Shaping light with metamaterials

Yuri S. Kivshar

Nonlinear Physics Centre, Australian National University, Canberra, Australia
St. Petersburg University of Information Technologies, Mechanics & Optics, Russia

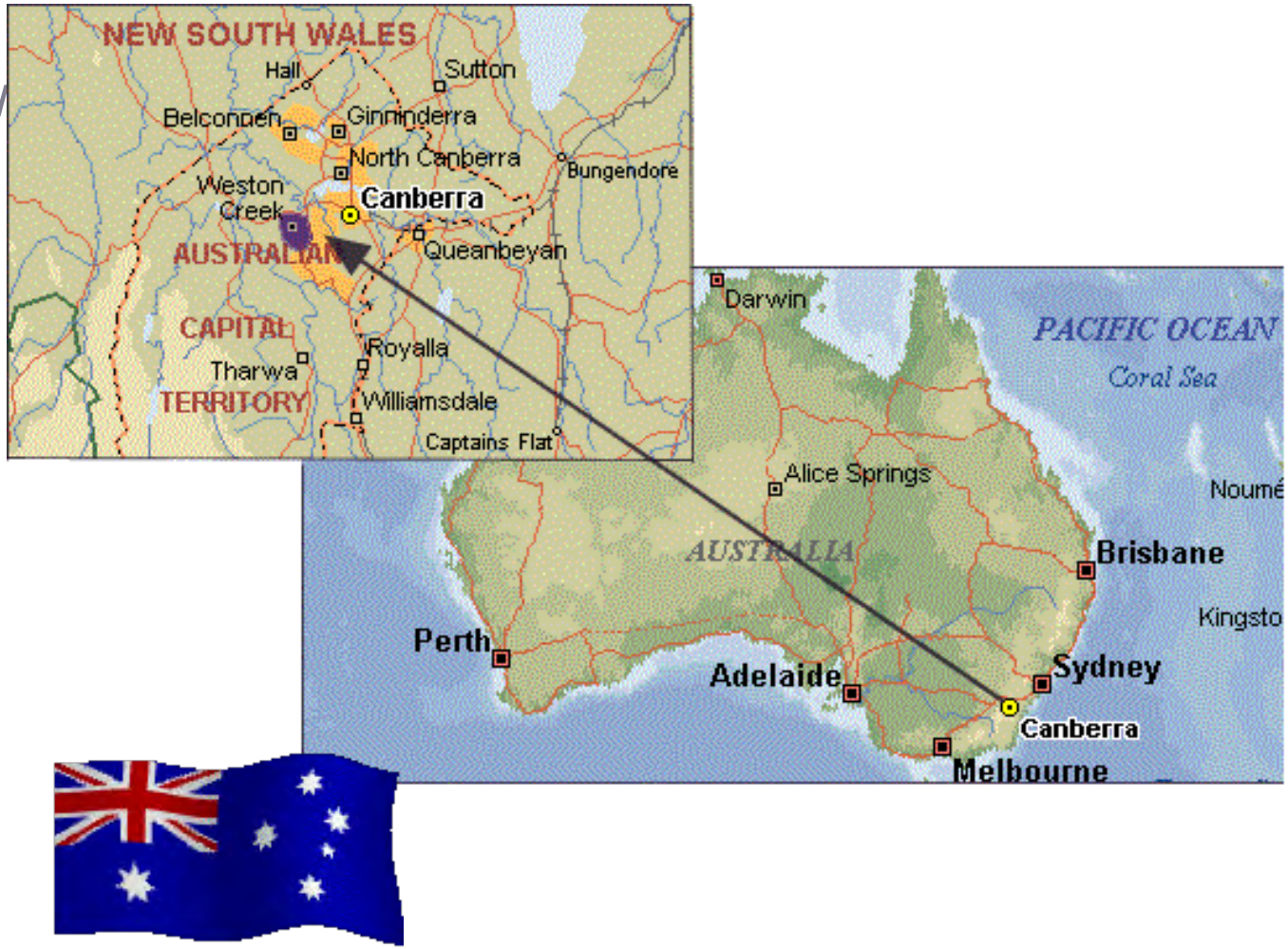
Australian National University

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

http://phoi.ifmo.ru/metamaterials//

Our group in Canberra

- ww



20 January 2009

World University Rankings 2008

THE THE TOP 200 WORLD UNIVERSITIES

2008 RANK	2007 RANK	INSTITUTION	COUNTRY	PEER REVIEW SCORE	EMPLOYER REVIEW SCORE	STAFF:STUDENT SCORE	CITATIONS/STAFF SCORE	INTERNATIONAL STAFF SCORE	INTERNATIONAL STUDENTS SCORE	OVERALL SCORE
1	1	Harvard University	US	100	100	96	100	87	81	100
2	2=	Yale University	US	100	100	100	98	89	71	99.8
3	2=	University of Cambridge	UK	100	100	99	89	98	95	99.5
4	2=	University of Oxford	UK	100	100	100	85	96	96	98.9
5	7=	California Institute of Technology	US	100	74	98	100	100	93	98.6
6	5	Imperial College London	UK	99	100	100	83	98	100	98.4
7	9	University College London	UK	96	99	100	89	96	100	98.1
8	7=	University of Chicago	US	100	99	98	91	78	83	98.0
9	10	Massachusetts Institute of Technology	US	100	100	90	100	33	94	96.7
10	11	Columbia University	US	100	99	98	94	29	89	96.3
11	14	University of Pennsylvania	US	97	98	88	99	83	79	96.1
12	6	Princeton University	US	100	98	75	100	91	82	95.7
13=	13	Duke University	US	97	98	100	94	30	66	94.4
13=	15	Johns Hopkins University	US	99	78	100	100	30	68	94.4
15	20=	Cornell University	US	100	99	90	96	28	76	94.3
16	16	Australian National University	Australia	100	93	82	74	99	91	92.0
17	19	Stanford University	US	100	100	67	100	26	87	91.2
18	38=	University of Michigan	US	99	99	85	84	59	51	91.0
19	17	University of Tokyo	Japan	100	94	98	78	27	40	90.0

Our team in Canberra

Experimental Photonics
A/Prof. Neshev

August 2013

15 research fellows
14 PhD students
4 visiting fellows
2 visiting students

Theoretical Photonics
A/Prof. Sukhorukov

Microwave & THz metamaterials
Dr. Shadrivov

Matter waves
Dr. Ostrovskaya

Plasmonics and nanoantennas
Dr. Miroshnichenko

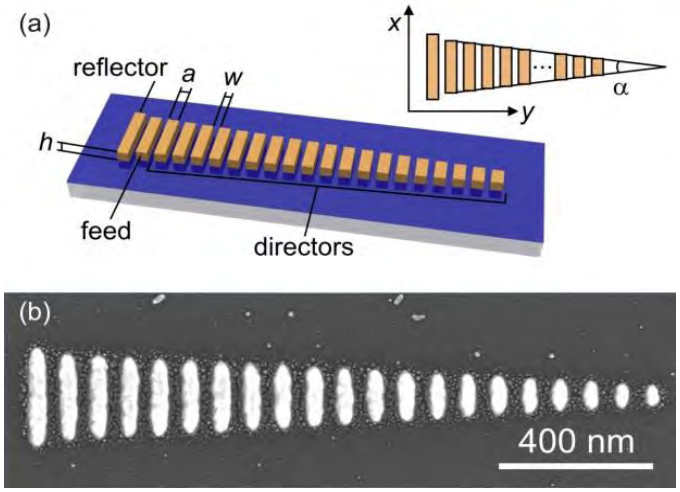
Singular fields
Dr. Desyatnikov

www.rsphysse.anu.edu.au/nonlinear

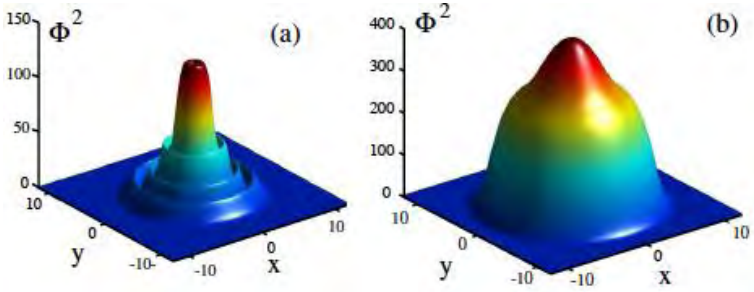
Canberra: Selected research activities

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

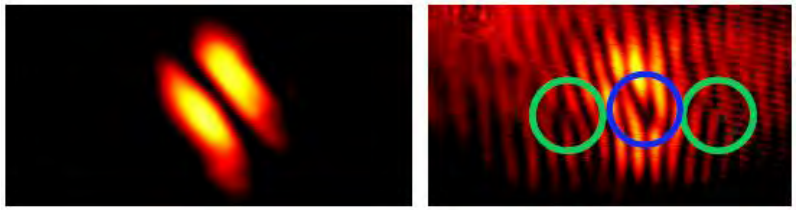
Nanoantennas



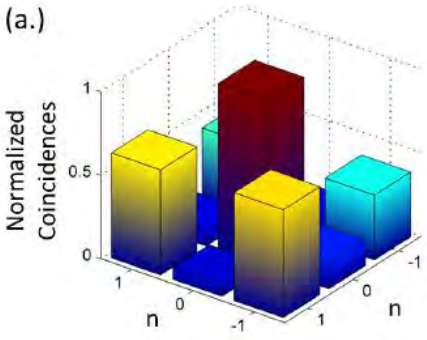
BEC condensates



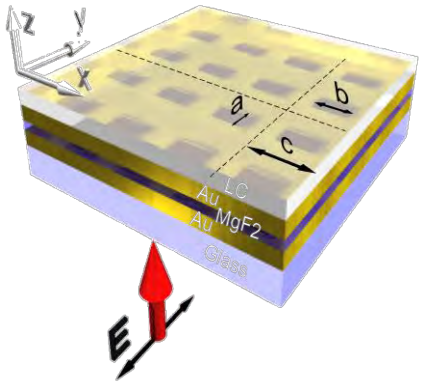
Optical vortices

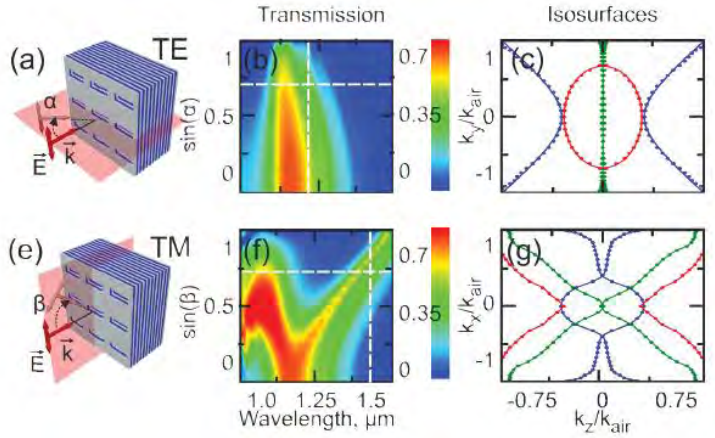


Photon pair generation and quantum walks



Metamaterials





Laboratory of Metamaterials in National Research University of Information Technologies, Mechanics and Optics, St. Petersburg, Russia

Financial support:

Ministry of Science and Education of Russian Federation

Our group in St. Petersburg

Лаборатория "Метаматериалы"
Кафедра Фотоники и Оптоинформатики

Главная Новости Сотрудники Публикации Семинары
Исследования Оборудование Сотрудничество Медиа Конференции

О лаборатории

Лаборатория создана в рамках гранта Правительства Российской Федерации, выделенного на конкурсной основе для государственной поддержки научных исследований, проводимых под руководством ведущих ученых в российских образовательных учреждениях высшего профессионального образования (постановление правительства №220 от 9 апреля 2010 года). Научный руководитель лаборатории - профессор Австралийского национального университета Юрий Семёнович Кившарь.

Объявление

Семинар

4.12.12 *(ВТ)* Красный домик (холл), 10:00
Dr. Andrey Miroshnichenko : *Magnetic response of dielectric nanostructures: theory and applications*
Михаил Петров : *Электрополевая модификация стёкол и стеклометаллических нанокомпозитов*
6.12.12 *(ЧТ)* Красный домик (холл), 9:45
Elena Semouchkina : *All-dielectric metamaterials: application perspectives and problems*
Сергей Анатольевич Третьяков : *Zero-scattering and perfect absorption*
11.12.12 *(ВТ)* Красный домик (холл), 10:00
Andrei Andryieuski : *Graphene Metamaterials for Terahertz Radiation*
Pavel Ginzburg : *Multi-photon processes in nano-plasmonic structures and metamaterials: Classical and Quantum*
Подробнее...

Последние новости

Книга
Сотрудники лаборатории "Метаматериалы" П.А. Белов, А.А. Орлов и С.Ю. Косульников выпустили книгу "Передача изображений со сверхразрешением. Преодолевая

...атория "Метаматериалы"
...а Фотоники и Оптоинформатики

Главная Новости Сотрудники Публикации Семинары
Исследования Оборудование Сотрудничество Медиа Конференции


Павел Белов
Главный научный сотрудник
Заведующий лабораторией


Юрий Кившарь
Ведущий учёный
Научный руководитель лаборатории


Николай Розанов
каф. Оптики Лазеров


Михаил Лимонов
Ведущий научный сотрудник


Константин Симовский
Профессор


Ирина Мельчакова
Зам. зав. лаб., Доцент


Марина Иордан
Менеджер


Старший научный сотрудник


Старший научный сотрудник

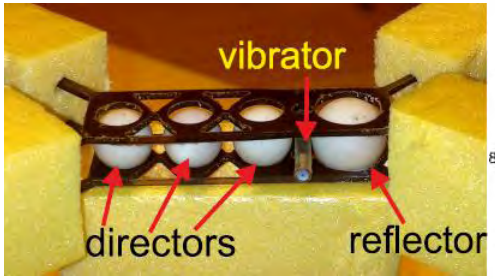

Старший научный сотрудник

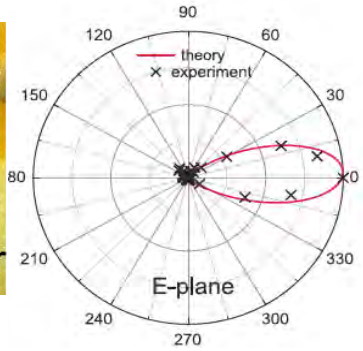

Старший научный сотрудник

http://phoi.ifmo.ru/metamaterials//

Other recent research activities: St. Petersburg

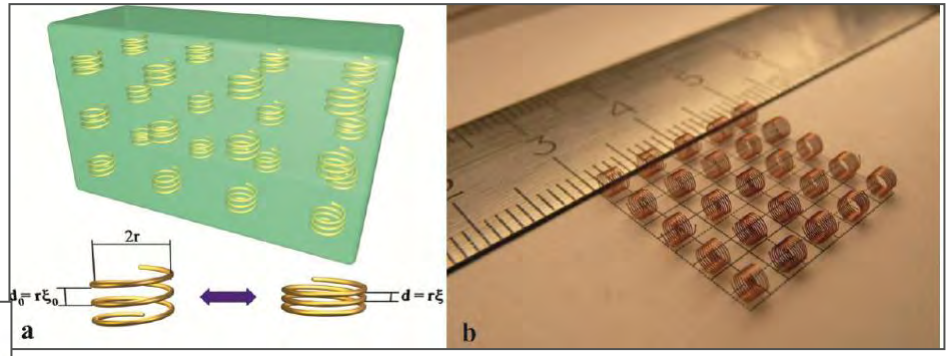
Microwave antennas



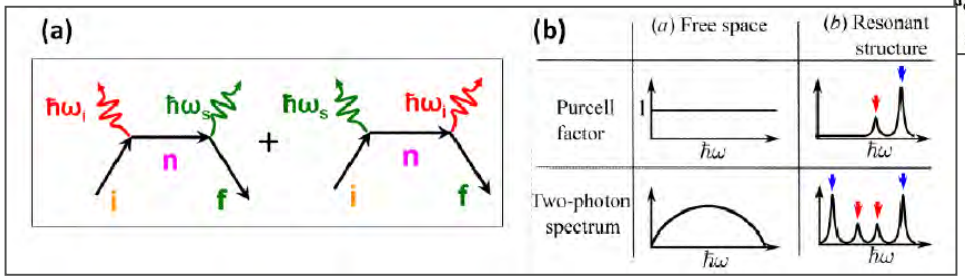


http://phoi.ifmo.ru/metamaterials//

Magnetoelastic metametarials

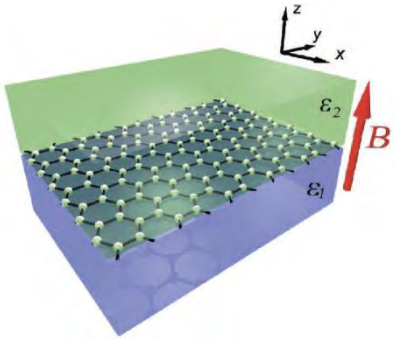


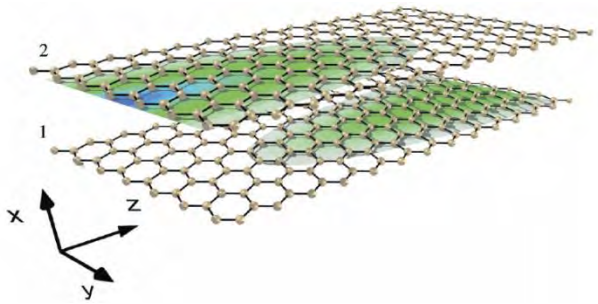
Purcell effect

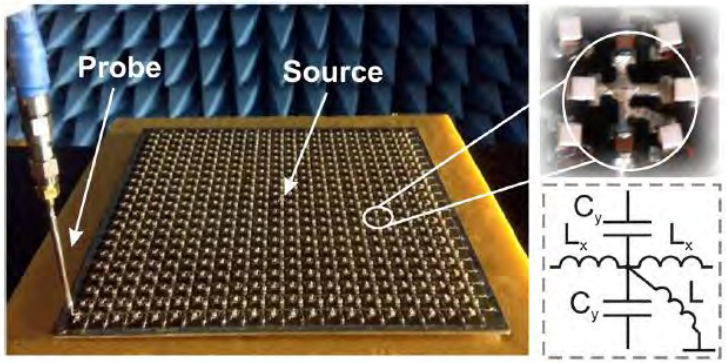


Transmission lines: hyperbolic metamaterials

Graphene nanophotonics



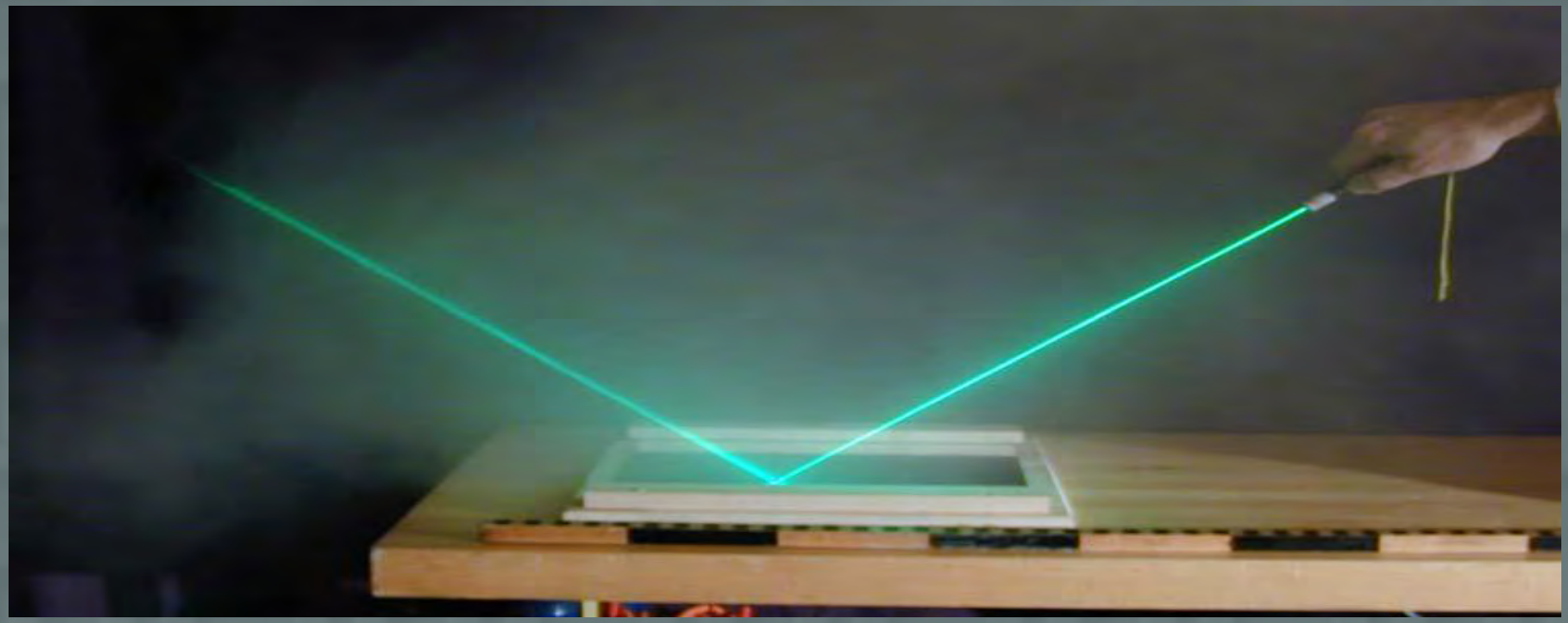




Outline of today's talk

- Introduction: the concepts & properties
- Backward waves
- Invisibility cloaking
- Tunable properties of metamaterials
- Nonlinear metamaterials
- Novel strategies: metamaterial circuitry

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

Natural materials

- Transparent

- Non-transparent

Electromagnetic properties of materials

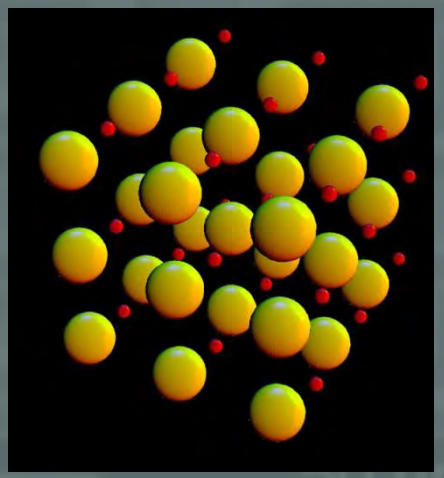
- Response to the electromagnetic field is determined by internal structure of the material
- For large wavelengths any material can be described by ε and μ
- Classical Macroscopic Electrodynamics

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

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

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

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



Natural materials and metamaterials

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

RHM

μ

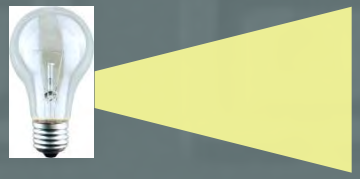
ε

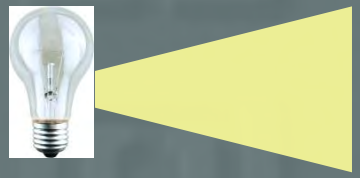
$\varepsilon < 0, \mu > 0$

$\varepsilon > 0, \mu > 0$

$\varepsilon < 0, \mu < 0$

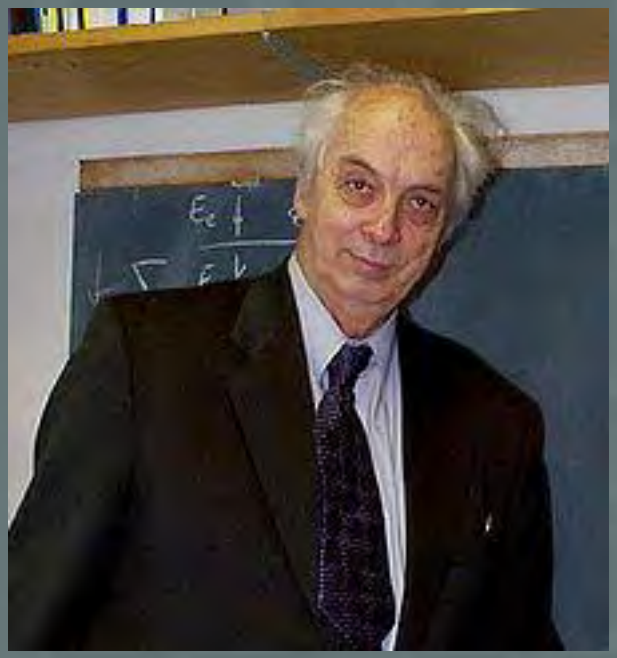
$\varepsilon > 0, \mu < 0$





LeftHandedMaterials

The first Paper on Left-Handed Materials



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

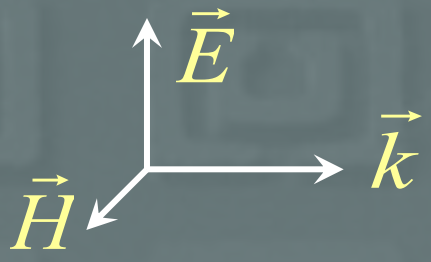
    Soviet Physics Uspekhi **10** (4), 509-514 (1968)

Left-handed waves

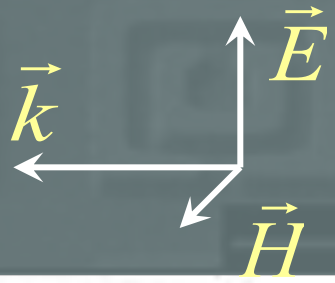
$$\vec{k} \times \vec{E} = \frac{\omega}{c} \mu \vec{H}$$

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

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

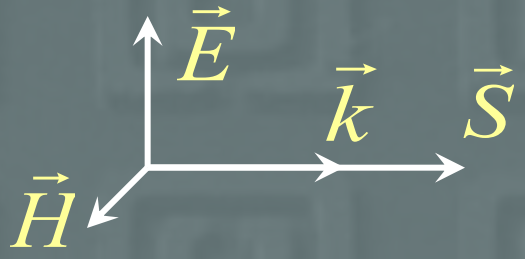


- If $\varepsilon < 0, \mu < 0$ then $\left(\vec{E}, \vec{H}, \vec{k}\right)$ is a *left* set of vectors:



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

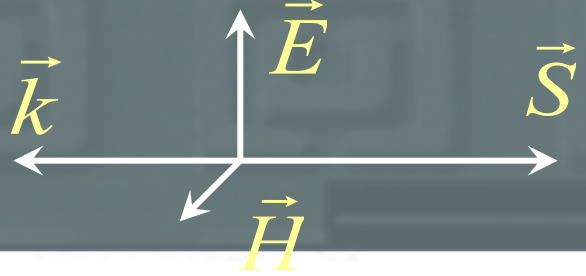


$\vec{S} \uparrow\uparrow \vec{k}$

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

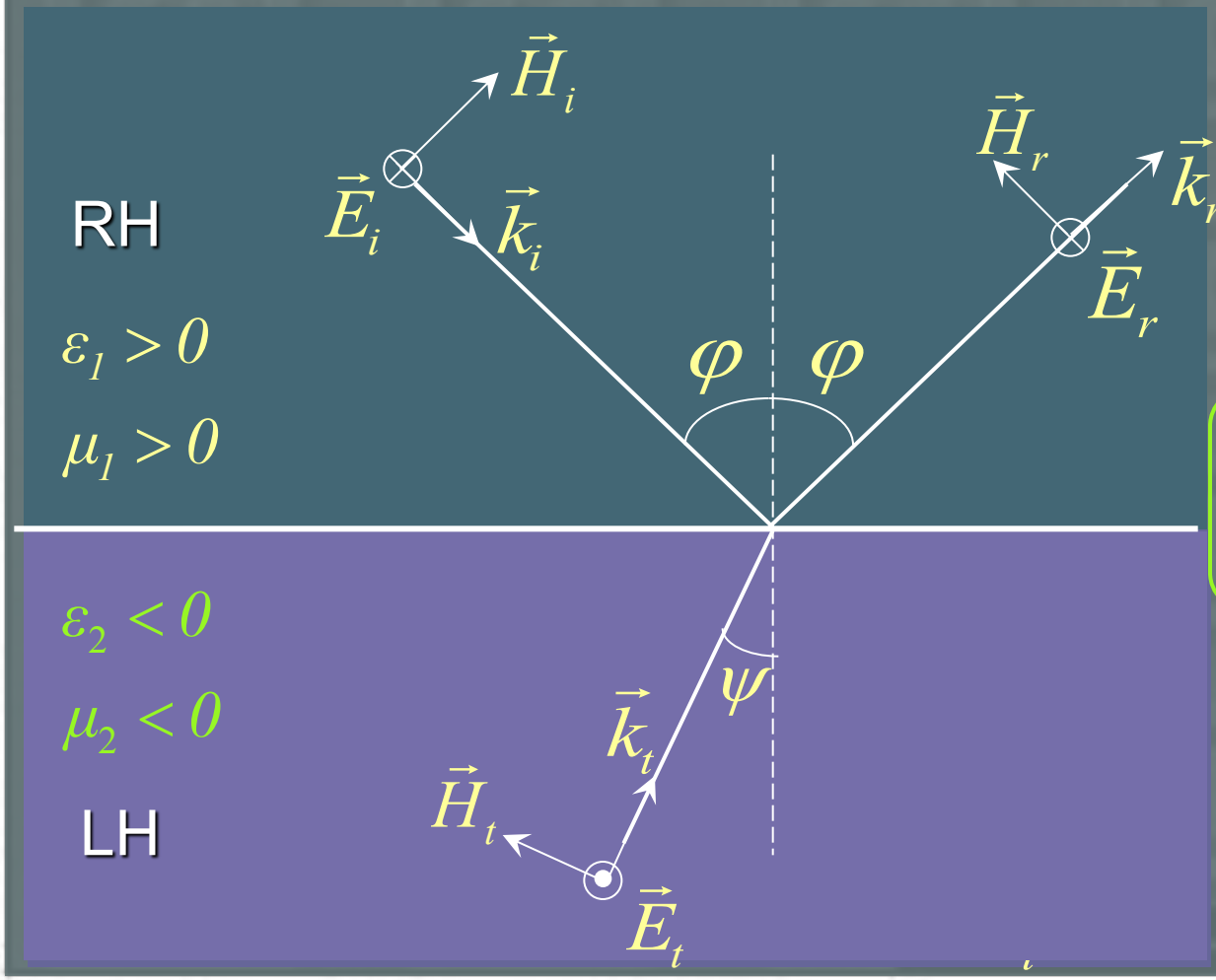
  - Left-handed medium

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



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

Refraction of light at the LH/RH interface



Snell's law:

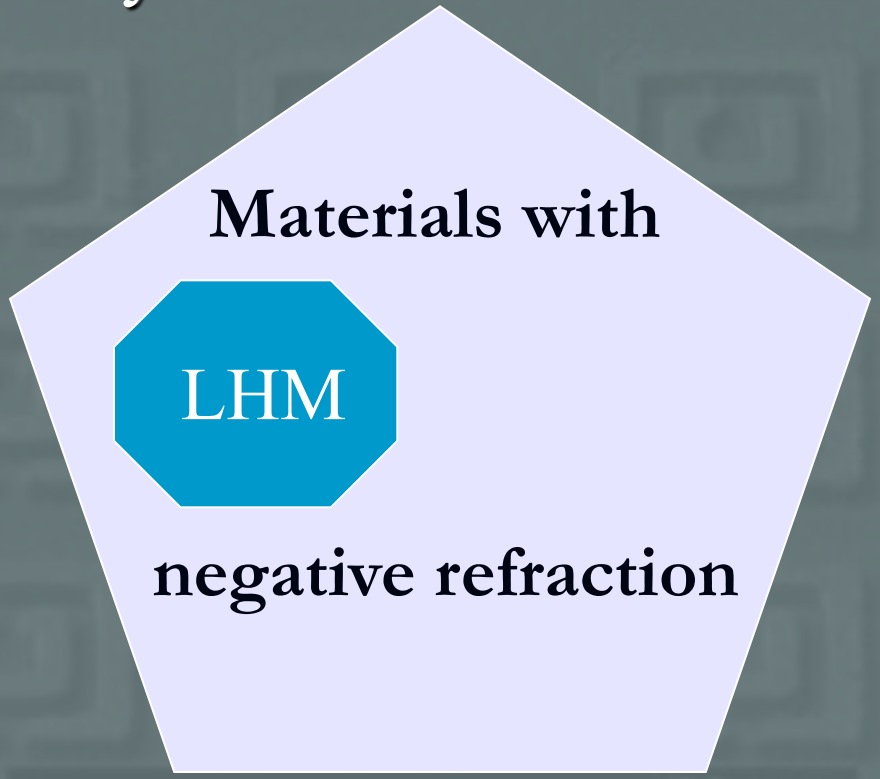
$$\frac{\sin\varphi}{\sin\psi} = \frac{n_2}{n_1} = \sqrt{\frac{\varepsilon_2\mu_2}{\varepsilon_1\mu_1}}$$

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

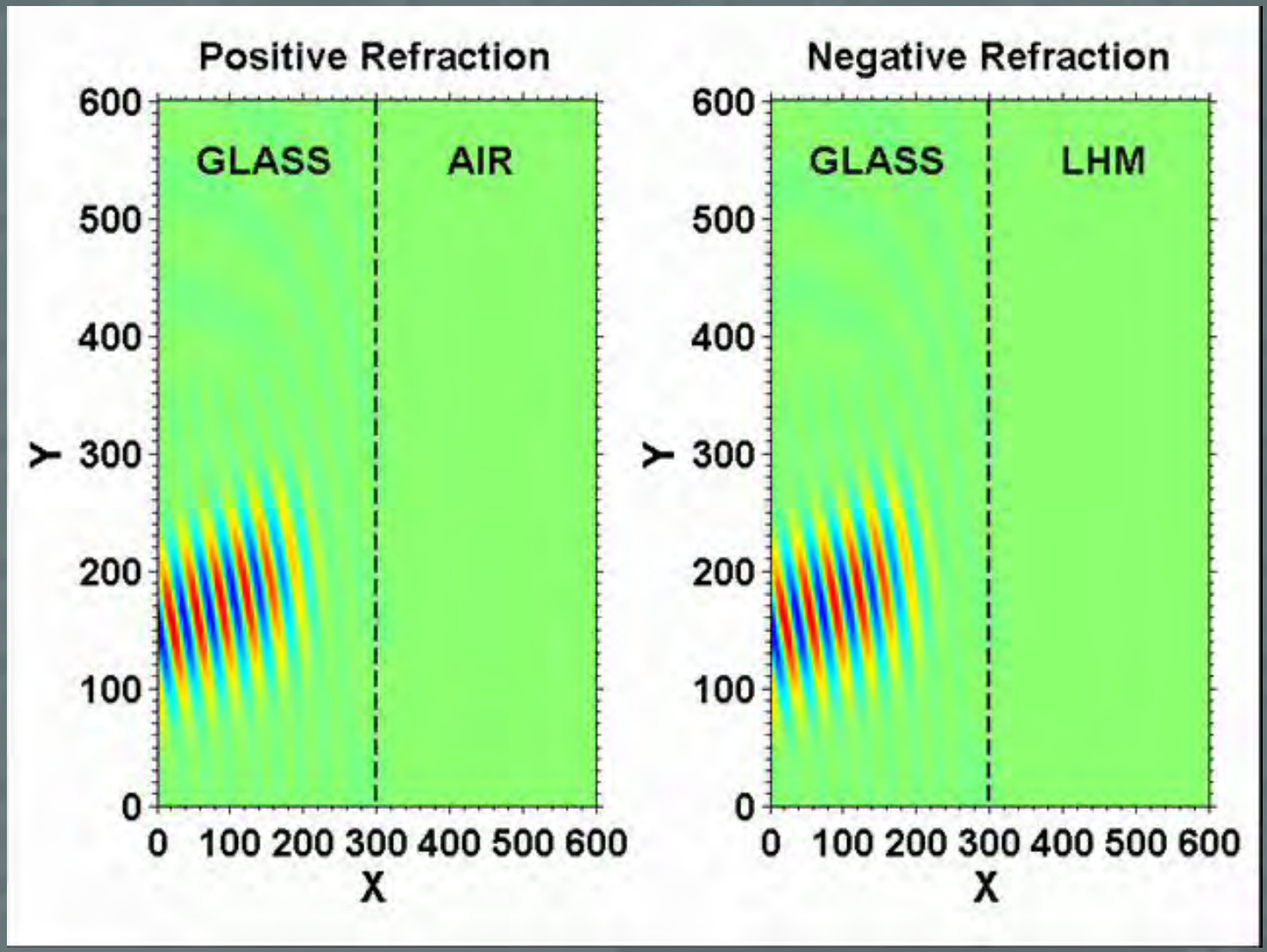
Negative refraction

- 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



Positive vs. negative refraction



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

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

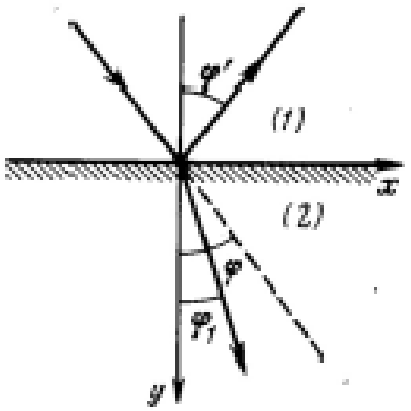


Рис. 12

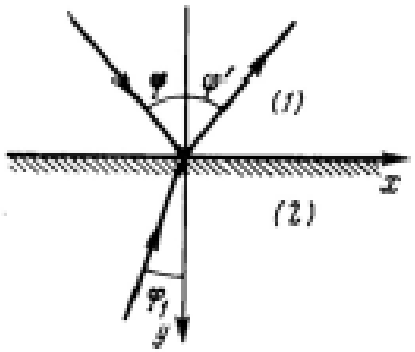


Рис. 13

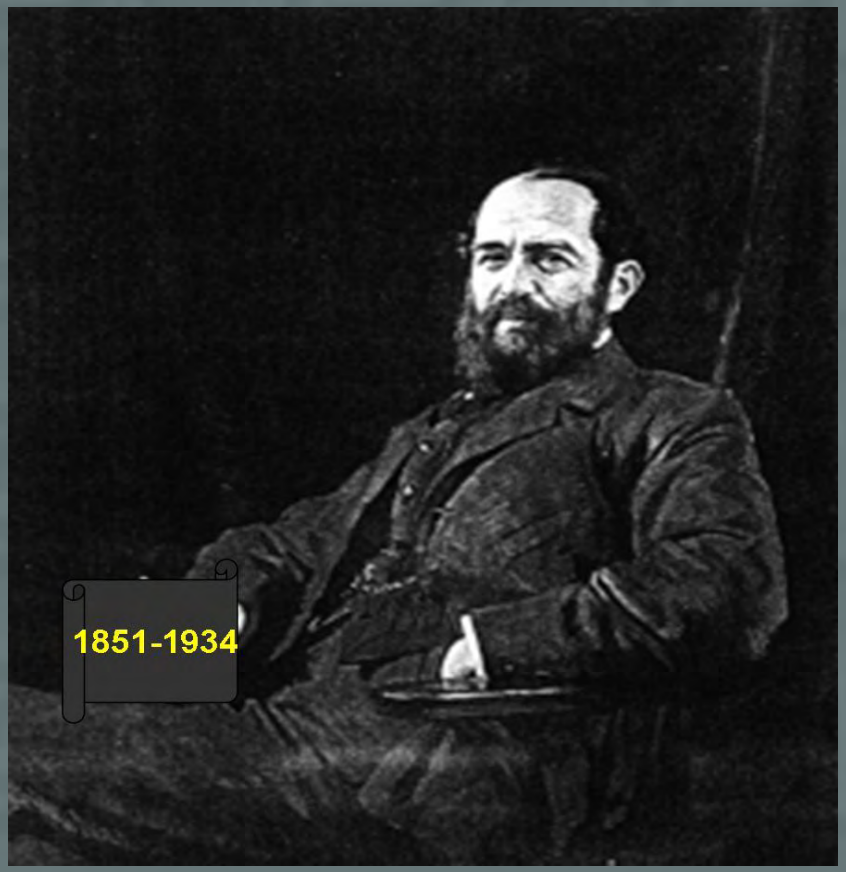
$\pi - \varphi_1$. Как ни непривычно такое построение, но, конечно, ничего удивительного в нем нет, ибо фазовая скорость еще ничего не говорит о направлении потока энергии.

Mandelshtam, 1942

"Lectures about waves"

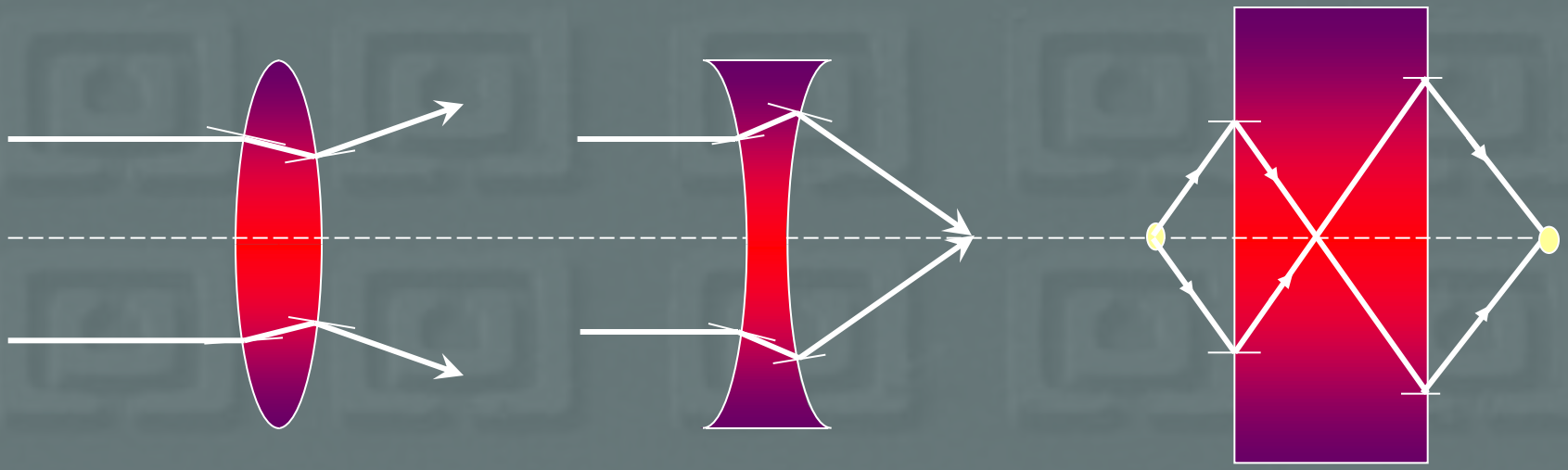
Backward waves: Manchester, 1904

Sir Horace Lamb : 1849-1934
Professor of Mathematics



Sir Arthur Schuster: 1851-1934
Professor of Physics

Unusual lenses

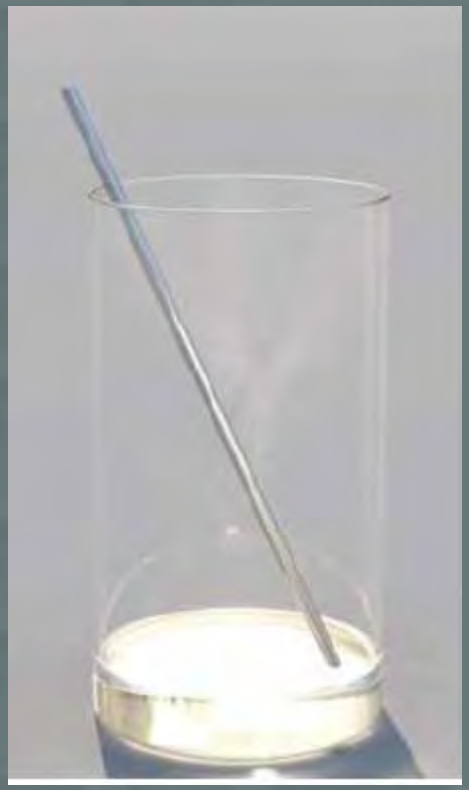


LH lens does not have a diffraction resolution limit

Improved resolution is due to the surface waves

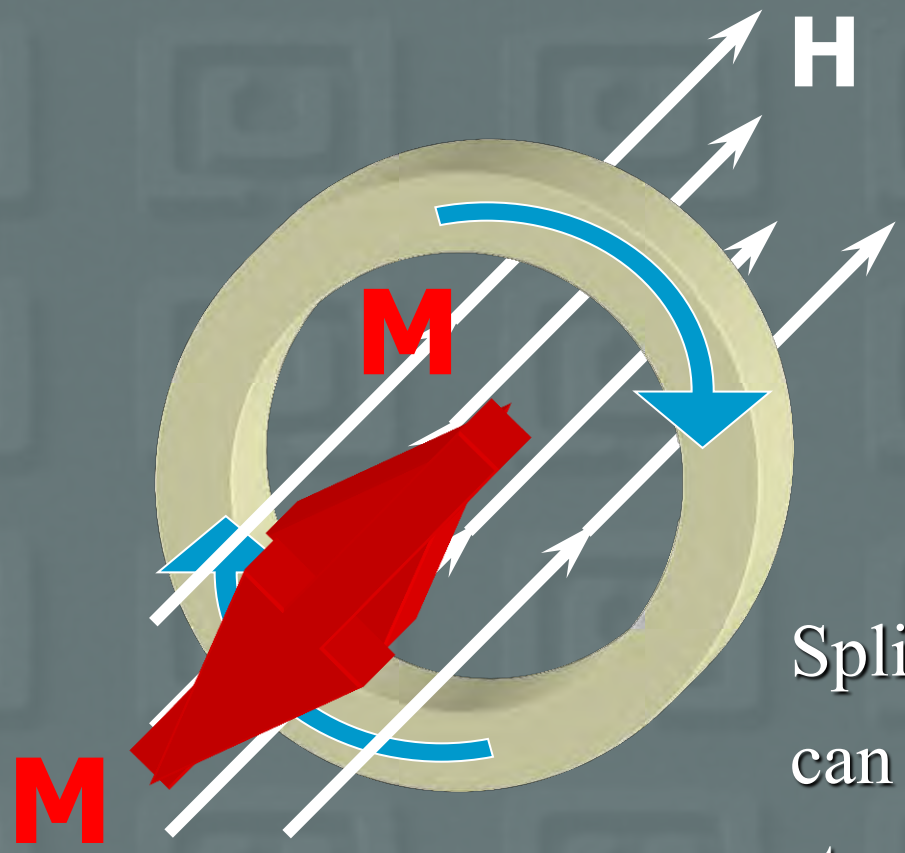
- V. G. Veselago, Soviet Physics Uspekhi **10** (4), 509-514 (1968)
- J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000)

Right- and left-handed water



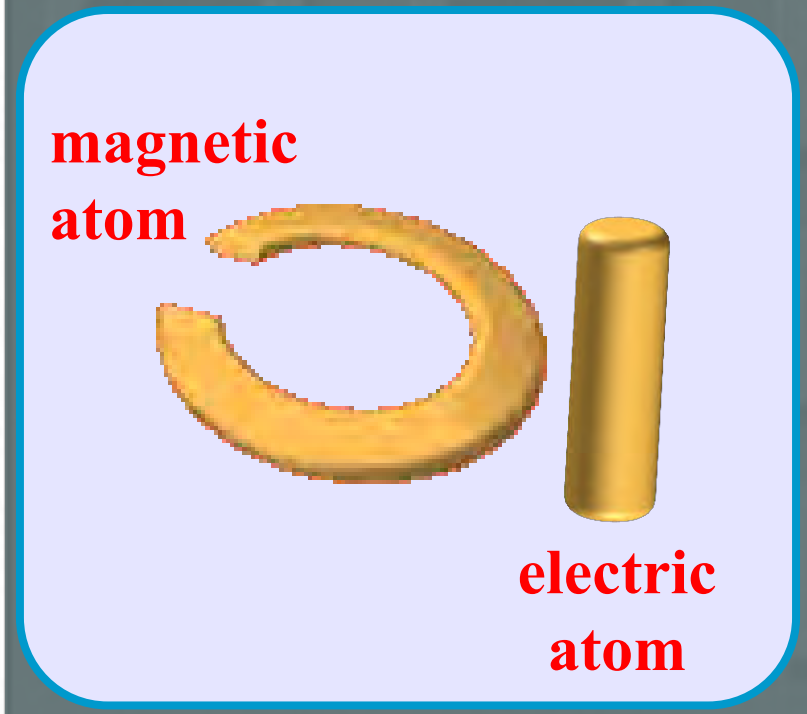
How to make a left-handed material ?

Magnetic response of a gold ring



Split-Ring Resonator
can produce
strong negative
magnetic response

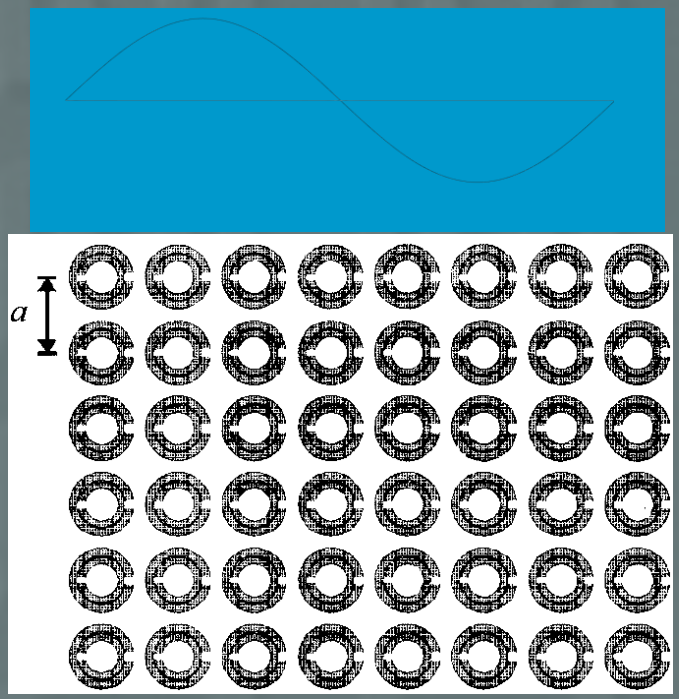
Concept of metamaterials



D. R. Smith et al, UCSD

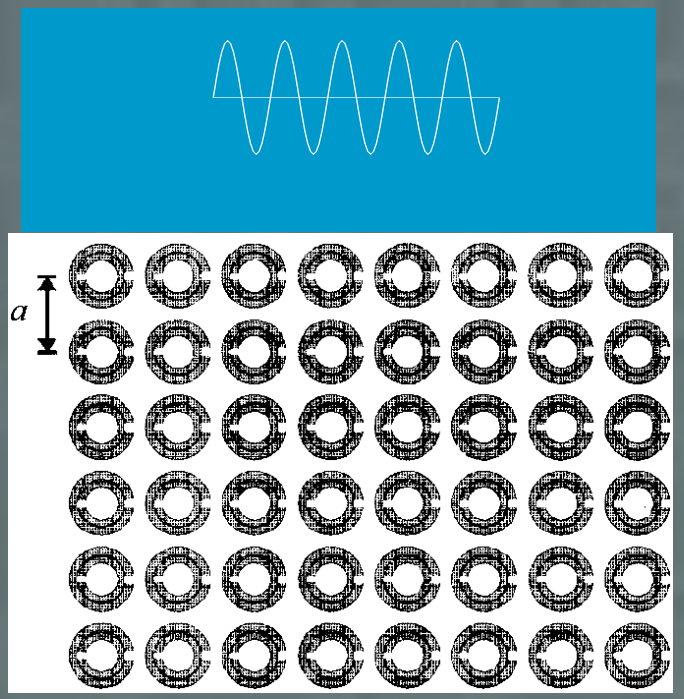
Periodic structures

$\lambda >> a$



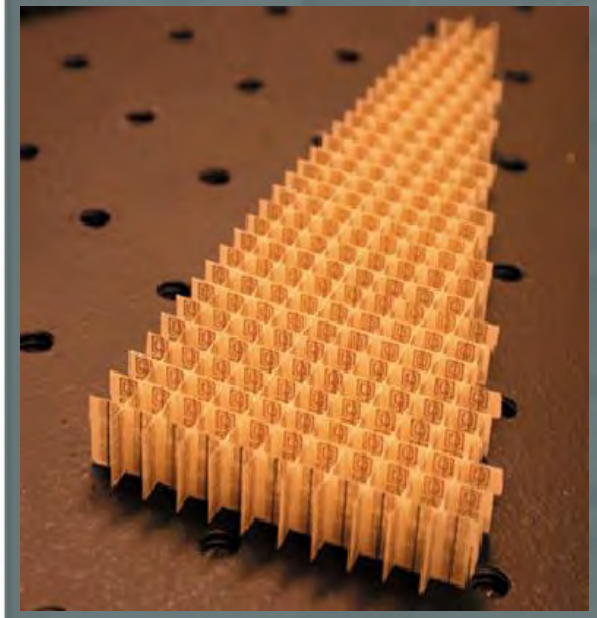
Continuous medium
(Effective medium)

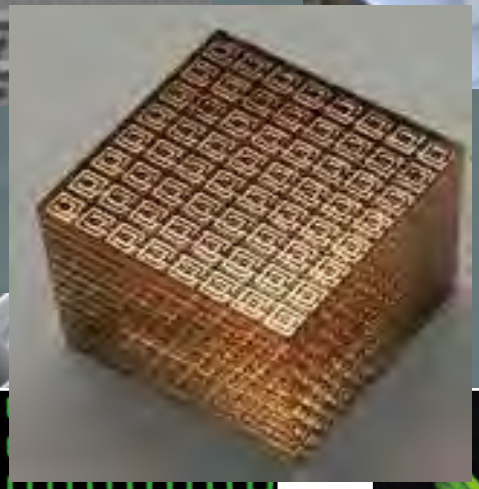
$\lambda \approx a$

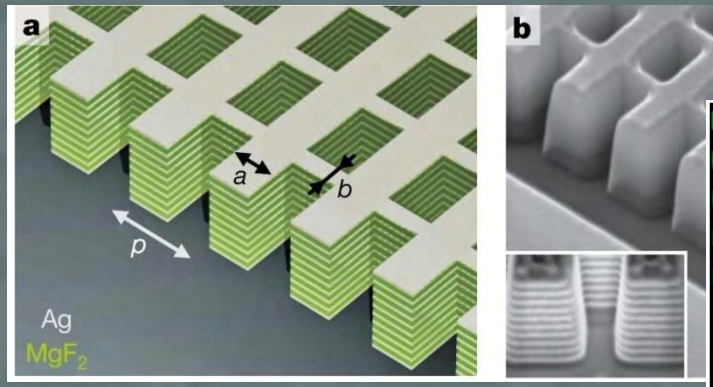


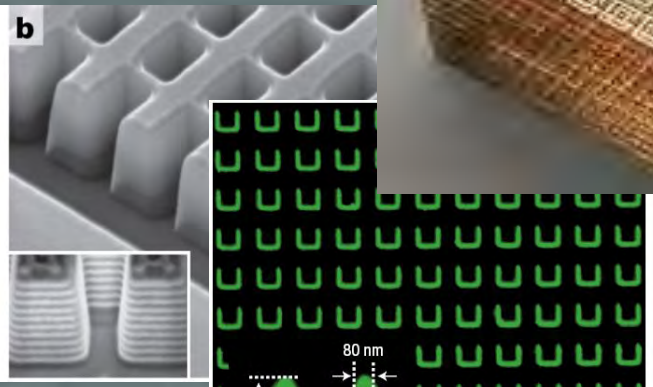
Photonic crystal

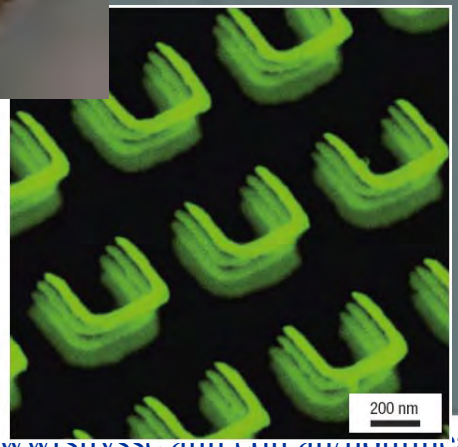
Examples of metamaterials









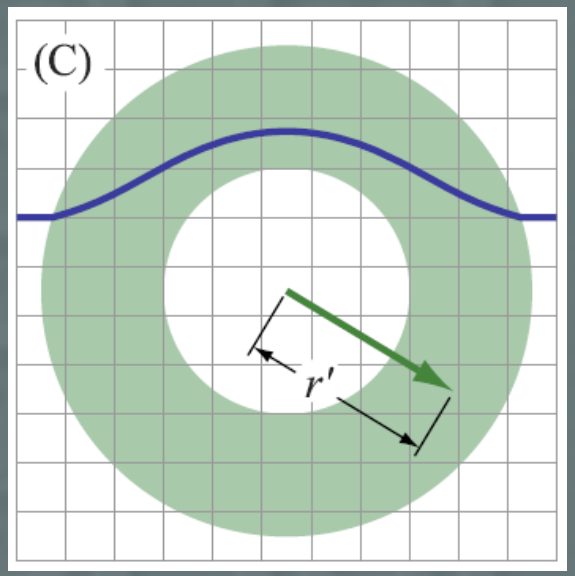


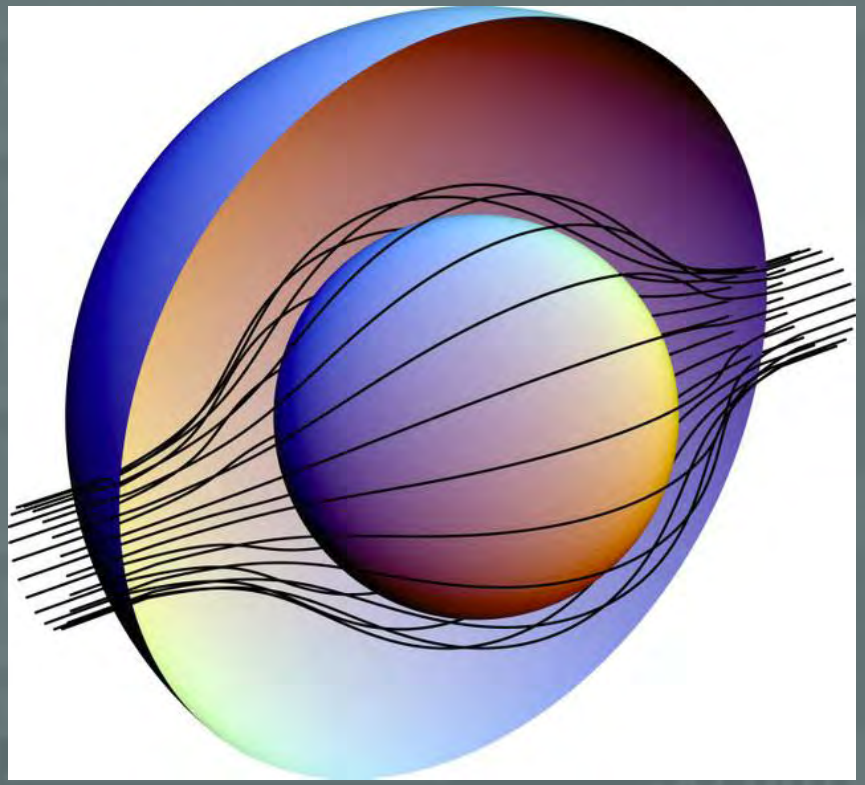
- Now we can engineer ‘atoms’ for artificial materials with desired properties – what can we do with them?

- Can we make an invisibility cloak?

Principle of invisibility cloak

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

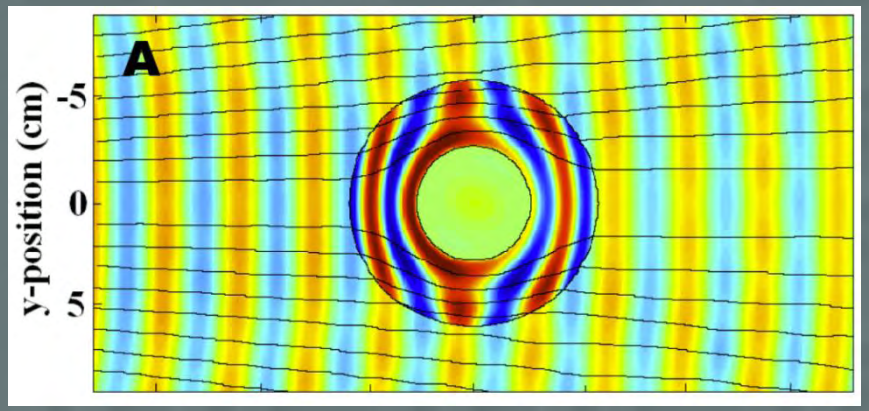




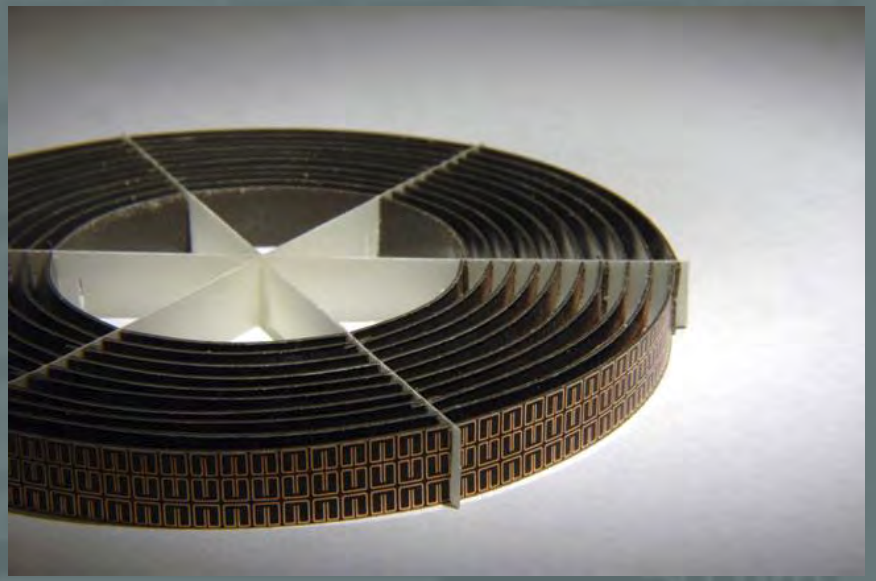
http://wwwrshysse.anu.edu.au/nonlinear

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.

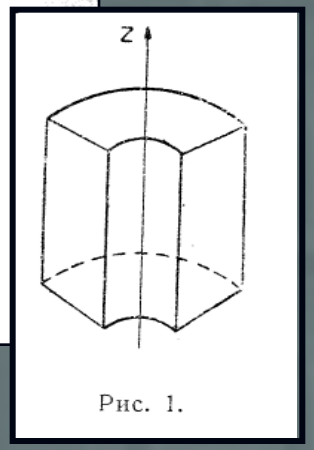


Рис. 1.

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

Cloaks of a complex form

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

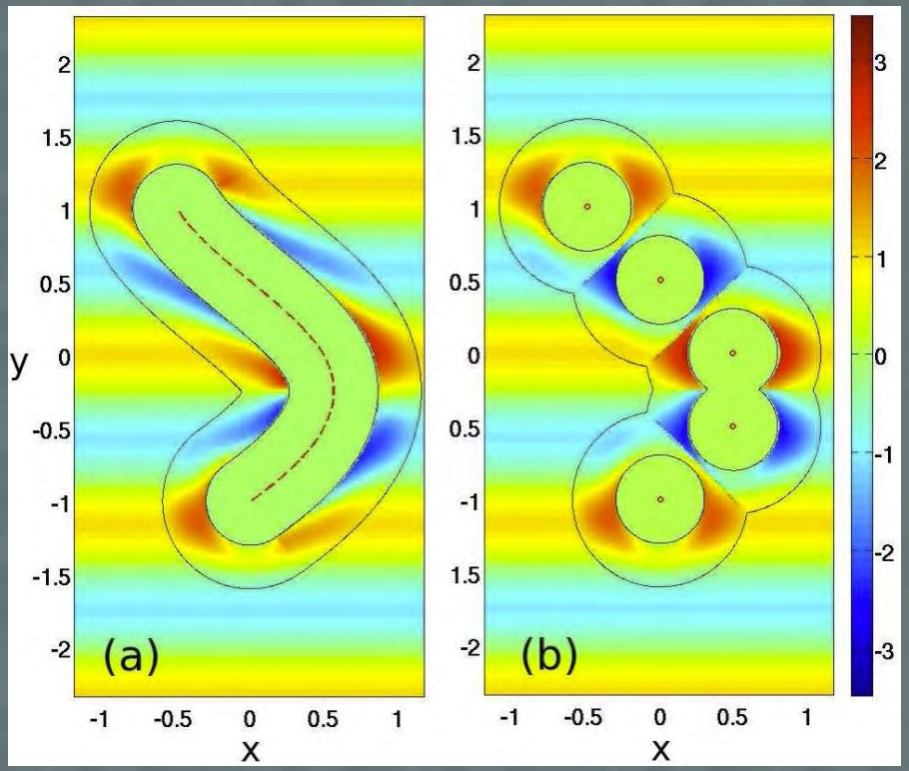
Coordinate transformation gives a recipe for creating the cloak

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

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

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)

"Invisibility" means "publicity"

Australians join race for invisibility

Weaving Harry Potter magic

EVONNE BARRY

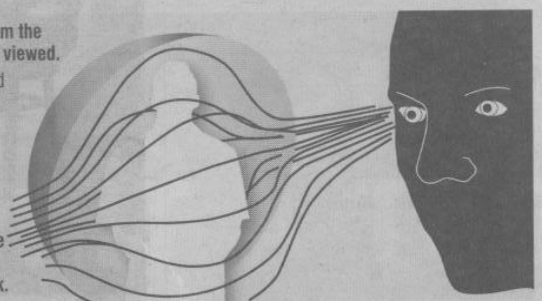
AN "invisibility cloak" that could make people and objects see-through is being developed by Australian scientists.

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."



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 turned conventional scientific theory on its head because of its ability to manipulate the natural passage of light.

"A good analogy is what happens when you throw a stone into a pond. Normally the ripples go away from the stone. But what happens to the lightwaves (when they hit the invisibility cloak) is like the ripples going towards the stone instead."

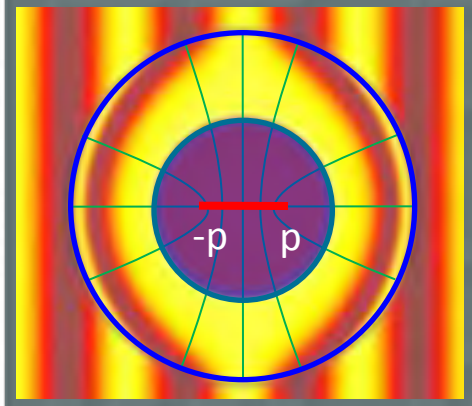
Dr Powell, who has joined forces with ANU professors Ilya Shadrivov and Yuri Kivshar and student Steven Morrison to work on the cloak, said it was hard to predict its future.

"It's wildly speculative at the moment," he said.

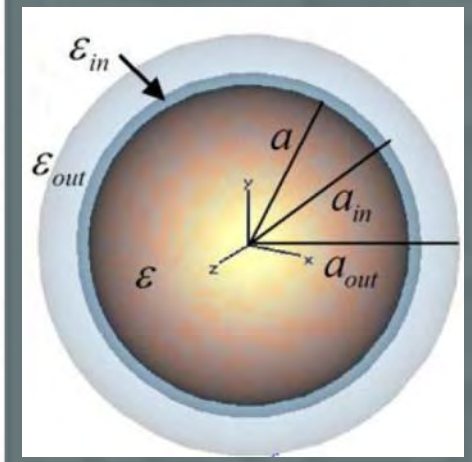
"Herald Sun": March 2008

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

Different approaches to cloaking

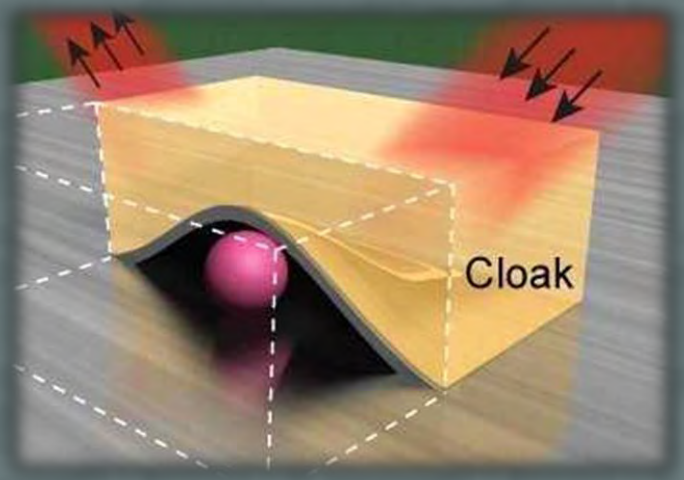


D. Smith, APL (2008)



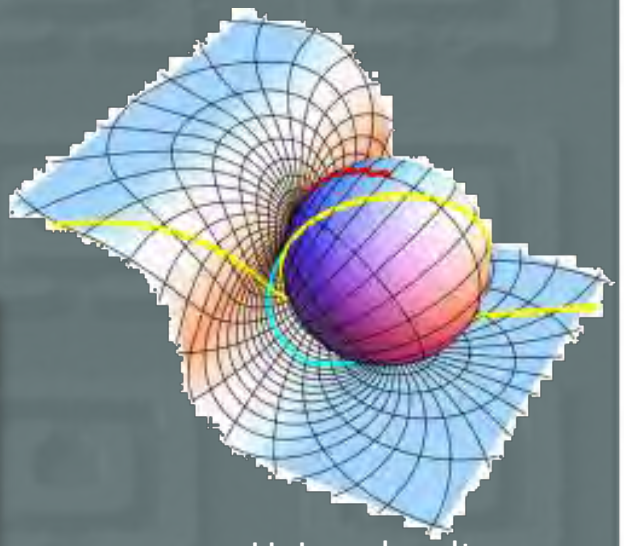
N. Engheta, PRL (2008)

Carpet Cloak: On a surface

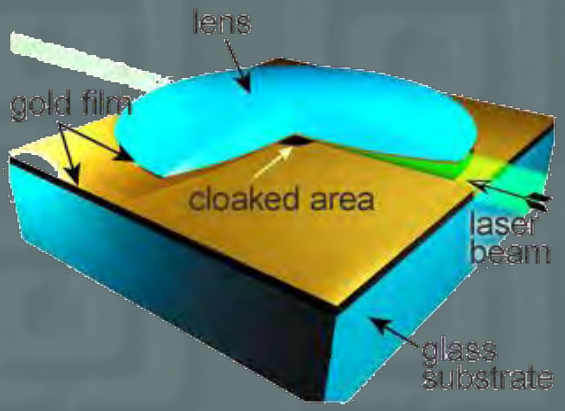


Jensen Li & Pendry, PRL (2008)

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



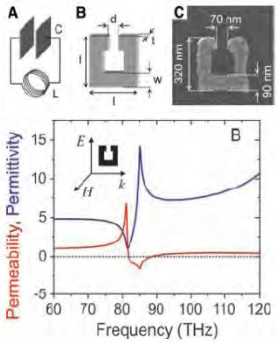
U. Leonhardt, Science (2009)



Smolyaninov,&Shalaev PRL (2009)

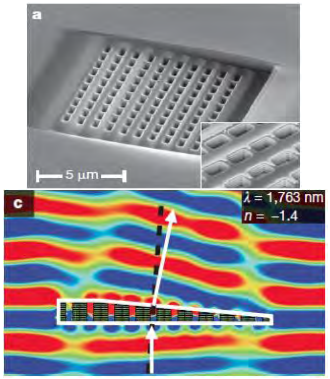
Metamaterials: Hypes and highlights

Optical Magnetism



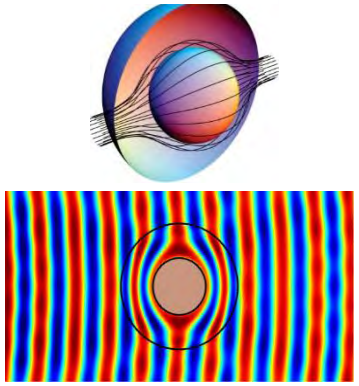
Linden et al., Science (2004)

Negative Refractive Index



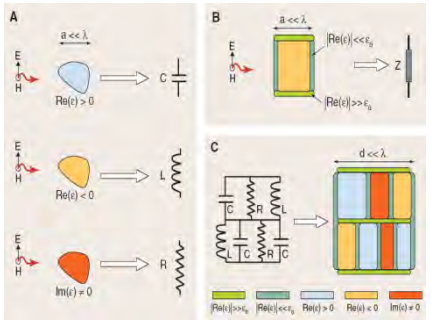
Valentine et al., Nature (2008)

Cloaking



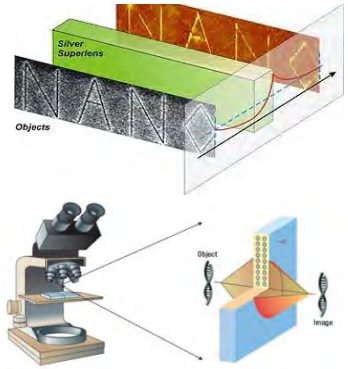
Pendry et al., Science (2006)

Optical Circuits



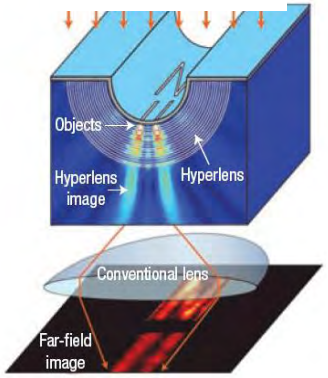
Engheta, Science (2007)

Superlens



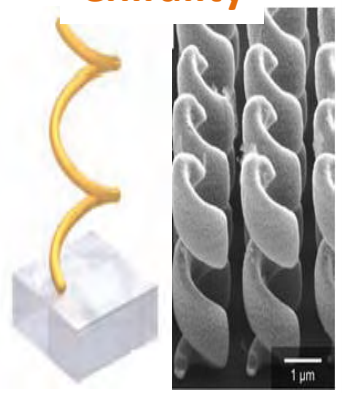
Fang et al., Science (2005)

Hyperlens



Liu et al., Science (2007)

Chirality

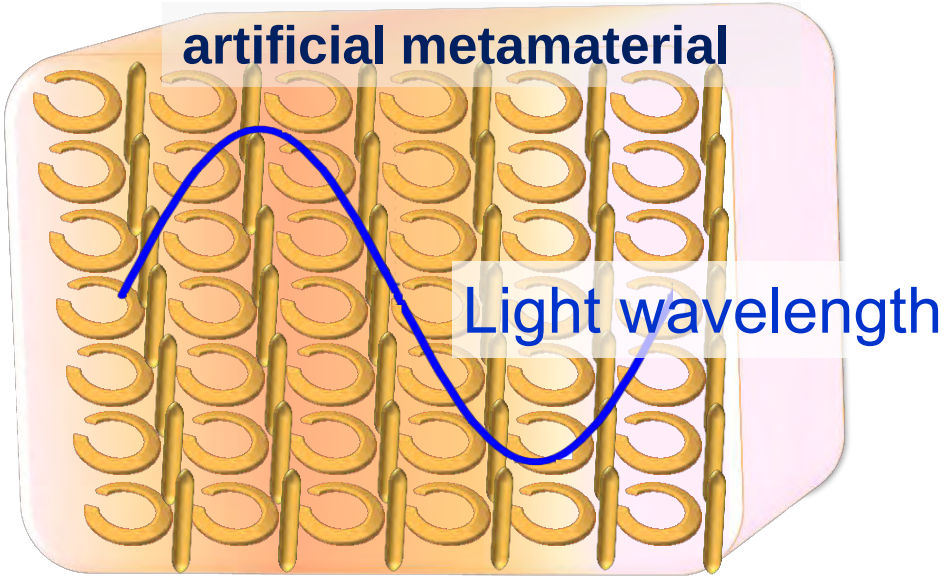


Gansel *et al*. Science (2009)

Current: Optical properties are fixed at the time of fabrication

Future: Active, tunable & reconfigurable metamaterials

Metamaterials: control of ε & μ



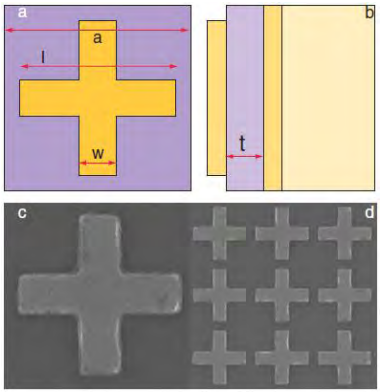
Two independent channels for control of **electric and magnetic** properties of light

Negative refraction

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

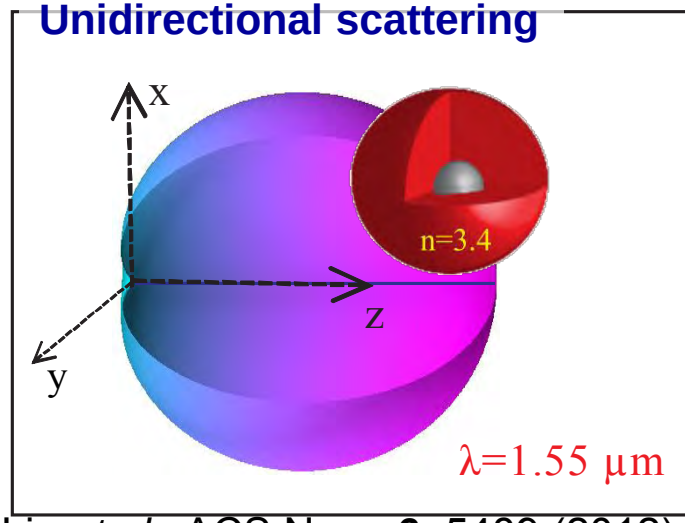
Veselago, Sov Phys Uspekhi (1968)
Pendry, Phys Rev Lett (2000)

Perfect absorber



Liu et al. PRL **104**, 207403 (2010)

Unidirectional scattering

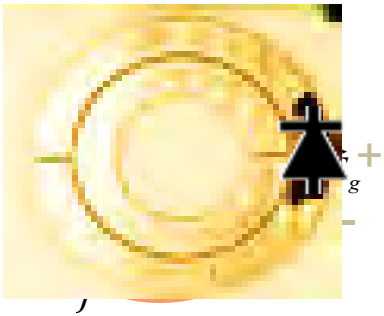


Liu *et al*., ACS Nano **6**, 5489 (2012)

Nonlinear response in metamaterials

$$P = \varepsilon_0\left(\chi^{(1)}\cdot E + \chi^{(2)} : EE + \chi^{(3)} \vdots EEE + \ldots\right)$$

$$M = \mu_0\left(\chi_m^{(1)}\cdot H + \chi_m^{(2)} : HH + \chi_m^{(3)} \vdots HHH + \ldots\right)$$



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

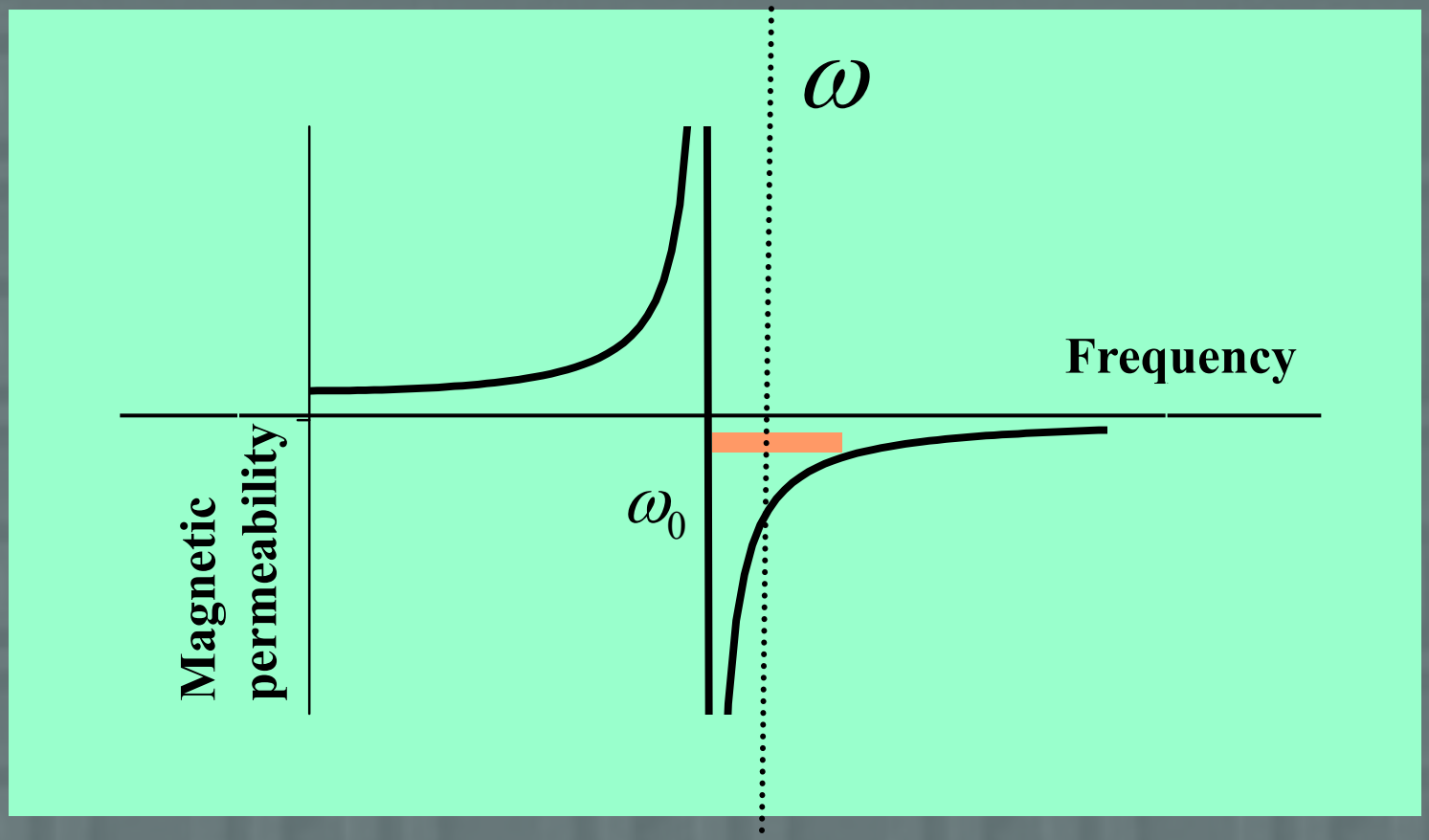
Zharov *et al*., PRL **91**, 037401 (2003)

$$\vec{P}^{(2)} \sim \sum_{q,r}\left[\bar{\bar{\chi}}^{(2)}_{eee}\vec{E}_q\vec{E}_r + \bar{\bar{\chi}}^{(2)}_{emm}\vec{H}_q\vec{H}_r + \bar{\bar{\chi}}^{(2)}_{eme}\vec{H}_q\vec{E}_r + \bar{\bar{\chi}}^{(2)}_{eem}\vec{E}_q\vec{H}_r\right]$$

$$\mu_0\vec{M}^{(2)} \sim \sum_{q,r}\left[\bar{\bar{\chi}}^{(2)}_{mmm}\vec{H}_q\vec{H}_r + \bar{\bar{\chi}}^{(2)}_{mee}\vec{E}_q\vec{E}_r + \bar{\bar{\chi}}^{(2)}_{mme}\vec{H}_q\vec{E}_r + \bar{\bar{\chi}}^{(2)}_{mem}\vec{E}_q\vec{H}_r\right]$$

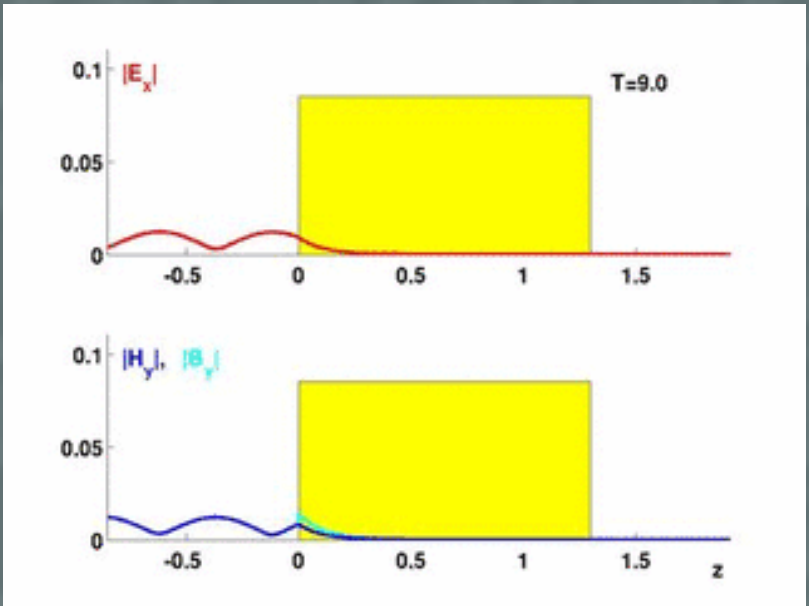
Two independent channels for control (enhancement) of *nonlinearity or emission*: electric and magnetic

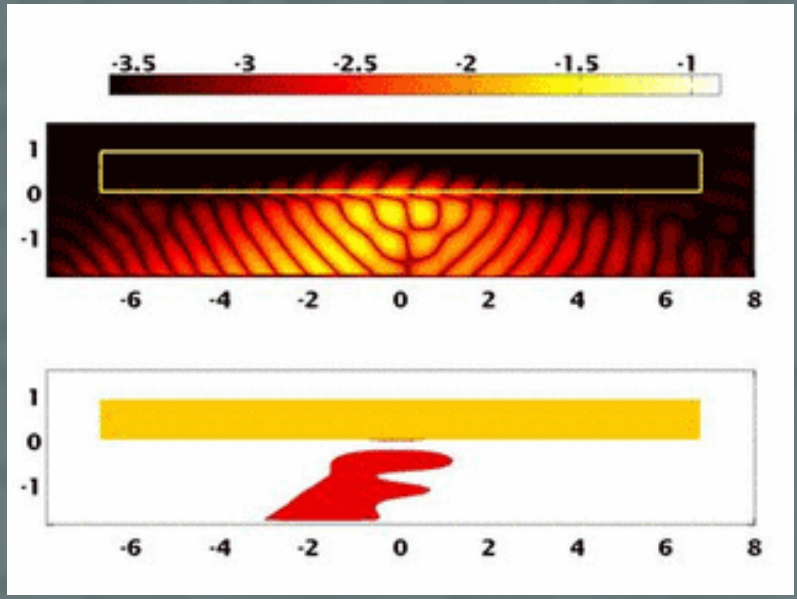
Why nonlinear metamaterials



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

Nonlinearity-induced transparency



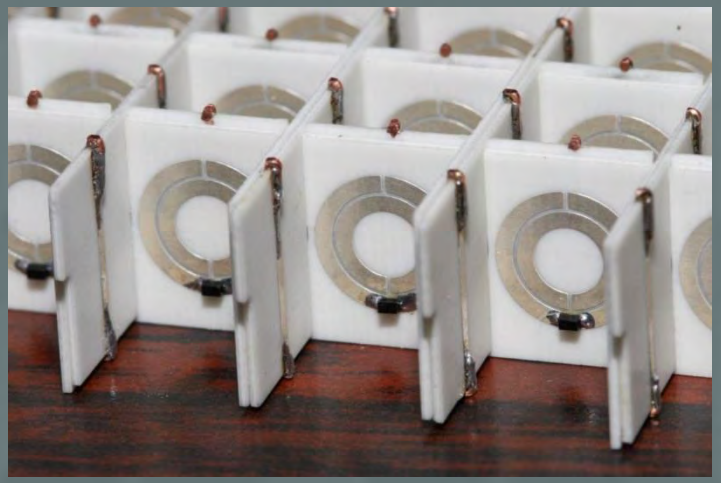


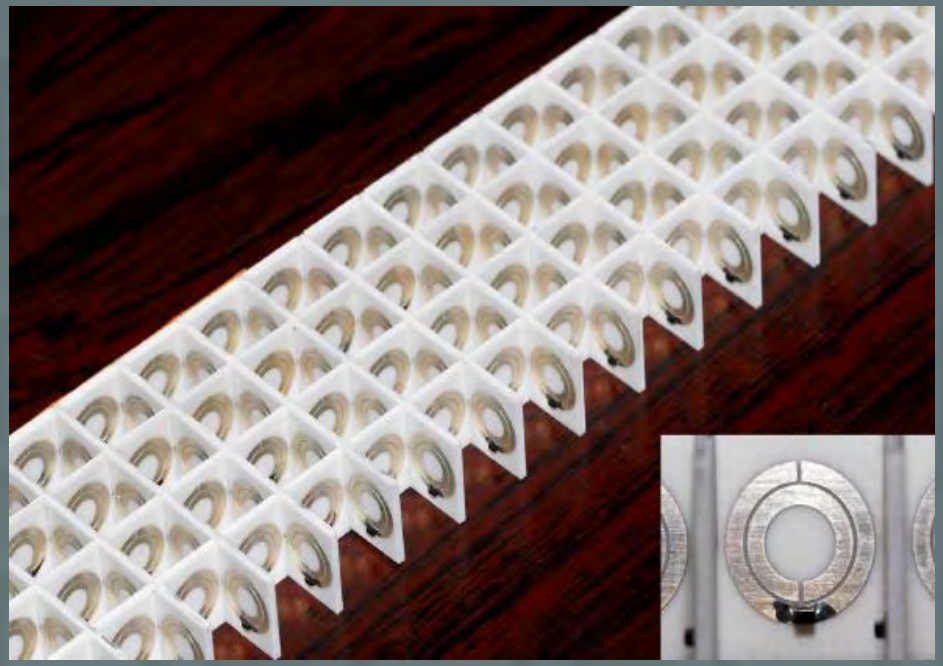
Optics Express 13 1291 (2005)

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

Nonlinear metamaterial for microwaves

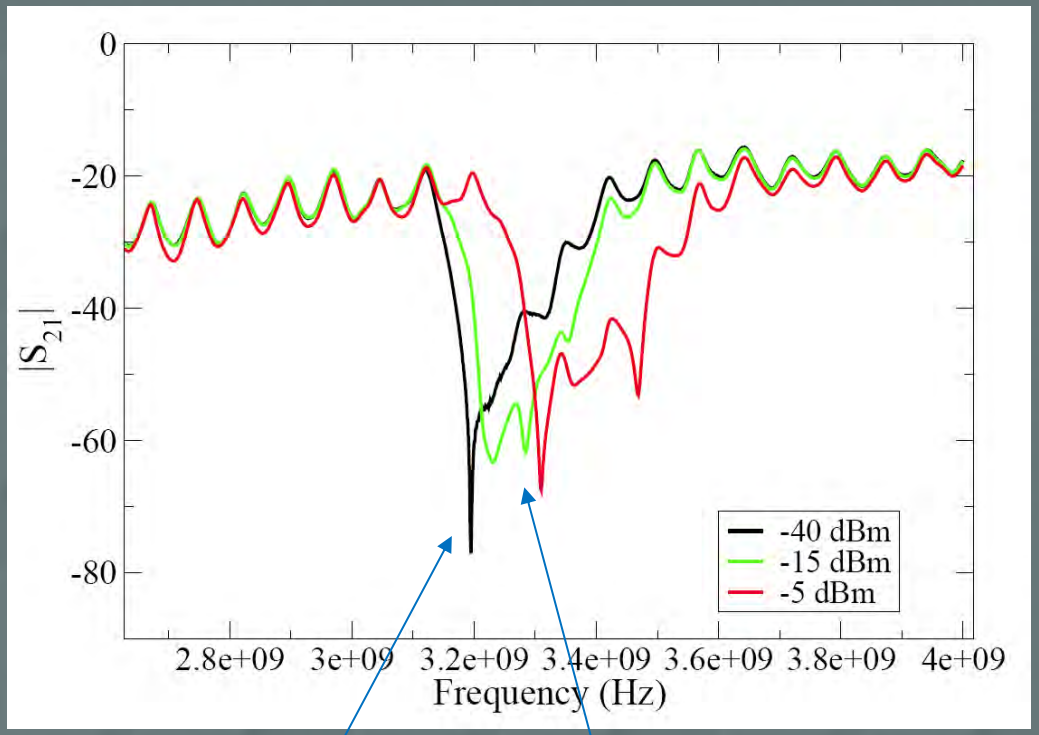
- Nonlinear electronic components provide required response
- Second and third order nonlinear response
  - Resonance shift
  - Harmonic generation

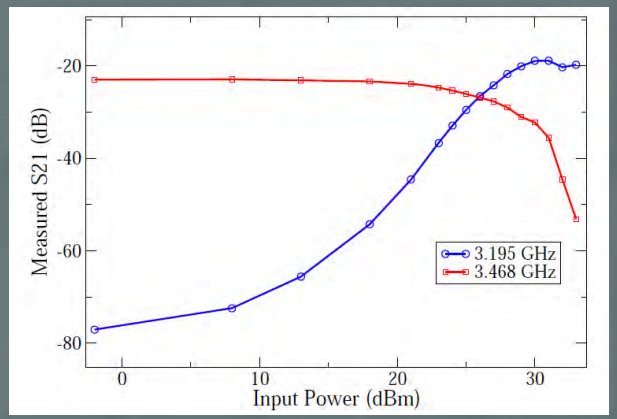




http://wwwrshysse.anu.edu.au/nonlinear

Nonlinear magnetic metamaterials





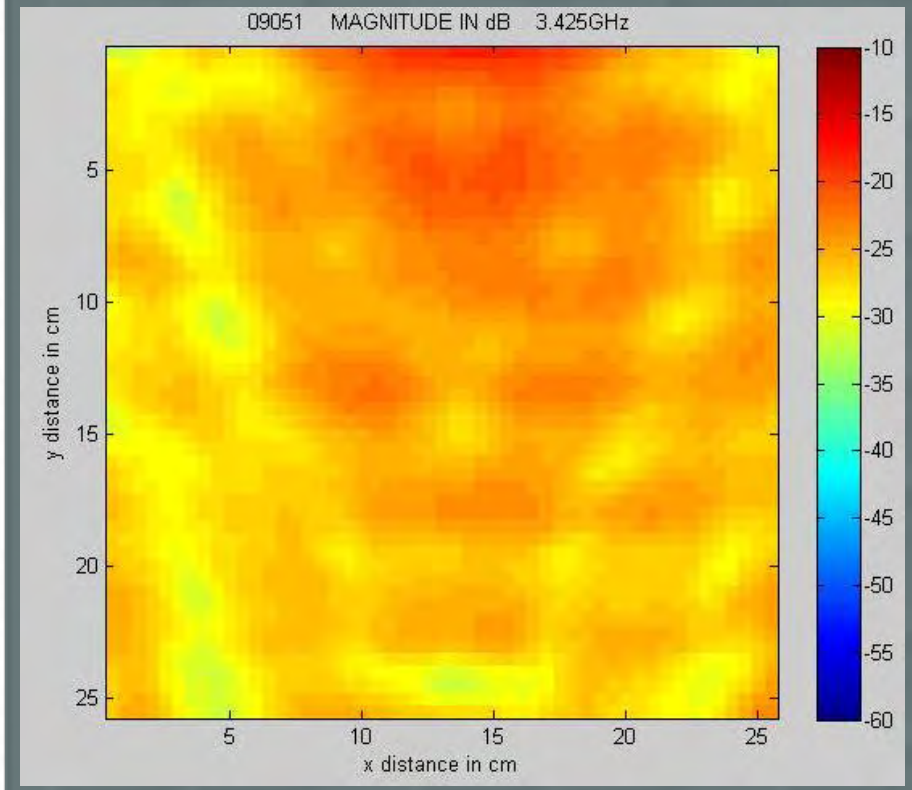
Induced transmission

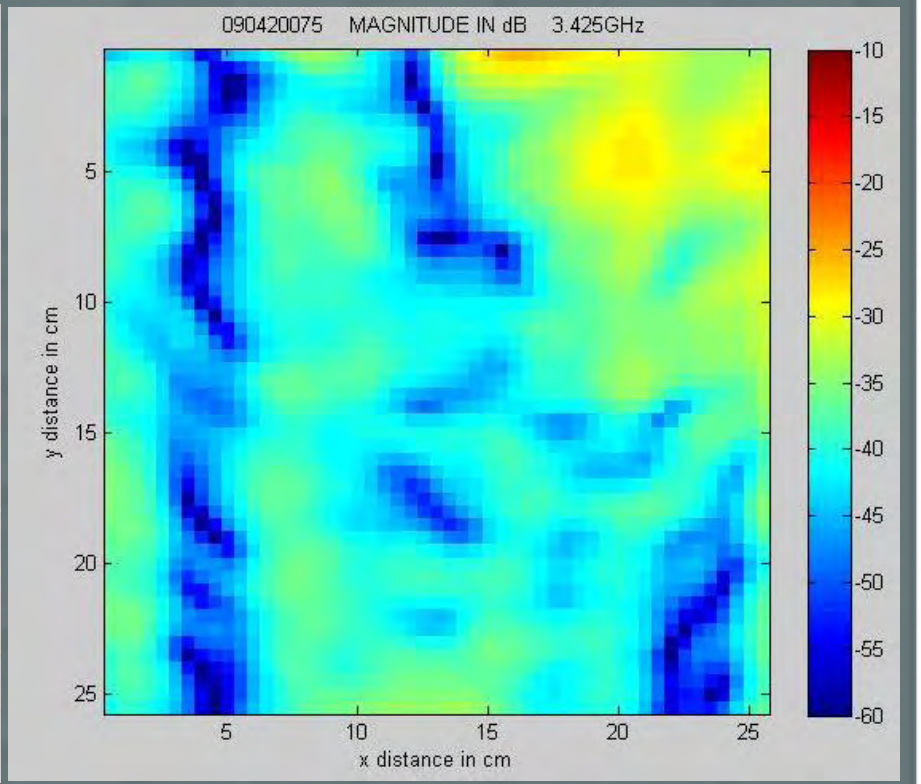
Suppressed transmission

8 December 2008 / Vol. 16, No. 25 / OPTICS EXPRESS 20271

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

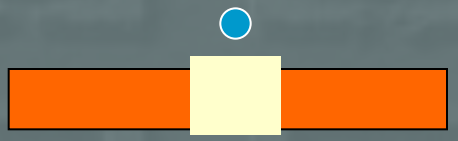
Nonlinearity-suppressed transmission

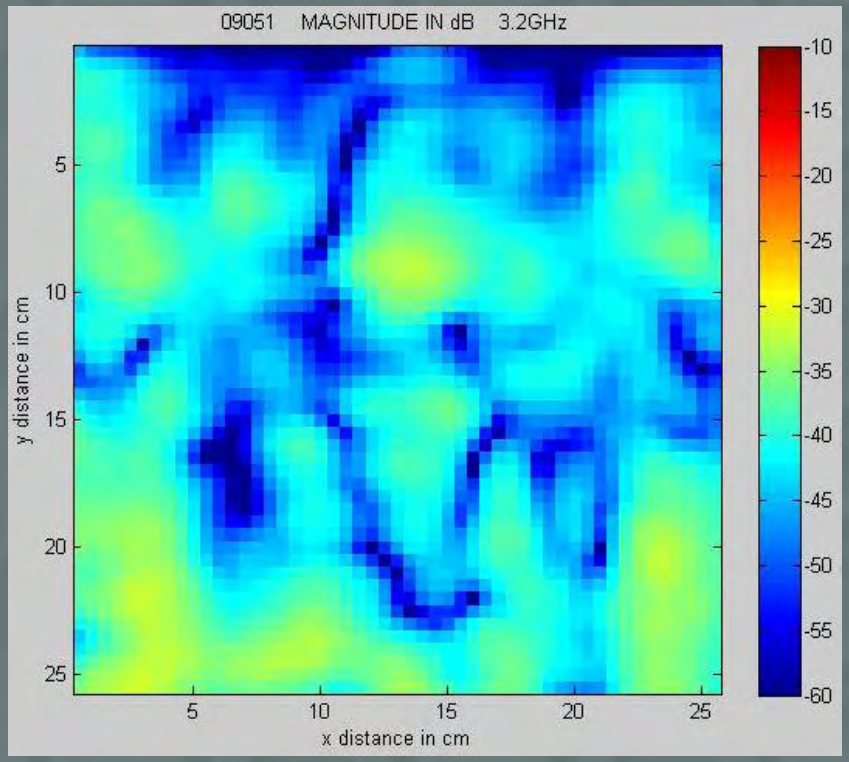


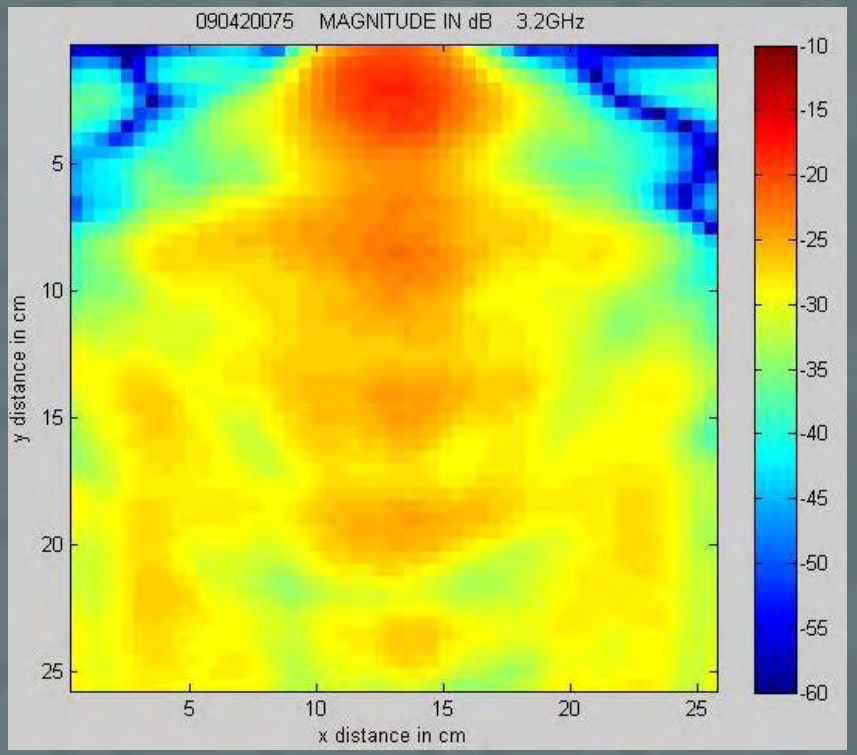


http://wwwrshysse.anu.edu.au/nonlinear

Nonlinearity-induced transparency



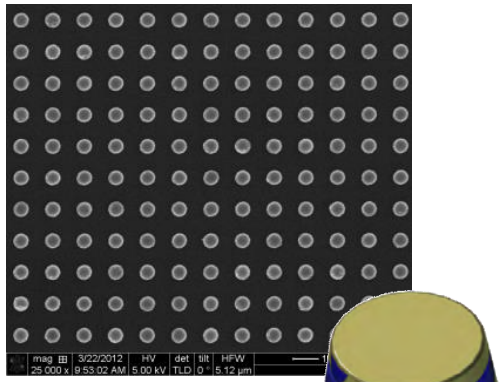


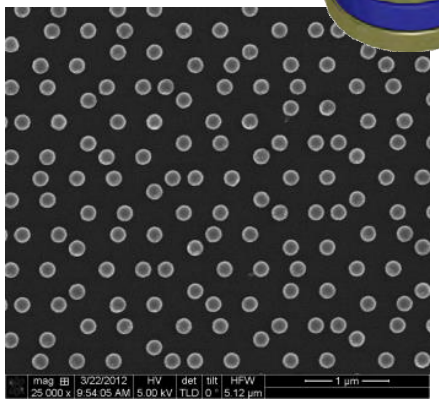


http://wwwrshysse.anu.edu.au/nonlinear

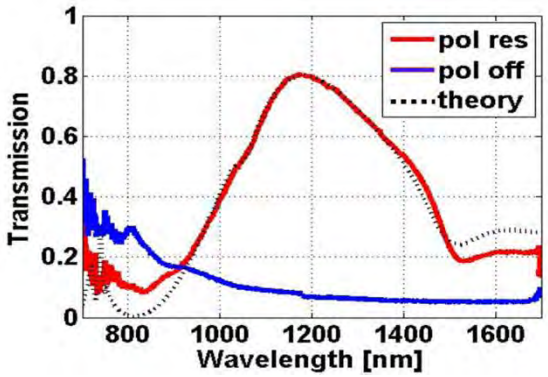
Optical metamaterials in Canberra

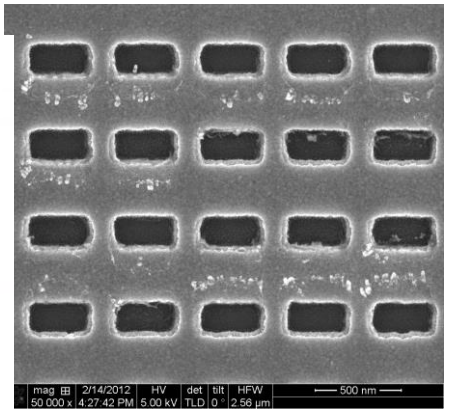
Regular and disordered lattices of meta-atoms



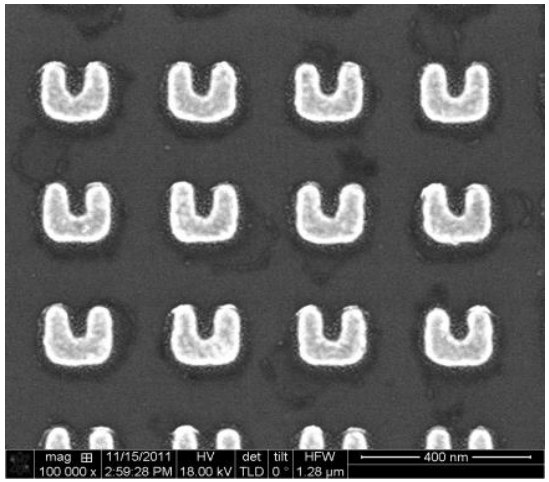


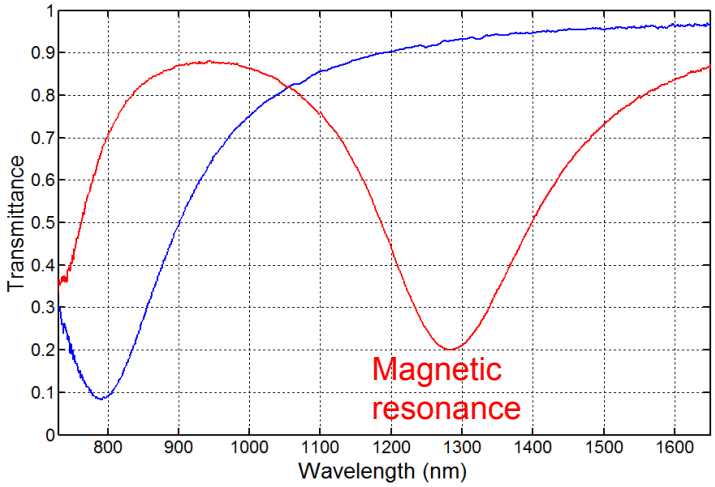
Fishnet metamaterials
Negative Index @ 1.45μm





Magnetic Metamaterials, resonances @ 1.3μm

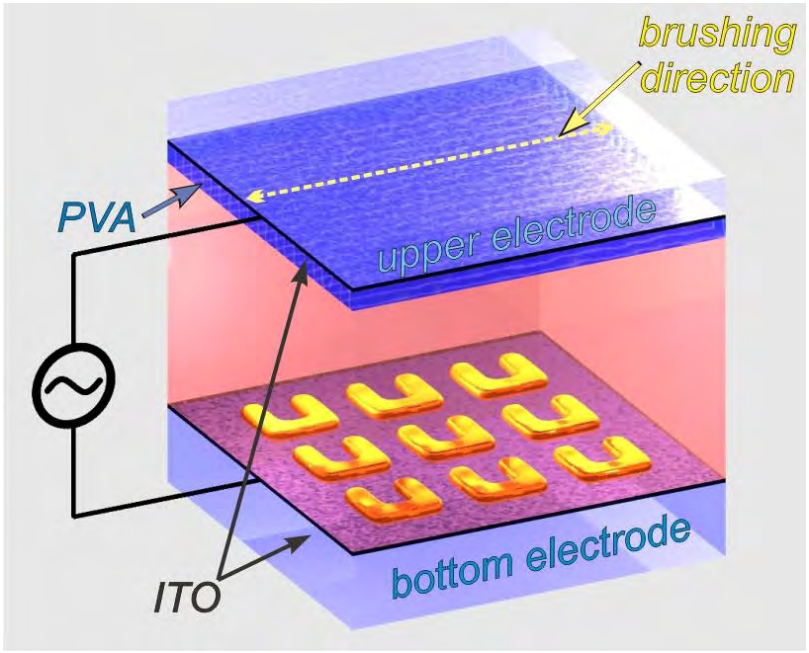




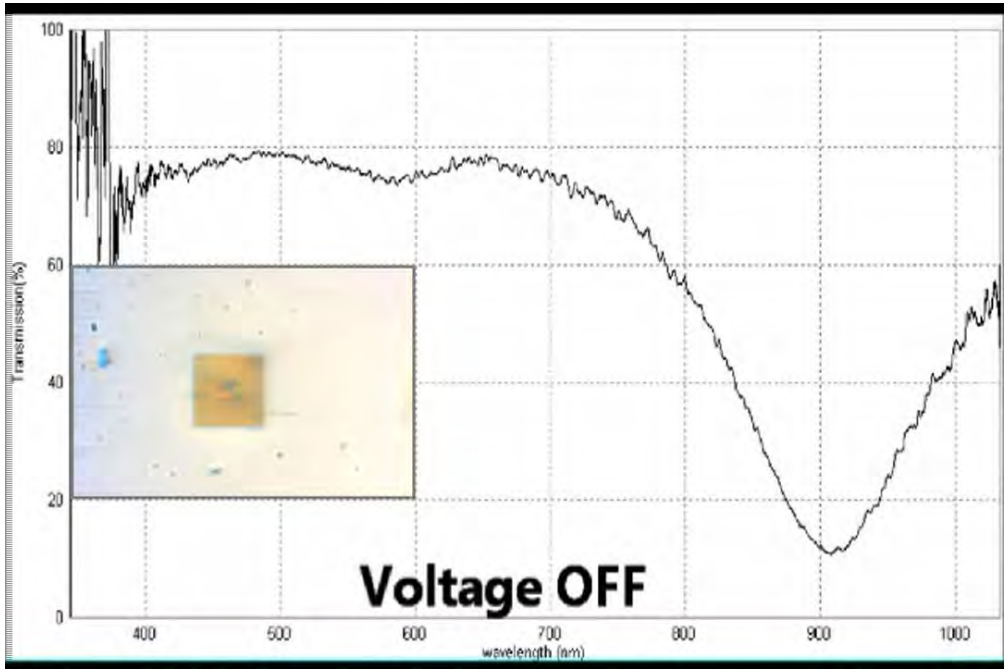
Liquid crystal tuning and switching

Electro-optical mode switching in SRR metamaterials:

Liquid-crystal cell

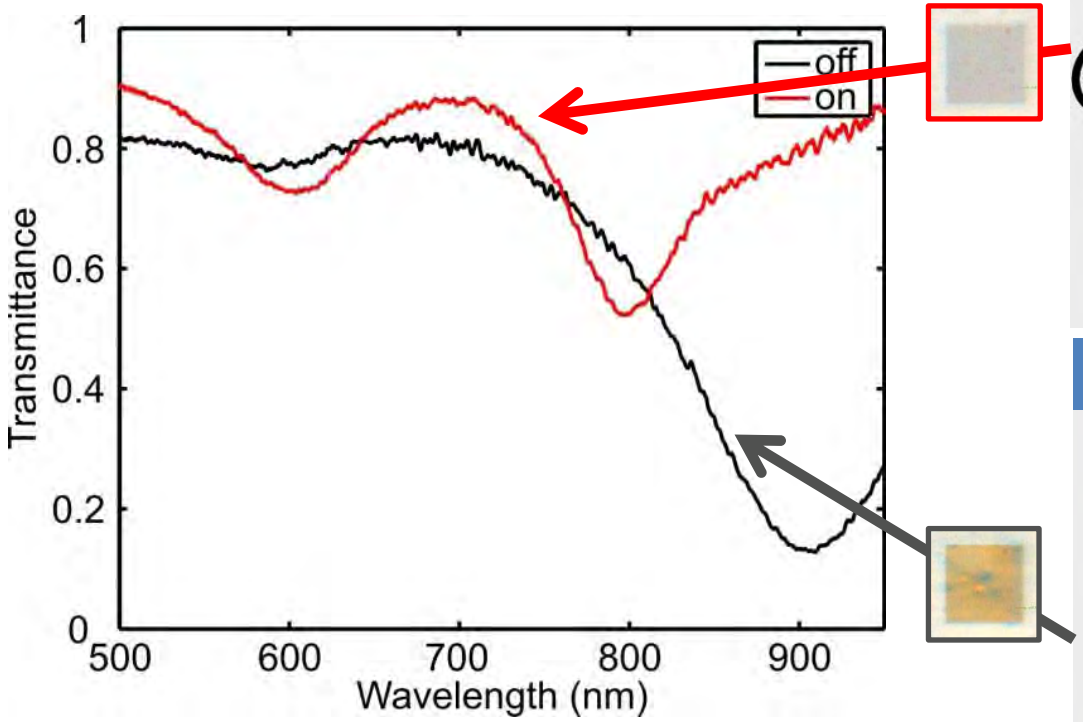


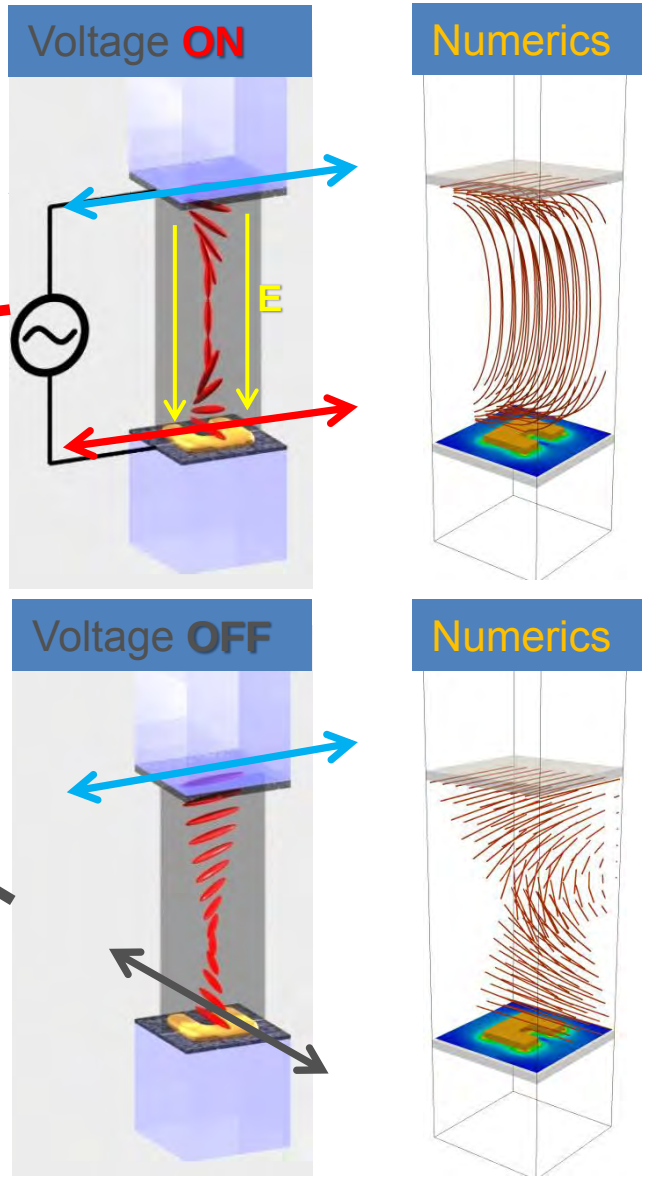
Experimental spectra



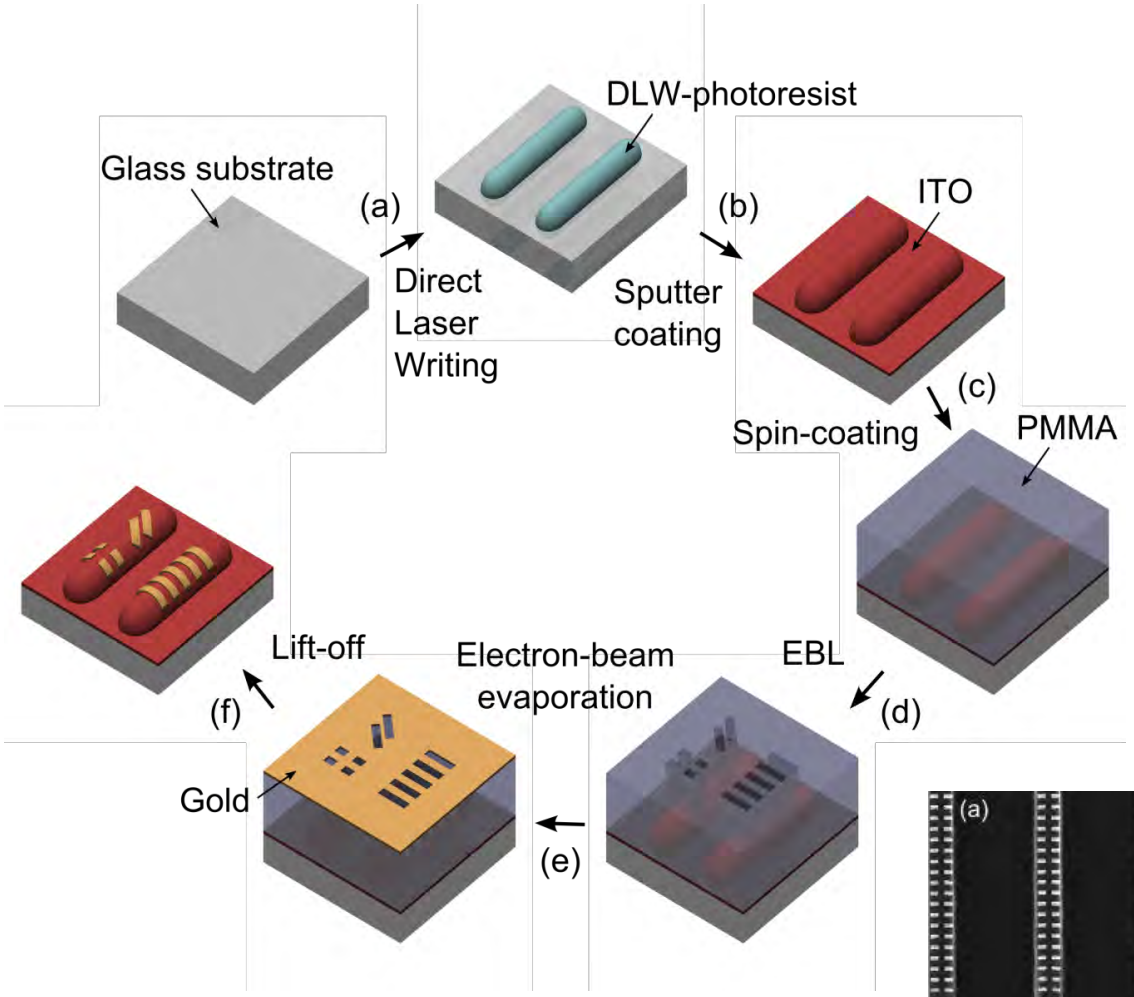
Functional metasurfaces

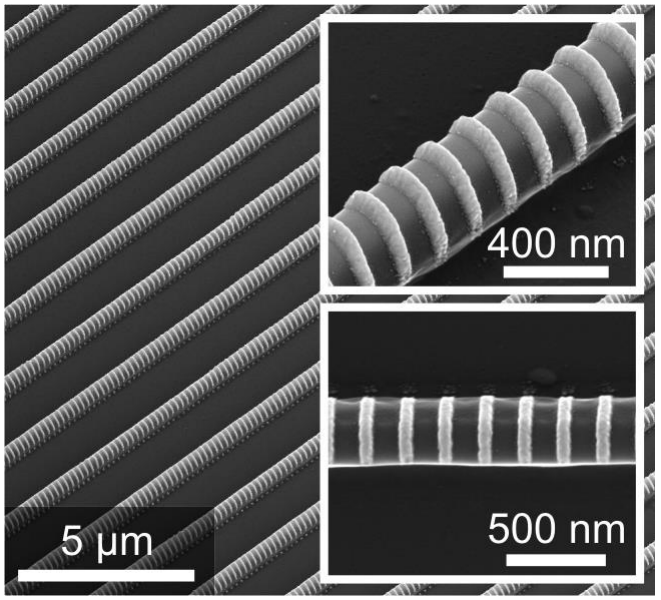
- Switching mechanism:

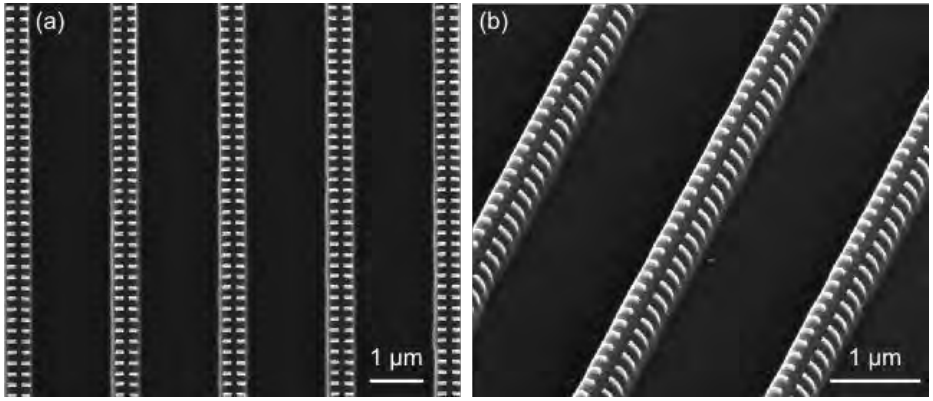




Towards metamaterial circuitry: Hybrid fabrication

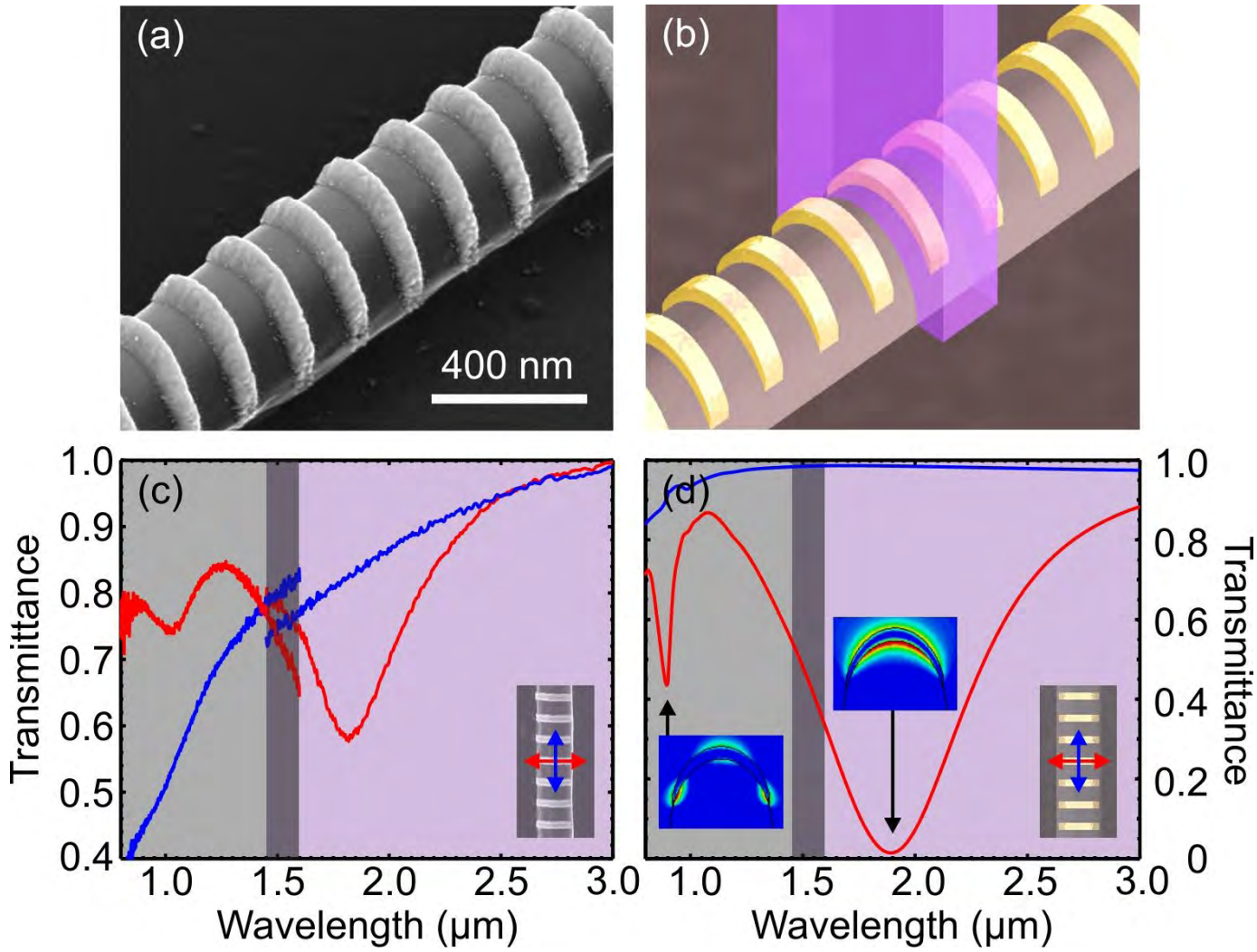






I. Staude et al, Adv Mat (2013)

Optical characterization: magnetic resonance



I. Staude et al, Adv Mat (2013)

All-Dielectric Nanophotonics

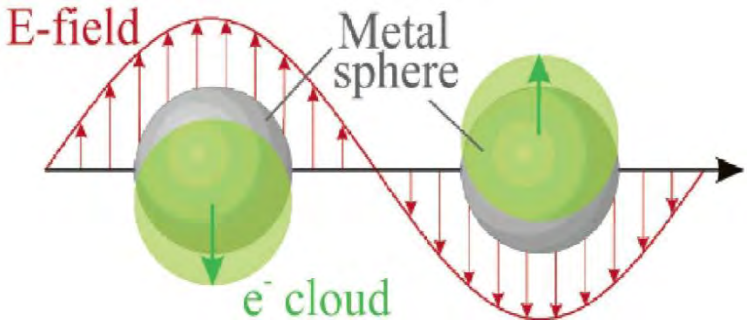
Australian National University

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

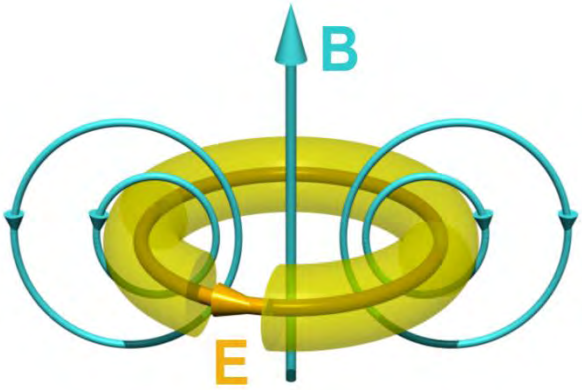
http://phoi.ifmo.ru/metamaterials//

ИТМО

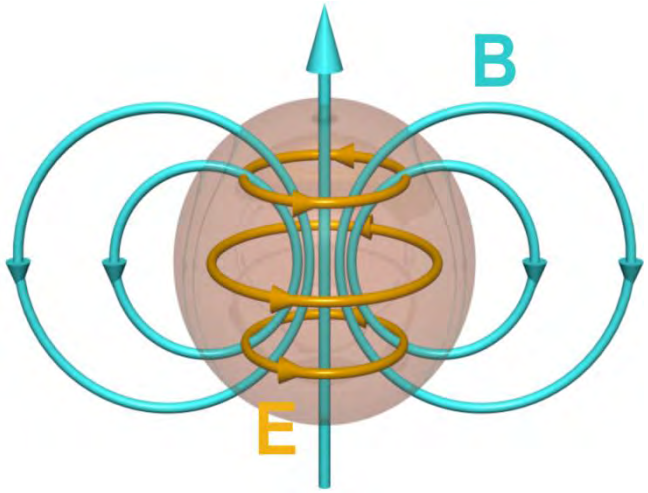
Electric and magnetic response of nanoparticles



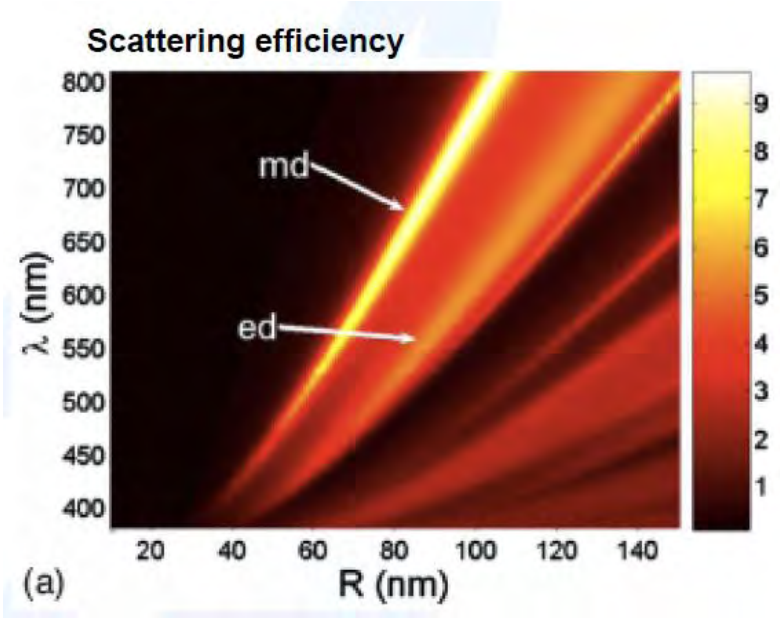
Metal nanoparticle
with electric response



Metal split-ring
with magnetic response

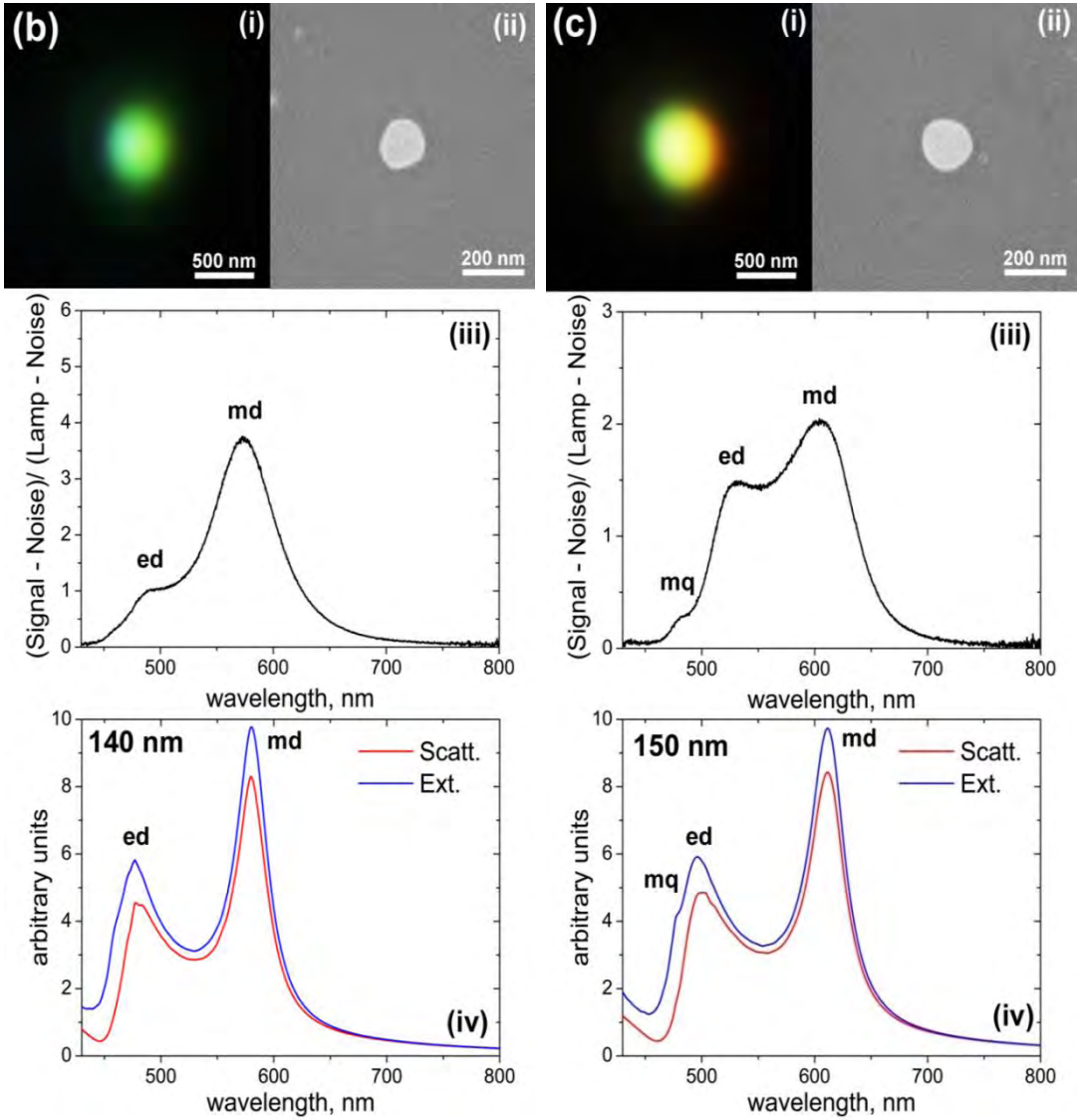


Dielectric nanoparticle
with magnetic response

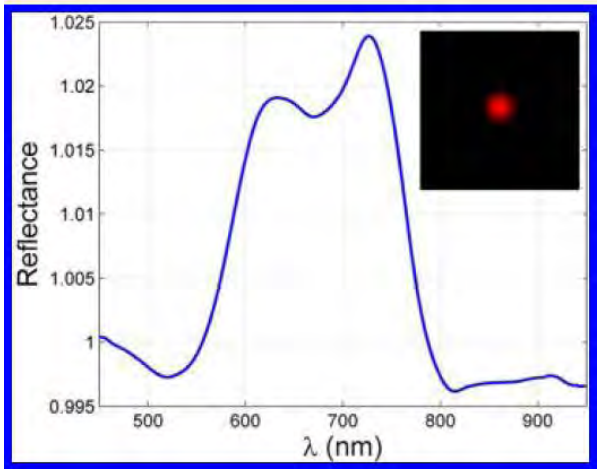


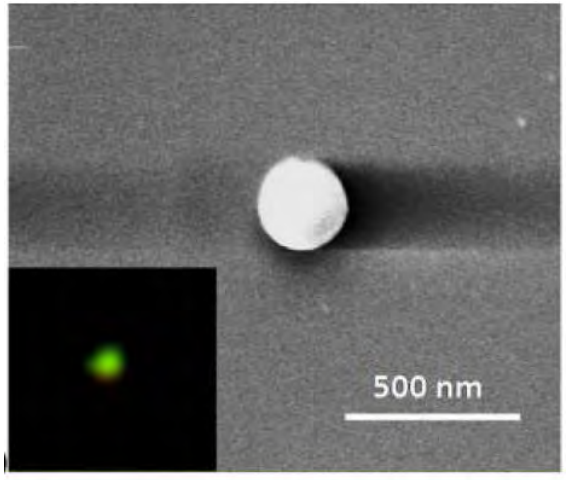
Experiment: Si nanoparticles

A. Kuznetsov et al, Sci. Rep. (2012)



A. Evlyukhin et al Nano Lett (2012)





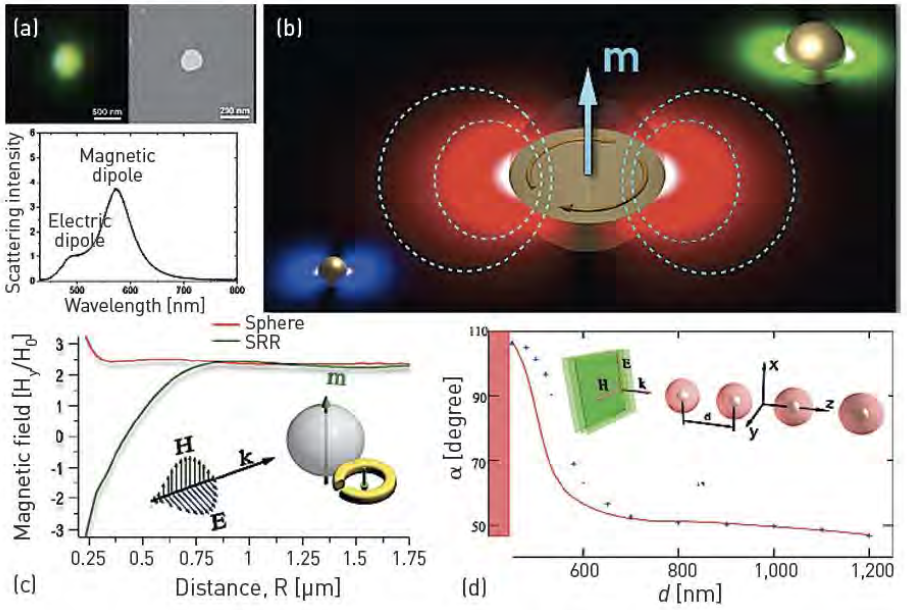
Optics & Photonics News, December 2012

METAMATERIALS

Magnetic Light: Optical Magnetism of Dielectric Nanoparticles

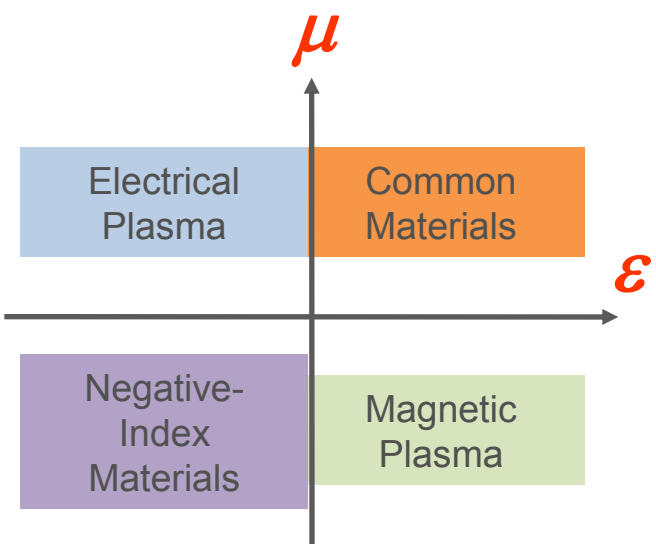
A split-ring resonator (SRR) is an inductive metallic ring with a gap that can support an oscillating current, giving rise to an optically induced magnetic moment. Unfortunately, metal intrinsic loss sets the limit for using SRRs at optical frequencies. But according to our work, spherical silicon nanoparticles can make an attractive alternative.

Dielectric nanoparticles exhibit strong magnetic resonances in the visible. Their excitation is similar to SRRs, but silicon nanoparticles have lower losses. Magnetic resonance originates from exciting an electromagnetic mode inside the nanoparticle

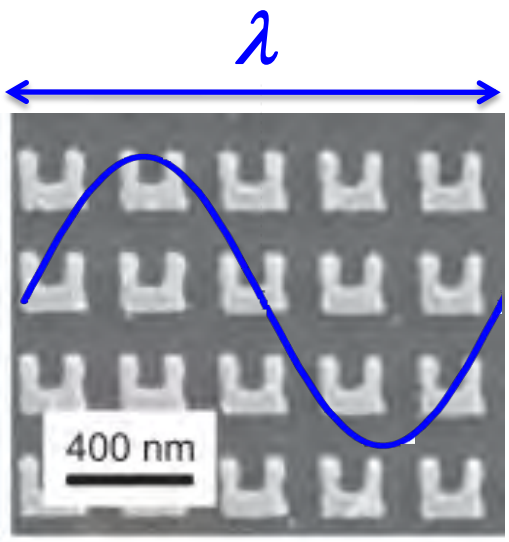


Opportunities with metamaterials

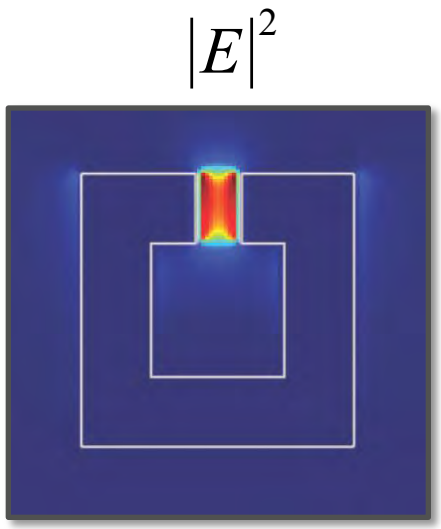
Dispersion engineering



Miniaturization



Strong Field Localization



Materials

Artificial Magnetism

Negative Index

Zero-index

Devices

Smaller

Thinner

Lightweight

Applications

Antennas

Sensors

Absorbers

Summary

- Novel approaches for controlling light with nanostructured matter--metamaterials
- Nonlinear effects in metamaterials
- Novel ideas for metamaterial integration
- New trends-- functional metadevices and all-dielectric nanophotonics

nature materials

REVIEW ARTICLE

PUBLISHED ONLINE: 23 OCTOBER 2012 | DOI: 10.1038/NMAT3431

From metamaterials to metadevices

Nikolay I. Zheludev[1,2]* and Yuri S. Kivshar[3]