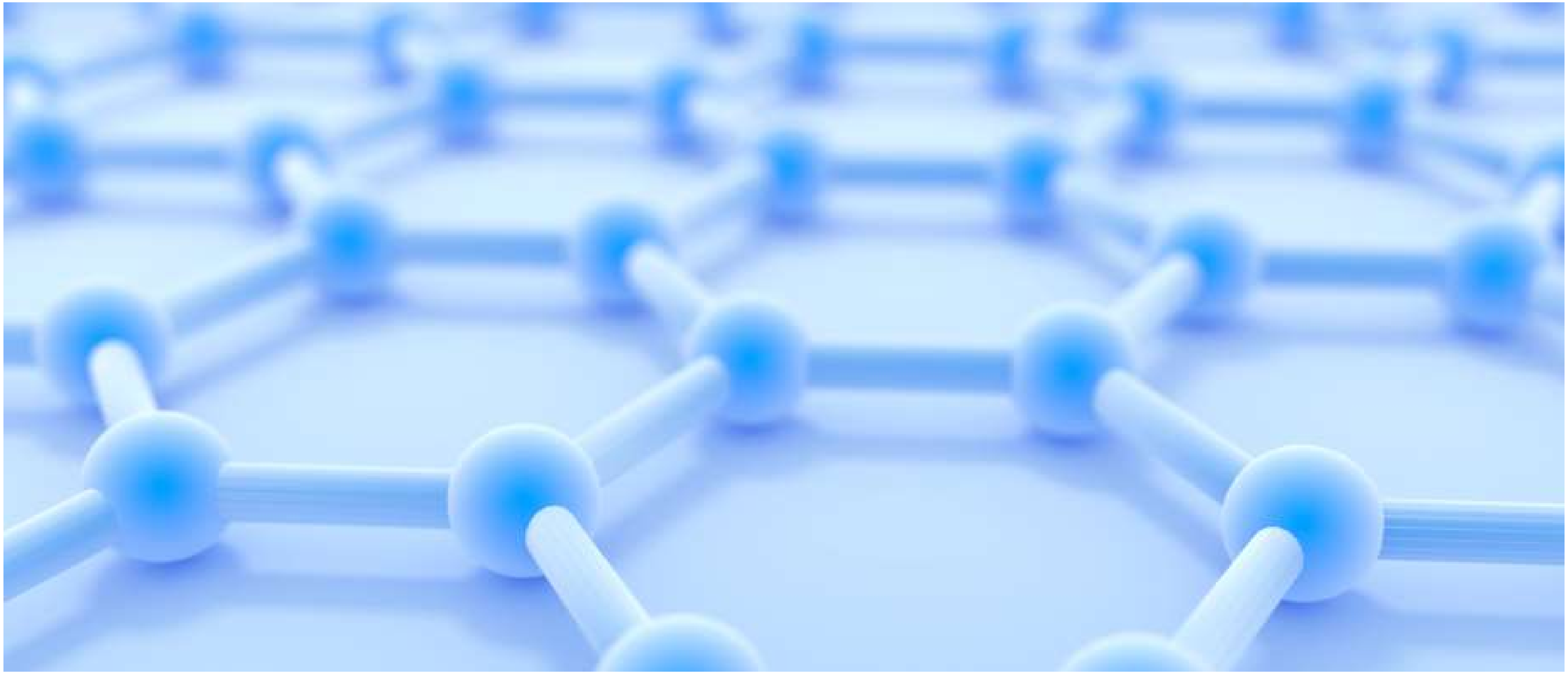
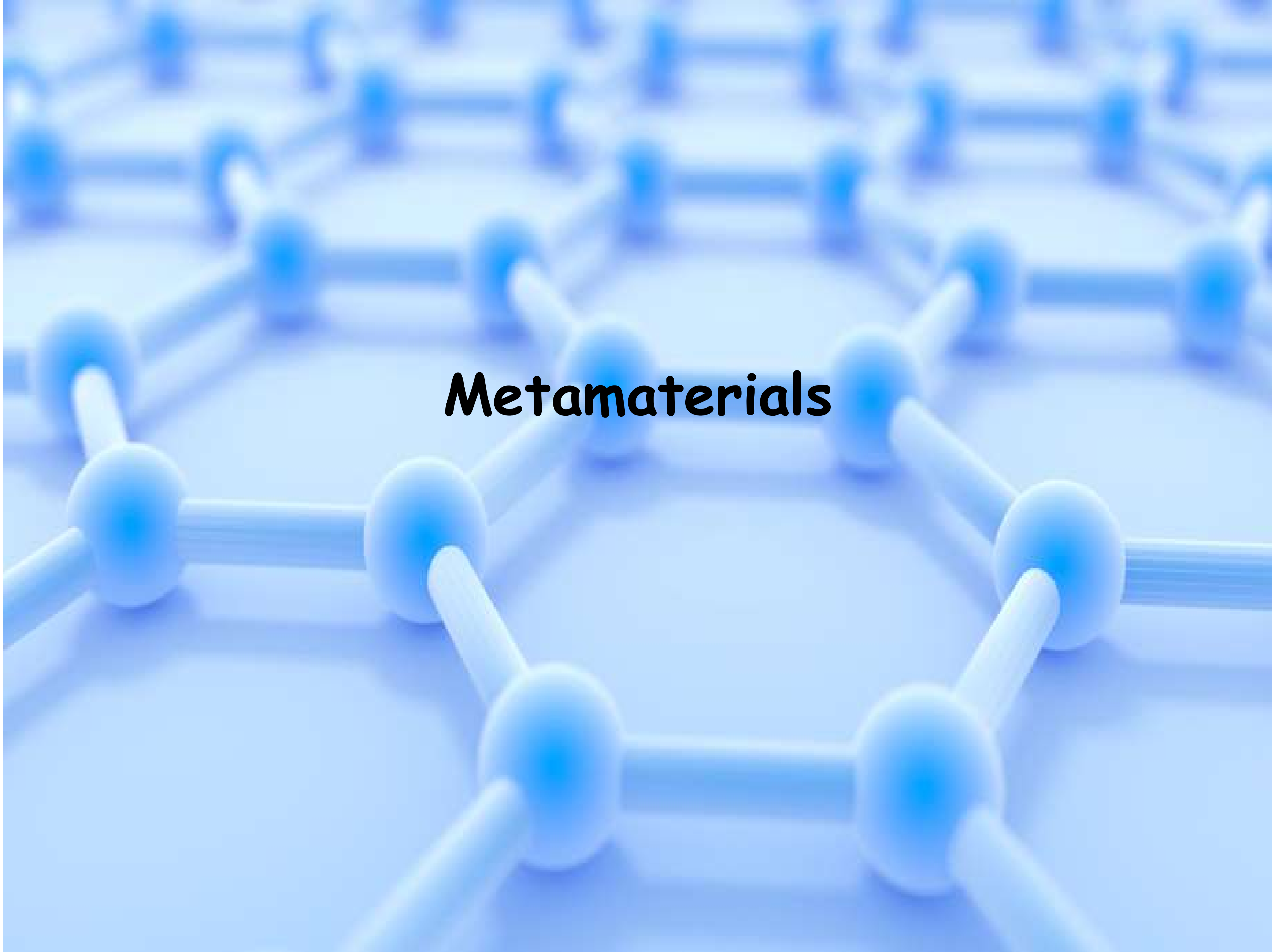


Photonics

Prof. Maria Antonietta Vincenti

Università degli Studi di Brescia

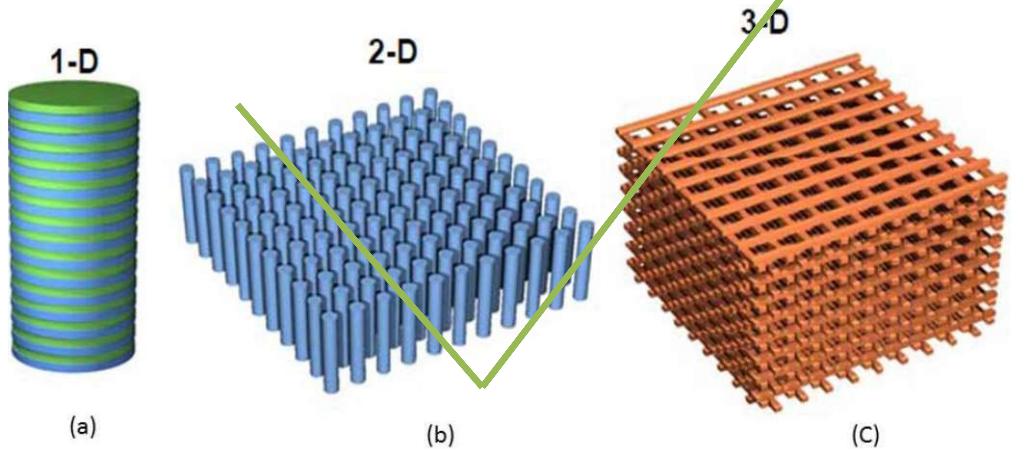

Metamaterials

UNIVERSITY OF BRESCIA

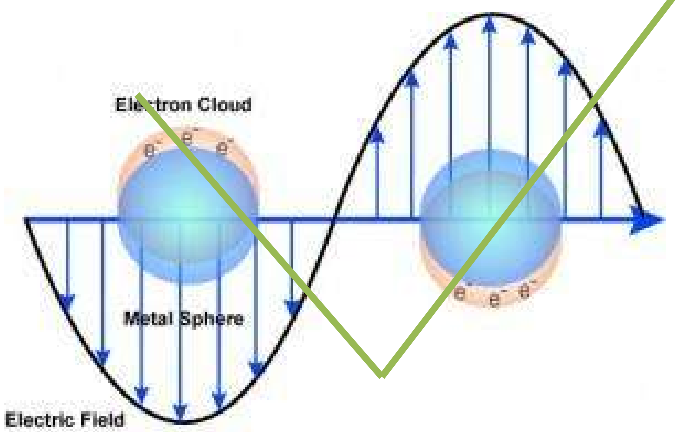
Introduction

Scientists and researchers refuse to be confined by the materials refined from naturally occurring compounds and they are creating new materials or nanostructured materials that exhibit unusual electronic and optical properties.

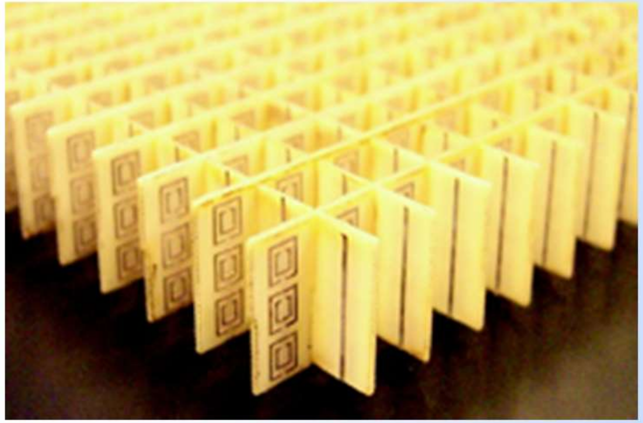
photonic crystals



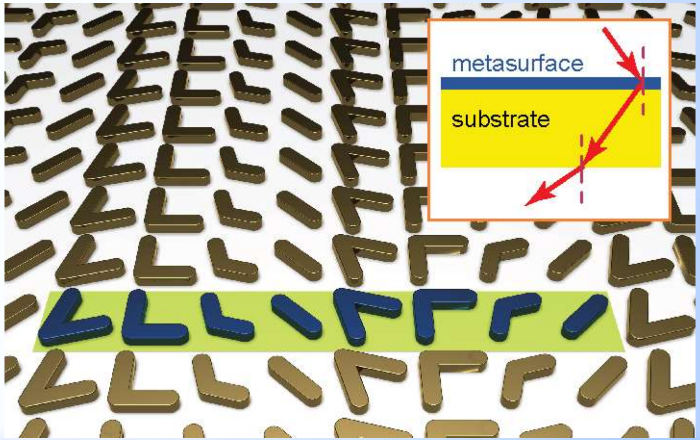
plasmonics



metamaterials



metasurfaces

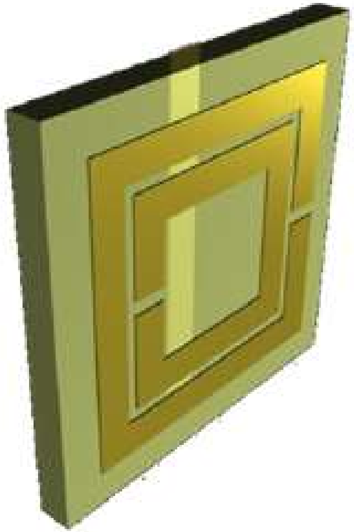


UNIVERSITY OF BRESCIA

Introduction

WHAT ARE METAMATERIALS?

There is no universally accepted definition



– Engineered composites

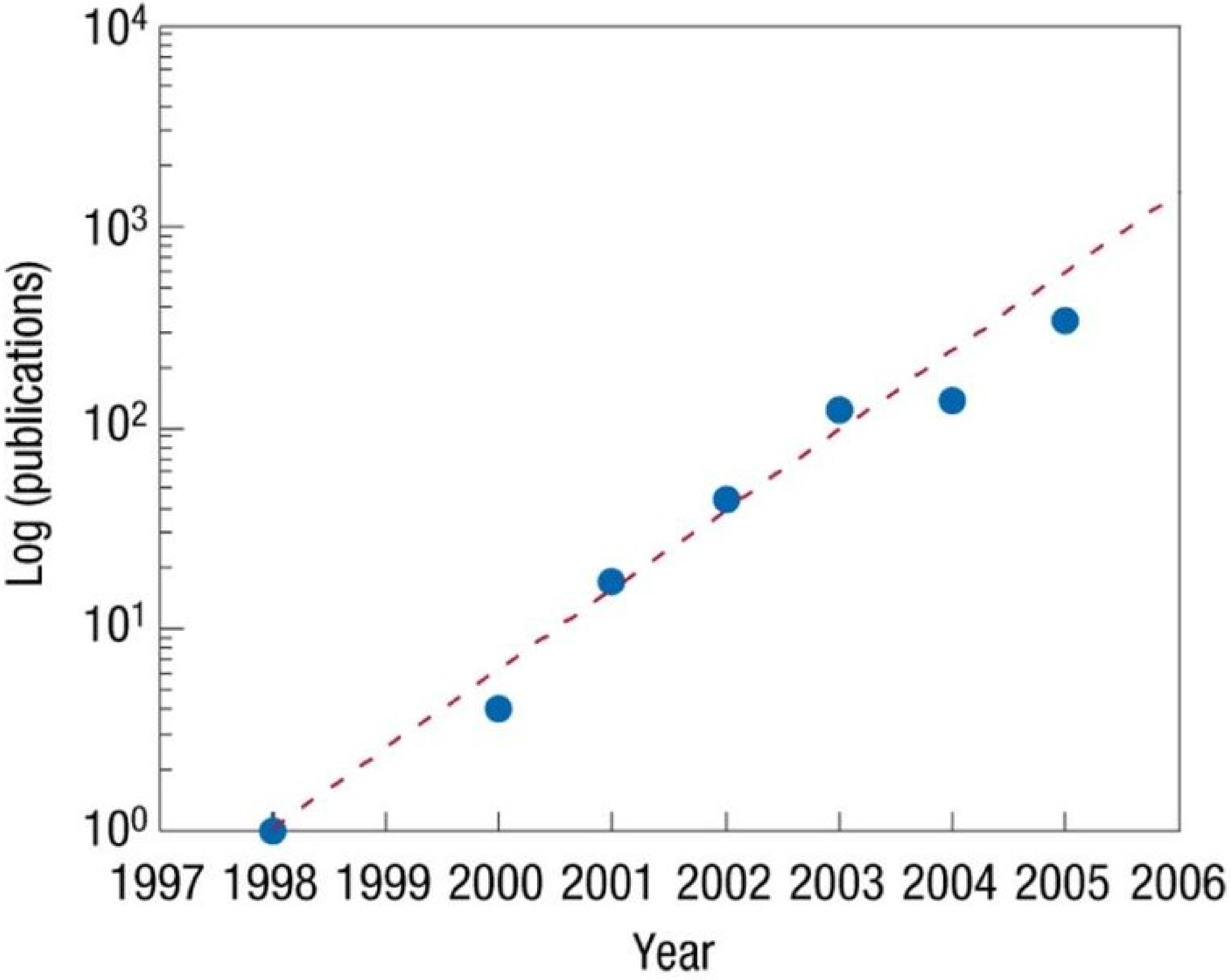
– Structures whose properties are derived from their physical structure and not their chemistry

– Structures that exhibit properties not observed in nature

– Structures that exhibit properties not observed in their constituent materials

– Composite materials that are purposely engineered to provide material properties that are not otherwise attainable with ordinary materials.

Introduction



Introduction

METAMATERIALS CAN BE

RESONANT

- Period is comparable to λ
- Oscillating currents emulate atomic resonances

▪ Frequency selective
▪ Sensitive to fabrication defects
▪ Can be designed at will to achieve certain properties

NON-RESONANT

- Period is much smaller than λ
- Nothing resonates or scatters from unit cells

▪ Greatest potential to be broadband
▪ Greatest potential for wide field-of-view
▪ Greatest tolerance to structural deformations
▪ Fewer "magical" properties than resonant metamaterials.

Motivation

Why do we need to make artificial materials?

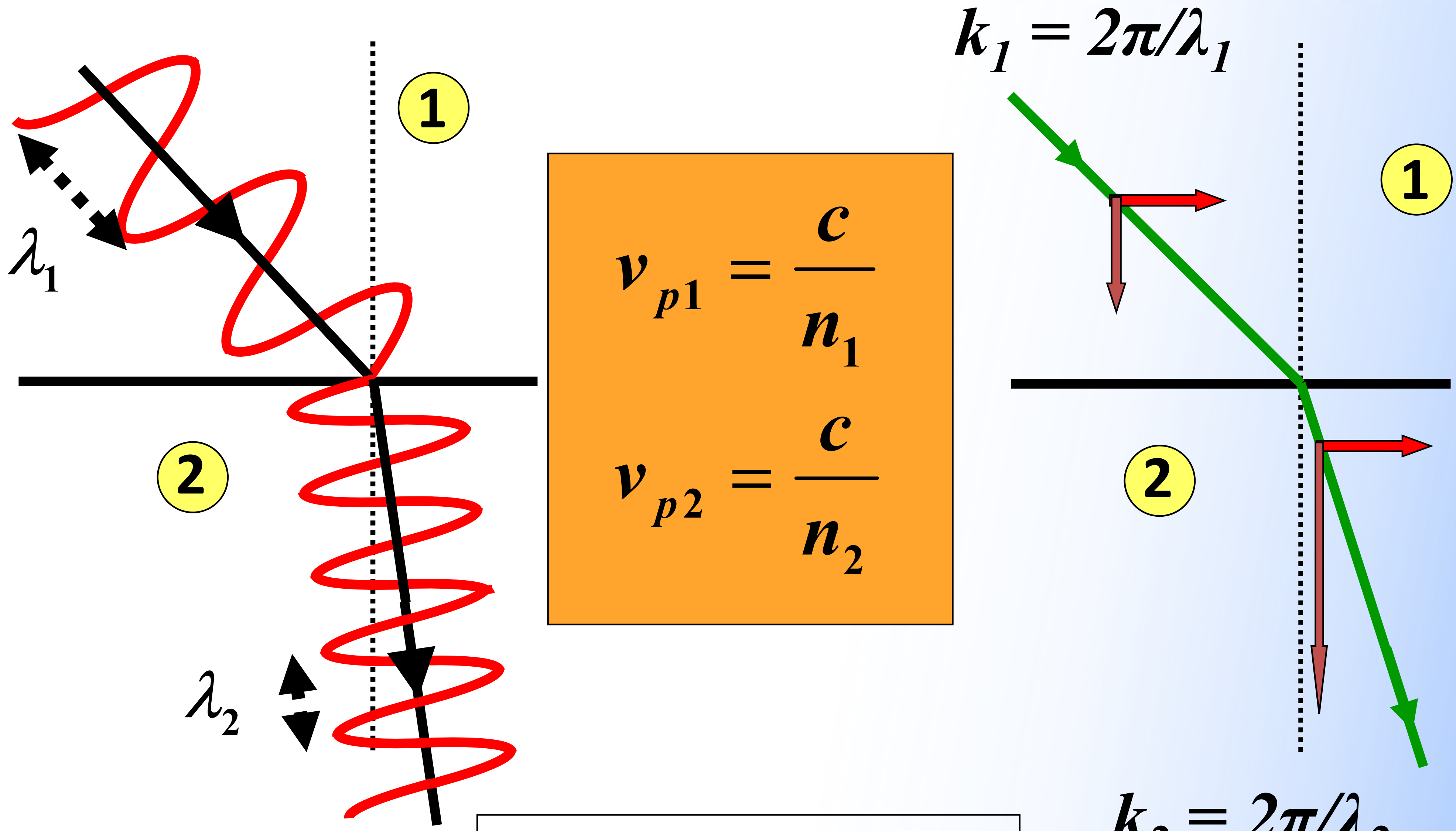
We have reached a stage when naturally available materials can no longer meet the demands of fast-developing fundamental science and applications.

Example:
The best resolution of a conventional microscope is on the order of 100nm because of the fundamental diffraction limit. Electron based microscopy allows to go under this limit but it works only for conducting materials.

Can we develop an all-optical technique for nano-scale imaging

?

This is what we studied so far…



c = speed of light in vacuum
$n_{1,2}$ = refractive indices

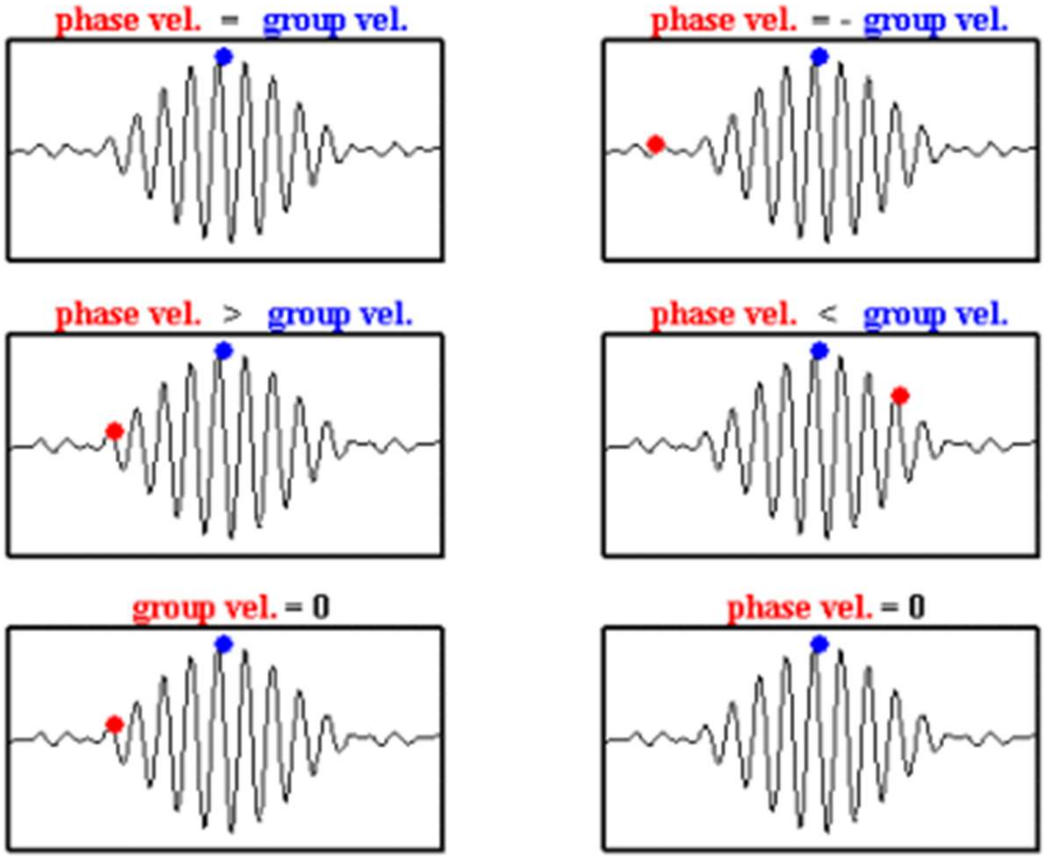
Definition of velocities

Phase Velocity:
Velocity of the phase front of the wave

$$\boxed{v_p = \frac{\omega}{k}}$$

Group Velocity:
Velocity of the wave envelope

$$\boxed{v_g = \frac{\partial \omega}{\partial k}}$$



isvr

UNIVERSITY OF BRESCIA

Refraction

From EM theory we have ω, k, ε, c

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

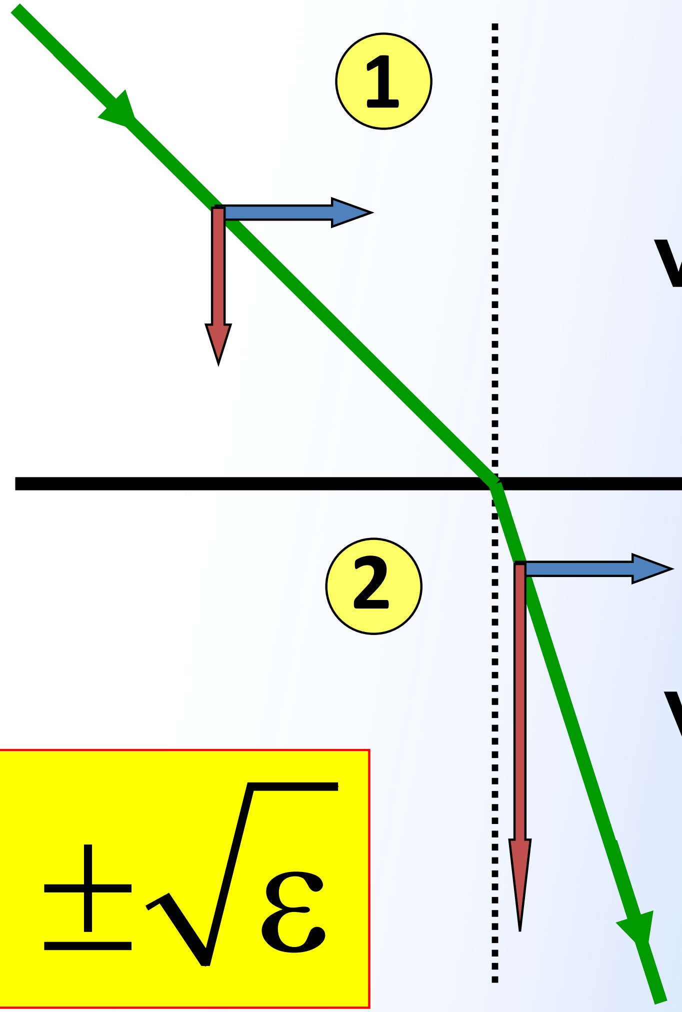
$$\boxed{k = \pm\frac{\omega}{c}\sqrt{\varepsilon}}$$

But people called this refractive index as a way of indicating the bending

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

So, define the refractive index

THE BLUE ARROWS MUST BE EQUAL

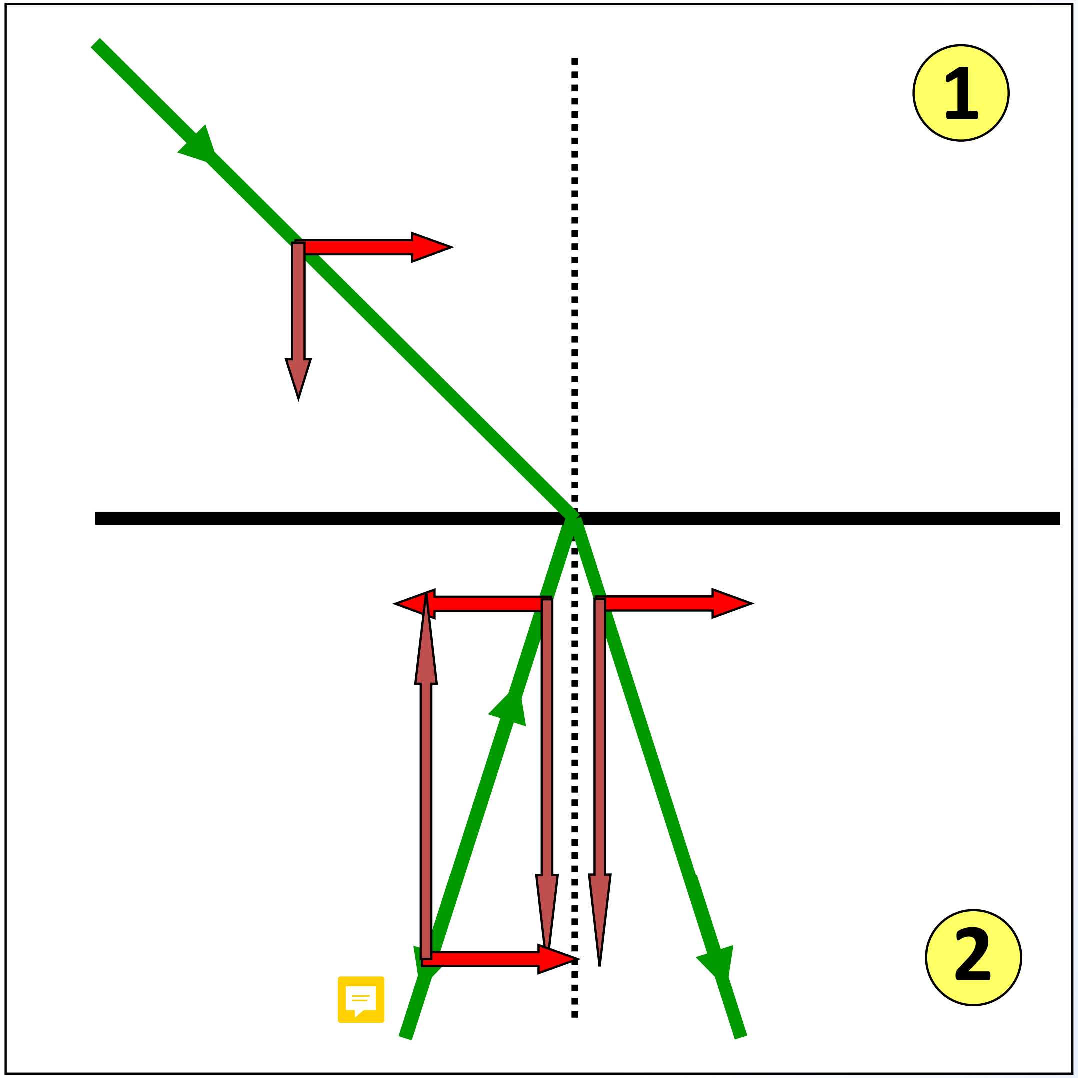


$$\mathbf{v}_{p1} = \frac{c}{n_1}$$

$$\mathbf{v}_{p2} = \frac{c}{n_2}$$

UNIVERSITY OF BRESCIA

Question: is negative refraction possible?



YES! AS A BACKWARD WAVE

UNIVERSITY OF BRESCIA

Question: is negative refraction possible?

Can this be done simply by choosing…

$$\boxed{\boldsymbol{n} = +\sqrt{\boldsymbol{\varepsilon}}}$$

OR

$$\boxed{\boldsymbol{n} = -\sqrt{\boldsymbol{\varepsilon}}}$$

?

UNIVERSITY OF BRESCIA

Is this refraction possible?

Well actually no…

we don’t have to forget about magnetic permeability!

So, what should the index *really* be?

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

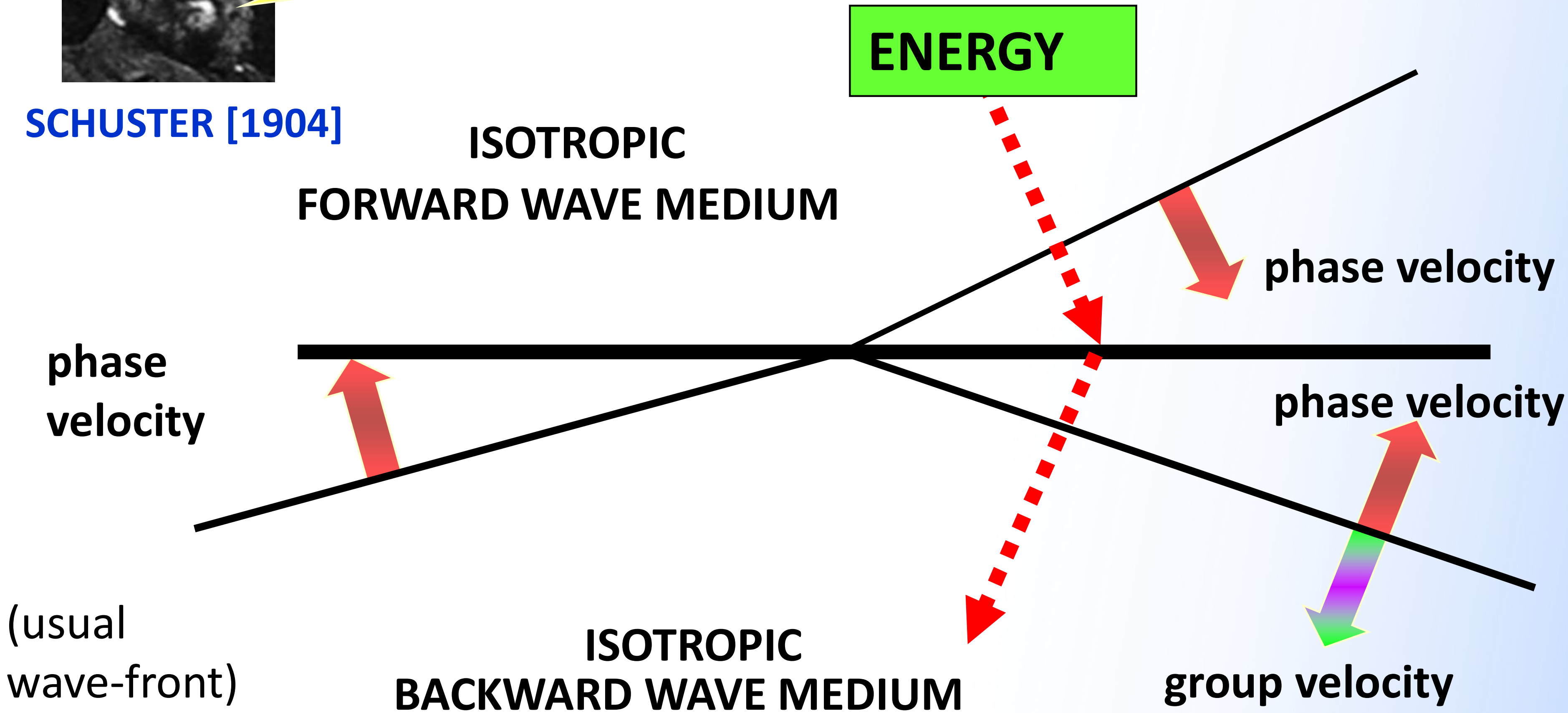
Did anyone spot this a long time ago?

Well... nearly

“a curious result follows”

“wave is bent over to other side of the normal”

SCHUSTER [1904]



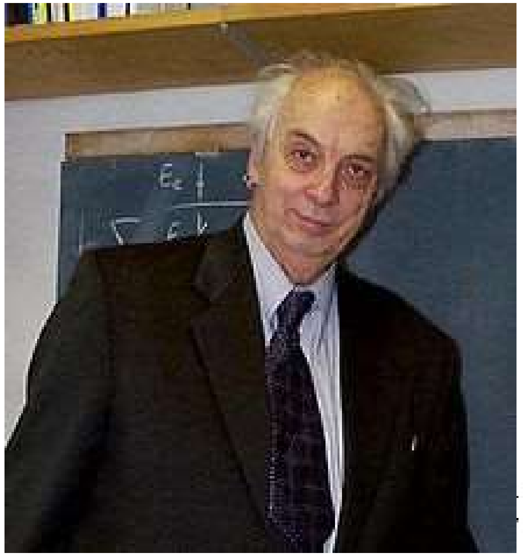
STILL μ WAS NOT CONSIDERED

Horace and Arthur 1904

Sir Horace Lamb (1849-1934)

Sir Arthur Schuster (1851-1934)

- LAMB: *"It is hardly to be expected that the notion of negative group velocity will have any important physical application"*
- SCHUSTER: *"It is doubtful how far the results have any application"*



First paper about negative refraction

VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

1. INTRODUCTION

THE dielectric constant ϵ and the magnetic permeability μ are the fundamental characteristic quantities which determine the propagation of electromagnetic waves in matter. This is due to the fact that they are the only parameters of the substance that appear in the dispersion equation

$$\left|\frac{\omega^2}{c^2}\varepsilon_{il}\mu_{lj} - k^2\delta_{ij} + k_i k_j\right| = 0, \qquad (1)$$

II. THE PROPAGATION OF WAVES IN A SUBSTANCE WITH $\epsilon < 0$ AND $\mu < 0$. "RIGHT-HANDED" AND "LEFT-HANDED" SUBSTANCES

To ascertain the electromagnetic laws essentially connected with the sign of ϵ and μ, we must turn to those relations in which ϵ and μ appear separately, and not in the form of their product, as in (1)—(3). These relations are primarily the Maxwell equations and the constitutive relations

How do we get negative refraction?

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}$$

For plane waves we have: $E(\omega)e^{-j(\omega t - \mathbf{k} \bullet \mathbf{r})}, \quad B(\omega)e^{-j(\omega t - \mathbf{k} \bullet \mathbf{r})}$

$$\mathbf{B} = \mu(\omega)\mathbf{H}, \quad \mathbf{D} = \varepsilon(\omega)\mathbf{E}$$

$$-j\mathbf{k} \times \mathbf{E} = -j\omega\mu\mathbf{H}$$

$$-j\mathbf{k} \times \mathbf{H} = j\omega\varepsilon\mathbf{E}$$

Apply $\underline{\mathbf{k} \times}$ operator to first equation to obtain:

$$\mathbf{k} \times \left(\mathbf{k} \times \mathbf{E}\right) = \left(\omega\mu\right)\mathbf{k} \times \mathbf{H} = -\left(\omega\mu\right)\left(\omega\varepsilon\mathbf{E}\right)$$

UNIVERSITY OF BRESCIA

How do we get negative refraction?

$$\mathbf{k}\times(\mathbf{k}\times\mathbf{E}) = (\omega\mu)\,\mathbf{k}\times\mathbf{H} = -(\omega\mu)(\omega\varepsilon\mathbf{E})$$

$\nabla\bullet\mathbf{E}=0$

$$\mathbf{k}\times(\mathbf{k}\times\mathbf{E}) = \cancel{\mathbf{k}(\mathbf{k}\bullet\mathbf{E})} - (\mathbf{k}\bullet\mathbf{k})\mathbf{E} = -(\omega\mu)(\omega\varepsilon\mathbf{E})$$

$$\mathbf{k}\bullet\mathbf{k} = \omega^2\mu\varepsilon \Rightarrow k = \pm\omega\sqrt{\mu\varepsilon} = \pm\frac{\omega}{c}n$$

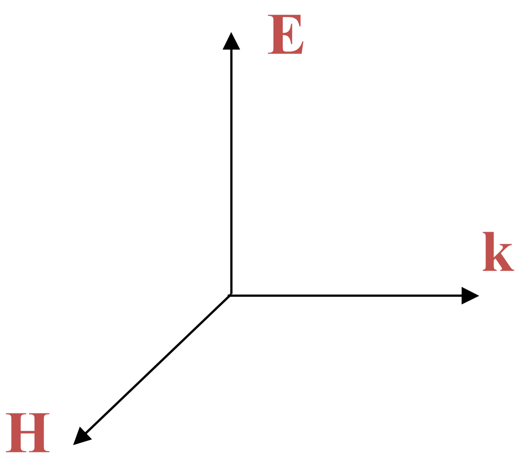
Refractive index can be either positive or negative

Right Handed and Left Handed Media

$\varepsilon, \mu > 0$

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

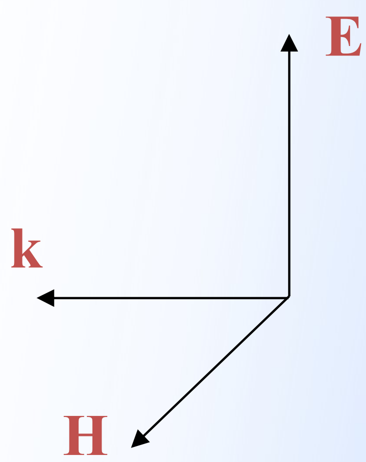
$$\mathbf{k} \times \mathbf{H} = -\omega\varepsilon\mathbf{E}$$



$\varepsilon, \mu < 0$

$$\mathbf{k} \times \mathbf{E} = -\left|\omega\mu\right|\mathbf{H}$$

$$\mathbf{k} \times \mathbf{H} = \left|\omega\varepsilon\right|\mathbf{E}$$



Where is the energy flowing?

$$\boxed{\begin{aligned}\mathbf{k}\times\mathbf{E} &= \omega\mu\mathbf{H} \\ \mathbf{k}\times\mathbf{H} &= -\omega\varepsilon\mathbf{E}\end{aligned}}$$

$$\mathbf{E}\times(\mathbf{k}\times\mathbf{E}) = \omega\mu\mathbf{E}\times\mathbf{H} = \omega\mu\mathbf{S}$$

$$\mathbf{E}\times(\mathbf{k}\times\mathbf{E}) = (\mathbf{E}\bullet\mathbf{E})\mathbf{k} - \cancel{(\mathbf{E}\bullet\mathbf{k})}\mathbf{E}$$

$$\boxed{\mathbf{S} = \frac{|E|^2}{\omega\mu}\mathbf{k}}$$

Energy flow is always a positive quantity

UNIVERSITY OF BRESCIA

Where is the energy flowing?

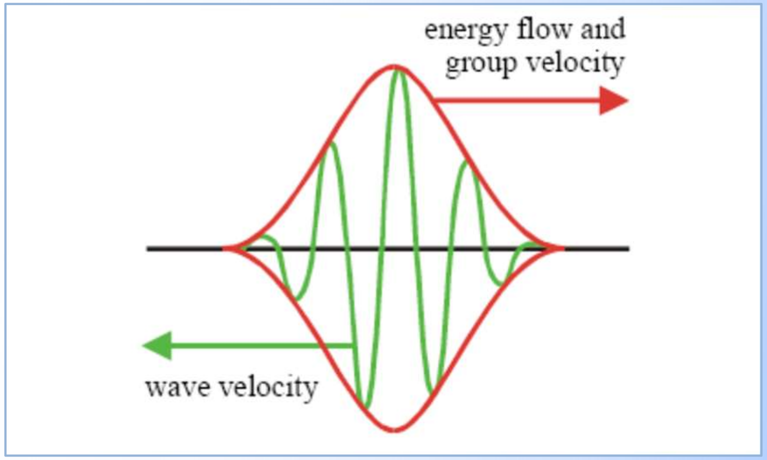
$$\boxed{\mathbf{k} = \pm \frac{\omega}{c}\sqrt{\mu\varepsilon}\,\hat{k}}$$

If both ε and μ are simultaneously negative, then the choice

$$\mathbf{k} = -\frac{\omega}{c} n\hat{k}$$ **is the only one that ensures positive energy flow.**

S and **k** always have to point in the opposite direction if μ **< 0**

$$\boxed{\mathbf{S} = \frac{|E|^2}{\omega\mu}\mathbf{k}}$$



Veselago: ***S*** *remains a right handed quantity, i.e., energy must flow away from the boundary and the source. The consequence of this is* ***forward propagation with negative phase velocity.***

In other words,

To obtain negative refraction we need to add magnetic effects where none seems to exist!

We need to make metamaterials

Supernatural or beyond Nature

Can we have negative refraction without having a negative index material?

YES

Negative permittivity

Diffraction managing

Negative Permittivity

Does negative permittivity exist in nature? YES, it does!

Metals below the plasma frequency
→ negative permittivity

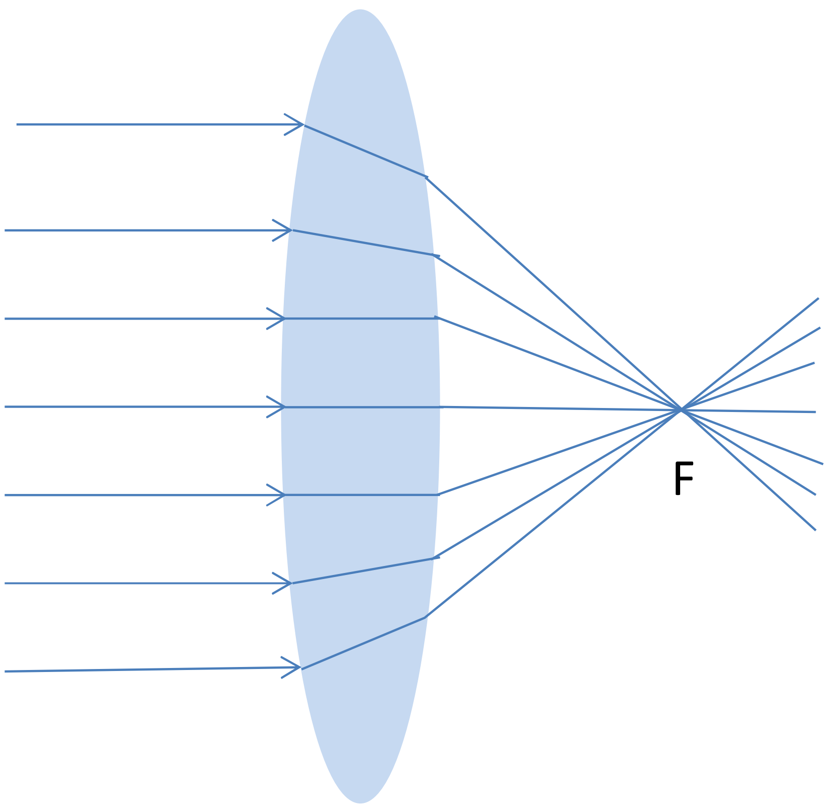
Prof. Sir J. B. Pendry, Imperial College in London (1999) showed that negative permittivity was sufficient to realize a perfect - flat - lens!

Sir John Pendry et al. J Phys. Cond. Matter ***15*** *6345 (2003)*

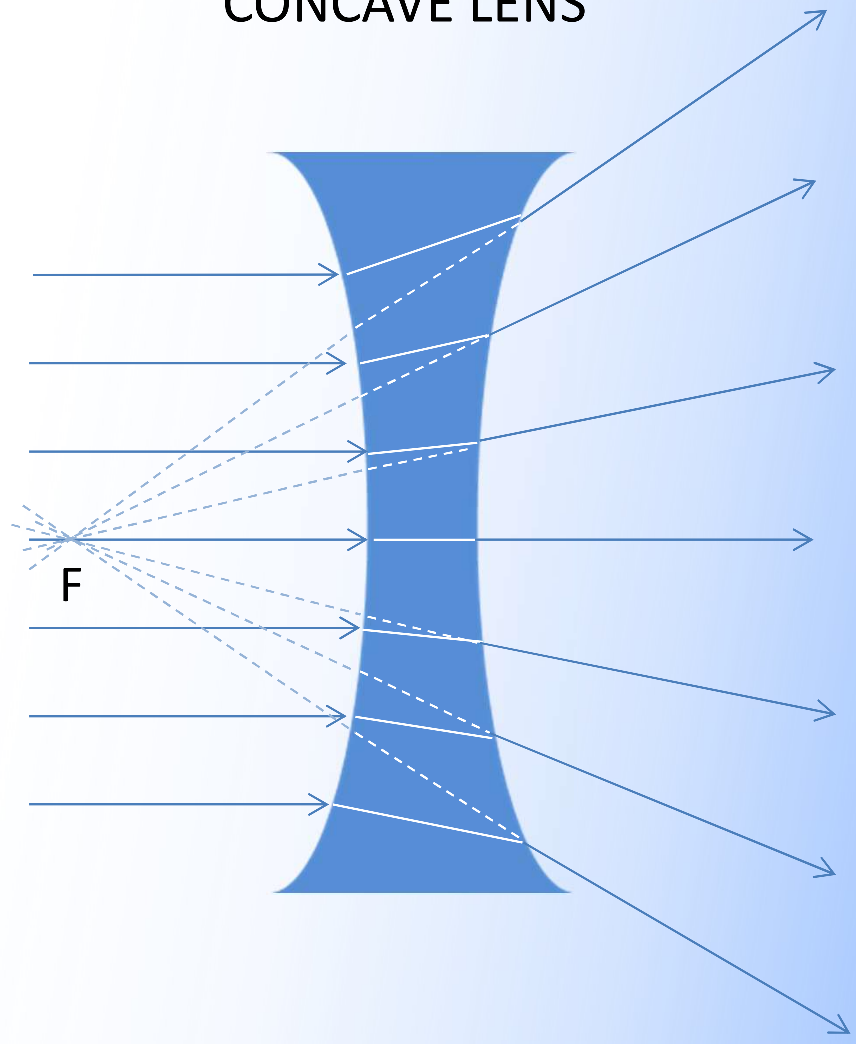
UNIVERSITY OF BRESCIA

Conventional Lenses

CONVEX LENS



CONCAVE LENS



Conventional Imaging

- Spot size is limited to $\lambda/2NA$:

  $\lambda \rightarrow$ wavelength used in the imaging system

  NA $\rightarrow$ Numerical Aperture of the imaging system ($NA = n\sin\theta$)

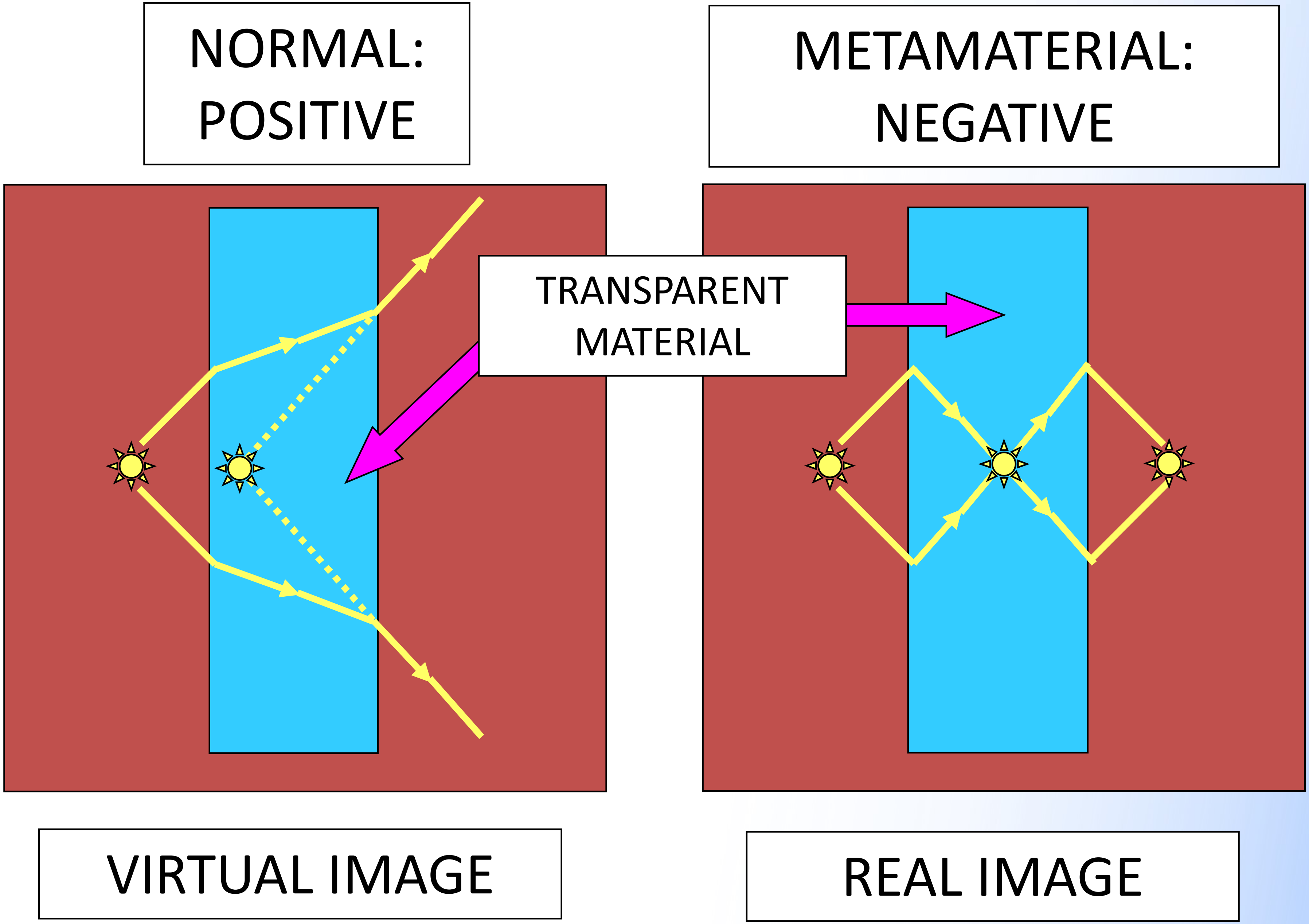
- Diffraction limit:

  Conventional imaging loses the information of the near-field

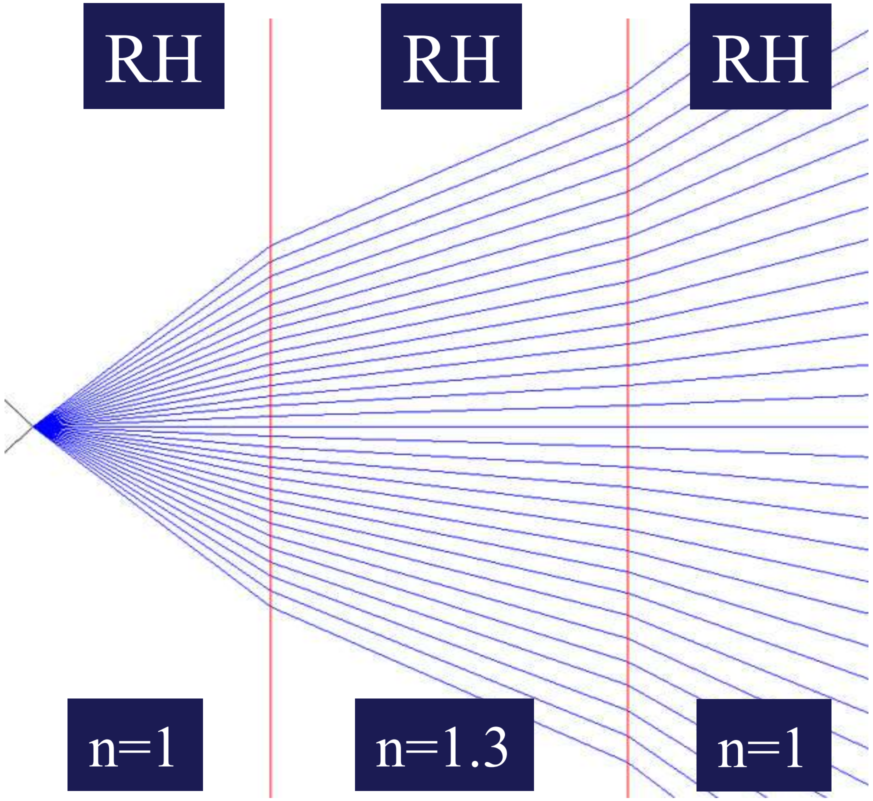
$\Downarrow$

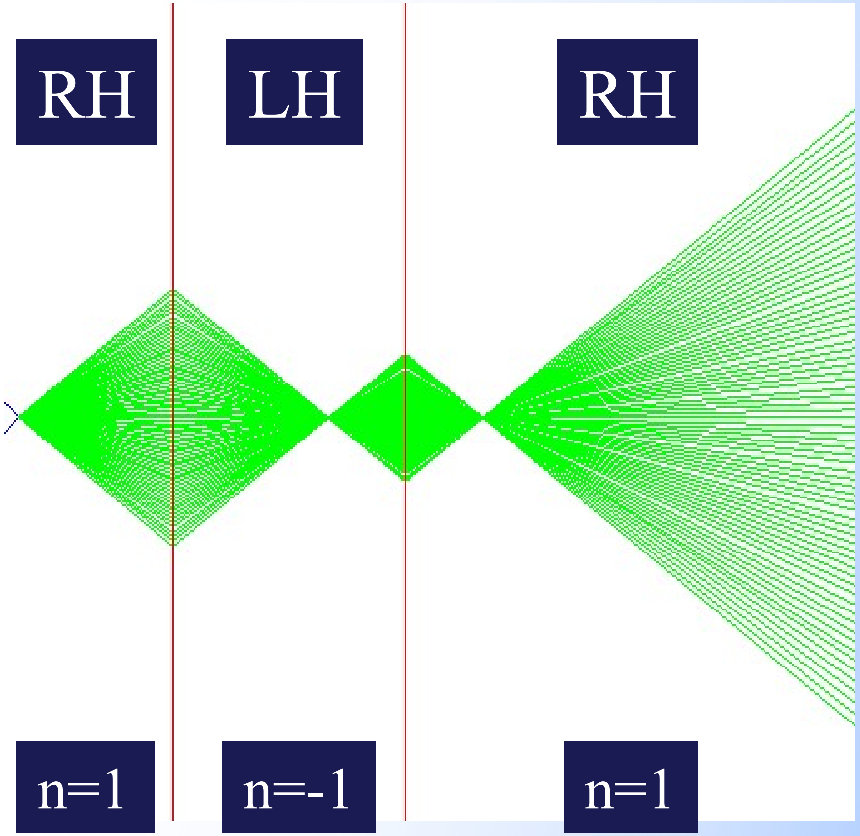
We can improve the resolution if we recover the information of the near-field

Flat Lenses

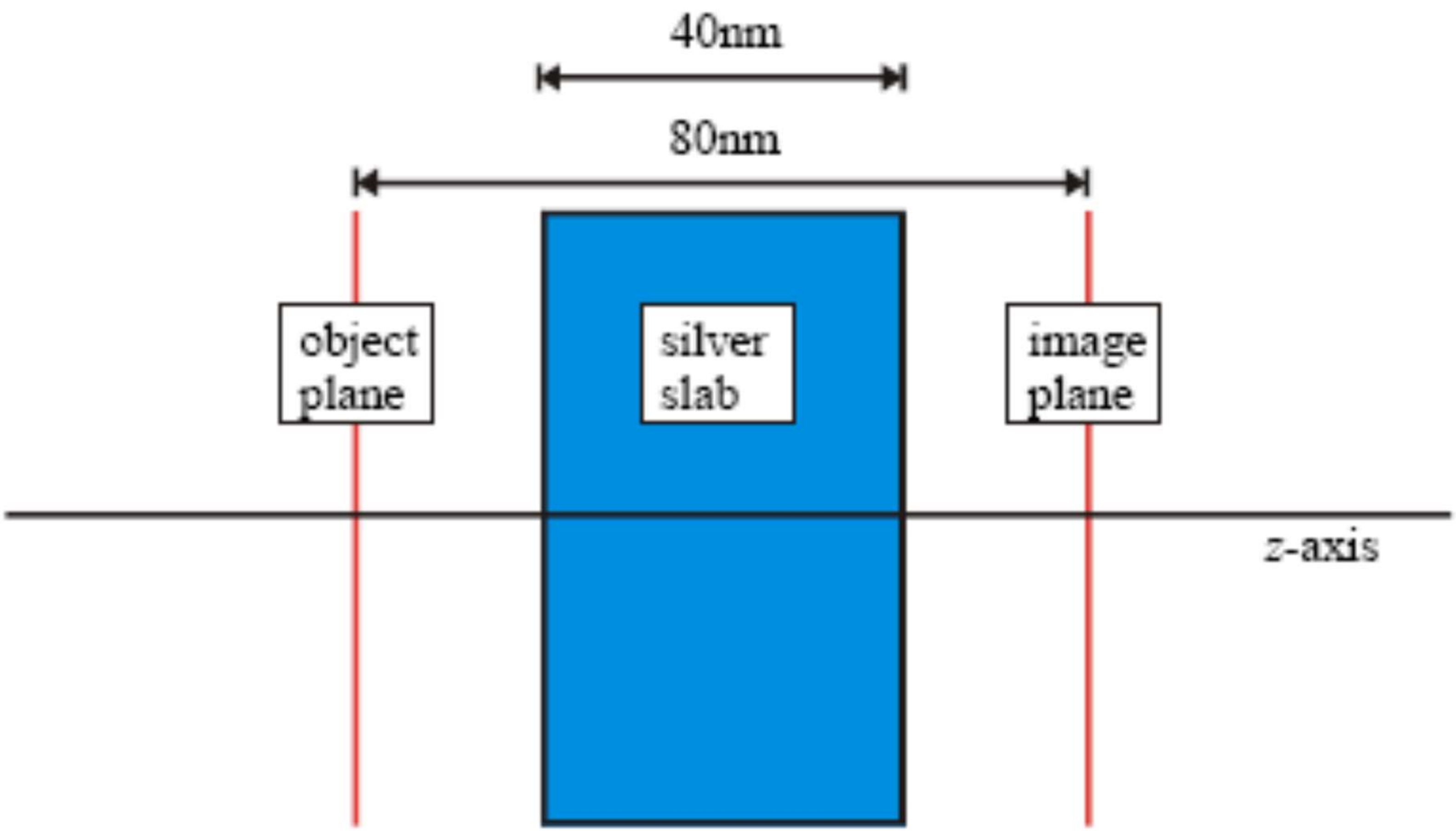

NORMAL:
POSITIVE
METAMATERIAL:
NEGATIVE
TRANSPARENT
MATERIAL
VIRTUAL IMAGE
REAL IMAGE

Flat Lenses

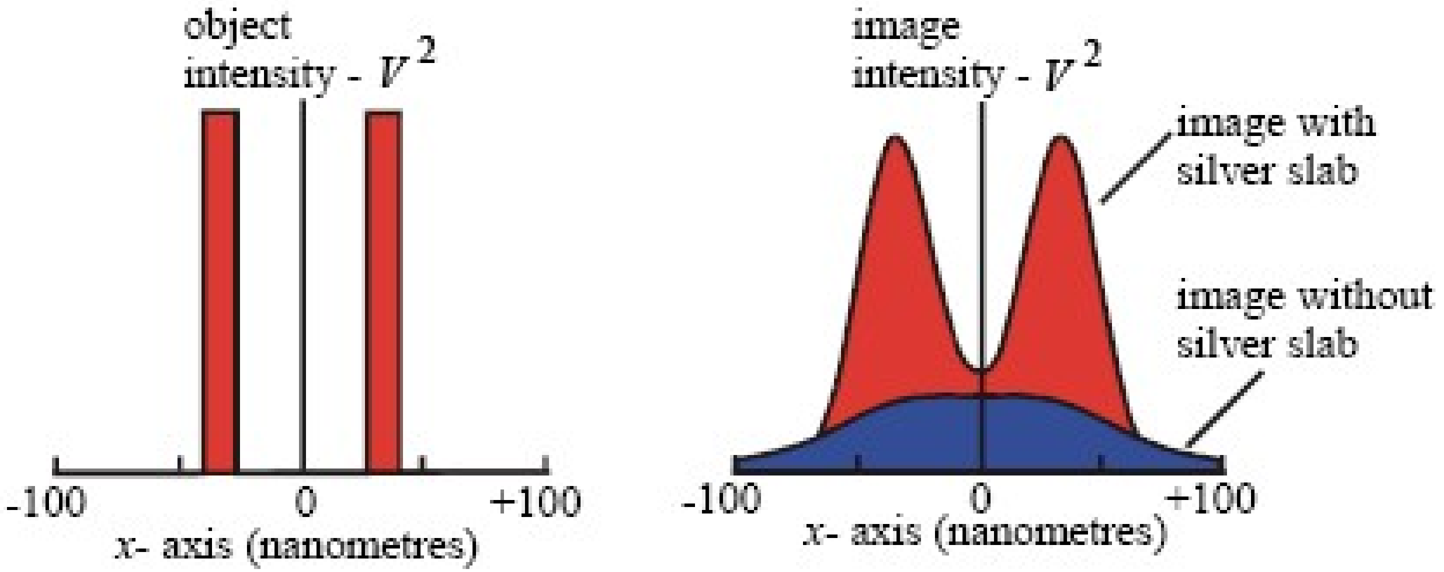




Flat lens with silver films

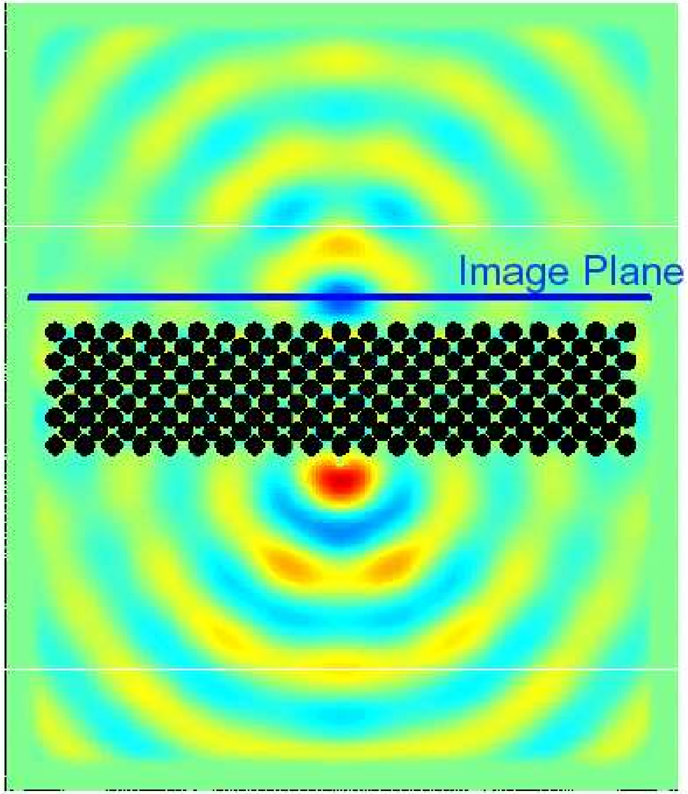


Super-resolution with silver slab



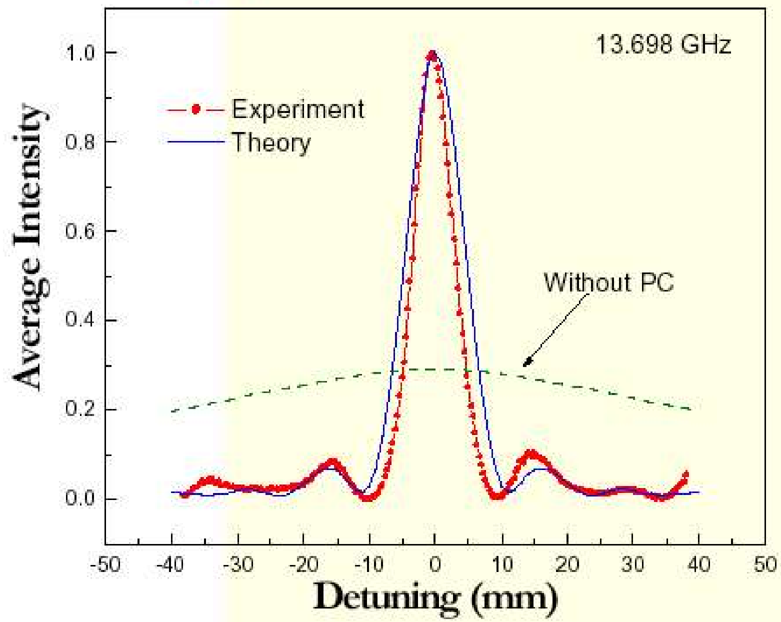
Losses limit the resolution in silver lenses

Photonic crystals



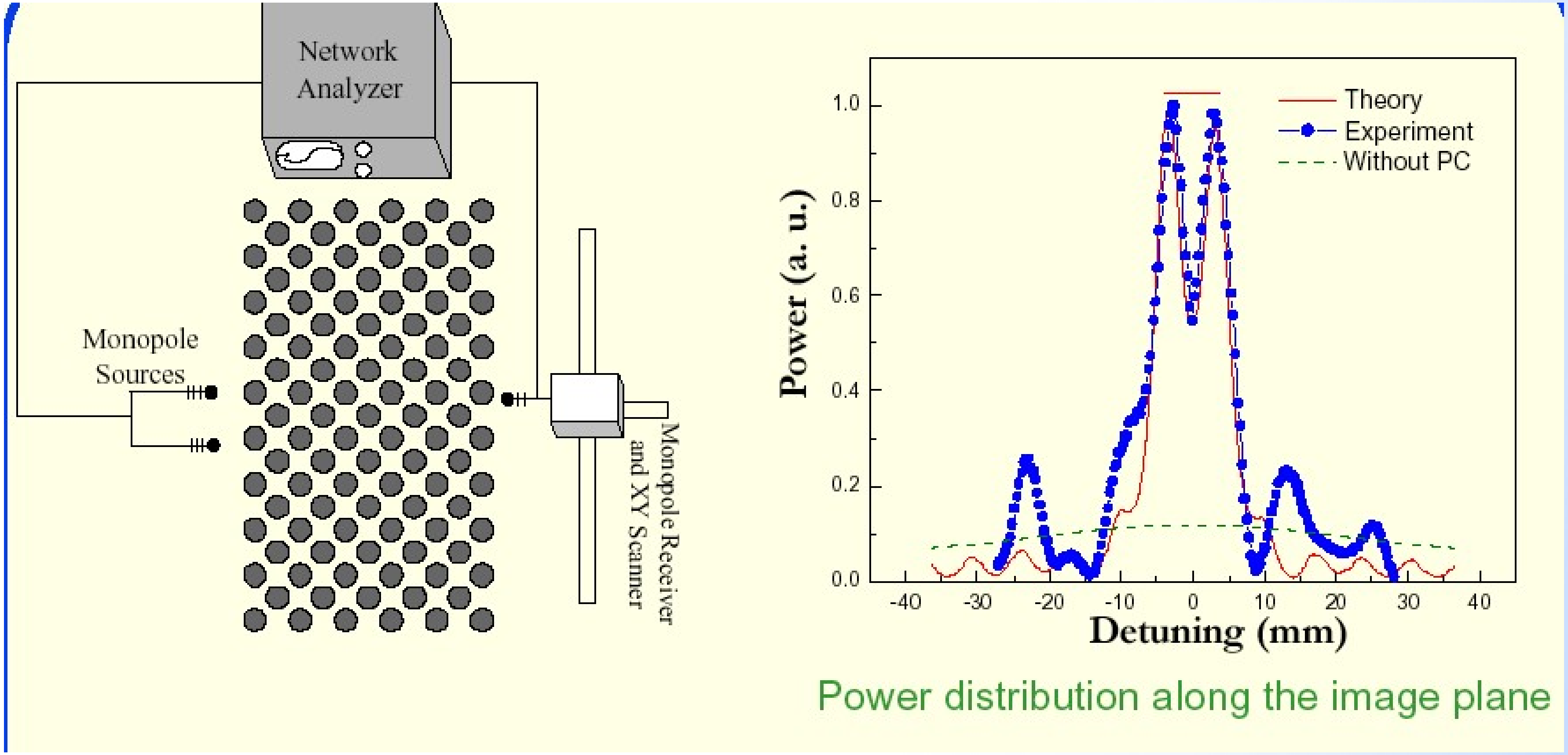
Electric field distribution after image formation

Time averaged intensity distribution along the image plane



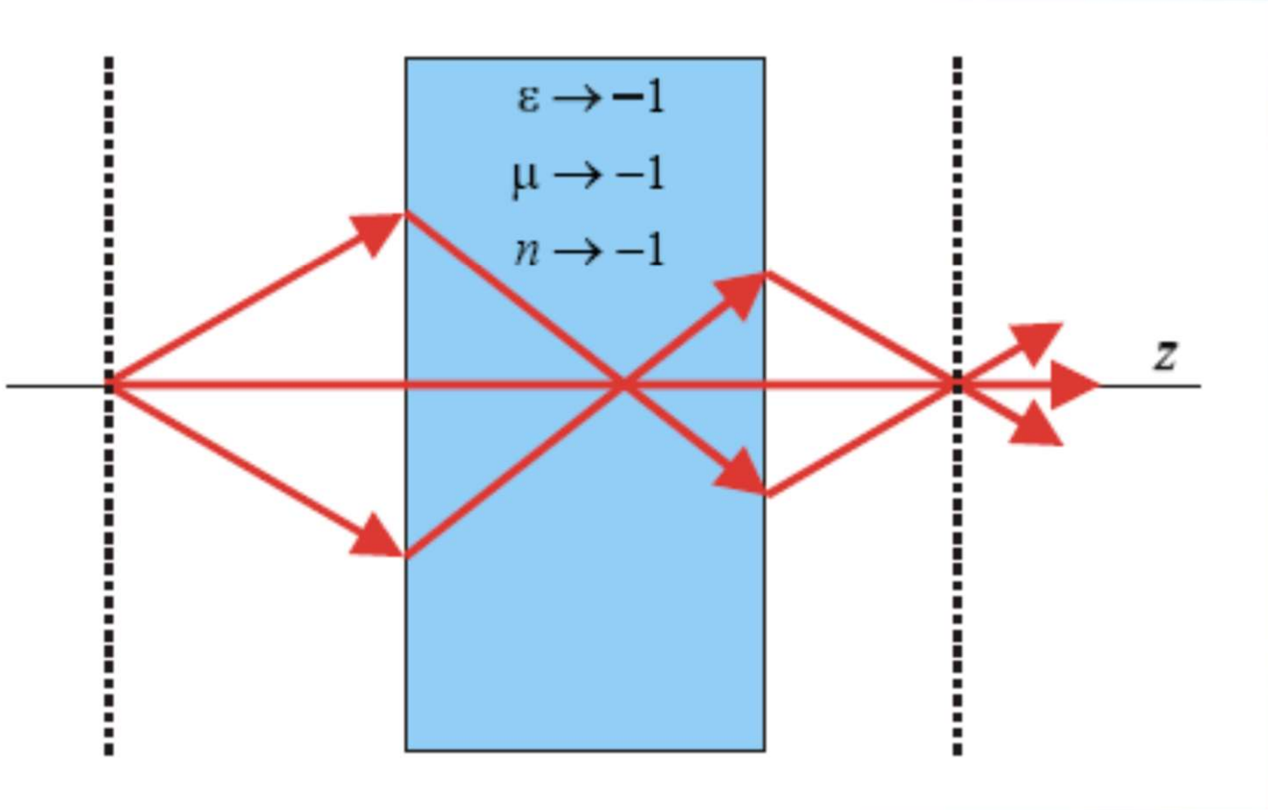
NOTE: Photonic crystals cannot be classified as metamaterials! Although the period and the unit cell size are comparable to the wavelength, the size of the meta-atoms are of the order of the wavelength as well. PhC cannot be considered as effective media, therefore they cannot be classified as metamaterials.

Super-resolution with photonic crystals



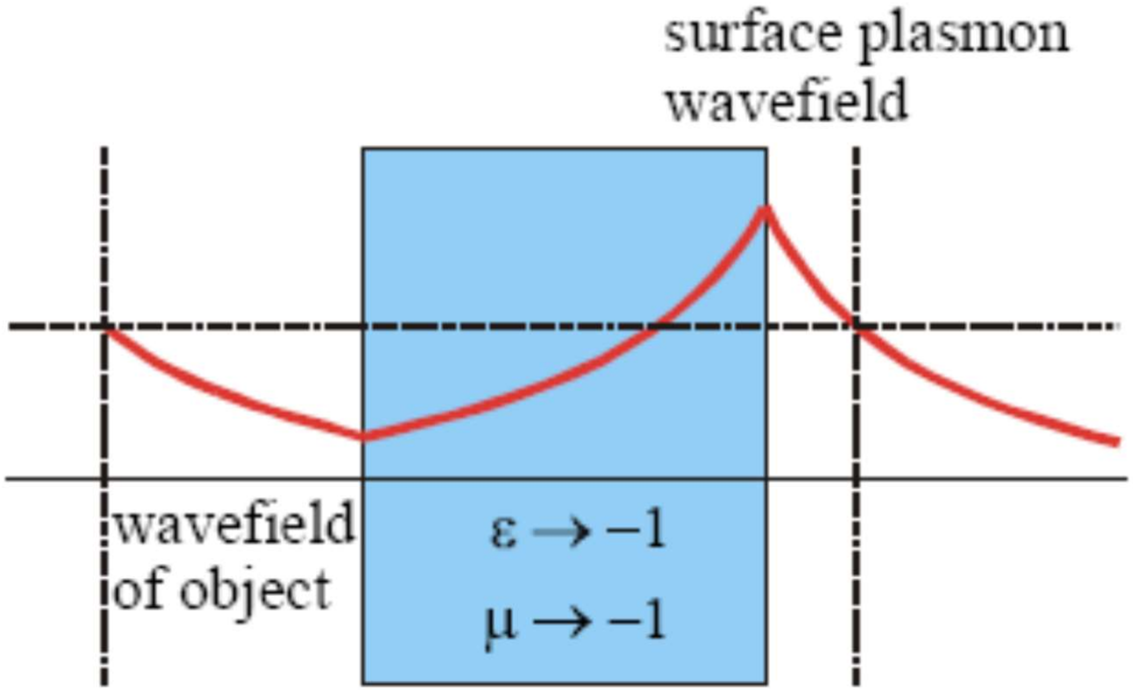
Separation between two sources is λ/3

Super-resolution with negative index slab



Negative Index Medium (NIM) must be impedance matched with the Positive Index Medium (PIM)

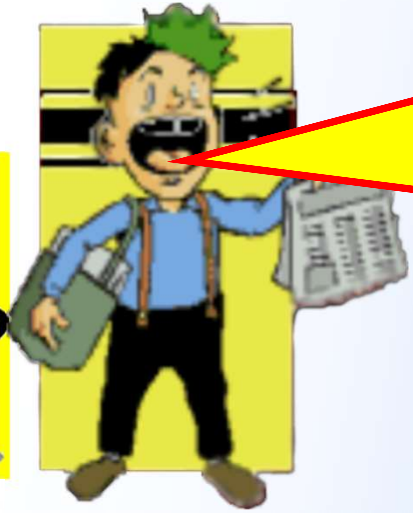
Super-resolution with negative index slab



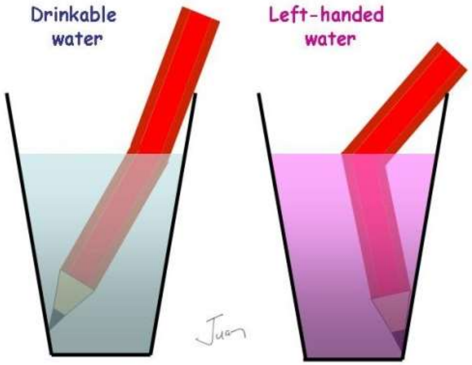
This lens works with the excitation of surface plasmons and is able to transfer the information of the near field that is commonly lost in conventional imaging

UNIVERSITY OF BRESCIA

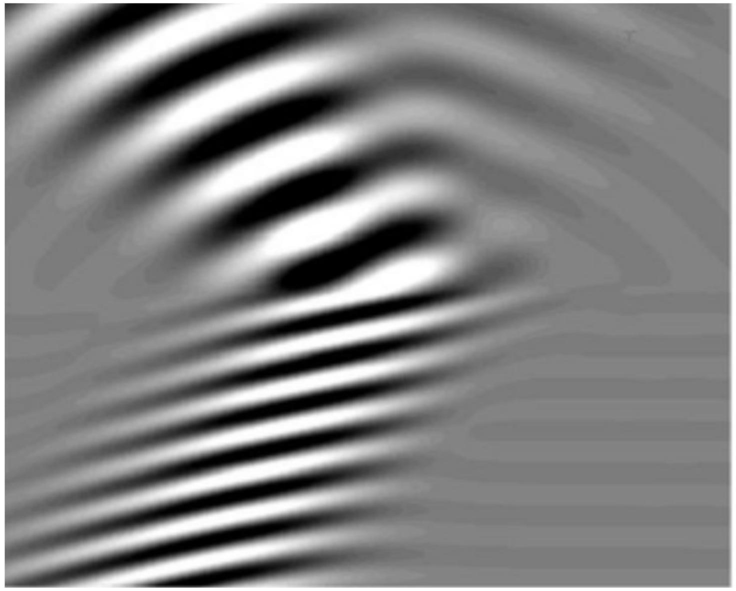
I don’t believe it! Light is bending the wrong way



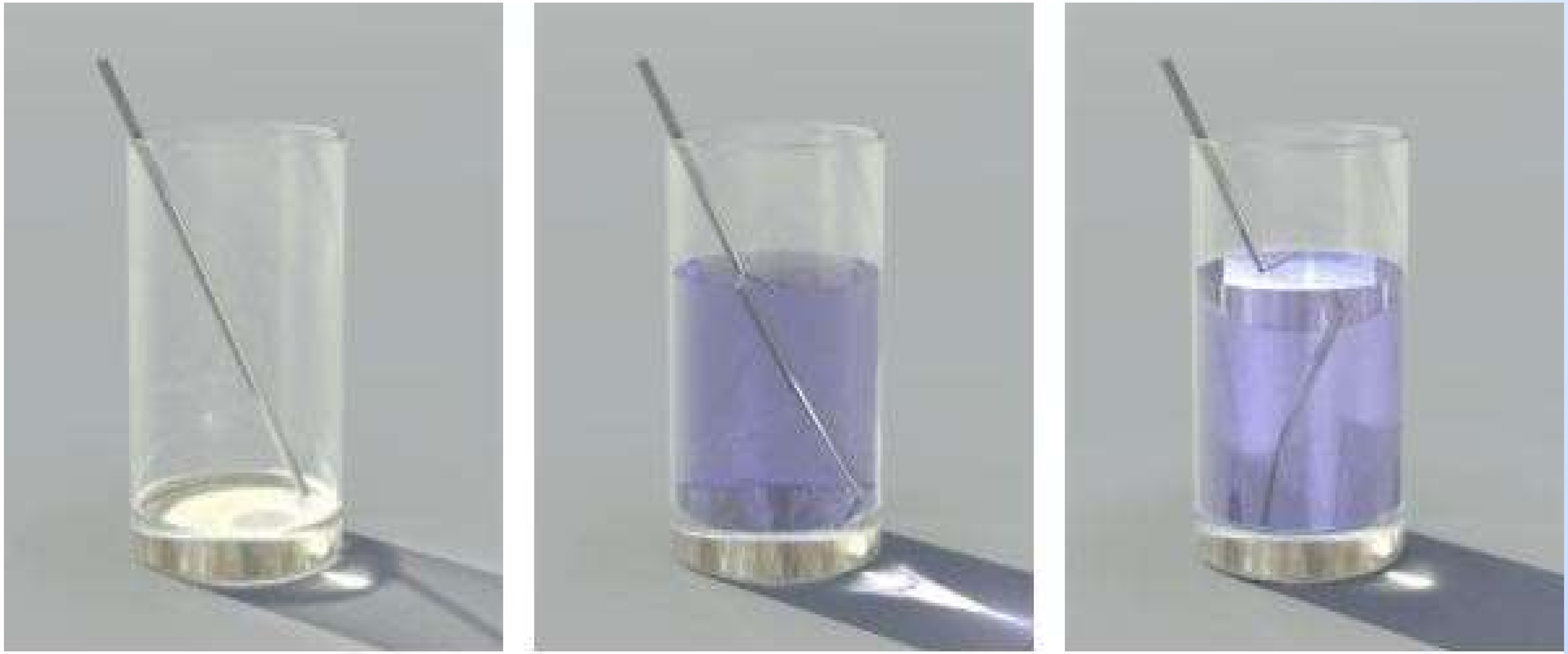
EXTRA, EXTRA!!! Are school text books wrong?!?



Inverted Snell’s law



Negative Refraction


(a) (b) (c)

- (a) Calculated ray-tracing image of a metal rod in an empty glass.
- (b) The glass is filled with normal water, (n=1.2) → ordinary refraction.
- (c) The water is replaced by "water" with a fictitious refractive index of n=-1.2 .

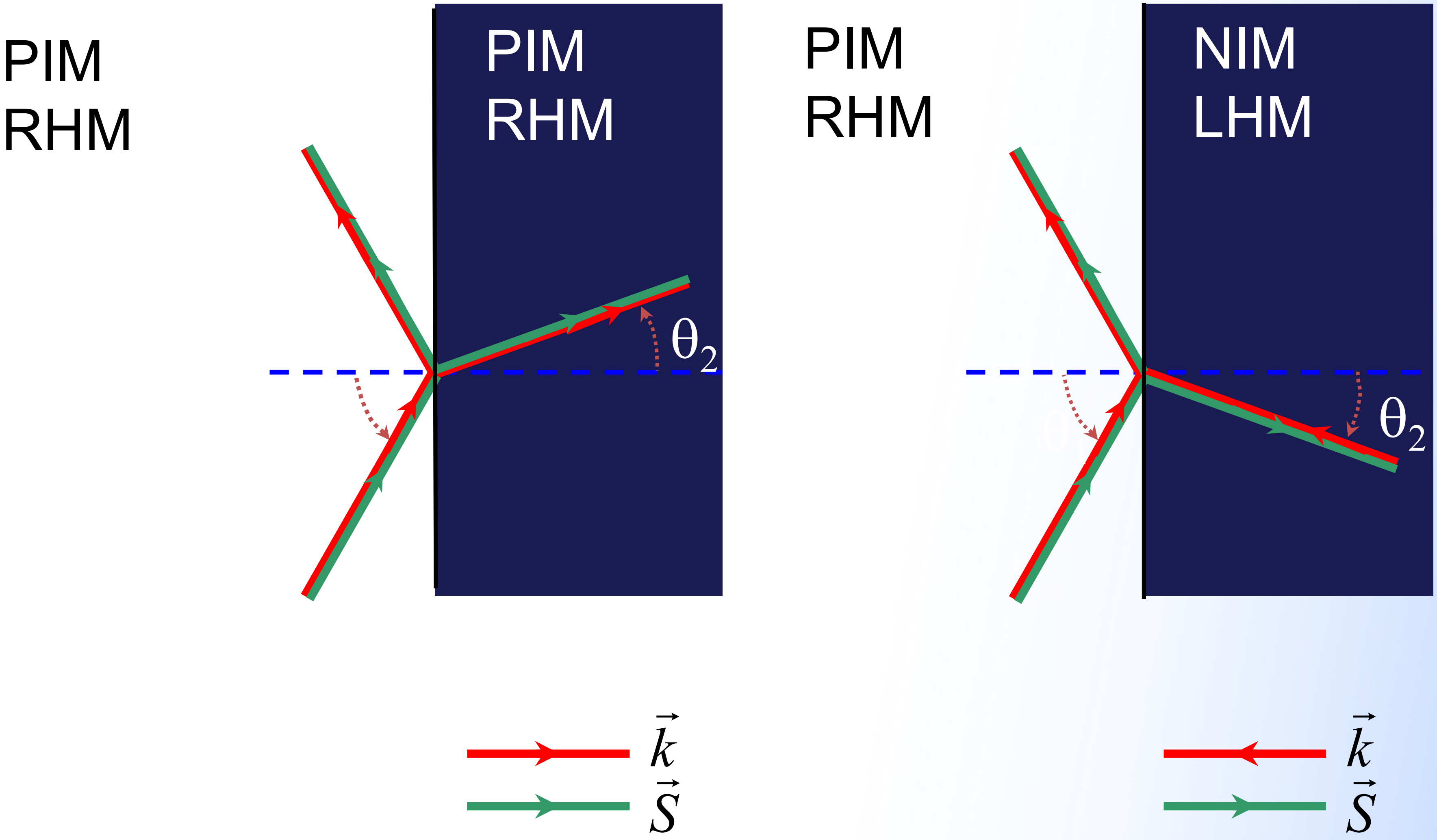
UNIVERSITY
OF BRESCIA

Negative index material properties

Reversal of Snell's law

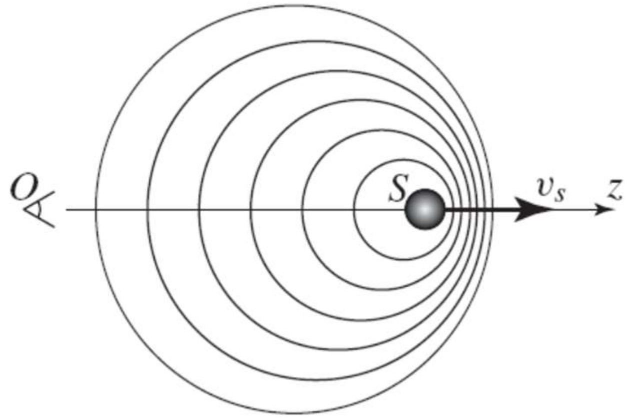
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\boxed{n_2 < 0 \Rightarrow \theta_2 < 0}$$

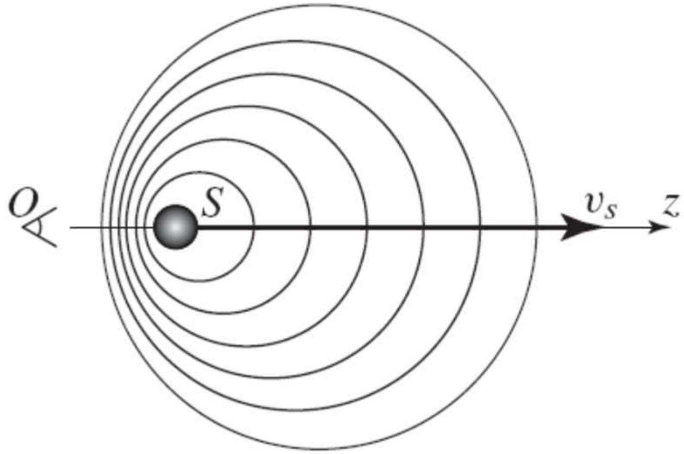


Reversal of Doppler effects

- Doppler effect in RH media



- Doppler effect in LH media



UNIVERSITY OF BRESCIA

Dispersion in negative index media

Group Velocity sign depends on the material:

$$v_g = \frac{\partial \omega}{\partial k};$$

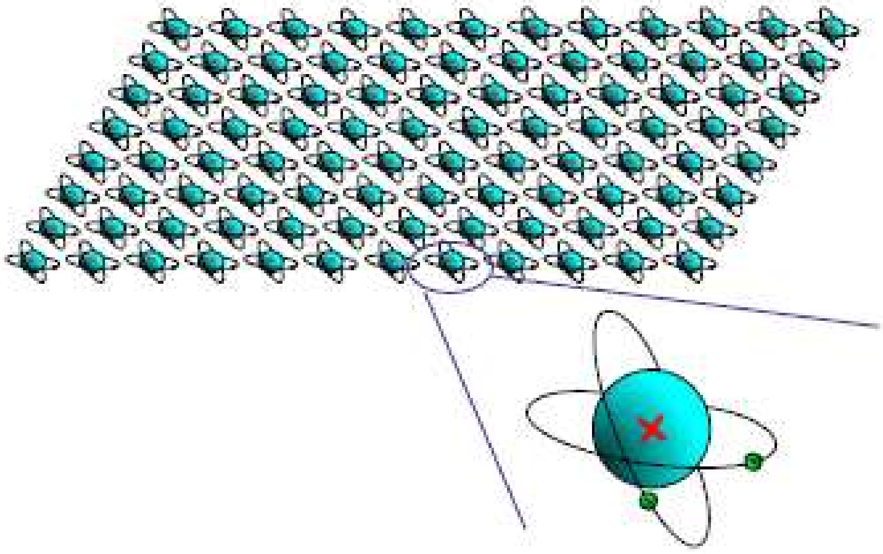
Negative phase Velocity:

$$\boxed{v_p = \frac{\omega}{k} < 0}$$

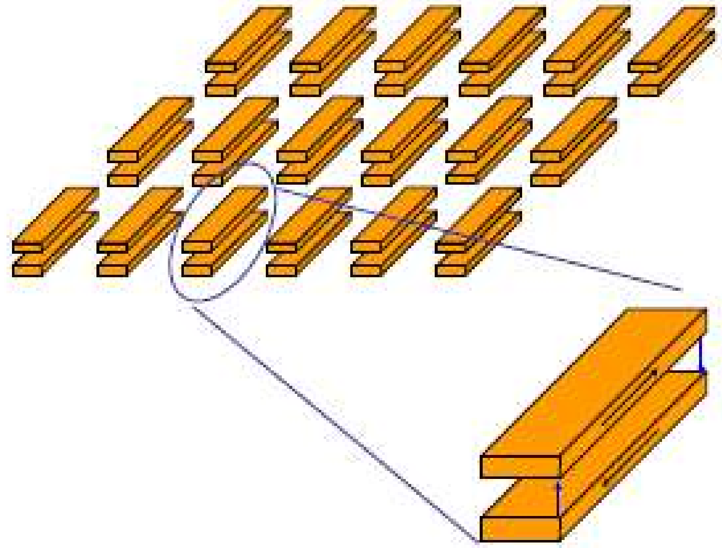
UNIVERSITY OF BRESCIA

How to make metamaterials

A Metamaterial is an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties. ---Metamorphose



A natural material with its atoms

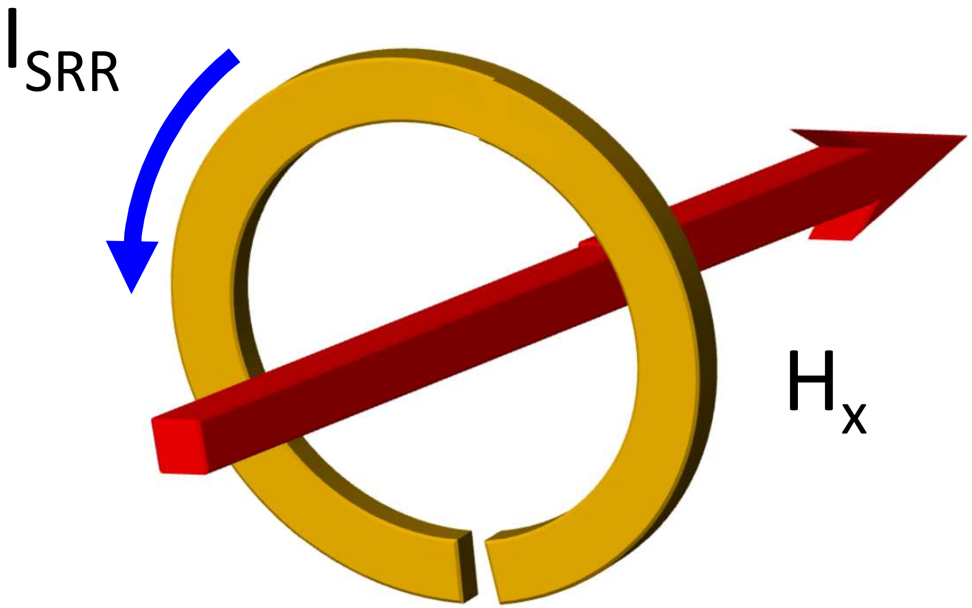


A metamaterial with artificially structured "atoms"

UNIVERSITY OF BRESCIA

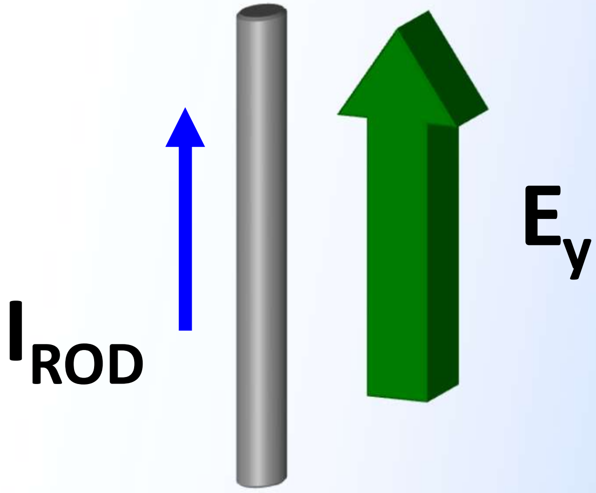
How to make metamaterials

Embedding a metal split-ring and a metal rod creates left-handedness



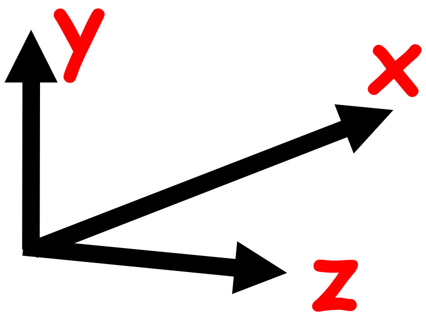
Magnetic resonance

(Negative μ)



Electric resonance

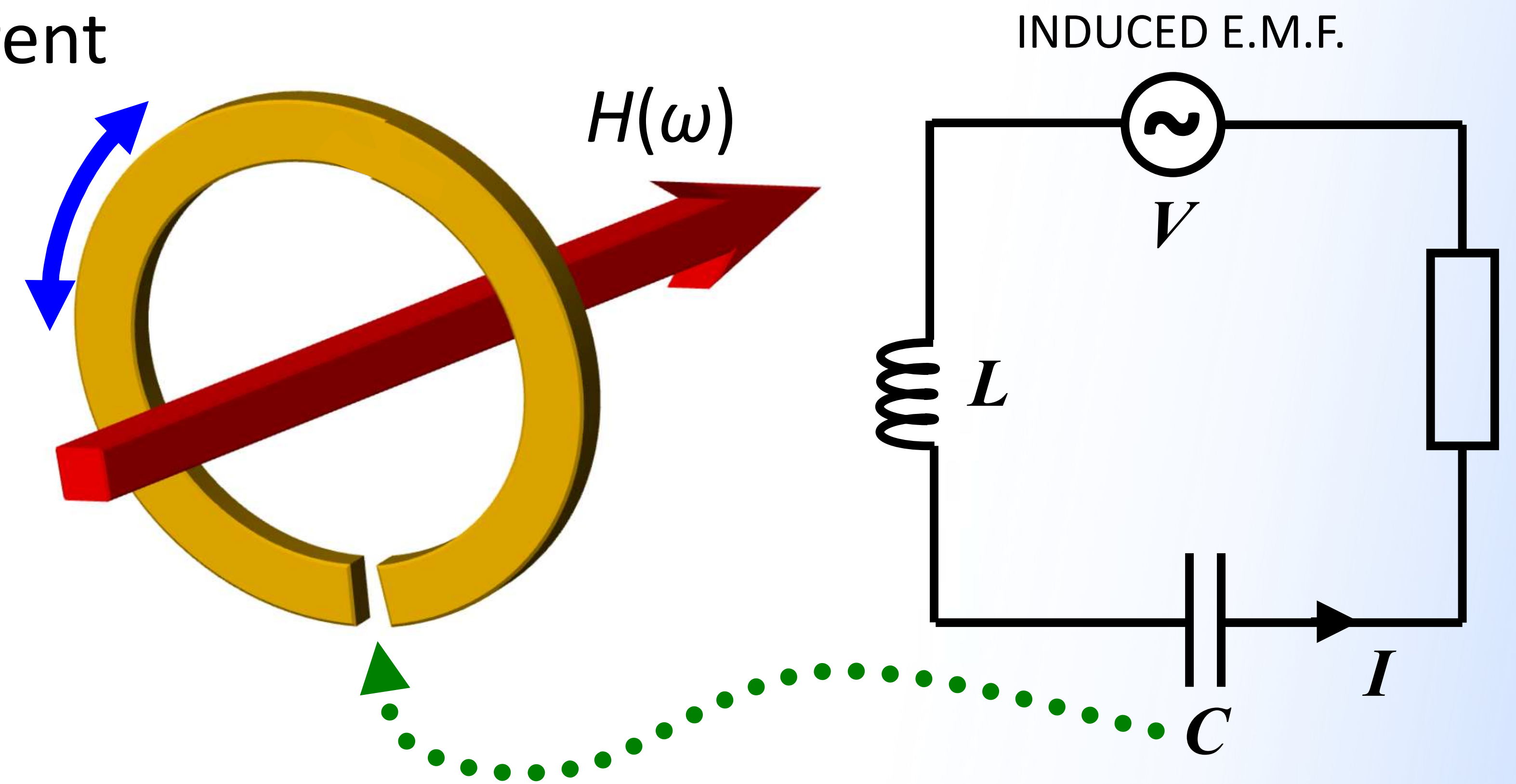
(Negative ε)



How to make a metamaterial

Split-Ring is an LCR Circuit

AC current

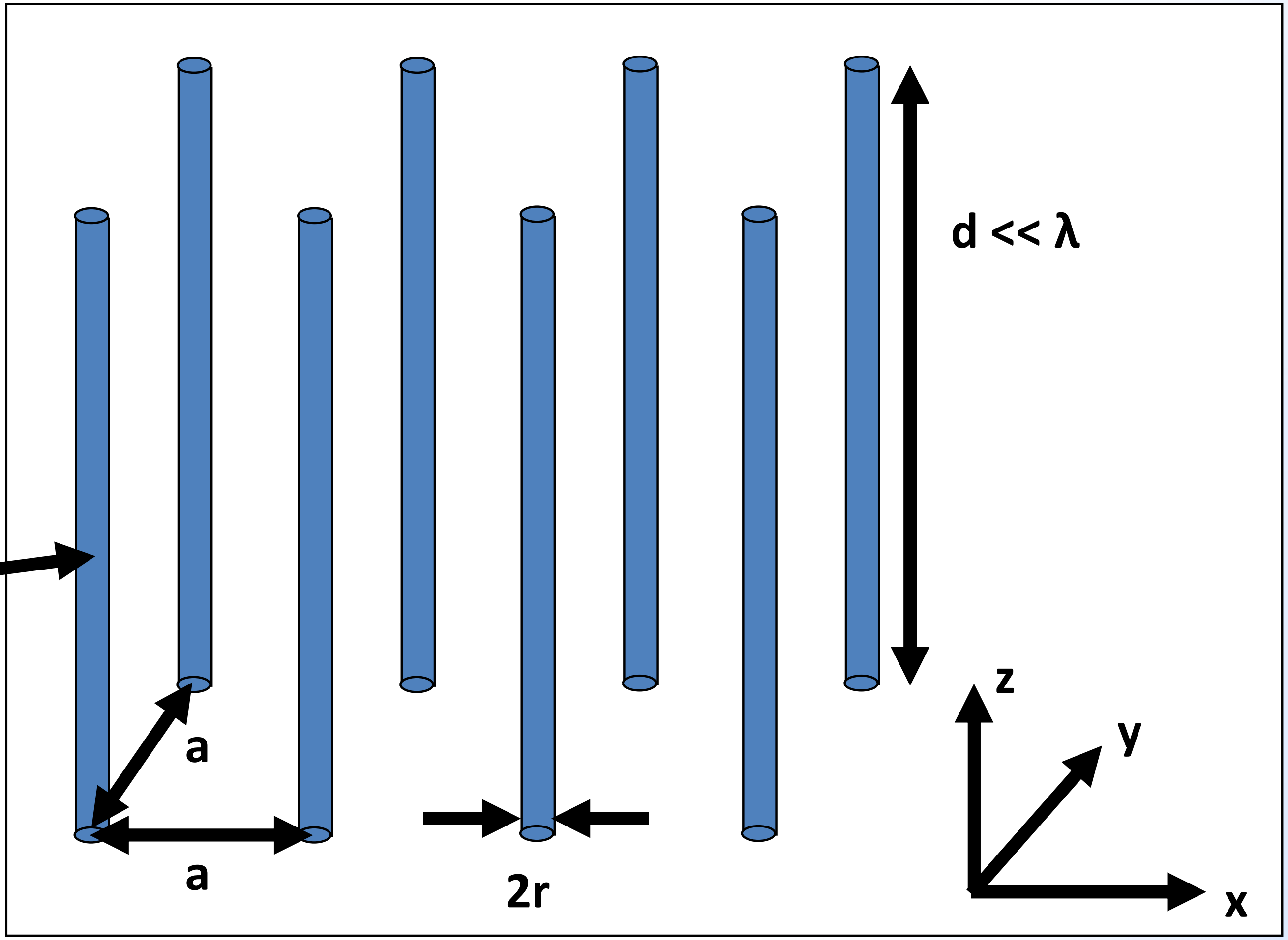


$$V = L\frac{dI}{dt} + IR + \frac{Q}{C} \rightarrow \mu(\omega)$$

How to make a metamaterial

Short Wires Lead To ε(ω)

Conducting Wire



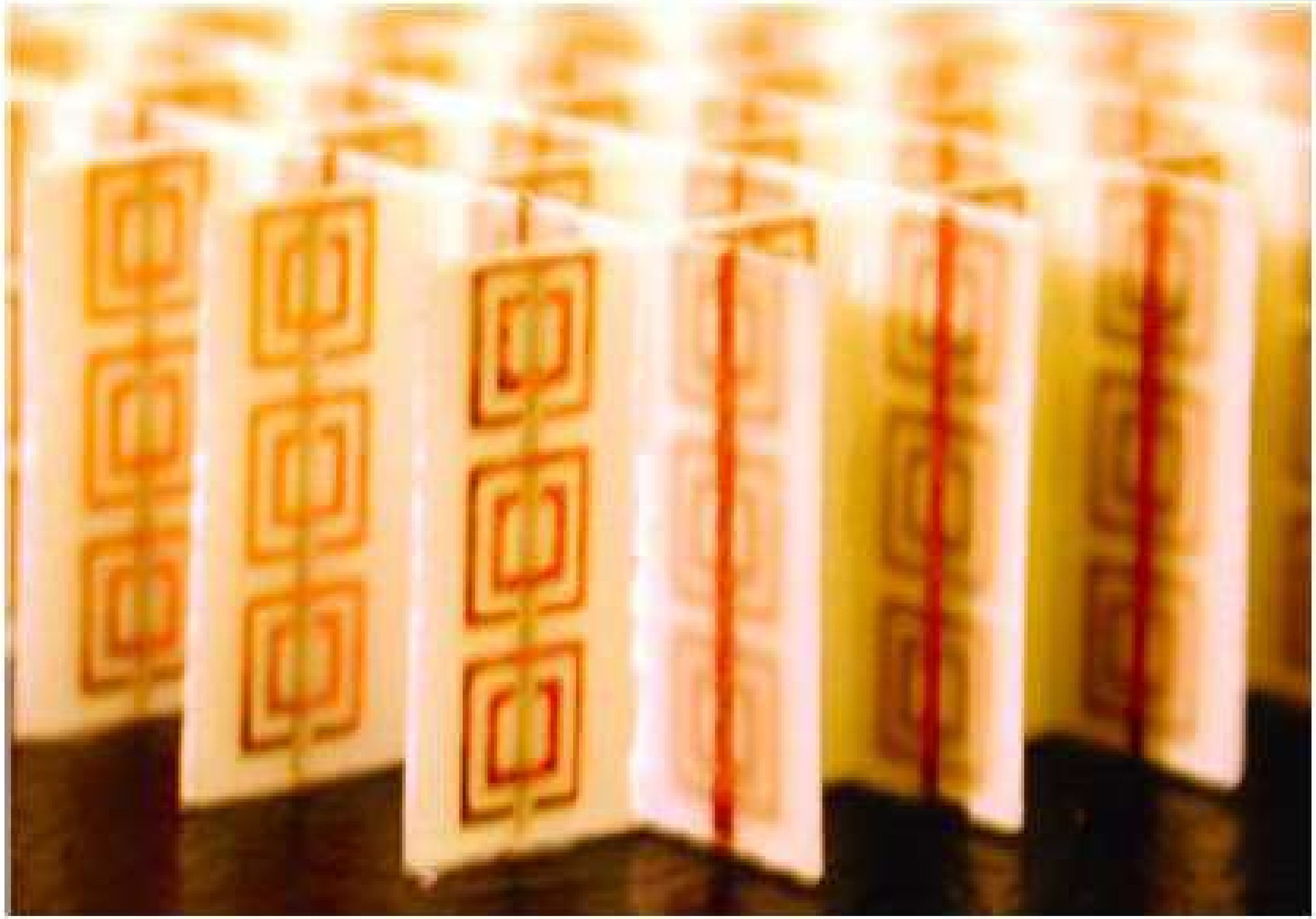
Infinite Periodic array of conducting wires

UNIVERSITY OF BRESCIA

Experimental Realizations

GHz range

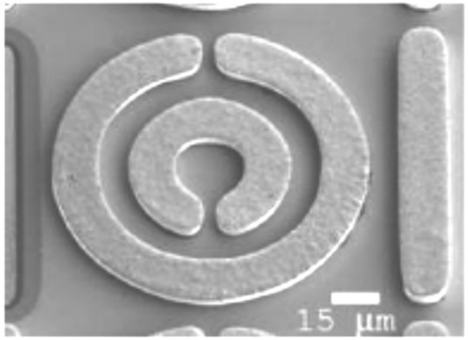
First experimental realization



Smith et al: Phys. Rev. Lett. 84, 4184 (2000)

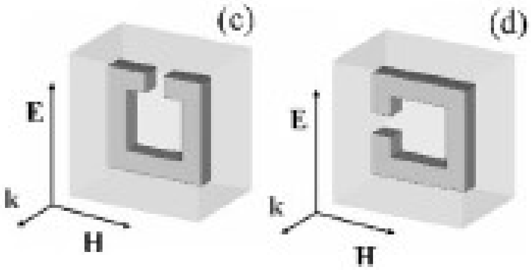
Experimental Realizations

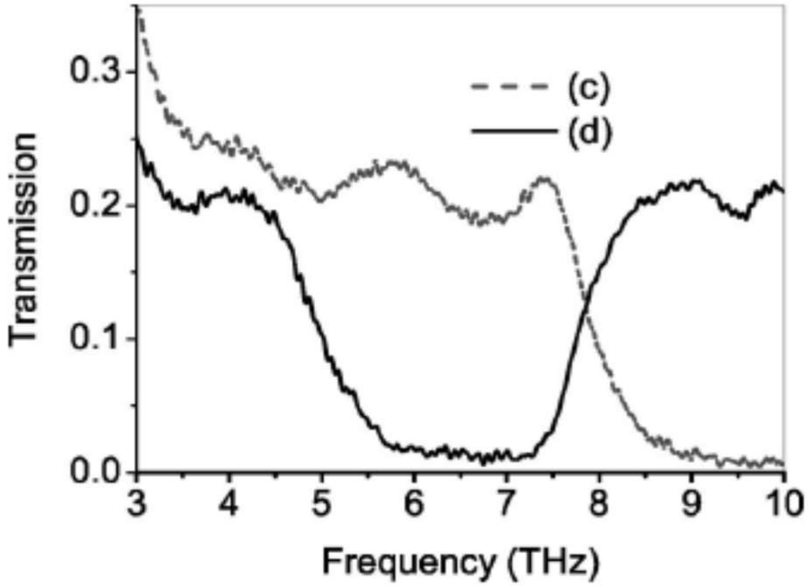
1–2.7 THz



*Moser et al. PRL **90** 063901 (2005)*

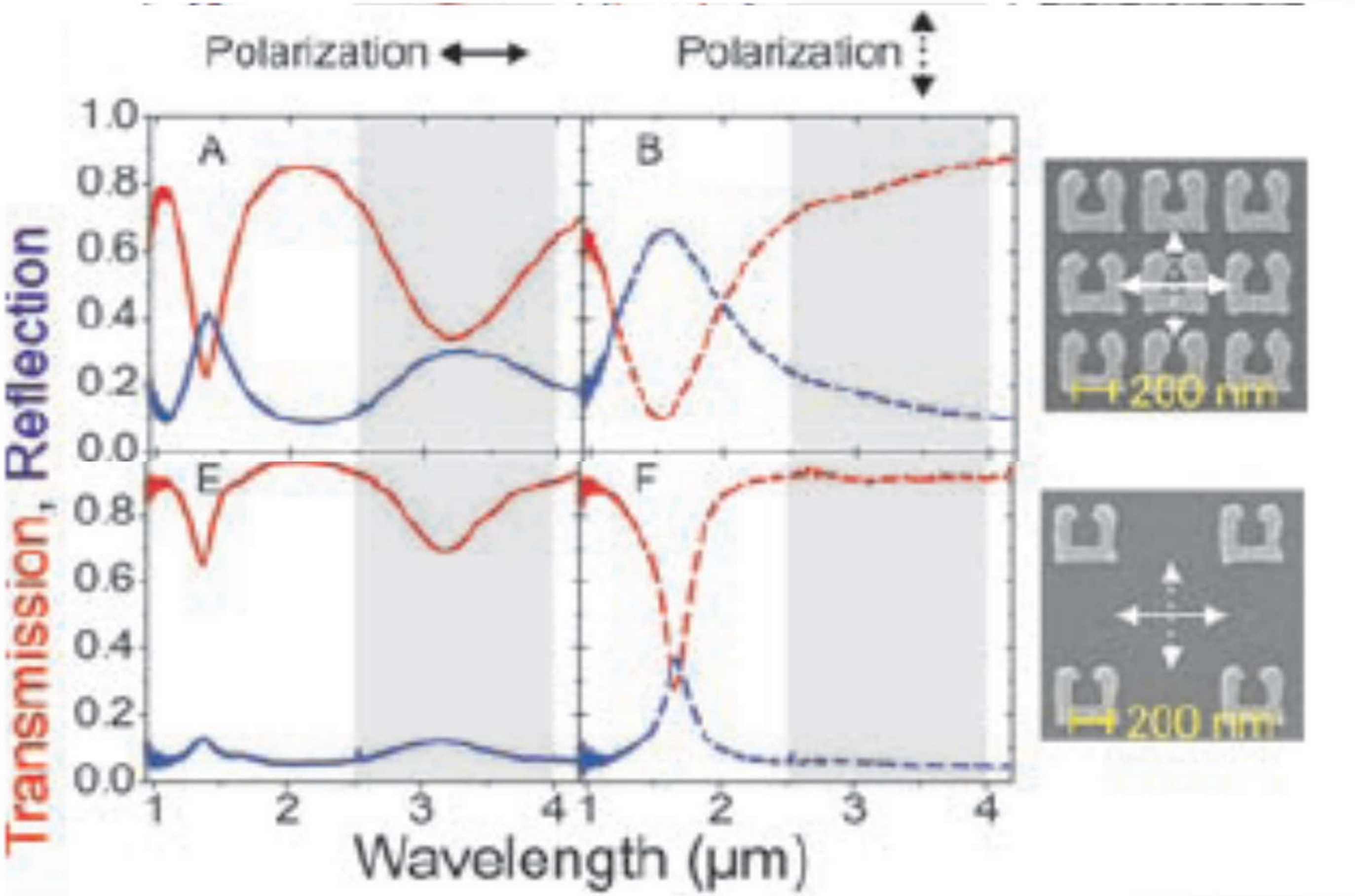
6 THz





*Katsarakis et al. Opt Lett **30**(11) 1348 (2005)*

Experimental Realizations

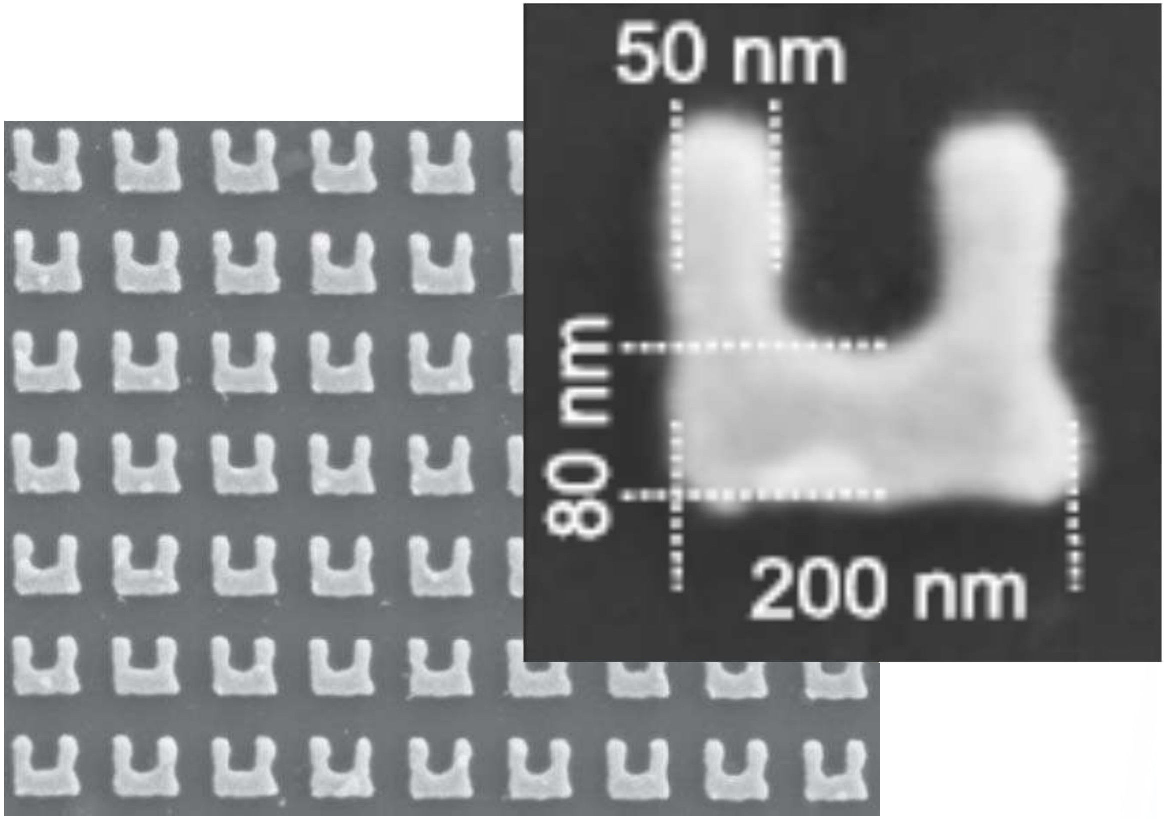


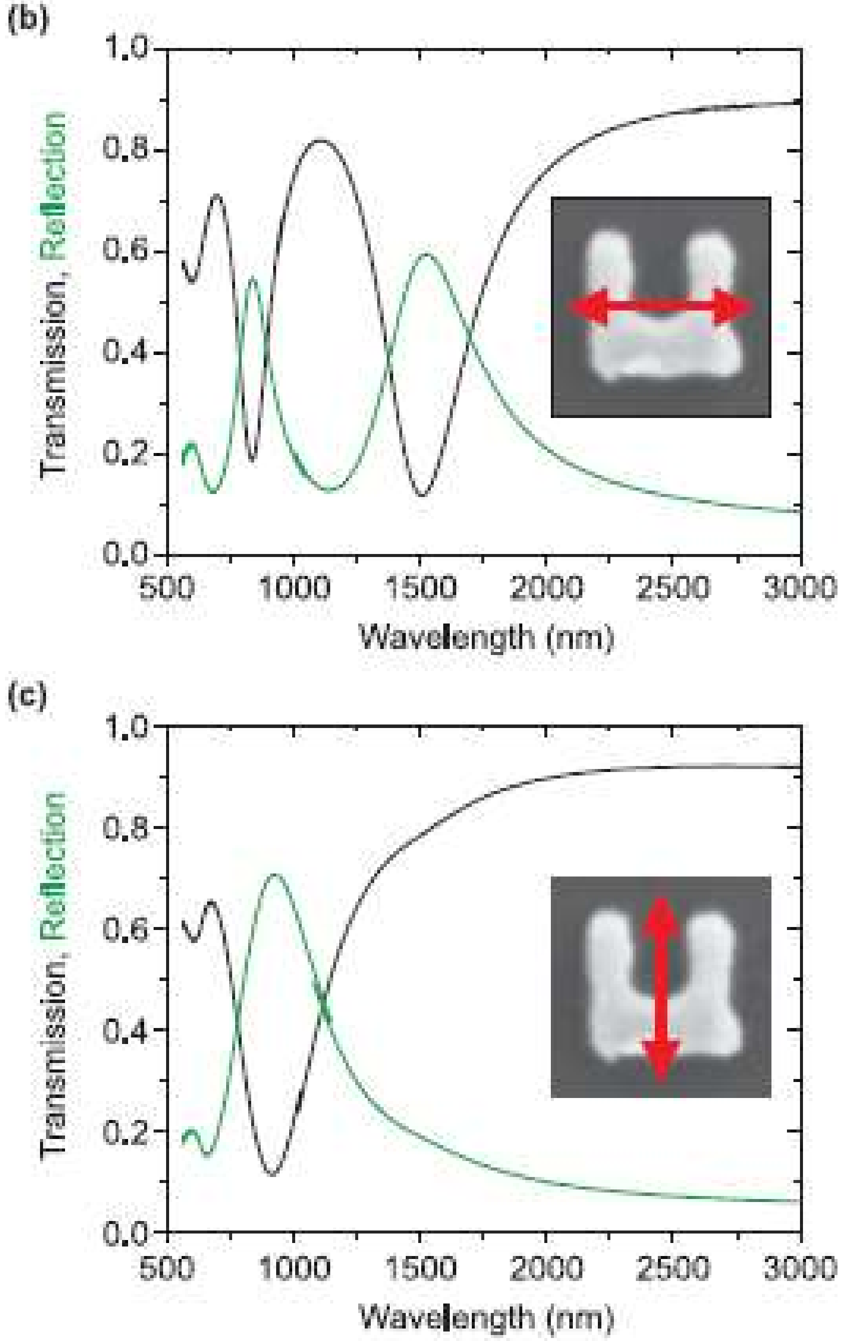
100 THz

Linden et al. SCIENCE ***306*** *1351 (2004)*

Experimental Realizations

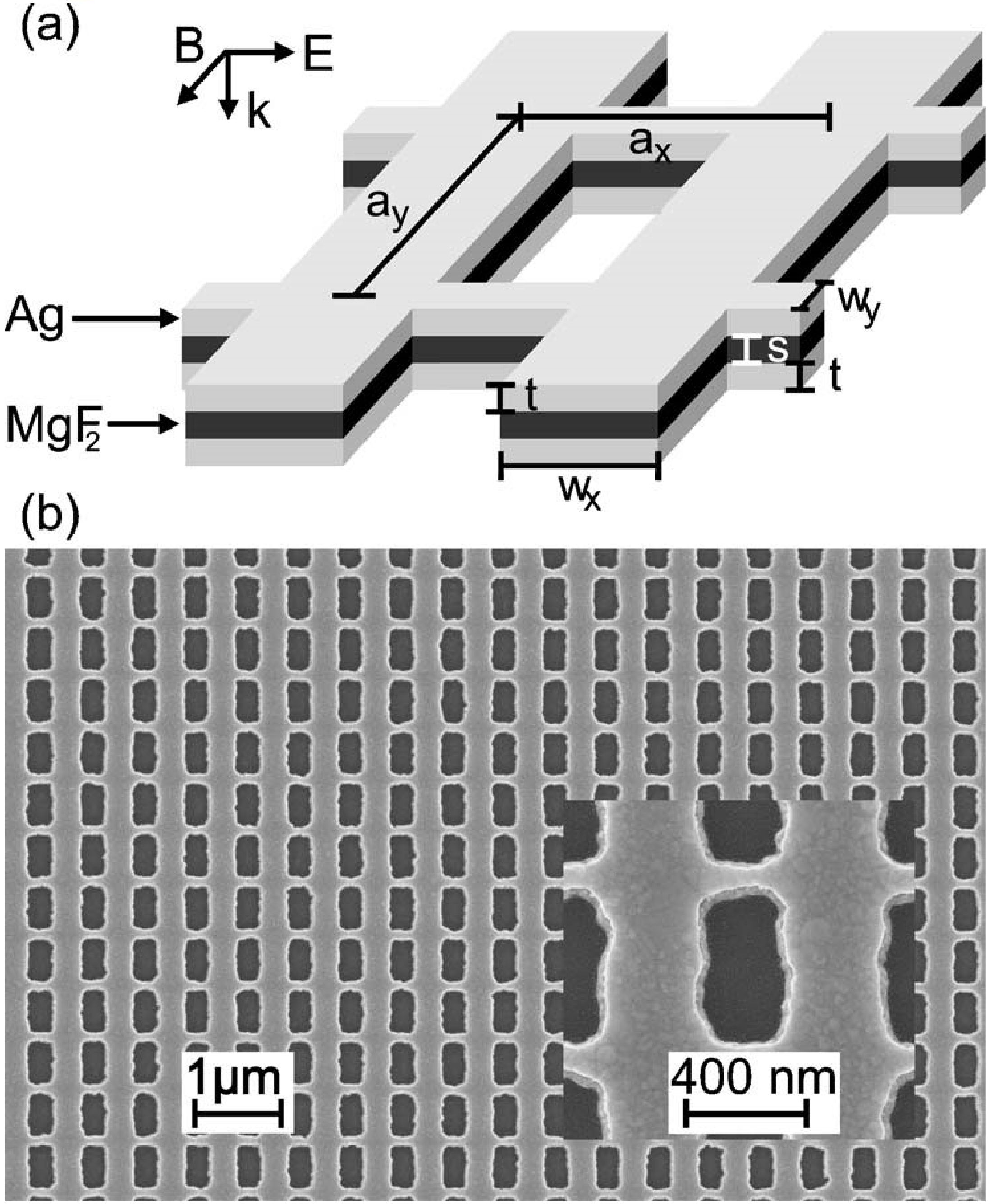
Magnetic resonances at
1.5 µm and 800 nm



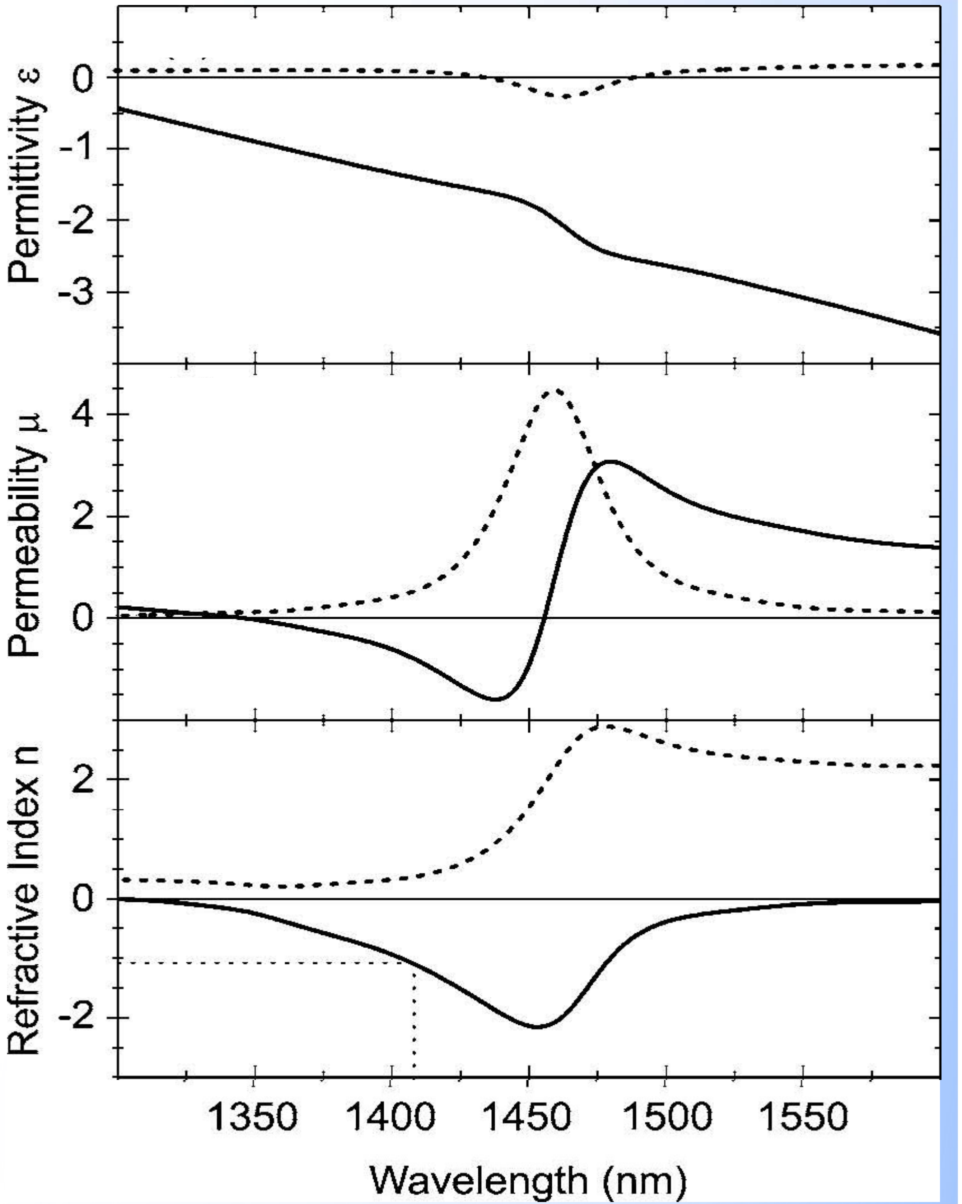


*C. Enkrich et al., Phys. Rev. Lett. **95**, 203901 (2005)*

Experimental Realizations

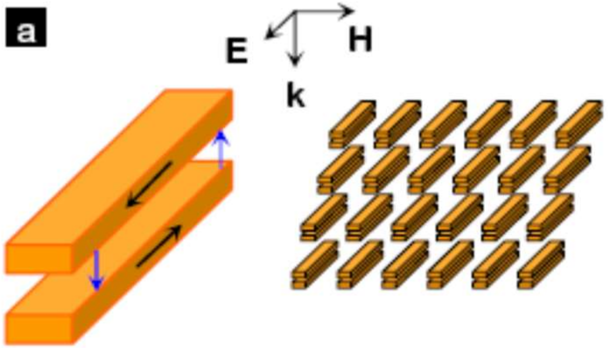


Operates at 1.5 μm



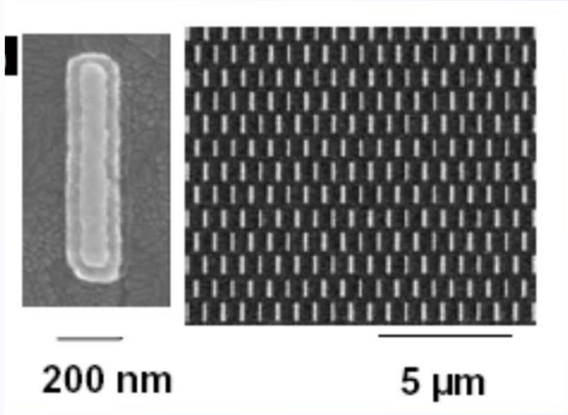
Dolling et al. Opt. Lett. ***31*** *1800 (2006)*

Experimental Realizations

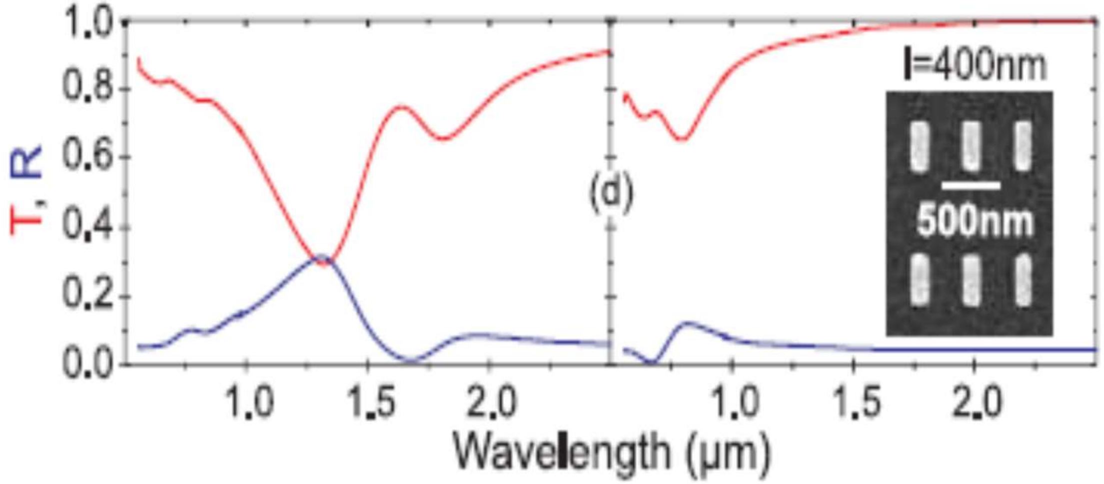


Re(n) = -0.3

λ = 1.5 µm



V. M. Shalaev et al., Opt. Lett. 30, 3356-3358 (2005)

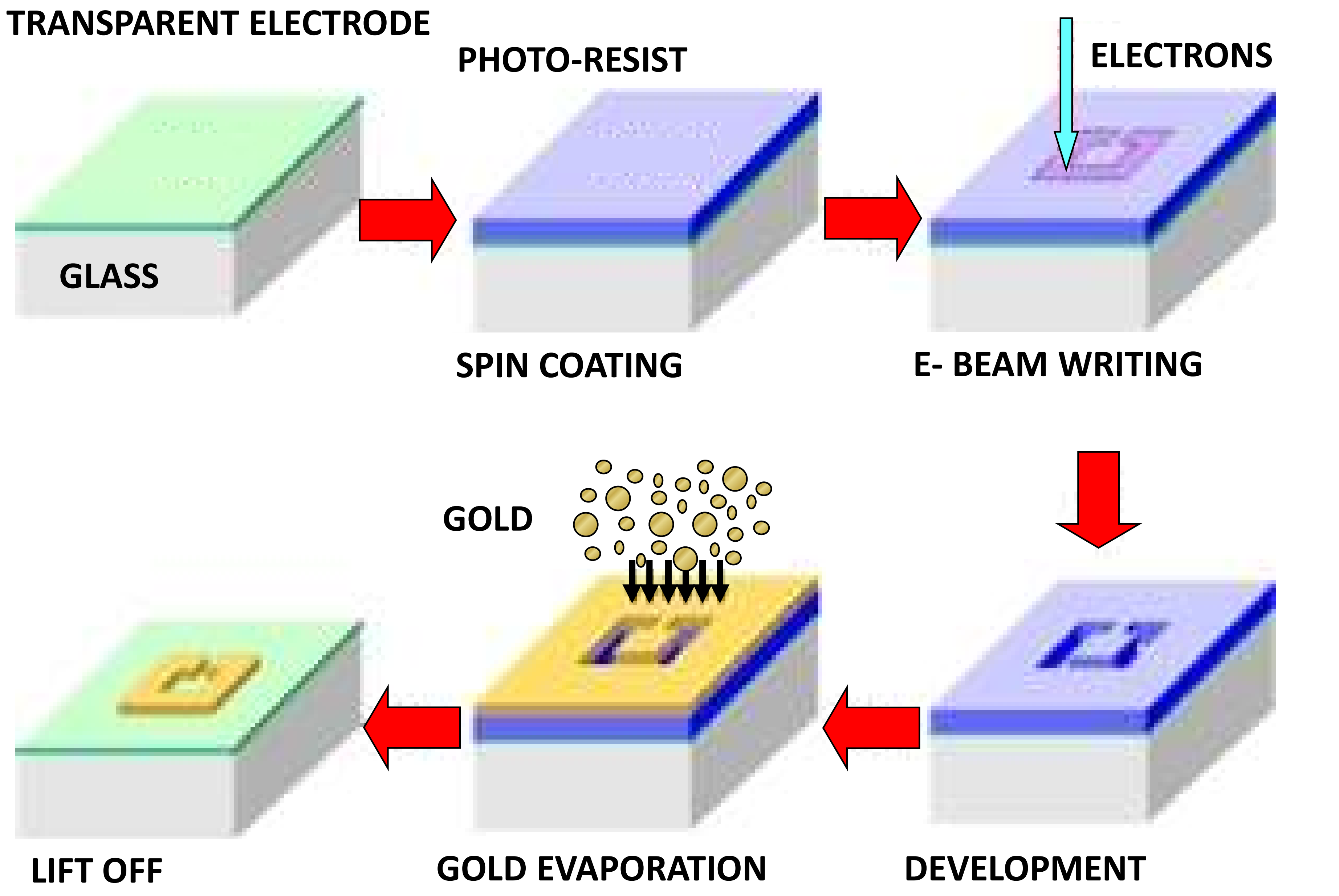


1.3 µm

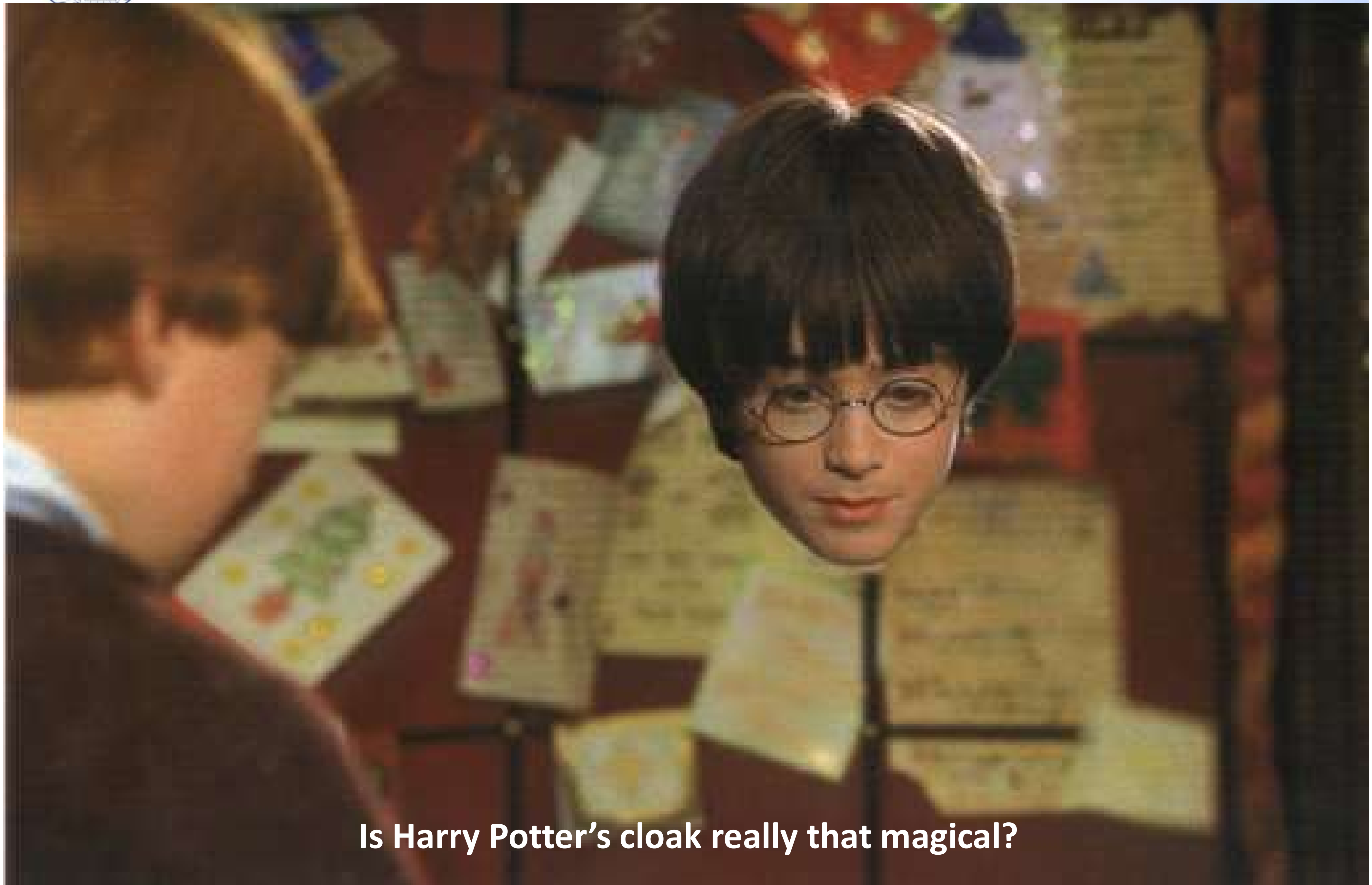
Negative permeability

G. Dolling et al., Opt. Lett. 30, 3198-3200 (2005)

Fabrication process



The quest for invisibility



Invisibility in Nature

Chameleon Camouflage

Invisibility to Radars

Stealth fighter

Very small radar cross section: shape and absorbing paint

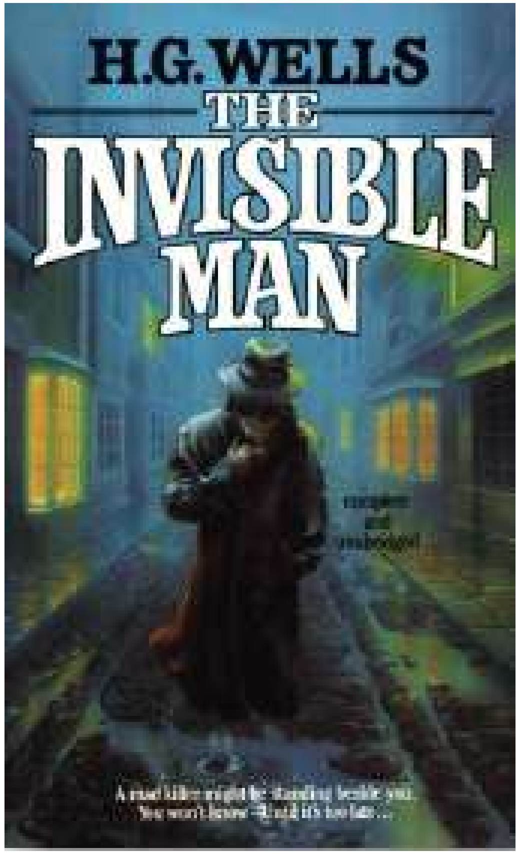
Invisibility in Hollywood

Fantastic 4:
The Invisible Woman
Lee and Kirby (1961)

"... she achieves these feats by bending all wavelengths of light in the vicinity around herself ... without causing any visible distortion." -- Introduction from Wikipedia

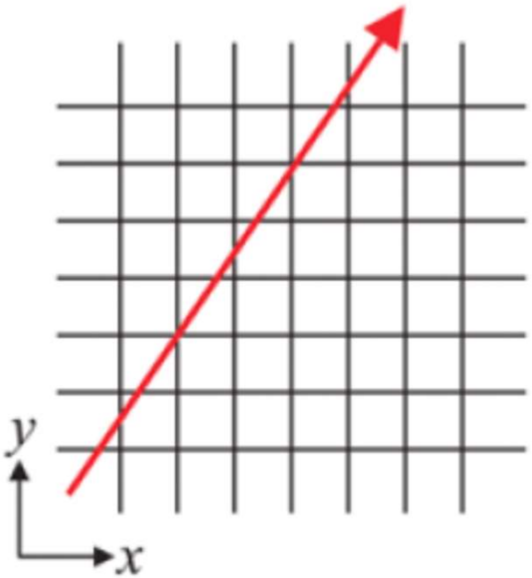
Invisibility in Hollywood

The Invisible Man
H.G. Wells (1897)



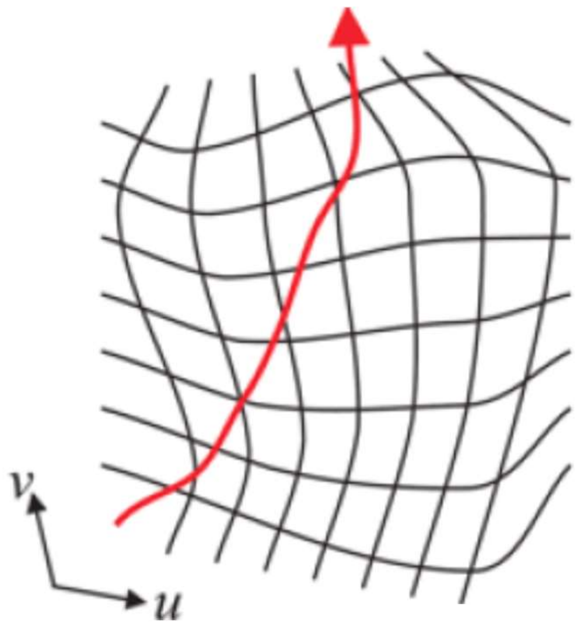
"... it was an idea ... to lower the refractive index of a substance, solid or liquid, to that of air — so far as all practical purposes are concerned.” -- Chapter 19 "Certain First Principles"

Transformation of Maxwell’s equations



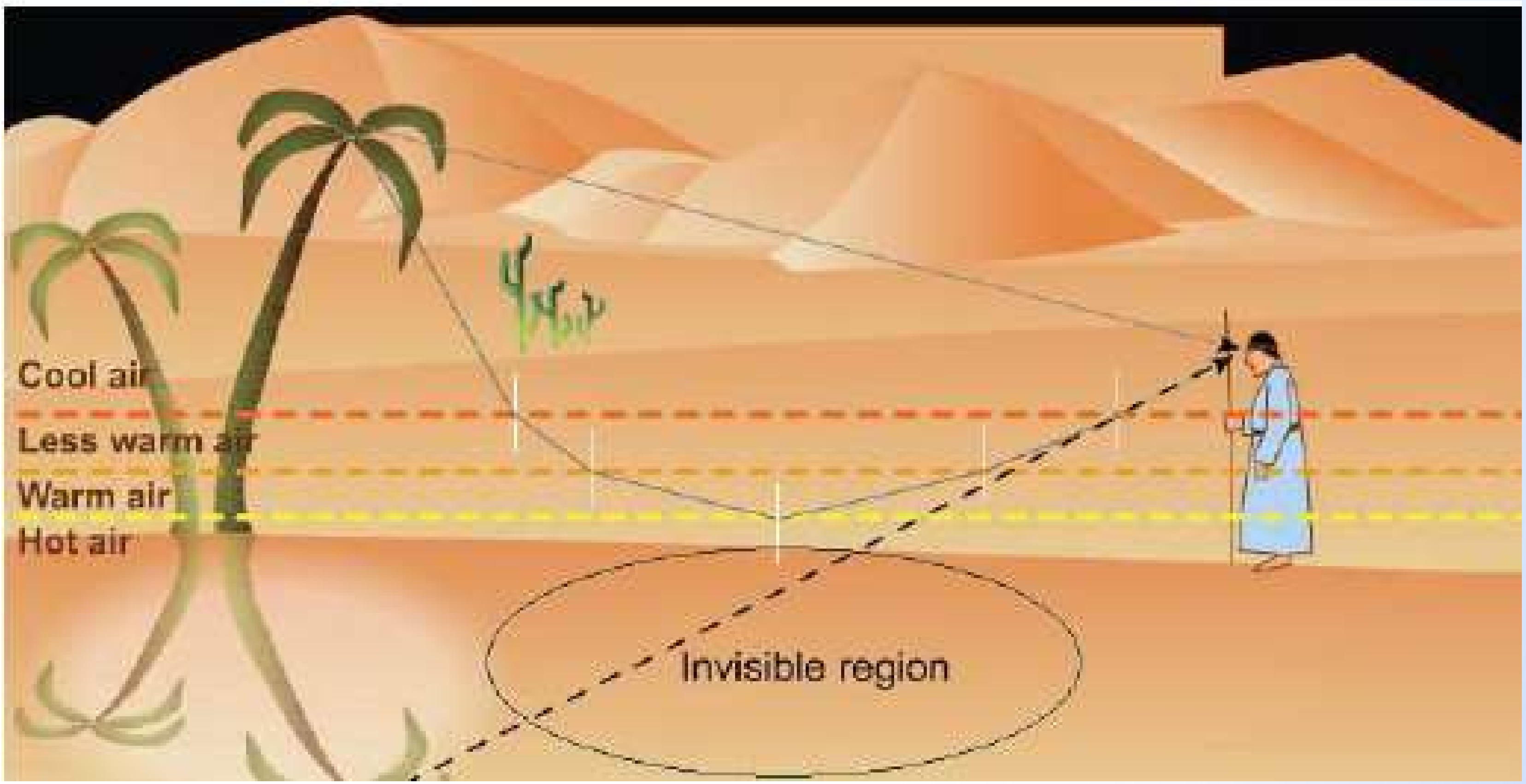
Straight field line in Cartesian coordinates

Cloaking can be realized by properly designing ε and μ tensors in the space to achieve the desired distortion and avoid a particular region in space.



Distorted field line in distorted coordinates

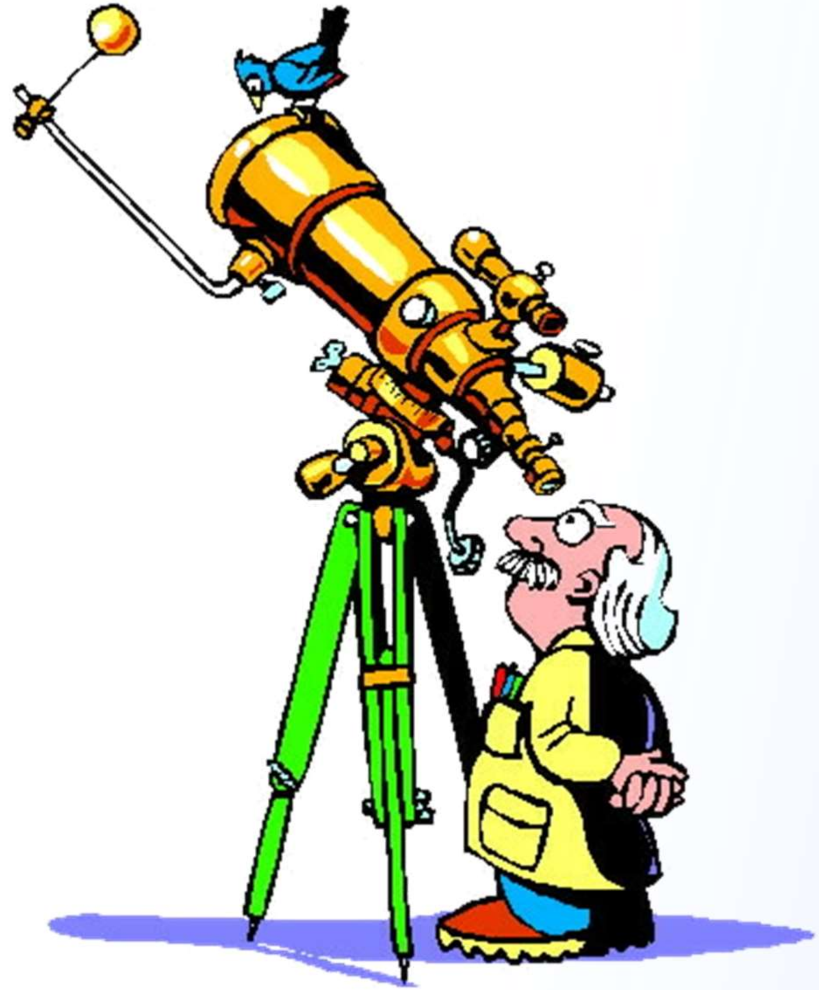
Example



The bending of light due to the gradient in refractive index in a desert mirage

Question

How do we design ε and μ tensors at will?



We need metamaterials!

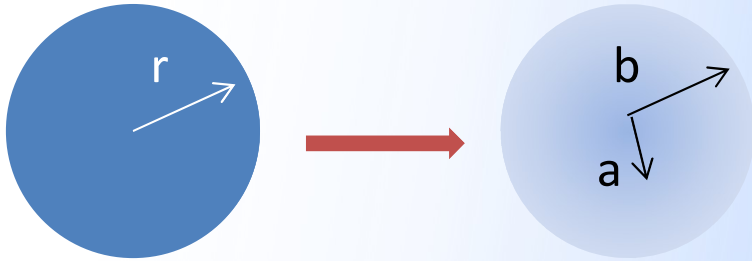
Invisibility Cloak

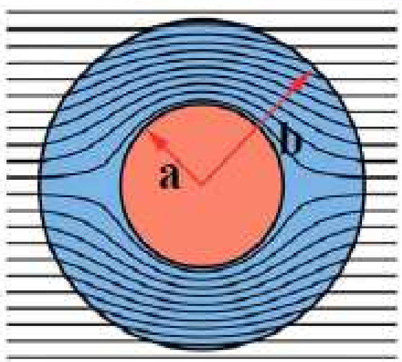
Spherical Coordinates

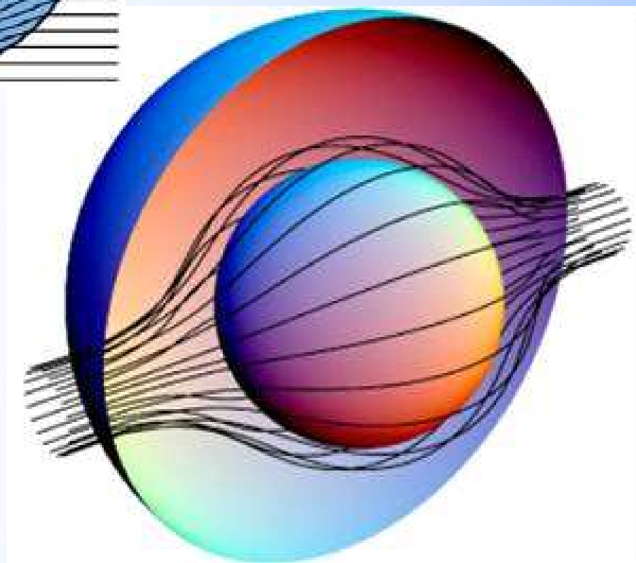
$$0 < r < b \Longrightarrow a < r' < b$$

$$r' = \frac{b-a}{b} r + a \qquad \theta' = \theta \qquad \varphi' = \varphi$$

$$\begin{cases} \varepsilon'_r = \mu'_r = \dfrac{b}{b-a}\dfrac{(r-a)^2}{r^2} \\ \varepsilon'_\theta = \mu'_\theta = \dfrac{b}{b-a} \\ \varepsilon'_\varphi = \mu'_\varphi = \dfrac{b}{b-a} \end{cases}$$

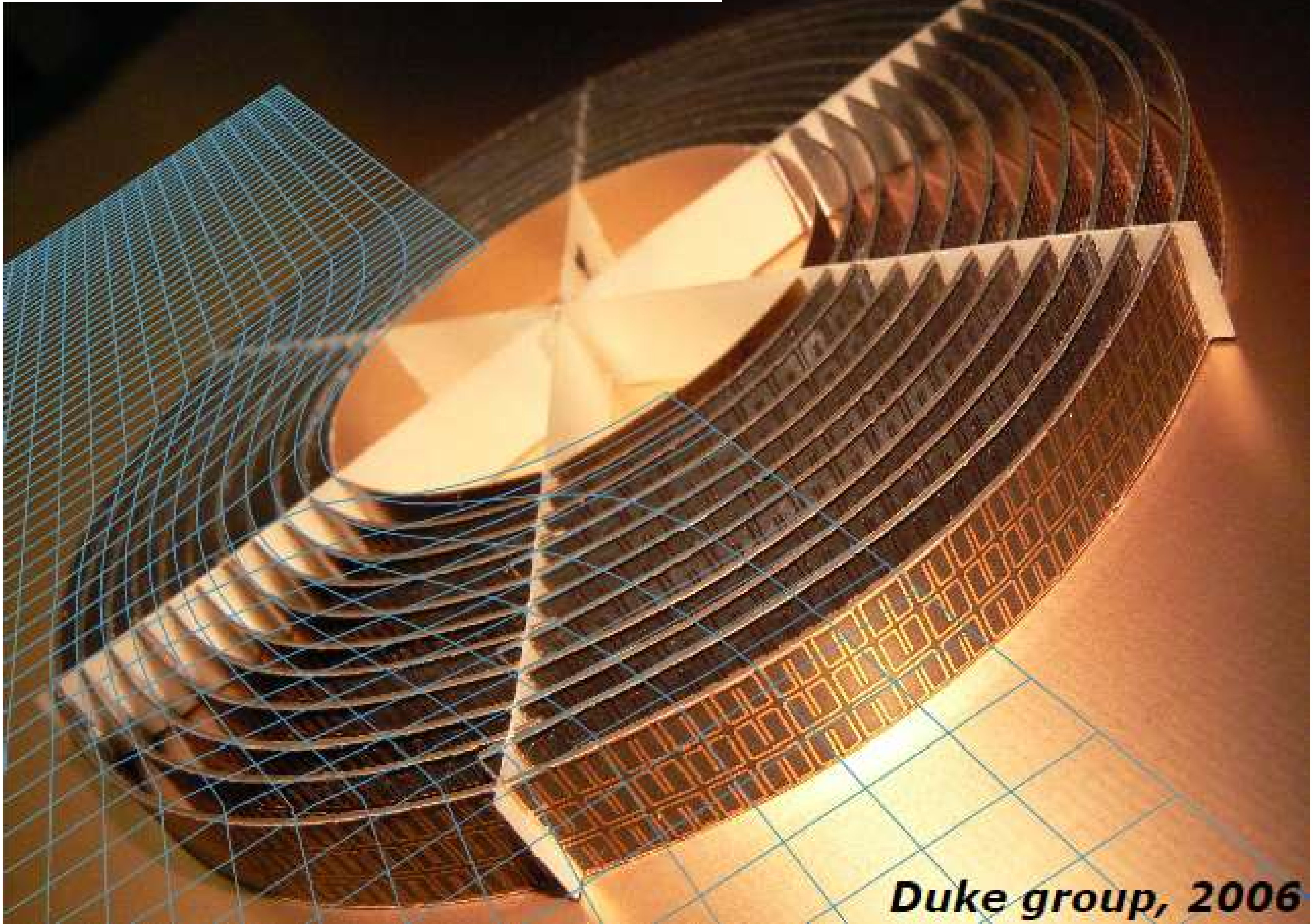




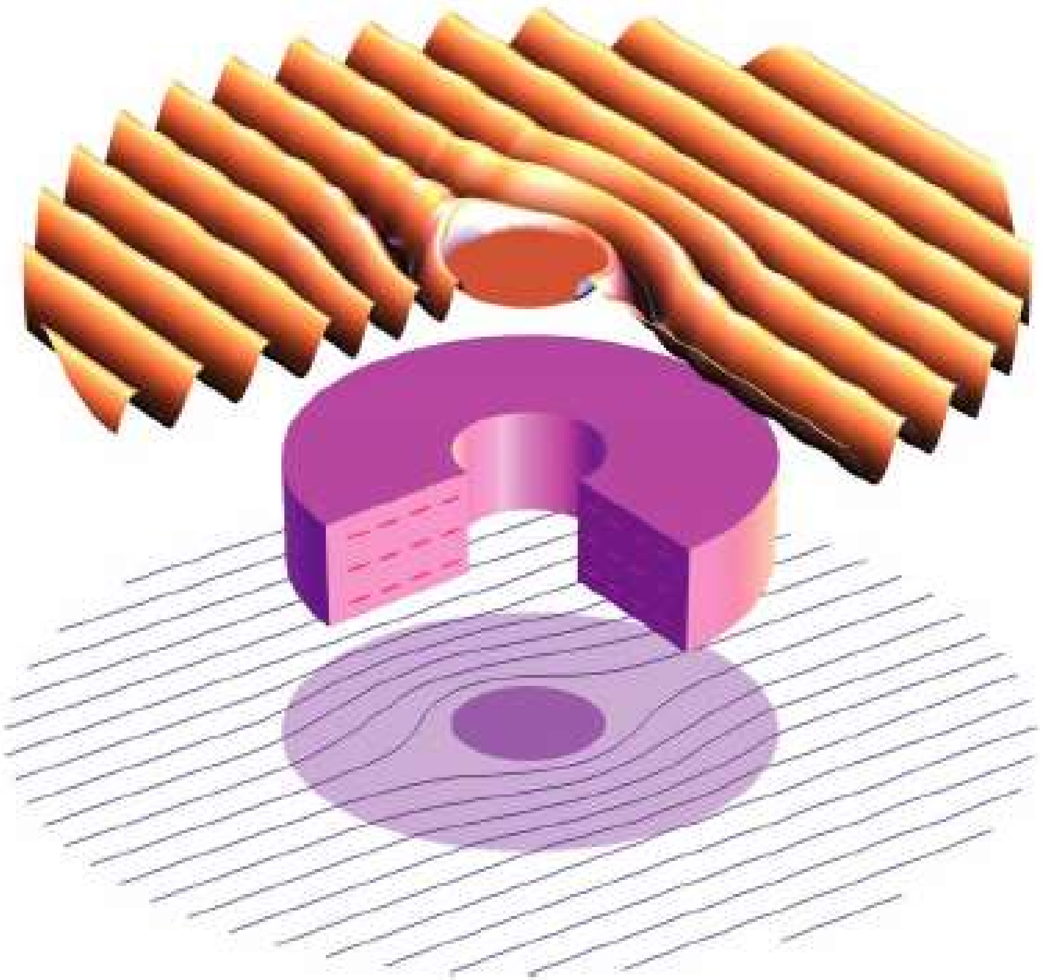


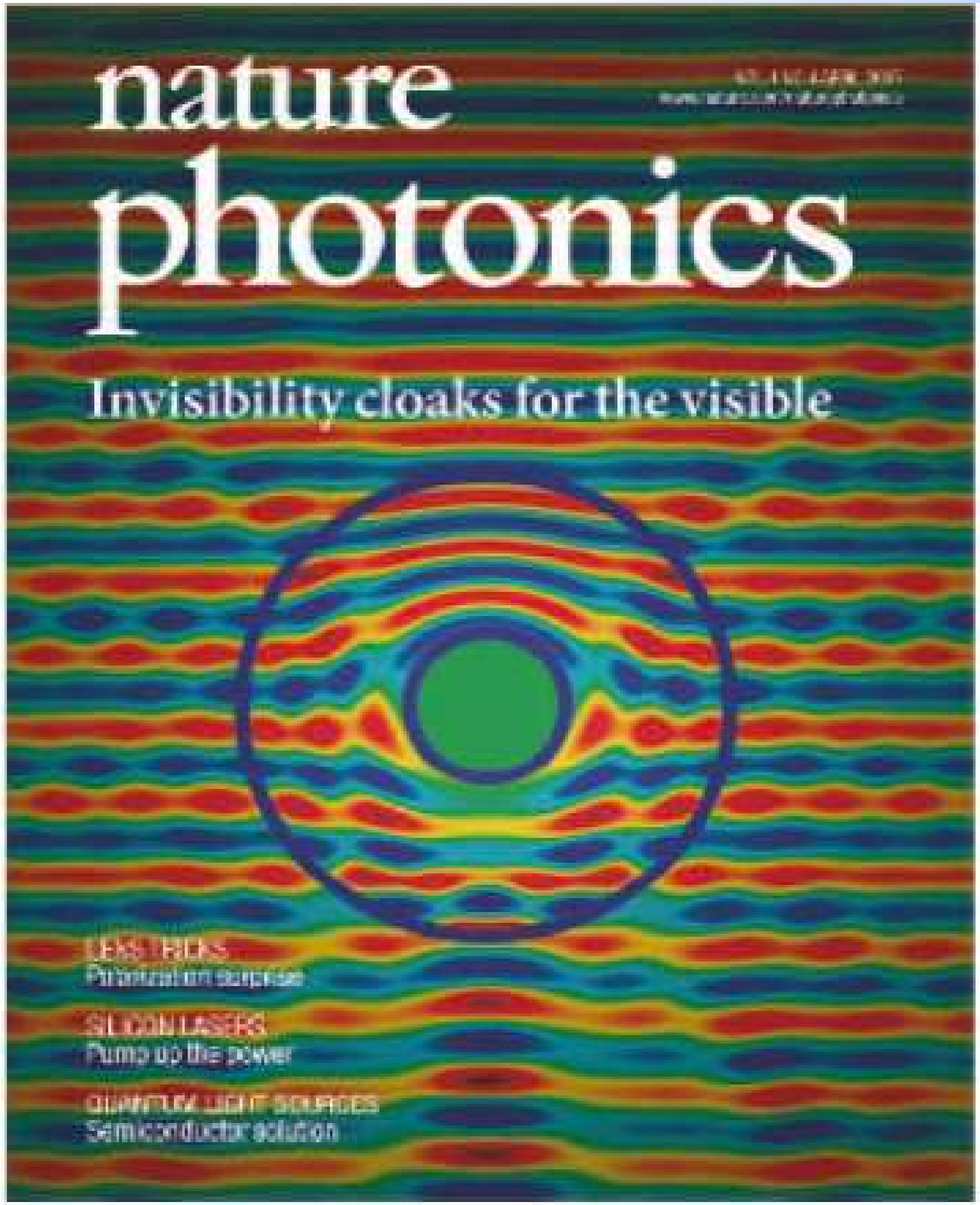
*Pendry, J. B., Schurig, D. & Smith, D. R. Science **312**, 1780–1782 (2006).*

https://www.youtube.com/watch?v=Ja_fuZyHDuk



Invisibility Cloak

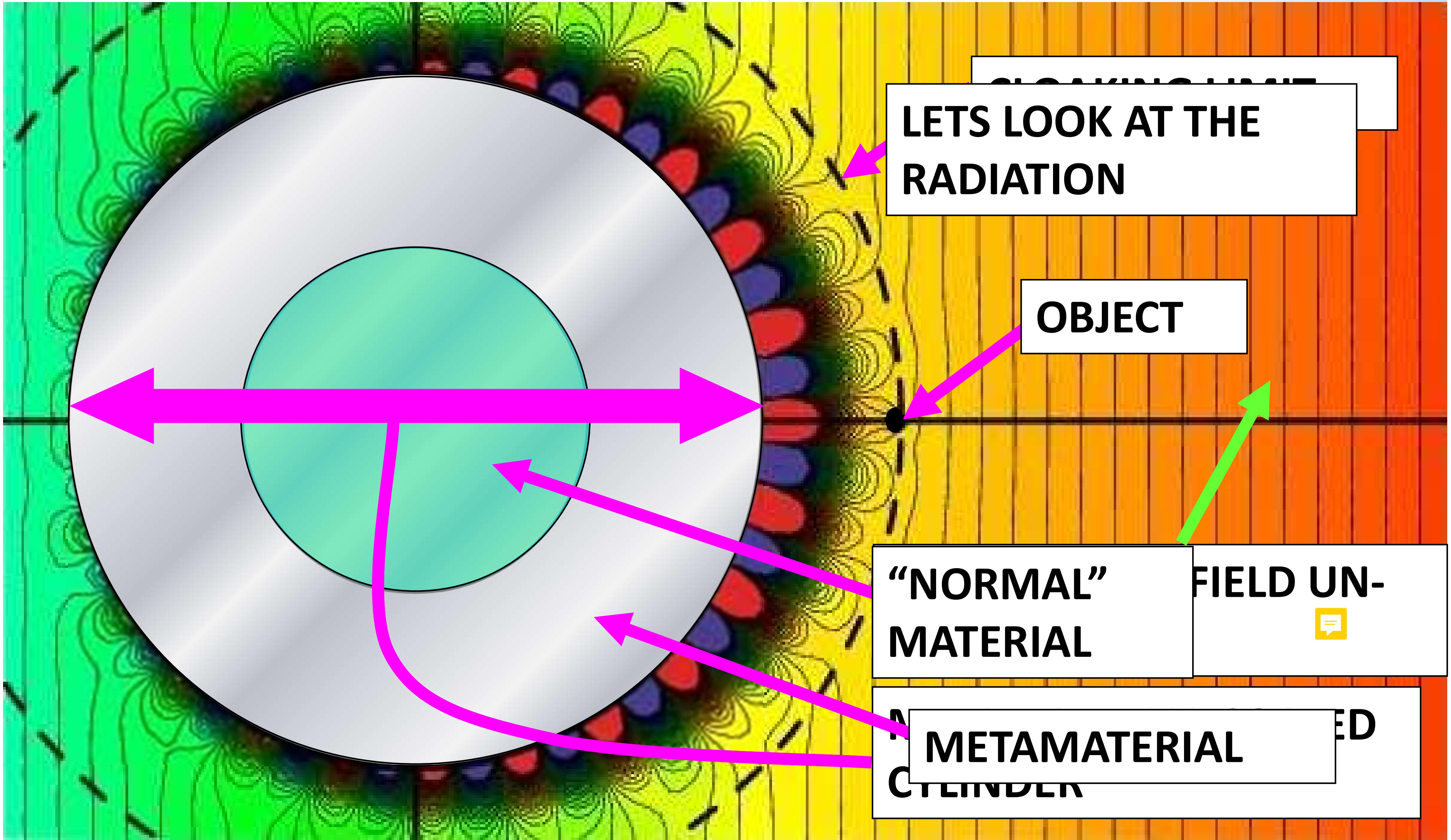




Cover article of Nature Photonics (April, 2007)

UNIVERSITY OF BRESCIA

Does the object need to be inside the cloak?



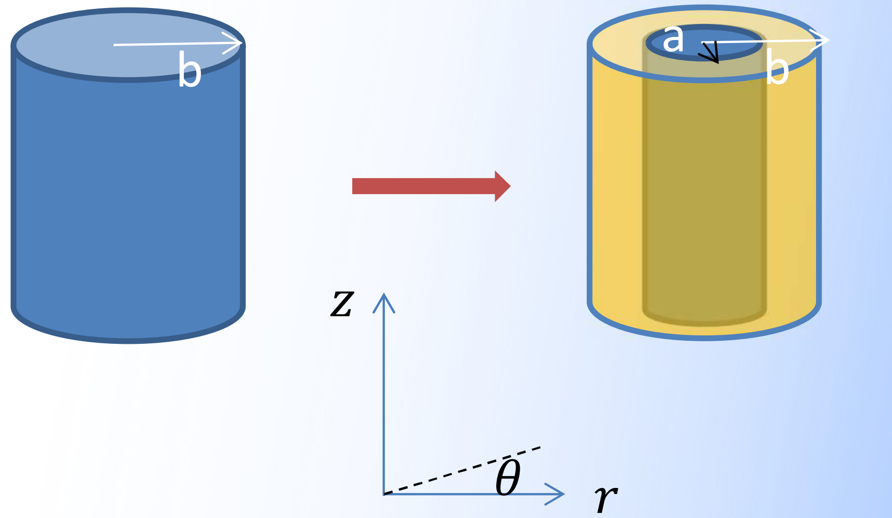
UNIVERSITY OF BRESCIA

Invisibility Cloak

Cilindrical Coordinates

$$0 < r < b \;\Rightarrow\; a < r' < b$$

$$r' = \frac{b-a}{b} r + a \qquad \theta' = \theta \qquad z' = z$$



$$\begin{cases} \varepsilon'_r = \mu'_r = \dfrac{r-a}{r} \\ \varepsilon'_\theta = \mu'_\theta = \dfrac{r}{r-a} \\ \varepsilon'_\varphi = \mu'_\varphi = \left(\dfrac{b}{b-a}\right)^2 \dfrac{r-a}{r} \end{cases}$$

TE incidence

$$\begin{cases} \varepsilon'_z = \left(\dfrac{b}{b-a}\right)^2 \dfrac{r-a}{r} \\ \mu'_\theta = \dfrac{r}{r-a} \\ \mu'_r = \dfrac{r-a}{r} \end{cases}$$

To maintain the dispersion relation only

$$\begin{cases} \mu'_\theta \varepsilon'_z = const \\ \mu'_r \varepsilon'_z = const \end{cases}$$

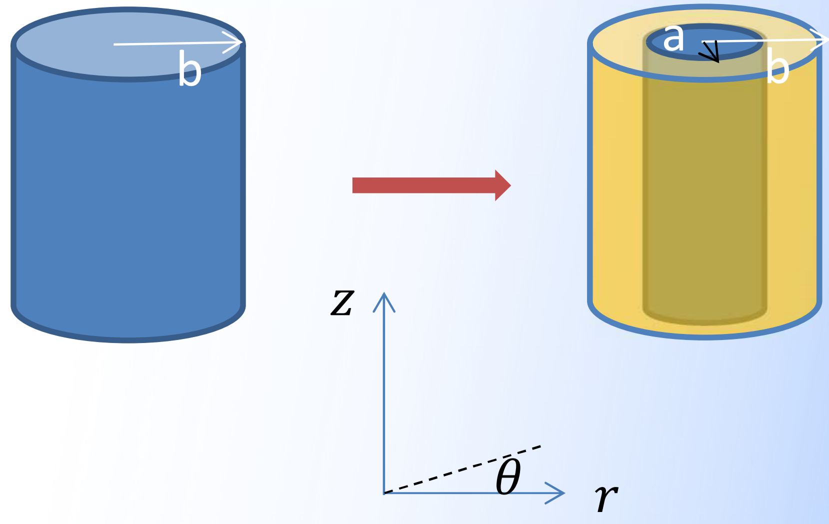
$$\begin{cases} \varepsilon'_z = \left(\dfrac{b}{b-a}\right)^2 \\ \mu'_\theta = 1 \\ \mu'_r = \left(\dfrac{r-a}{r}\right)^2 \end{cases}$$

Invisibility Cloak

UNIVERSITY OF BRESCIA

Cilindrical Coordinates

$$0 < r < b \Rightarrow a < r' < b$$



$$r' = \frac{b-a}{b} r + a \qquad \theta' = \theta \qquad z' = z$$

$$\begin{cases} \varepsilon'_r = \mu'_r = \dfrac{r-a}{r} \\ \varepsilon'_\theta = \mu'_\theta = \dfrac{r}{r-a} \\ \varepsilon'_\varphi = \mu'_\varphi = \left(\dfrac{b}{b-a}\right)^2 \dfrac{r-a}{r} \end{cases}$$

TM incidence

$$\begin{cases} \mu'_z = \left(\dfrac{b}{b-a}\right)^2 \dfrac{r-a}{r} \\ \varepsilon'_\theta = \dfrac{r}{r-a} \\ \varepsilon'_r = \dfrac{r-a}{r} \end{cases}$$

To maintain the dispersion relation

$$\begin{cases} \mu'_z \varepsilon'_\theta = const \\ \mu'_z \varepsilon'_r = const \end{cases}$$

$$\begin{cases} \mu'_z = 1 \\ \varepsilon'_\theta = \left(\dfrac{b}{b-a}\right)^2 \\ \varepsilon'_r = \left(\dfrac{b}{b-a}\right)^2 \left(\dfrac{r-a}{r}\right)^2 \end{cases}$$

Non magnetic Cloak

$$
\begin{cases}
\mu'_z = 1 \\
\varepsilon'_\theta = \left(\dfrac{b}{b-a}\right)^2 \\
\varepsilon'_r = \left(\dfrac{b}{b-a}\right)^2 \left(\dfrac{r-a}{r}\right)^2
\end{cases}
$$

NO MAGNETISM REQUIRED

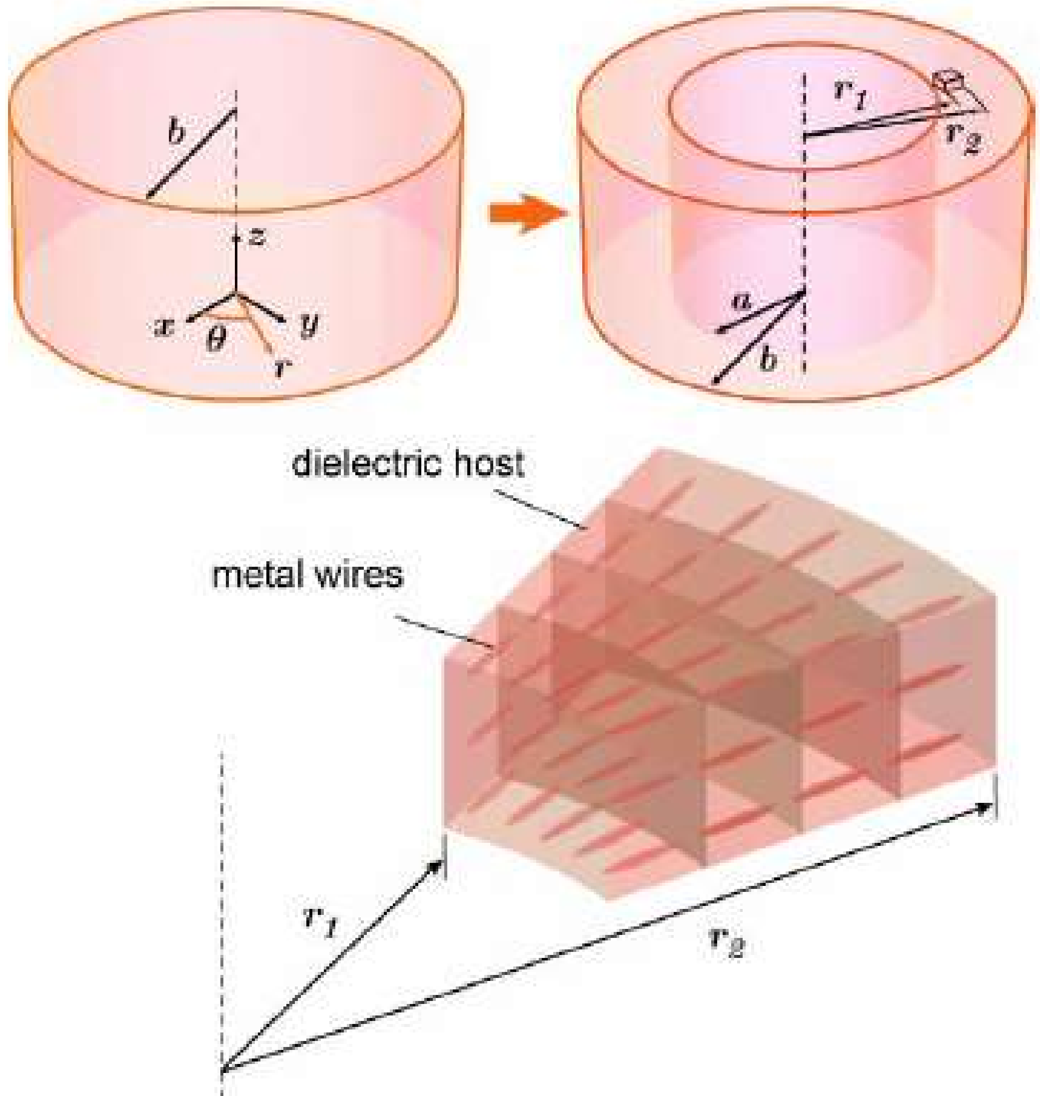
PERMITTIVITY >1

GRADIENT PERMITTIVITY IN r DIRECTION.
PERMITTIVITY VARIES FROM 0 TO 1

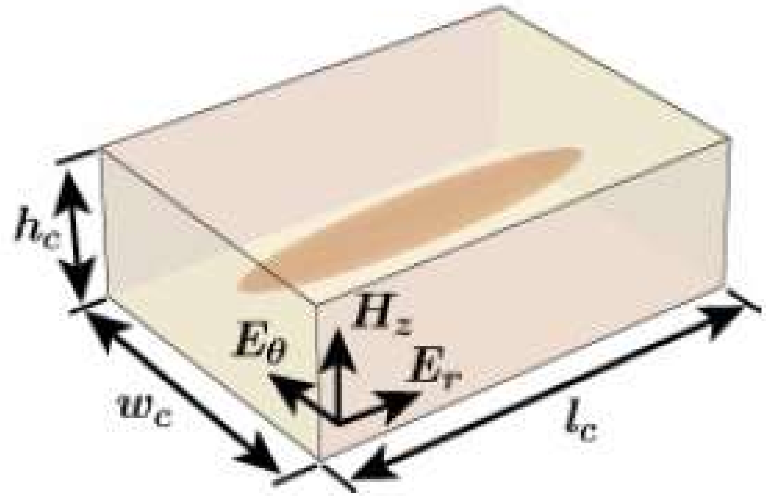
- The magnetic cloak shows zero reflection
- Non-magnetic cloak → non-zero reflection
- Non-magnetic nature removes the challenging issue of the design
- The key to the implementation: radial distribution

Non magnetic Cloak: Round Brush

ε_r realized by metal wires of sub-wavelength size in radial direction



Unit Cell



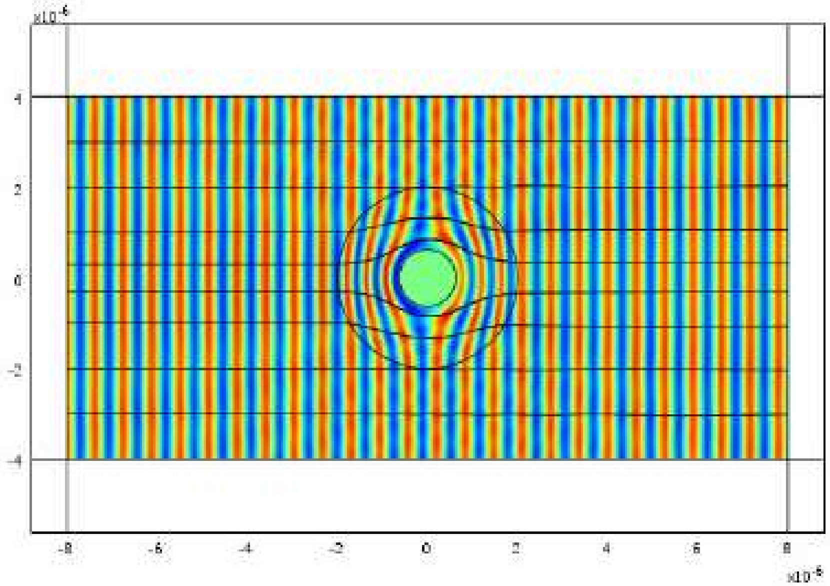
Flexible control of ε_r ;

Negligible perturbation in ε_θ

Cai, et al.,
Nature Photonics, 1, 224 (2007)

Magnetic vs Non Magnetic Cloak

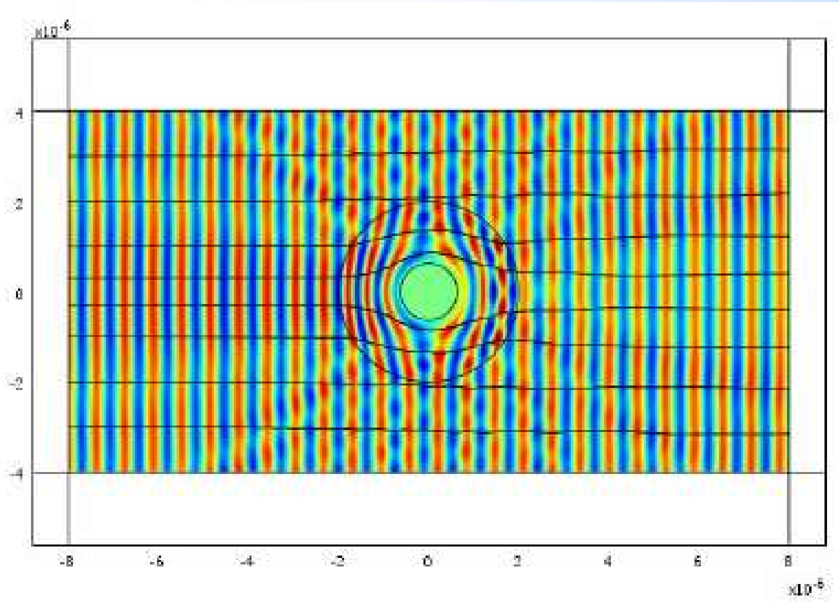
Ideal Cloak



$$Z\big|_{r=b} = \sqrt{\mu_z / \varepsilon_\theta}\Big|_{r=b} = 1$$

Perfectly matched impedance results in zero scattering

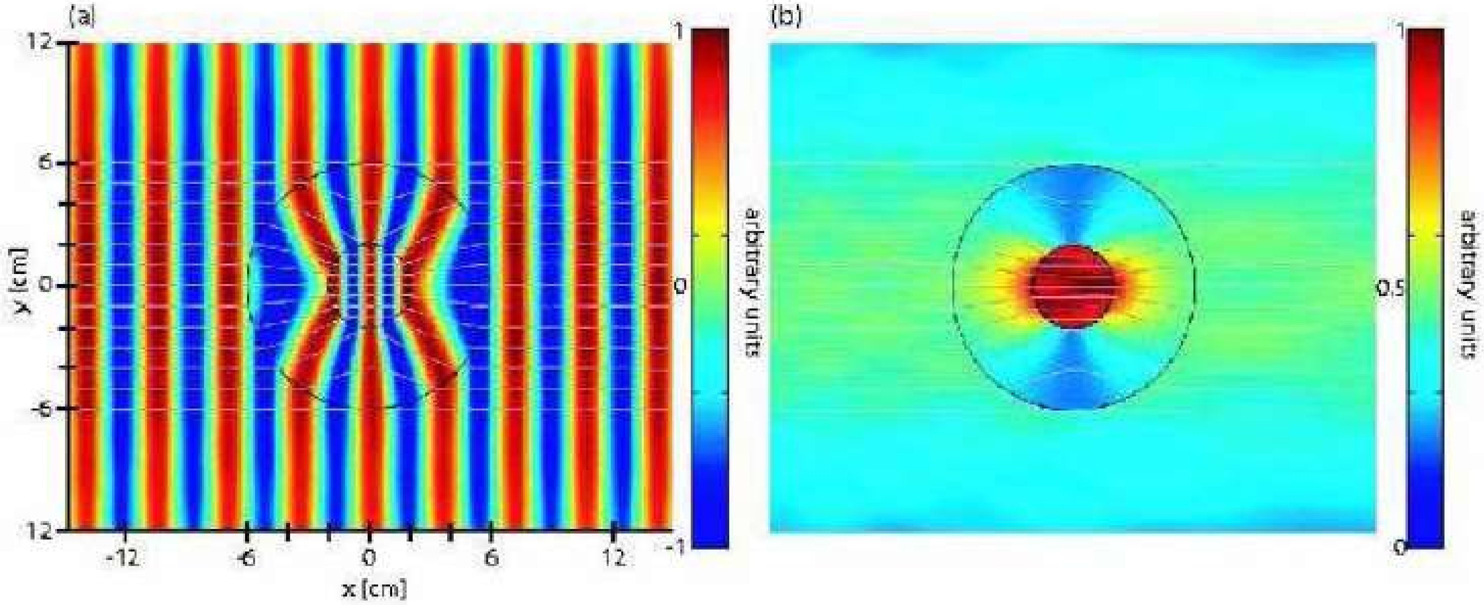
Non Magnetic Cloak



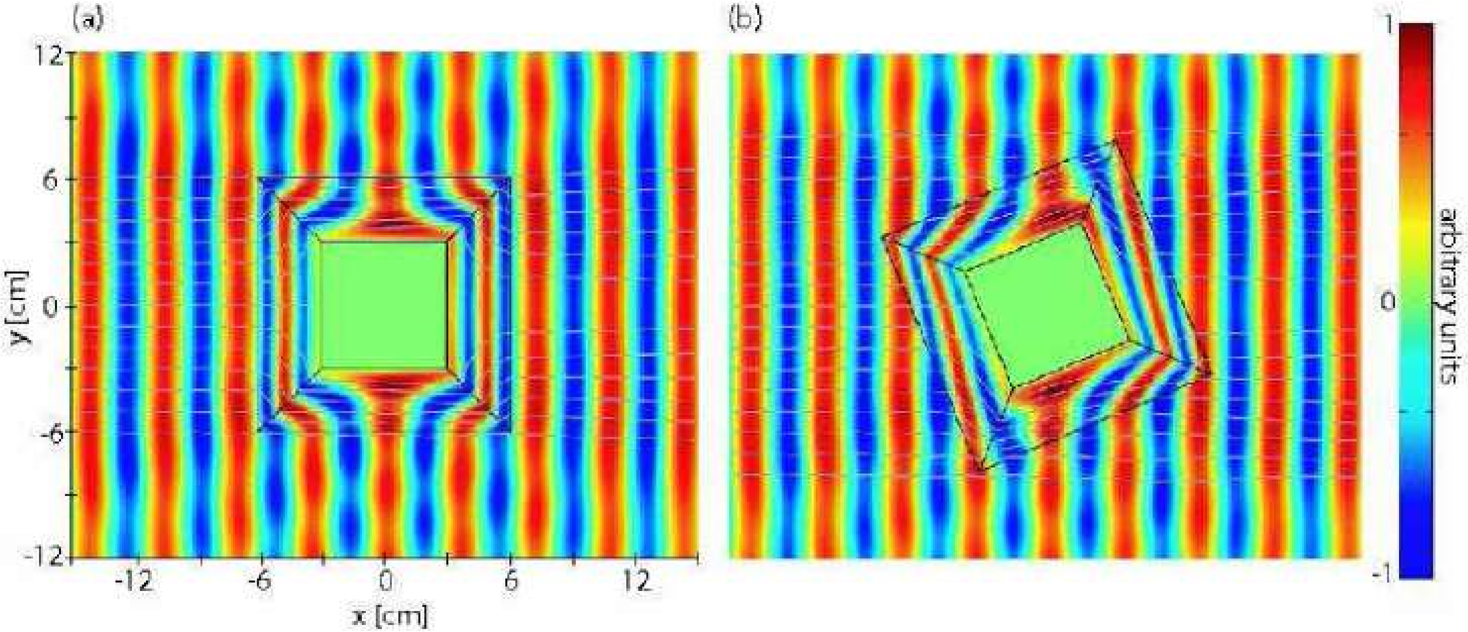
$$Z\big|_{r=b} = \sqrt{\mu_z / \varepsilon_\theta}\Big|_{r=b} = 1 - a/b$$

Detrimental scattering due to impedance mismatch

Engineered Optical Meta-Spaces



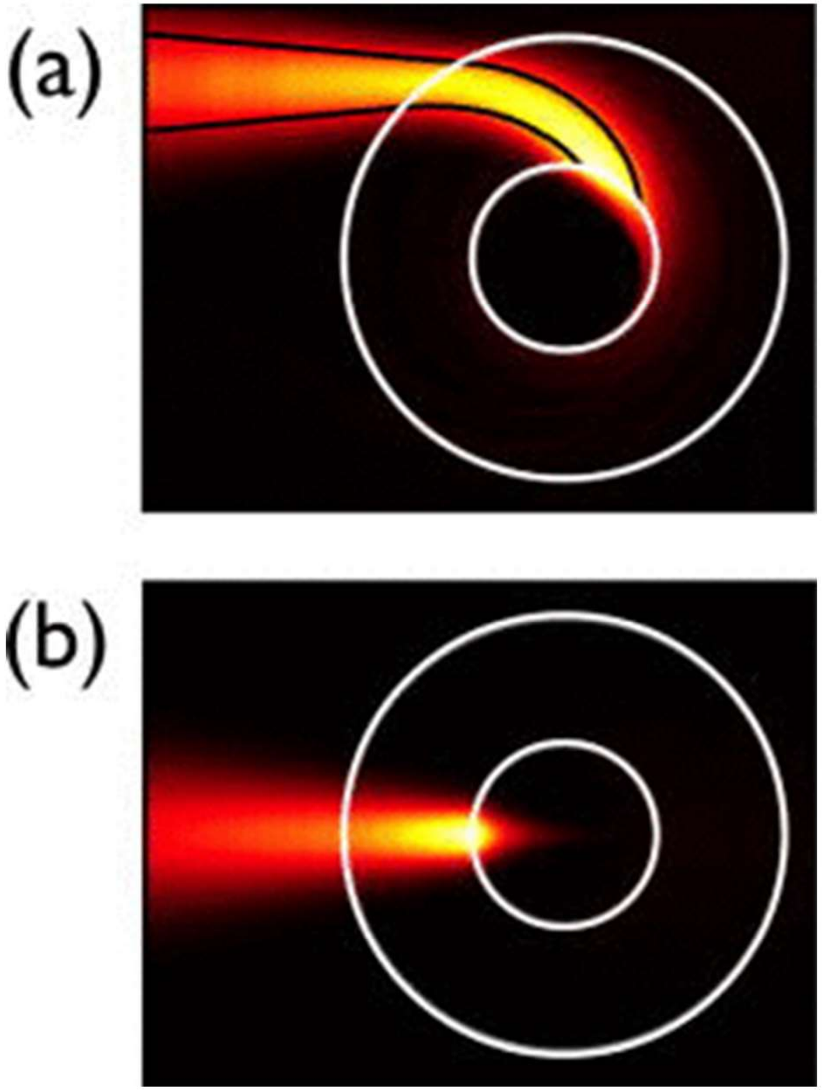
Optical Concentrator



Square Cloak

M. Rahm et al., Photonics and Nanostructures - Fundamentals and Applications 6, 87-95 (2008)

Engineered Optical Meta-Spaces

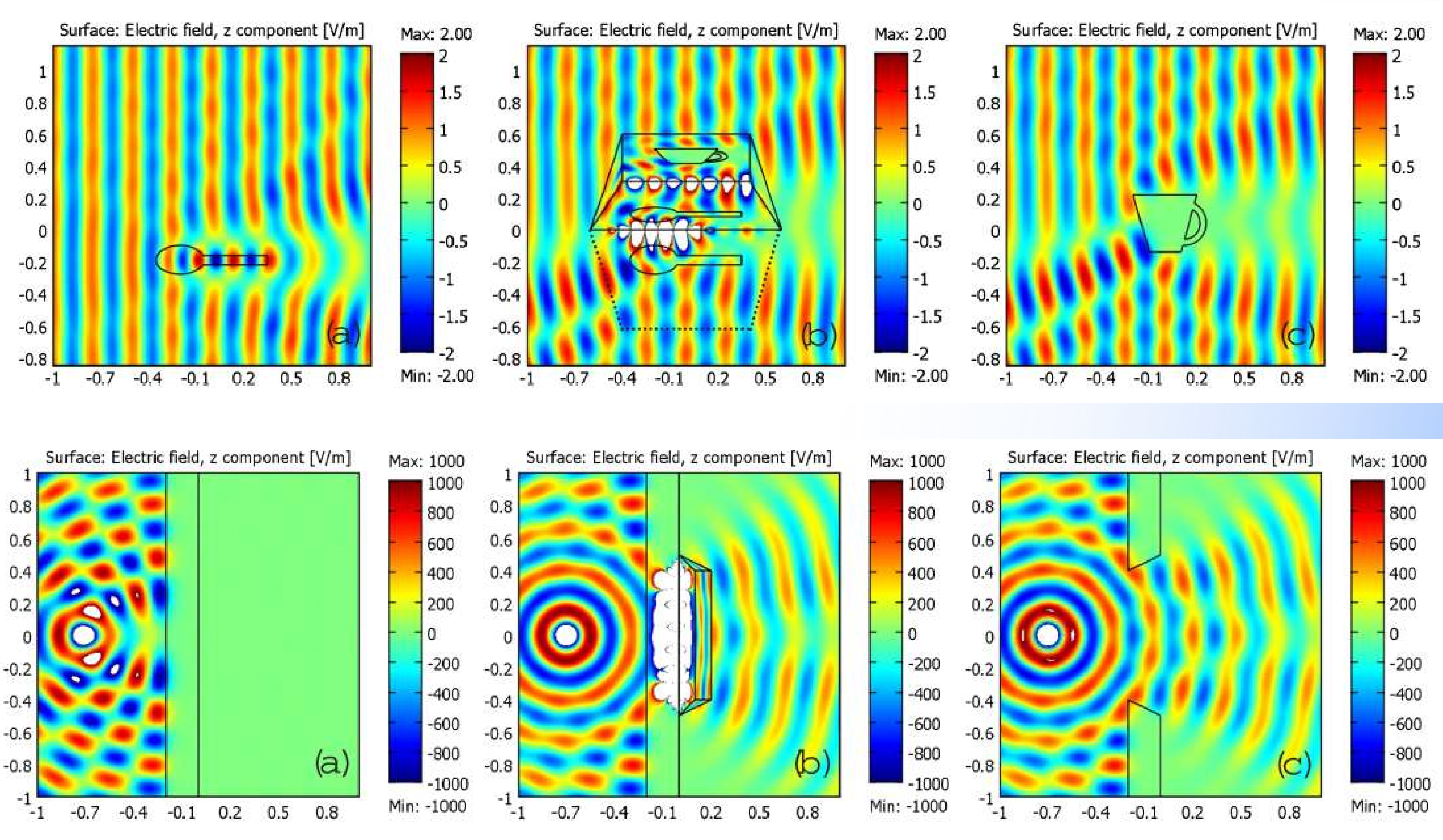


Metamaterial Black hole

E. Narimanov, A. Kildishev,
“Optical black hole:
Broadband omnidirectional light absorber,”
Applied Physics Letters. 95. 041106 (2009).

Engineered Optical Meta-Spaces

Illusion Optics

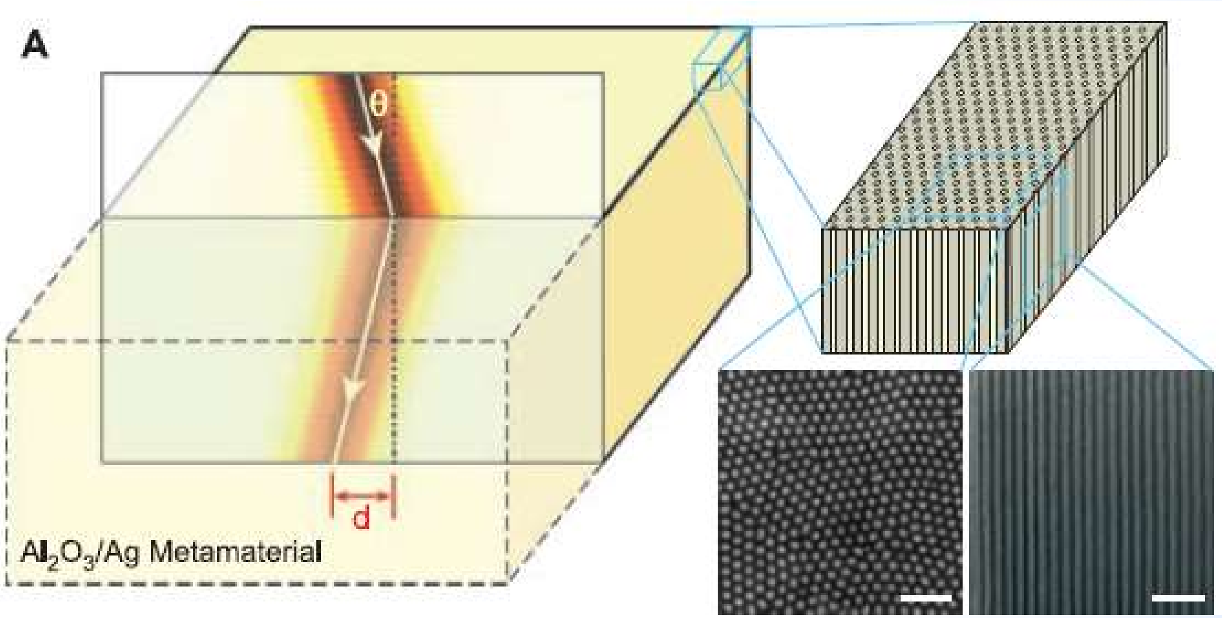


Y. Lai et a. ,Phys. Rev. Lett. ***102****, 253902 (2009)*

Hyperbolic Metamaterials

Hyperbolic materials, also called indefinite materials, are strongly anisotropic, artificial media. The term **indefinite** material refers to a medium whose permittivity and permeability along the principal axes are of opposite signs, resulting a strong anisotropy.

Anisotropic permittivity or permeability can enable negative refraction!



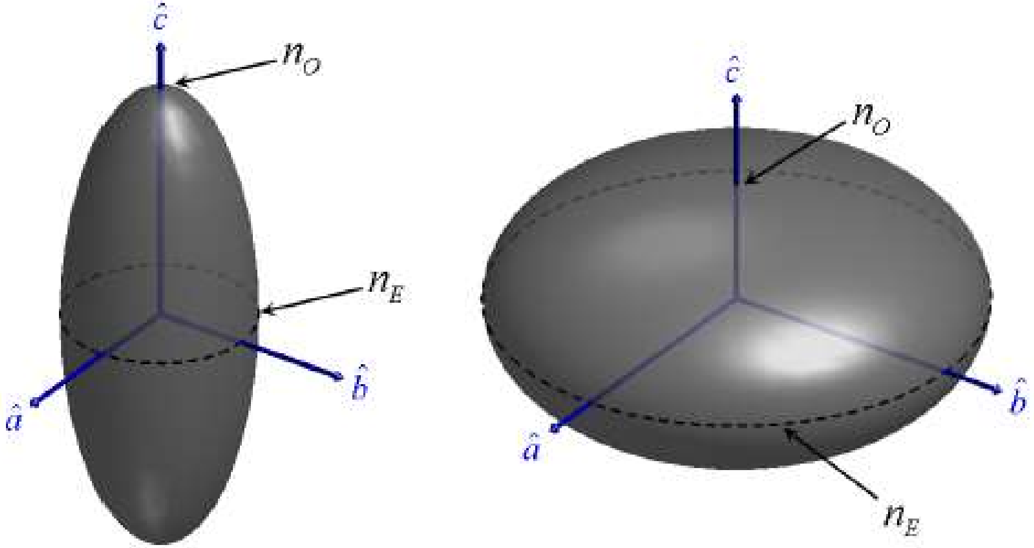
Yao et al, Science 321, (2008)

UNIVERSITY OF BRESCIA

Dispersion surfaces of uniaxial crystals

Dielectric Tensor

$$\begin{bmatrix} \varepsilon_0 & 0 & 0 \\ 0 & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_e \end{bmatrix}$$



Dispersion Relation (ellipsoids)

$$\frac{k_x^2 + k_y^2}{\varepsilon_e} + \frac{k_z^2}{\varepsilon_o} = \left(\frac{\omega}{c_0} \right)^2$$

These ellipsoids are closed surfaces.
Possible values of k are limited.

Dispersion surfaces of hyperbolic metamaterials

If the tensor elements ε_o and ε_e have opposite sign then:

$\varepsilon_o\, \varepsilon_e < 0$

The dispersion relation now describes open surfaces - hyperbolas - that extend to infinity.

$$\boxed{\frac{k_x^2 + k_y^2}{\varepsilon_e} + \frac{k_z^2}{\varepsilon_o} = \left(\frac{\omega}{c_0}\right)^2}$$

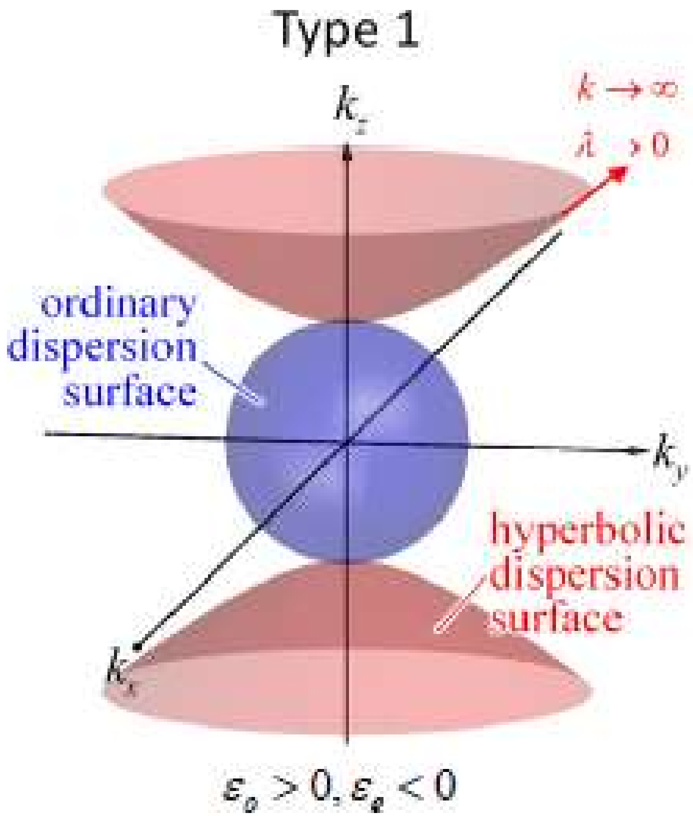
Values of k in hyperbolic materials can go to infinity (in absence of losses!). This means there can exist propagating waves in hyperbolic materials with extremely large values of k. For a given frequency, these will have extremely small wavelength. These waves would be cutoff, or evanescent, in ordinary materials.

$$|k| = \frac{2\pi}{\lambda}, \qquad k \to 0 \Rightarrow \lambda \to 0$$

Hyperbolic metamaterials

Type 1

$$\begin{bmatrix} -\varepsilon_a & 0 & 0 \\ 0 & \varepsilon_b & 0 \\ 0 & 0 & \varepsilon_c \end{bmatrix} \text{ or } \begin{bmatrix} \varepsilon_a & 0 & 0 \\ 0 & -\varepsilon_b & 0 \\ 0 & 0 & \varepsilon_c \end{bmatrix} \text{ or } \begin{bmatrix} \varepsilon_a & 0 & 0 \\ 0 & \varepsilon_b & 0 \\ 0 & 0 & -\varepsilon_c \end{bmatrix}$$

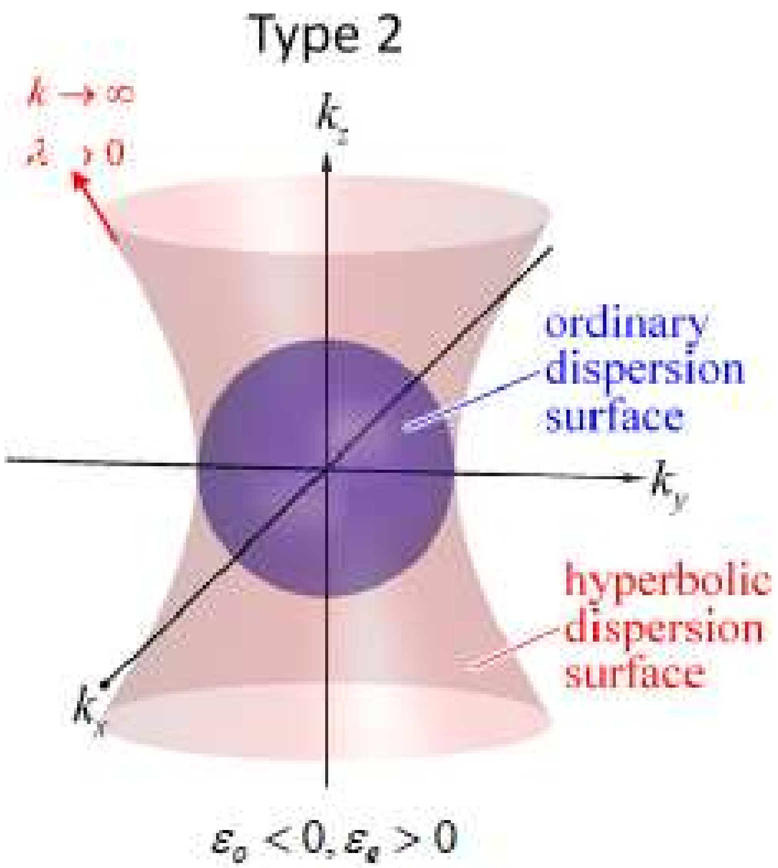


Low loss, good impedance match to air because they are predominantly dielectric like.

Hyperbolic metamaterials

Type 2

$$\begin{bmatrix} -\varepsilon_a & 0 & 0 \\ 0 & -\varepsilon_b & 0 \\ 0 & 0 & \varepsilon_c \end{bmatrix} \text{ or } \begin{bmatrix} -\varepsilon_a & 0 & 0 \\ 0 & \varepsilon_b & 0 \\ 0 & 0 & -\varepsilon_c \end{bmatrix} \text{ or } \begin{bmatrix} \varepsilon_a & 0 & 0 \\ 0 & -\varepsilon_b & 0 \\ 0 & 0 & -\varepsilon_c \end{bmatrix}$$



High loss, high impedance mismatch because they are predominantly metal like.

How to make Hyperbolic metamaterials

Example: We know that in metals the dielectric constant is negative below the plasma frequency. In hyperbolic metamaterials, not all of the tensor elements are negative. This means we have to break the continuity of the metal in the direction of positive tensor elements. So, any structure where metal is continuous on some directions but not others will be hyperbolic.

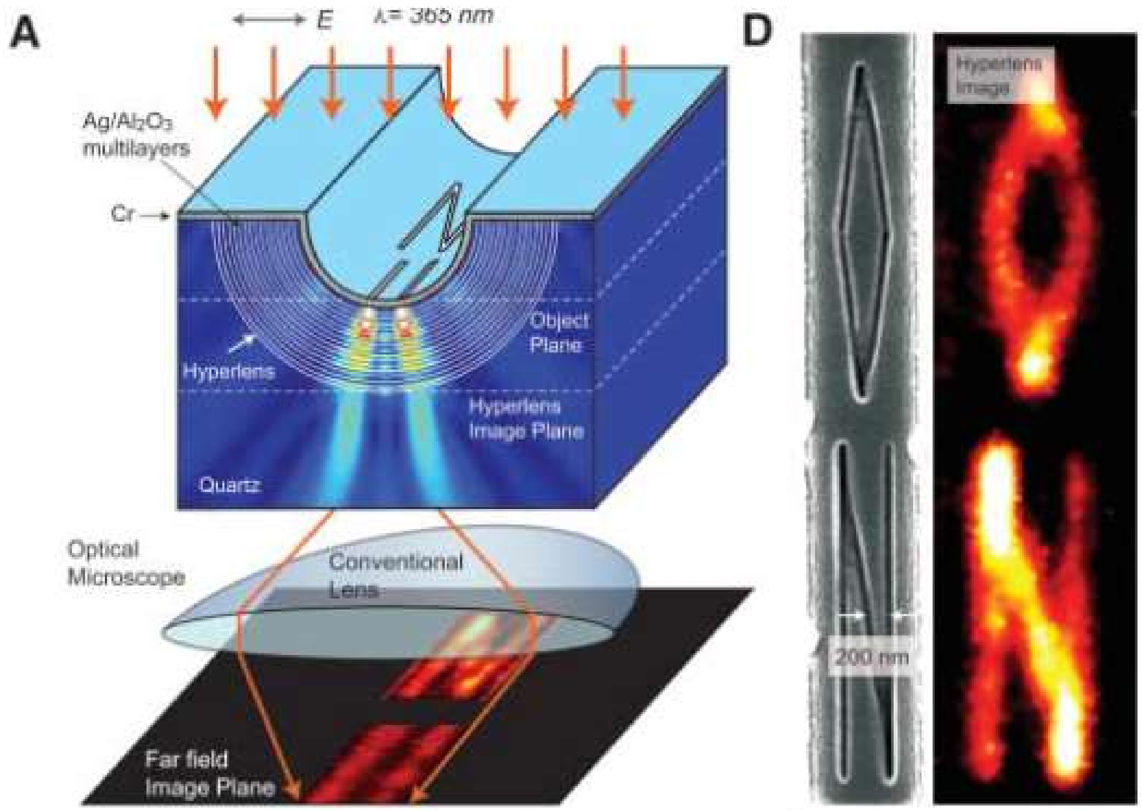
Layers of metal-dielectric | Hyper lens | Multilayer fishnet | Array of nanorods | Array of metal-dielectric nanopyramids | Graphene metamaterial

A. Poddubny, I. Iorsh, P. Belov, Y. Kivshar, Nature Photonics, vol. 7, pp. 958-967, 2013.

Hyperbolic metamaterials applications

- ✓ Negative Refraction (from dispersion, not Negative Refractive Index)
- ✓ Lensing
- ✓ Spontaneous emission engineering (Purcell-factor enhancement)
- ✓ Minaturization
- ✓ Tunable active devices
- ✓ Heat transfer engineering

Liu et al, Science. 315 1686 (2007)



UNIVERSITY OF BRESCIA

Metasurfaces

Why going 2D?

- ✓ Planar technology is central to Integrated Circuit technology ;
- ✓ 2D metasurfaces have better chance to have major technological impact because they are easier to fabricate than their 3D counterparts;

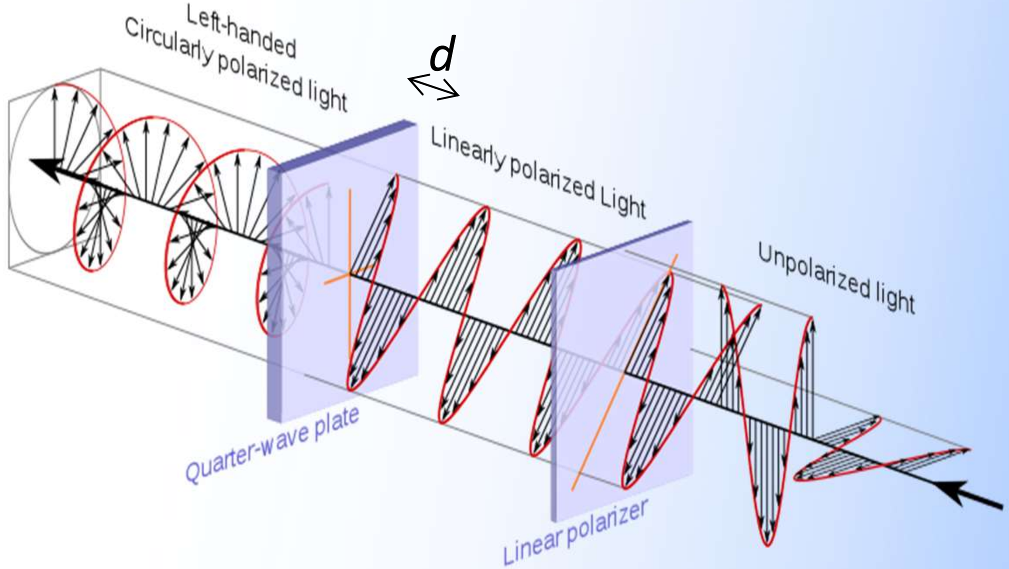
What can we do with Metasurfaces?

- ✓ Metasurfaces allow for local phase and amplitude control of light along the surface using optical antennas;
- ✓ New class of flat, compact and broadband components:(lenses, polarizers, etc.), beyond conventional diffractive optics ;
- ✓ Optical phased arrays for high speed wavefront control.

Metasurfaces

Conventional optical components rely on propagation effects

Camera lens



Quarter waveplate

Can we introduce an abrupt phase jump in the path?

Metasurfaces

How do we introduce an abrupt phase jump in the propagation?

We can use subwavelenth optical resonators properly organized on a metasurface with suitably designed geometry in order to scatter light with the desired phase distribution.

What are the requirements for the metasurface elements?

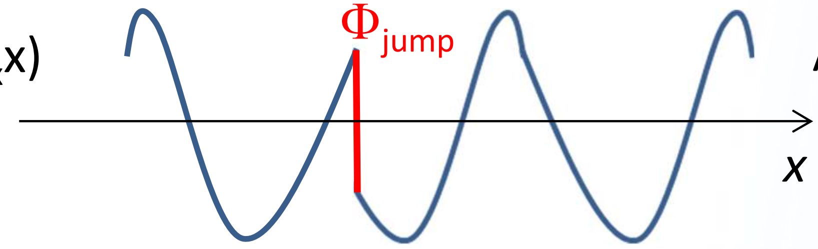
- Deep sub-wavelength thickness
- Sub-wavelength separation between the elements
- 2 π phase coverage
- High and uniform scattering amplitude

What optical components can be fabricated with a metasurface?

- Lenses and Axicons
- Polarizers
- Vortex plates
- Optical phased arrays

Light propagation and phase discontinuities

$A \sin(\omega t - k_x x)$

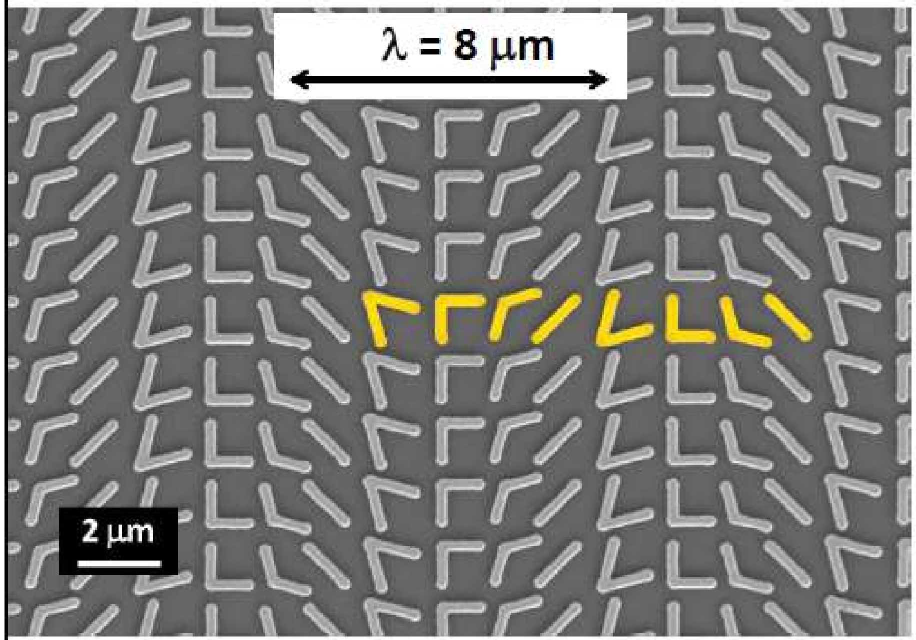


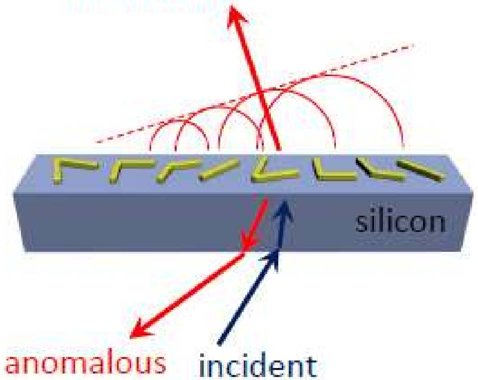
$A \sin(\omega t - k_x x + \Phi_{jump})$

If we create a spatial distribution of different phase discontinuities along the entire interface we can make any desired wave front !

How?
Optically thin array of sub-wavelength spaced antennas

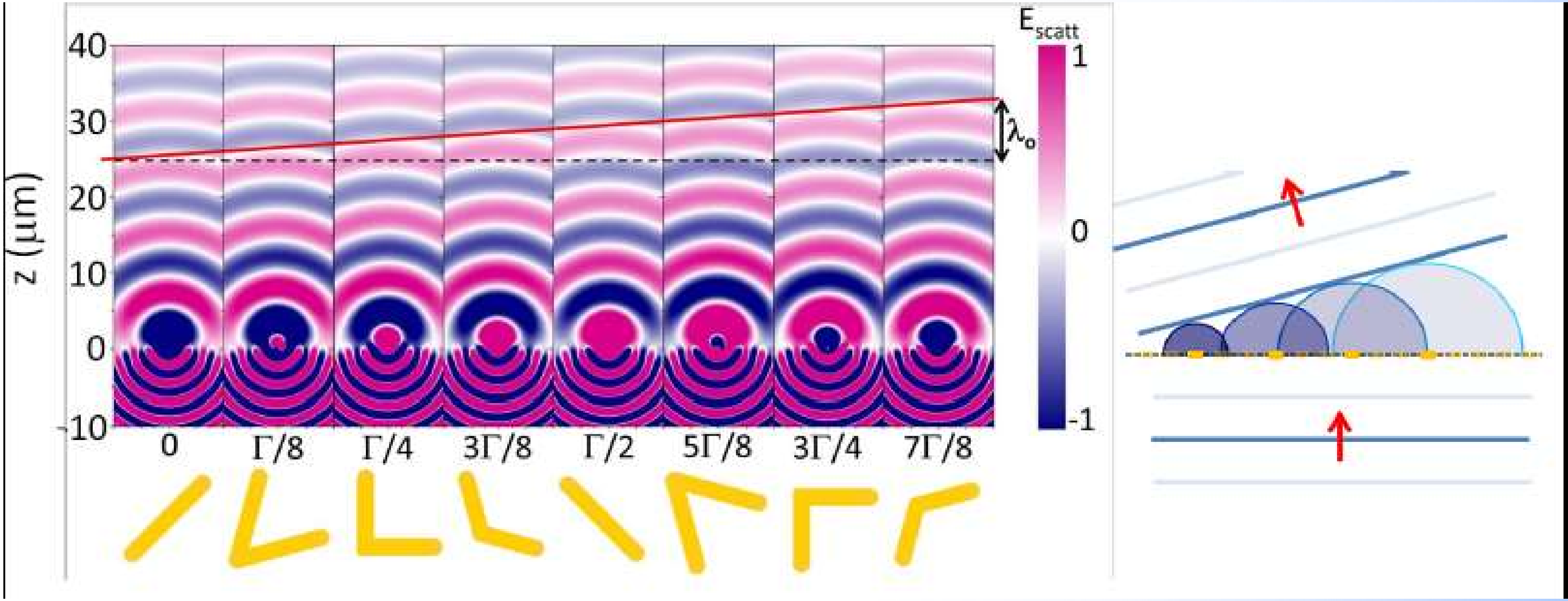
N. Yu et al.,
Science ***334****, 333 (2011)*





Metasurfaces

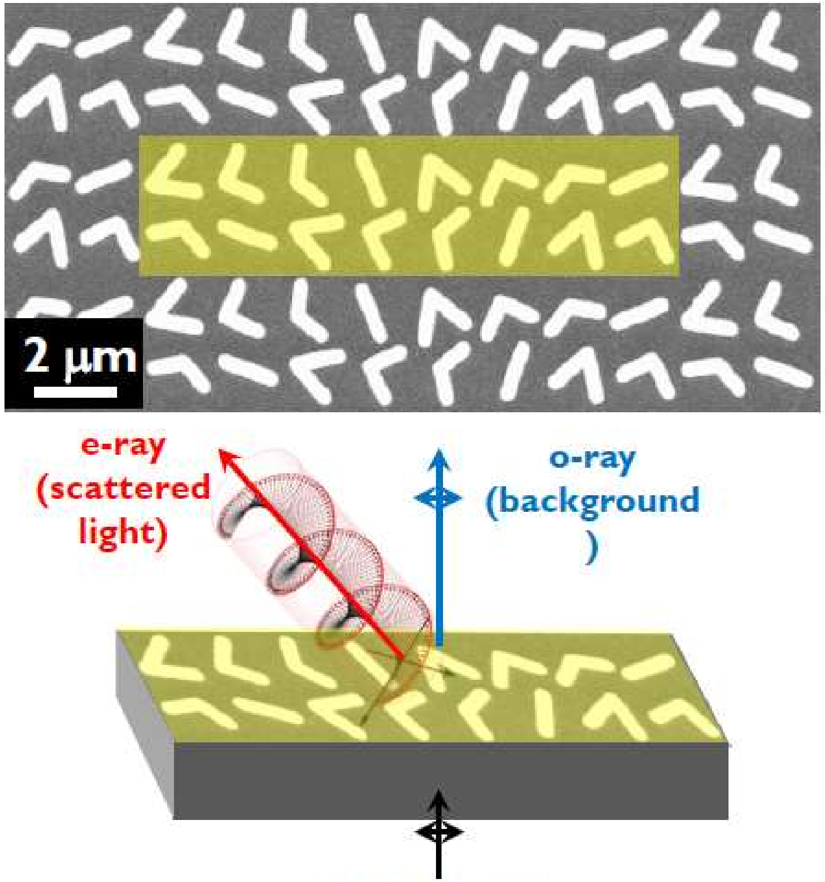
The antenna operate as secondary scatterers with a tailorable phase response, re-directing a normally-incident beam away from the normal



N. Yu et al.,
Science ***334****, 333 (2011)*

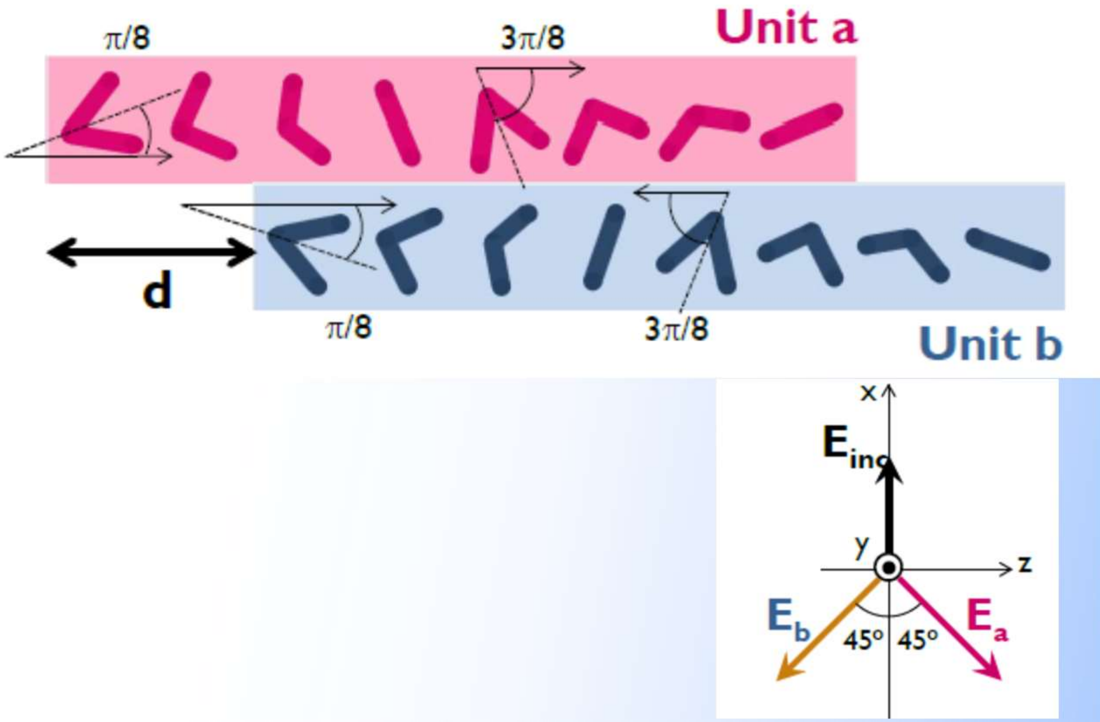
Metasurfaces

Quarter wave plate



Design based on
phased optical antennas

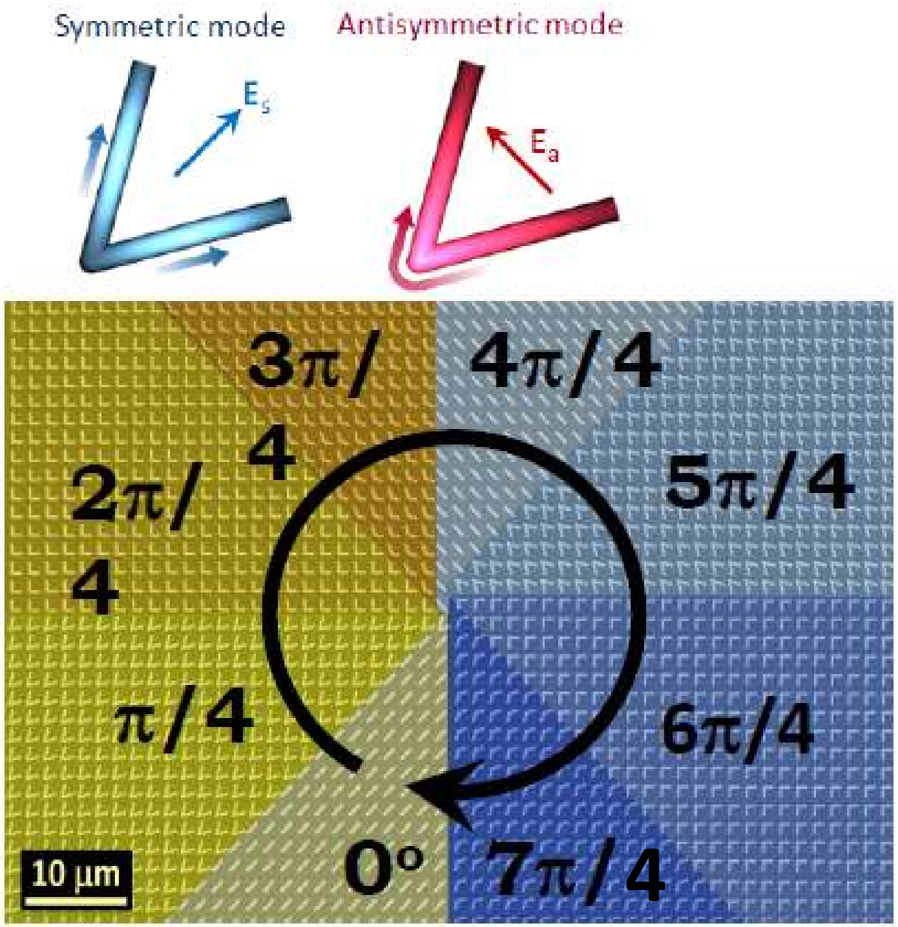
Wavefront reconfiguration



The two rows of antennas in the unit cell create the two orthogonal polarized components with 90 degree phase difference

Metasurfaces

Vortex plates



NOTE:

- ✓ Angular arrangements of antennas create optical vortices
- ✓ Radial arrangements create flat lenses