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Workshop on New Materials for Renewable Energy

31 October - 11 November 201

Metamaterials: Past, Present, and Future

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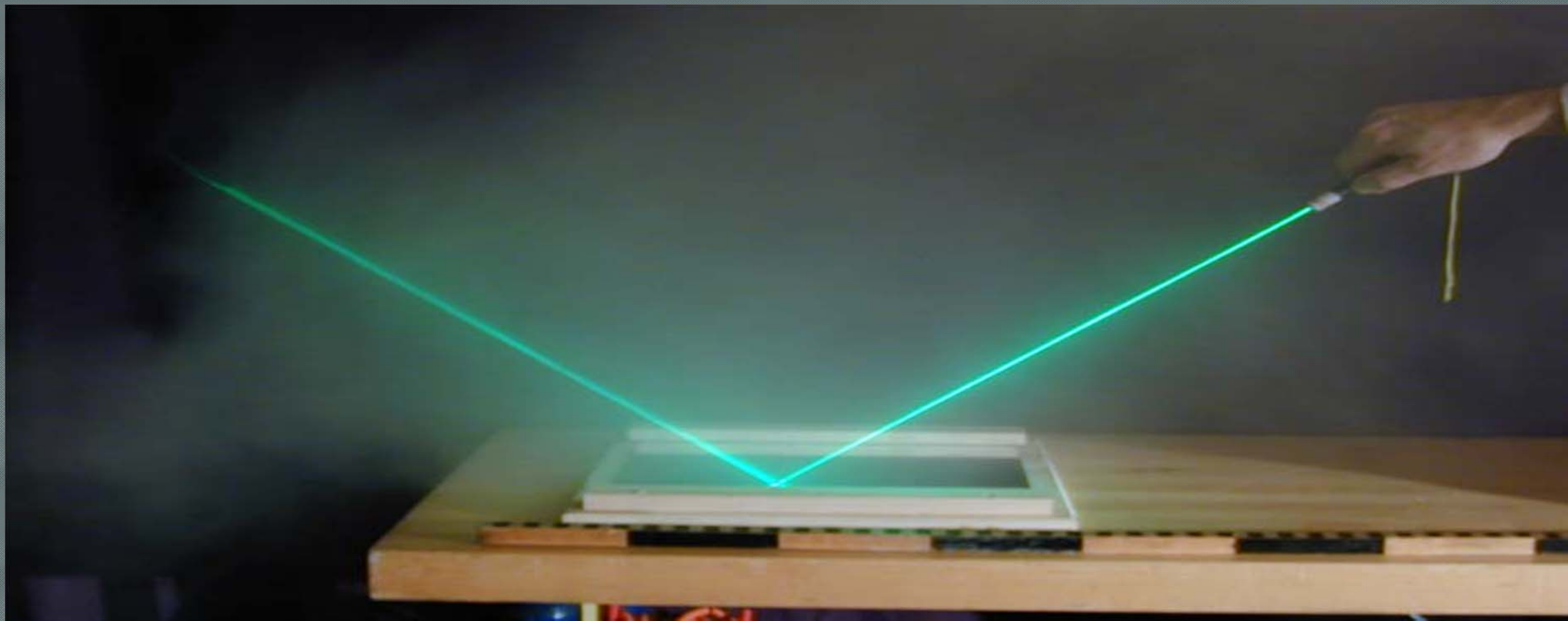
NONLINEAR PHYSICS CENTER

THE AUSTRALIAN NATIONAL UNIVERSITY

Outline

- Metamaterials: Basic properties
- Negative refraction
- The first experiment and a variety of designs
- From microwaves to optics
- Nonlinear metamaterials
- Optical cloaking
- Roadmap for metamaterials

Light interaction with matter



- Interaction depends on ε and μ of the medium
- ε characterizes response to the electric field
- μ characterizes response to the magnetic field

http://wwwrshysse.anu.edu.au/nonlinear

Electromagnetic properties of materials

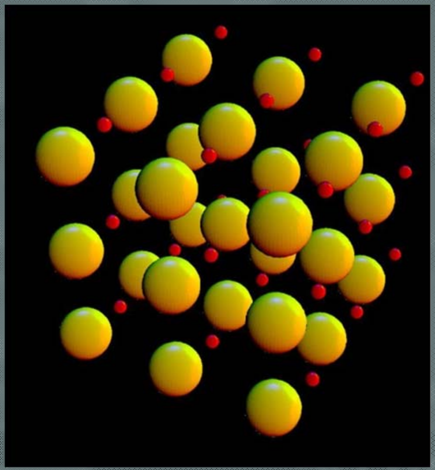
- Response to the electromagnetic field is determined by internal structure of the material
- For large wavelengths any material can be described by ε and μ
- Classical Macroscopic Electrodynamics

$$curl\,\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$curl\,\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t}$$

$$\widetilde{\mathbf{D}} = \varepsilon(\omega)\widetilde{\mathbf{E}}$$

$$\widetilde{\mathbf{B}} = \mu(\omega)\widetilde{\mathbf{H}}$$



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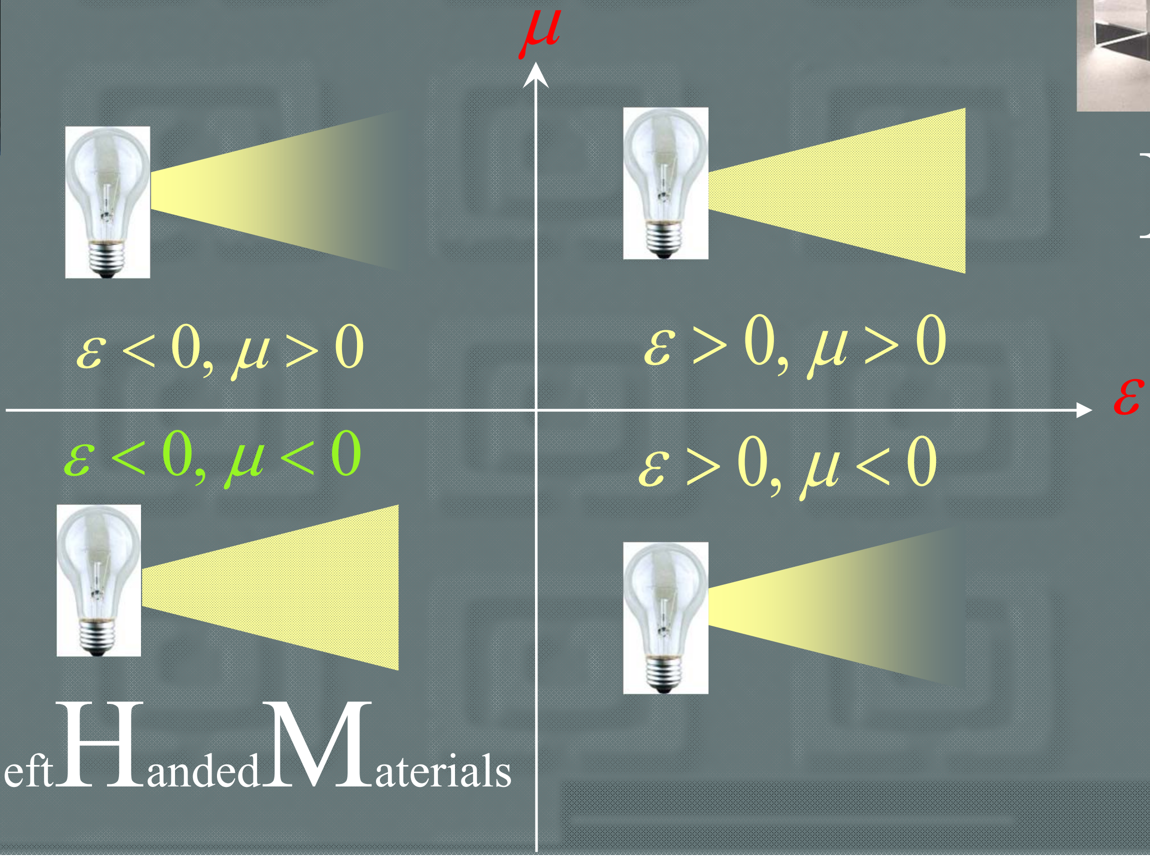
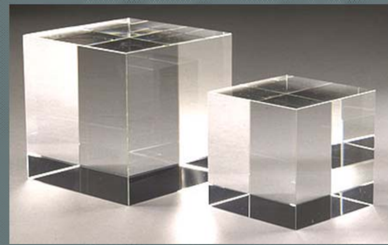
Natural materials and metamaterials

$$k^2 = \frac{\omega^2}{c^2}\varepsilon\mu$$





RHM

LeftHandedMaterials

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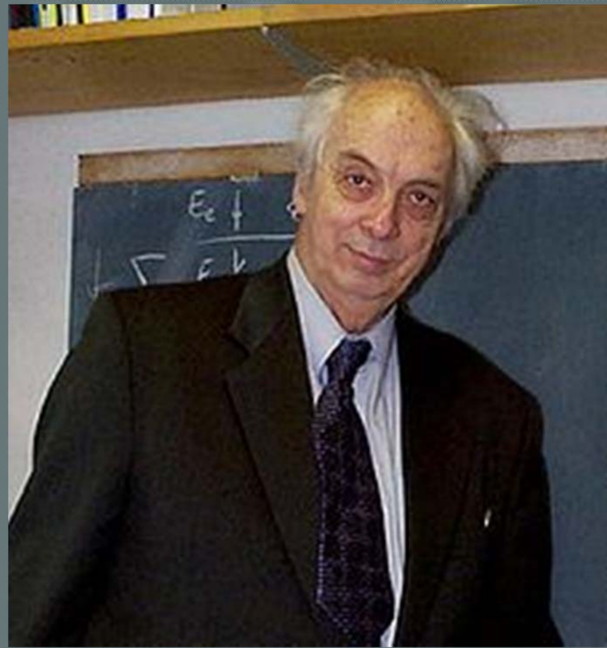
The first Paper
Left-Handed Materials



- V.G.Veselago,
  - The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ.

    Soviet Physics Uspekhi **10** (4), 509-514 (1968)

Even earlier papers

D. Sivukhin, Opt. Spectroscopy **3**, 308 (1957)

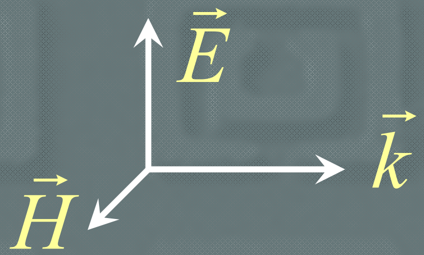
B. Pakhomov, Zh. Eksp. Theor. Fiz. **36**, 3966 (1959)

Left-handed waves

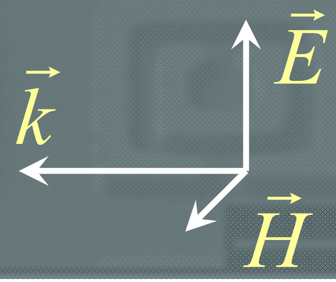
$$\vec{k} \times \vec{E} = \frac{\omega}{c} \mu \vec{H}$$

$$\vec{k} \times \vec{H} = -\frac{\omega}{c} \varepsilon \vec{E}$$

- If $\varepsilon > 0, \mu > 0$ then $\left(\vec{E}, \vec{H}, \vec{k}\right)$ is a *right* set of vectors:



- If $\varepsilon < 0, \mu < 0$ then $\left(\vec{E}, \vec{H}, \vec{k}\right)$ is a *left* set of vectors:



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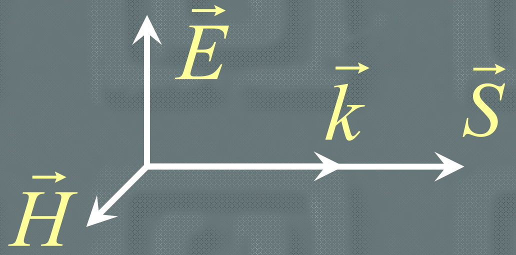
Energy flow in left-handed waves

- Energy flow (Poynting vector): $\vec{S} = \frac{c}{4\pi}\left[\vec{E} \times \vec{H}\right]$
  - Conventional (right-handed) medium

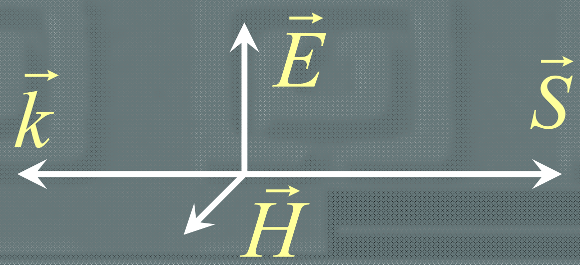


$\vec{S} \uparrow\uparrow \vec{k}$

$\vec{V}_{gr} \uparrow\uparrow \vec{V}_{ph}$

  - Left-handed medium

$\vec{S} \uparrow\downarrow \vec{k}$



$$\boxed{\vec{V}_{gr} \uparrow\downarrow \vec{V}_{ph}}$$

Frequency dispersion of LH medium

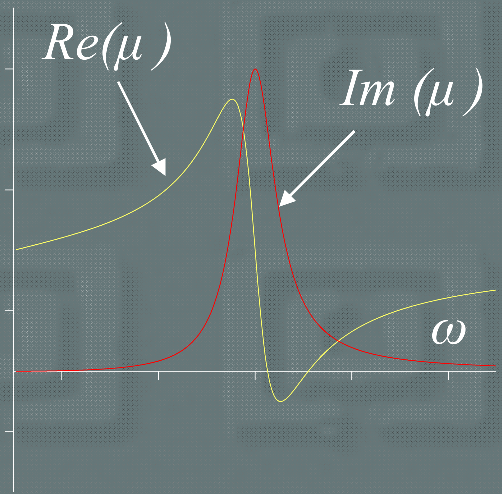
- Energy density in the dispersive medium

$$W = \frac{\partial(\varepsilon\omega)}{\partial\omega} E^2 + \frac{\partial(\mu\omega)}{\partial\omega} H^2$$

- Positivity of ***W*** requires

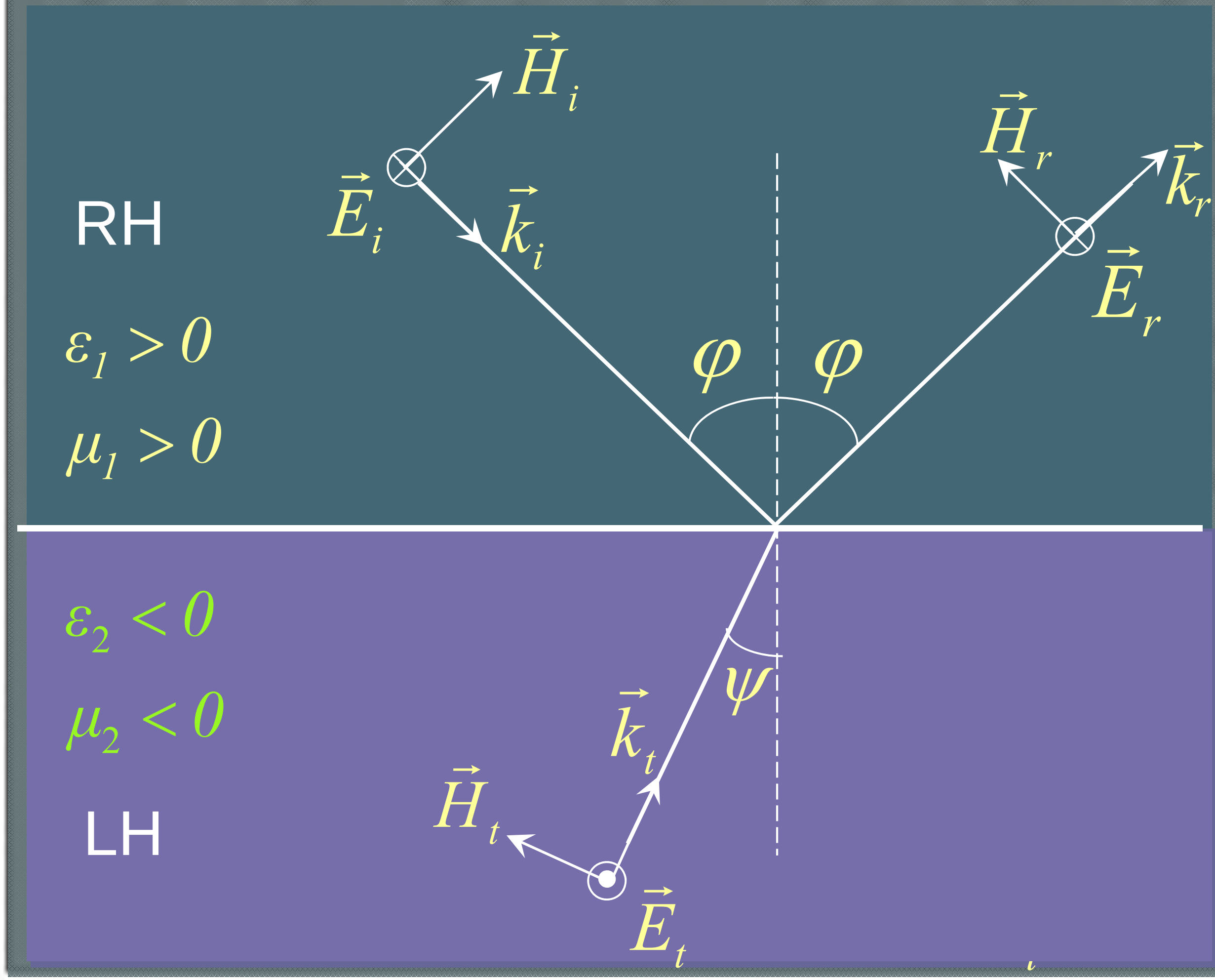
$$\frac{\partial(\varepsilon\omega)}{\partial\omega} > 0\,; \qquad \frac{\partial(\mu\omega)}{\partial\omega} > 0$$

- *LH medium is <u>dispersive</u>*



- According to the Kramers-Kronig relations – it is *<u>always dissipative</u>*

Refraction of light at the LH/RH interface



Snell's law:

$$\frac{\sin\varphi}{\sin\psi} = \frac{n_2}{n_1} = -\sqrt{\frac{\varepsilon_2\mu_2}{\varepsilon_1\mu_1}}$$

$$\frac{\sin\varphi}{\sin\psi} = \frac{n_2}{n_1} = \sqrt{\frac{\varepsilon_2\mu_2}{\varepsilon_1\mu_1}}$$

$$\boxed{n_2 = -\sqrt{\varepsilon_2\mu_2}}$$

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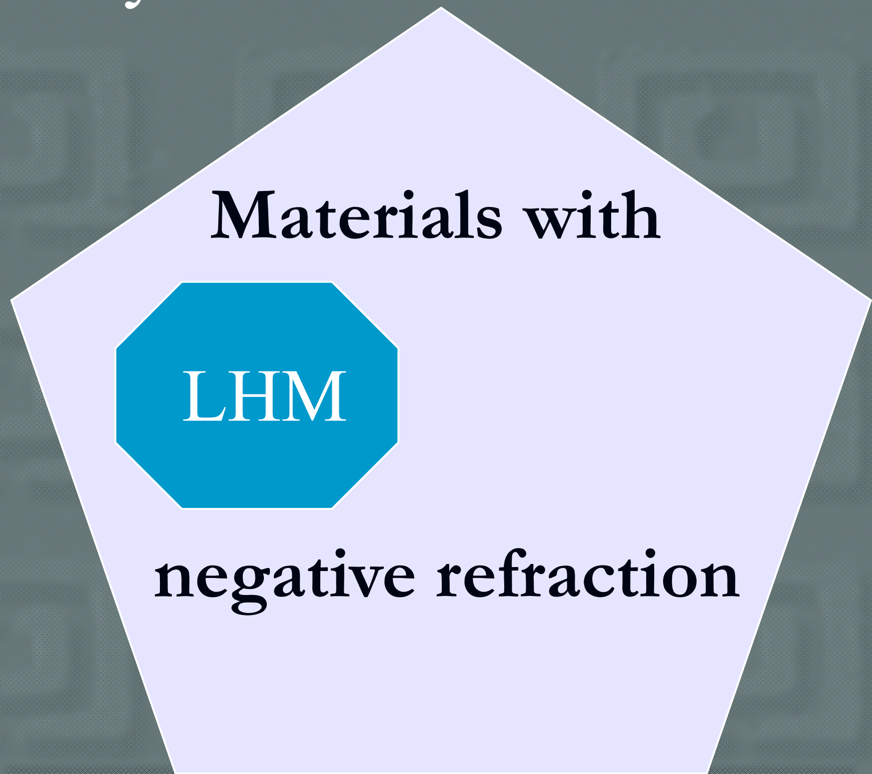
Negative refraction *vs.* LHM

- Negative refraction is a property of backward waves and it has been observed in many materials:
  - Photonic crystals
  - Anisotropic media
  - Left-handed materials

- LHM are materials with negative refraction
- Not all materials with negative refraction are LHM



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Negative refraction—back to 1942

Требуя по-прежнему, чтобы энергия во второй среде *оттекала* от границы раздела, мы приходим тогда к тому, что фаза должна *набегать* на эту границу и, следовательно, направление распространения преломленной волны будет составлять с нормалью угол

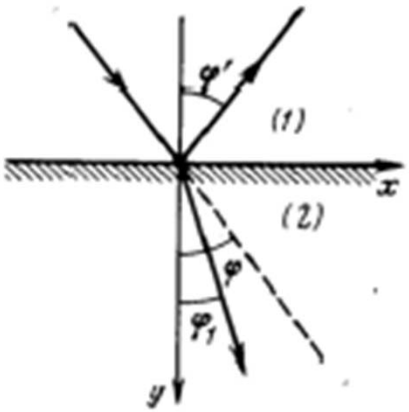


Рис. 12

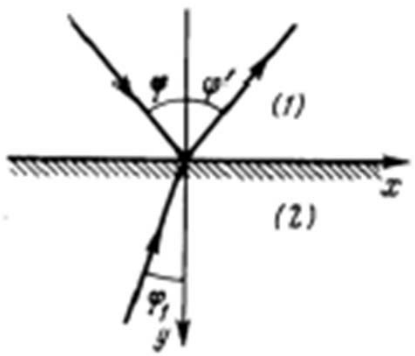


Рис. 13

$\pi - \varphi_1$. Как ни непривычно такое построение, но, конечно, ничего удивительного в нем нет, ибо фазовая скорость еще ничего не говорит о направлении потока энергии.

Mandelshtam, 1942

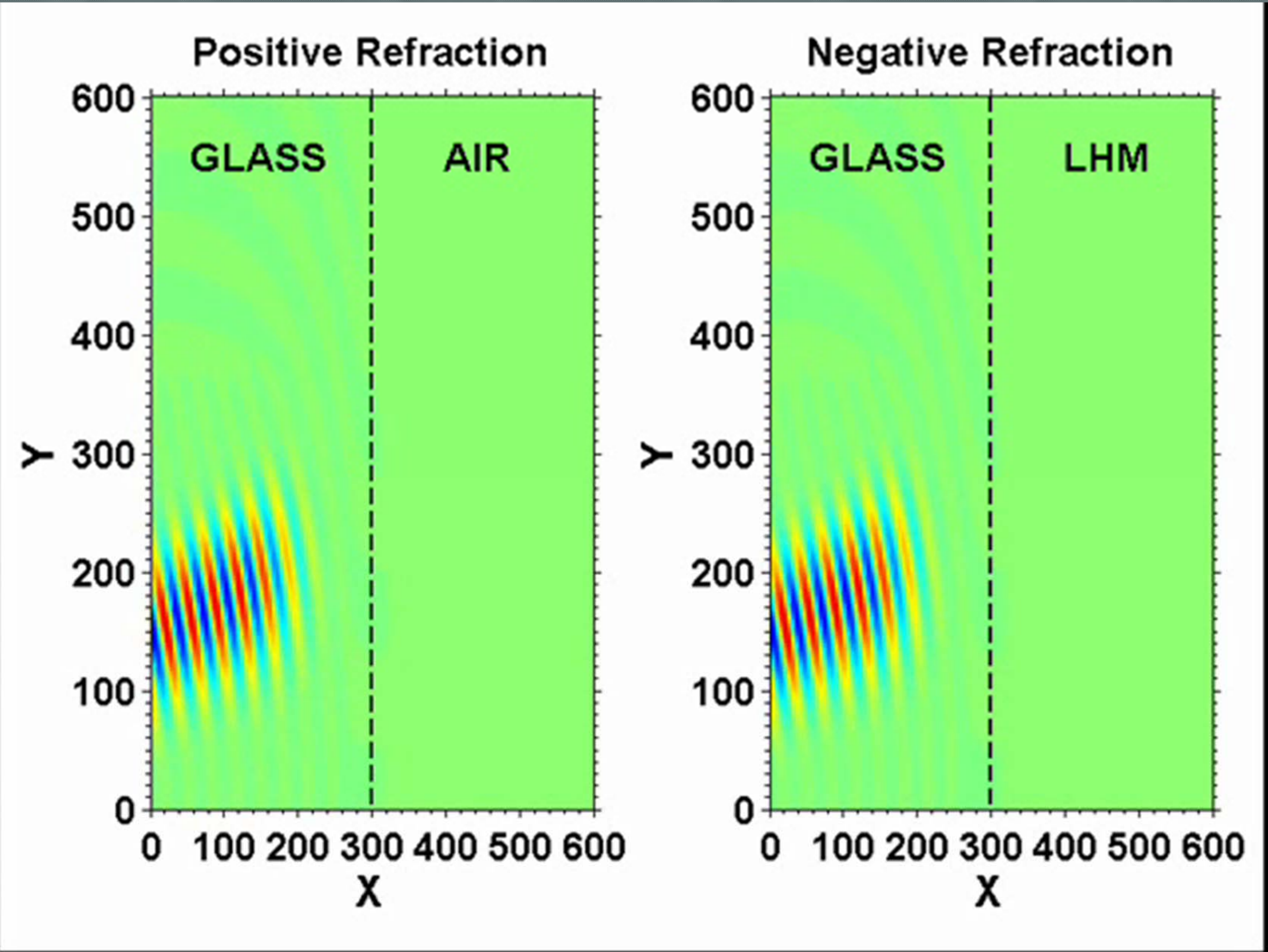
“Lectures about waves”

Backward waves: Manchester, 1904

Sir Horace Lamb : 1849-1934
Professor of Mathematics

Sir Arthur Schuster
Professor of Physics

Positive vs. negative refraction



www.rsphysse.anu.edu.au/n

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Right- and left-handed water

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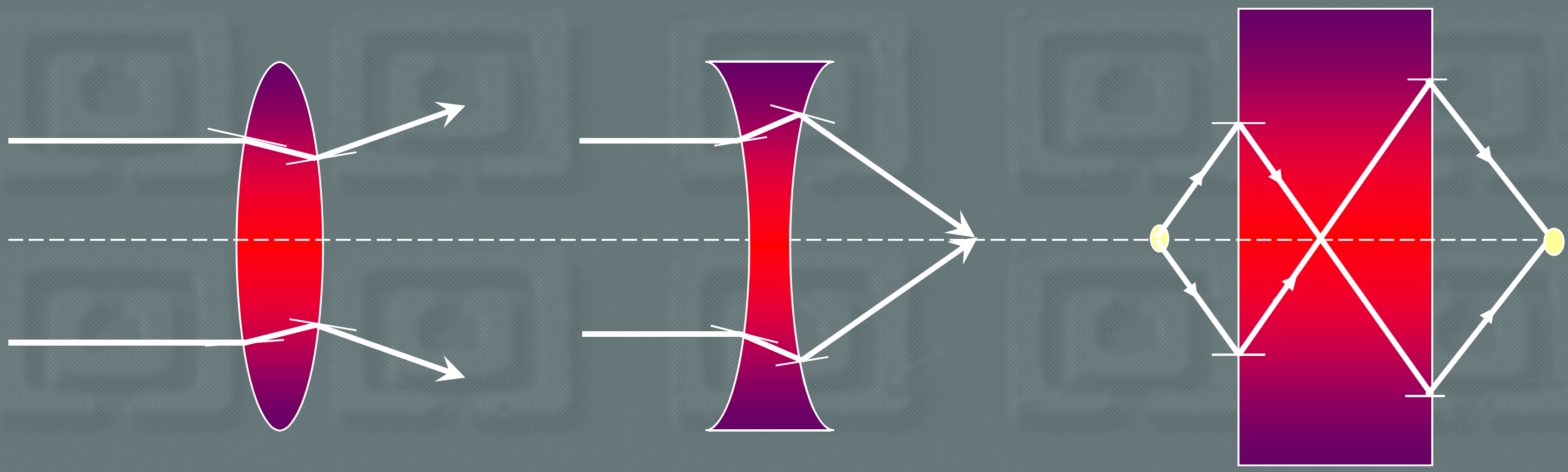
Unusual lenses

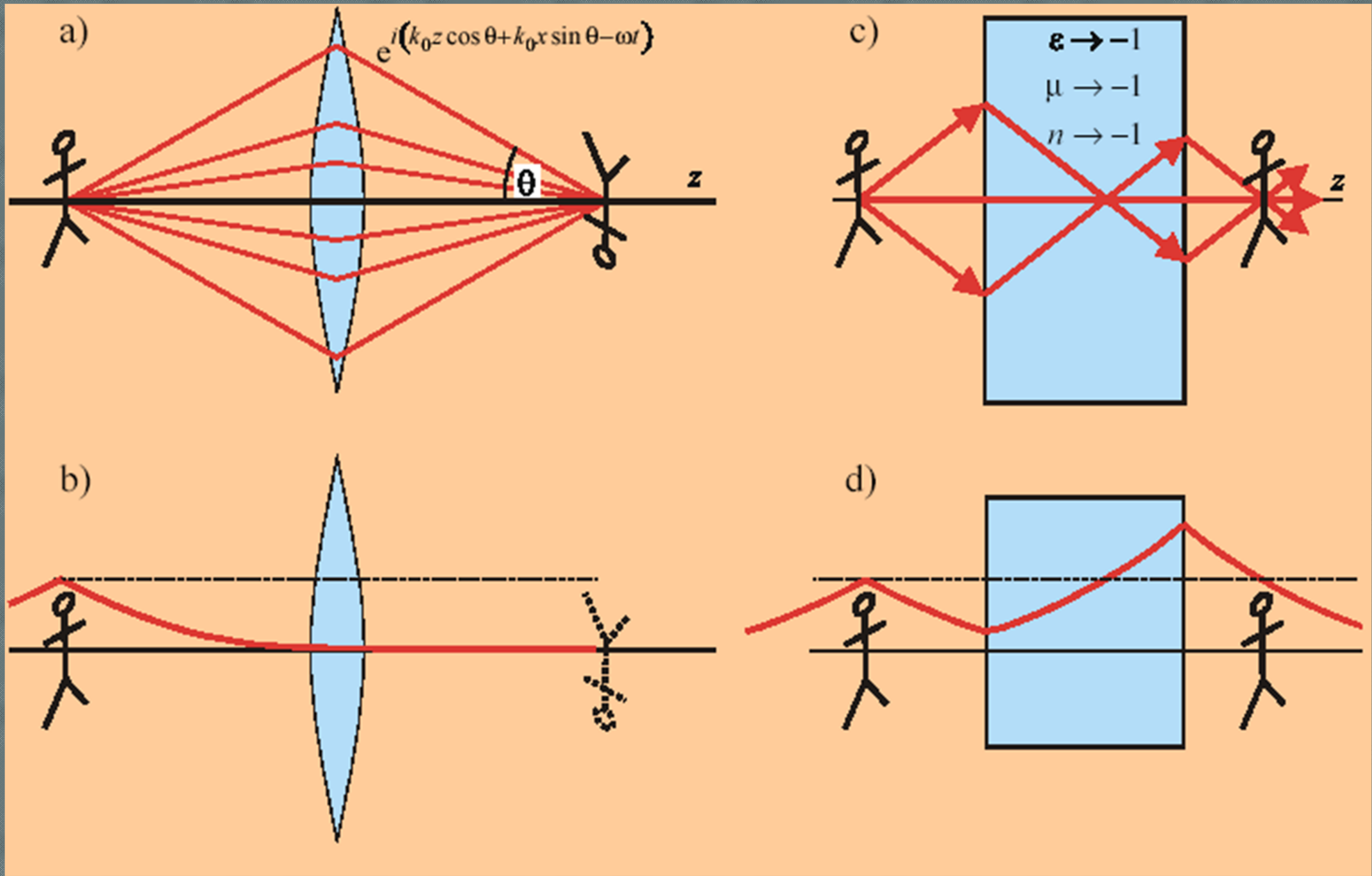


LH lens does not have a diffraction resolution limit

Improved resolution is due to the surface waves

- V. G. Veselago, Soviet Physics Uspekhi **10** (4), 509-514 (1968)
- J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000)

“Perfect” lens



- V. G. Veselago, Soviet Physics Uspekhi **10** (4), 509-514 (1968)
- J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000)

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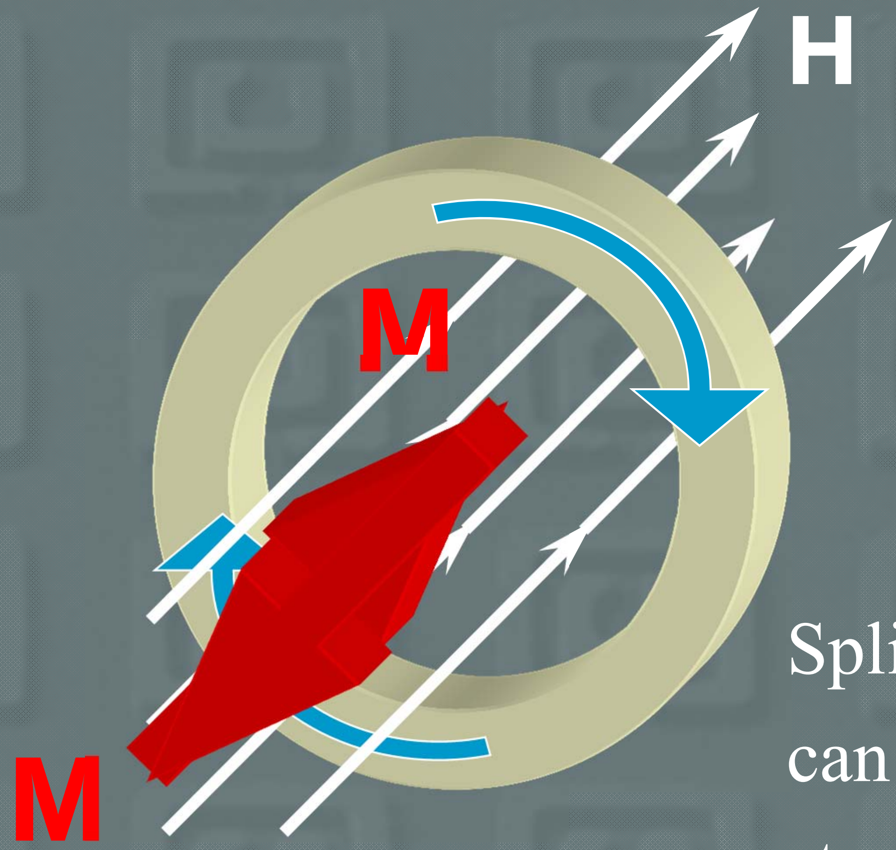
How to make a left-handed material ?

http://wwwrshysse.anu.edu.au/nonlinear

Magnetic response of a gold ring



Split-Ring Resonator can produce strong negative magnetic response

http://wwwrshysse.anu.edu.au/nonlinear

The first experiment on LH media

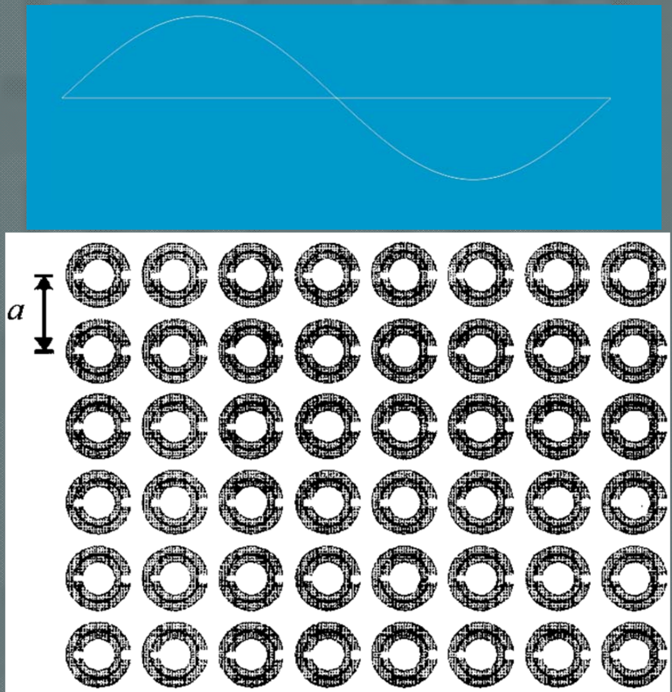
D.R.Smith, W.J.Padilla, D.C.Vier, S.C.Nenat-Nasser and S.Schultz, Composite medium with simultaneously negative permeability and permittivity, Phys. Rev. Lett. **84**, 4184 (2000)

Idea: to combine a wire structure with the SRR array:

Metamaterial

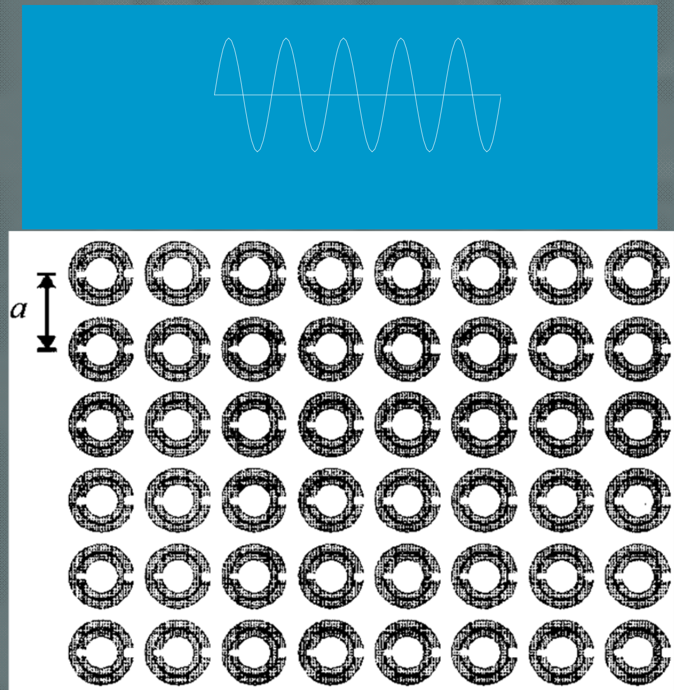
Periodic structures

$\lambda >> a$



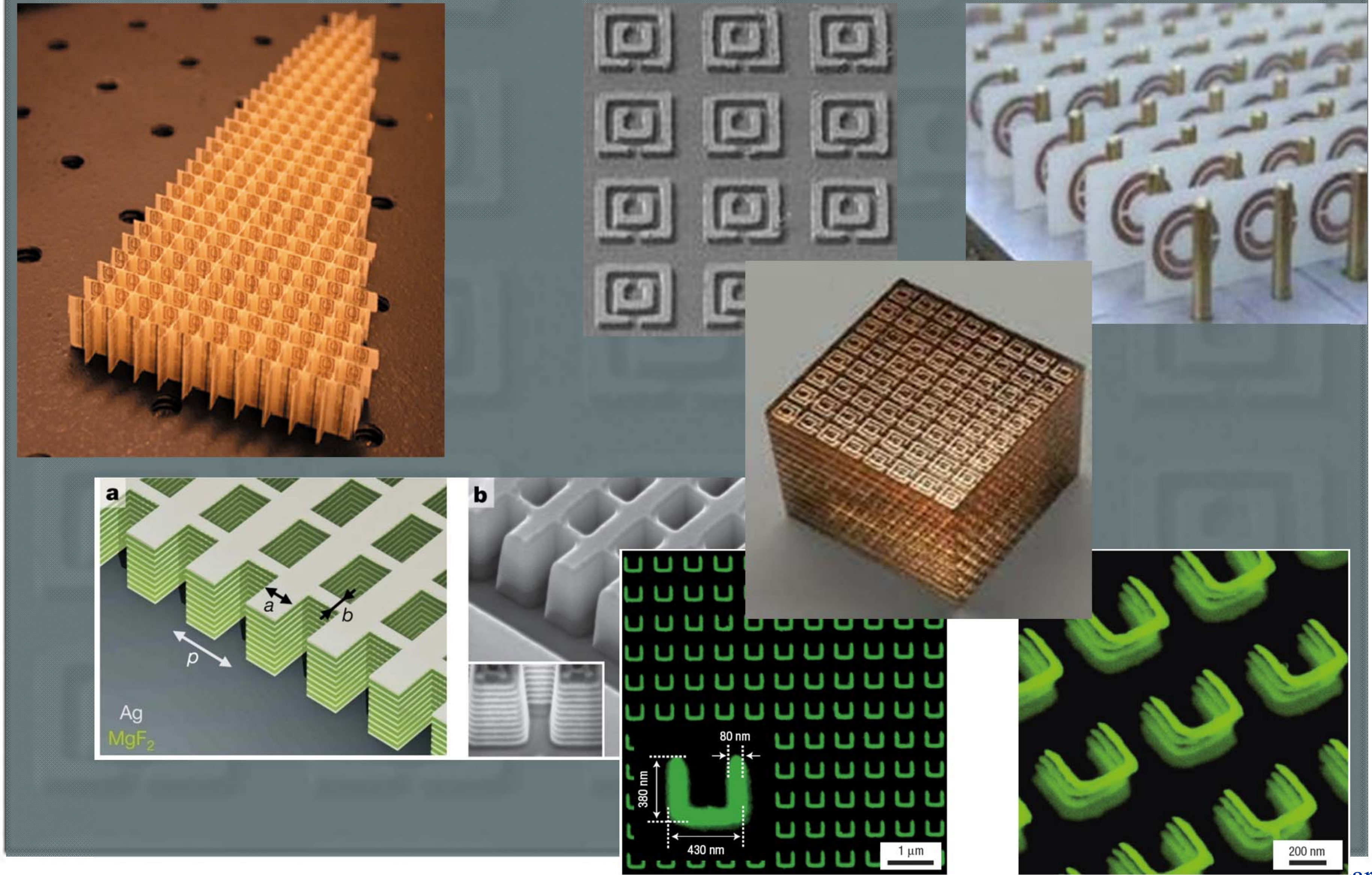
Continuous medium
(Effective medium)

$\lambda \approx a$



Photonic crystal

Examples of metamaterials



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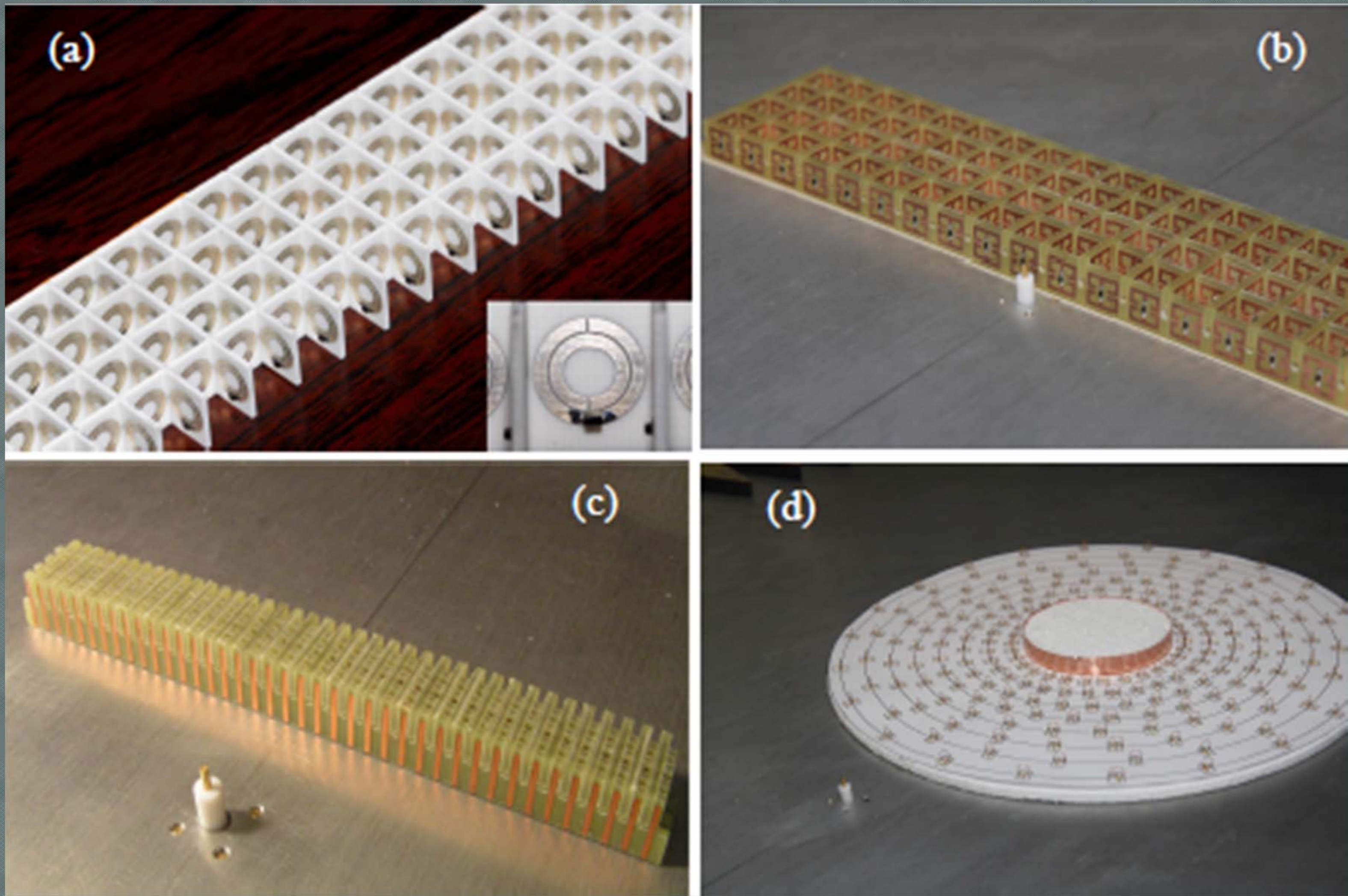
Microwave metamaterials in Canberra



www.rsphysse.anu.edu.au/n

50 μm

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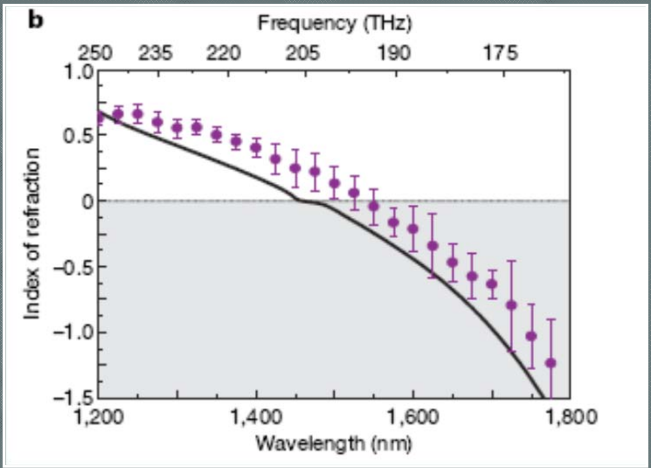
The first step into 3D

nature Vol 455 | 18 September 2008 | doi:10.1038/nature07247

LETTERS

Three-dimensional optical metamaterial with a negative refractive index

Jason Valentine[1]*, Shuang Zhang[1]*, Thomas Zentgraf[1]*, Erick Ulin-Avila[1], Dentcho A. Genov[1], Guy Bartal[1] & Xiang Zhang[1,2]



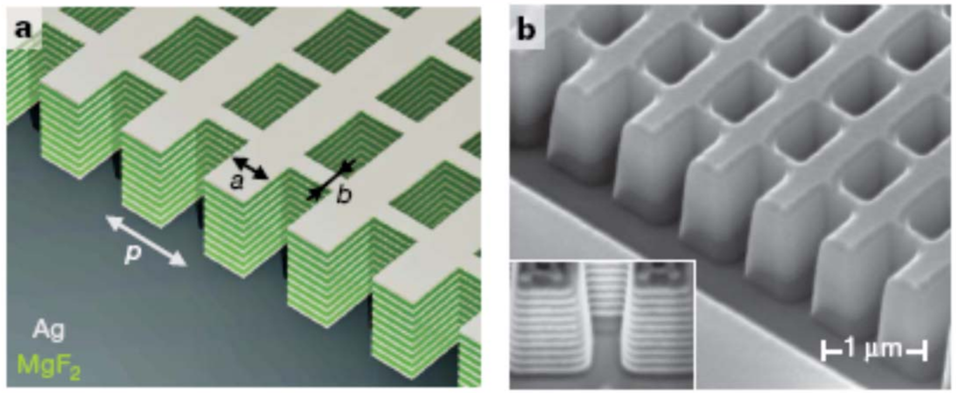


Figure 1 | Diagram and SEM image of fabricated fishnet structure.

Nonlinear properties

- Amplitude-dependent effects have been observed in experiments but were never analyzed

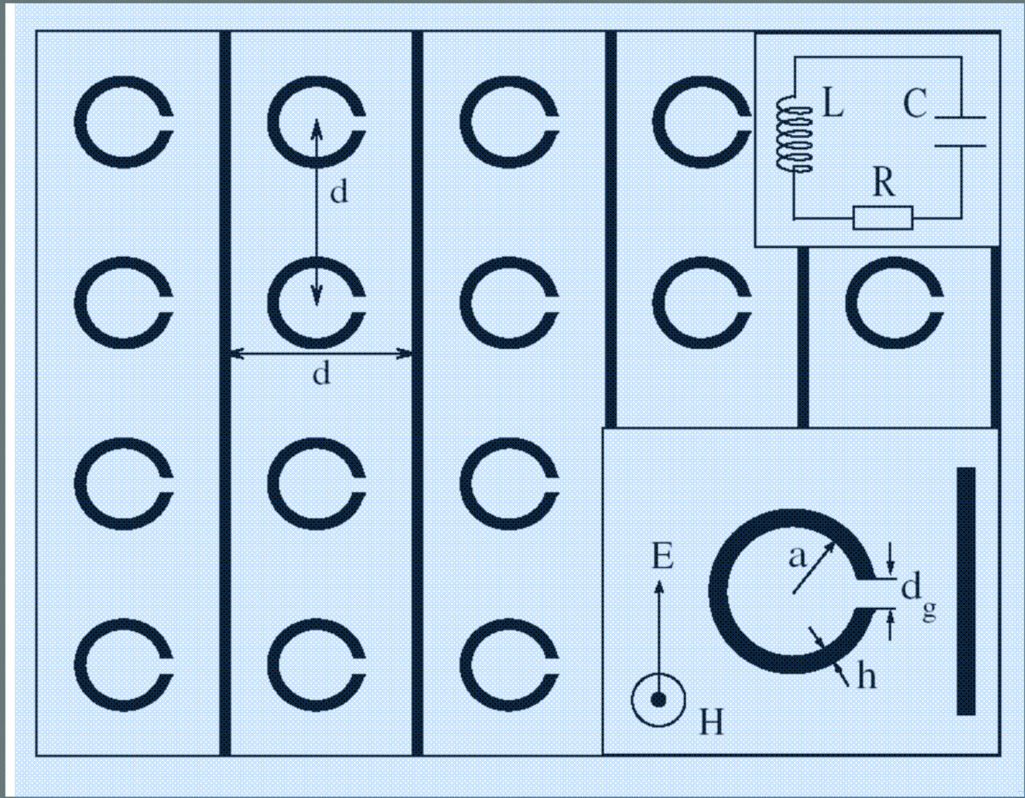
- We conducted the first analysis of nonlinear properties of LHM and predicted **the field-driven phase transitions in transmission properties**

Phys. Rev. Lett. 91, 037401 (2003)

http://wwwrshysse.anu.edu.au/nonlinear

Nonlinear left-handed materials

- Metallic composite structure embedded into a nonlinear dielectric



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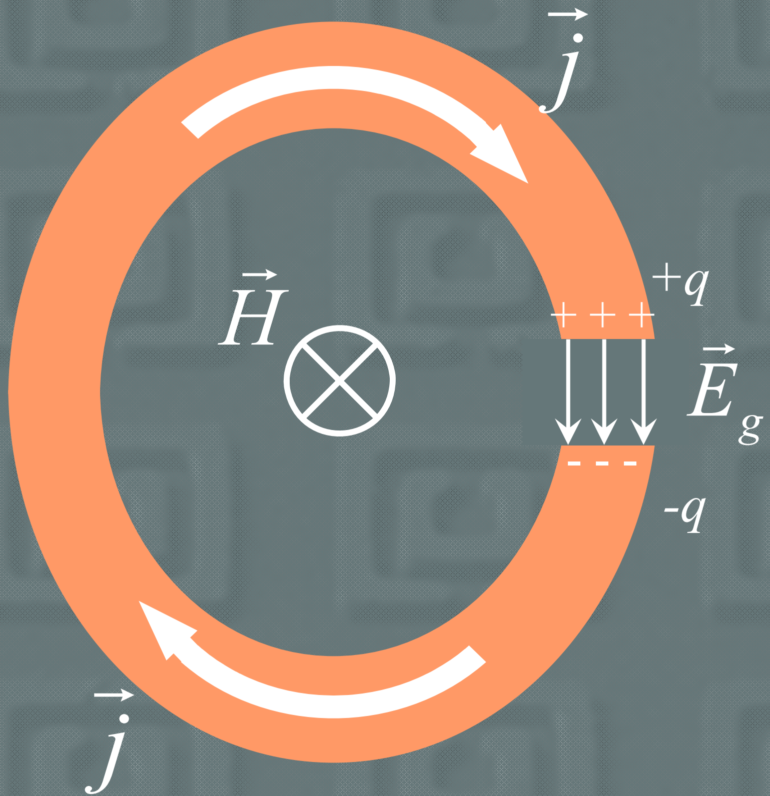
Effective magnetic permeability



Effective medium approximation

$$\mu_{eff}(\omega) = 1 + \frac{F\omega^2}{\omega_0^2 - \omega^2 + i\Gamma\omega}$$

$$\omega_0^2 = \frac{1}{LC}$$

$$C \sim \varepsilon\left(\left|E_g\right|^2\right) \qquad E_g(H)$$

$$\boxed{\mu_{eff}(H)}$$

50 um

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Nonlinear dielectric constant

- *Microscopic* derivation in the effective medium approximation

$$\varepsilon_{eff}\left(|E|^2\right) = \varepsilon_D\left(|E|^2\right) - \frac{\omega_p^2}{\omega(\omega - i\gamma_\varepsilon)}$$

Contribution from nonlinear dielectric

Contribution from metallic wires

50 μm

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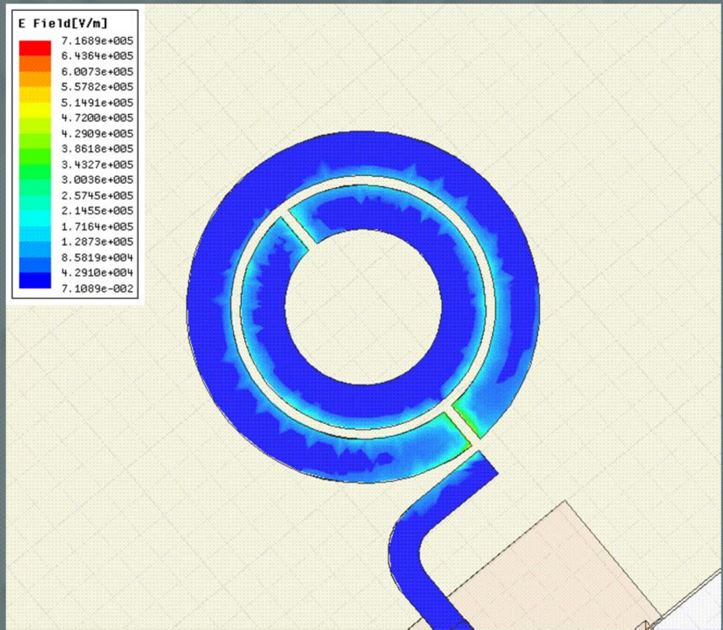
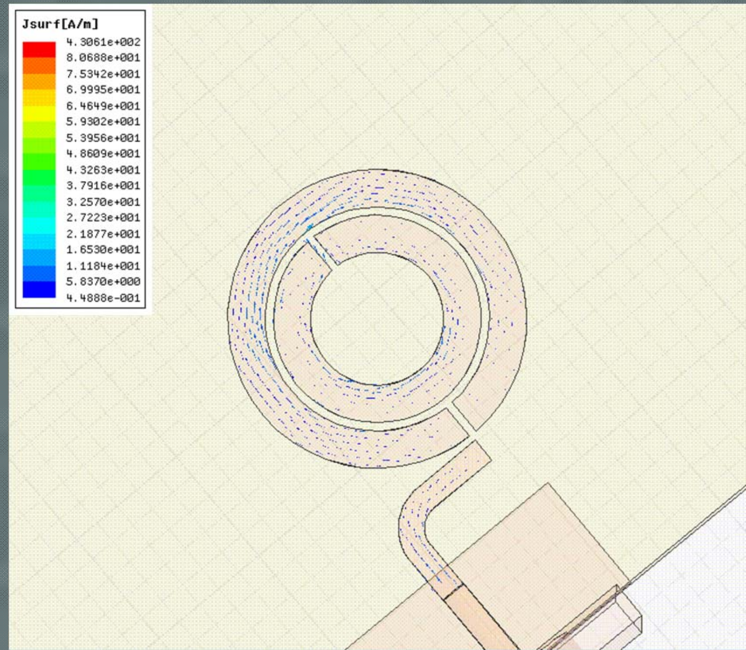
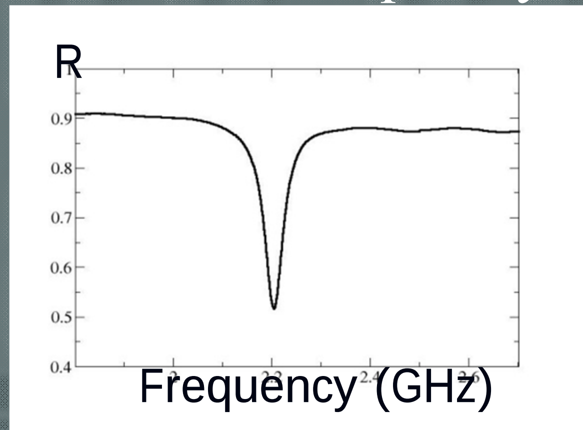
Excitation of SRRs





- In-phase currents in both rings of resonator for low-frequency resonance



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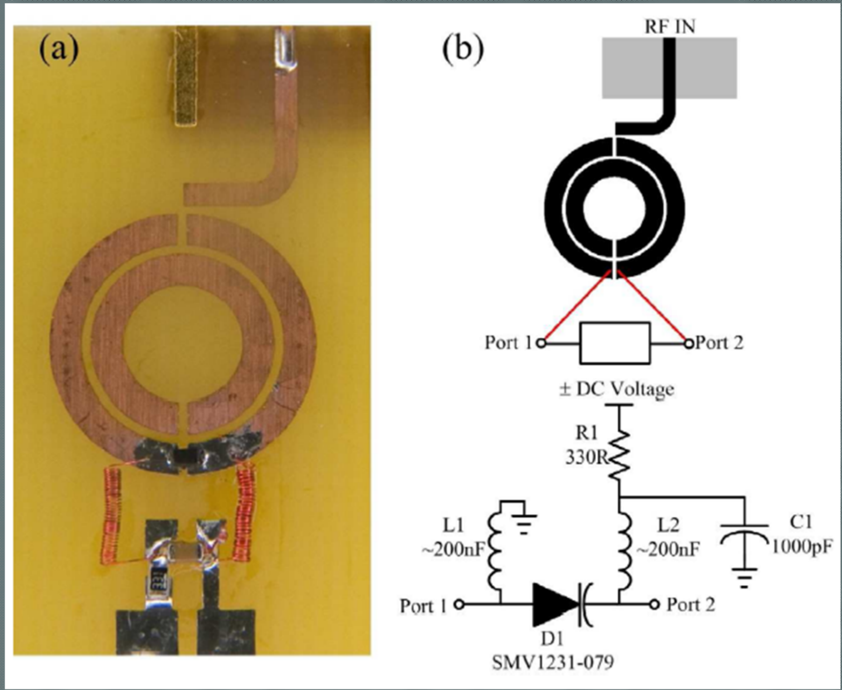
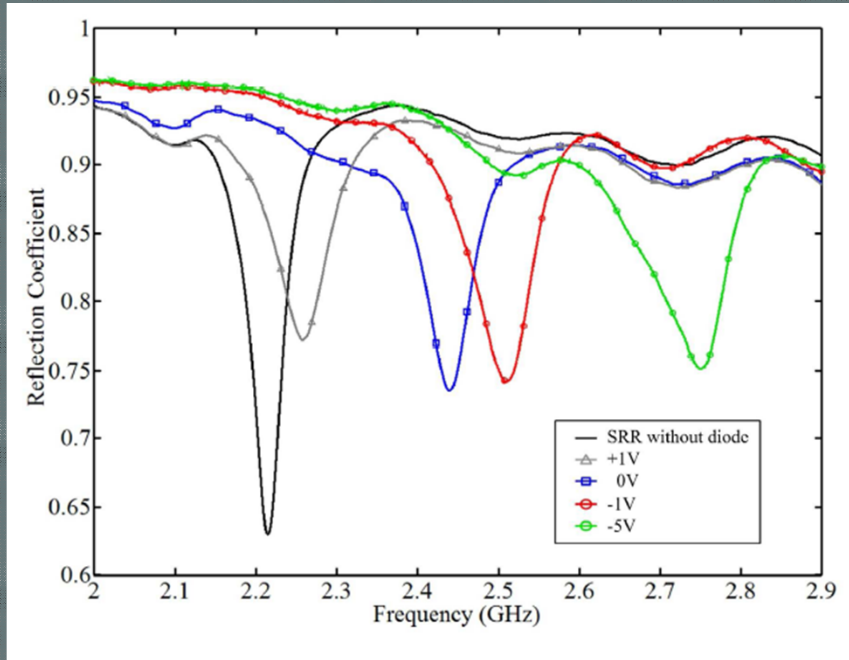
Tunable nonlinear SRRs





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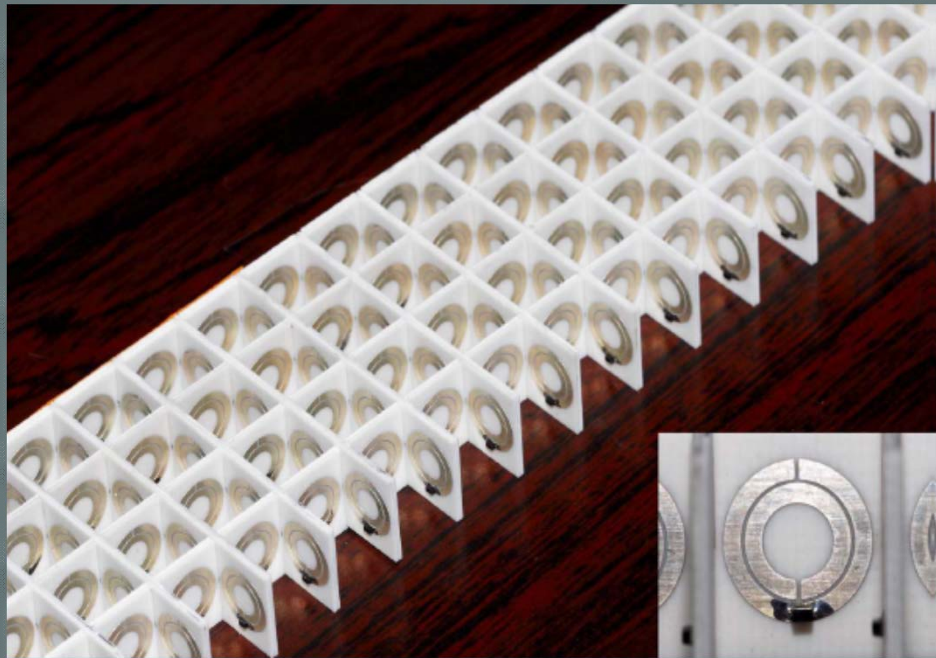
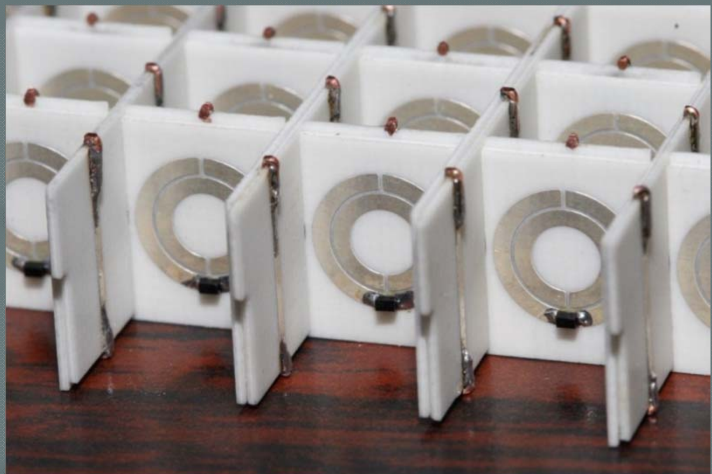
Nonlinear metamaterial for microwaves

- Nonlinear electronic components provide required response
- Second and third order nonlinear response
  - Resonance shift
  - Harmonic generation





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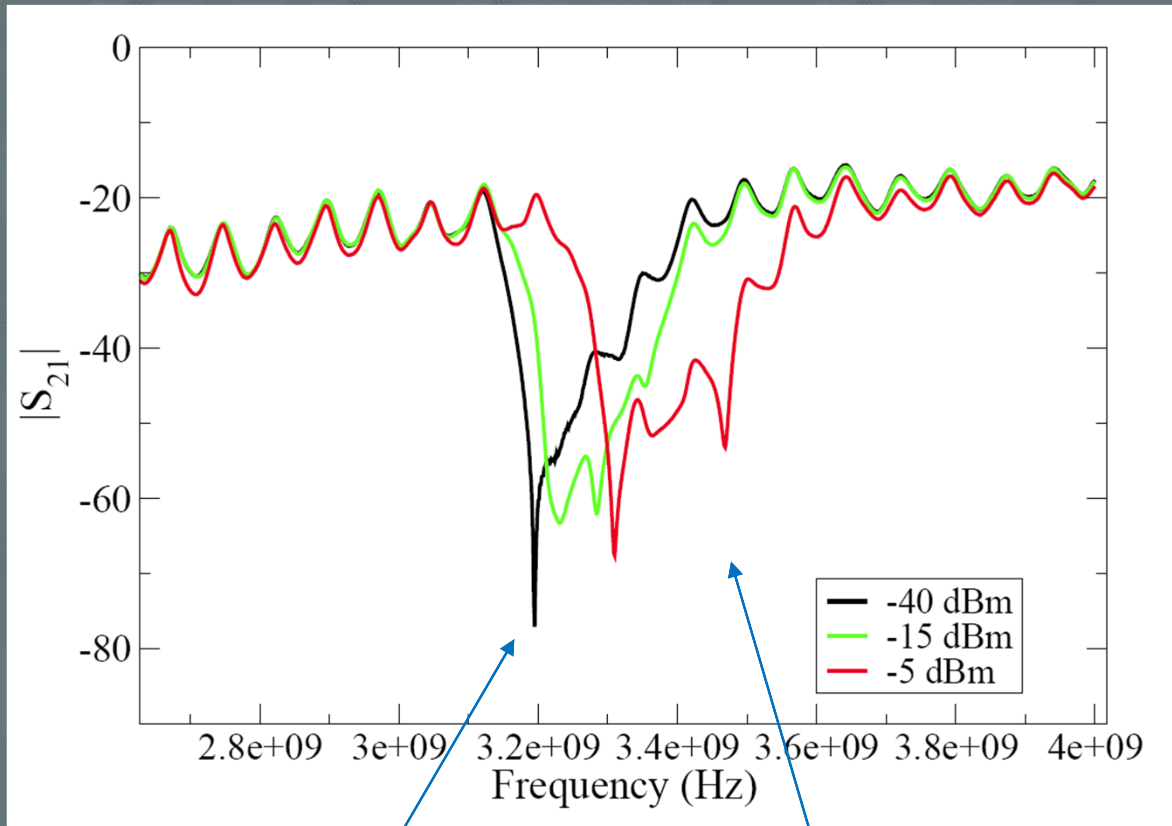
Nonlinear Magnetic Metamaterial



Induced transmission

Suppressed transmission

50 µm

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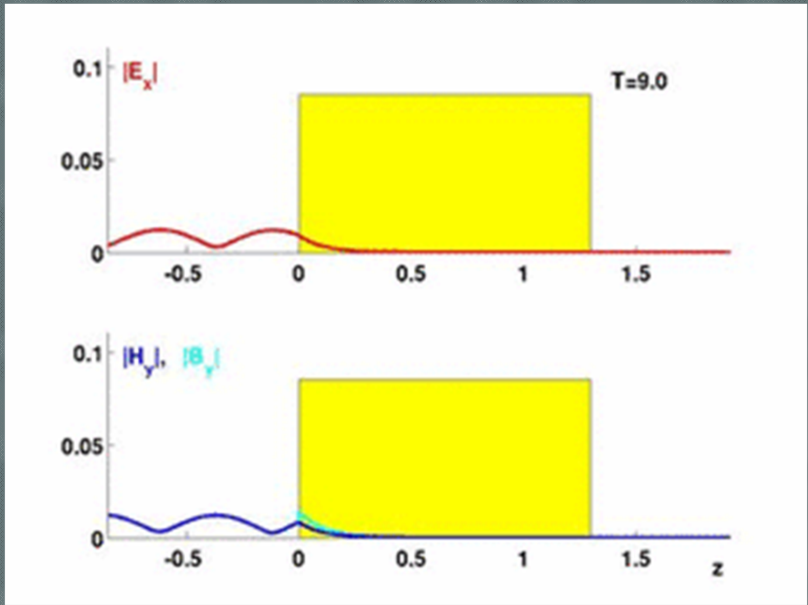
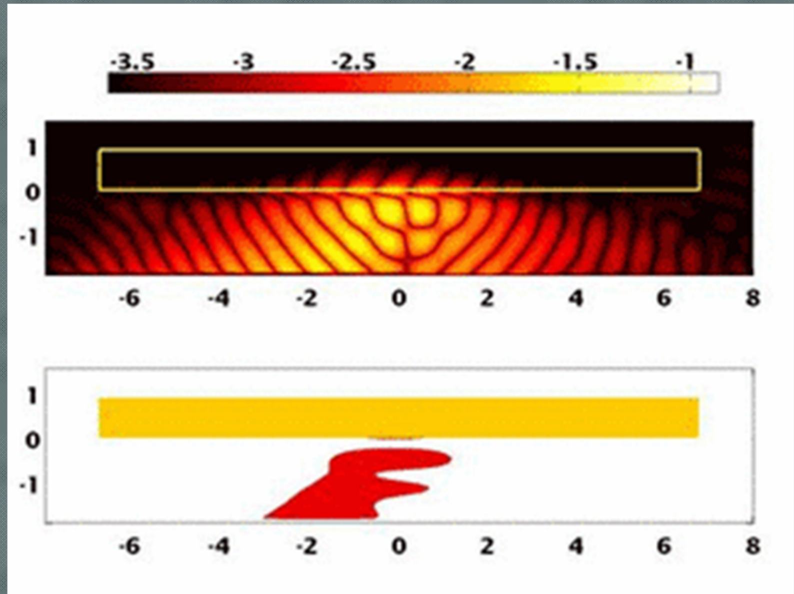
Nonlinearity-induced transparency

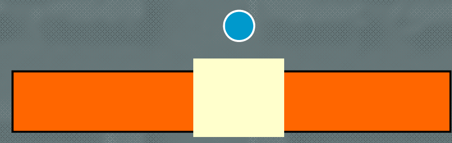


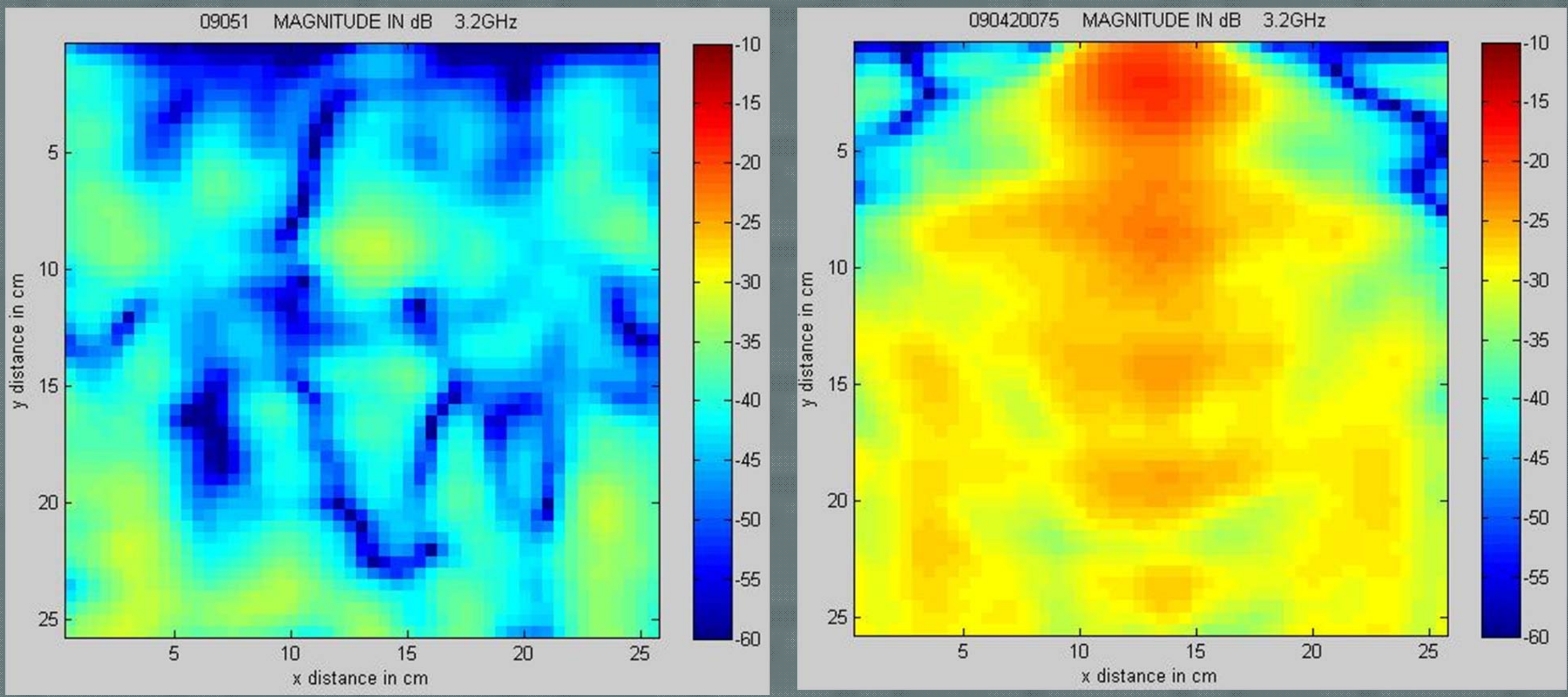


Optics Express 13 1291 (2005)

http://wwwrshysse.anu.edu.au/nonlinear

Induced transparency in magnetic metamaterial





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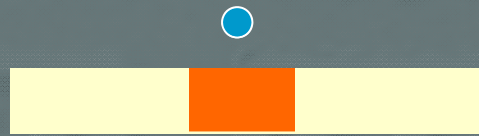
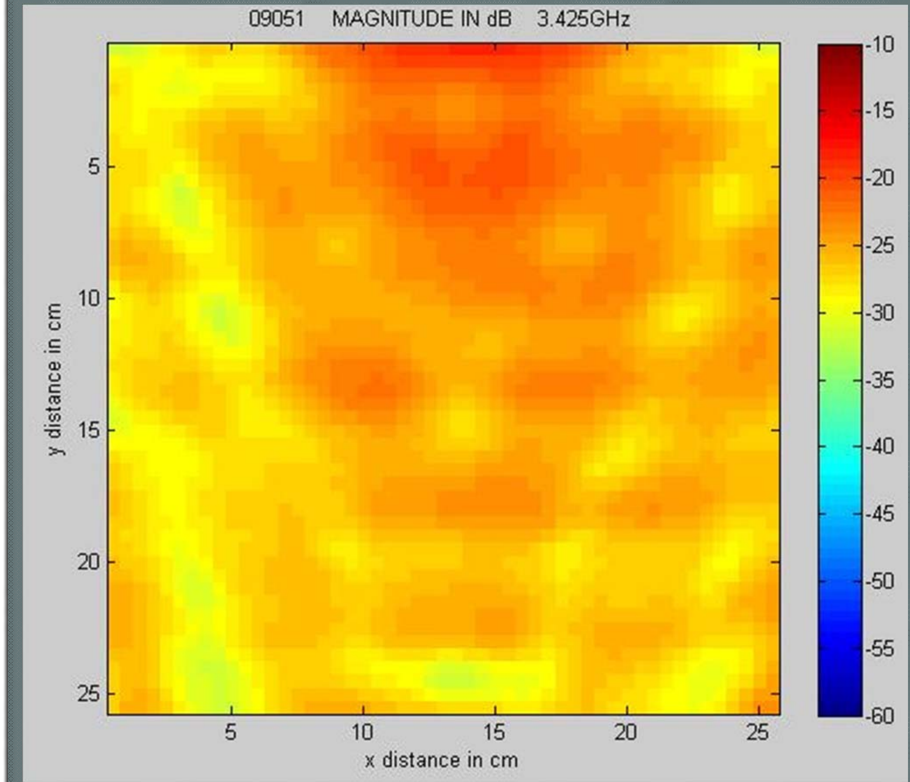
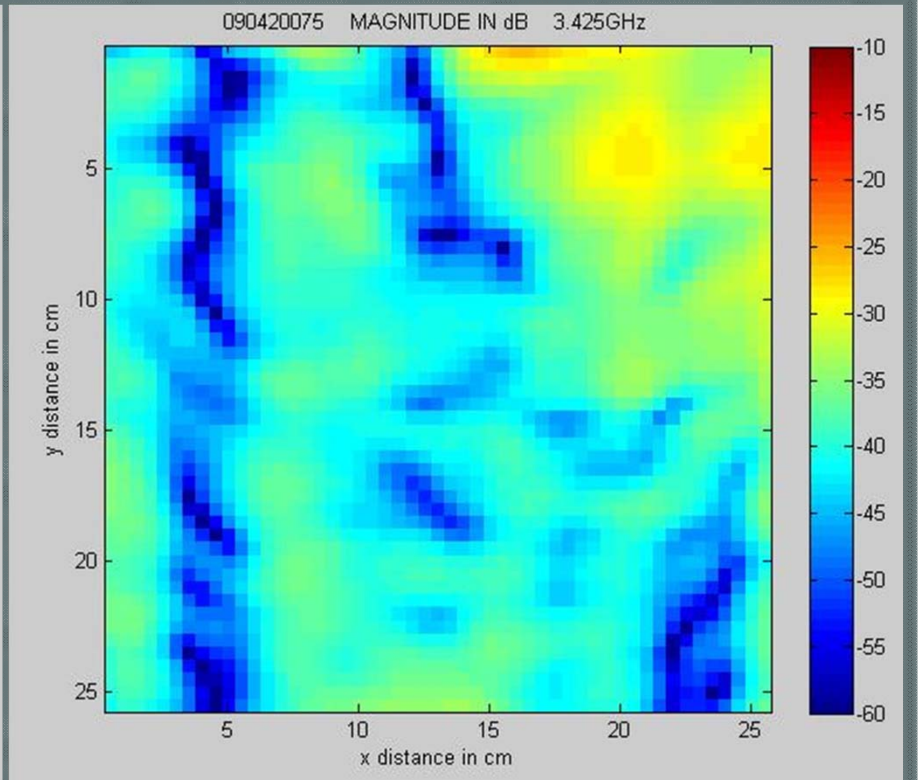
Nonlinearity suppressed transmission







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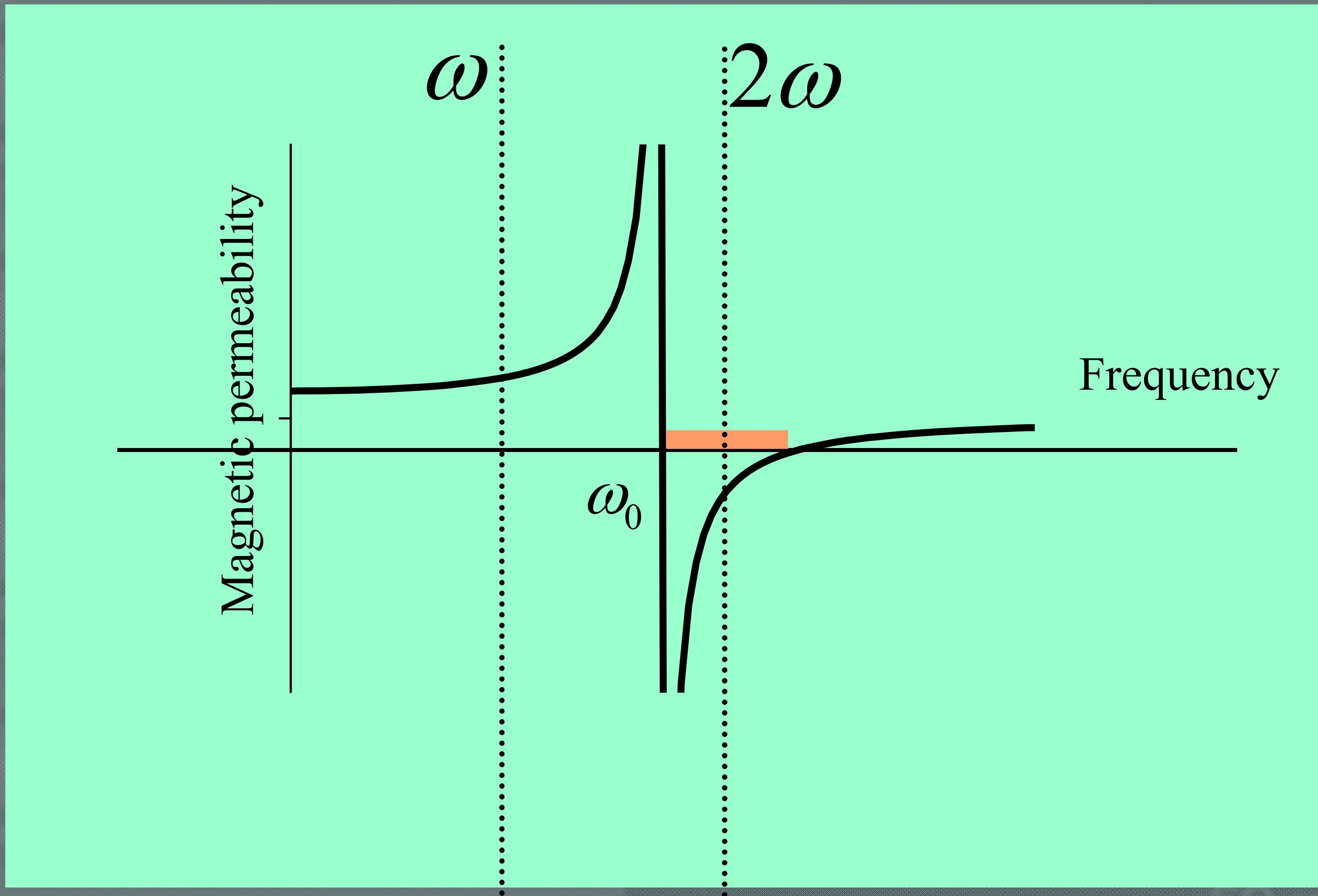
Opaque nonlinear lens: a concept



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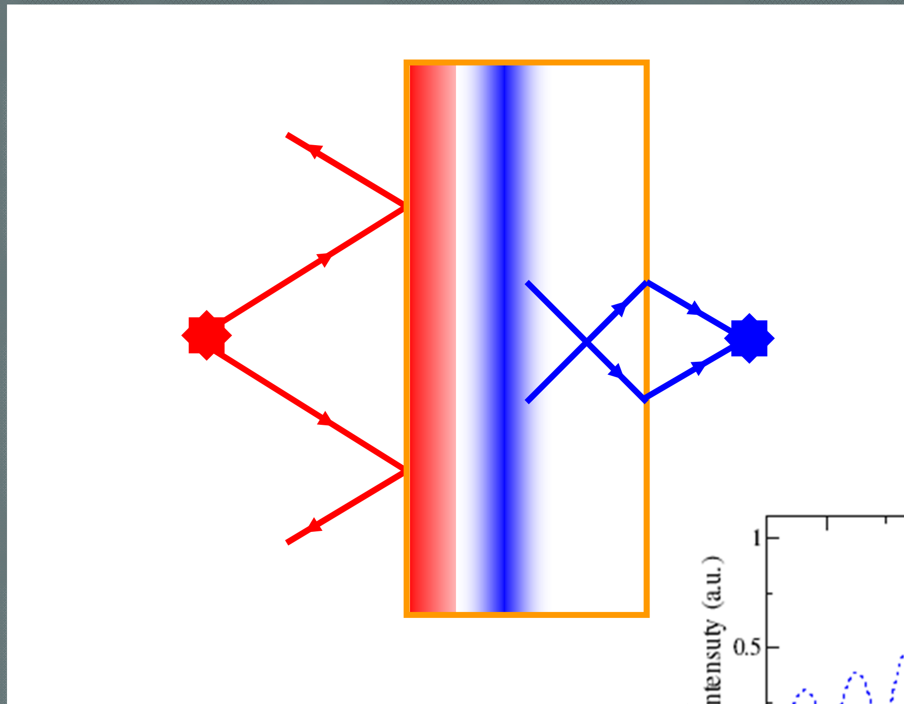
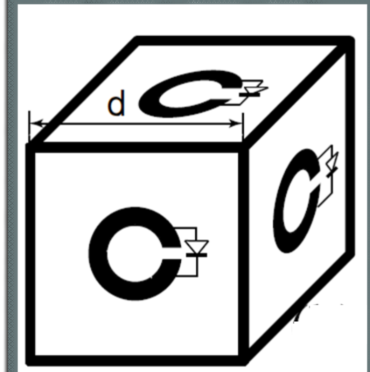
Nonlinear lens



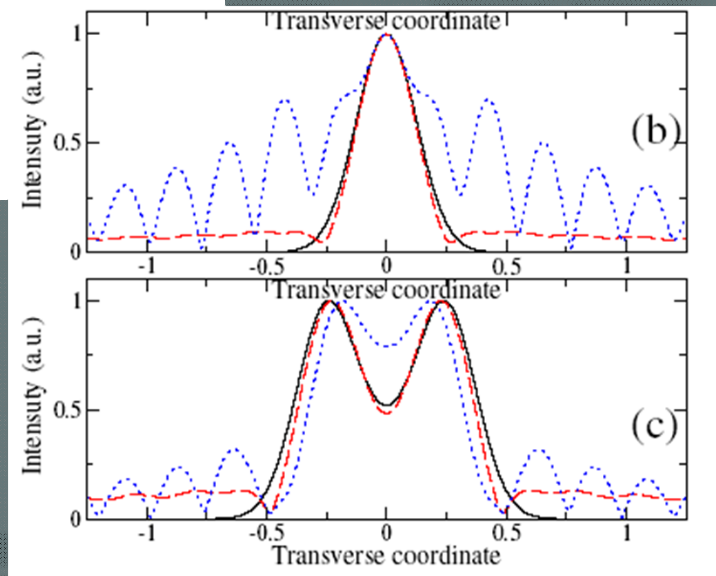
$$\epsilon(\omega) = -7$$

$$\mu(\omega) = (3-F)/(3-2F)$$

$$\mu(2\omega) = -1,\ \epsilon(2\omega) = -1$$



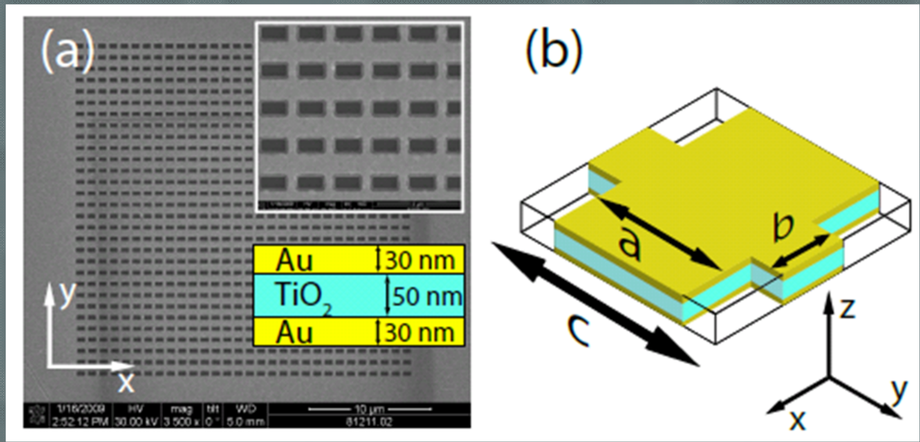
A.A. Zharov, N.A. Zharova, I.V. Shadrivov, and Yu.S. Kivshar, Appl. Phys. Lett (2006)



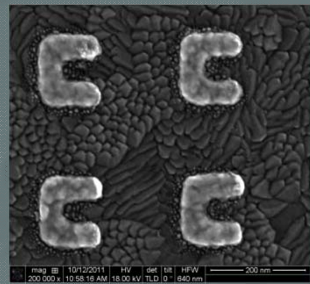
http://wwwrshysse.anu.edu.au/nonlinear

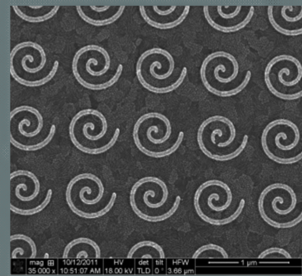
Our recent structures and results

Fishnet metamaterials

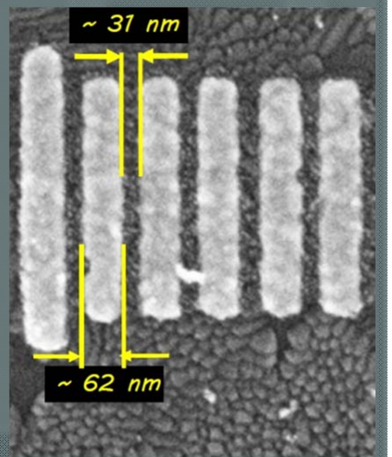


Magnetic arrays

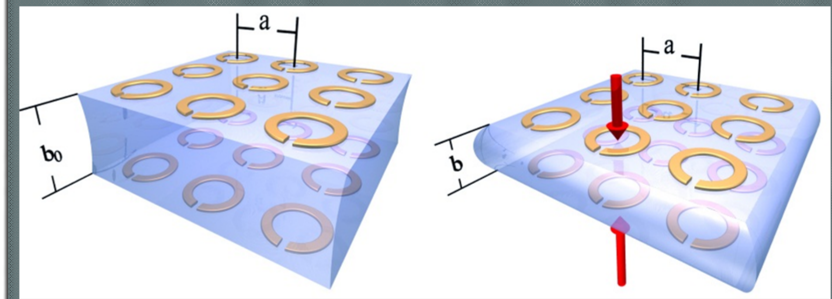




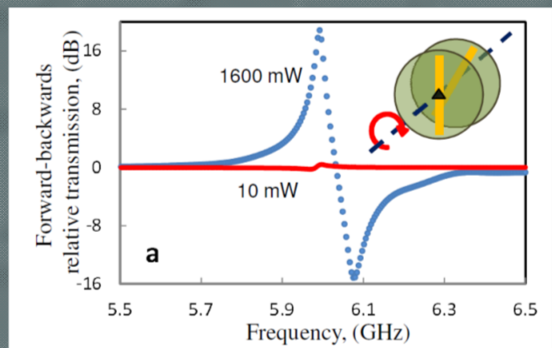
Nanoantennas



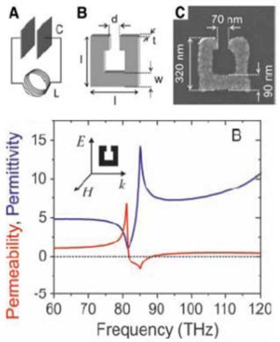
Magnetoelastic metamaterials



Giant nonlinear optical activity

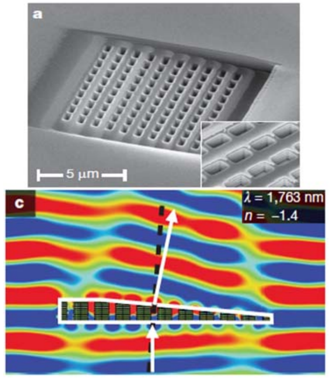


Optical Magnetism



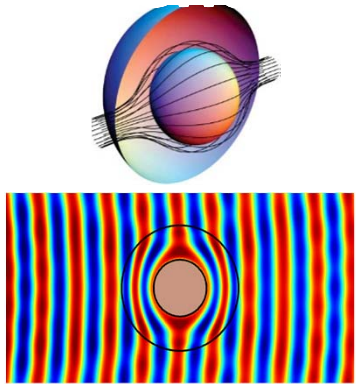
Linden et al., Science (2004)

Negative Refractive Index



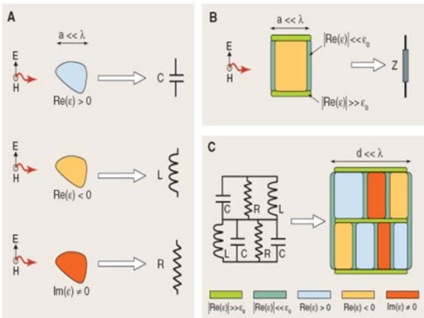
Valentine et al., Nature (2008)

Cloaking



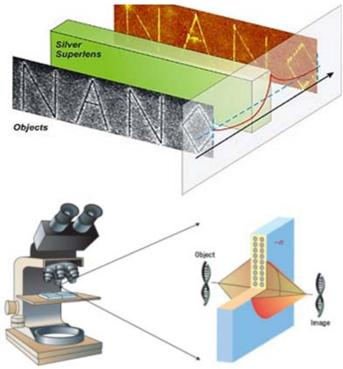
Pendry et al., Science (2006)

Optical Circuits



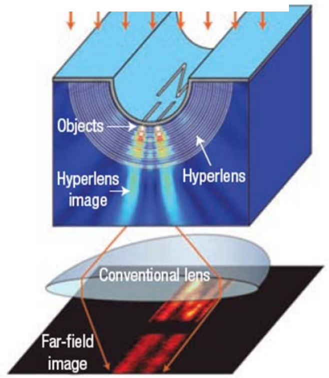
Engheta, Science (2007)

Superlens



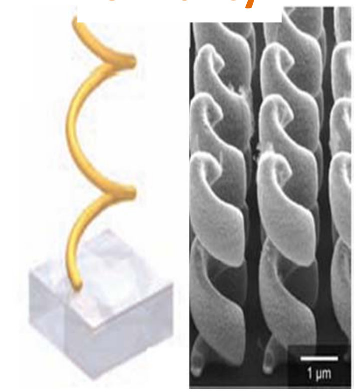
Fang et al., Science (2005)

Hyperlens



Liu et al., Science (2007)

Chirality



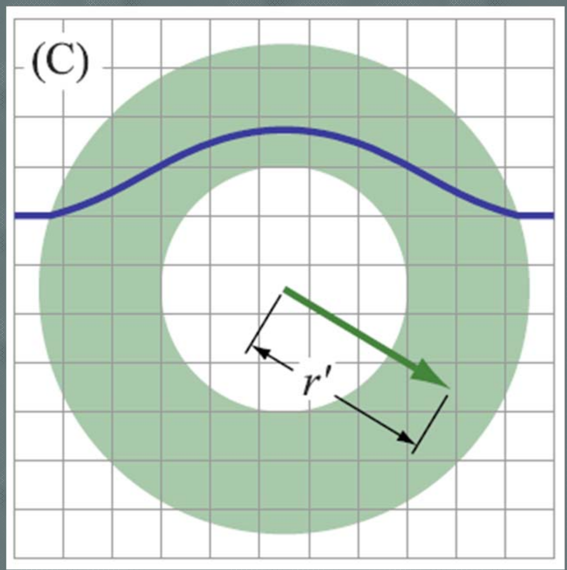
Gansel *et al*. Science (2009)

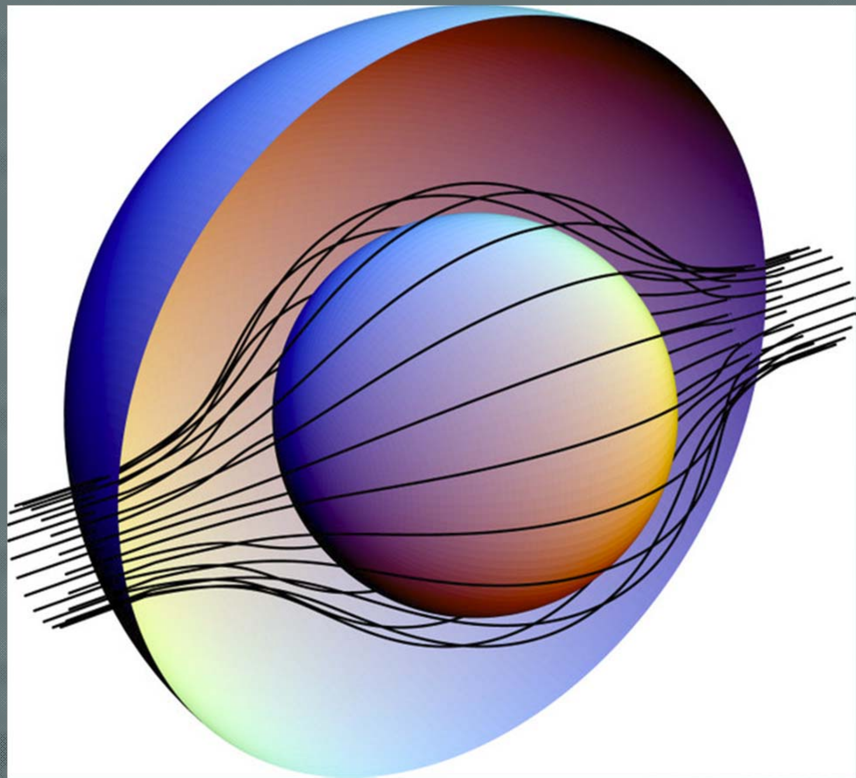
Now: Optical properties are fixed at the time of fabrication

Future: Active, tunable & reconfigurable metamaterials

Principle of invisibility cloak

- Guide light around the object, so that it appears on the other side of the object unperturbed.

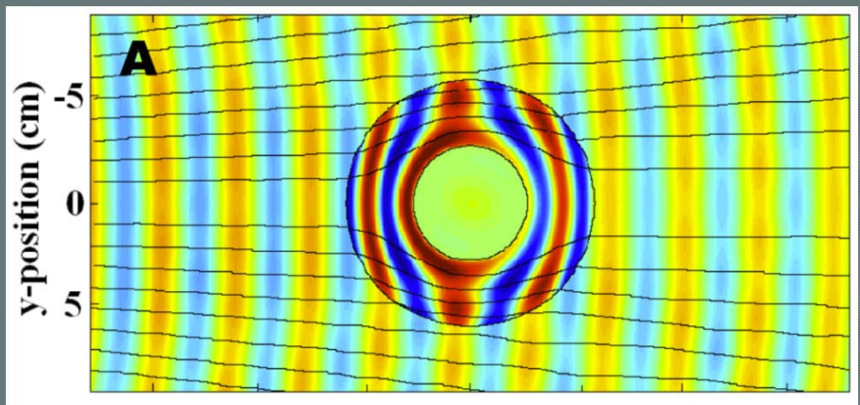




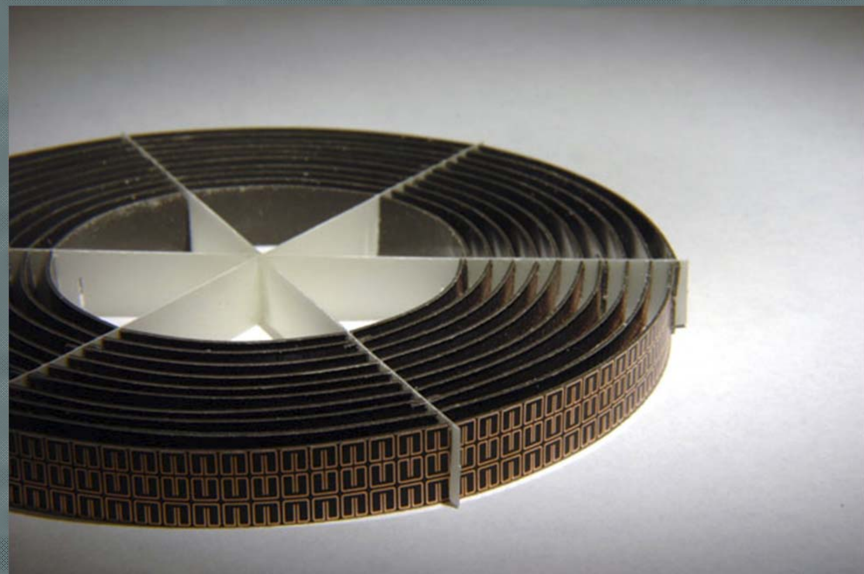
http://wwwrshysse.anu.edu.au/nonlinear

How does it work

- Complex mathematical approach
  'Transforming Space'
- Challenging manufacturing requirements
- The first microwave cloak (by D. Smith)



D. Schurig et al, Science **314**, 977 (2006)



Earlier suggestions: 1961

ИЗВЕСТИЯ ВЫСШИХ УЧЕБНЫХ ЗАВЕДЕНИЙ

Том IV, № 5 — *РАДИОФИЗИКА* — *1961*

О ВОЗМОЖНОСТИ СОПОСТАВЛЕНИЯ ТРЕХМЕРНЫХ ЭЛЕКТРОМАГНИТНЫХ СИСТЕМ С НЕОДНОРОДНЫМ АНИЗОТРОПНЫМ ЗАПОЛНЕНИЕМ

Л. С. Долин

Показано, что, основываясь на инвариантности уравнений Максвелла, относительно определенного вида преобразований метрики пространства и проницаемостей среды, можно исследовать трехмерные системы с неоднородным анизотропным заполнением путем их сопоставления с другими, более простыми трехмерными системами.

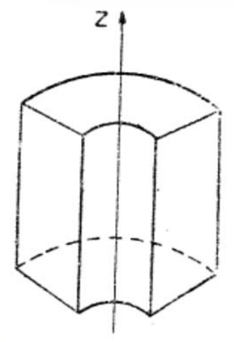


Рис. 1.

L. S. Dolin, Izv. VUZov Radiofizika **4**, 964-967 (1961)

Cloaking with a complex shape

- The transformation are used to find the fields inside the cloak

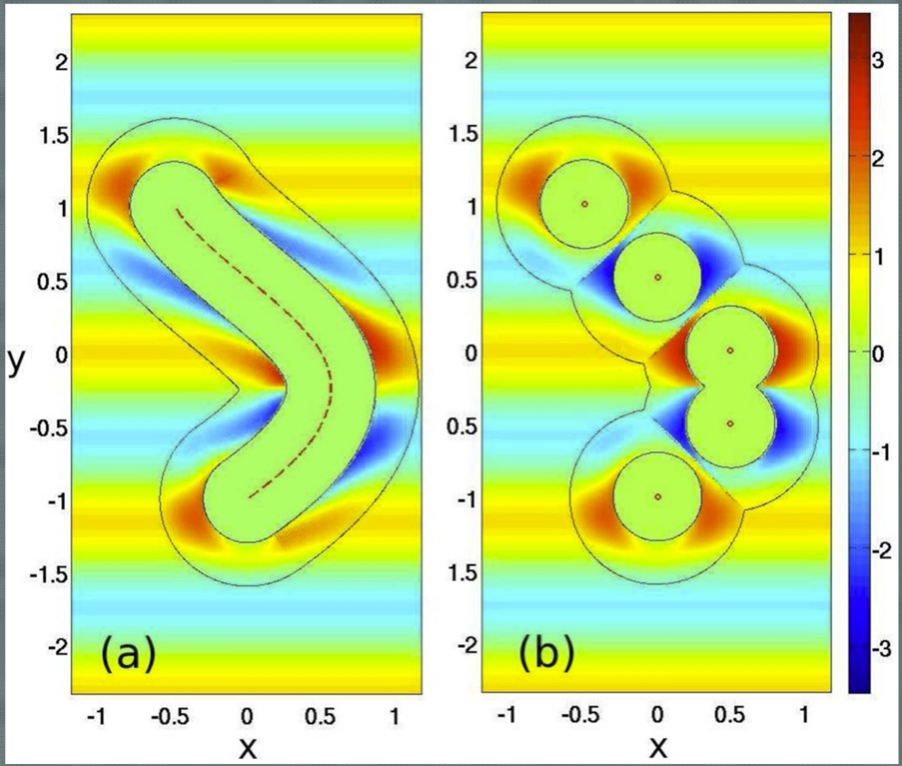
Coordinate transformation gives
a recipe for creating the cloak

$$\tilde{\varepsilon}^{mn} = \frac{1}{\sqrt{g}} \frac{\partial \tilde{x}^m}{\partial x^a} \frac{\partial \tilde{x}^n}{\partial x^b} \varepsilon^{mn}$$

$$\tilde{\mu}^{mn} = \frac{1}{\sqrt{g}} \frac{\partial \tilde{x}^m}{\partial x^a} \frac{\partial \tilde{x}^n}{\partial x^b} \mu^{mn}$$

and the field distribution in the cloak

$$\tilde{\mathrm{E}}_{\mathrm{i}} = \frac{\partial x^k}{\partial \tilde{x}^i} \mathrm{E}_{\mathrm{k}} \qquad \tilde{\mathrm{H}}_{\mathrm{i}} = \frac{\partial x^k}{\partial \tilde{x}^i} \mathrm{H}_{\mathrm{k}}$$



N.A. Zharova, I.V. Shadrivov, A.A. Zharov, Yu.S. Kivshar (2008)

“Invisibity” means “publicity”

Australians join race for invisibility

Weaving Harry Potter magic

EVONNE BARRY

AN “invisibility cloak” that could make people and objects see-through is being developed by Australian scientists.

Turning science fiction into reality, researchers from the Australian National University in Canberra have created a material that — when wrapped around a solid object — makes it appear transparent.

The concept was dreamed up by a British scientist and now Australian academics have joined the international race to put it into practice.

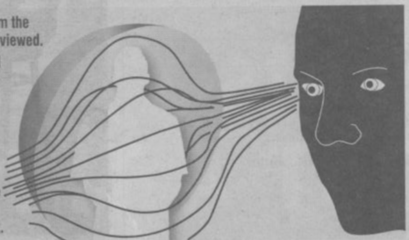
Dr David Powell, an electronics engineer, said his team at ANU's Nonlinear Physics Centre had built “artificial atoms” capable of producing the hi-tech illusion.

“The concept has been proved. We're hoping to see a real device within the next decade.”

1. Light rays travel from the eye to an object being viewed.

2. The object is cloaked by a piece of ‘smart metamaterial’ which bends light around the object rather than letting it bounce back.

3. The viewer sees whatever is behind the cloaked object as the light rays bounce back.



The real-life version of Harry Potter's invisibility cloak is so far confined to a 30cm squared piece of “smart metamaterial” in Dr Powell's laboratory.

The metamaterial is made up of “kind of artificial atoms”.

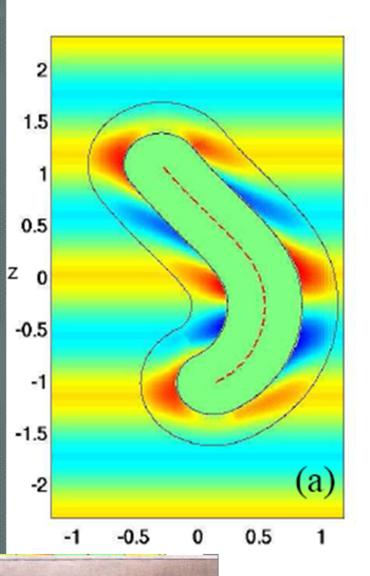
“They are a million times bigger than a real atom, and what happens is that these artificial atoms do things that real atoms can't do.

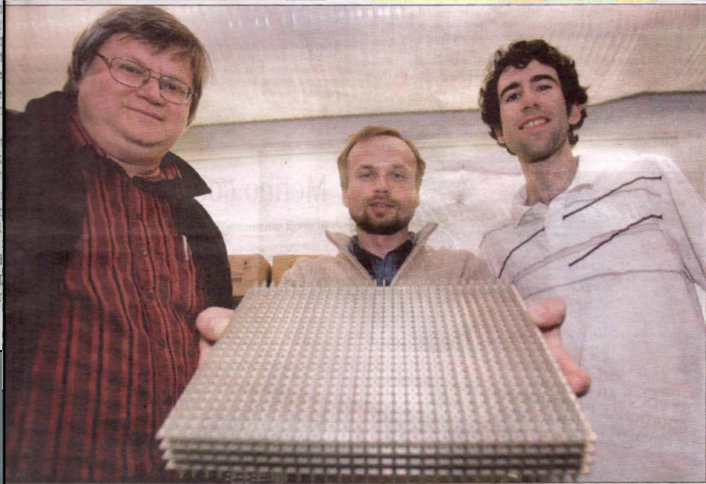
“They can bend light in strange ways, and that's where the ‘invisibility cloak’ comes into it. It bends light around the object, rather than bouncing off it,” Dr Powell said.

The result is that the light bypasses the “cloaked” object, hitting the scene behind it instead. This is why the background becomes visible, not the “invisible” object in the foreground.

Dr Powell says “metamaterial” has

“Herald Sun”: March 2008





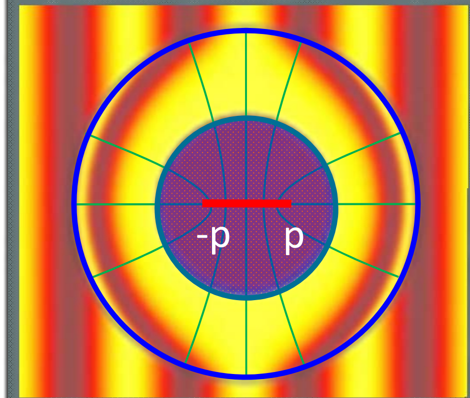
NU scientists Yuri Kivshar, Alye Shadrivov and David Powell with the prototype of a material they are trying to make invisible. Photo: ANDREW SHEARGOLD

Light-bending material to conjure cloak of invisibility

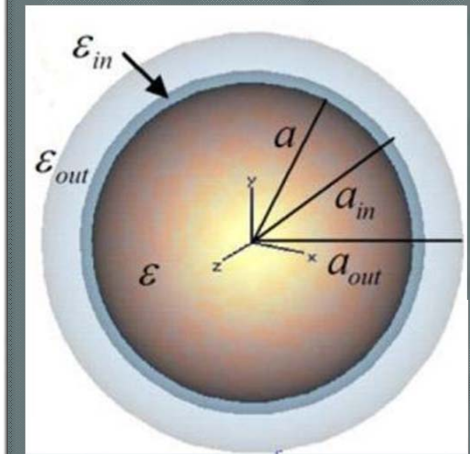
“Canberra Times”, April 2008

http://wwwrshysse.anu.edu.au/nonlinear

Different approaches to cloaking

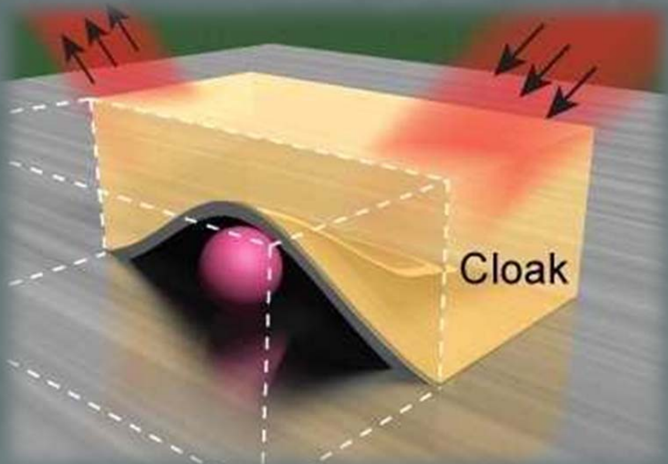


D. Smith, APL (2008)



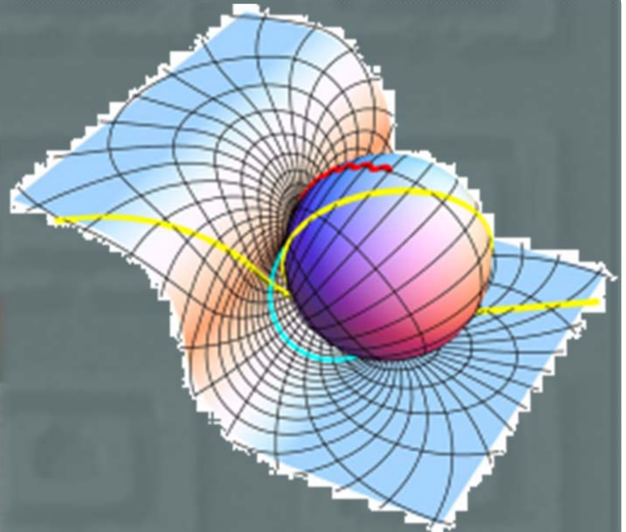
N. Engheta, PRL (2008)

Carpet Cloak: On a surface

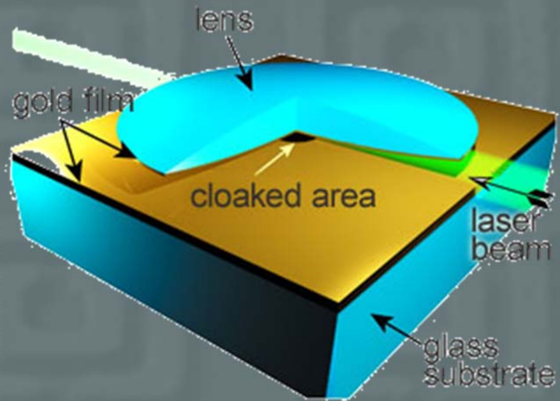


Jensen Li & Pendry, PRL (2008)

R. Liu, C. Ji, and D. Smith, *Science* (2009)



U. Leonhardt, Science (2009)



Smolyaninov,&Shalaev PRL (2009)

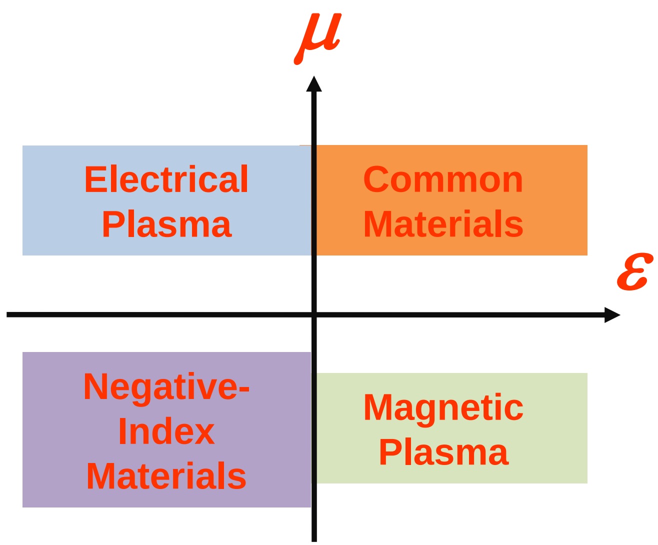
http://wwwrshysse.anu.edu.au/nonlinear

Why do we need metamaterials?

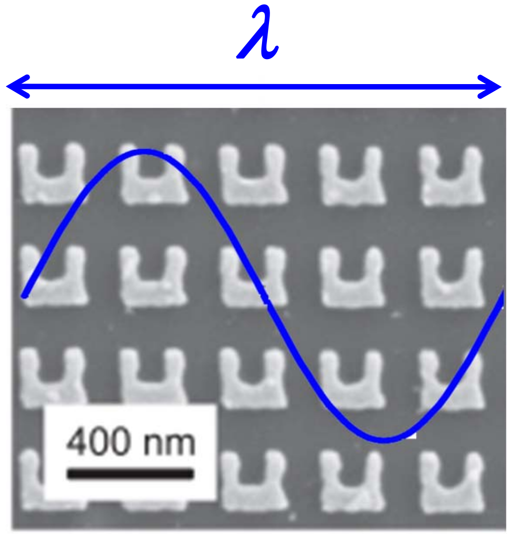
- They ‘reverse’ various physical phenomena
  - e.g., unusual wave refraction
- Very unusual linear and nonlinear properties
- Perfect imaging and flat lenses
- Novel photonic and plasmonic structures
- Novel opportunities for optical devices

http://wwwrshysse.anu.edu.au/nonlinear

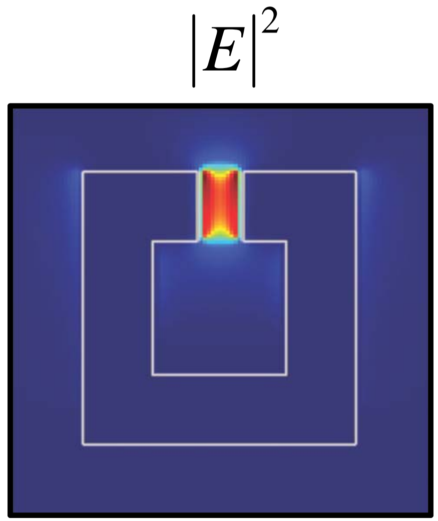
Dispersion engineering



Miniaturization



Strong Field Localization



Materials

Artificial Magnetism

Negative Index

Zero-index

Devices

Smaller

Thinner

Lightweight

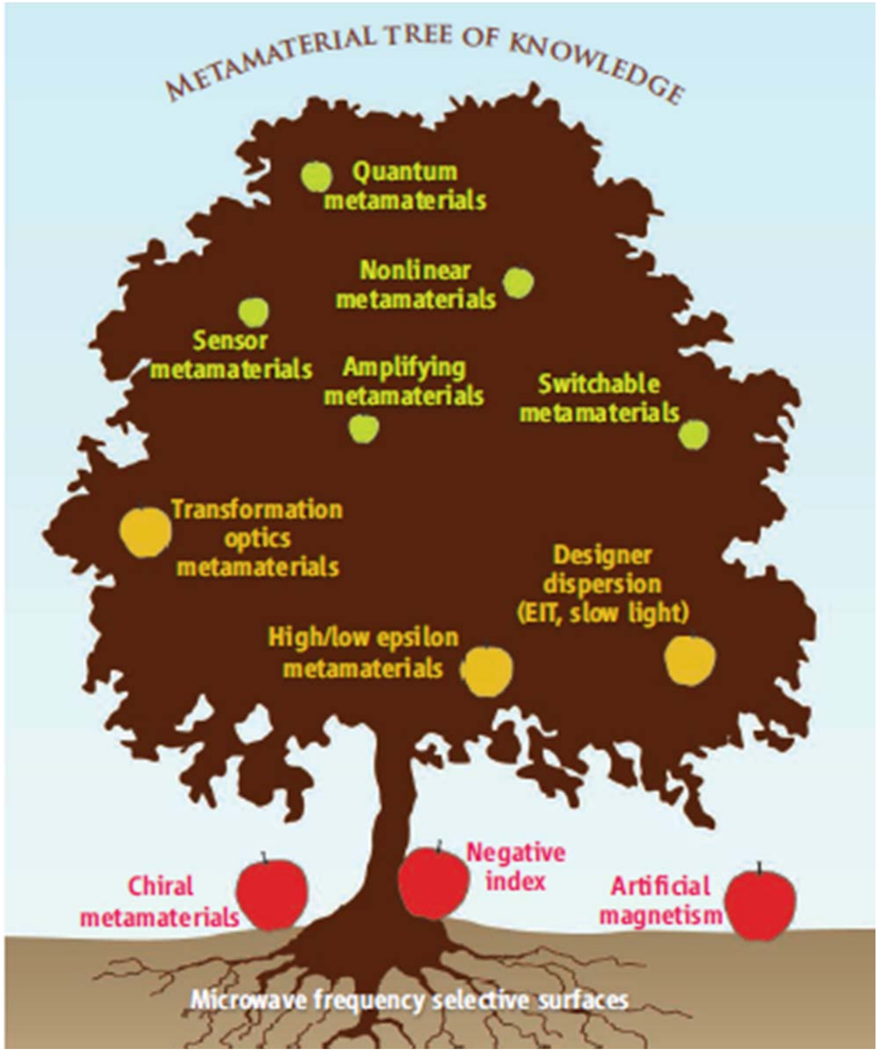
Applications

Antennas

Sensors

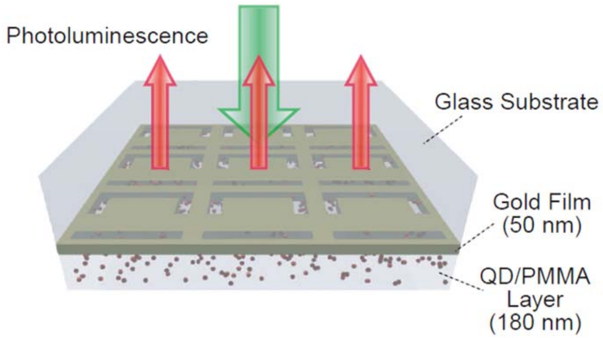
Absorbers

Metamaterials research vision



Zheludev, 2010

Integration with semiconductor technology enabling of gain



Phys. Rev. Lett. **105**, 227403 (2010)

Integration of metamaterials on a photonic chip for signal processing

CUDOS