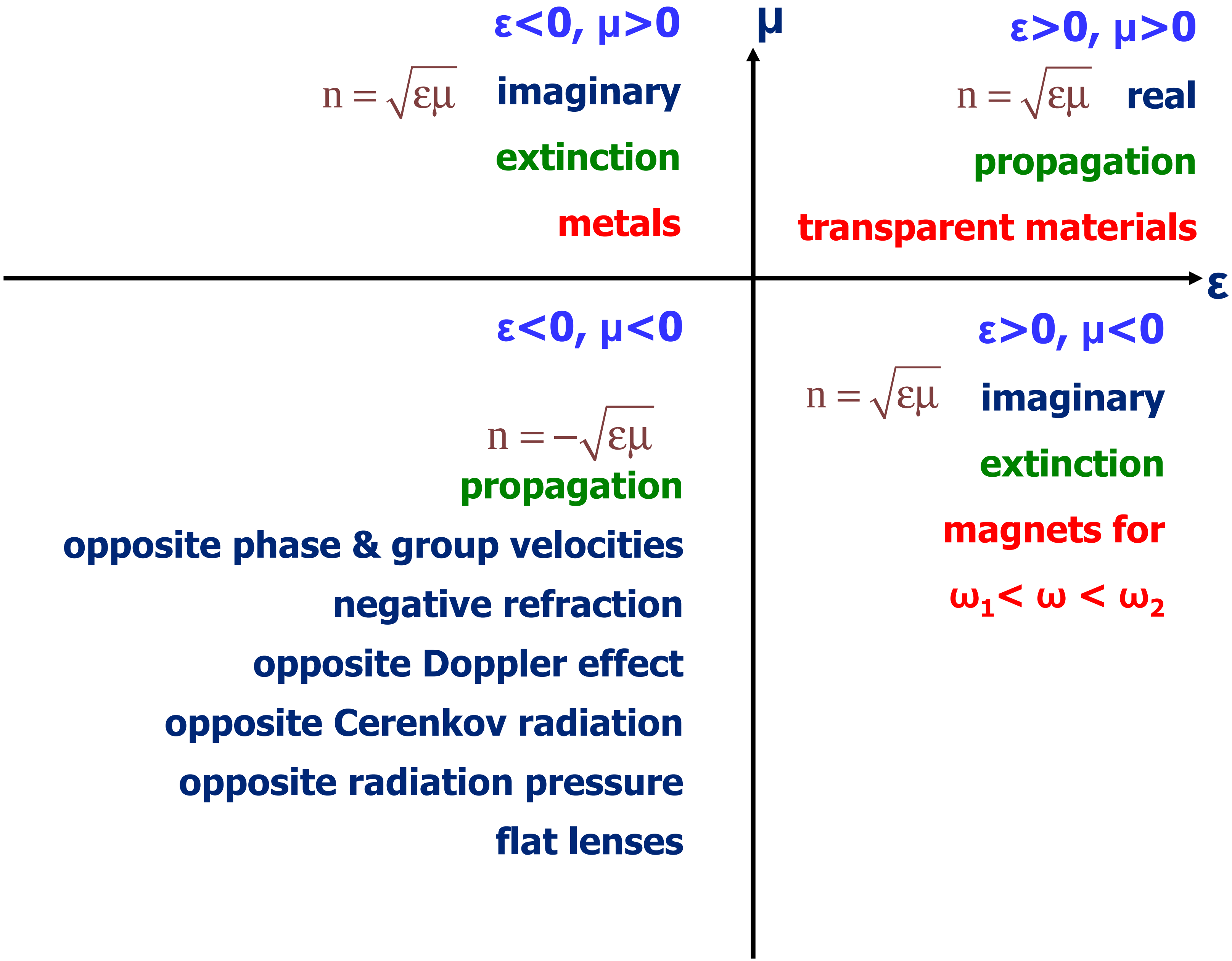




$$\sin\theta_2 = \frac{1}{n}\sin\theta_1$$

Snell-Descartes' law valid with n<0

Negative refraction - Snell's law reversion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negative refraction
opposite Doppler effect
opposite Cerenkov radiation
opposite radiation pressure
flat lenses
ε>0, μ<0
$n = \sqrt{\varepsilon\mu}$ imaginary
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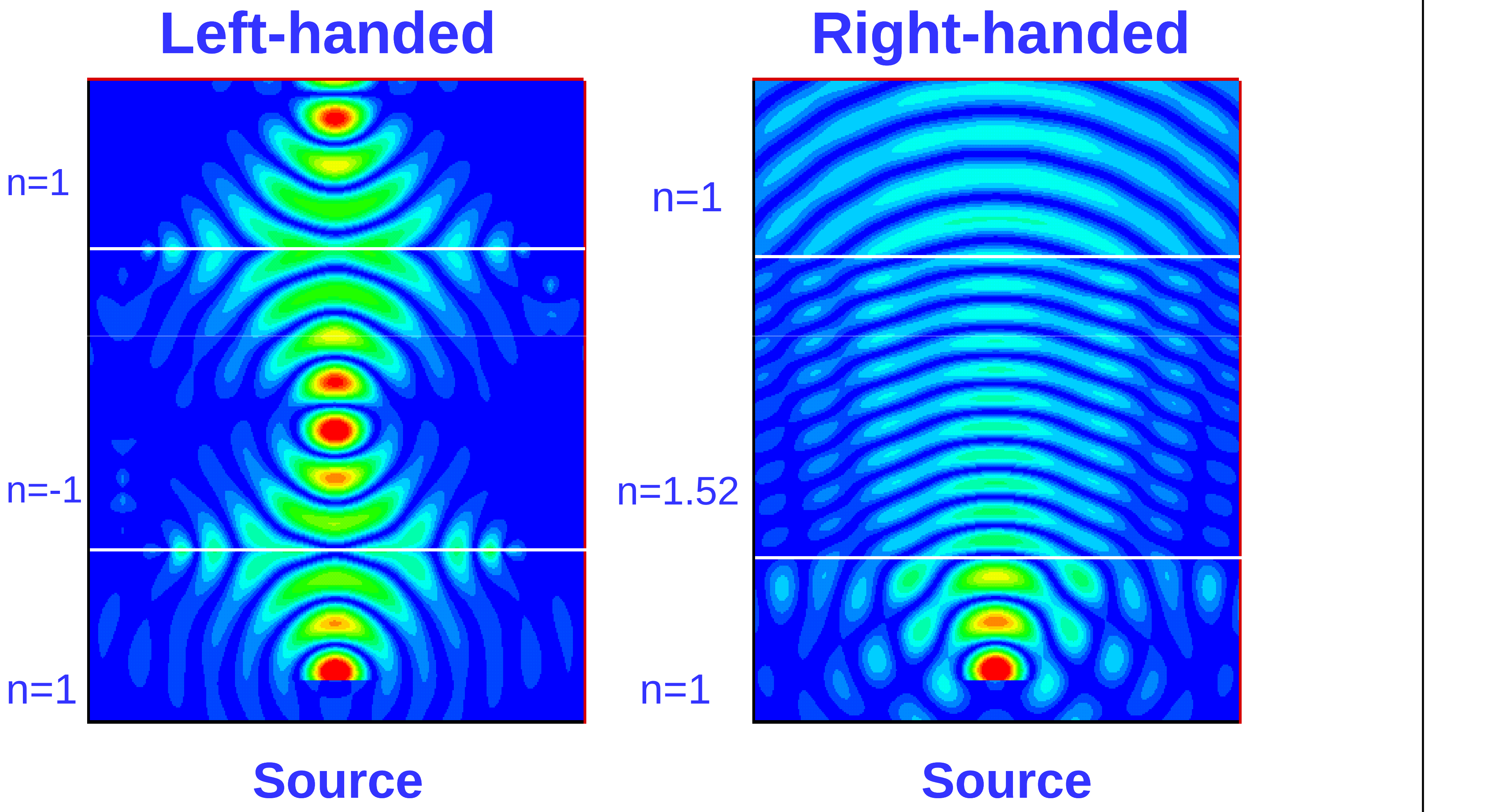
Left-handed media as flat lenses



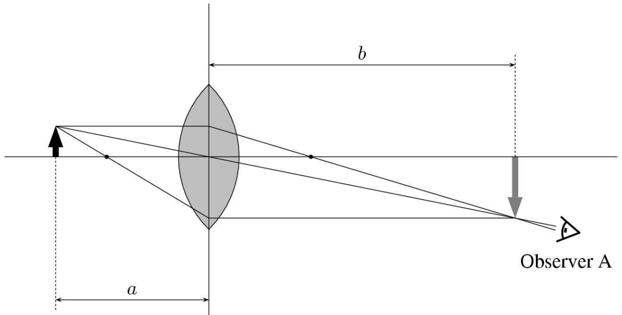
Left-handed media as flat lenses

Normal lens

real, inverse 2d-image

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

$$\frac{\partial b}{\partial a} = -\left(\frac{b}{a}\right)^2$$

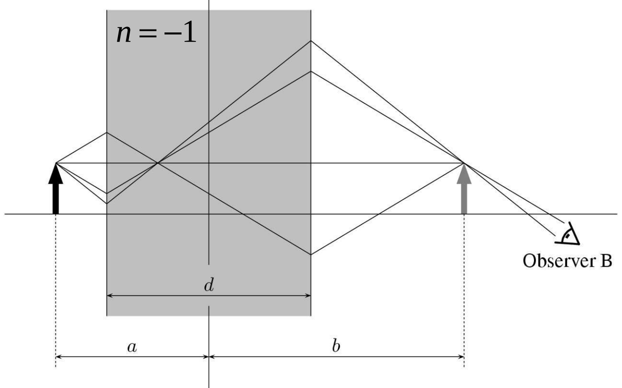


Flat LH lens

real, (semi-) 3d-image

$$a + b = 2d$$

$$\frac{\partial b}{\partial a} = -1$$



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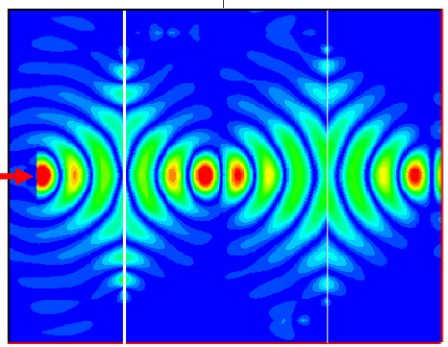
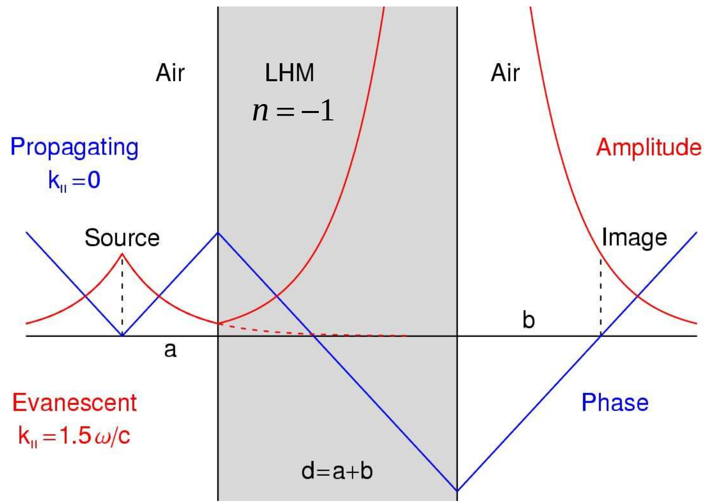


Super lens

Optical lens = phase restoration
(for propagating modes, evanescent waves are lost)



Super-lens = phase + amplitude restoration
(propagating and evanescent waves are recovered)

$$k_{\perp} = -k_{\perp}'$$

$\varepsilon<0, \mu>0$

$n = \sqrt{\varepsilon\mu}$ **imaginary**

extinction

metals

$\varepsilon>0, \mu>0$

$n = \sqrt{\varepsilon\mu}$ **real**

propagation

transparent materials

$\varepsilon<0, \mu<0$

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

propagation

opposite phase & group velocities

negative refraction

opposite Doppler effect

opposite Cerenkov radiation

opposite radiation pressure

flat lenses

perfect lenses

optical antimatter

$\varepsilon>0, \mu<0$

$n = \sqrt{\varepsilon\mu}$ **imaginary**

extinction

magnets for

$\omega_1 < \omega < \omega_2$

Axes: μ (vertical), ε (horizontal)

- Suggested theoretically by Veselago et al. Sov. Phys. Usp. 10, 509 (1968)
- Ignored, because of lack of materials with $\varepsilon < 0$, $\mu < 0$ (secret garden of electromagnetics)

A dream that had to wait for ~ 30 years

$\varepsilon<0,\ \mu>0$

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

extinction

metals

μ

$\varepsilon>0,\ \mu>0$

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

propagation

transparent materials

ε

$\varepsilon<0,\ \mu<0$

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

propagation

opposite phase & group velocities

negative refraction

opposite Doppler effect

opposite Cerenkov radiation

flat lenses

perfect lenses

zero index of refraction

zero reflection

$\varepsilon>0,\ \mu<0$

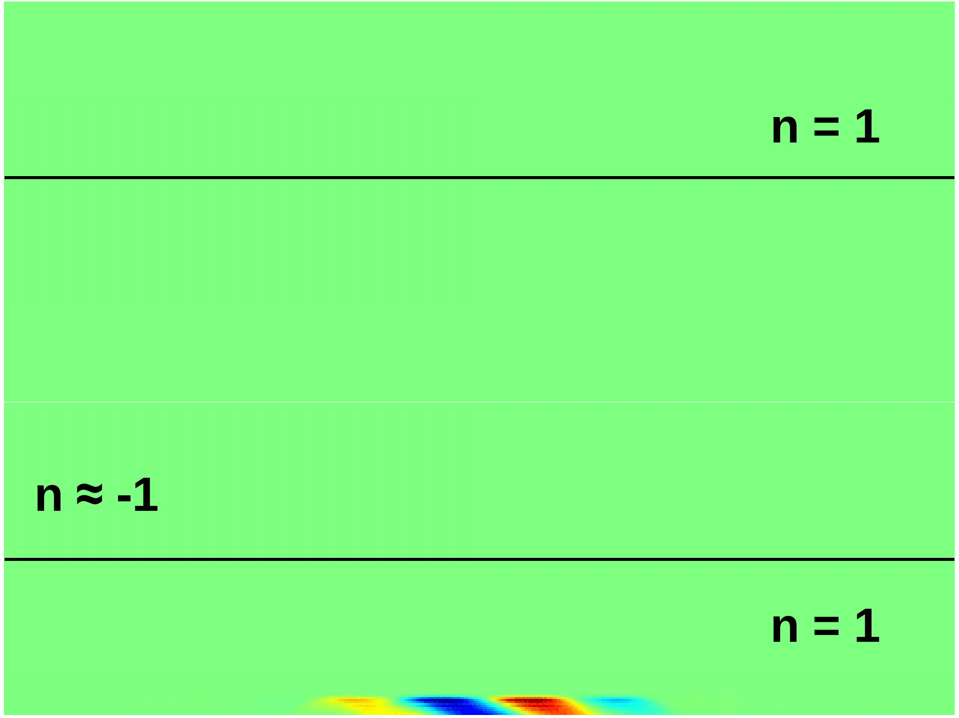
$n=\sqrt{\varepsilon\mu}$ imaginary

extinction

magnets for

$\omega_1<\omega<\omega_2$

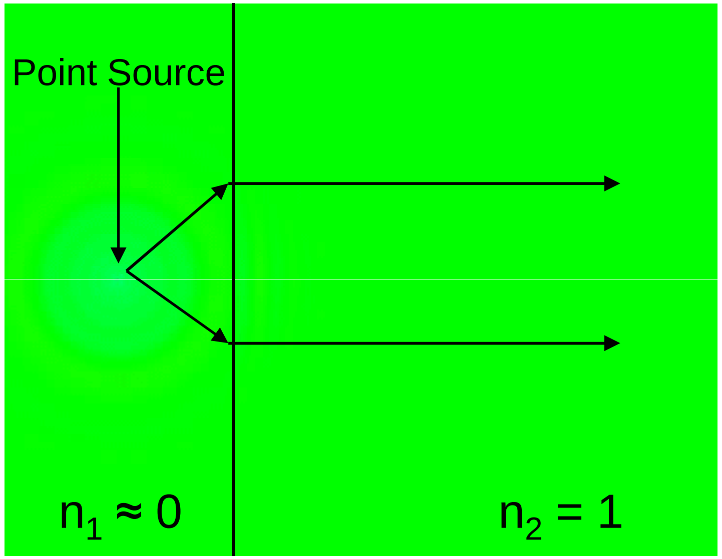
Negative refraction in metamaterials



ε = μ= -1+0.001 i

Frequency=30 GHz, λ=0.01 m, thickness of metamaterial = 4 λ

Metamaterials with zero index of refraction



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

A dream comes true: Prof. Pendry suggests structures with ε<0 and μ<0

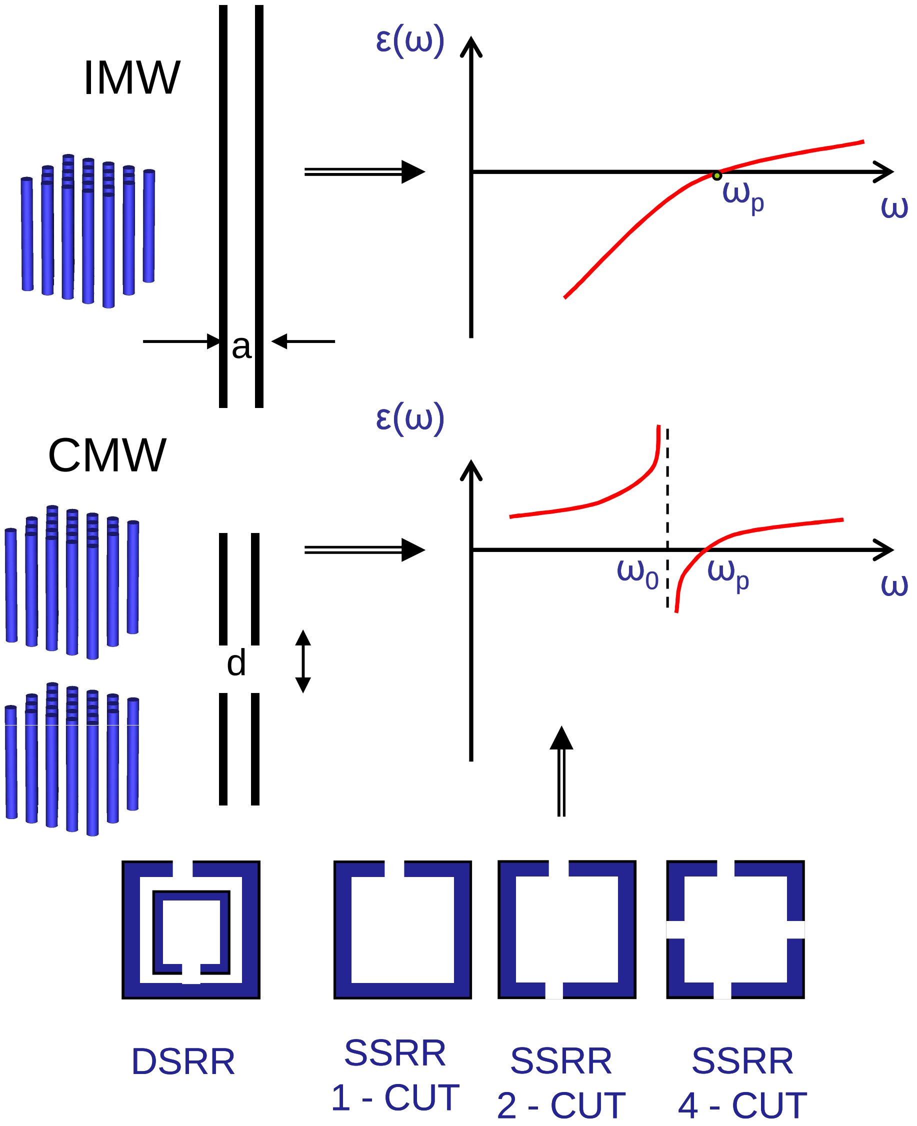
Basic idea behind: RESONANCES

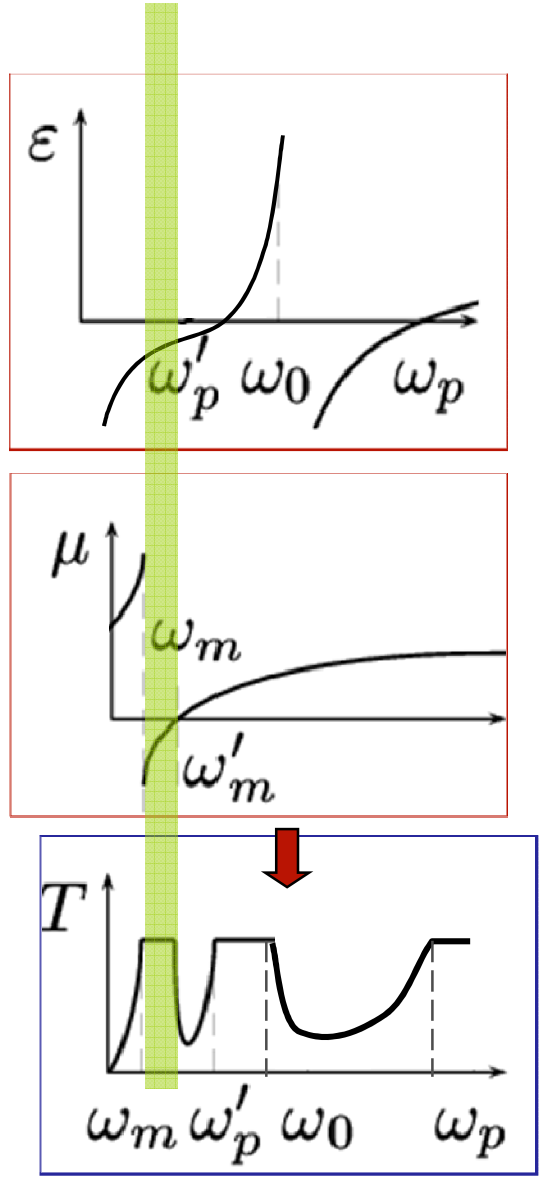
- **For ε < 0: A wire medium. It can yield ε < 0 in a tunable frequency range (Pendry et al., PRL 1996). Artificial dielectrics using metals!!**
- **For μ < 0: Split ring resonators. They yield μ < 0 in a tunable frequency range (Pendry et al., IEEE, 1999). Artificial magnetic materials using non-magnetic metals!!**
- **A combined medium can yield *both* ε < 0 *and* μ < 0 simultaneously.**
- **A medium with negative index of refraction should be possible by using these suggested structures?**

Frequency dispersion of LH medium

- Energy density in the dispersive medium
- Energy density ***W*** must be positive and this requires
- *LH medium is always dispersive*
- According to the Kramers-Kronig relations – it is *always dissipative*

ω_p=1/a & ω_o=d





PRB **65**, 195104 (2002)

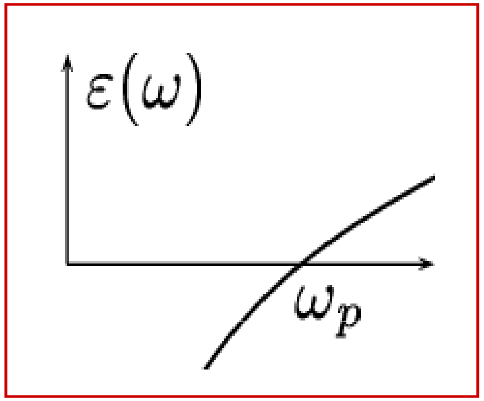
PRE **71**, 121103 (2005)

PRL **93**, 107402 (2004)

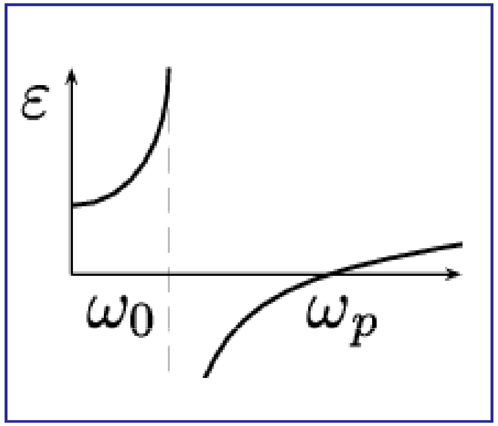
PRB **70**, 201101 (2004)

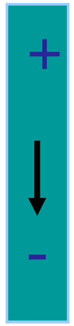
Cut-wire response

Continuous-wires



Cut-wires





$$m\frac{\partial^2 \mathbf{x}}{\partial t^2} = e\mathbf{E}$$

$$m\frac{\partial^2 \mathbf{x}}{\partial t^2} = e\mathbf{E} - m\omega_0^2\mathbf{x}$$

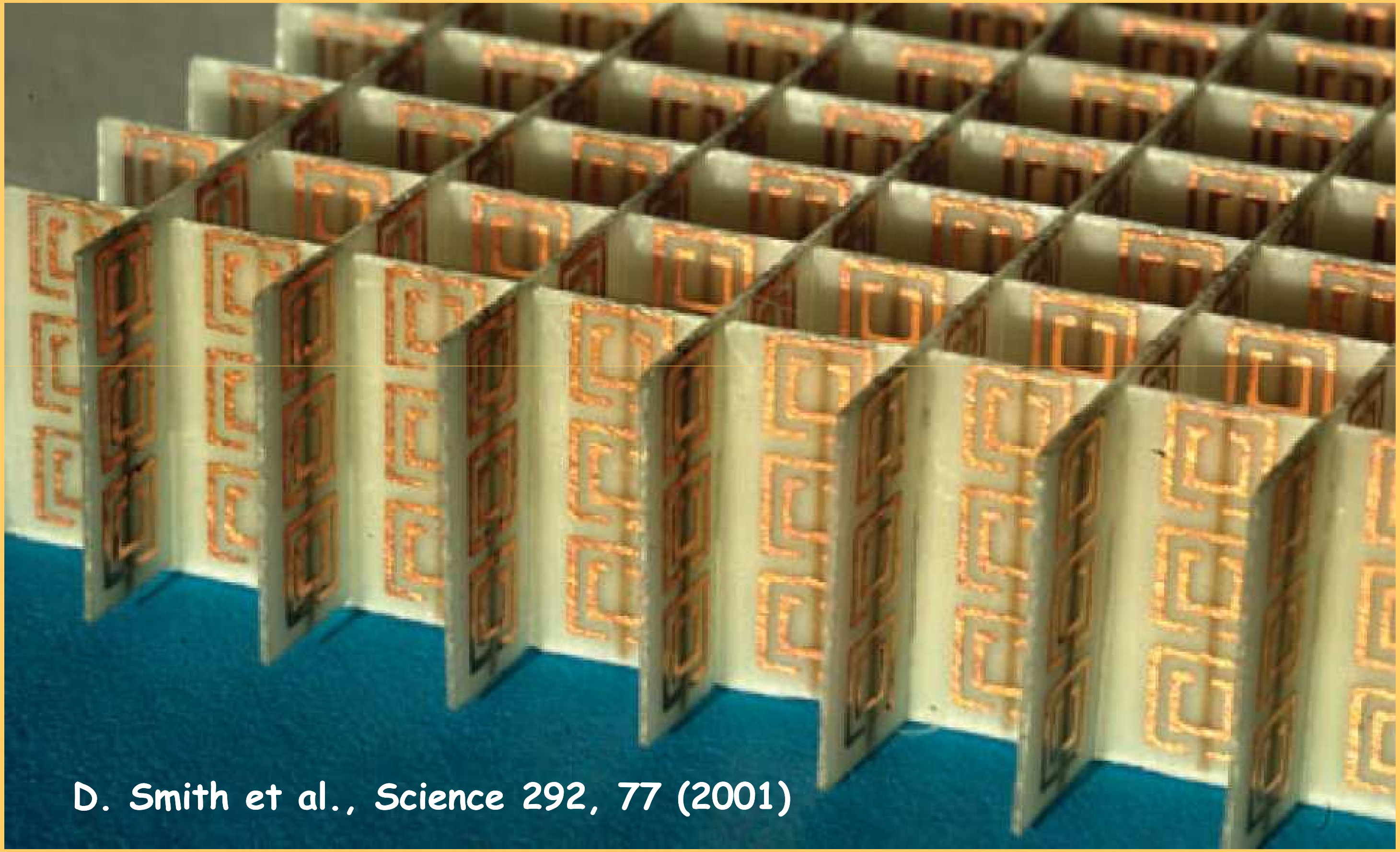
$$\mathbf{j} = -i\omega\mathbf{P} = ne\mathbf{v} = ne(-i\omega\mathbf{x}) \Rightarrow \mathbf{P} = ne\mathbf{x} \Rightarrow \mathbf{P} = f(\mathbf{E})$$

The SRR is like an LC resonator

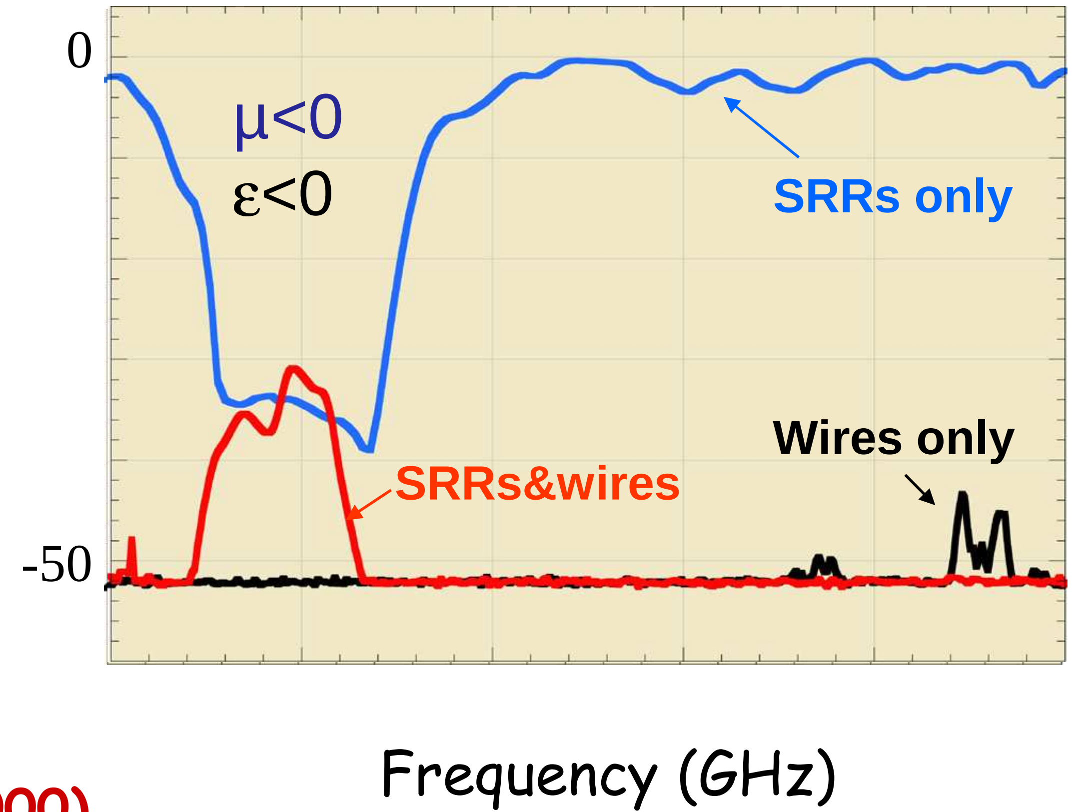
First Left-Handed Test Structure

UCSD, PRL 84, 4184 (2000)

David Smith (UCSD) used Prof. Pendry's suggested structures to demonstrate the first material with a negative index of refraction

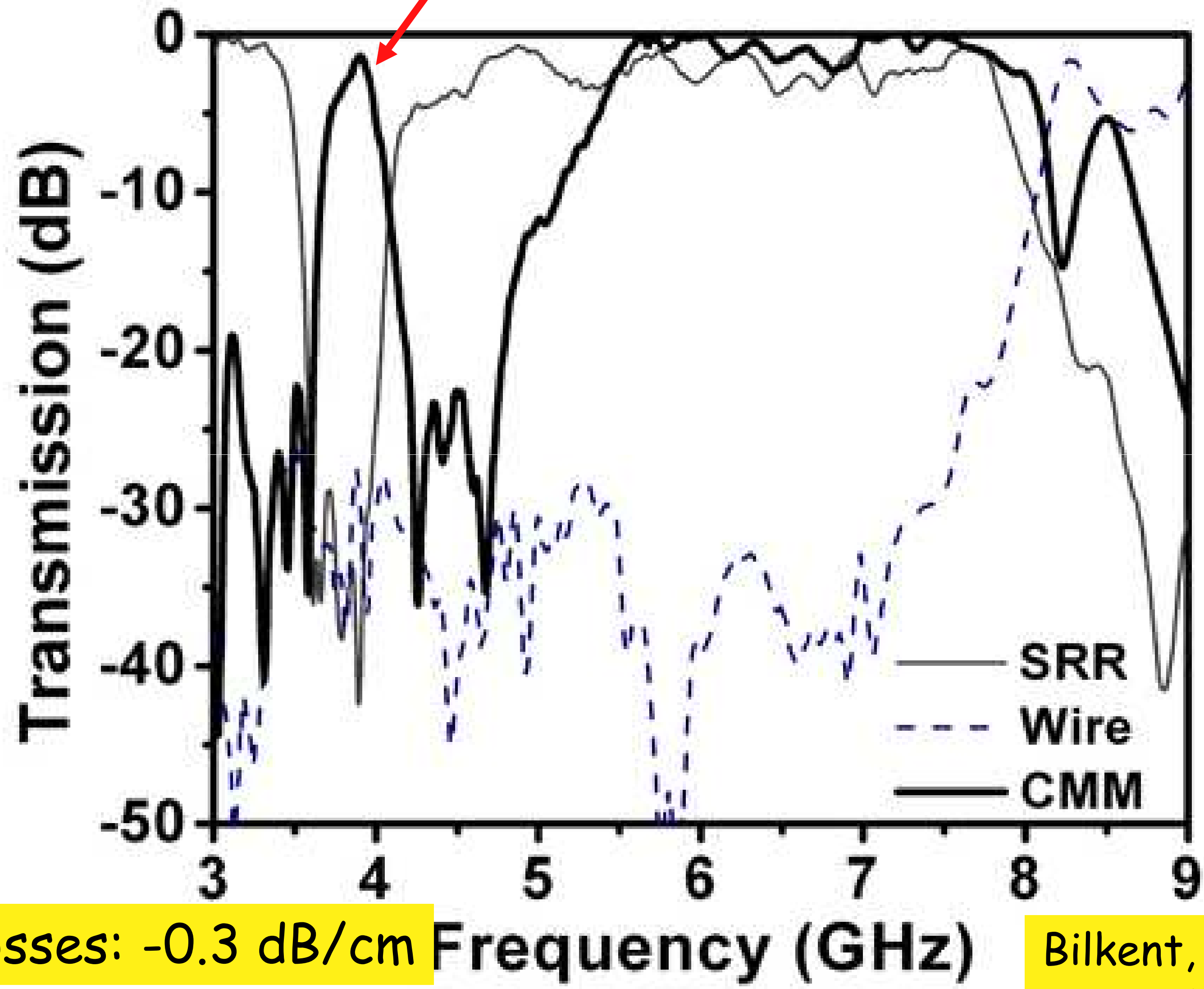


First experimental verification of a NIM



UCSD, PRL 84, 4184 (2000)

Best LH peak in a left-handed material



Peak at
f=4 GHz
λ=75 mm

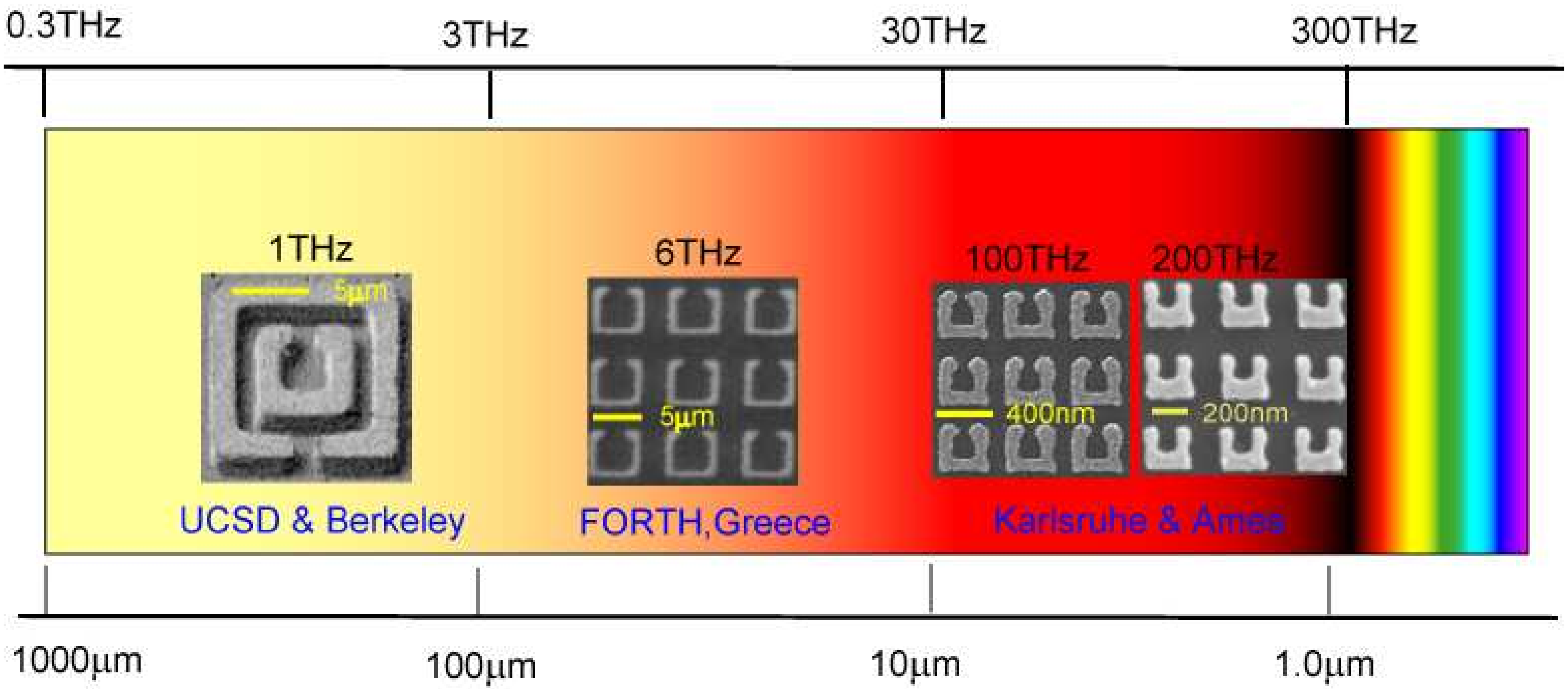
much larger
than the
size of SRR

a=3.6 mm

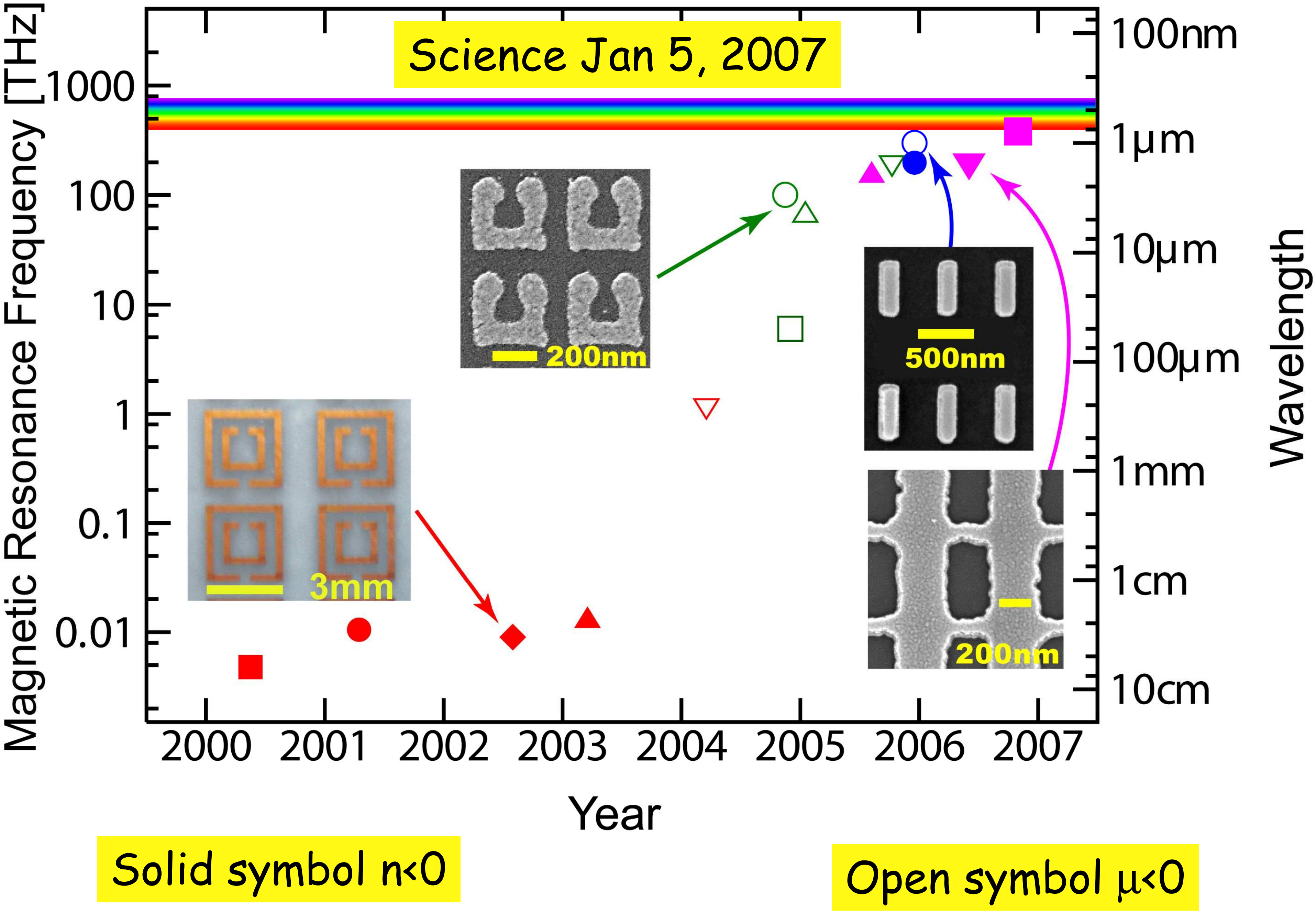
Losses: -0.3 dB/cm

Bilkent, Crete, & Ames
Optics Lett. 29, 2623 (2004)

The progress of scaling metamaterials



Advances in scaling metamaterials with artificial magnetic response for high-frequency structures has been rapid. The 1, 6 and 100 THz models were fabricated in 2004, and the 200 THz in 2005.

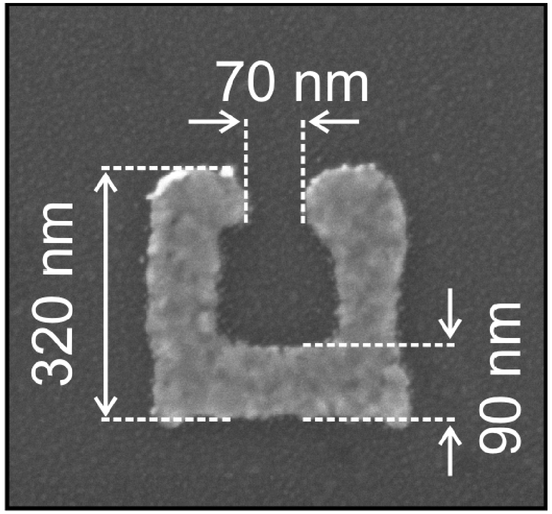

Science Jan 5, 2007
Magnetic Resonance Frequency [THz]
1000
100
10
1
0.1
0.01
Wavelength
100nm
1μm
10μm
100μm
1mm
1cm
10cm
200nm
500nm
3mm
200nm
2000
2001
2002
2003
2004
2005
2006
2007
Year
Solid symbol n<0
Open symbol μ<0

Metamaterials structures shown in these split-ring resonators (SRRs) are amenable to manufacture by common planar lithography.

It has a magnetic response perpendicular to the plane, which is difficult to detect by direct incidence measurements.

Use of multilayer processing can been used to fabricate metamaterials that give both negative ε and μ, as well as n for perpendicular propagation.

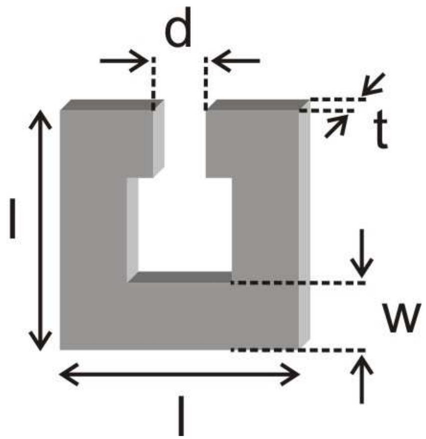
Estimating the LC-resonance



$$L = \mu_0 \frac{l^2}{t} = 5.6\,\mathrm{pH}$$

$$C = \varepsilon_0 \varepsilon_C \frac{wt}{d} = 0.5\,\mathrm{aF}$$

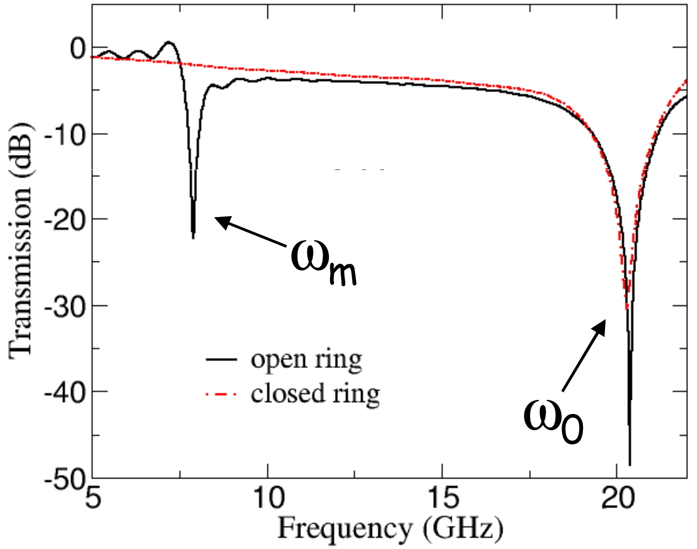
$$\omega_{LC} = \frac{1}{\sqrt{LC}} = 2\pi\, 100\,\mathrm{THz}$$

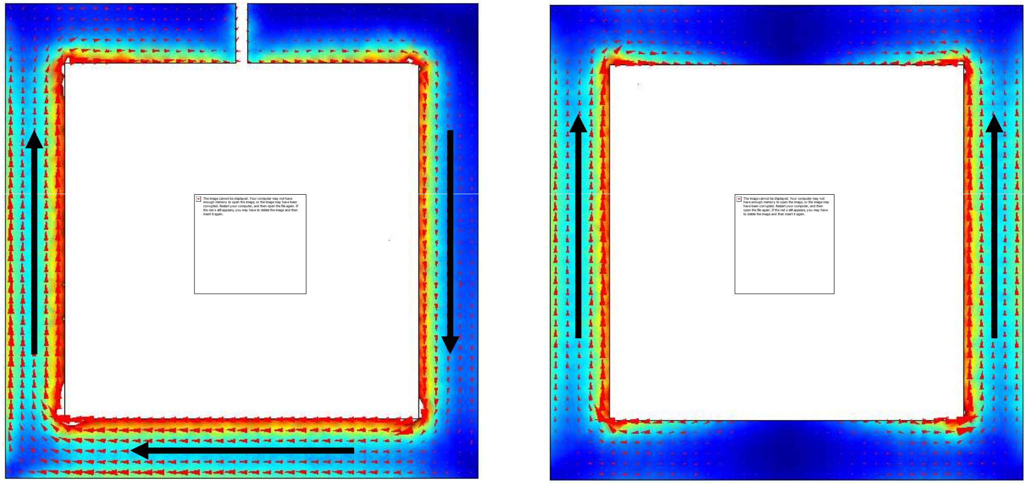


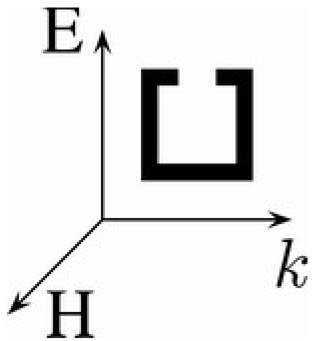
$$\Rightarrow \lambda_{LC} = l\, 2\pi \sqrt{\varepsilon_C} \sqrt{\frac{w}{d}} \approx 3\,\mu\mathrm{m}$$

Electric response of the SRRs?

SRRs have also resonant electric response, cut-wire like



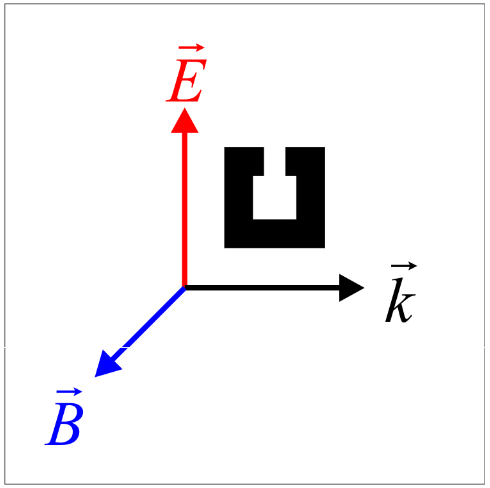


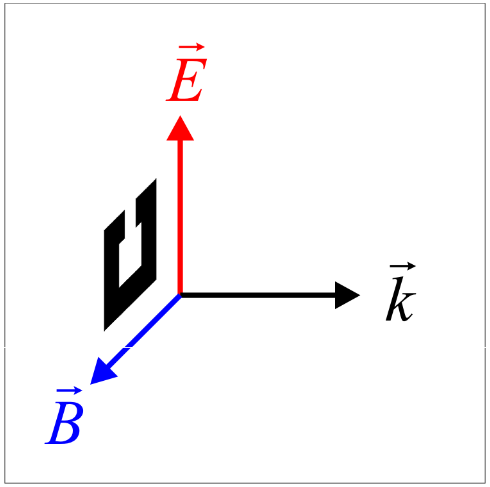


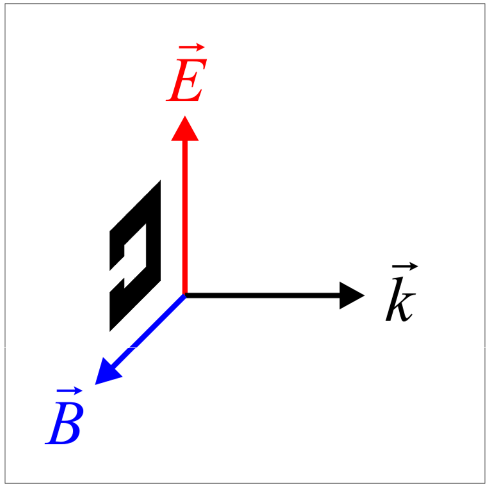
Closing the gap: Magnetic response off

Electric response unaffected

Polarization dependence







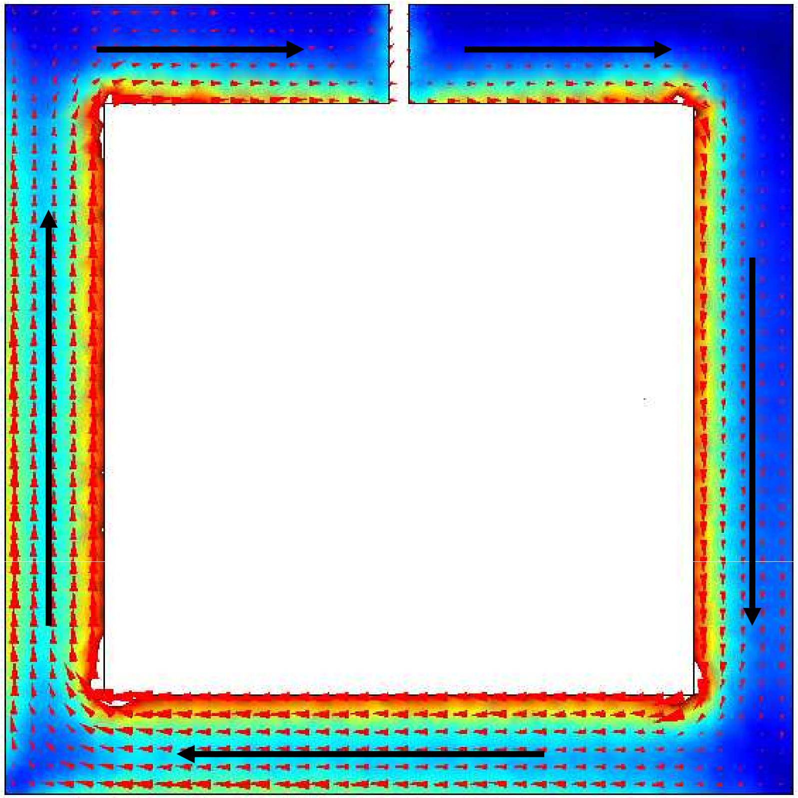
Coupling to *LC*-resonance via *B*, not accessible for normal incidence.

No coupling to *LC*-resonance, normal incidence.

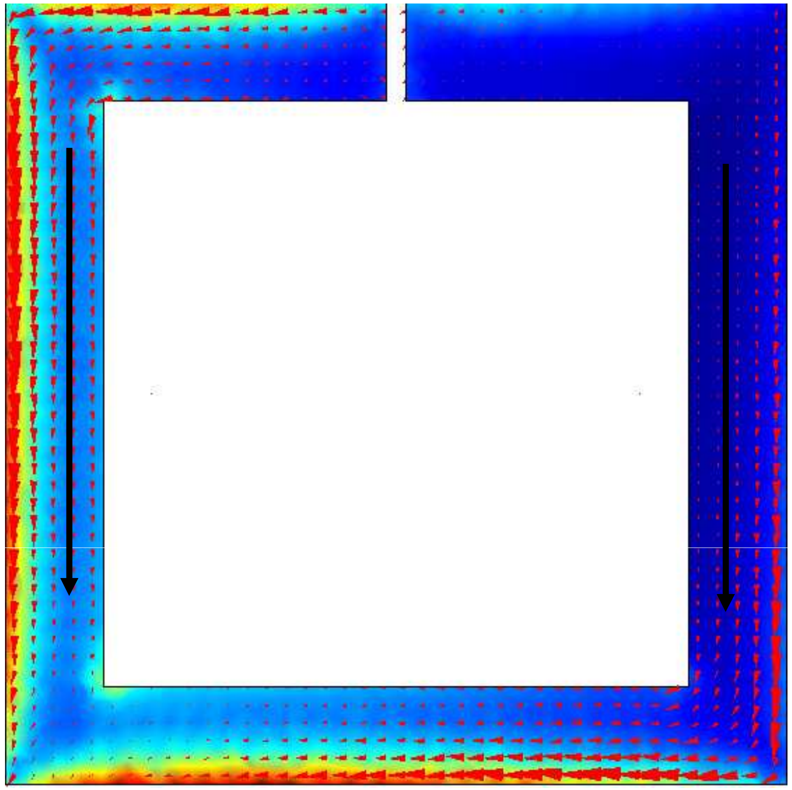
Coupling to *LC*-resonance via *E*, accessible for normal incidence

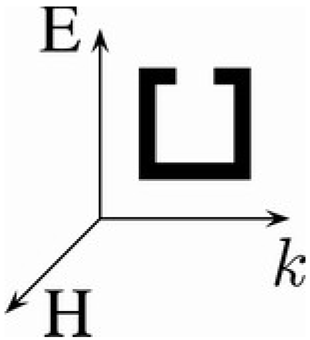
N. Katsarakis et al., Appl. Phys. Lett. **84**, 2943 (2004).

Magnetic Resonance



Electric Resonance

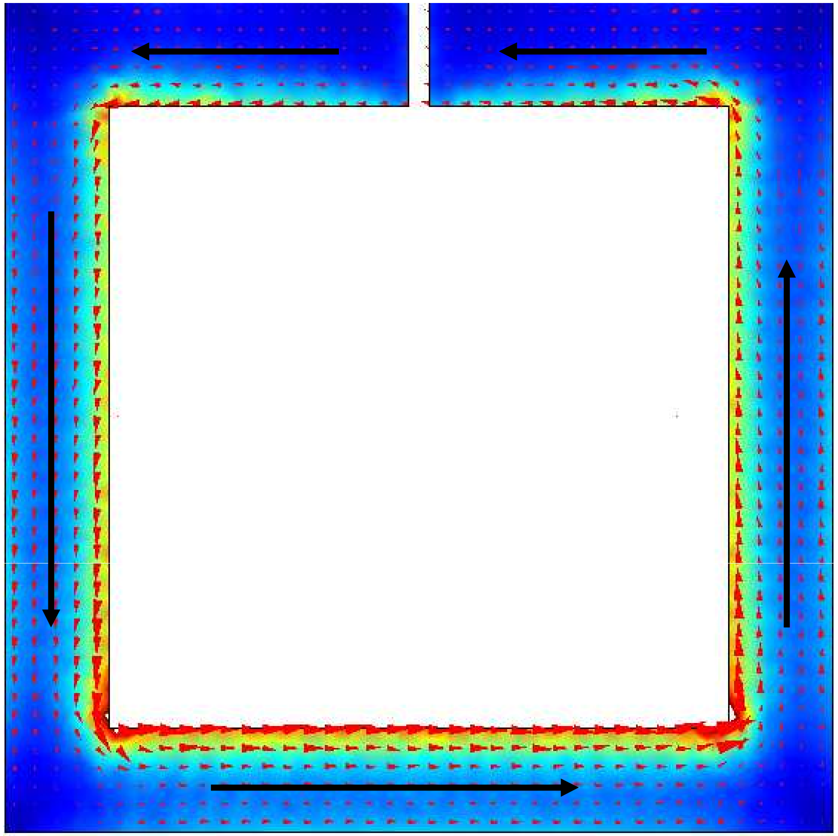




27.4 THz

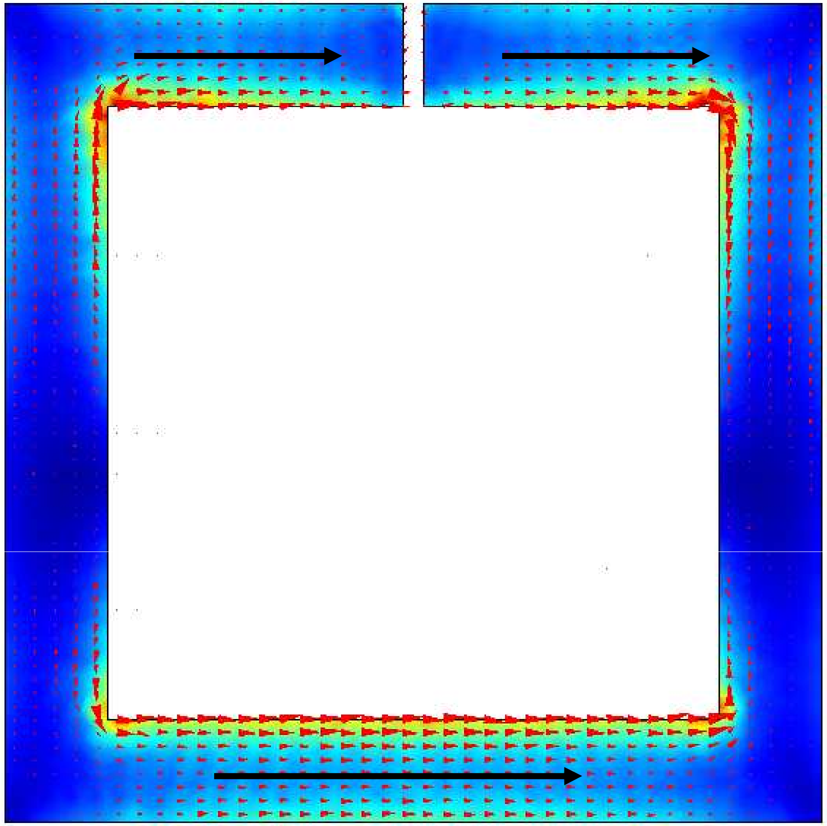
90.3 THz

Magnetic Resonance

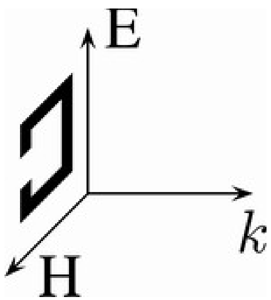


27.4 THz

Electric Resonance



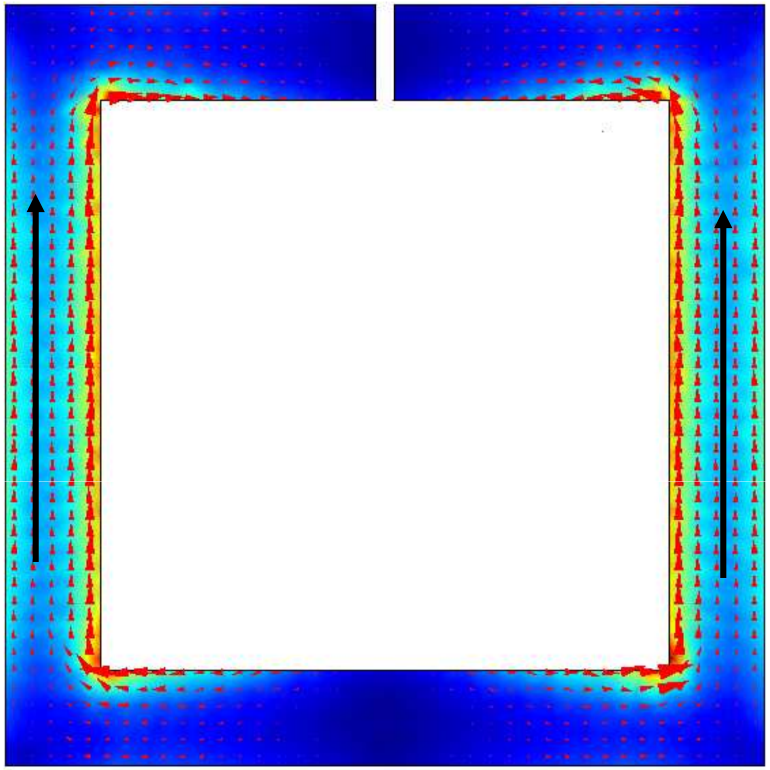
117.9 THz

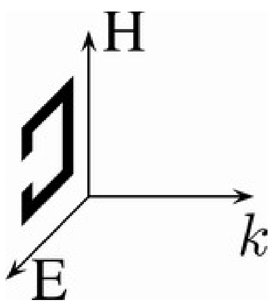


The magnetic resonance frequency is the same for both polarizations

The electric resonance frequency is higher than the previous case

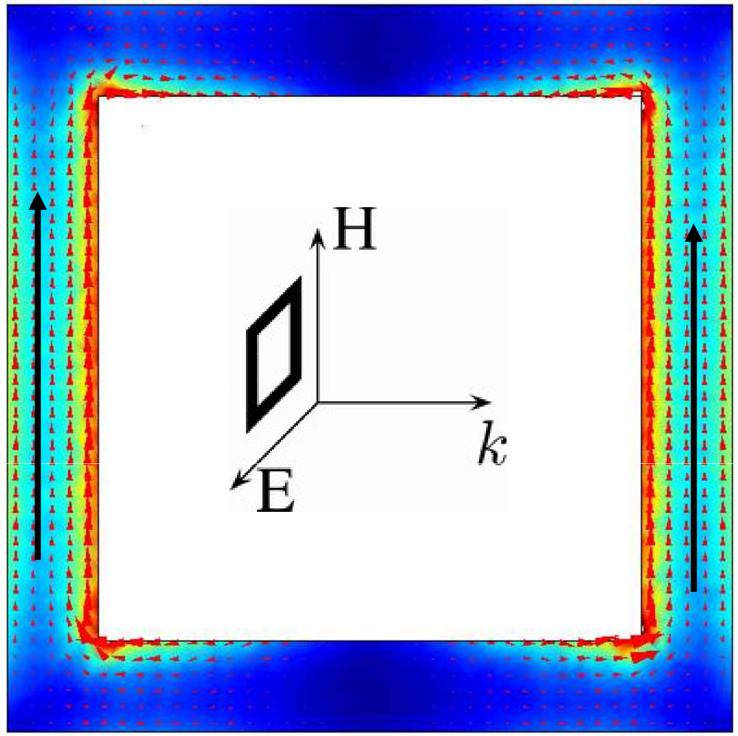
Electric Resonance





87.4
THz

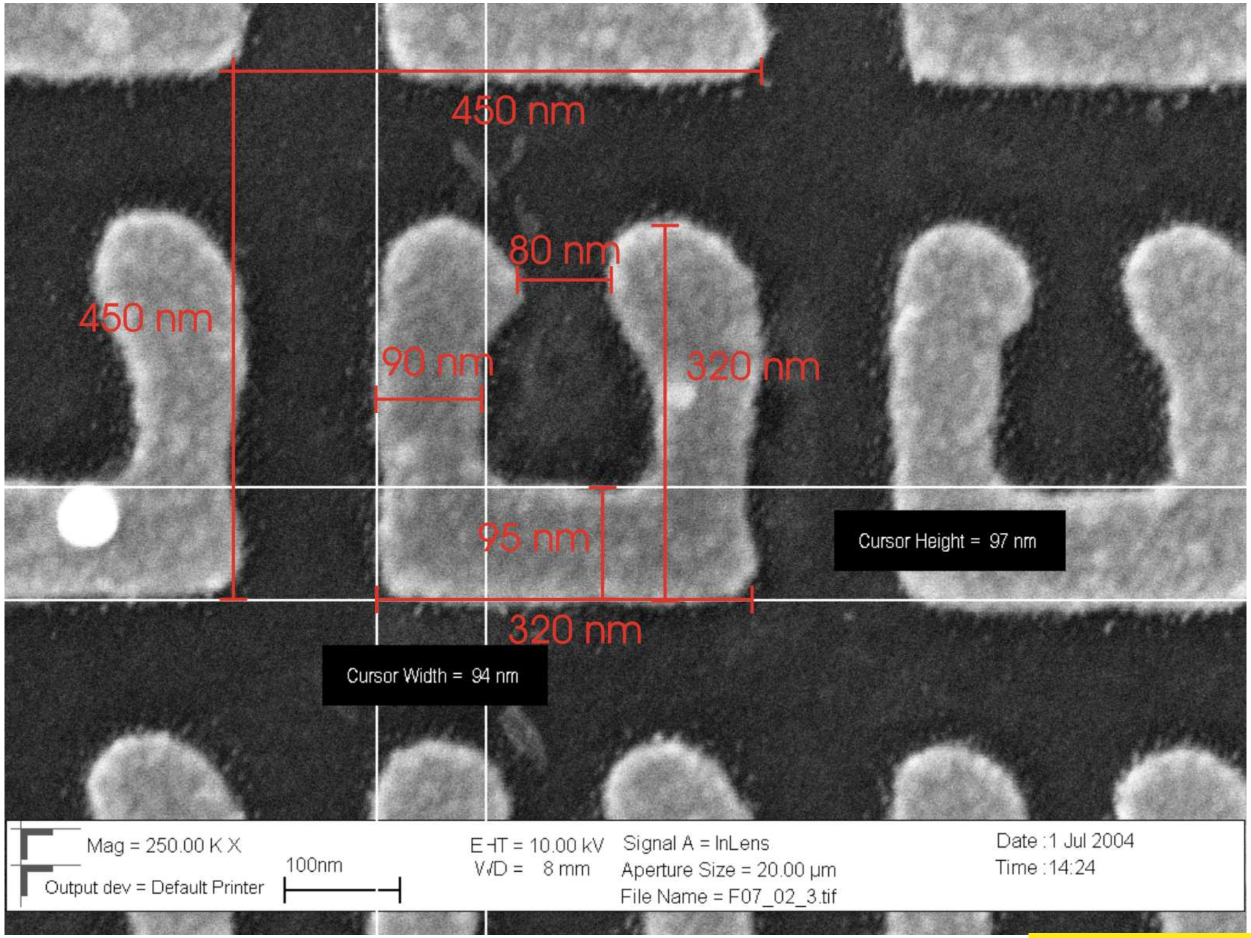
Electric Resonance



87.4 THz
close ring

Notice that the electric resonance frequency is the same for the open and closed ring SRR for this incident polarization

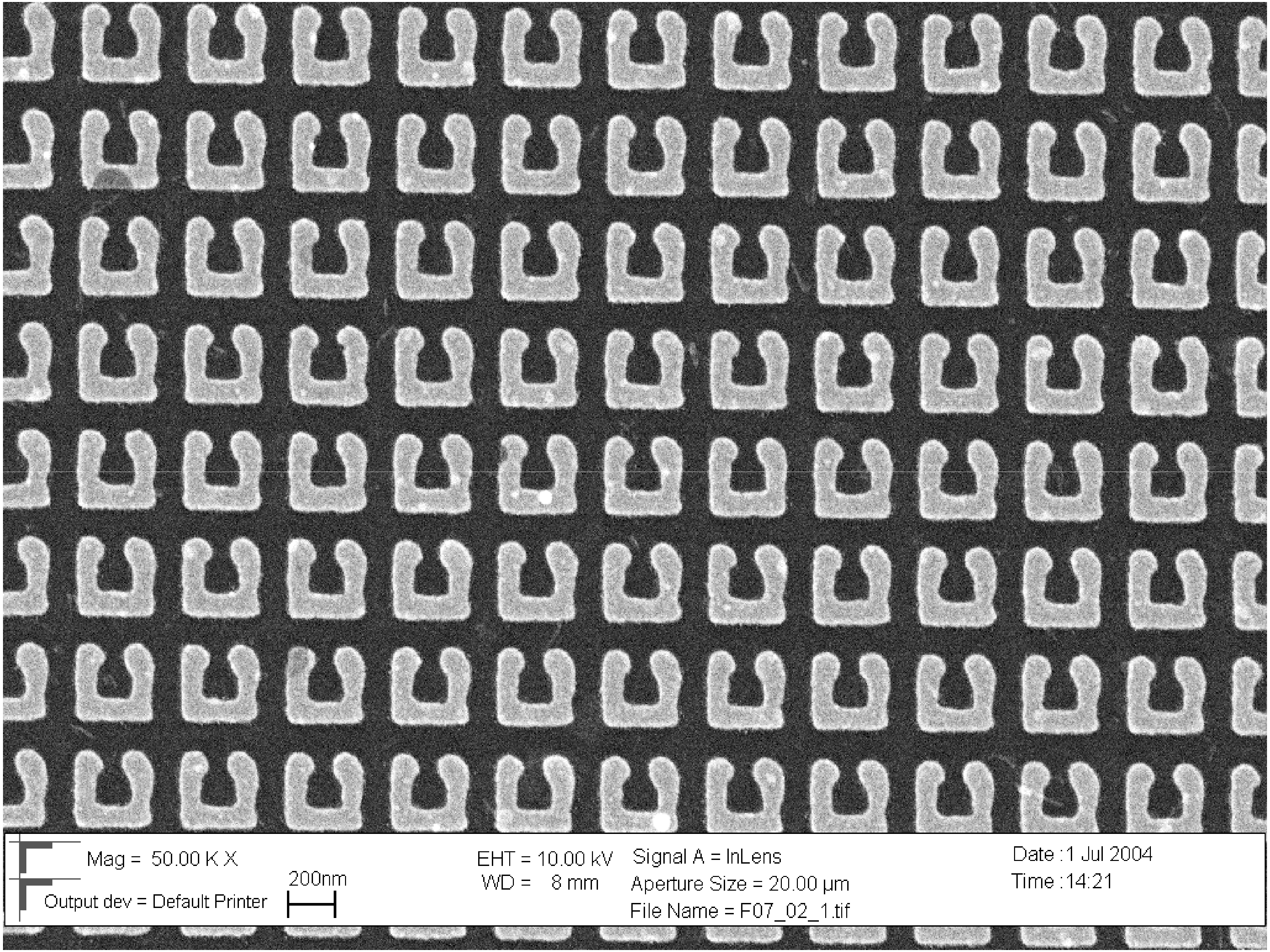
Magnetic response at 100 THz
almost optical frequencies



λ~10 a

Science, Nov 19, 2004

Univ. of Karlsruhe, & Ames Lab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WD = 8 mm
Signal A = InLens
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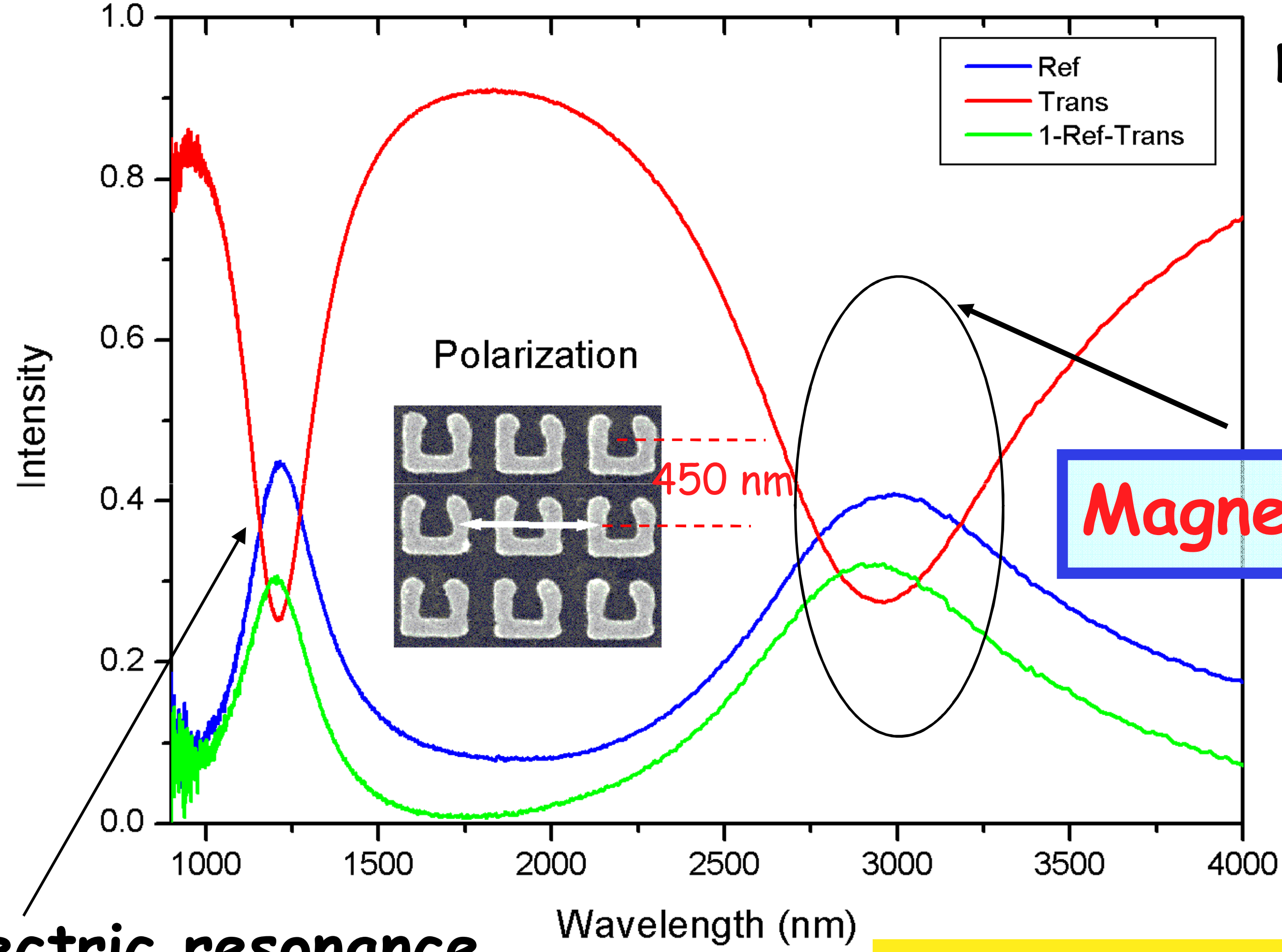
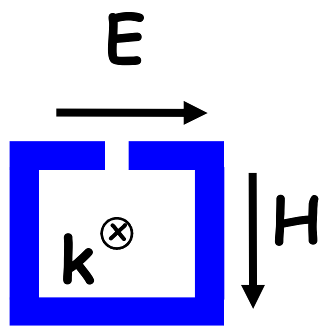
Date :1 Jul 2004
Time :14:21

Magnetic response at 100 THz

Experimental spectra for sample



Normal illumination



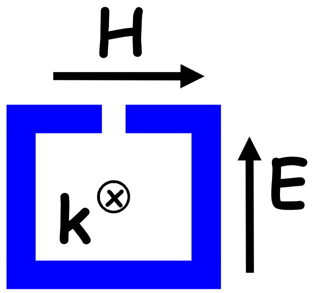
Magnetic resonance

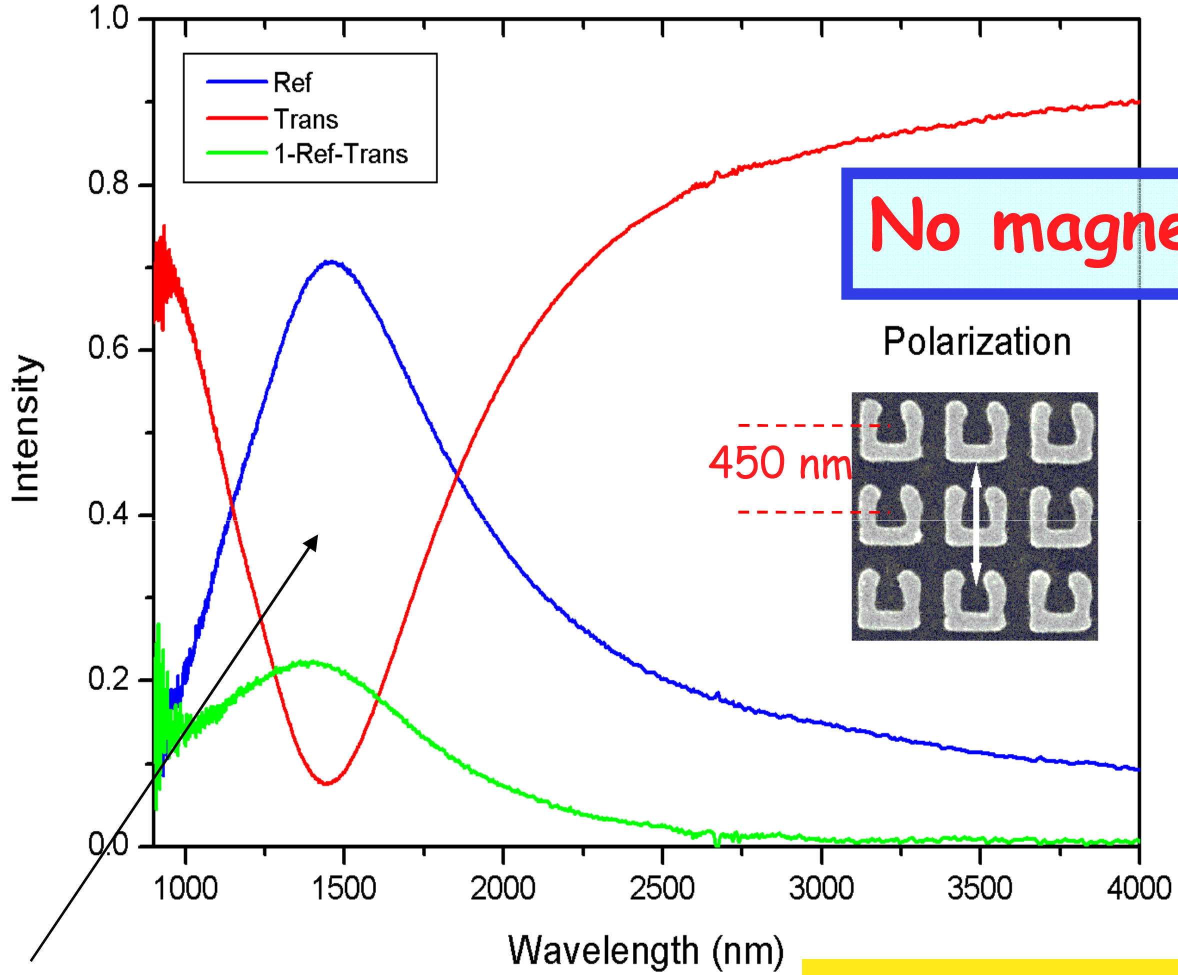
Electric resonance

Science, Nov 19, 2004

Univ. of Karlsruhe and Ames Lab

Experimental spectra for sample





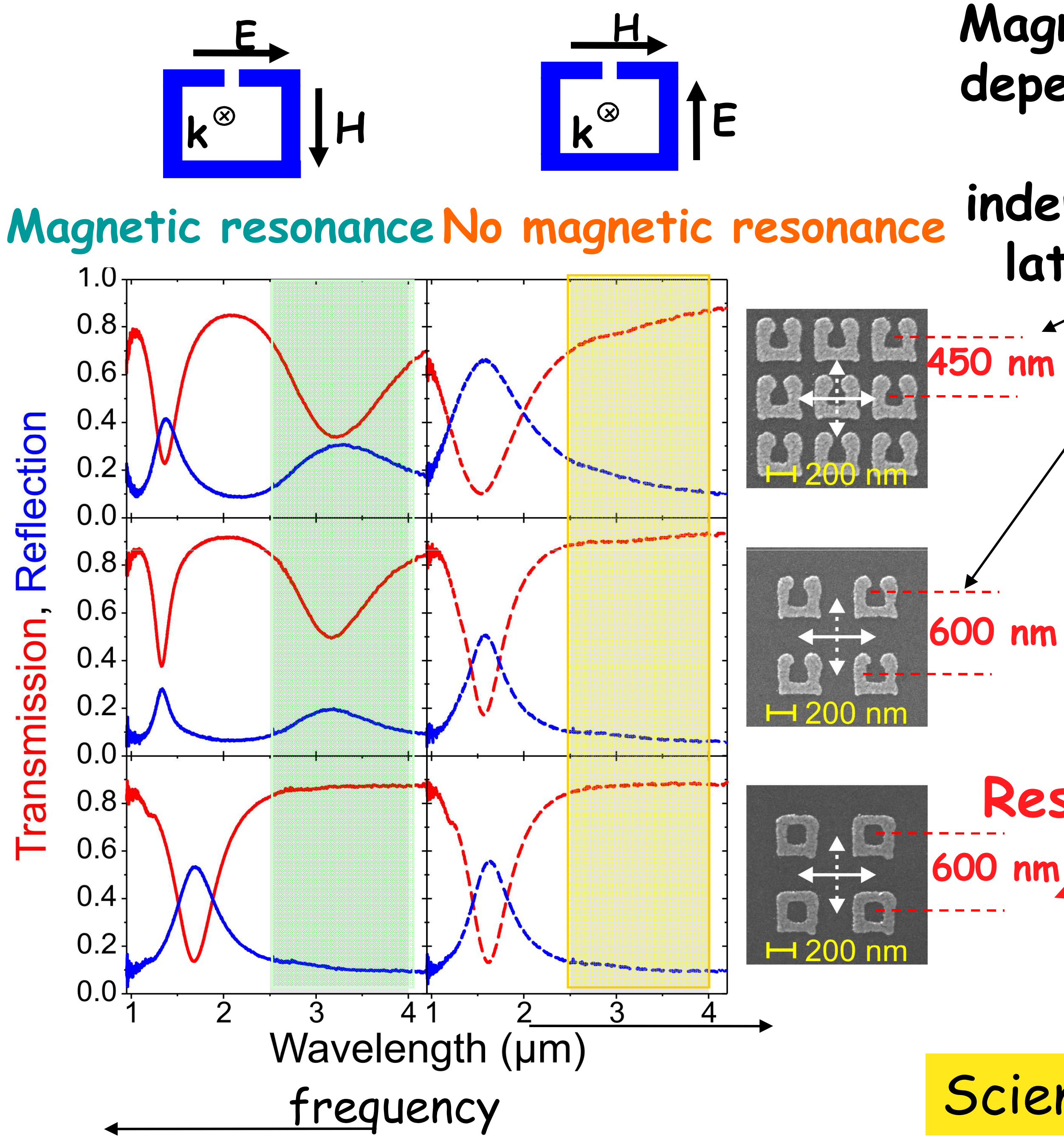
No magnetic resonance

Electric resonance

Science, Nov 19, 2004

Univ. of Karlsruhe and Ames Lab

Magnetic resonance depends on feature size and is independent of the lattice constant

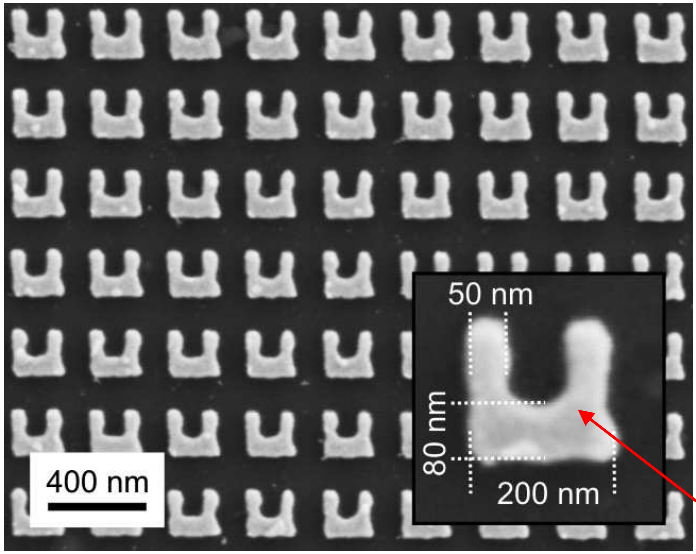


Closed rings
Resonance disappears

Science, Nov 19, 2004

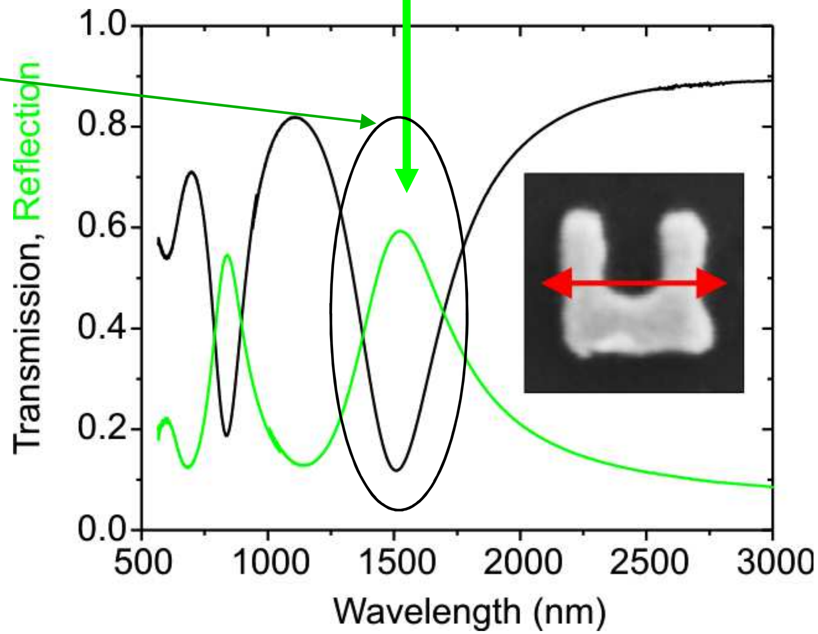
Negative at telecommunication wavelengths (~1.5 μm)

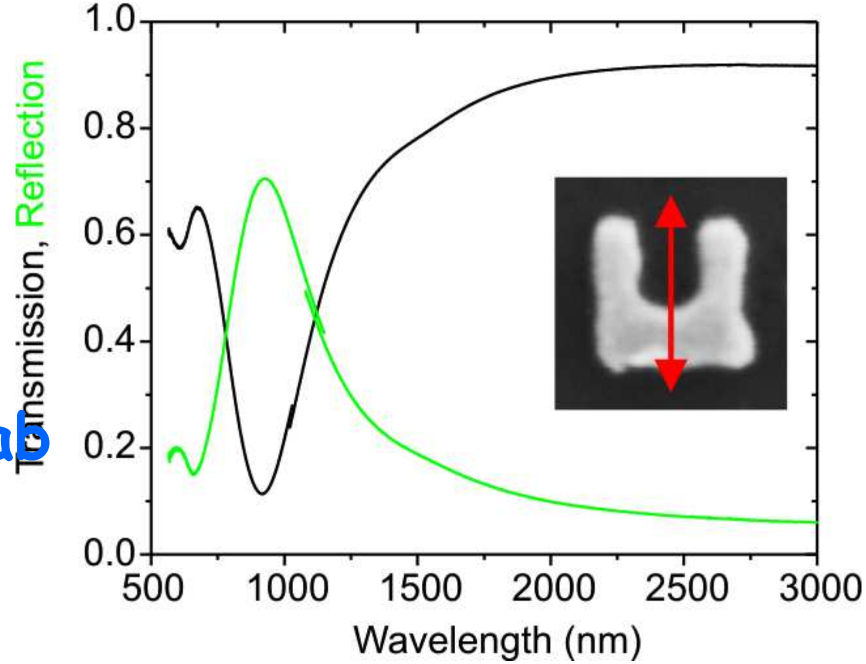
Electric coupling to the magnetic resonance



Au

Fabricated with e-beam lithography





Univ. of Karlsruhe and Ames Lab

PRL **95**, 203901 (2005)

Going to THz Frequencies

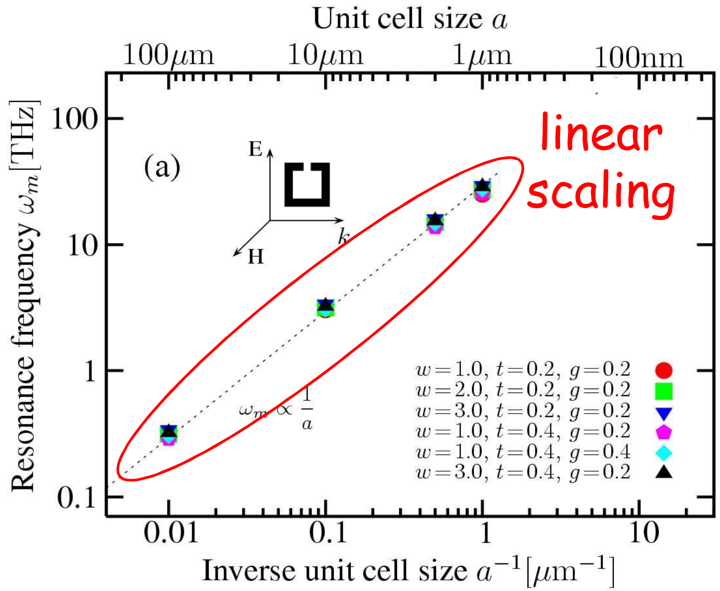
Idea: geometric scaling

Metals are near-perfect conductors
LC-resonator

$$C \approx \varepsilon_0 \varepsilon_{rel} \frac{A}{d} \qquad \mu_0 \frac{\pi R^2}{l} \approx L \approx \mu_0 R \left(\log \frac{8R}{r_0} - 2 \right)$$

densely stacked rings — sparse rings

Depends on geometry only

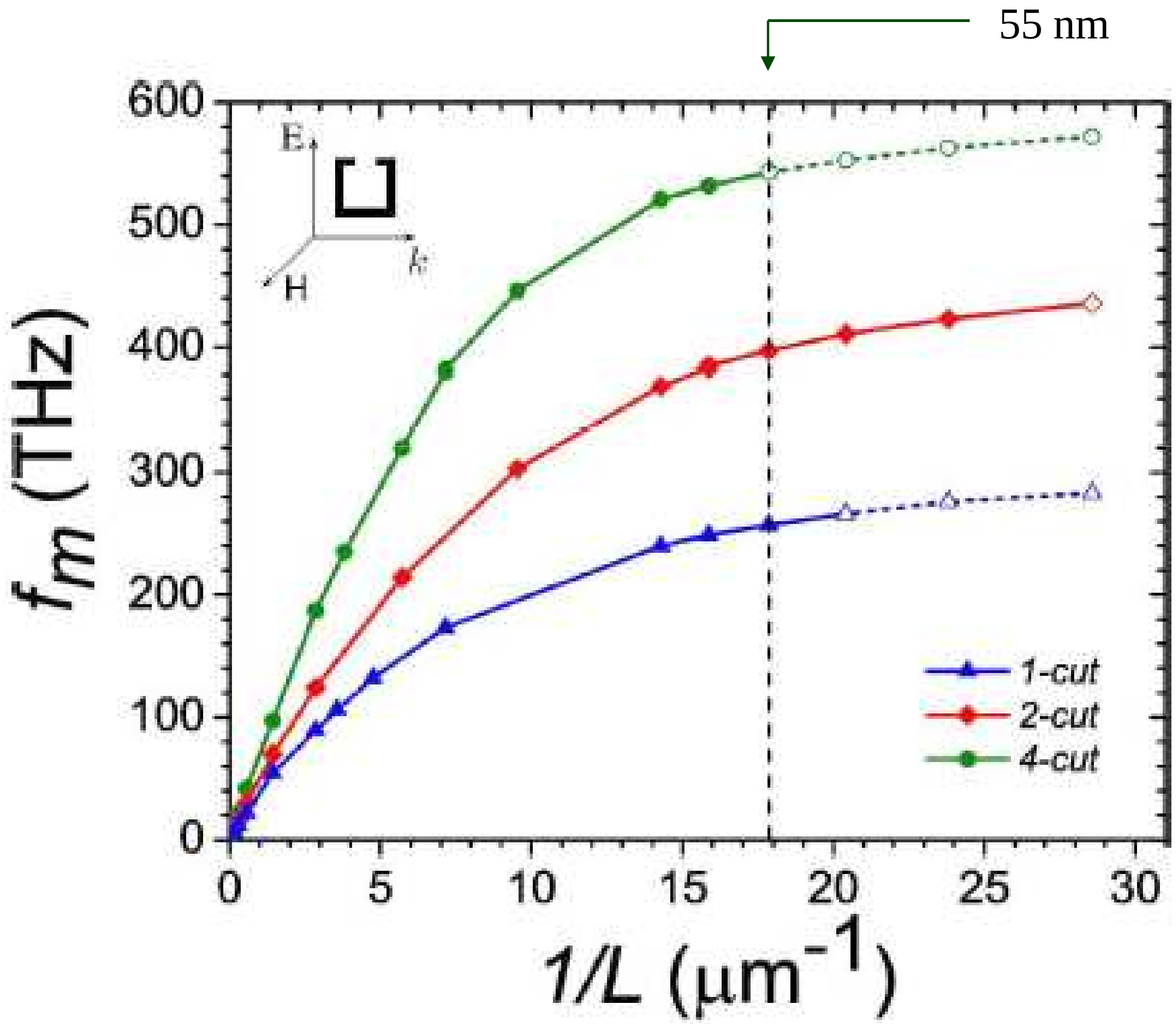


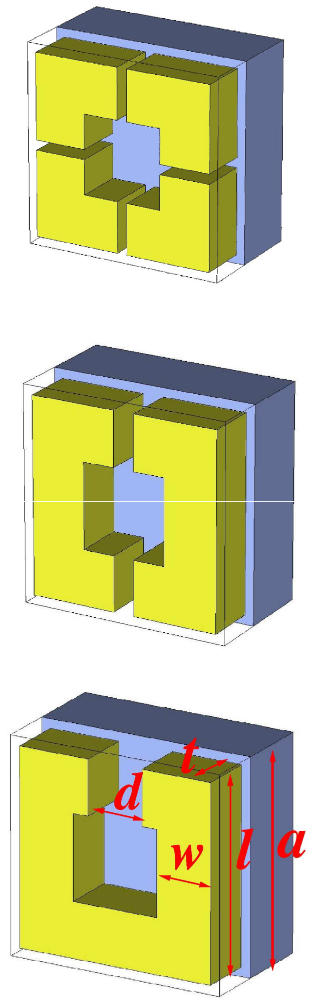
Scale: $lenght \rightarrow S \times length \ \wedge \ time \rightarrow S \times time$

Such that speed of light invariant and $S \rightarrow 0$

$$C \propto S \ \wedge \ L \propto S \quad \Rightarrow \quad \omega_m = \frac{1}{\sqrt{LC}} \propto \frac{1}{S}$$

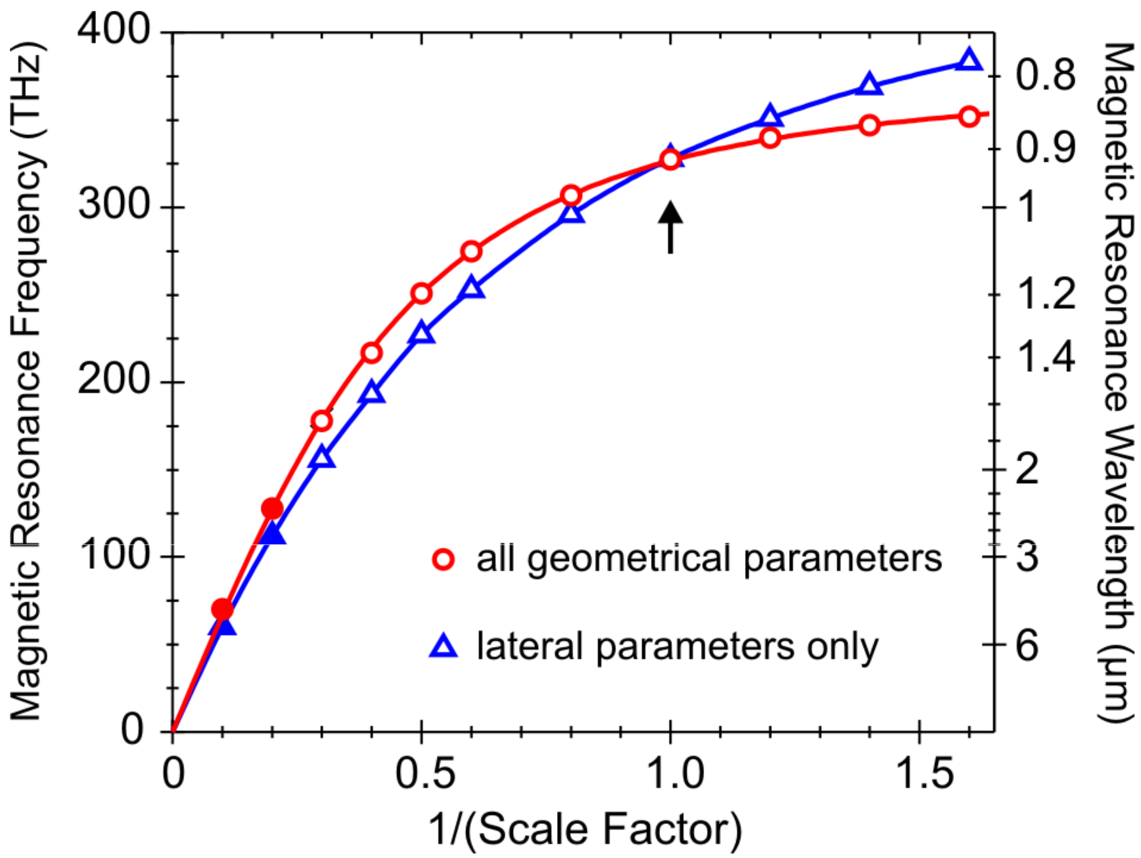
Upper frequency limit of the SRRs?





PRL 95, 223902 (2005).

Limits of size scaling



$$\omega_{LC} = \frac{1}{\sqrt{LC}} \propto \frac{1}{\sqrt{size^2 + const}}$$

E_{kin} of electrons!

M.W. Klein *et al.*, Opt. Lett. 31, 1259-1261 (2006)

Why saturation of ω_m?

$$\omega_m = \frac{1}{\sqrt{L_m C}}$$

$$E_m = \frac{1}{2} L_m I^2$$

$L_m \propto a$ $C \propto a$

$\omega_m \propto 1/a$ (*a*: u.c. size)

Key point: Kinetic energy of the electrons becomes comparable to magnetic energy in small scale structures

$$E_e = \frac{1}{2}(n_e V) m_e v_e^2 = \frac{1}{2} L_e I^2$$

$$v_e = \frac{I}{S e n_e}$$

$$L_e = \frac{m_e}{n_e e^2} \frac{V}{S^2} \sim \frac{1}{a}$$

$$\omega_m = \frac{1}{\sqrt{(L_m + L_e)C}} = \frac{1}{\sqrt{c_1 a^2 + c_2}}$$

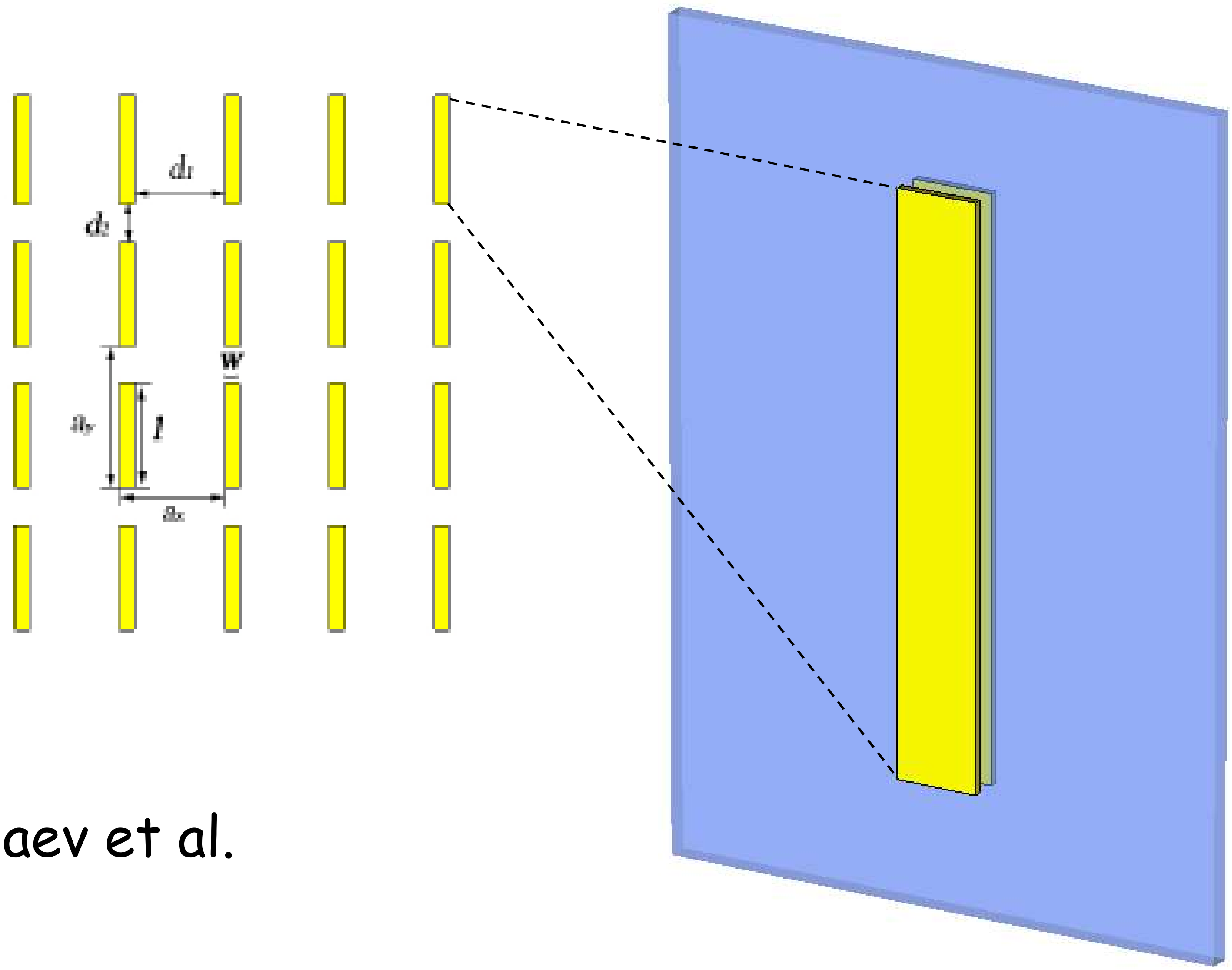
V: wire effective volume
S: wire effective cross-section
n_e: e^- number density

Metamaterials structures shown in these split-ring resonators (SRRs) are amenable to manufacture by common planar lithography.

It has a magnetic response perpendicular to the plane, which is difficult to detect by direct incidence measurements.

Use of multilayer processing can been used to fabricate metamaterials that give both negative ε and μ, as well as n for perpendicular propagation.

LHM by Double Layer Cut - Wires

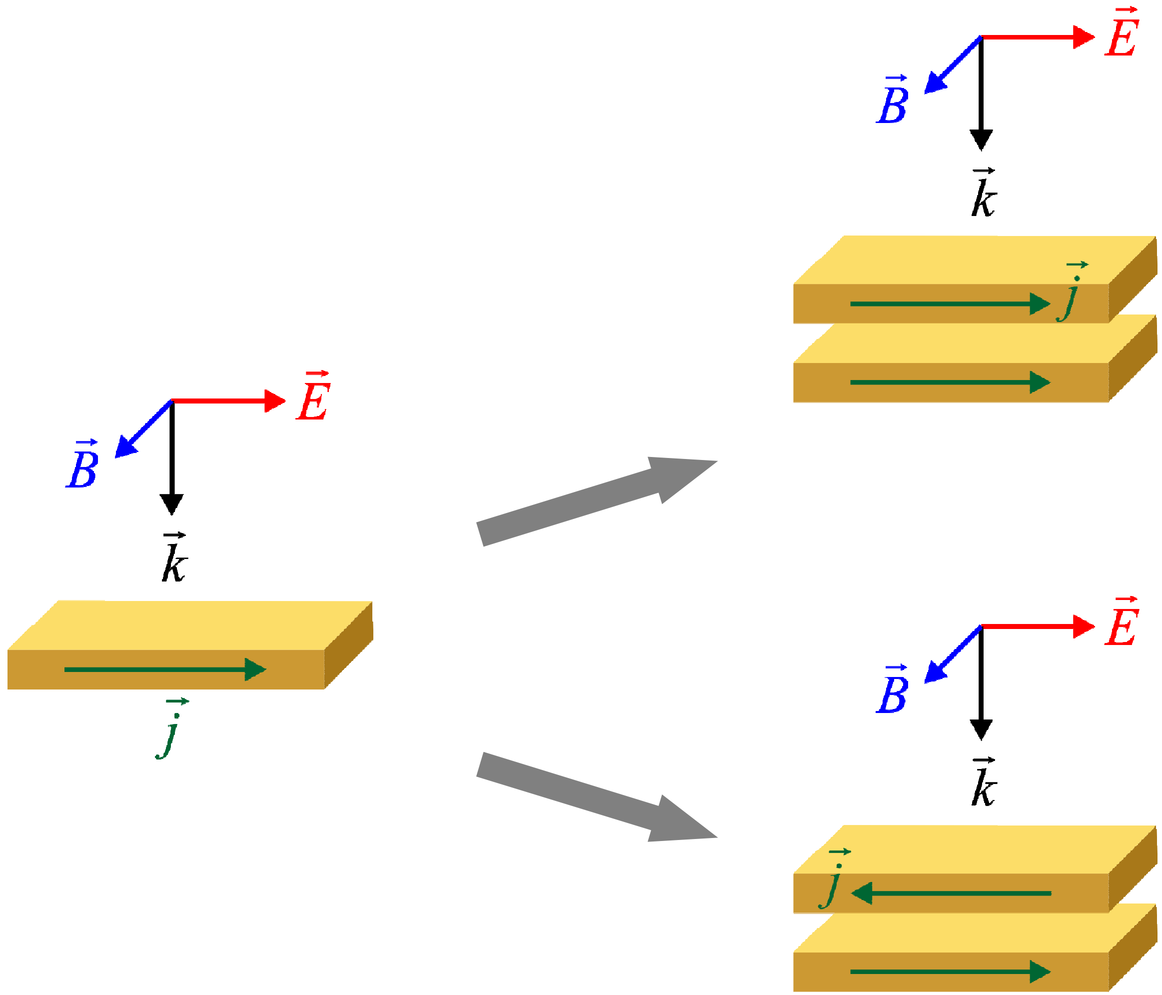


Shalaev et al.

Magnetic response from cut-wire pairs

Single cut-wire

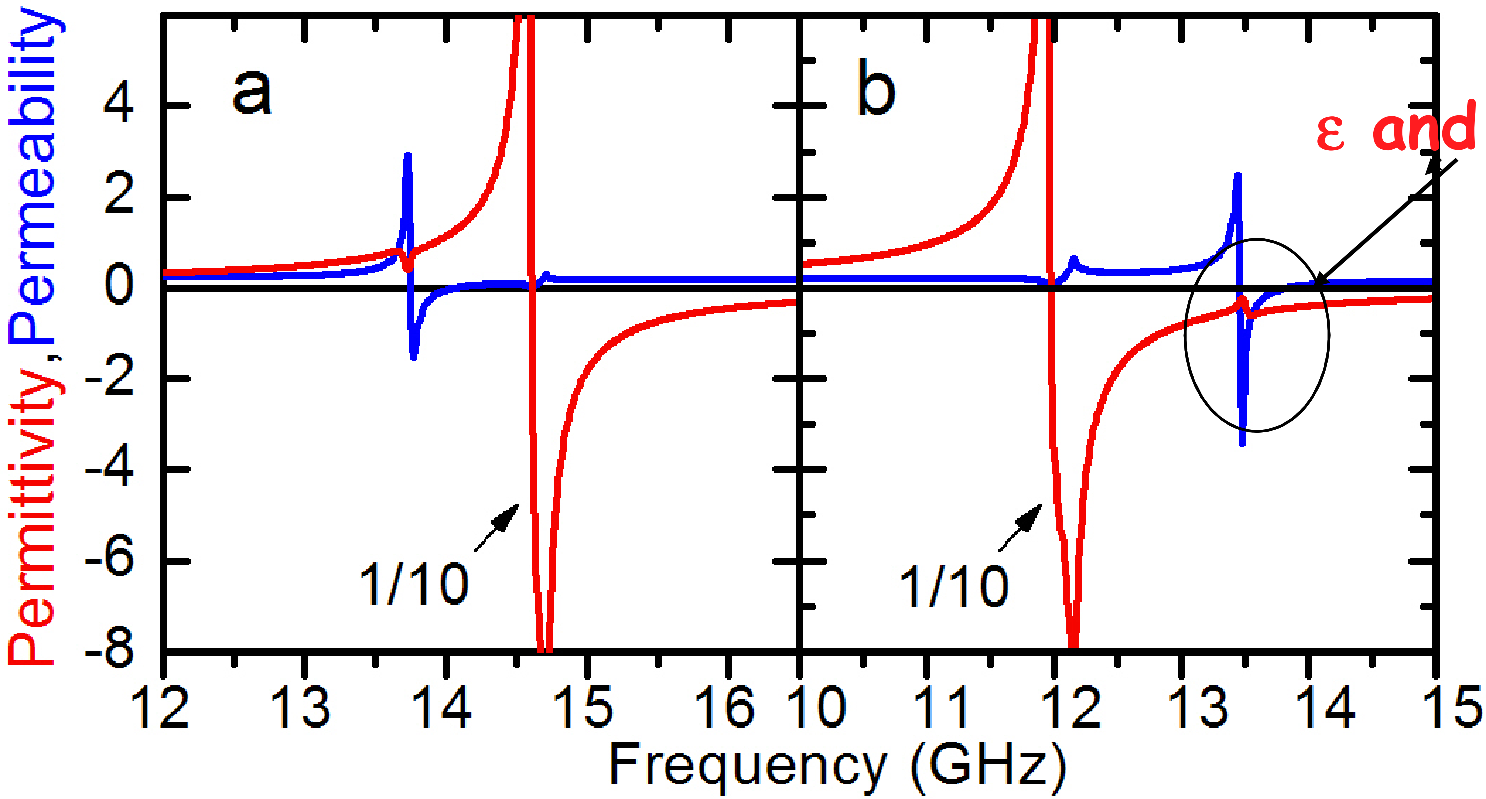
Cut-wire pair



Symmetric mode,
no magnetic dipole

Anti-symmetric mode,
magnetic dipole

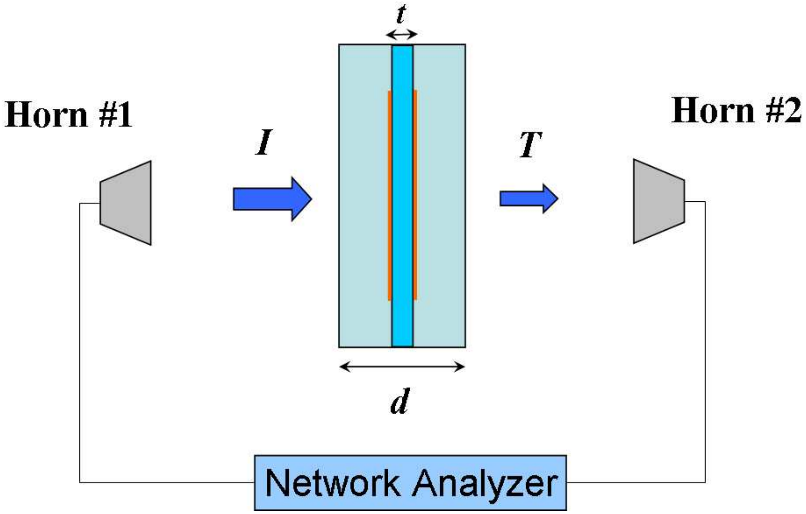
Difficulties in obtaining both ε and μ < 0 in cut wire pairs

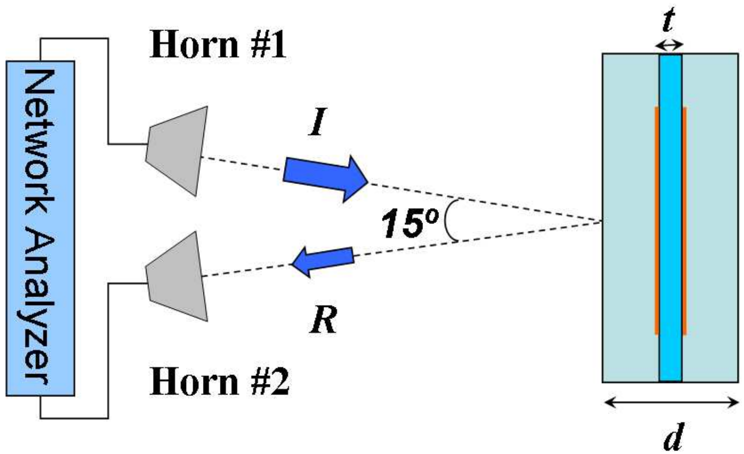


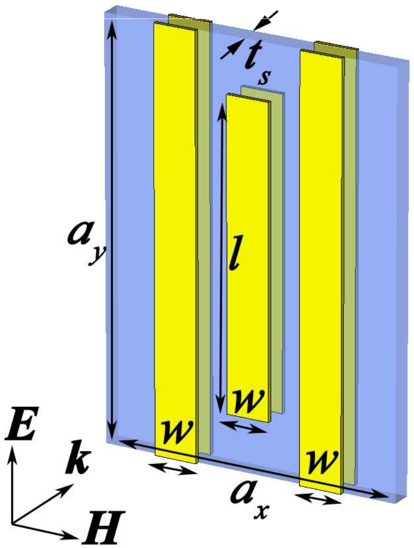
Strong electric resonance and weak magnetic resonance

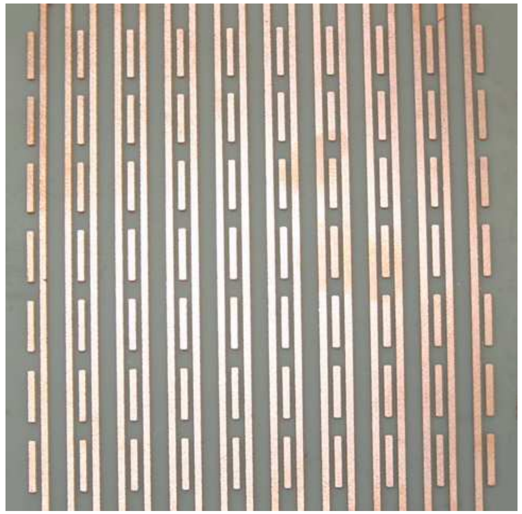
To get **ε and μ < 0, one needs to have $\omega_e < \omega_m$**

Resonance and anti-resonance effects in **ε and μ**



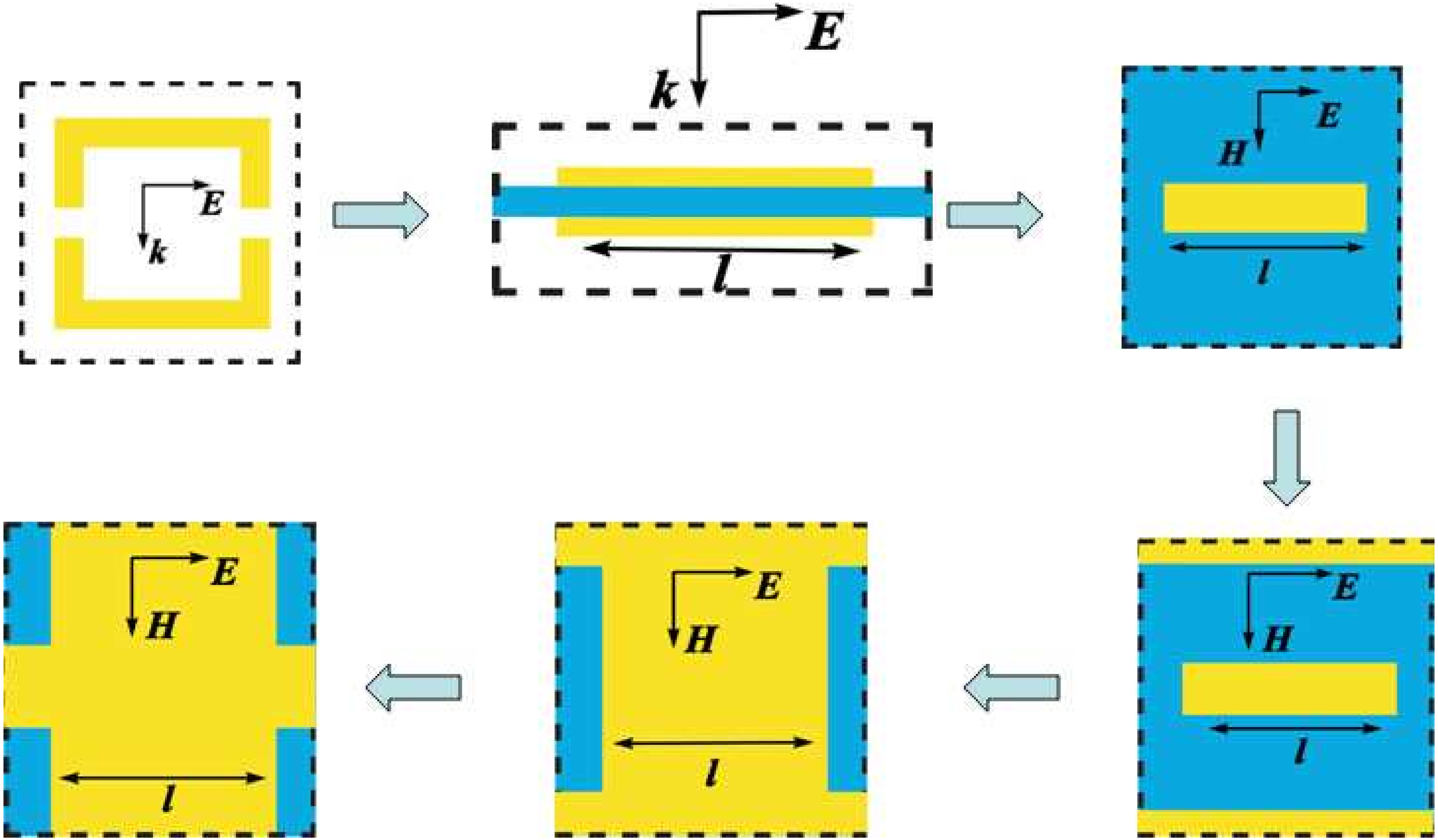






PRB **73**, 041101(R) (2006)

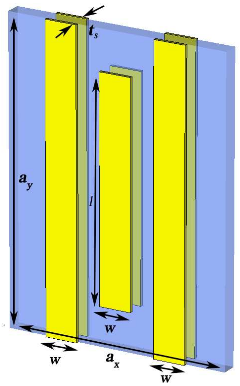
Development of the 2-cut SRR to the fish-net structure

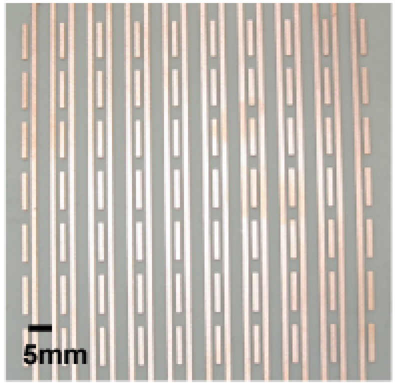


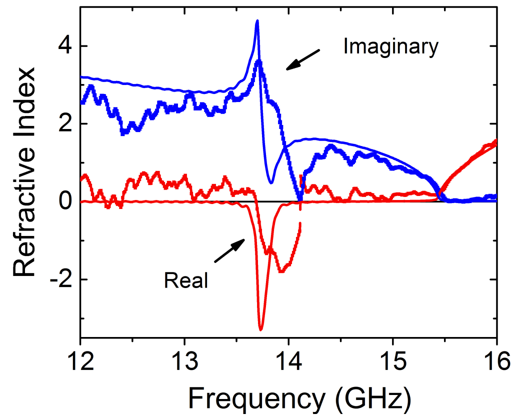
Negative Index at GHz and THz: Short-wire pairs and Fishnet Structure

Short-wire pair
+ Continuous wire

PRB **73**, 041101(R) (2006).

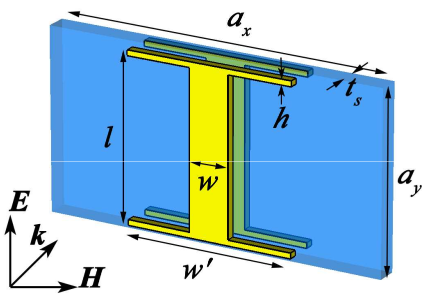


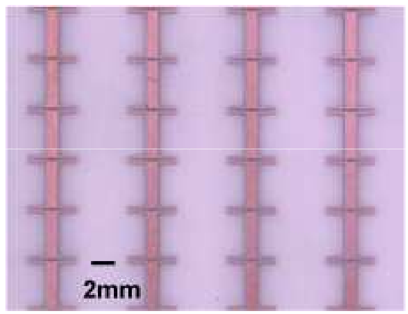


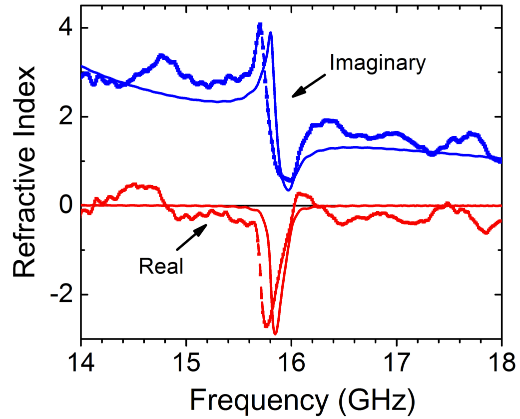


H-shaped
Short-wire pair

APL **88**, 221103 (2006).

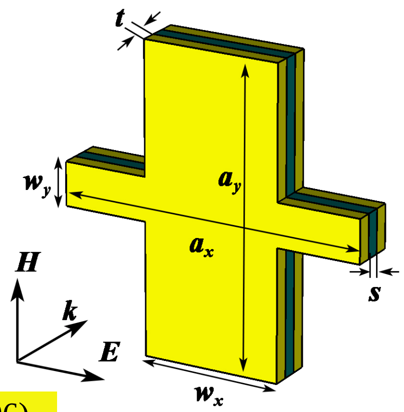


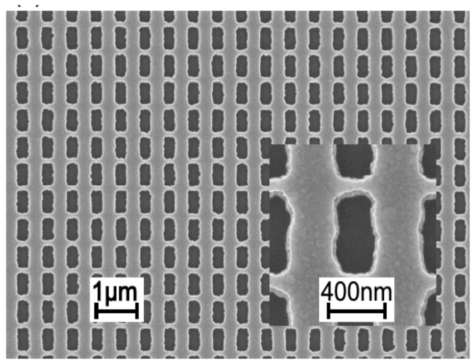


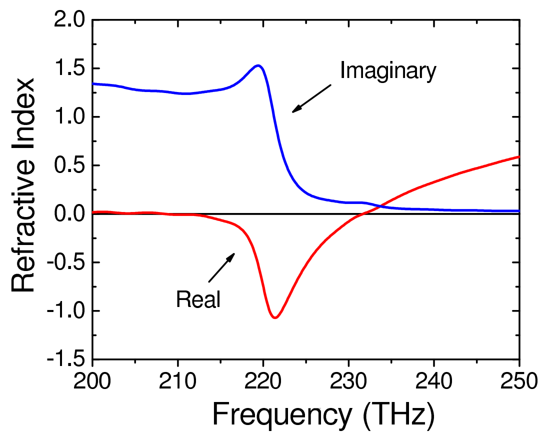


Fishnet

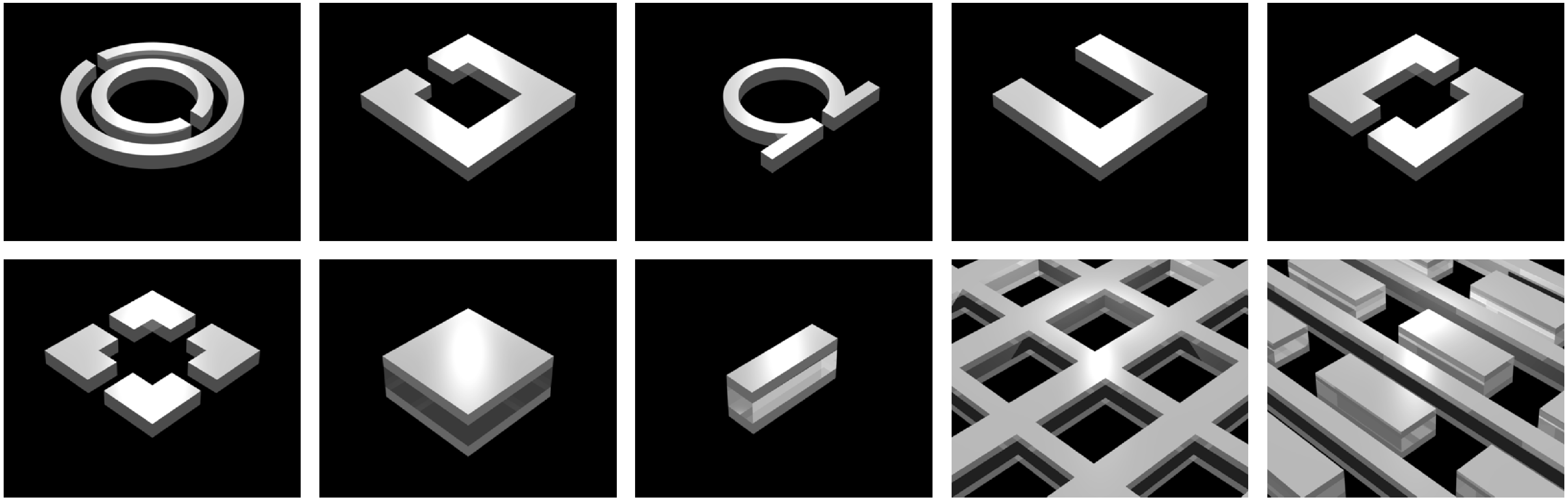
Science **312**, 5775 (2006)
Opt. Lett. **32**, 53 (2007)

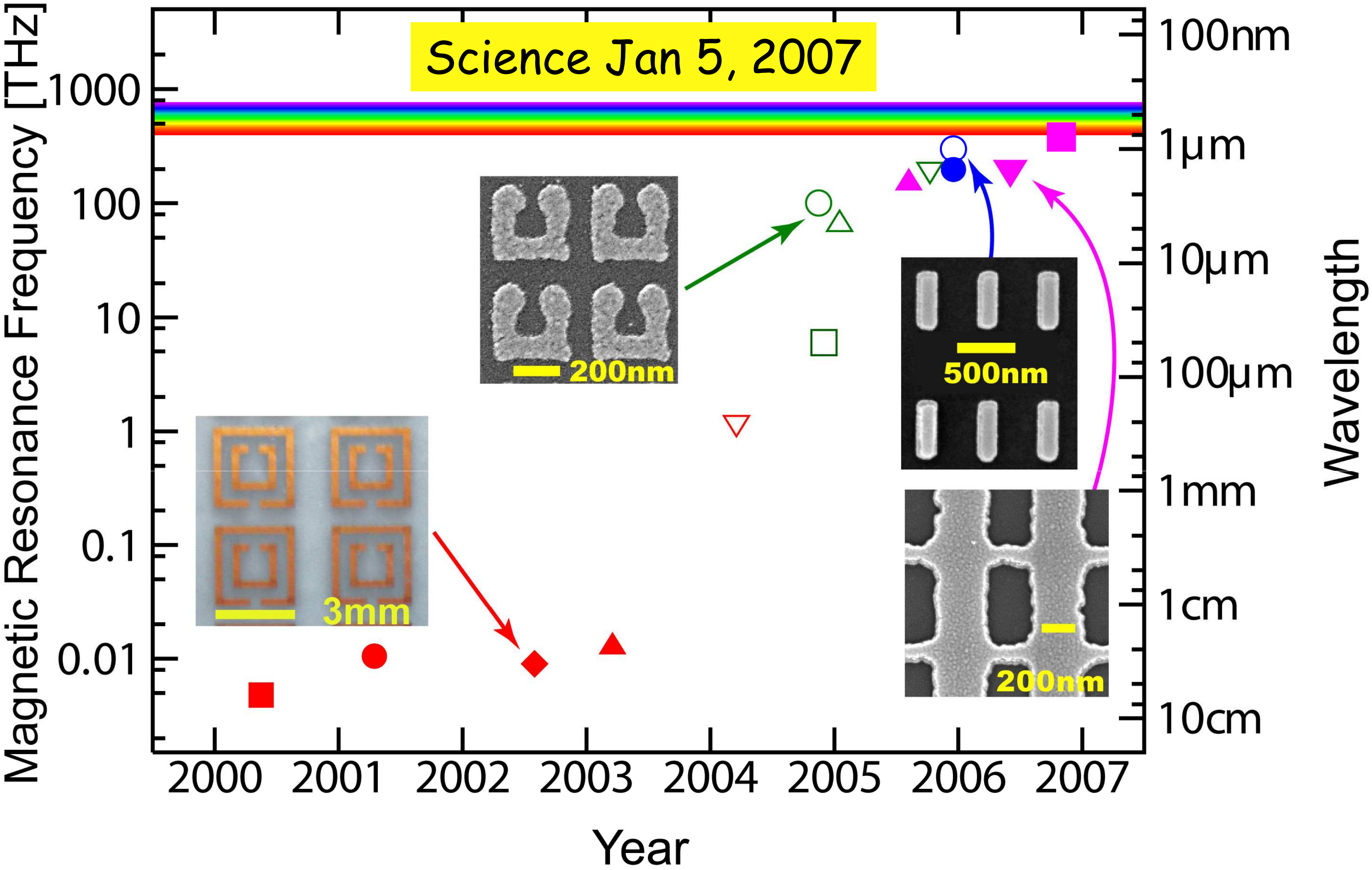






Different designs used in fabricating LHMs with negative μ and n





Solid symbol n<0

Open symbol μ<0

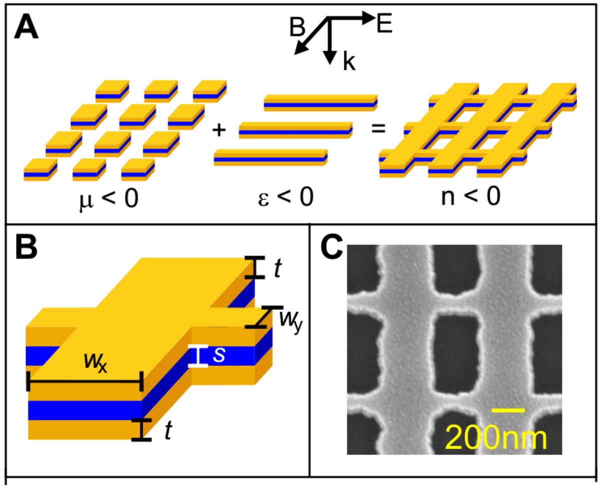
Metamaterials Used to Alter Light's Path, Speed

Karlsruhe and Ames Lab., designed and fabricated for the first time NIMs at 1.5 μm with low losses! The design is shown below.

Science 312, 892 (2006)

Phase and group velocity can be both negative!
n is dispersive in NIMs

"Reversing and accelerating the speed of light," (http://www.ameslab.gov/final/News/2006rel/metamaterials.htm)

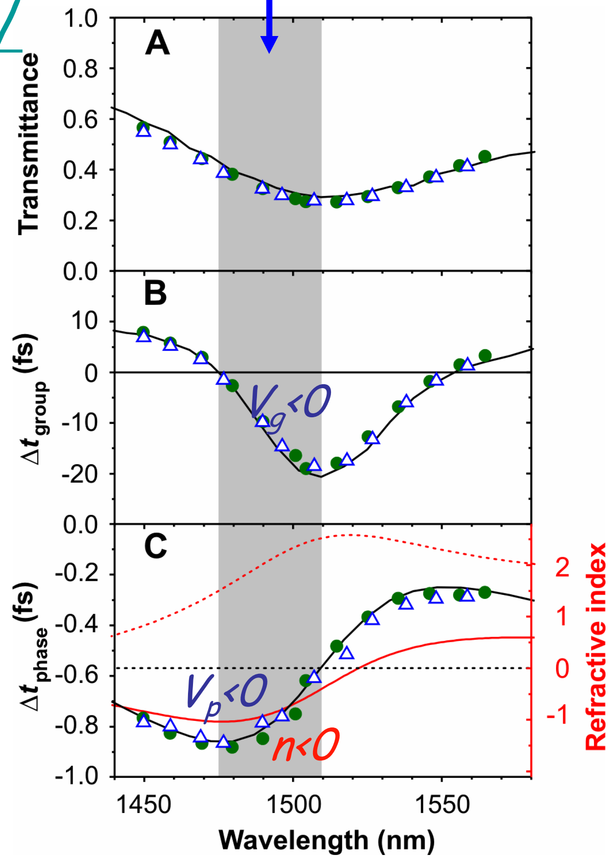


$$v_p = c/n$$

$$v_g = v_p / \left(1 + \frac{\omega}{n}\frac{dn}{d\omega}\right)$$

If n is negative and dispersive, both v_p and v_g *can be negative!*

Causality and relativity are ok



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The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

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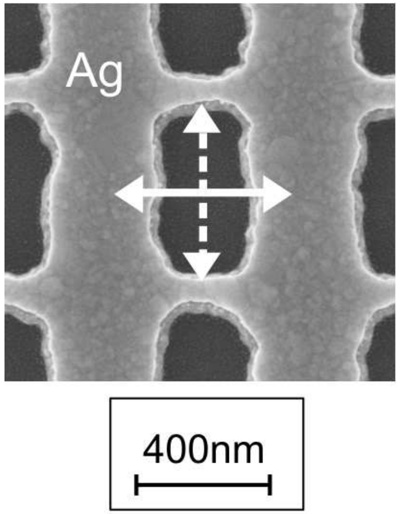
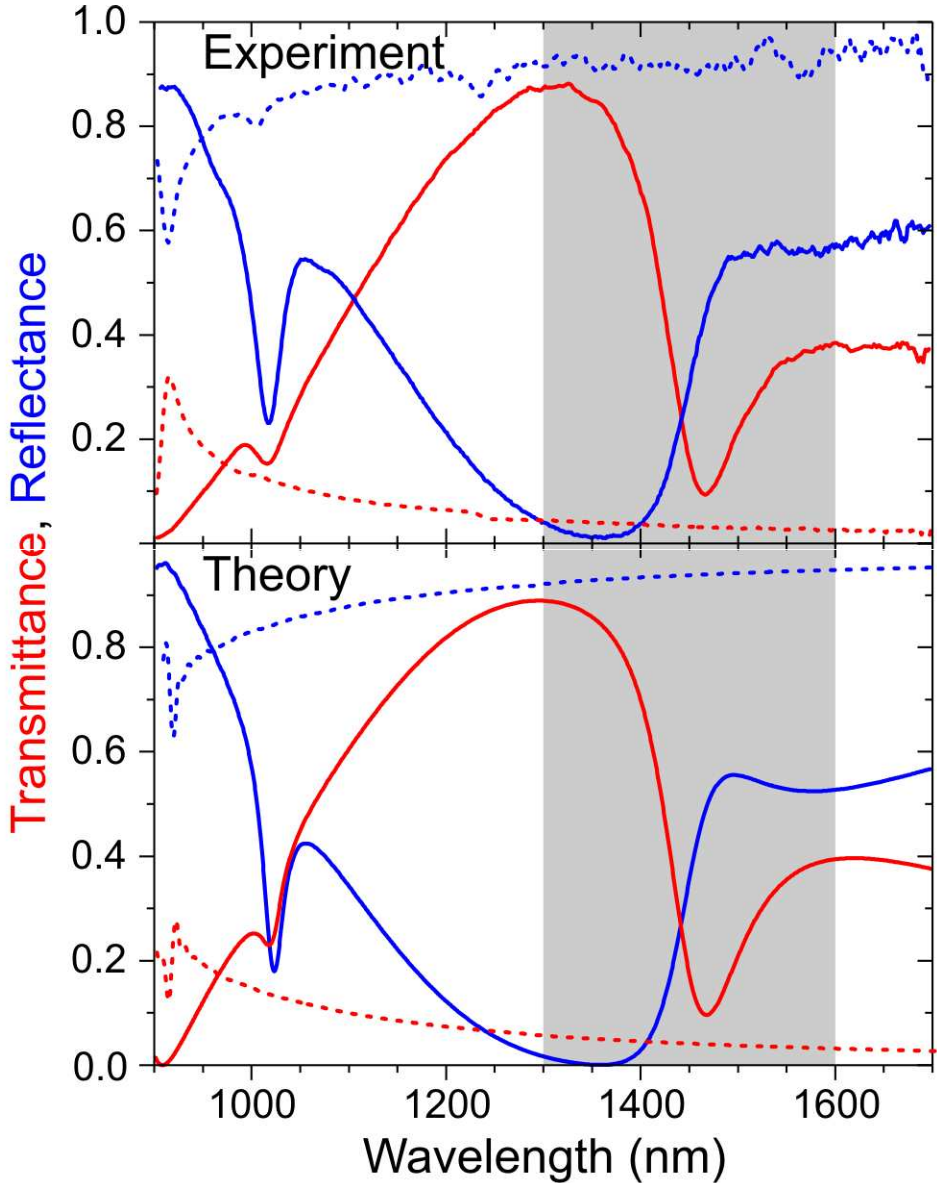
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

$\varepsilon = \mu = n = -1$

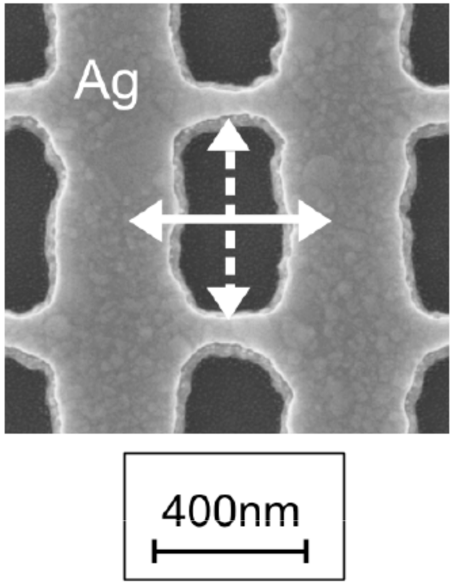
Low loss negative index metamaterials

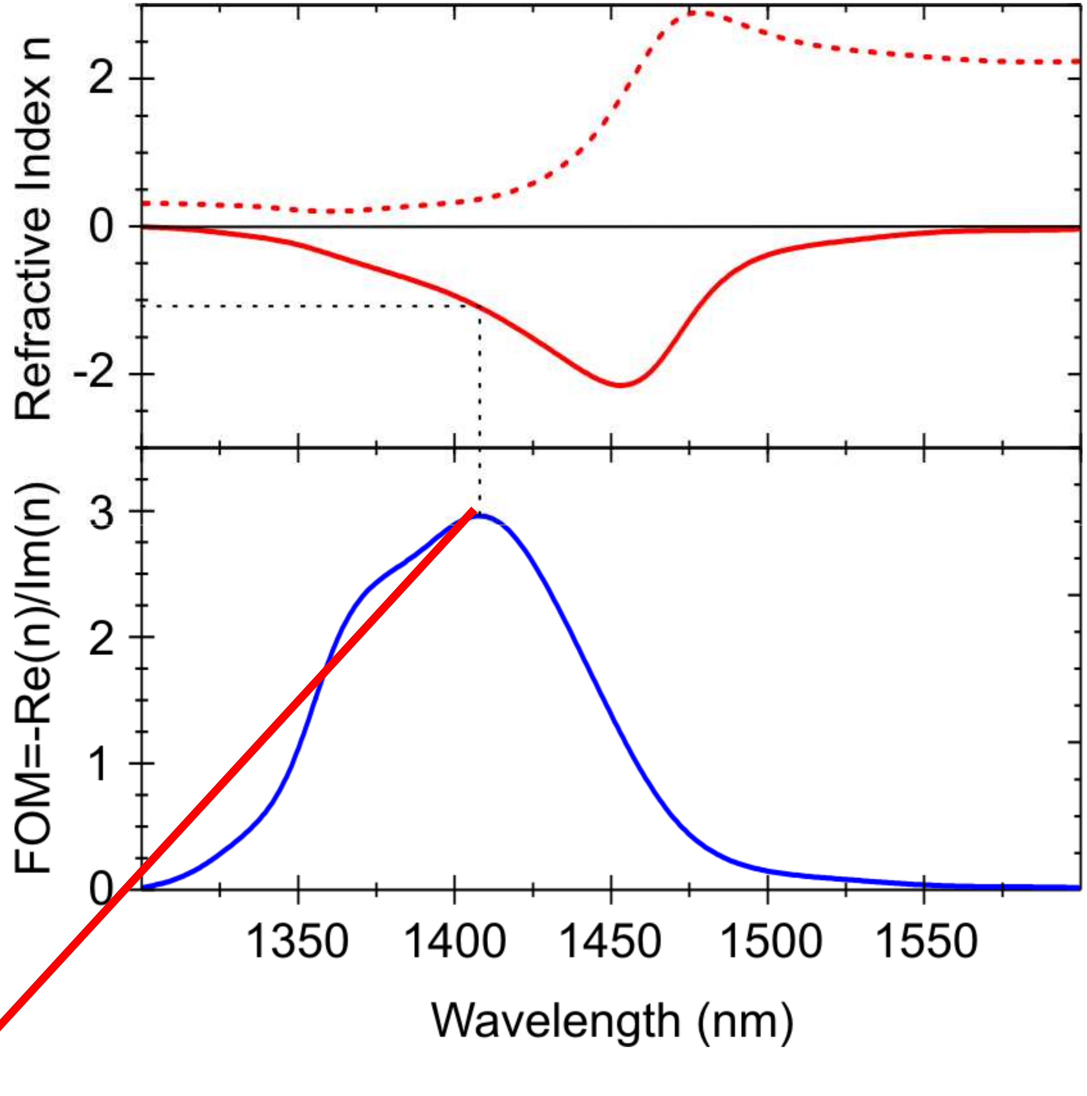




G. Dolling *et al.*, Opt. Lett. 31, 1800 (2006)

Low loss negative index metamaterials



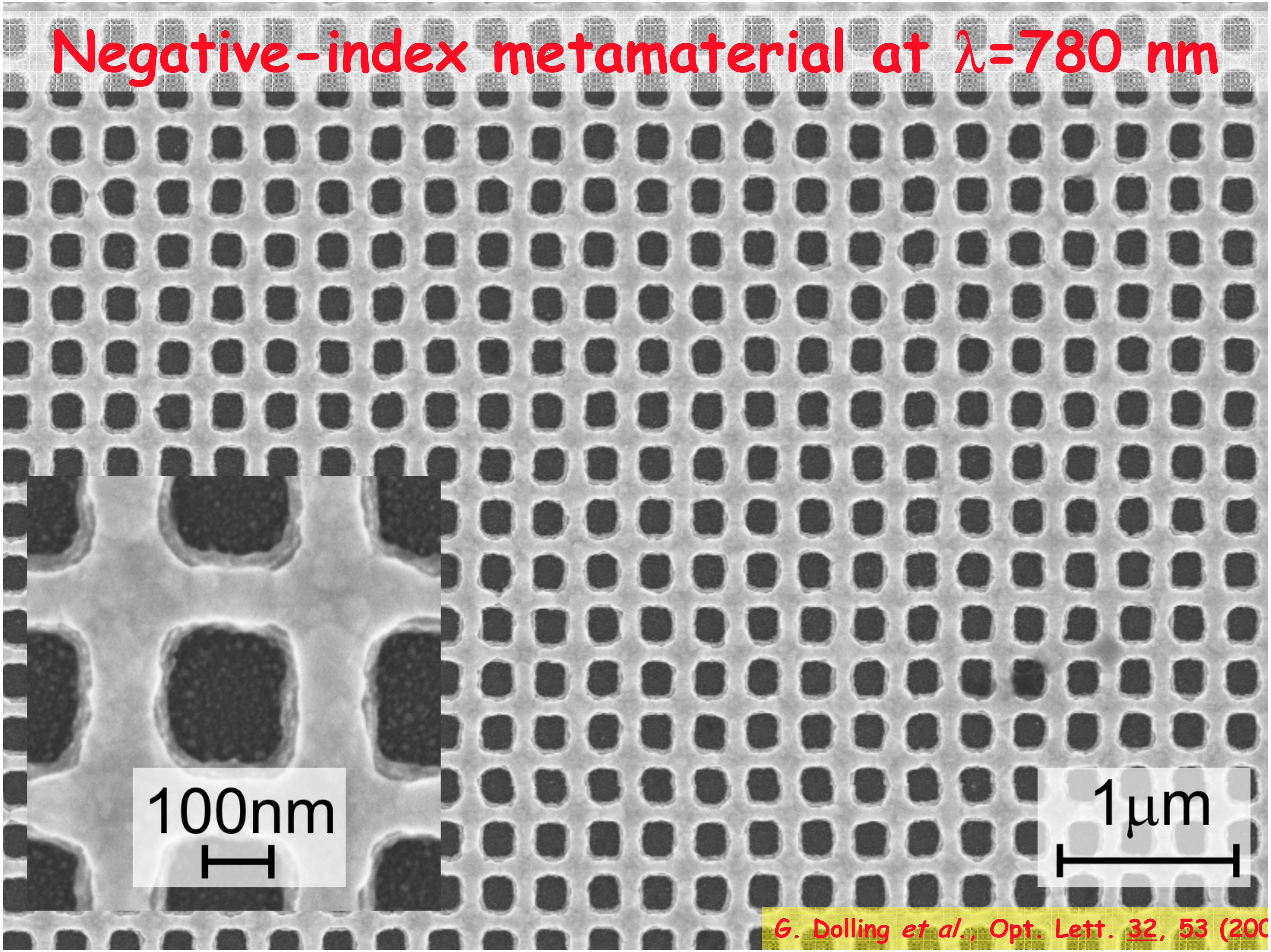


Decay per period

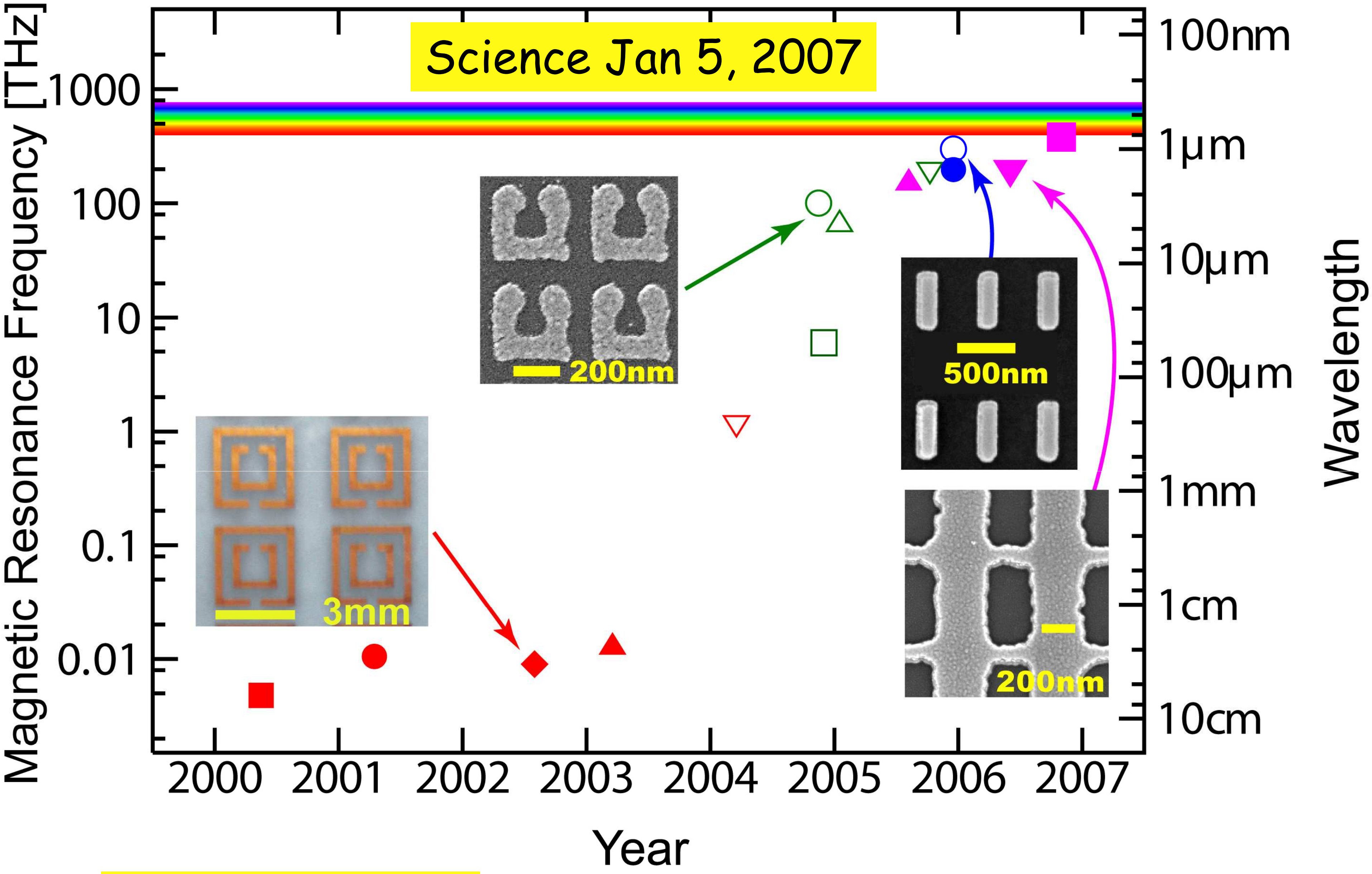
Best system has

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

Negative-index metamaterial at λ=780 nm



G. Dolling *et al.*, Opt. Lett. 32, 53 (200



Solid symbol n<0

Open symbol μ<0

Significant contributions to the development of LHMs by our group:

- Electric response of SRRs
- Electric excitation of the magnetic resonance
- Retrieval calculations for ε, μ
- Closed rings for distinguishing LH from RH peaks
- Negative μ at THz and visible.
- Negative n at 1.5 μ and 780 nm.
- Upper frequency limit of the SRRs. Diamagnetic response of SRRs.
- Negative n at GHz and THz. Negative phase and group velocities.
- Designs for **3d isotropic LHMs.**

Future directions:

- Understanding and reducing losses. Introduce gain to reduce losses.
- Fabrication of 3d LHMs. Direct laser writing. (Karlsruhe)
- Electromagnetic induced transparency. Slow light, low losses.
- Non-linear effects. Chirality effects.
- Anisotropic metamaterials. Pseudo-focusing.
- Applications

$$$ DOE, DARPA, MURI, NATO, EU, EU-PHOME

Conclusions

- Our team has been instrumental in creating and developing a new revolutionary field, which extends the realm of electromagnetism and opens up exciting technological applications from the MHz range to optical frequencies

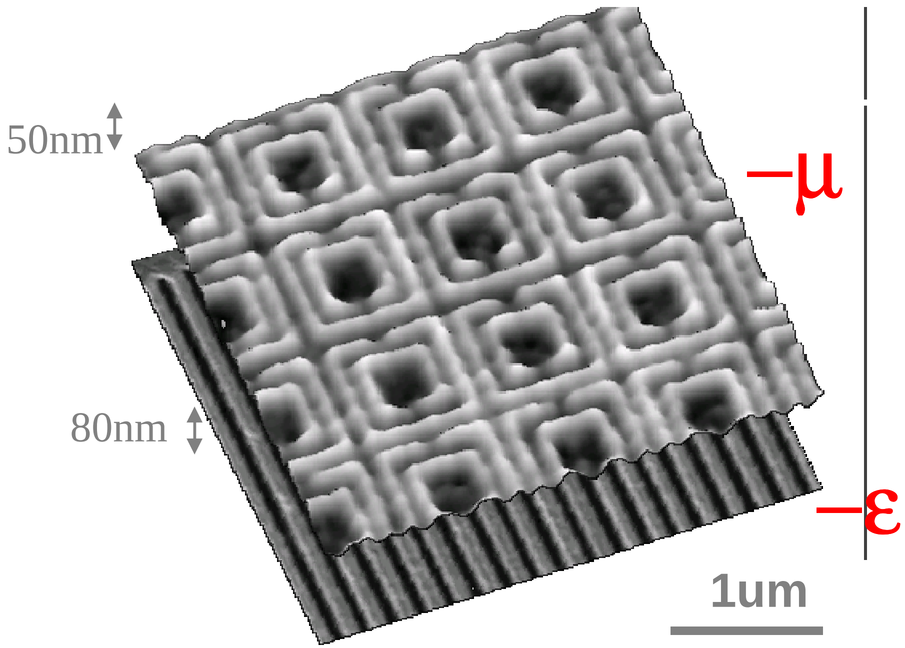
- The realization of negative index materials has opened up the possibility of unprecedented applications and devices.
    - MHz: Artificial magnetic materials for MRI applications
    - GHz: Cellular communications
        - Miniaturized antennas and waveguides
    - Optics: Superlenses with subwavelength imaging

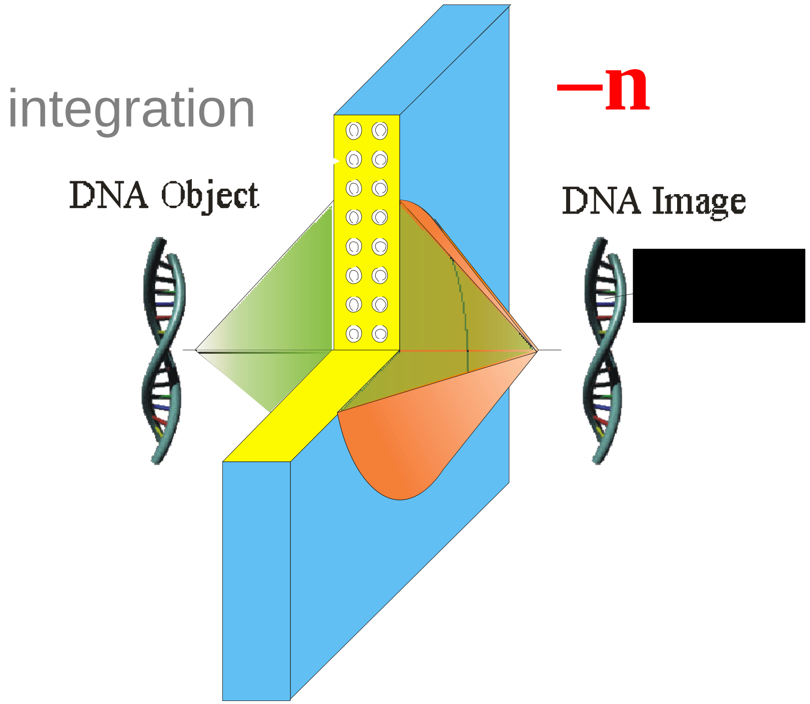
Nano Plasmonics at Near-IR and Visible

Nanowires and Nano-Rings as resonating elements

W= 75 nm ; G= 50 nm *Ultra Optical Imaging?*

L= 667 nm ; P=717 nm





W= 80 nm ; P= 200 nm

Conclusions

- Our team has been instrumental in creating and developing a new revolutionary field, which extends the realm of electromagnetism and opens up exciting technological applications from the MHz range to optical frequencies

- The realization of negative index materials has opened up the possibility of unprecedented applications and devices.
  - MHz: Artificial magnetic materials for MRI applications
  - GHz: Cellular communications
    - Miniaturized antennas and waveguides
  - Optics: Superlenses with subwavelength imaging
    - 10 nm VLSI nanolithography using optics
      - smaller integrated circuits
    - Molecular Imaging (Medicine, Biology)
  - Optics: DVDs with 100x capacity

These applications are just a start and more inventions will come from hundreds of research groups working on the newly created area of metamaterials

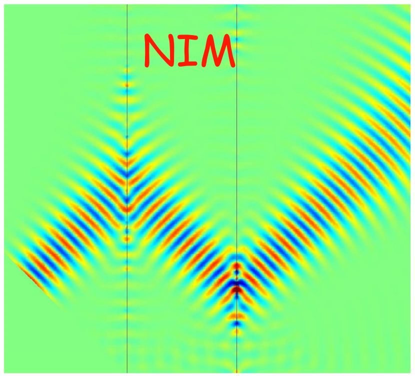
Some reviews articles from our group

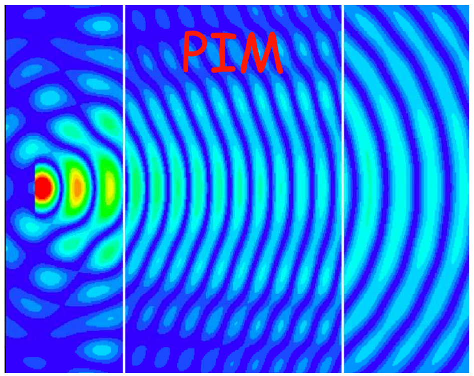
1) Bending Back Light: The Science of Negative Index Materials
   Optics and Photonics News, June 2006

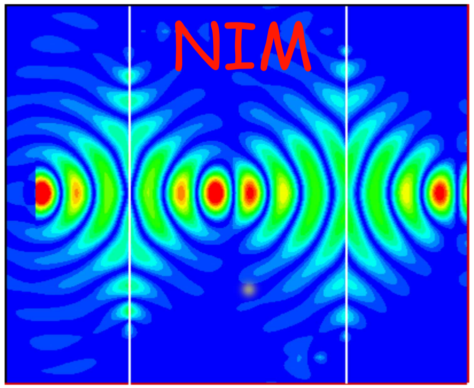
2) Negative index materials: New frontiers in optics
   Adv. Mater. **18**, 1941 (2006)

3) Photonic metamaterials: Magnetism at optical frequencies,
   IEEE J. of Selected Topics in Quant. Electr. **12**, 1097 (2006)

4) Negative Refractive Index at Optical Wavelengths
   Science **315**, 47 (2007)







Functional cloaking device !