电子科技大学

University of Electronic Science and Technology of China

Metamaterials

物理电子学院

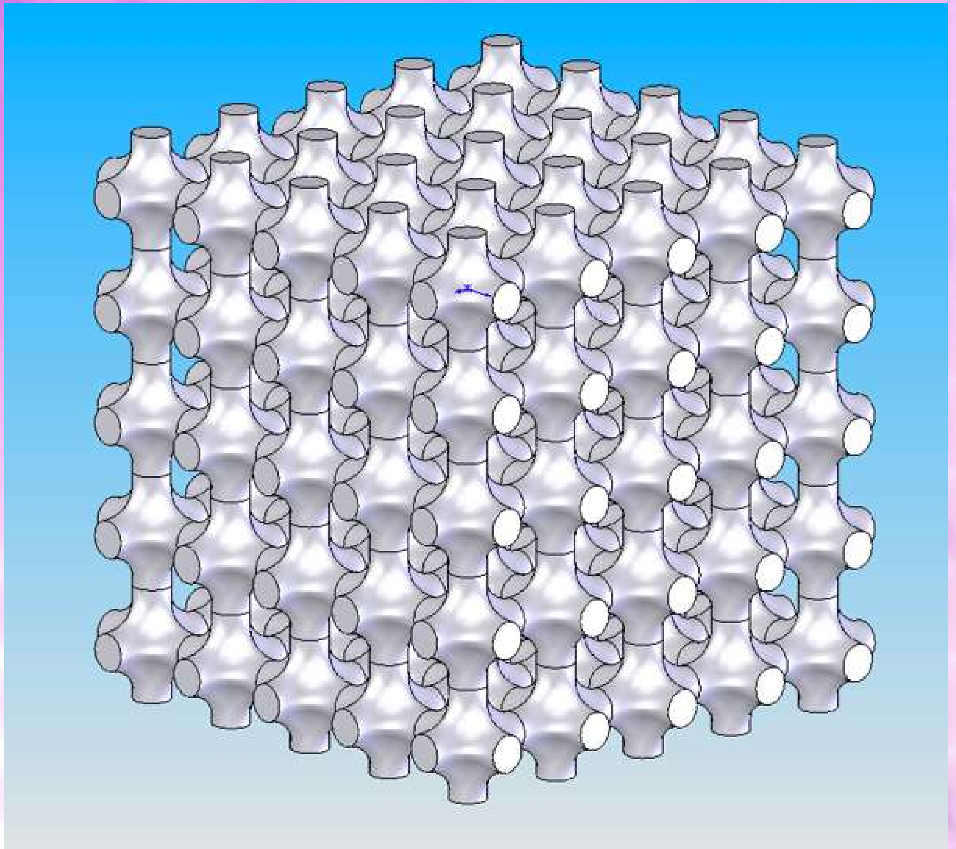
School of Physical Electronics

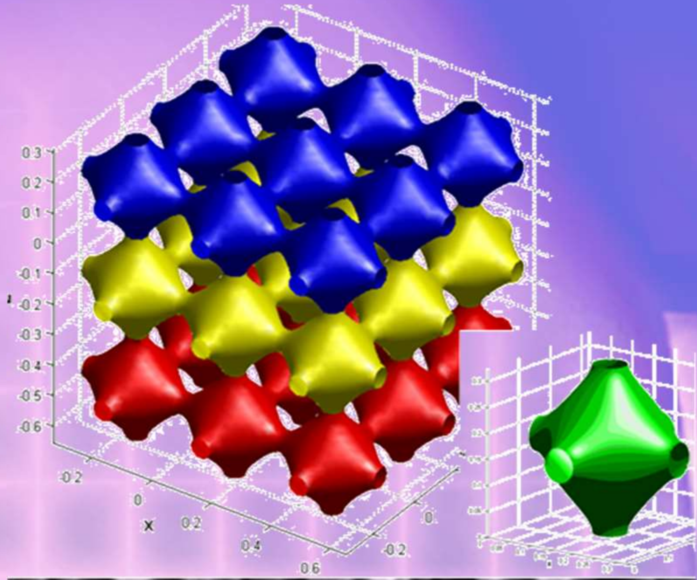
内容

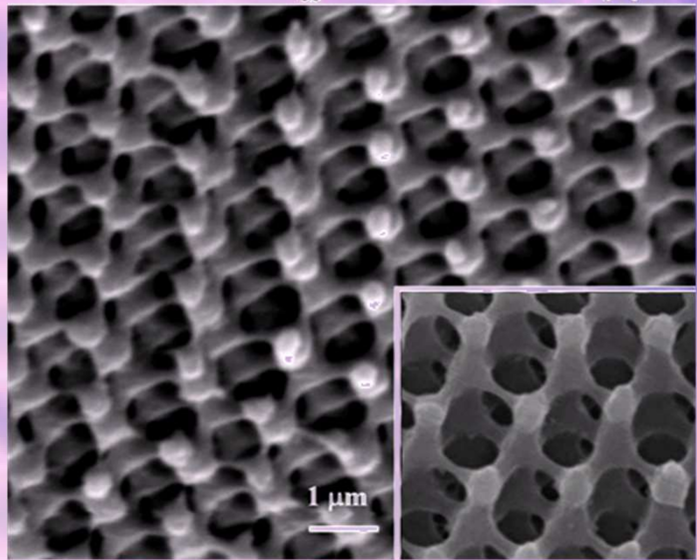
- 特异性材料介绍及应用分类；
- 负折射率材料概念介绍；
- 特异性材料结构的尺度范围；
- 负折射率材料的仿真分析；
- 负折射率材料的设计思想；
- 负折射率材料的制备方法；
- 光子晶体用于负折射率材料介绍。

What is a Metamaterial?

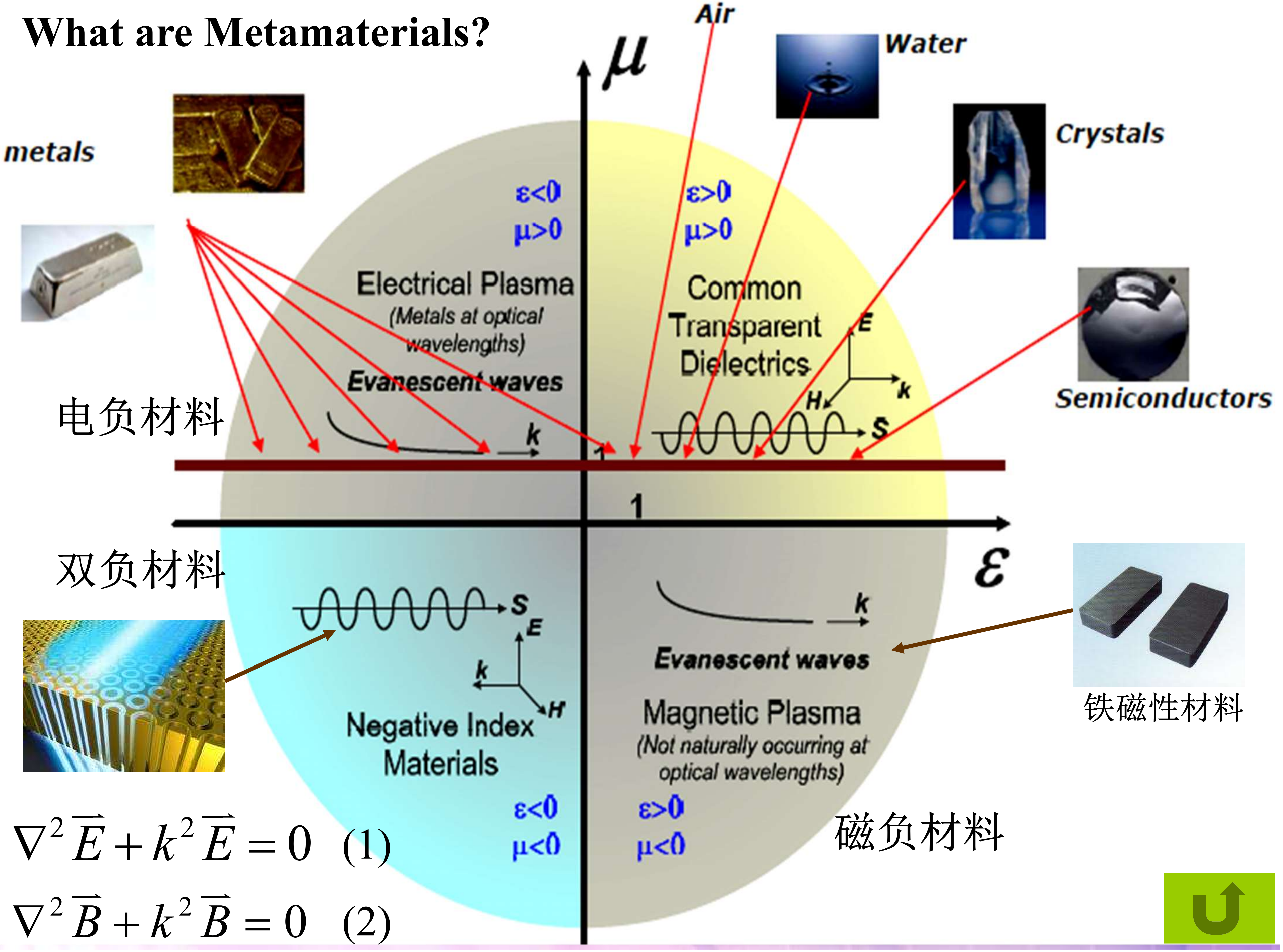
A periodic material that derives its properties from its structure rather than its components.







What are Metamaterials?



$$\nabla^2 \overrightarrow{E} + k^2 \overrightarrow{E} = 0 \quad (1)$$

$$\nabla^2 \overrightarrow{B} + k^2 \overrightarrow{B} = 0 \quad (2)$$

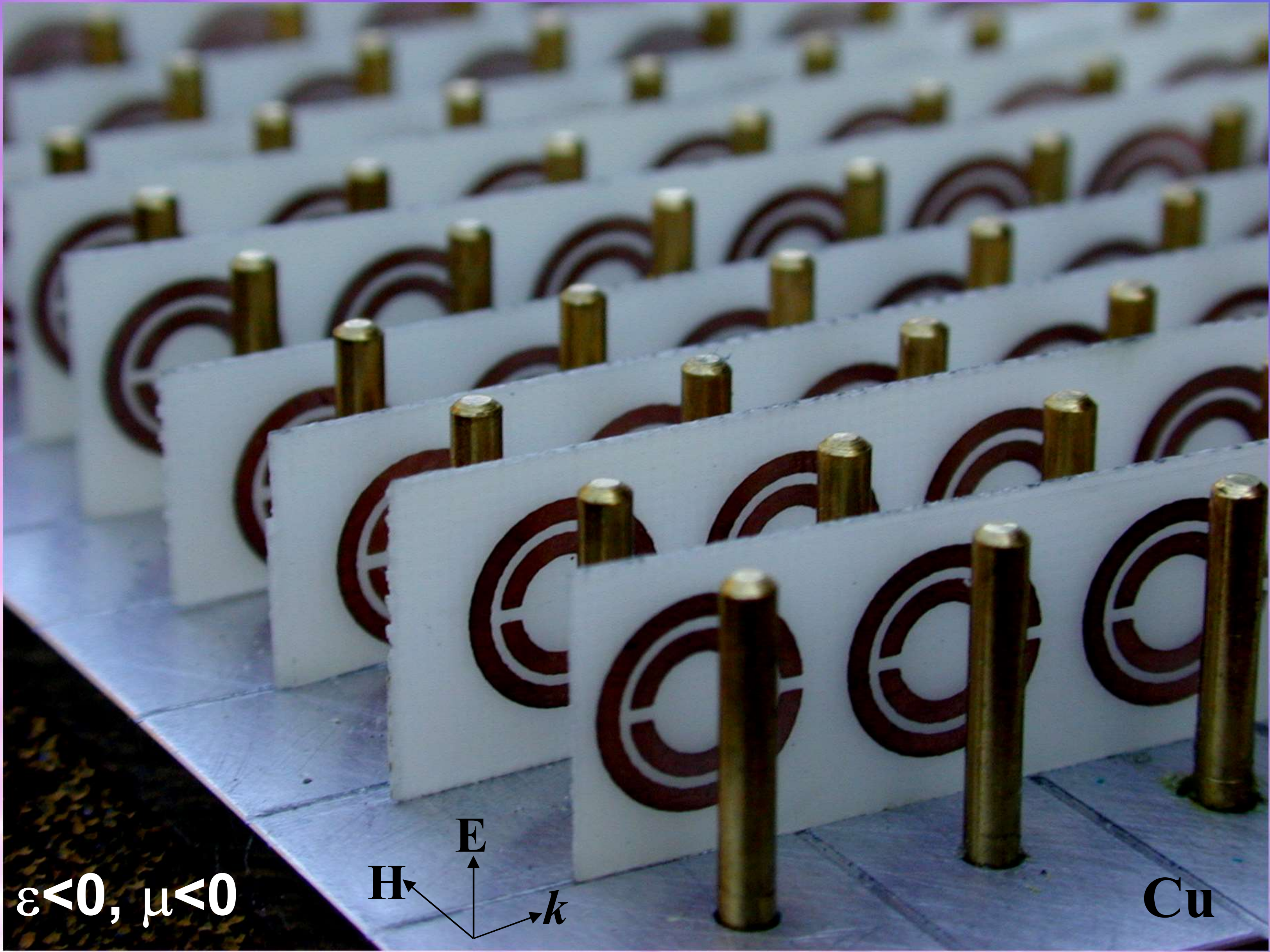
1. $\varepsilon>0,\mu>0$，自然界中绝大多数材料都满足这个条件，此时方程（1）和（2）有波动解，电磁波能在其中传播。**k**、**E**和**H**之间满足右手螺旋关系，通常的介质就被称为“右手材料”（Right-Handed Materials，RHM），也就是目前自然界已发现介质的归类，位于第I象限。

2. $\varepsilon<0,\mu>0$，则$k^2<0$，k无实数解，折射率为虚数，此时方程（1）和（2）无波动解，电磁波不能在其中传播。此类媒质的典型代表是表面等离子体和处于光波段的金属，位于第II象限，也叫电负材料（Epsilon-Negative Materials，ENM）。在该材料内传播的电磁波为倏逝波。

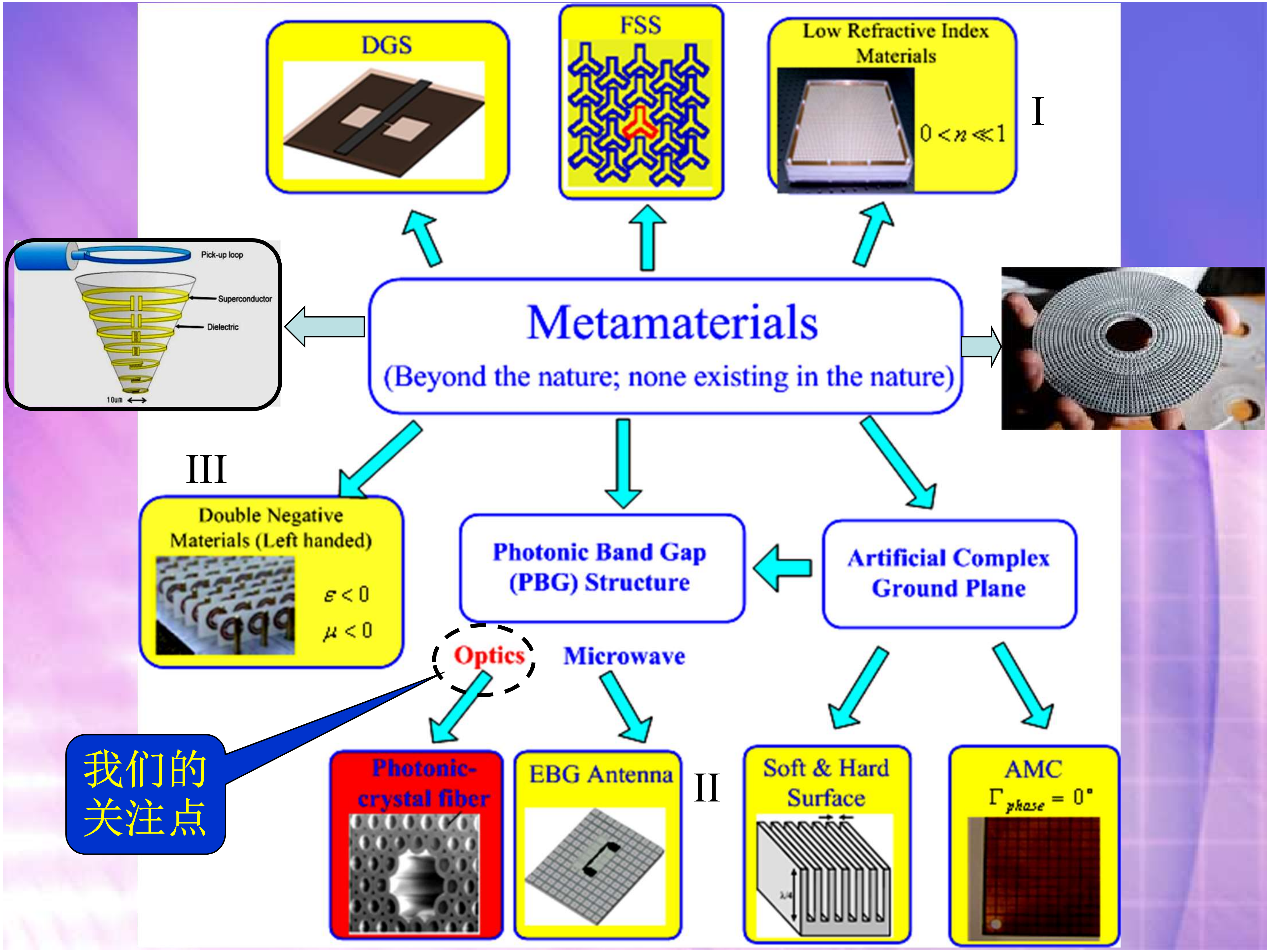
3. $\varepsilon>0,\mu<0$，则$k^2<0$，k无实数解，折射率为虚数，此时方程（1）和（2）无波动解，电磁波不能在其中传播。此类媒质的典型代表是处于铁磁谐振频率附近的铁氧体，位于第IV象限，也叫磁负材料（Mu-Negative Materials，MNM）。该材料内传播的电磁波也为倏逝波。

4. $\varepsilon<0,\mu<0$，其折射率为实数，如同象限I内的材料一样，电磁波能在其中传播，但是**k**、**E**、**H**之间不再满足右手螺旋关系而是满足左手螺旋关系，这种介质就被称为“左手材料”(Left-Handed Materials, LHM)。由于电磁波能流的方向取决于玻印廷矢量**S**的方向，而**S**=**E**x**H**,即**S**、**E**和**H**始终构成右手螺旋关系。因此在左手材料中，***k***(它的方向代表电磁波相速的方向)和**S**的方向相反。$k=-\omega\sqrt{\varepsilon\mu}$为负数，折射率也为负数$n=c/v_p=ck/\omega$，所以这种介质也被称为“负折射率物质” (Negative Index of Refraction Material, NIRM)。1967年，前苏联物理学家Veselago首次对这种材料进行了理论研究，并将这种材料称为LHM。

First NRI/Left-Handed Test Structure



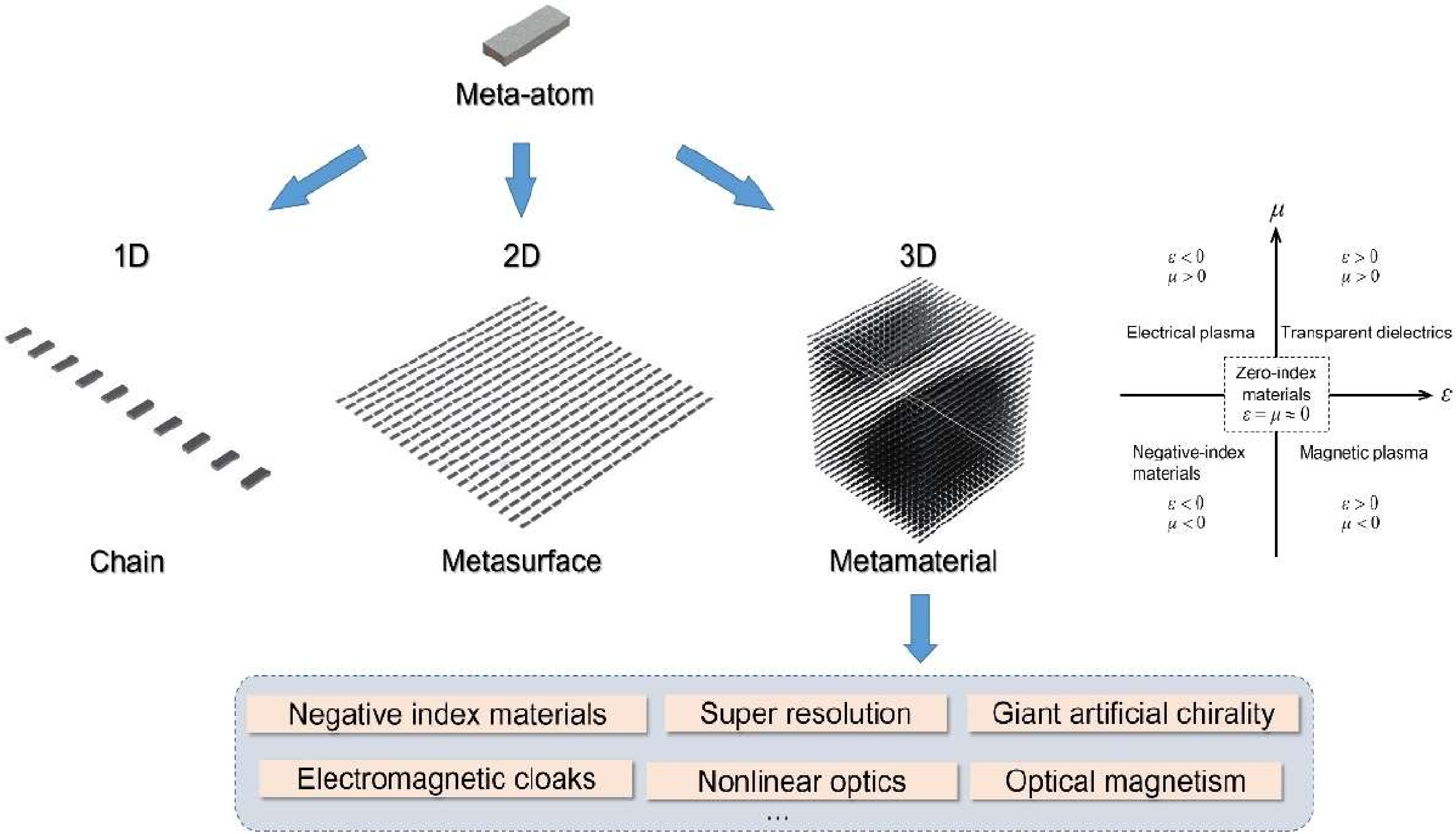
D.R. Smith, S. Schultz, et. al., UCSD, PRL 84, 4184 (2000).



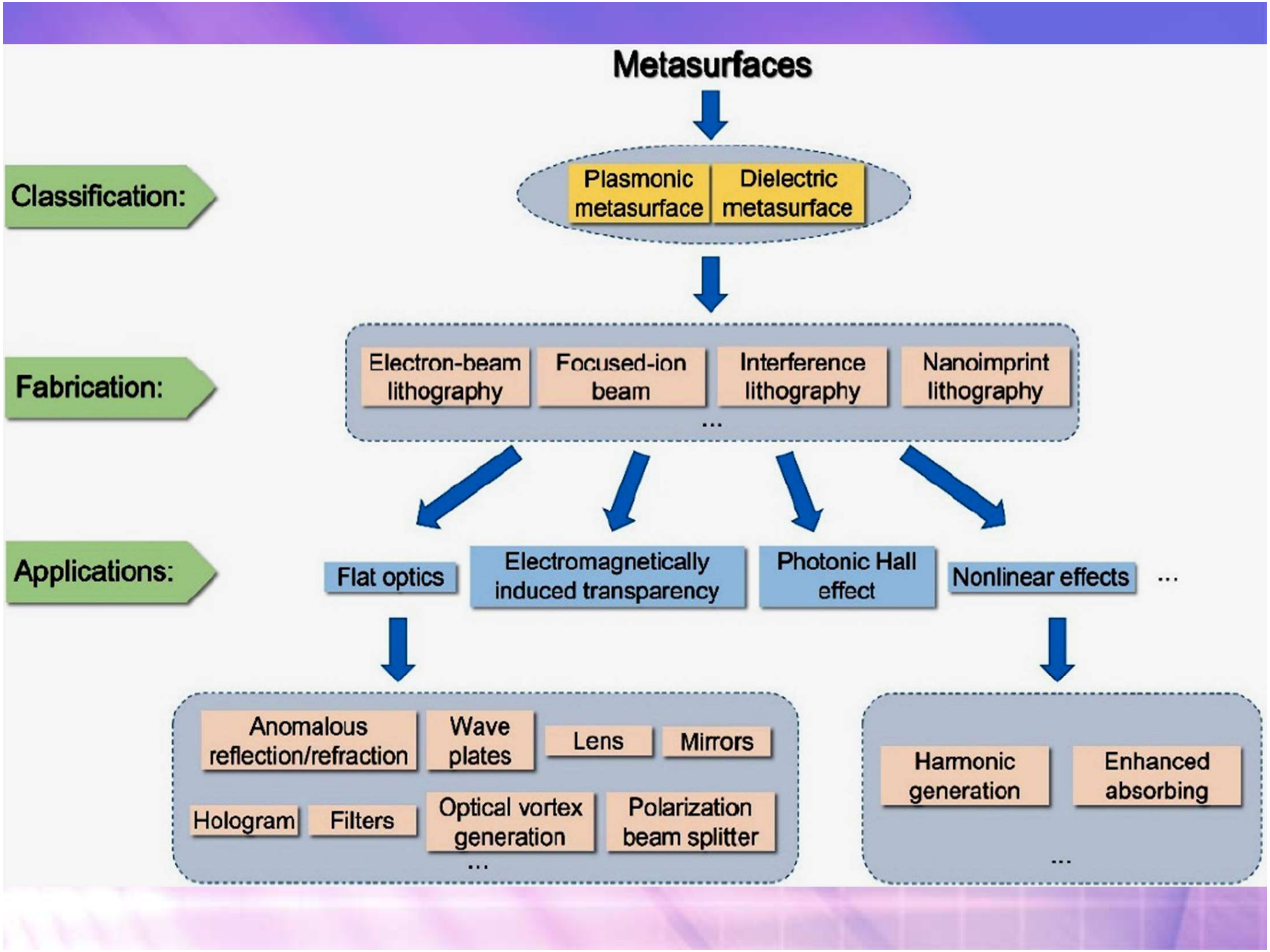
DGS
FSS
Low Refractive Index Materials
0 < n ≪ 1
I
Pick-up loop
Superconductor
Dielectric
10um
Metamaterials
(Beyond the nature; none existing in the nature)
III
Double Negative Materials (Left handed)
ε < 0
μ < 0
Photonic Band Gap (PBG) Structure
Artificial Complex Ground Plane
Optics
Microwave
我们的关注点
Photonic-crystal fiber
EBG Antenna
II
Soft & Hard Surface
AMC
Γphase = 0°

特异性材料（NIMs）的主要应用

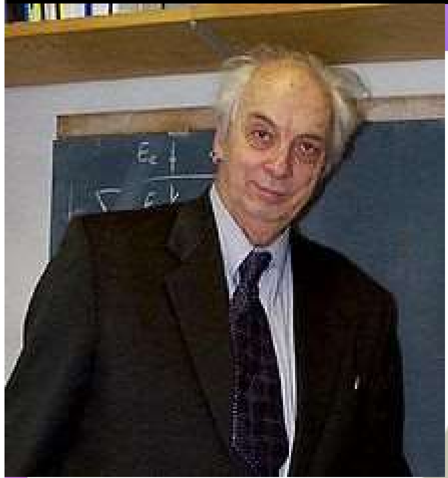
- 超分辨成像；
- 隐形：空气/真空环境隐形、水下声纳隐形；
- 微波天线如EBG增益天线、近零折射率发射天线；
- 超导体（超导近场显微镜）；
- 纳米光刻。



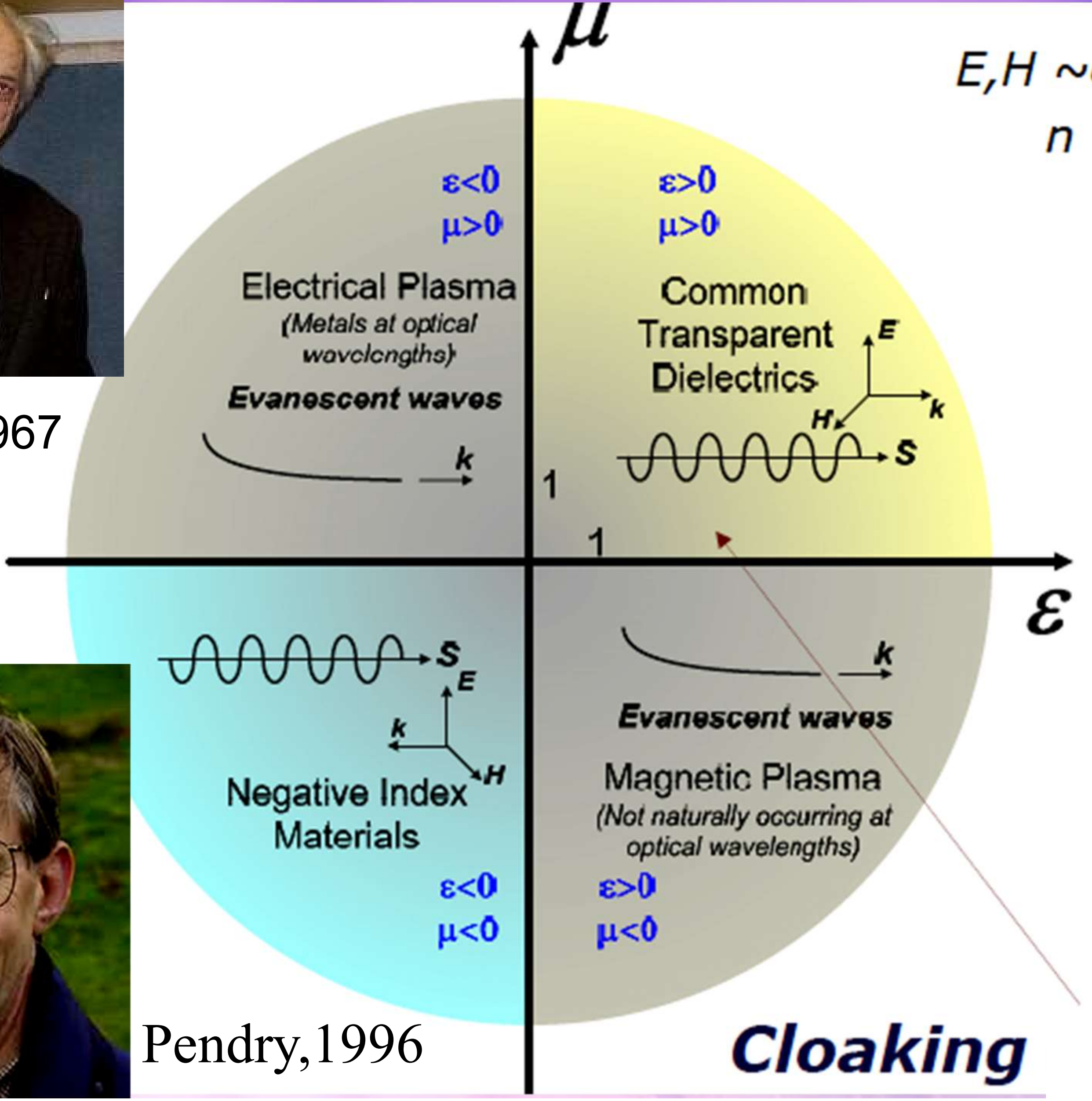
Meta-atom
1D
2D
3D
Chain
Metasurface
Metamaterial
μ
ε
$\varepsilon < 0$, $\mu > 0$
$\varepsilon > 0$, $\mu > 0$
Electrical plasma
Transparent dielectrics
Zero-index materials $\varepsilon = \mu \approx 0$
Negative-index materials
Magnetic plasma
$\varepsilon < 0$, $\mu < 0$
$\varepsilon > 0$, $\mu < 0$
Negative index materials
Super resolution
Giant artificial chirality
Electromagnetic cloaks
Nonlinear optics
Optical magnetism
...


Metasurfaces
Classification:
Plasmonic metasurface
Dielectric metasurface
Fabrication:
Electron-beam lithography
Focused-ion beam
Interference lithography
Nanoimprint lithography
...
Applications:
Flat optics
Electromagnetically induced transparency
Photonic Hall effect
Nonlinear effects
...
Anomalous reflection/refraction
Wave plates
Lens
Mirrors
Hologram
Filters
Optical vortex generation
Polarization beam splitter
...
Harmonic generation
Enhanced absorbing
...

Materials & Metamaterials

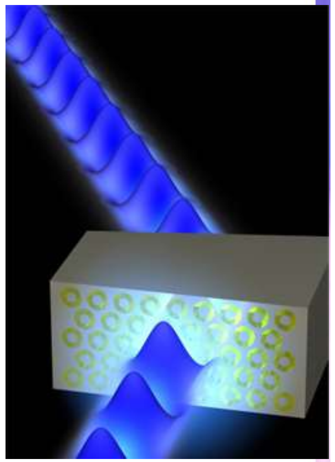


Veselago,1967



$E,H \sim exp[in(\omega/c)z]$

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



Pendry,1996

Cloaking

Milestone of NRI development

1967 — Veselago first studies the effect a negative permittivity and permeability has on wave propagation

1996 — Pendry proposes metal wire structures to realize a negative permittivity(-ε)

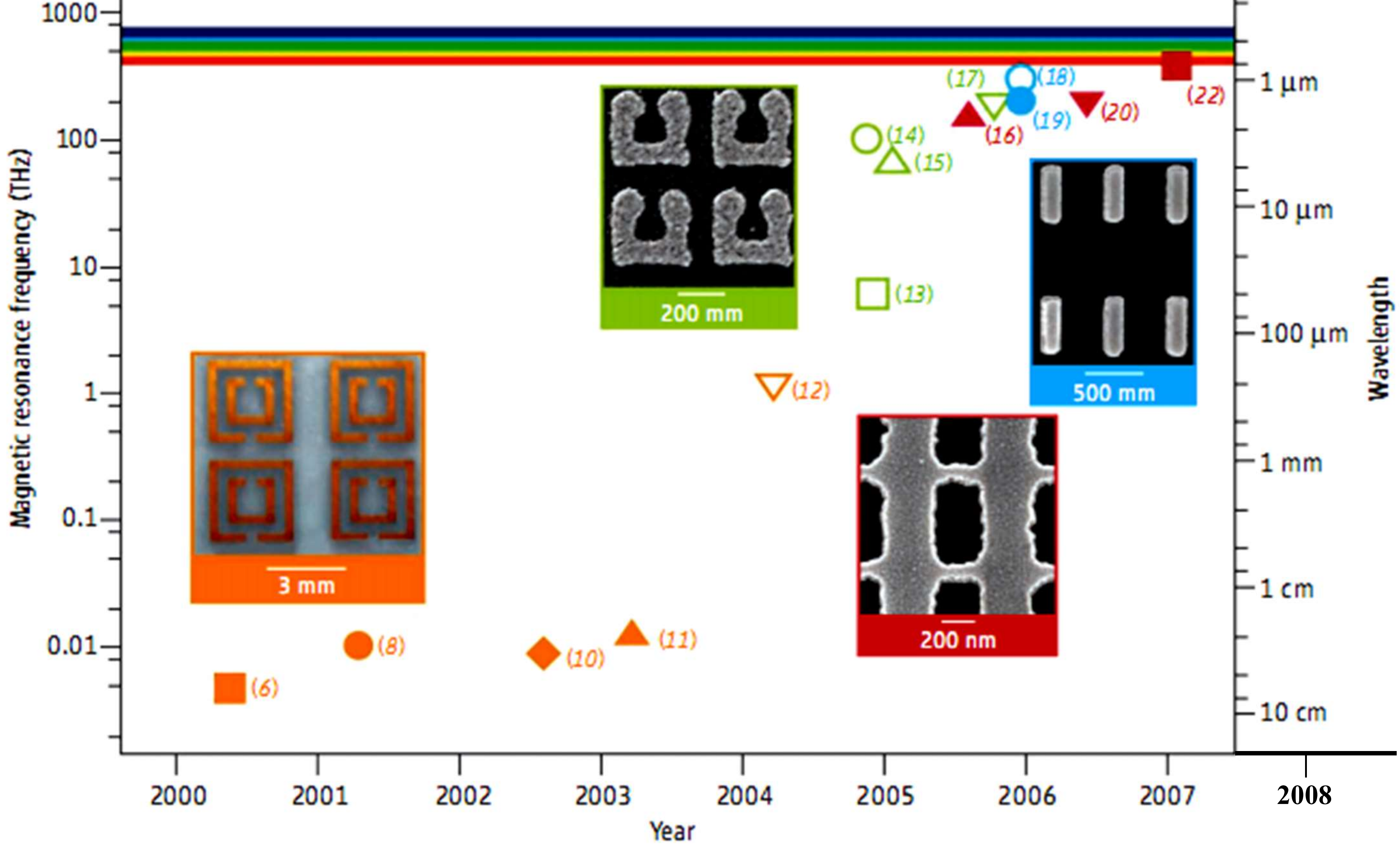
1999 — Pendry proposes Split Ring Resonators (SRR's) to realize a negative permeability(-μ)

2000 — Smith is the first in the world to realize a medium with an effective negative index of refraction

Time

Realizing a Negative Permittivity

Milestone of NRI development (cont.)



Advances in metamaterials. The solid symbols denote $n < 0$; the open symbols denote $\mu < 0$. Orange: data from structures based on the double split-ring resonator (SRR); green: data from U-shaped SRRs; blue: data red: data from the "fishnet" structure. The four insets give pictures of fabricated structures

Science 315,47 (2007).

Left-handed Materials (LHM) with Negative Refractive Index (NIR)

Refractive index: $n^2 = \varepsilon\mu$

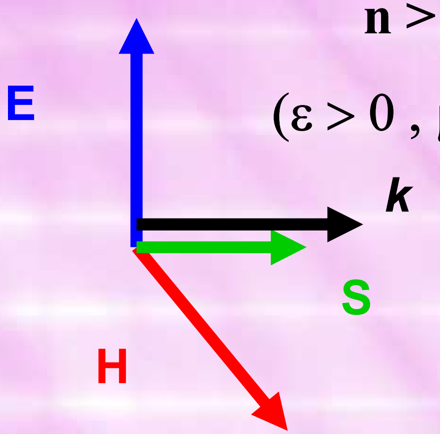
When ε < 0 and μ < 0 simultaneously, we have to choose

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

Maxwell's equation: $\vec{k} \times \vec{E} = \omega\mu\vec{H}, \quad \vec{k} \times \vec{H} = -\omega\varepsilon\vec{E}$

n > 0

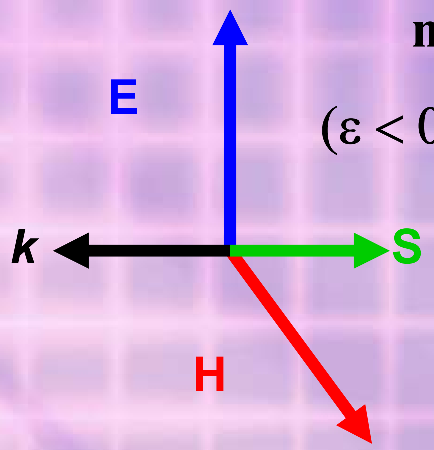
$(\varepsilon > 0, \mu > 0)$



Right handed materials (RHM)

n < 0

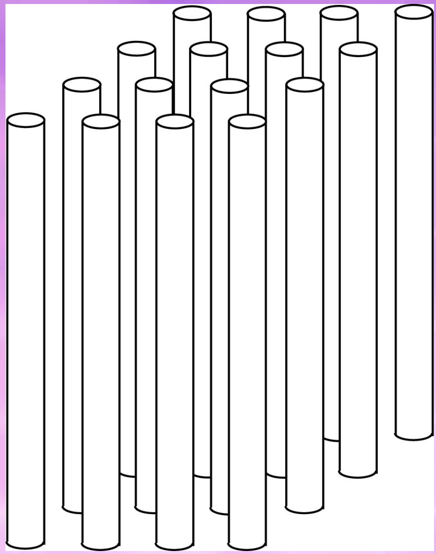
$(\varepsilon < 0, \mu < 0)$

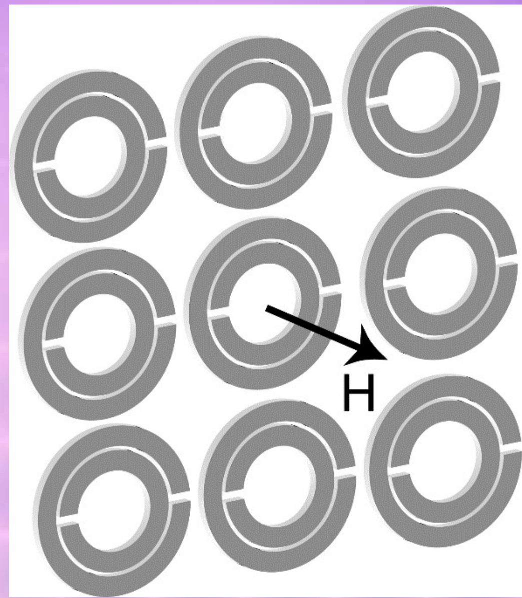


Left handed materials (LHM)

Metamaterials Extend Properties

-ε





-μ

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

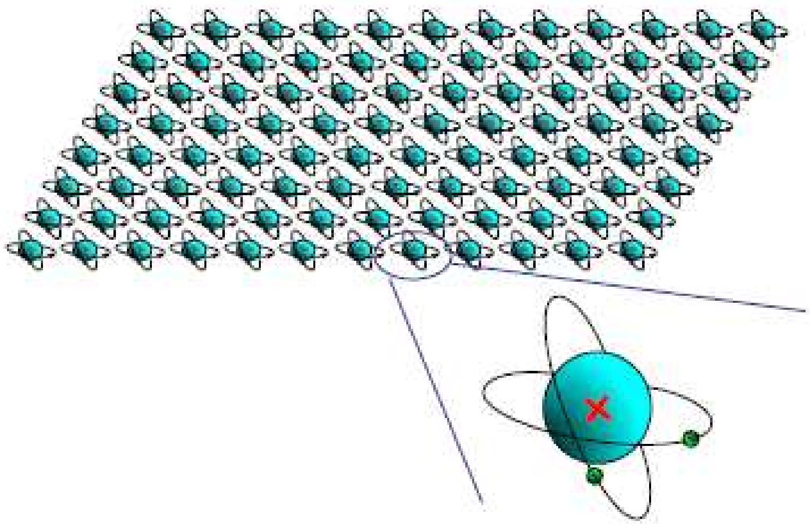
$$n = \sqrt{\varepsilon(\omega)\mu(\omega)}$$

$$\mu(\omega) = 1 - \frac{\omega_{mp}^2}{\omega^2 - \omega_0^2}$$

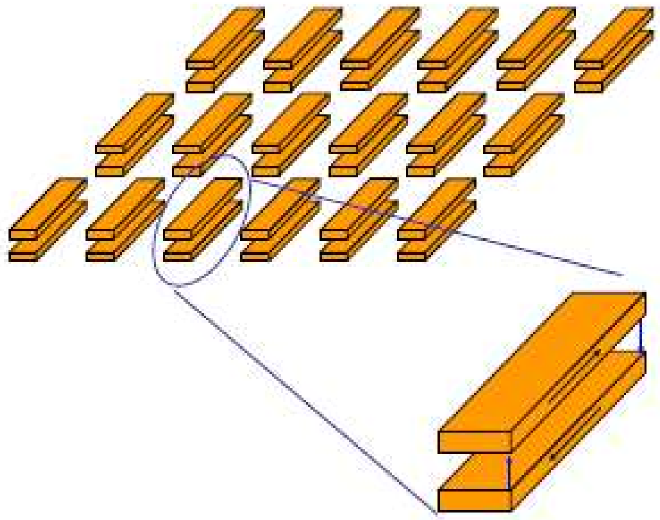
What is a metamaterial?

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

$\mu\epsilon\tau\alpha$ **= meta = beyond (Greek)**



A natural material with its atoms



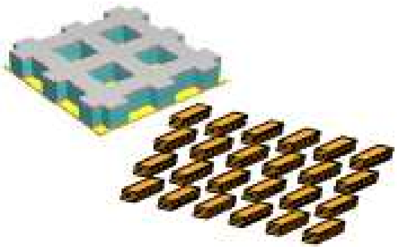
A metamaterial with artificially structured "atoms"

Photonic crystals *vs.* Optical metamaterials: connections and differences

0 — 1 — ∞ — a/λ

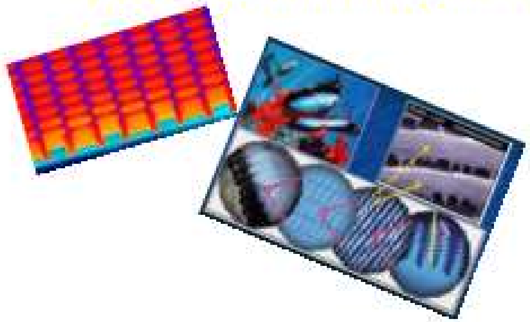
$a \ll \lambda$.
Effective medium description using Maxwell equations with μ, ε, n, Z

Example:
Optical crystals
Metamaterials



$a \sim \lambda$.
Structure dominates. Properties determined by diffraction and interference

Example:
Photonics crystals
Phased array radar
X-ray diffraction optics



$a \gg \lambda$.
Properties described using geometrical optics and ray tracing

Example:
Lens system
Shadows

材料举例

Natural Crystals

... have lattice constants much smaller than light wavelengths: $a \ll \lambda$

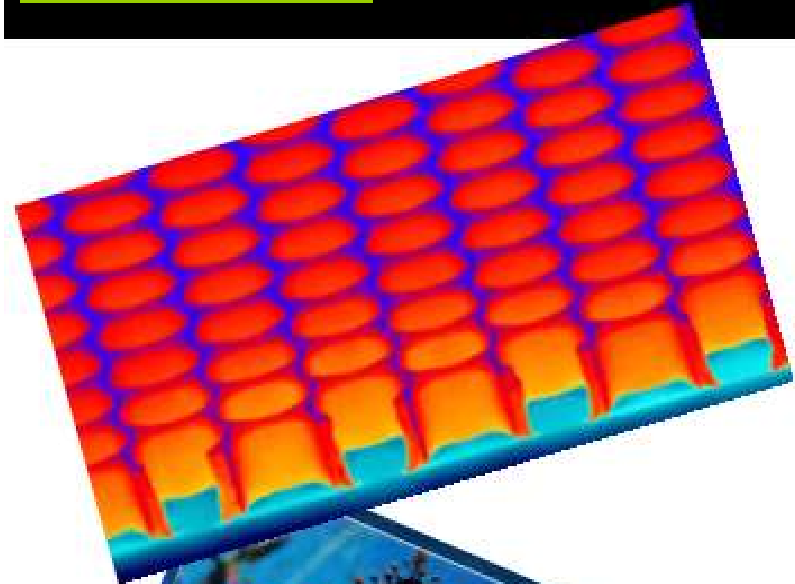
... are treated as homogeneous media with parameters ε, μ, n, Z (tensors in anisotropic crystals)

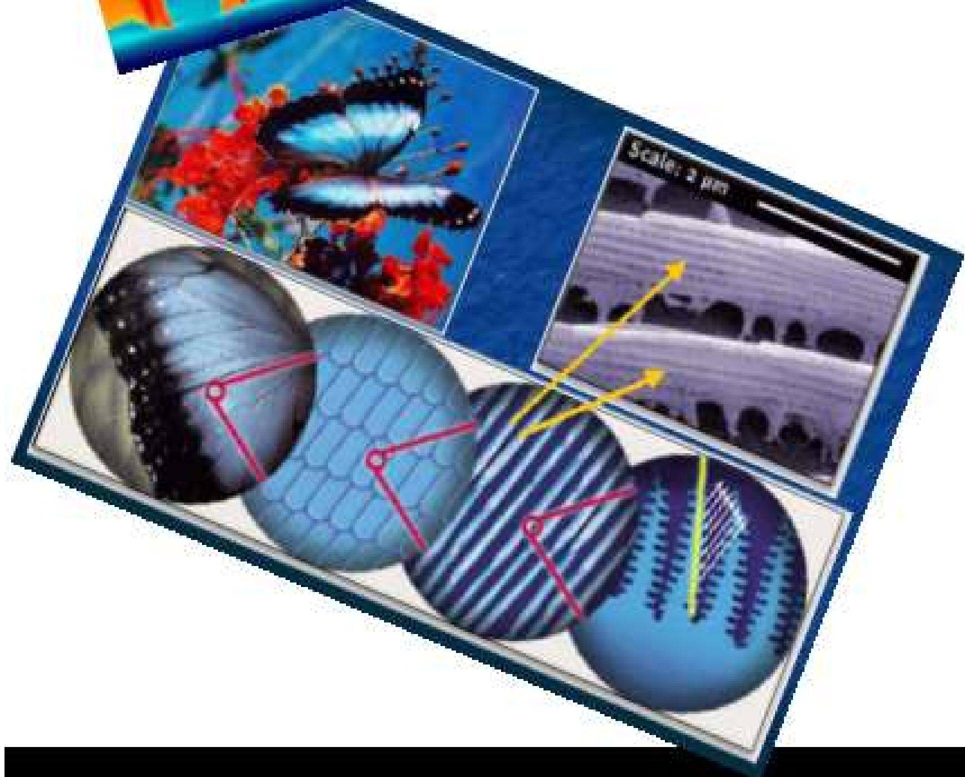
... have a positive refractive index: $n > 1$

... show no magnetic response at optical wavelengths: $\mu = 1$

材料举例

Photonic crystals





... have lattice constants comparable to light wavelengths: $a \sim \lambda$

... can be artificial or natural

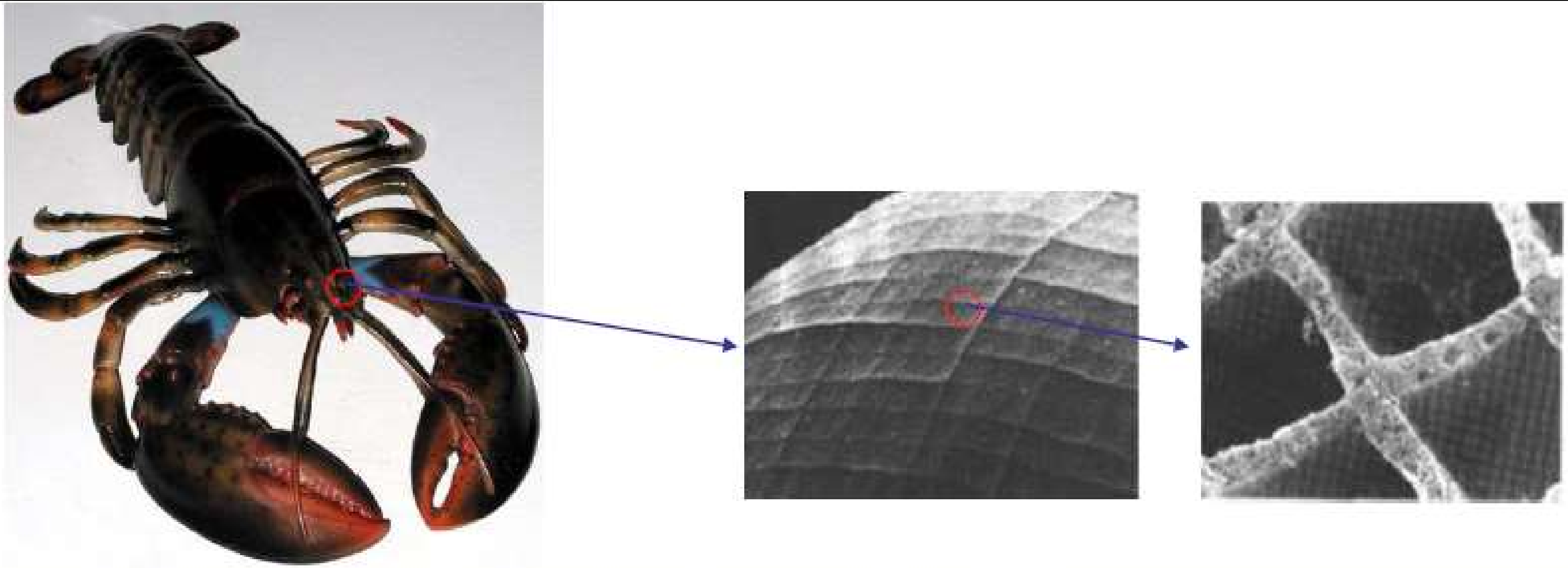
... have properties governed by the diffraction of the periodic structures

... may exhibit a bandgap for photons

... typically are *not* well described using effective parameters ε, μ, n, Z

... often behave like but they are *not* true metamaterials

Metamaterials: Properties not found in nature?



Journal of the European Optical Society - Rapid Publications 1, 06010 (2006)

www.jeos.org

Invertebrate superposition eyes-structures that behave like metamaterial with negative ~~refractive index~~

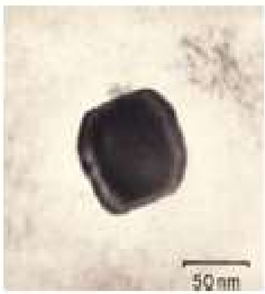
(refraction!)

D.G. Stavenga
D.G.Stavenga@rug.nl

Department of Neurobiophysics, University of Groningen, NL 9747 AG Groningen, the Netherlands

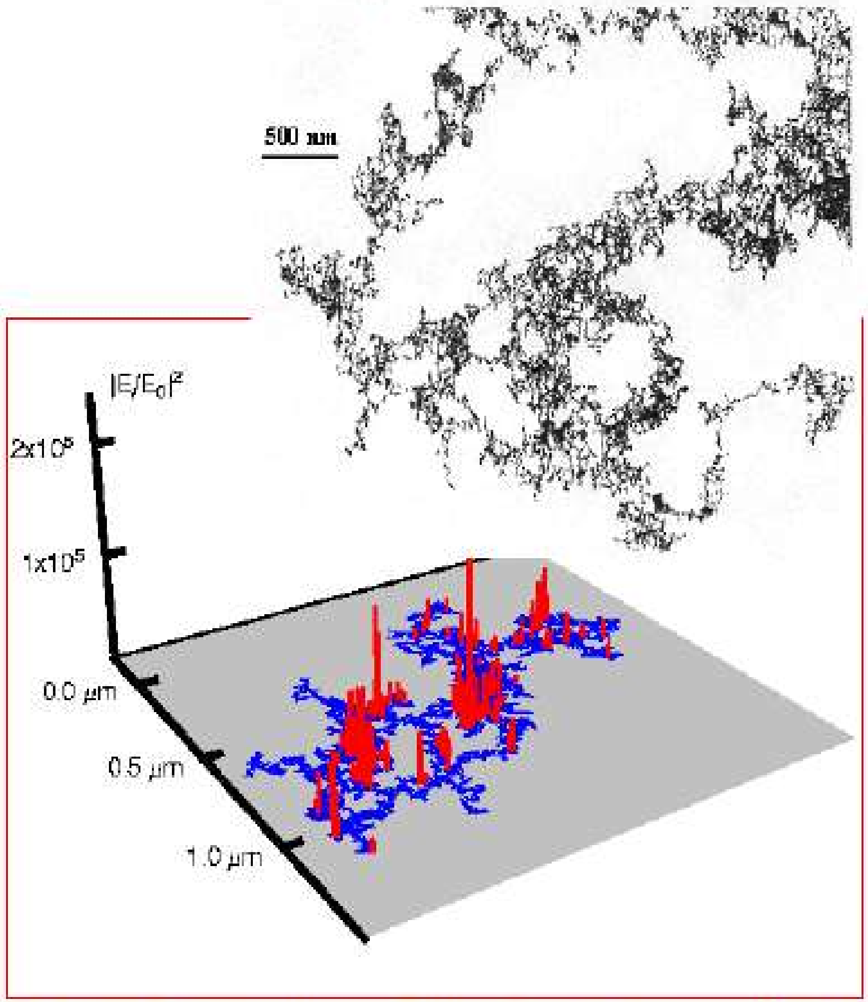
Metamaterials: Artificial periodic structures?

Lycurgus Cup (4th century AD)



Ancient (first?) random metamaterial (carved in Rome!) with gold nano particles

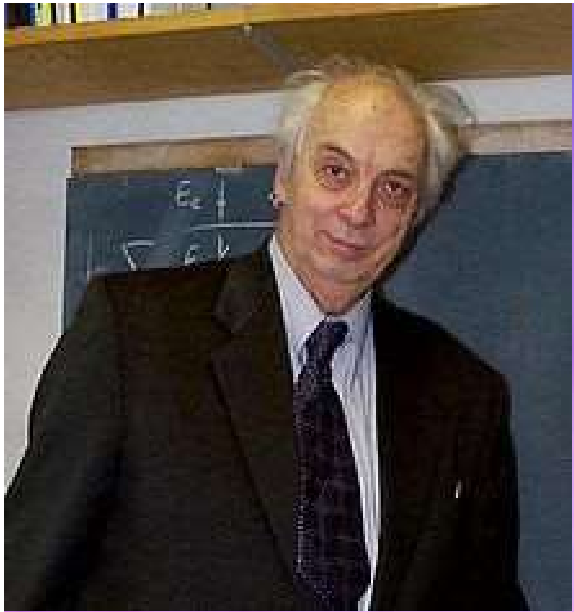
"Hot-spots" in fractals



Shalaev, Nonlinear Optics of Random Media, Springer, 2000; see also papers by Stockman

Light-matter interaction vs. structure size

structure	atomic lattice	meta-material	photonic crystal	waveguide array
size	Å	~100 nm	~500 nm	~10 μm
interaction	electronic phononic	plasmonic	diffraction	diffraction
description	dielectric function $\varepsilon(\omega)$, [$\mu(\omega)$] $\rightarrow n(\omega)$	bi-anisotropic function $\varepsilon(k,\omega)$, $\mu(k,\omega)$ $n(k,\omega) = \pm\sqrt{\varepsilon(k,\omega)\mu(k,\omega)}$ $Z(k,\omega) = Z_0 \pm \sqrt{\frac{\mu(k,\omega)}{\varepsilon(k,\omega)}}$	photonic band structure (multiple modes) $k_j(\omega)$	
realization	nature (chemistry)	nanotechnologies (metal-dielectric)	microtechnologies (dielectrics)	



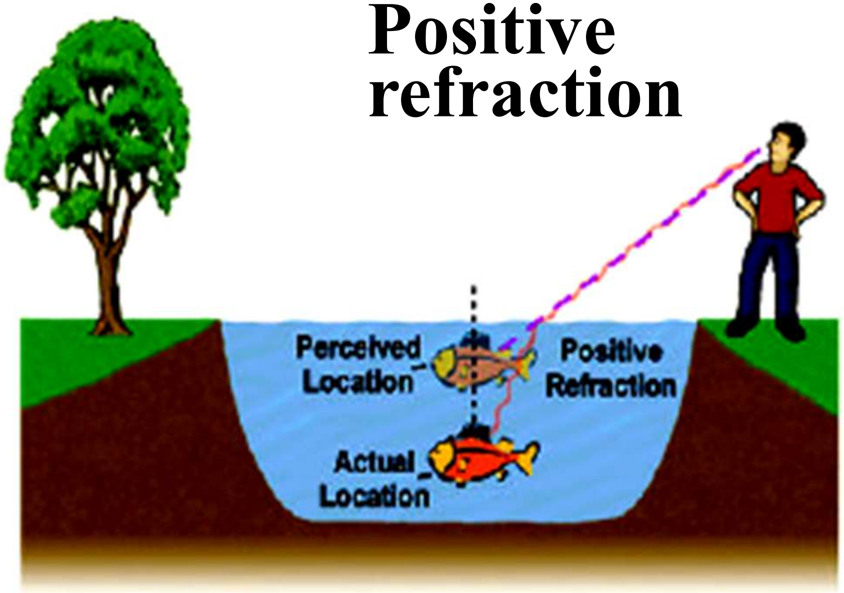
Negative refractive index

—A new concept/frontier in optics

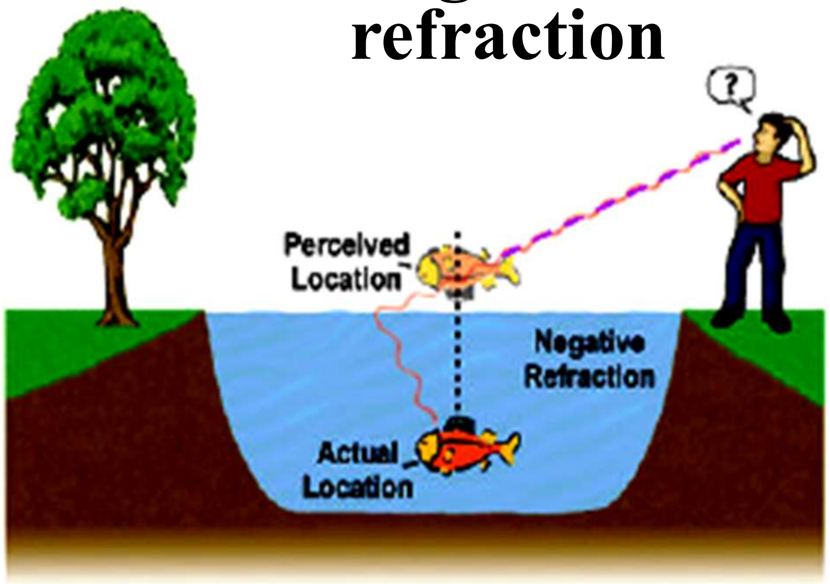
Any special with negative refraction?

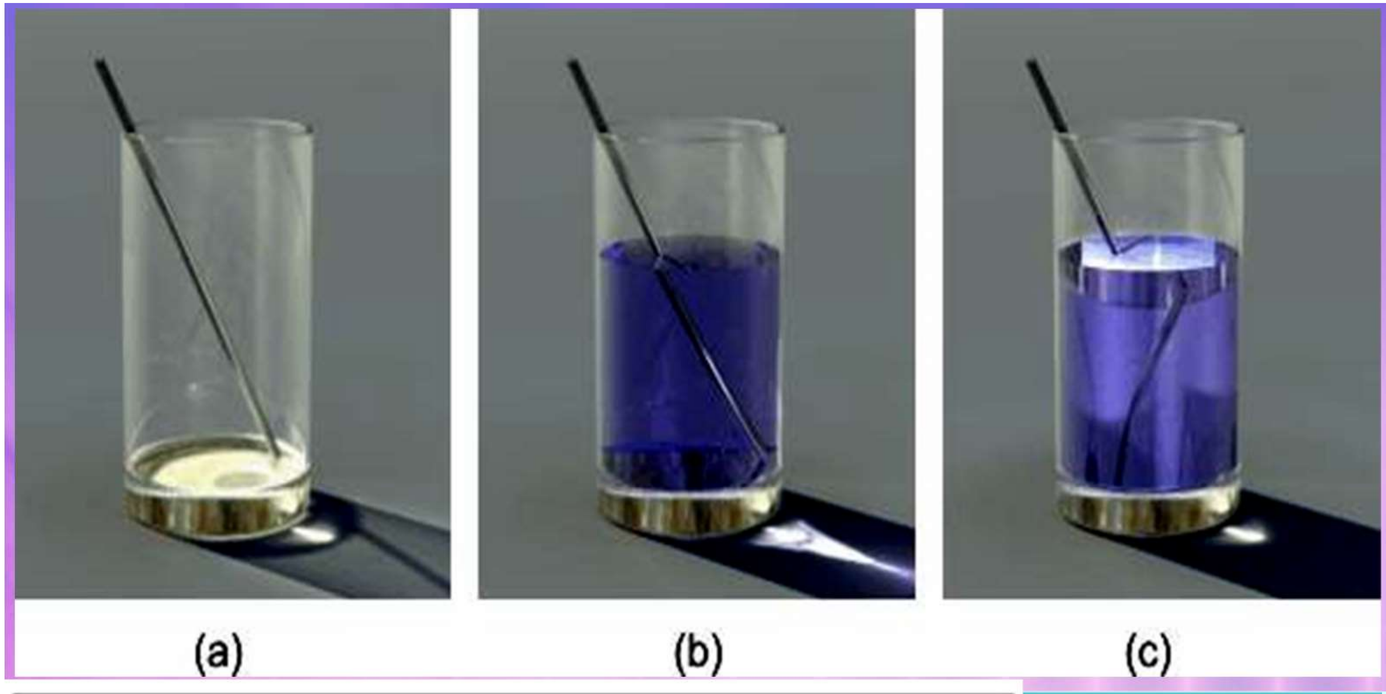
One of the most important and very interesting characteristics of metamaterials is the *negative refraction*

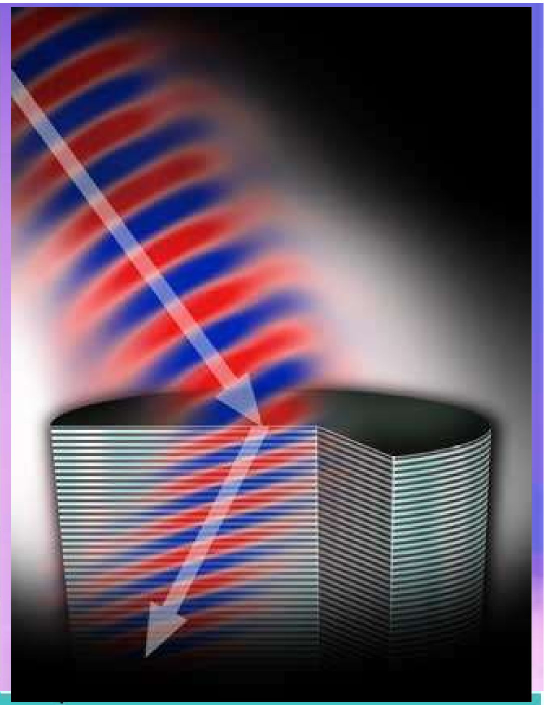
Positive refraction



Negative refraction




(a)
(b)
(c)



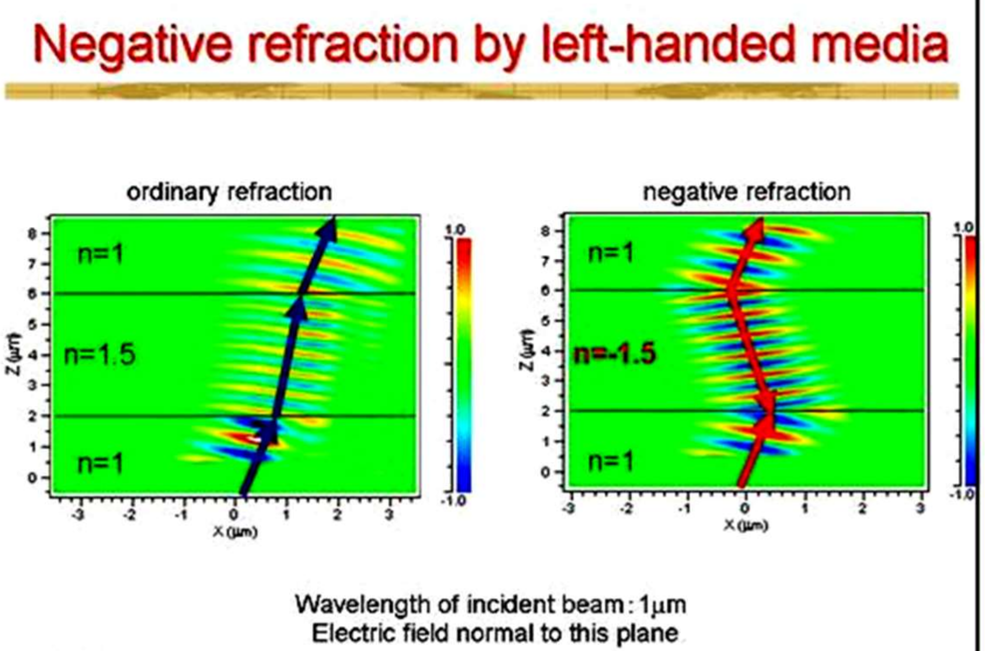
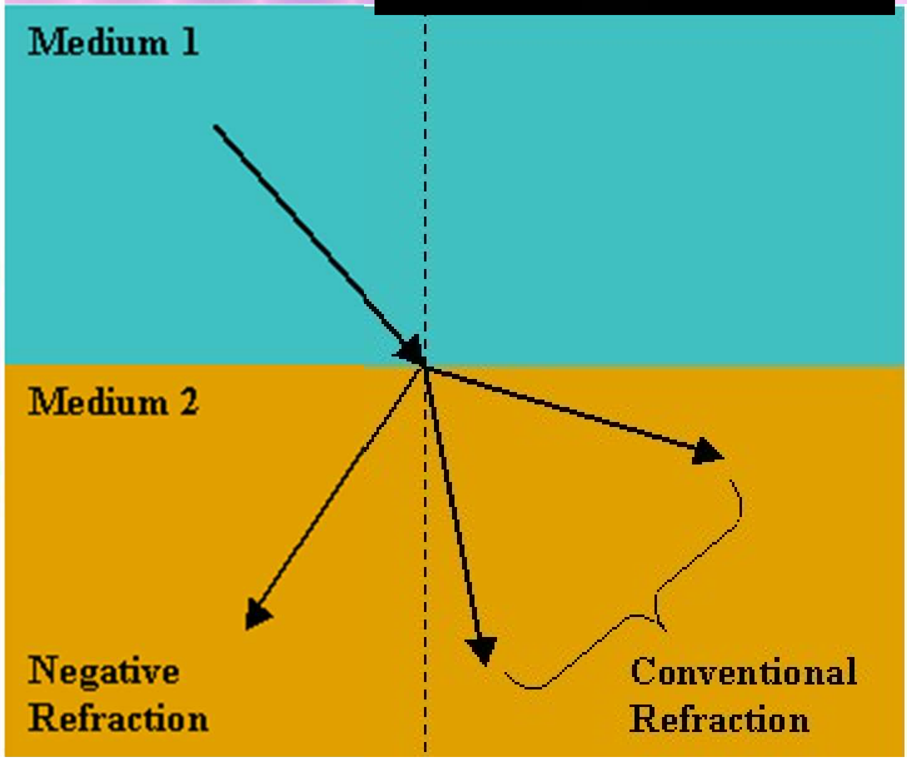
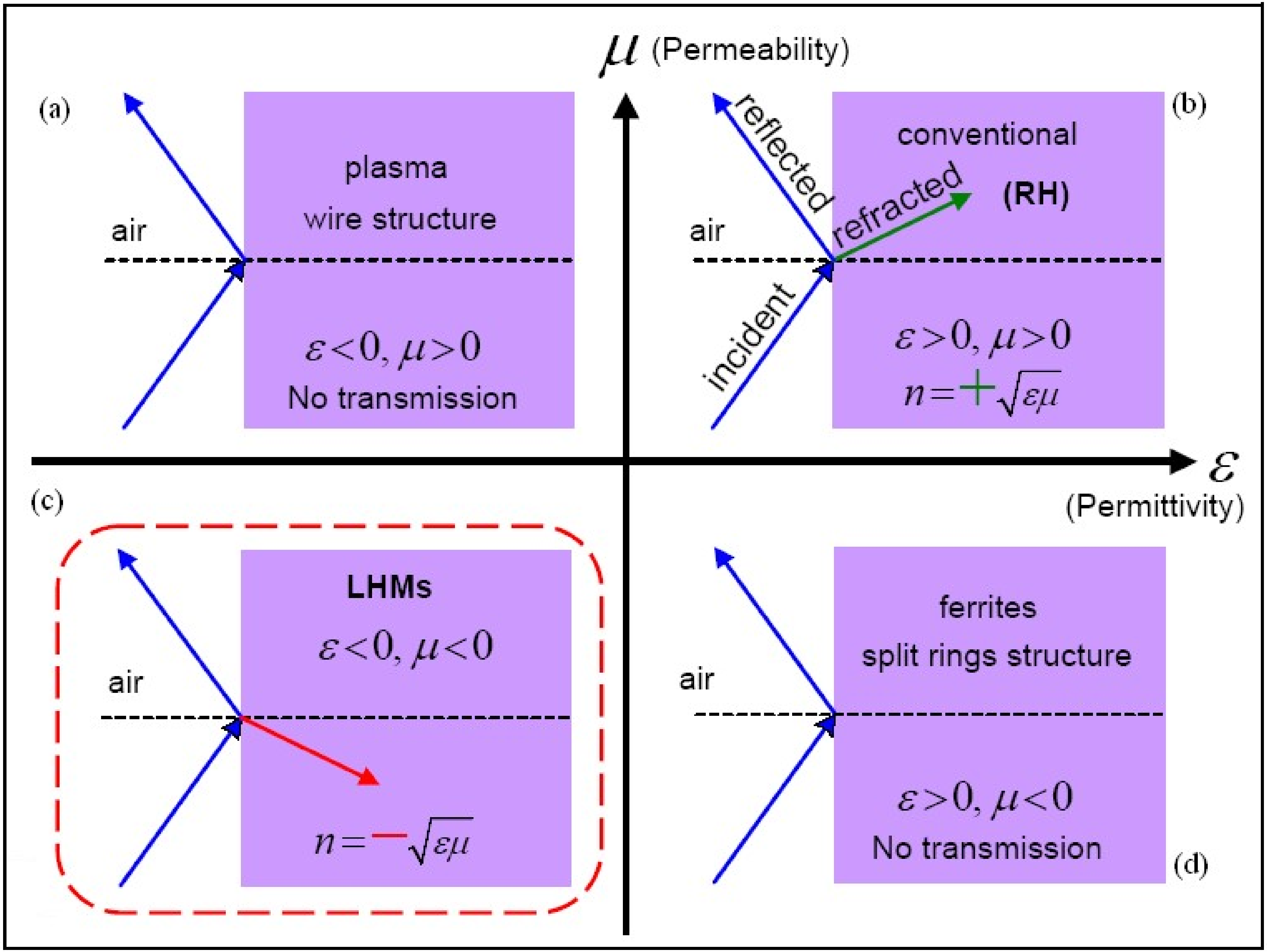

Negative refraction by left-handed media
ordinary refraction
negative refraction
n=1
n=1.5
n=1
n=1
n=-1.5
n=1
Z (μm)
X (μm)
Wavelength of incident beam: 1μm
Electric field normal to this plane

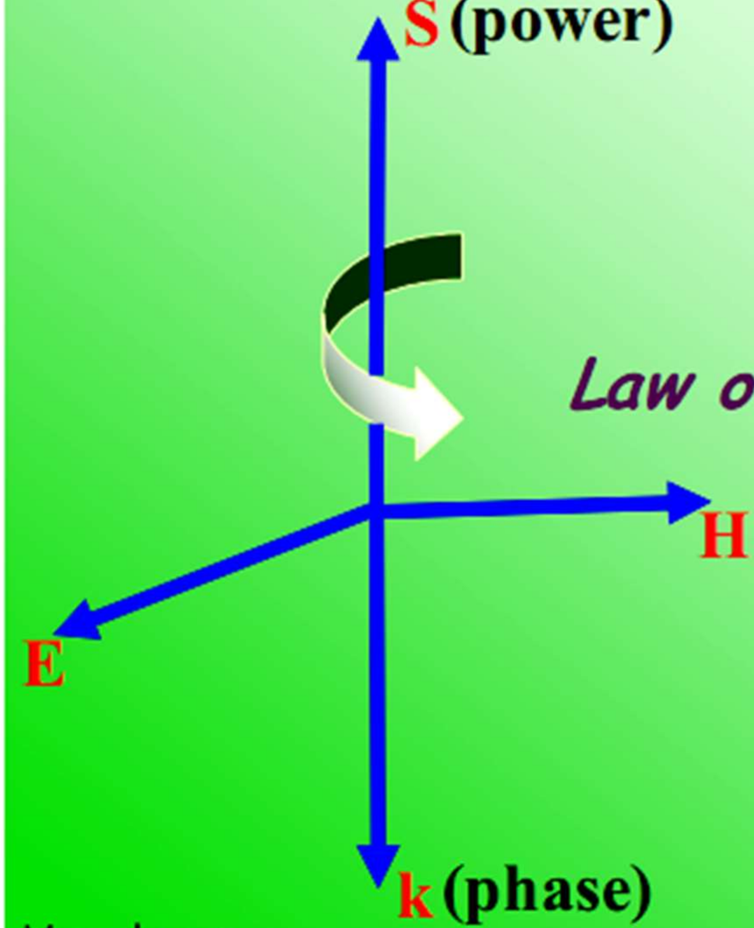
Fig.2


Medium 1
Medium 2
Negative Refraction
Conventional Refraction



μ (Permeability)
ε (Permittivity)
(a)
air
plasma
wire structure
ε<0, μ>0
No transmission
(b)
reflected
refracted
incident
air
conventional
(RH)
ε>0, μ>0
n=+√εμ
(c)
air
LHMs
ε<0, μ<0
n=−√εμ
(d)
air
ferrites
split rings structure
ε>0, μ<0
No transmission

A LEFT-HANDED MATERIAL(LHM)?



Backward waves

Law of unintended consequences

LEFT-HANDED MEDIUM

$$\varepsilon(\omega) < 0, \quad \mu(\omega) < 0$$

Veselago:
Sov Phys Usp **10** 509
(1968)

More Choices

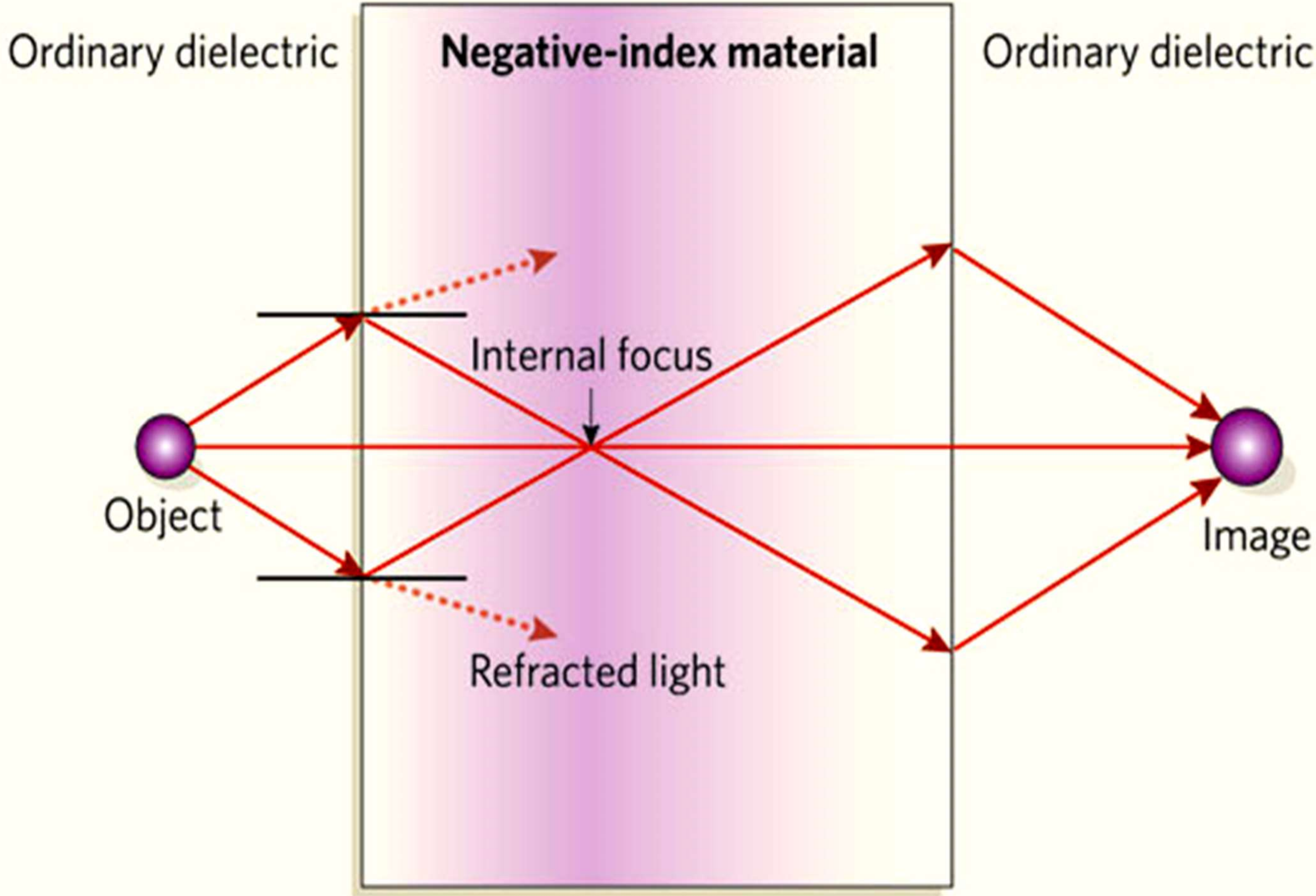
$$n = \pm\sqrt{\varepsilon\mu}$$

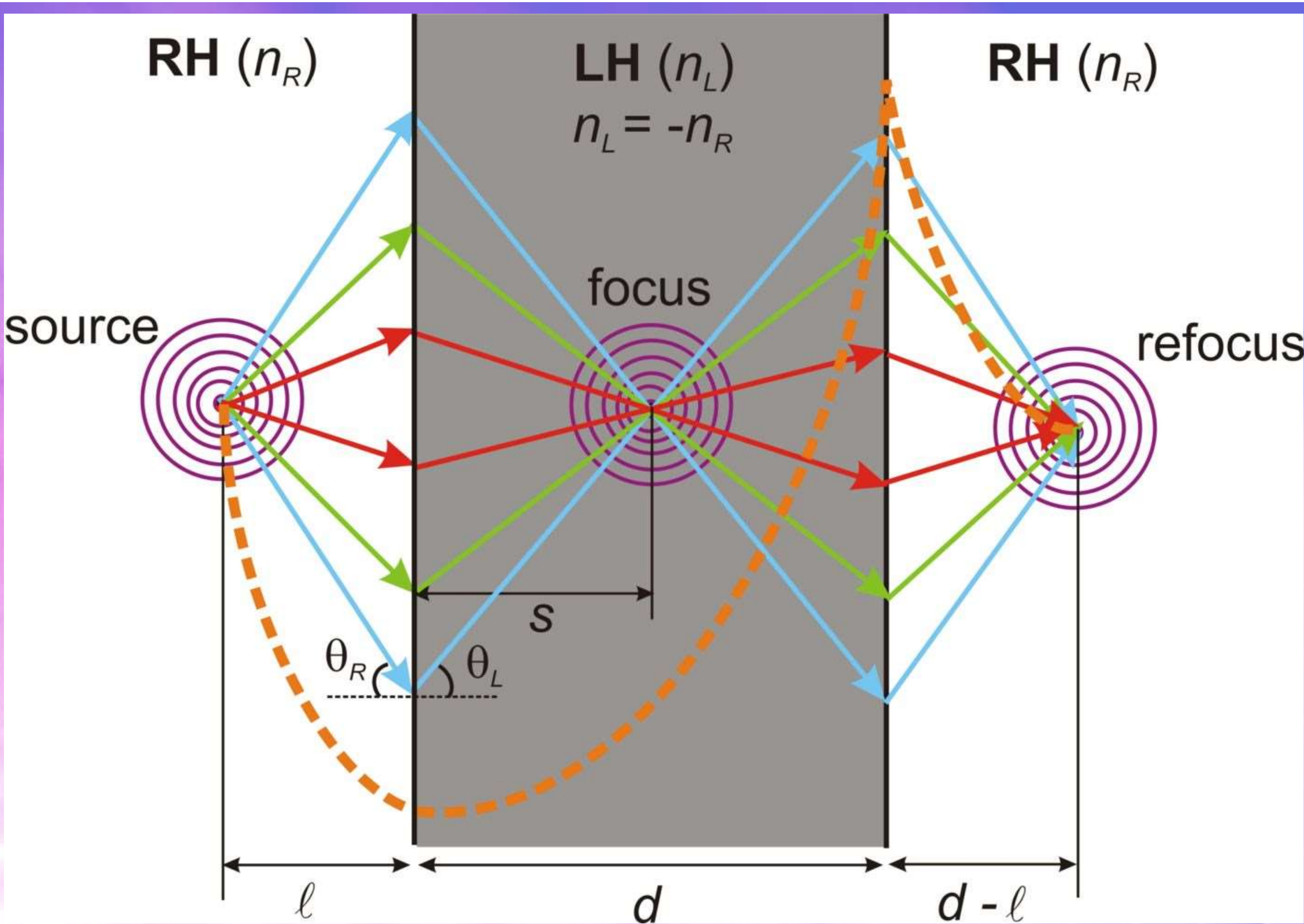
OR

$$n = \pm\sqrt{(-\varepsilon)(-\mu)}$$

ABSORPTION	$+\varepsilon, -\mu$ ✗	$+\varepsilon, +\mu$ ✗	POSITIVE REFRACTION
NEGATIVE REFRACTION!!	$-\varepsilon, -\mu$ ✓	$-\varepsilon, +\mu$ ✗	ABSORPTION

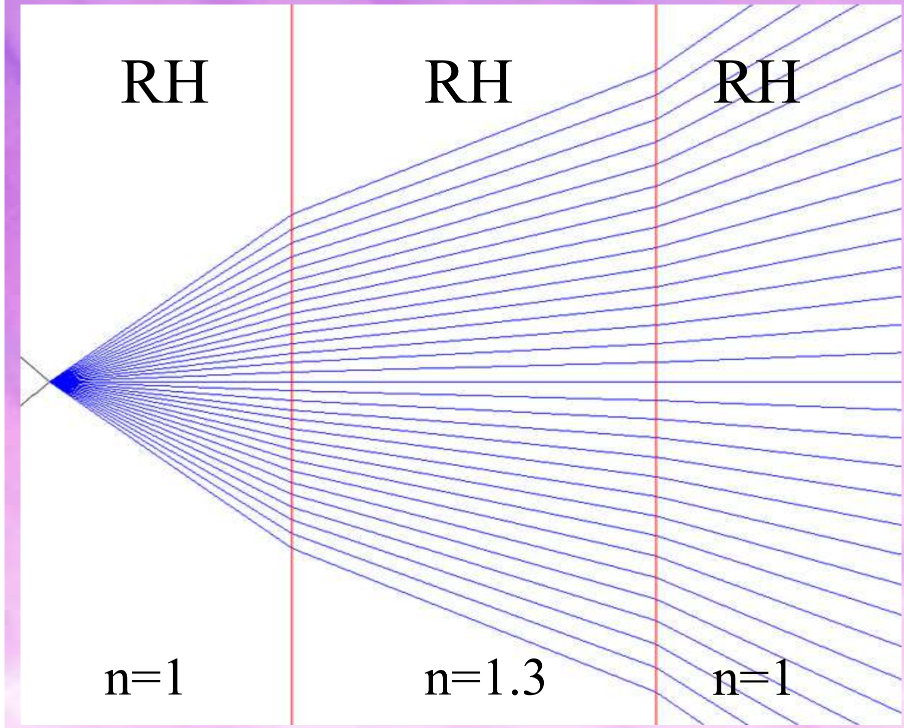
Diffraction free imaging

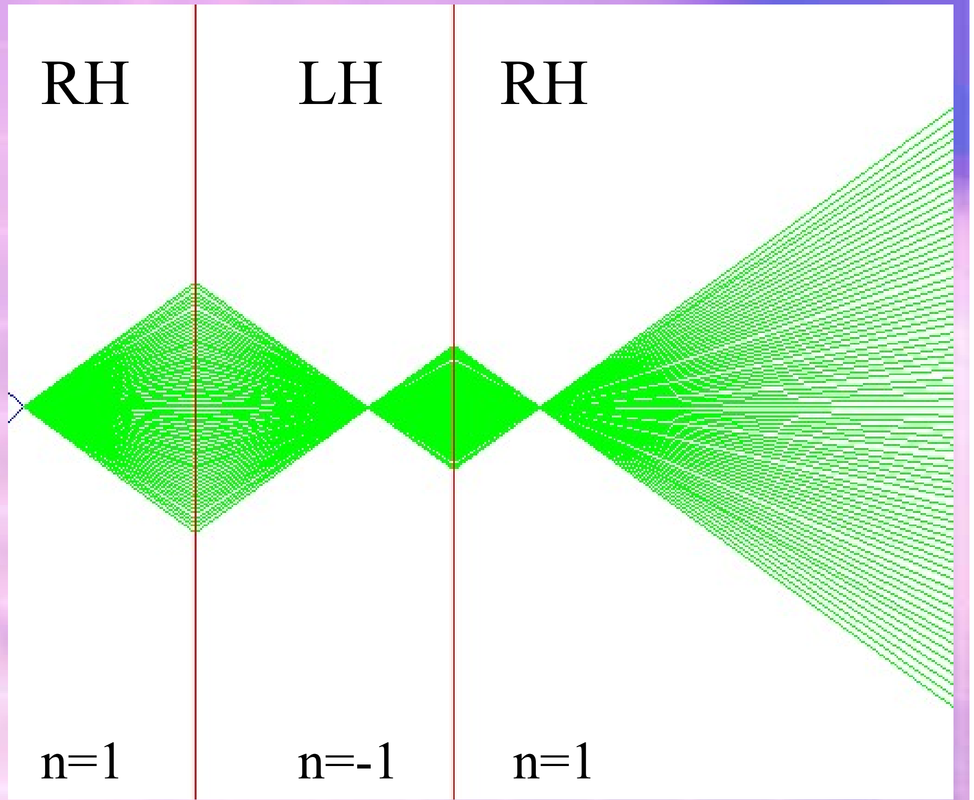




Ray-model analysis of the double-focusing effect in a NRI heterostructure. Also shown is the amplification of the source's near-field.

Focusing in a Left-Handed Medium

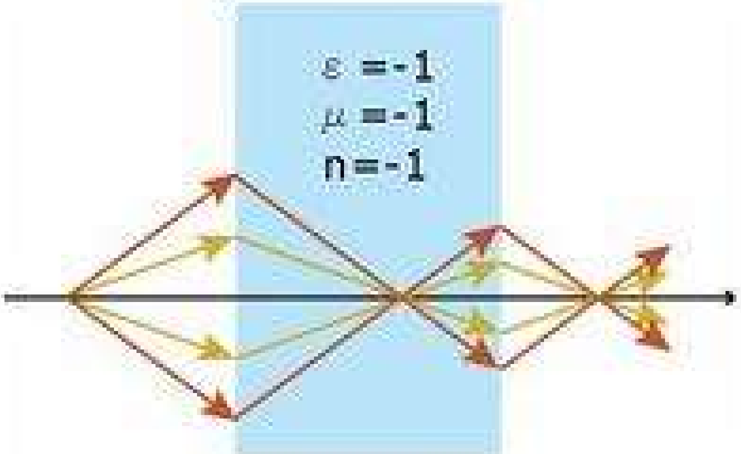


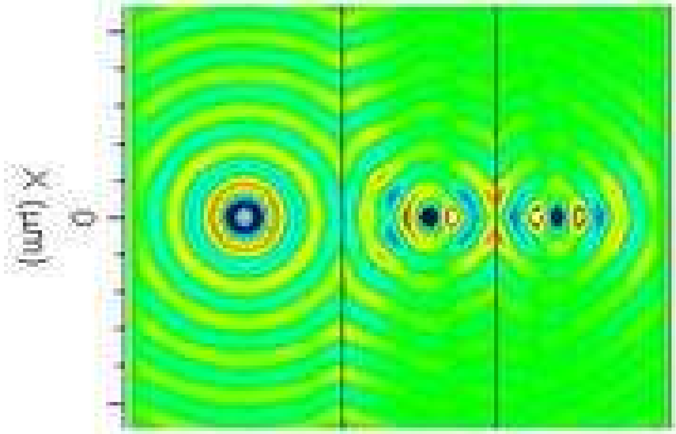


Realize diffraction free!

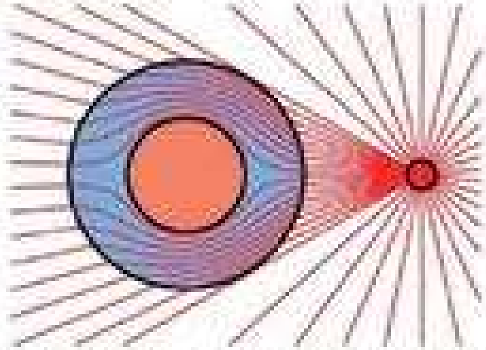
Applications of metamaterials

perfect lens

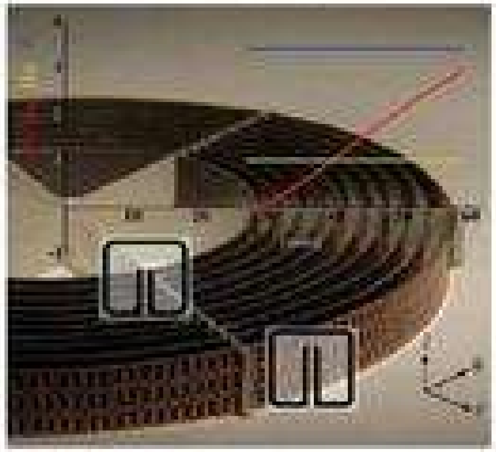




optical cloaking



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



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

Fig.3

隐身技术

电磁隐身是隐身技术的进一步提升

什么是隐身技术?

使雷达看不到飞机的技术，具有有两种途径实现：

–飞机机身特定的形状可以使雷达波发生漫反射；

–机身涂层采用高吸收波材料

Stealth Technology: F117 Night Hawk

Stealth Technology

Stealth Technology: F117 Night Hawk

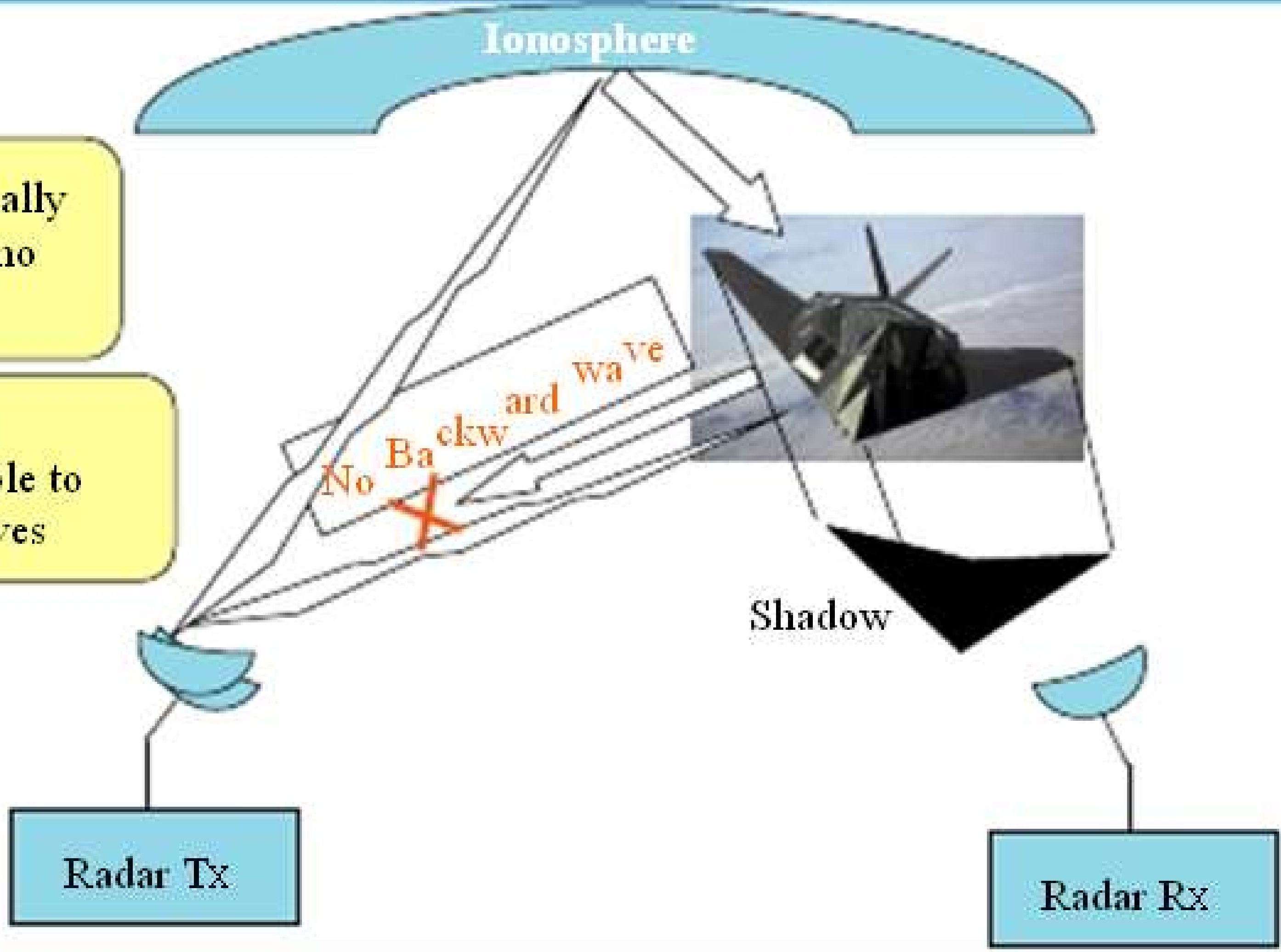
The main feature of this plane is its reduced RADAR cross section which results mainly due to its very odd mechanical design.

Stealth Technology: B2 Bomber

Electromagnetic Cloaking

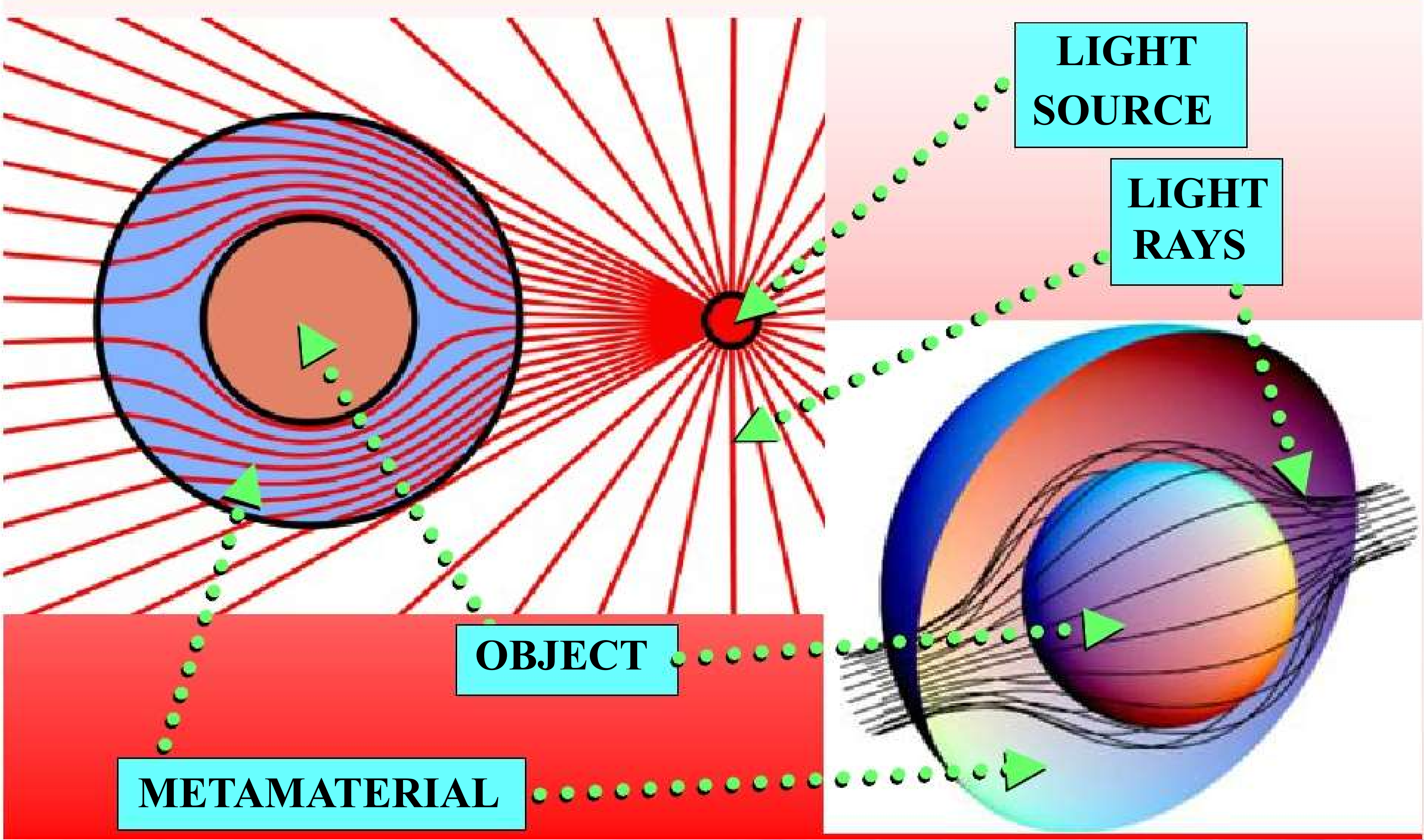
An electromagnetically cloaked object has no shadow

Cloaking means to render things invisible to electromagnetic waves

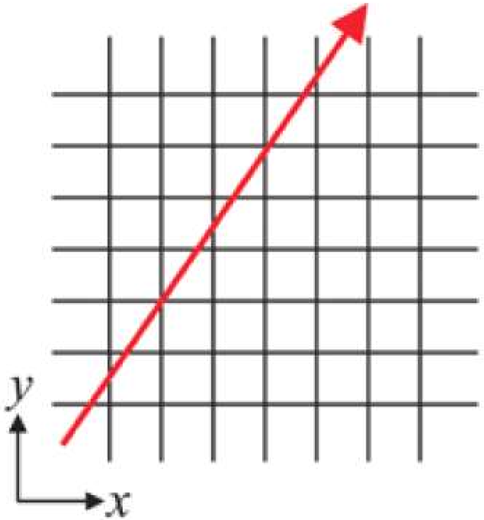


基于超表面结构法人隐身技术

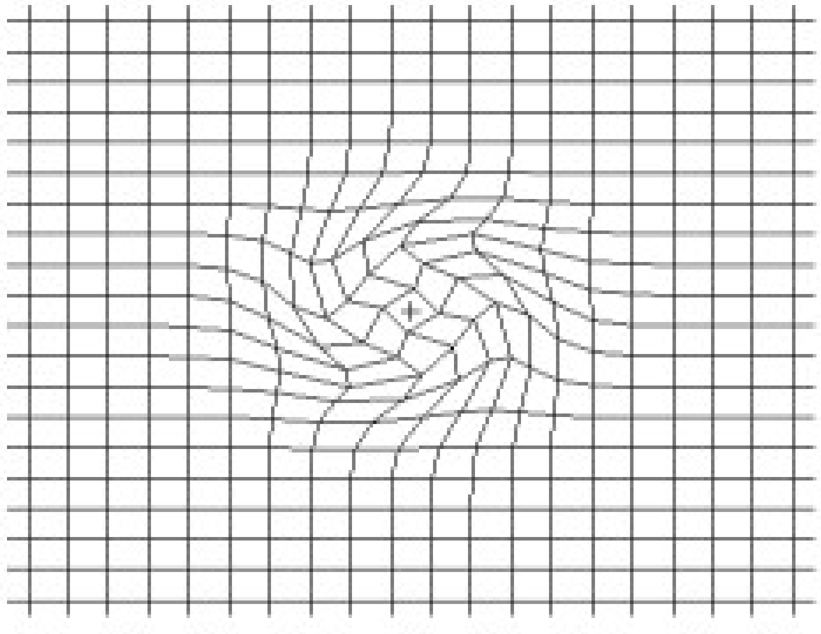
We can use metamaterials as an invisibility cloak



变换光学



Straight field line in Cartesian coordinate



Distorted field line in distorted coordinate

Spatial profile of ε & μ tensors determines the distortion of coordinates
Optical metamaterials provide unprecedented control of electromagnetic fields. If we can change the path of light at will …

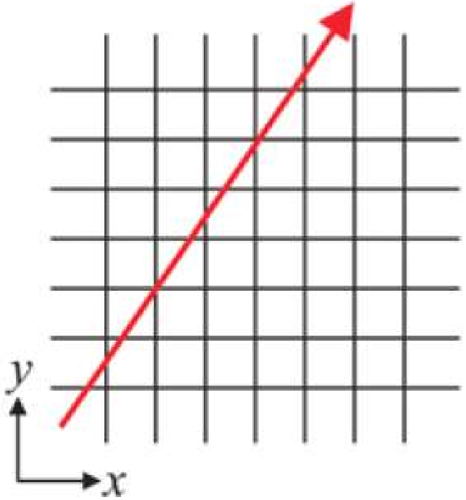
Pendry et al., Science, 2006
Leonhard, Science, 2006

Pendry, Smith, "Controlling electromagnetic fields," Science 312, 1780 (2006)

D. Schurig et al., "Metamaterial electromagnetic cloak at microwave frequencies," Science 314, 977 (2006)

变换光学

C (x, y, z) 虚空间



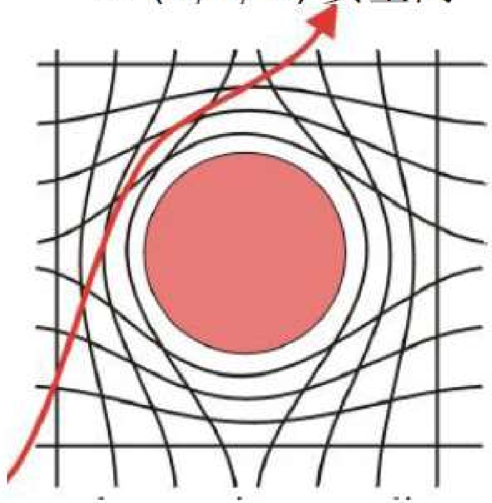
黎曼度量

$$L_u = \left[\left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2\right]^{\frac{1}{2}}$$

$$L_v = \left[\left(\frac{\partial x}{\partial v}\right)^2 + \left(\frac{\partial y}{\partial v}\right)^2 + \left(\frac{\partial y}{\partial v}\right)^2\right]^{\frac{1}{2}}$$

$$L_w = \left[\left(\frac{\partial x}{\partial w}\right)^2 + \left(\frac{\partial y}{\partial w}\right)^2 + \left(\frac{\partial y}{\partial w}\right)^2\right]^{\frac{1}{2}}$$

S' (u, v, w) 实空间



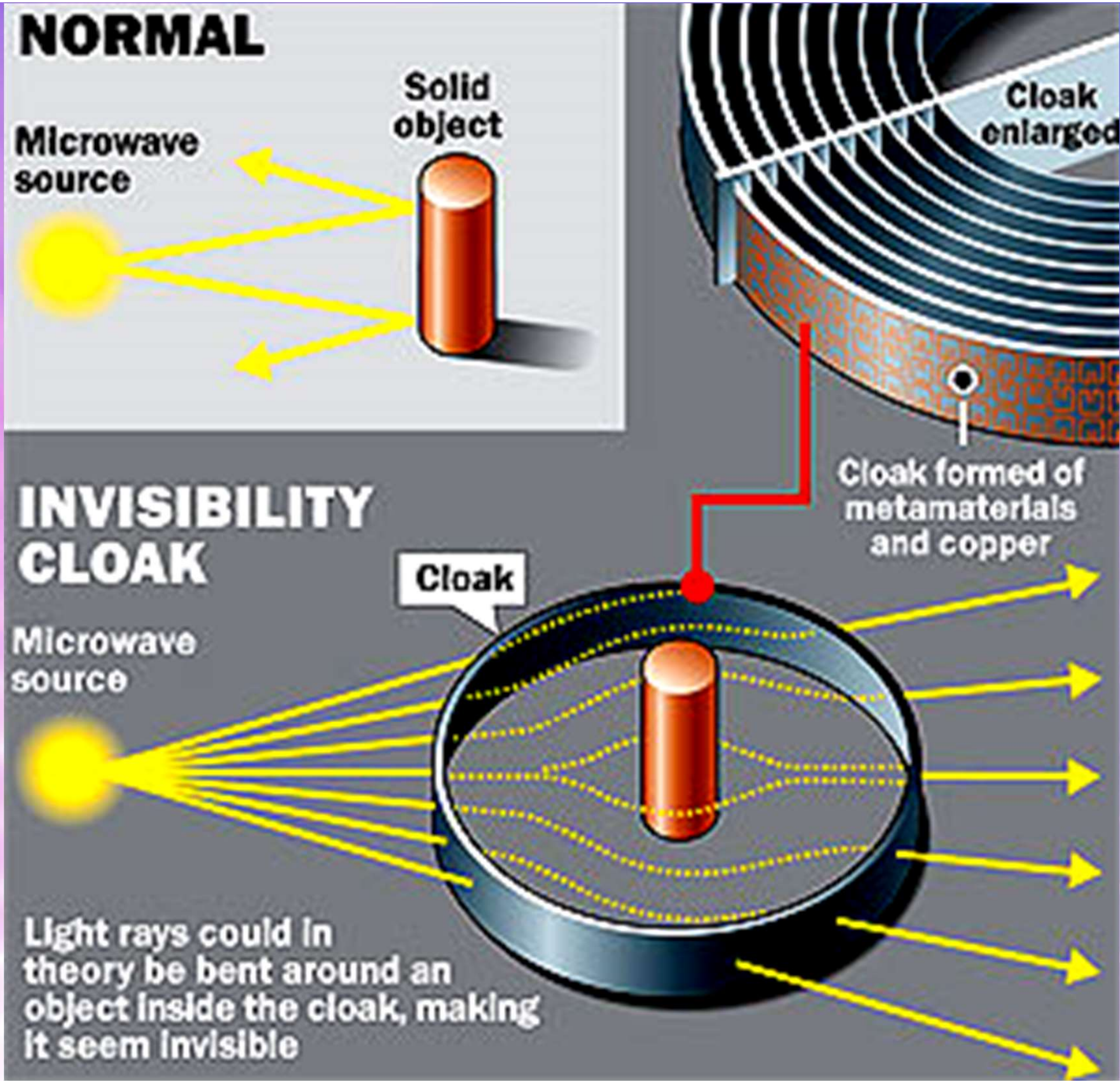
Maxwell's equations have exactly the same form in any coordinate system

$$\varepsilon_u' = \varepsilon_u \frac{L_u L_v L_w}{L_u^2}$$

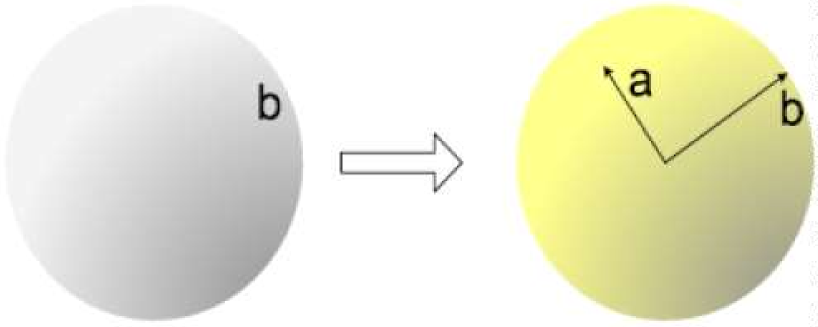
$$\mu_u' = \mu_u \frac{L_u L_v L_w}{L_u^2}$$

Seeking for profile of ε & μ to make light avoid particular region in space — optical cloaking

Pendry, Science, 2006
Leonhard, Science, 2006


NORMAL
Solid object
Microwave source
Cloak enlarged
Cloak formed of metamaterials and copper
INVISIBILITY CLOAK
Cloak
Microwave source
Light rays could in theory be bent around an object inside the cloak, making it seem invisible

实验实现（微波）

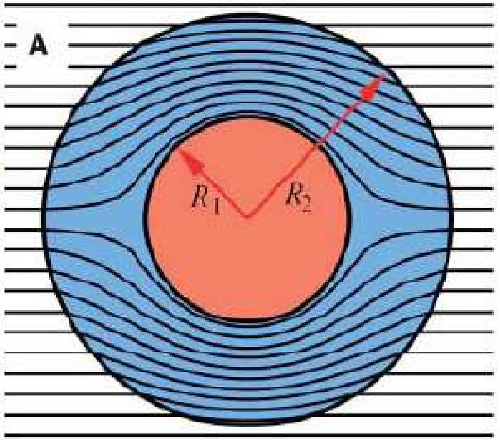


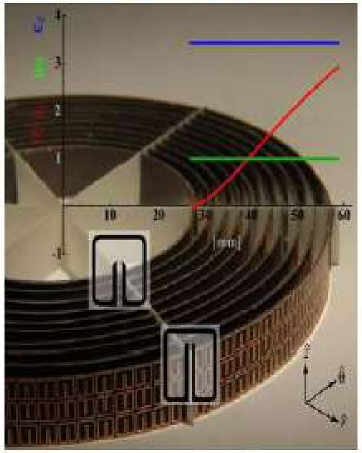
The coordinate transformation that compresses a cylindrical region b into a concentric cylindrical shell a <r<b.

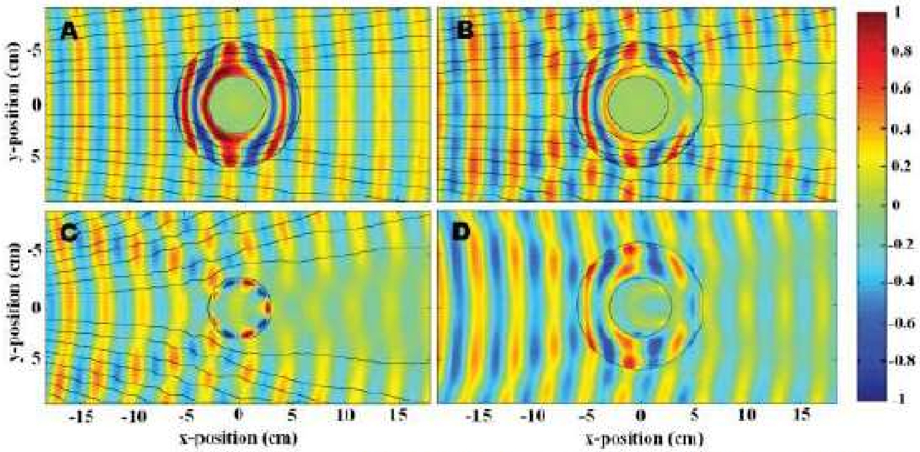
$$0<r<b \longrightarrow a<r'<b$$

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

$$\begin{cases} \varepsilon_r=\mu_r=\dfrac{b}{b-a}\dfrac{(r-a)^2}{r^2} \\ \varepsilon_\theta=\mu_\theta=\dfrac{b}{b-a} \\ \varepsilon_\phi=\mu_\phi=\dfrac{b}{b-a} \end{cases}$$

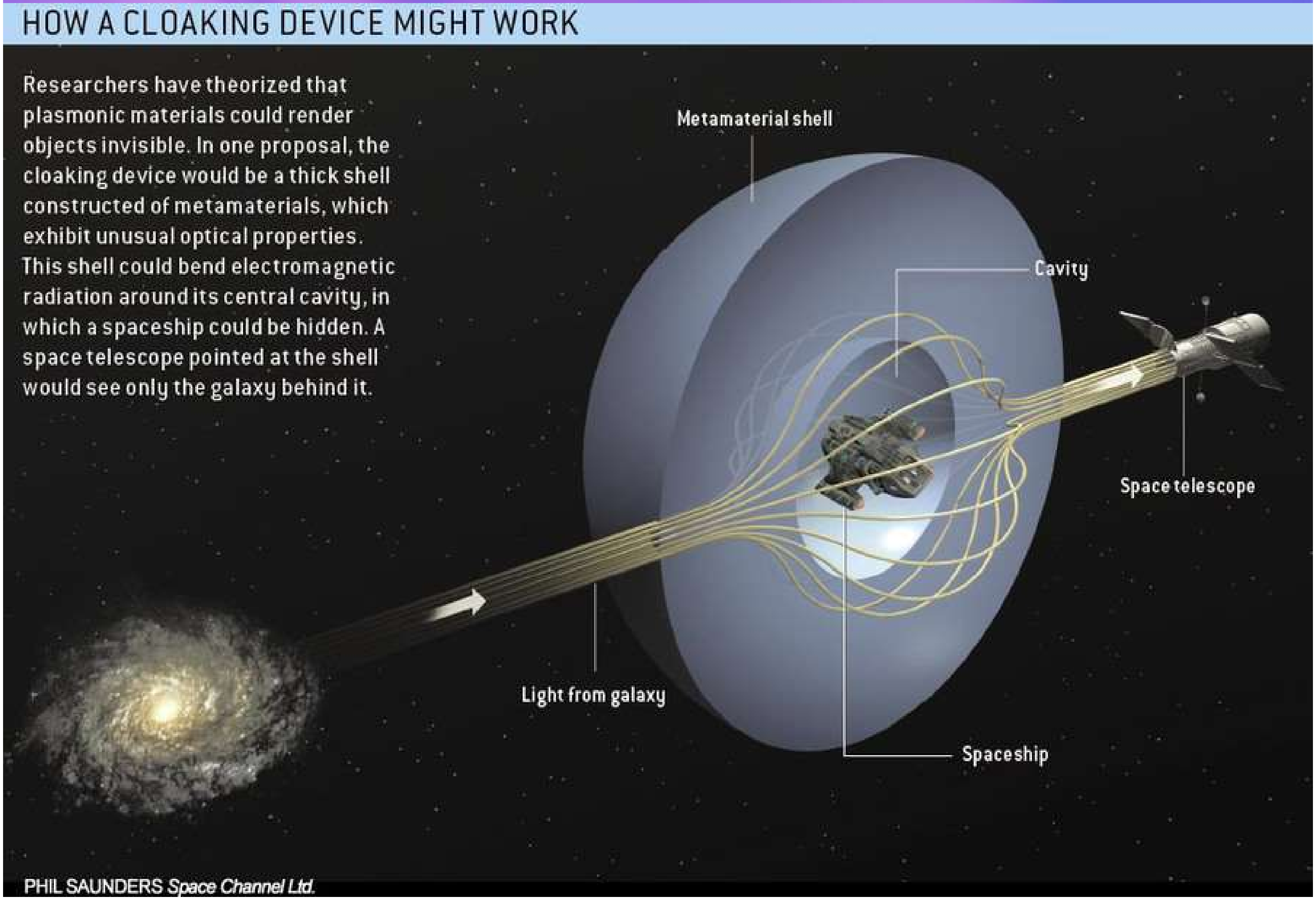






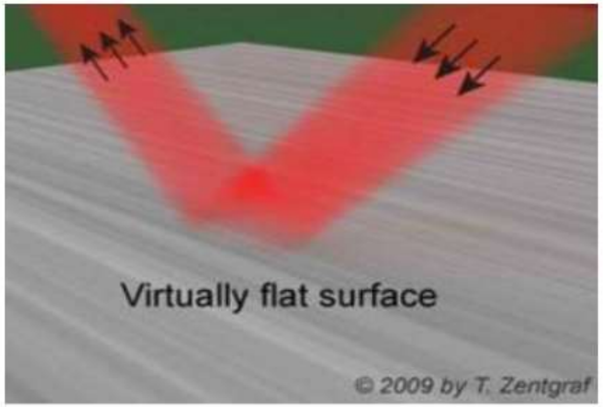
D. Schuriget al., Science Express (2006)

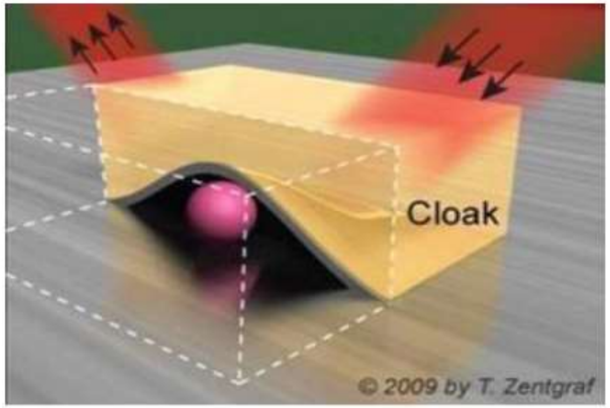
Metamaterials render objects invisible

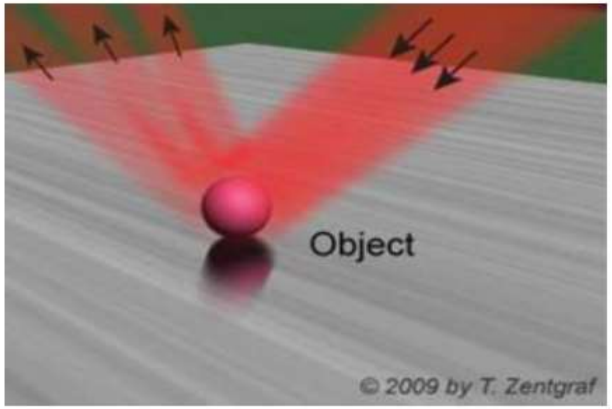


借助于超表面的地毯式隐身技术

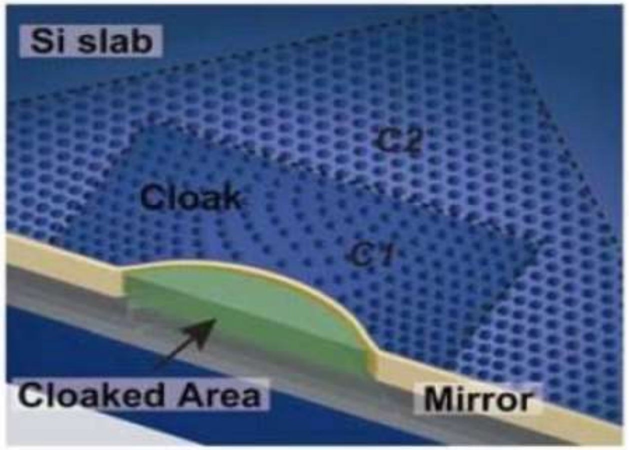
地毯式隐身

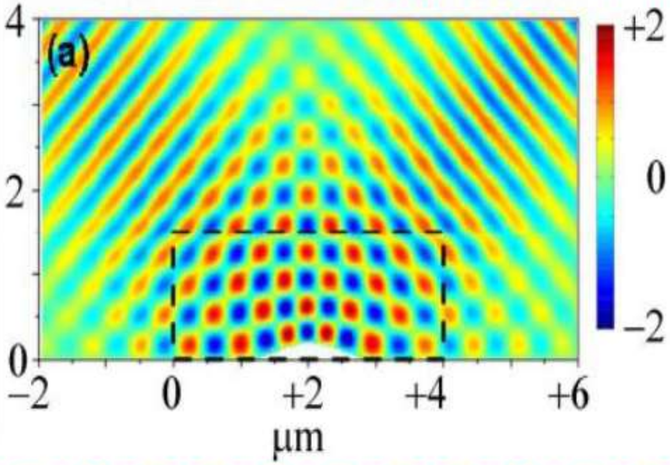






Progress Towards True Invisibility on May.17, 2009, under Science
www.codingfuture.com

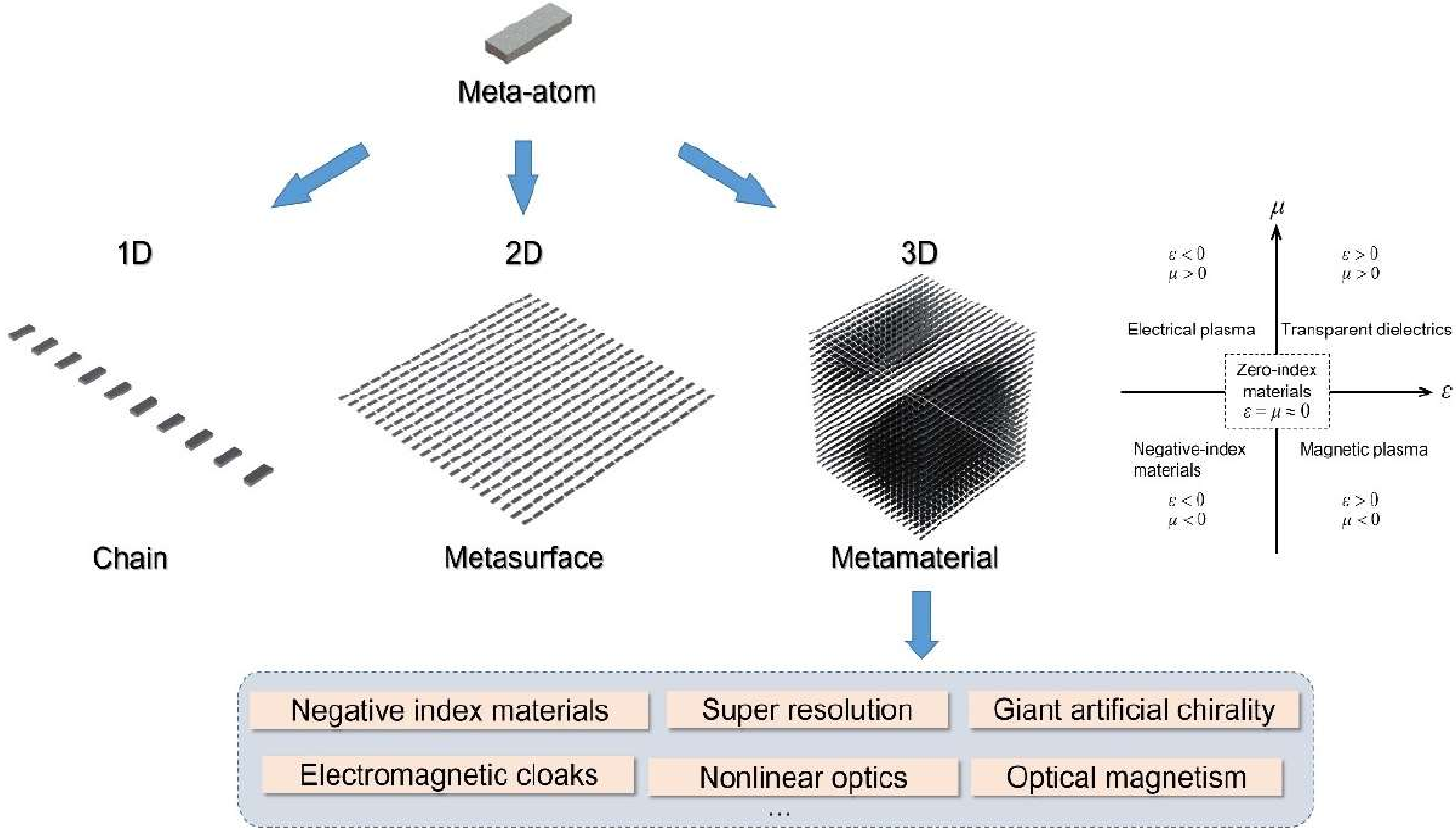


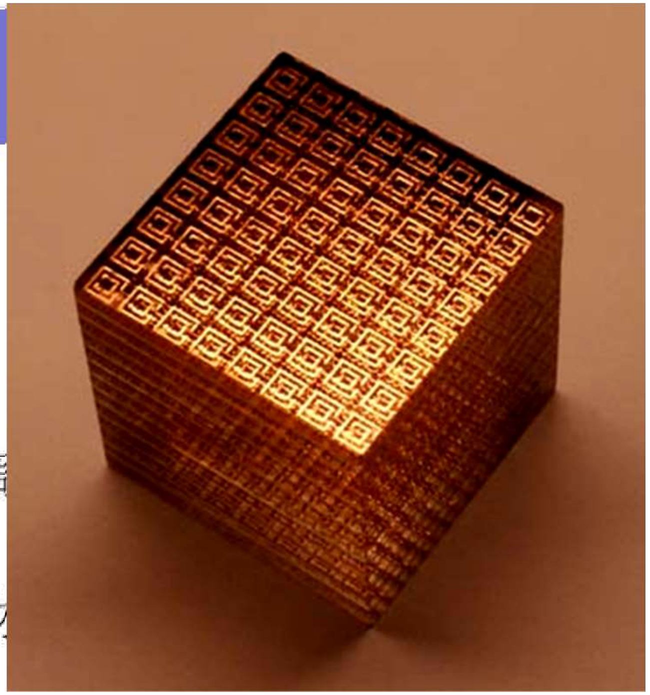


C1 is the gradient index cloak and C2 is a uniform index background.
The cloak will transform the shape of the bump back into a virtually flat object.

Theory: J. Li, J. Pendry
GHz: Smith et al (Duke)
Optical: Zhang et al (Berkeley)

超材料与超表面


Meta-atom
1D
2D
3D
Chain
Metasurface
Metamaterial
μ
$\varepsilon < 0$ $\mu > 0$
$\varepsilon > 0$ $\mu > 0$
Electrical plasma
Transparent dielectrics
Zero-index materials $\varepsilon = \mu \approx 0$
ε
Negative-index materials
Magnetic plasma
$\varepsilon < 0$ $\mu < 0$
$\varepsilon > 0$ $\mu < 0$
Negative index materials
Super resolution
Giant artificial chirality
Electromagnetic cloaks
Nonlinear optics
Optical magnetism
...



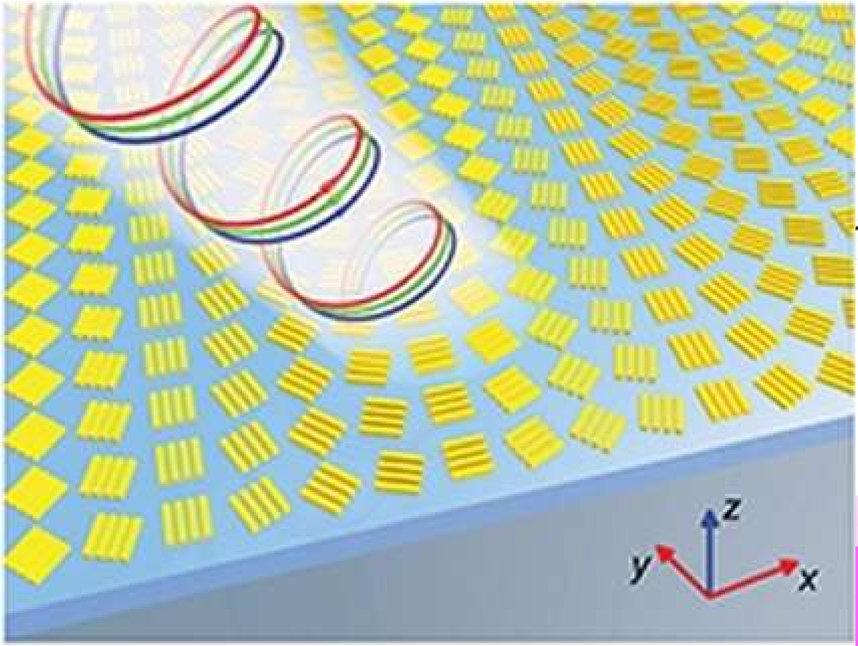
二、超表面与超材料

1、新型人工电磁材料（超材料）

将具有特定几何形状的亚波长宏观基本单元周
列所构成的人工材料。

就是用有序的人造单元“粒子”代替自然界材
本粒子，所组成一种等效材料

2、超表面



通过控制波前相位、振幅以及偏振进行

由超材料结构单元组成，它可以灵活有
式、传播模式等特性。

超表面(2D)与超材料(3D)的差异

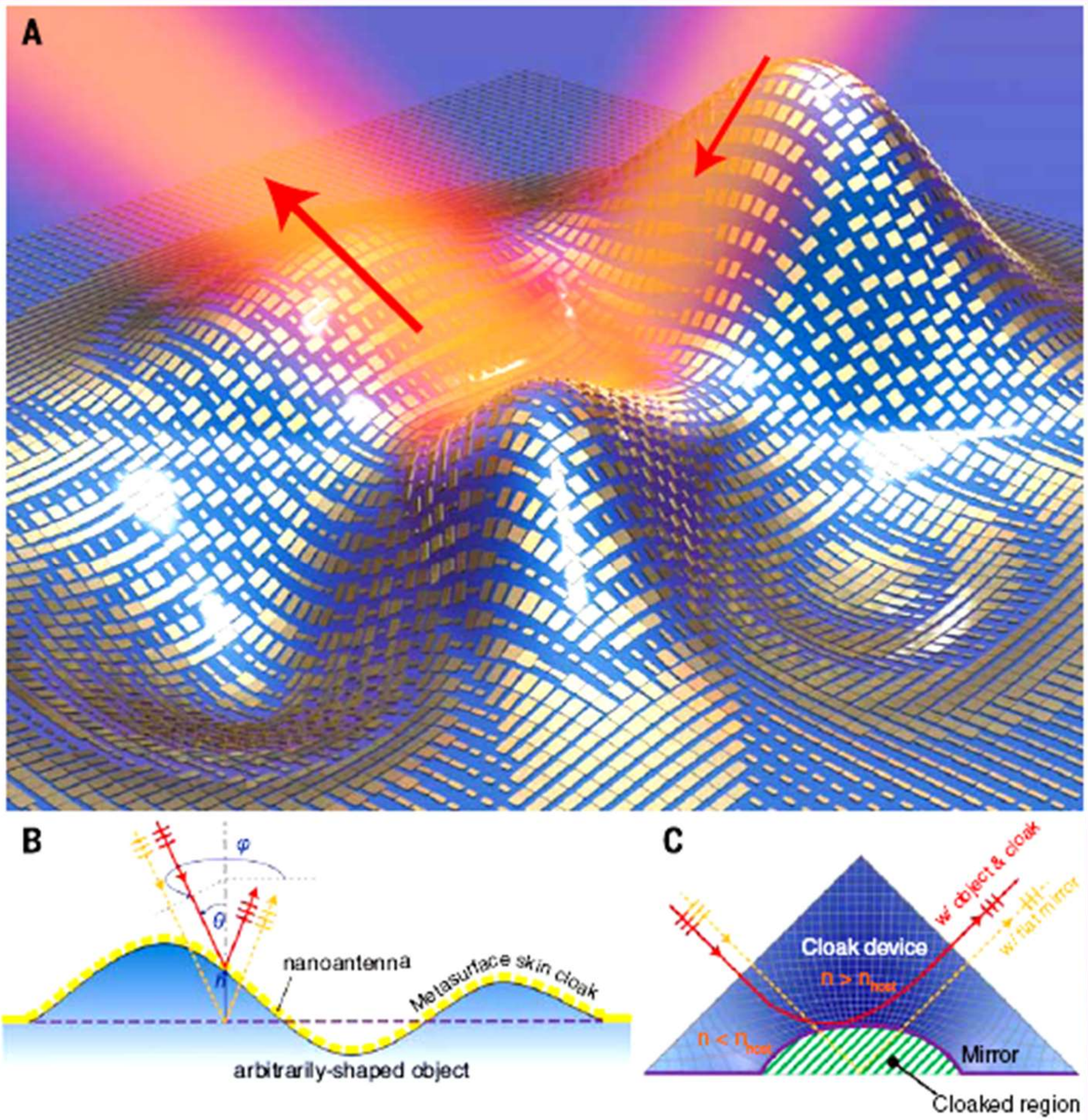
超表面：相位不连续引起的奇异电磁现象。

超材料：通过操作庞大的人工电磁超材料获得的奇异电磁现象。

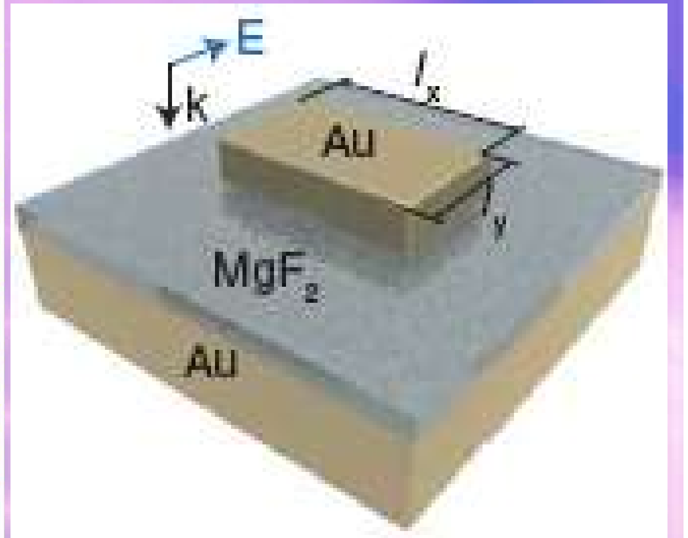
二者的差异：

超材料一般是通过负介电常数、负磁导率材料或者沿着或垂直于表面的方向引入具有不同介电常数张量特性的各向异性介电常数来实现，通常情况下比较复杂且难以操作。

Ultrathin invisibility skin cloak for visible light

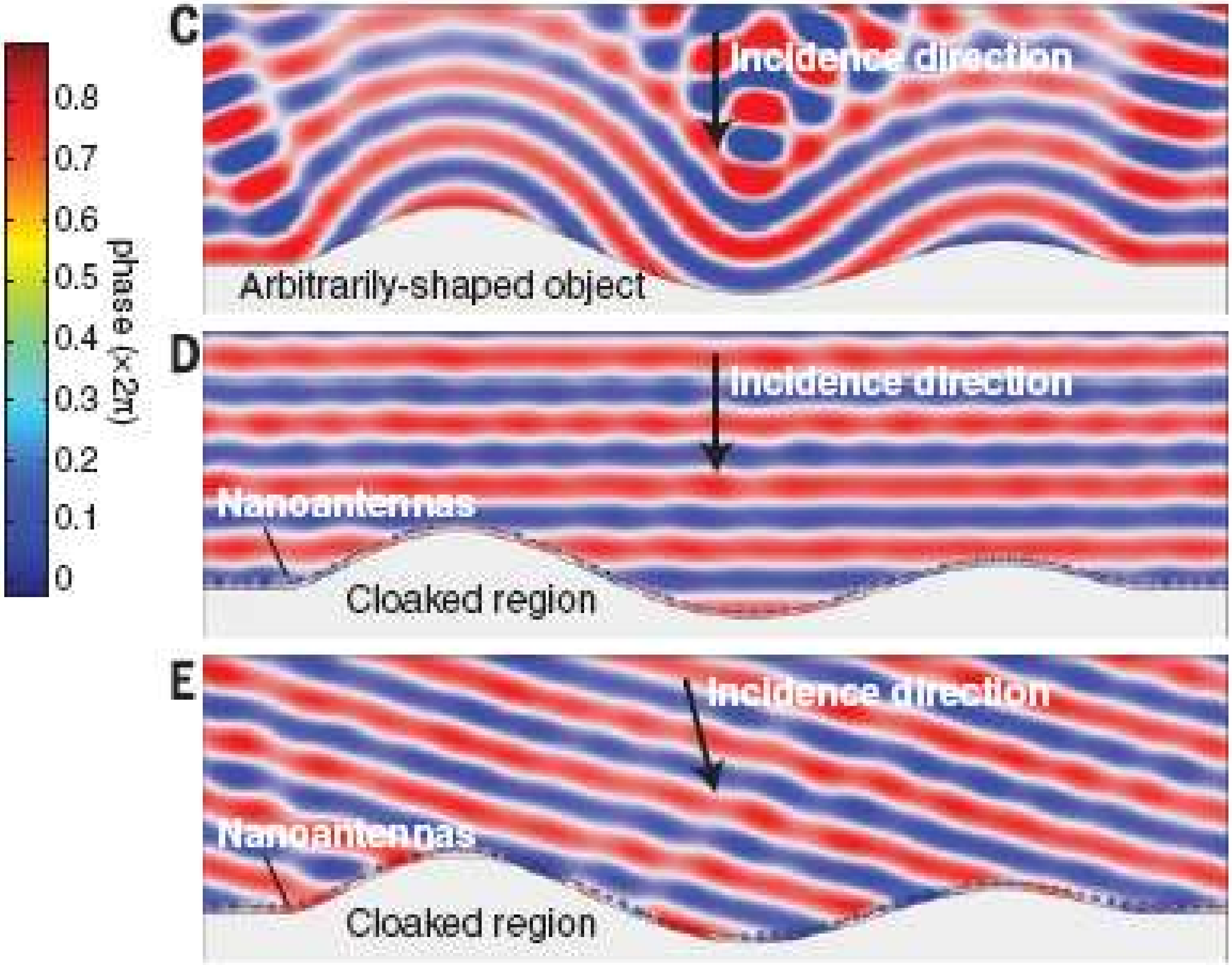


地毯式隐身



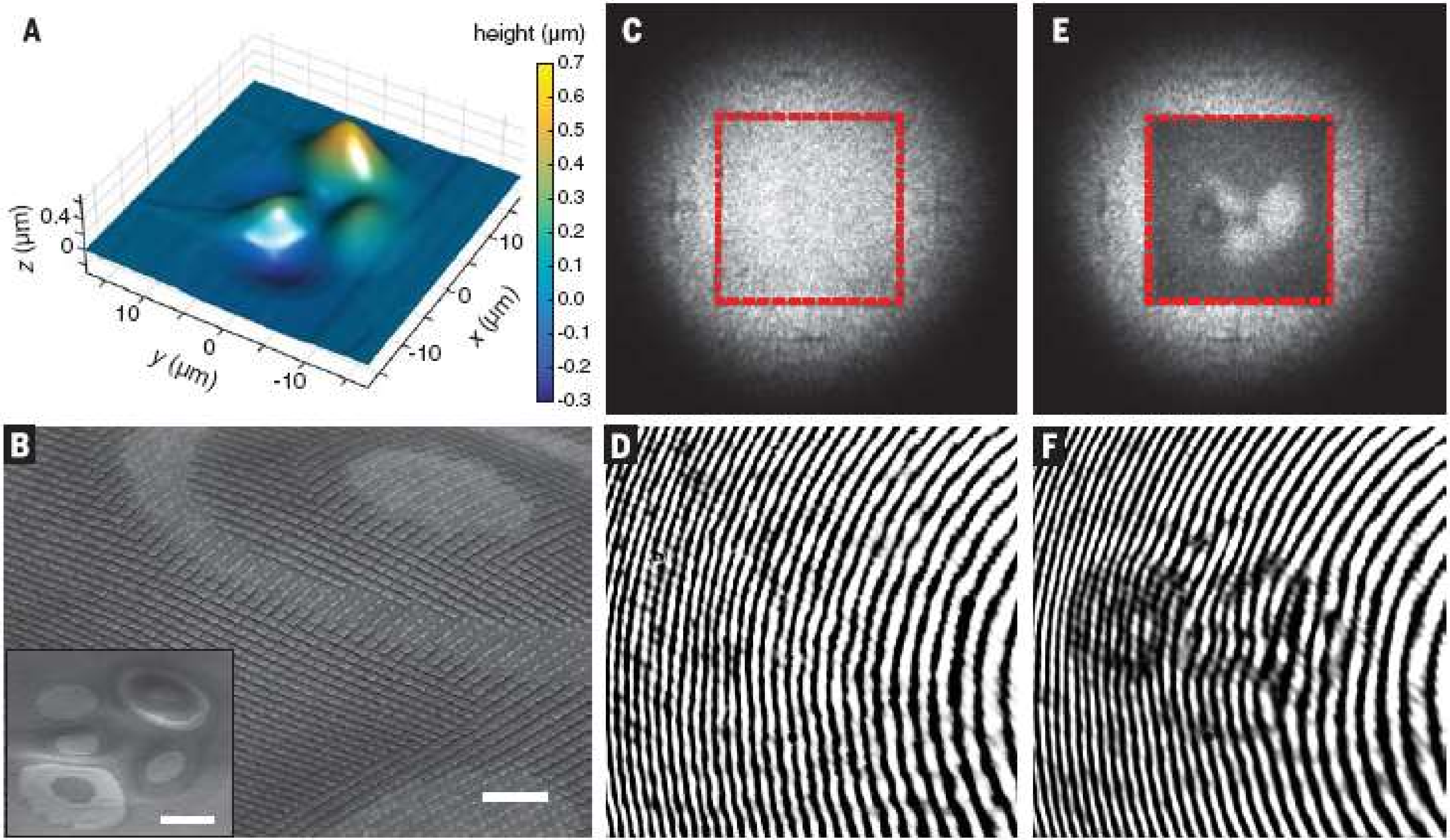
Nano-antenna

Science 349, 1310 (2015)



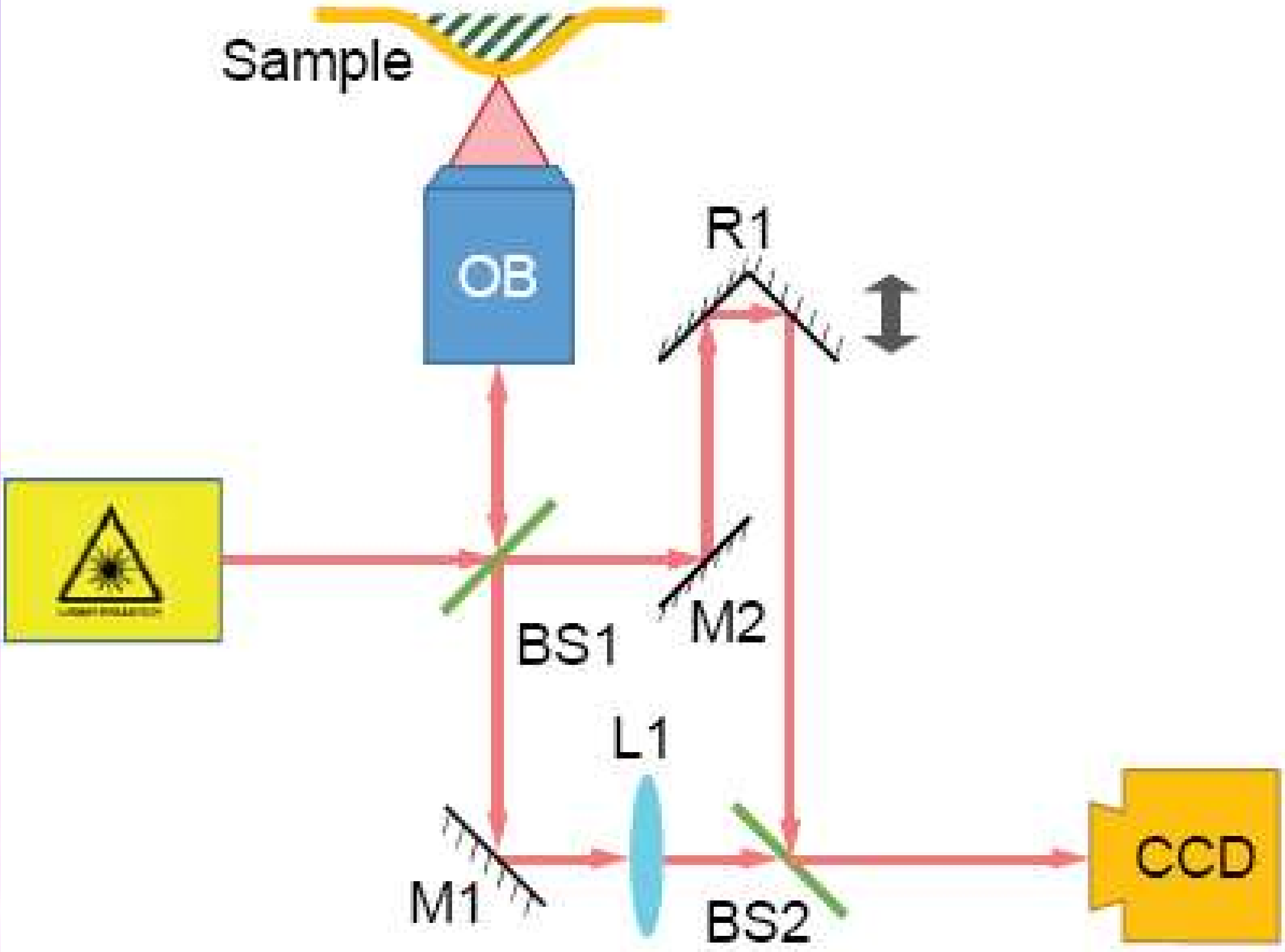
Changing polarization state of the incident light, can realize on and off of the invisibility function.

Science 349, 1310 (2015)



Metasurface invisibility skin cloak for a 3D arbitrary shaped object

Science 349, 1310 (2015)



Mach-Zehnder interferometer setup for obtaining the phase information of the reflected light

Science 349, 1310 (2015)

加拿大公司造出“量子隐形衣”

加拿大公司造出“量子隐形衣”


We need to add magnetic effects where none seems to exist
We need to make metamaterials
Supernatural or beyond Nature

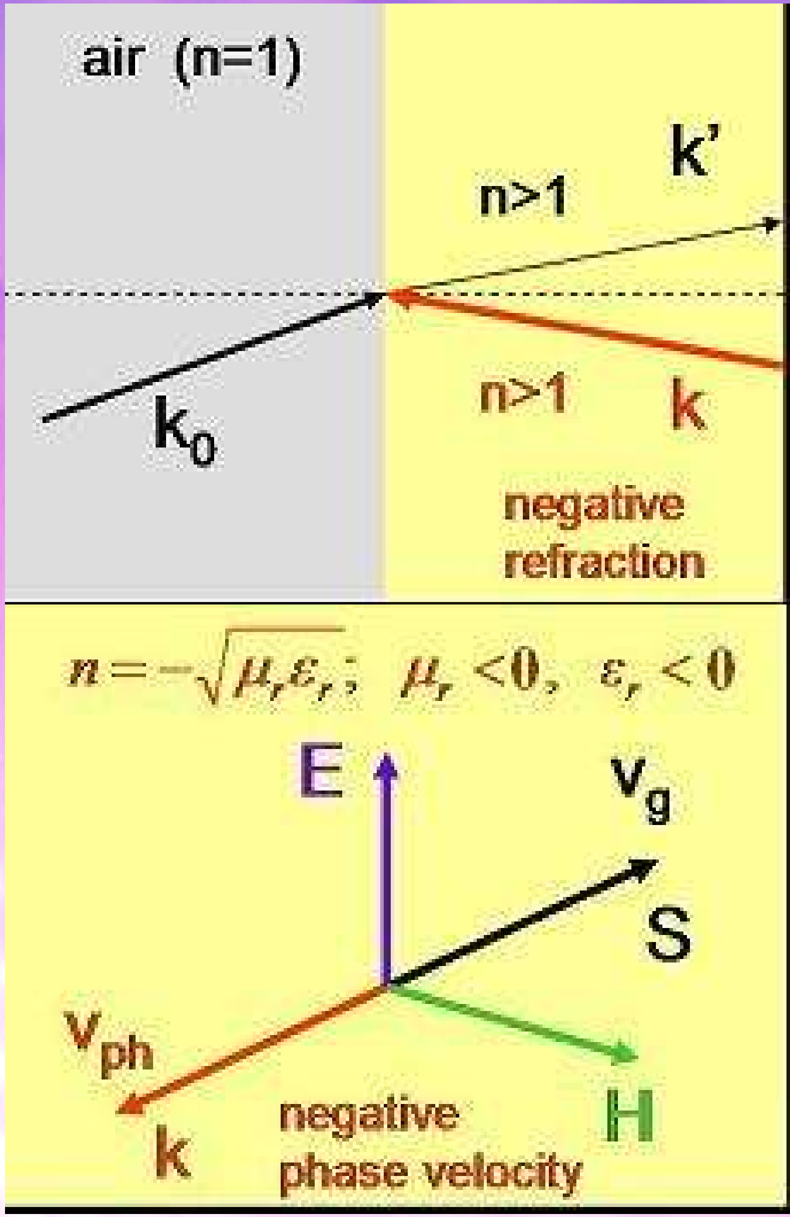
How on earth can these be created??

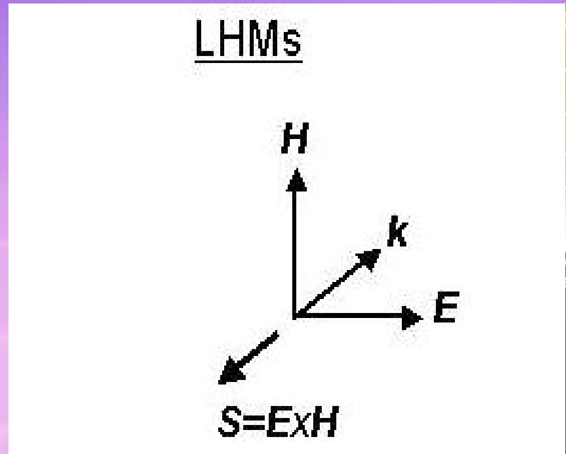
- **Material comprised of artificial molecules**
- **Effective ε and effective μ**

负折射率材料的研制

- 2001年加州大学的David Smith等人根据Pendry等人的建议，利用以铜为主的复合材料首次制造出在微波波段具有负介电常数、负磁导率的物质，并观察到了其中的反常折射定律。
- 负的介电常数可以由长金属导线阵列（the array of long metallic wires，ALMWs）这种结构获得。
- 负的磁导率可以由微型金属共振器，比如具有高磁化率的开口环形共振器（the split ring resonators， SRRs）来获得 。

微波波段验证的第一个特异性材料结构

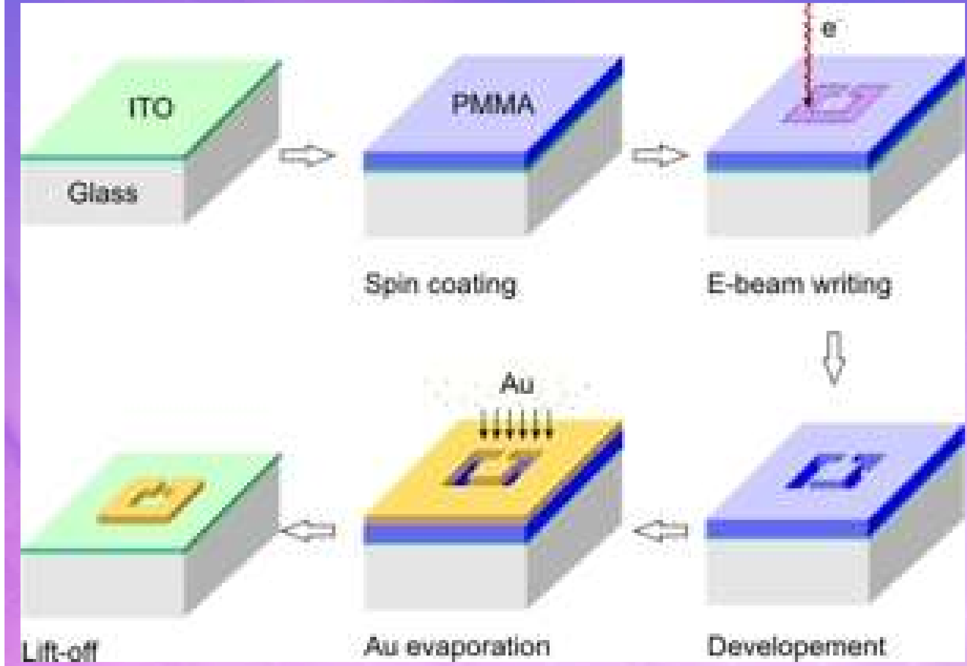


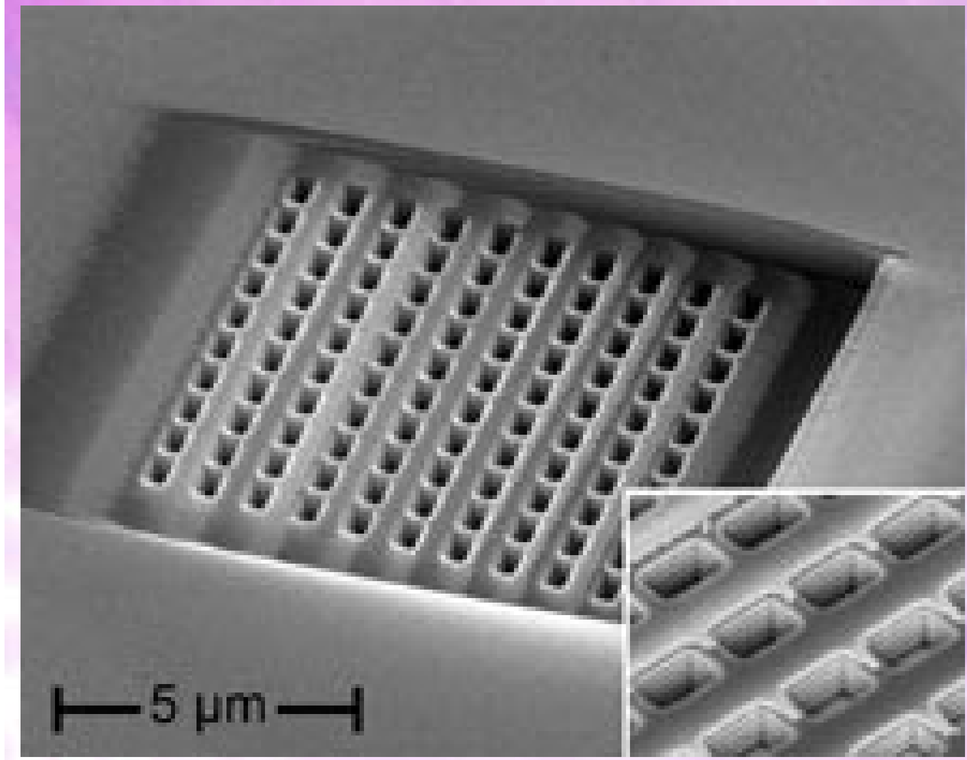


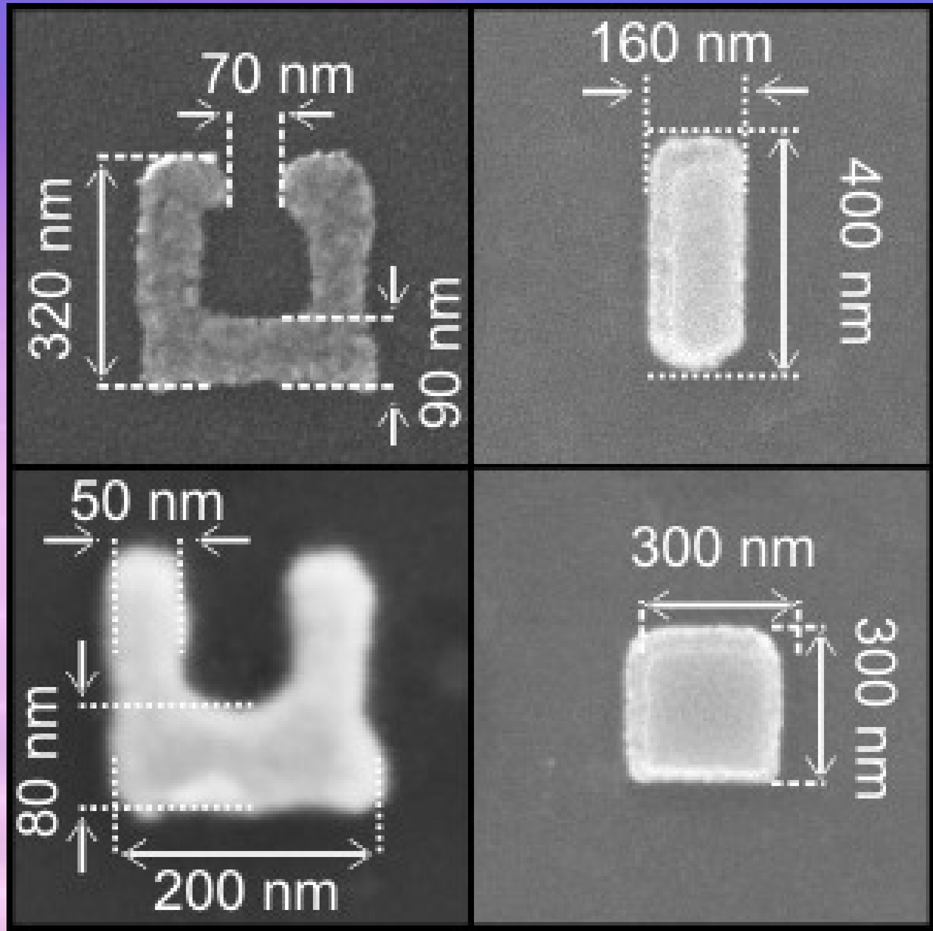
Smith et. al. UCSD, PRL 84, 4184 (2000)

实验制得的左手材料结构

左手材料的研制被《科学》杂志评为**2003**年度全球十大科学进展。


e
ITO
Glass
PMMA
Spin coating
E-beam writing
Au
Lift-off
Au evaporation
Developement


5 µm


70 nm
320 nm
90 nm
160 nm
400 nm
50 nm
80 nm
200 nm
300 nm
300 nm


E
H
k

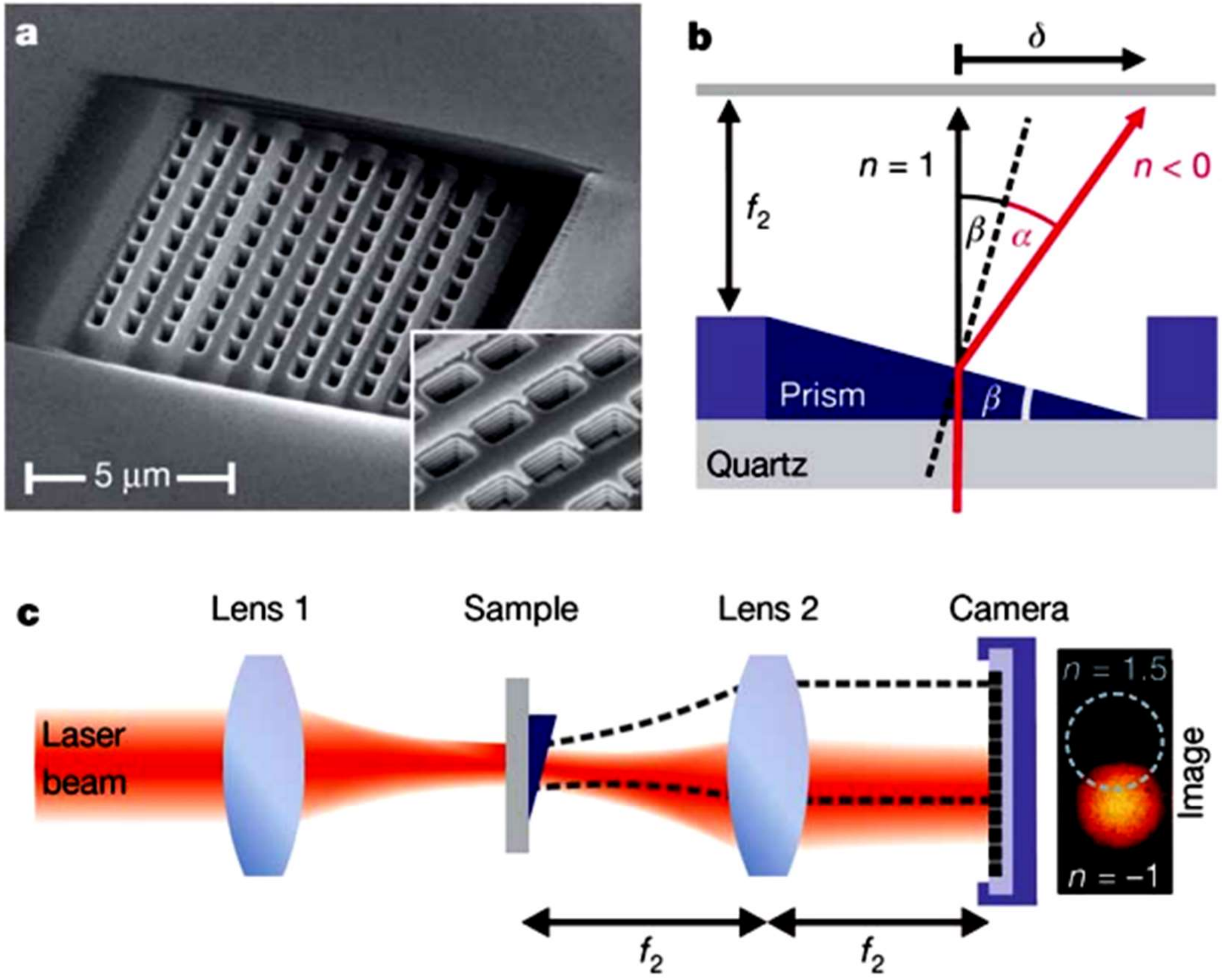


图 1.5 三维"渔网"人工电磁材料棱镜及实验方案。(a)制作出的三维"渔网"棱镜扫描电镜照片；(b)折射角测试原理图；(c)光束偏折测试方案。

Ag-MgF_2-Ag "三明治"结构；

结构参数取 W_x=316nm, W_y=100nm, t=45 nm, s=30 nm,

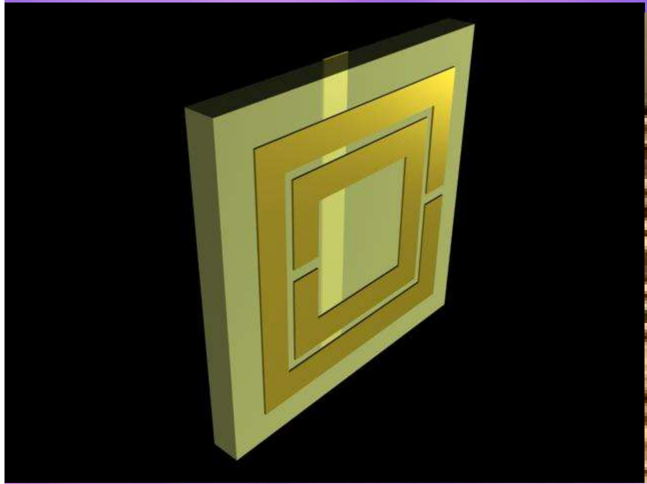
周期 a_x=a_y=600 nm;

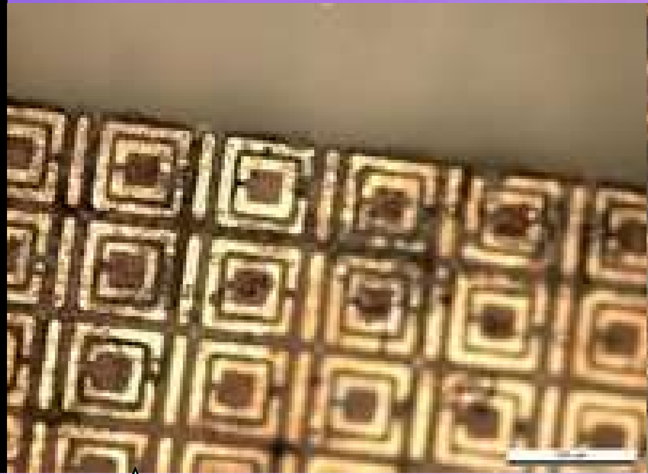
利用电子束直写和真空蒸镀技术制作;

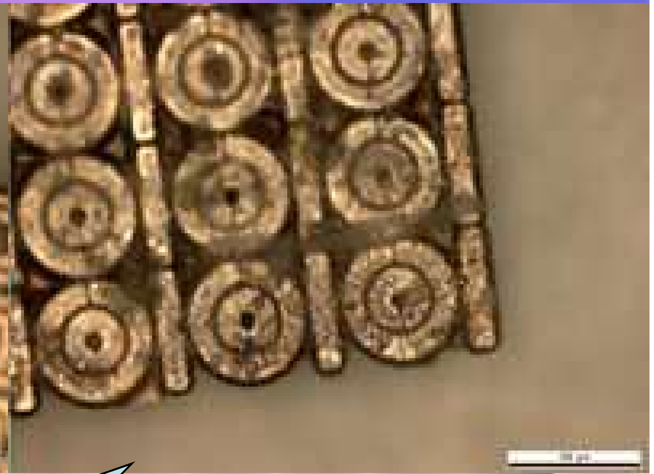
波长为1.5 μm。

Nature 455, 376-379 (2008).

两种代表性特异性材料结构

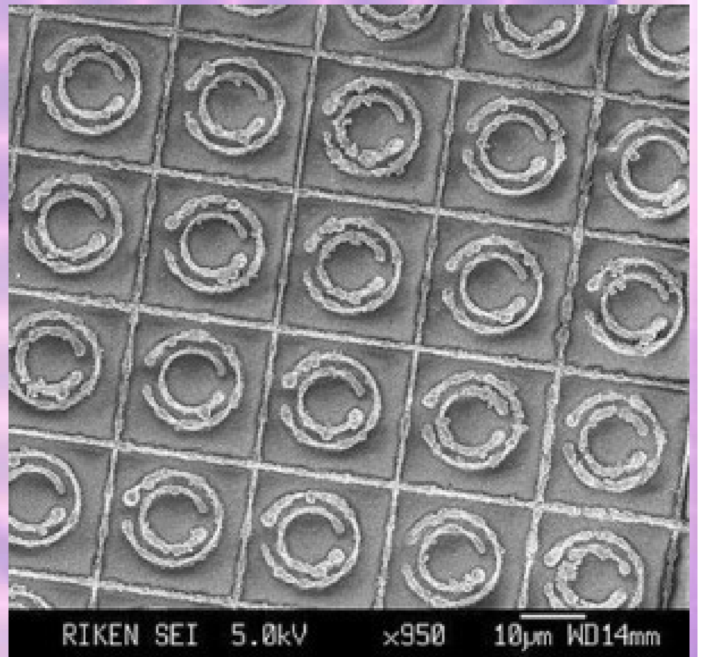




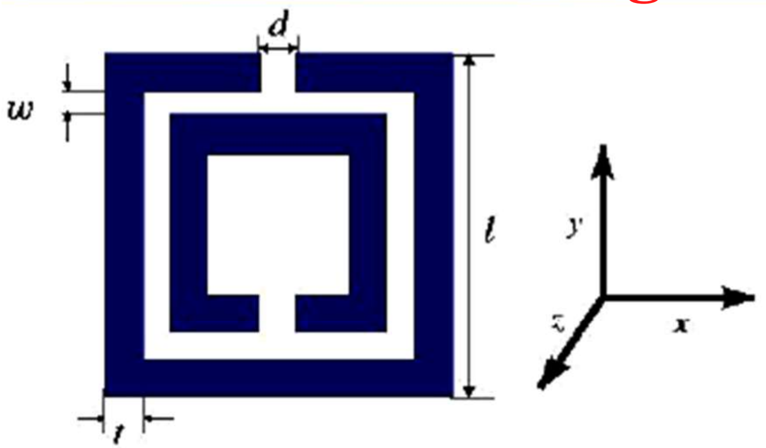


微波波段

毫米波波段

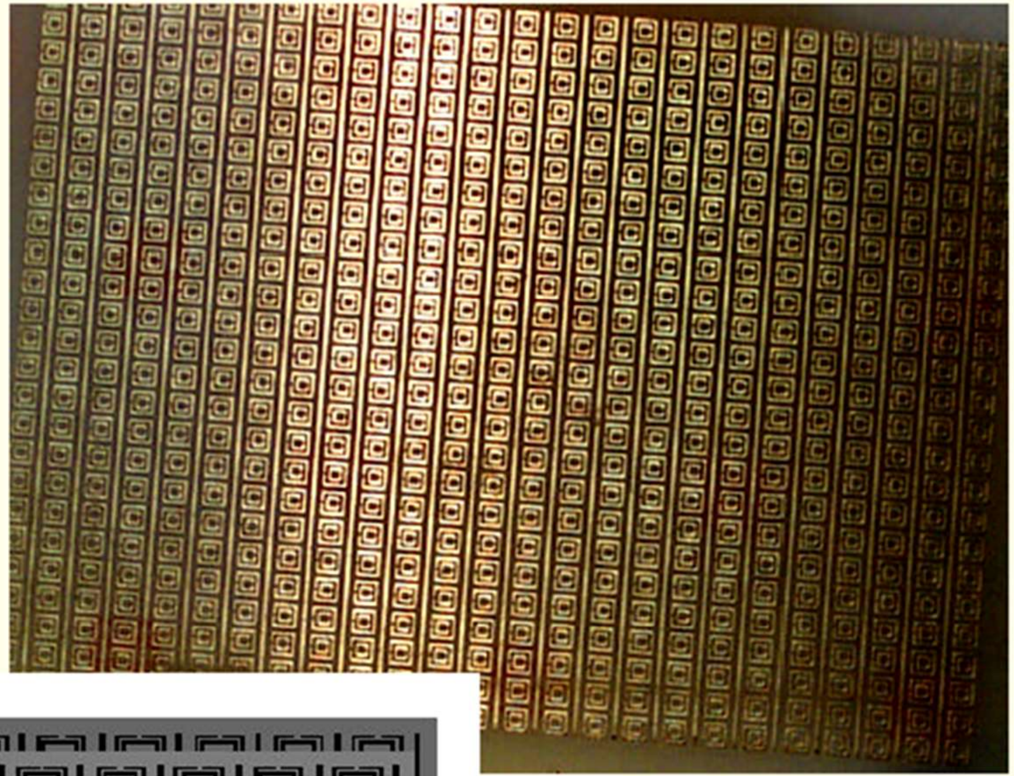


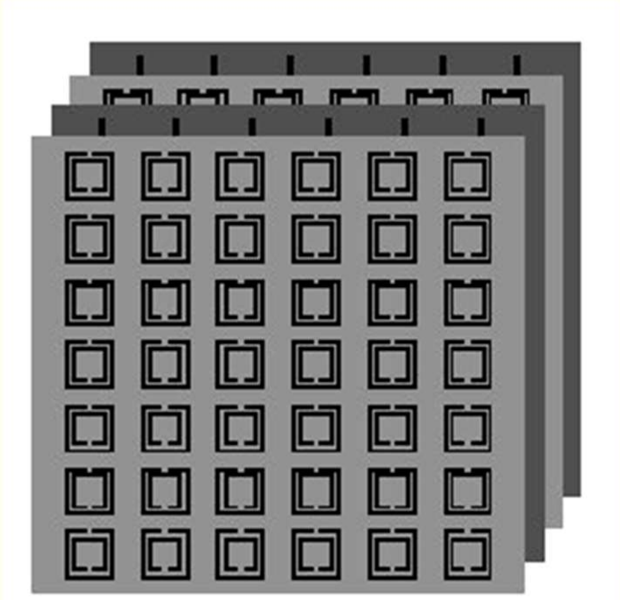
New designs for left-handed materials

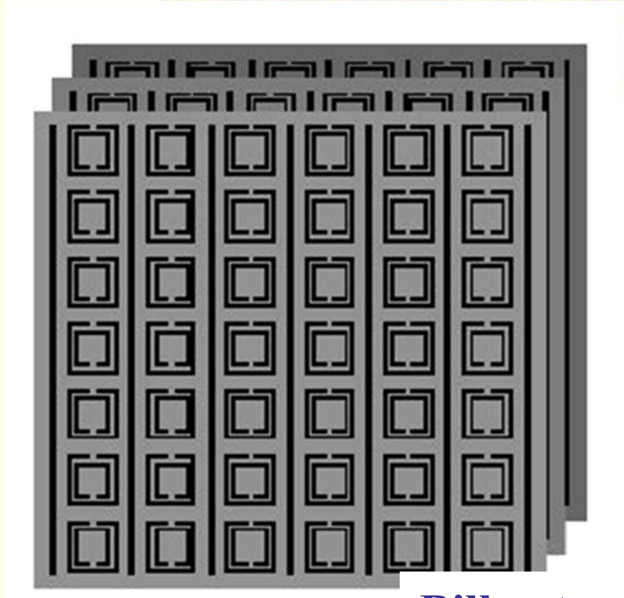


Parameters:

l=3 mm, d=t=w=0.33 mm







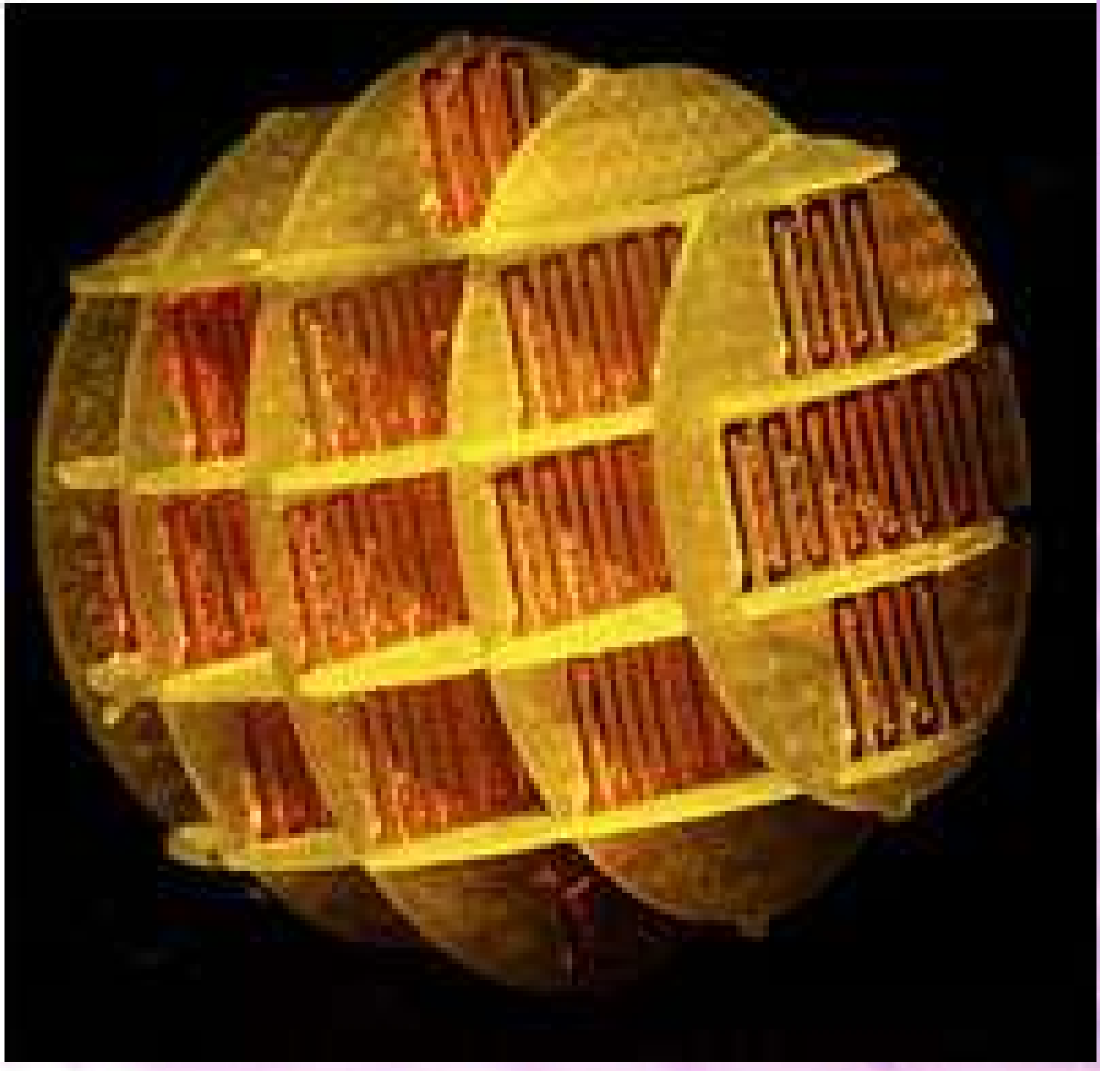
Depositing metal (Sn or Cu) on dielectic board

ε_b=4.4

Thickness of board =0.45 mm

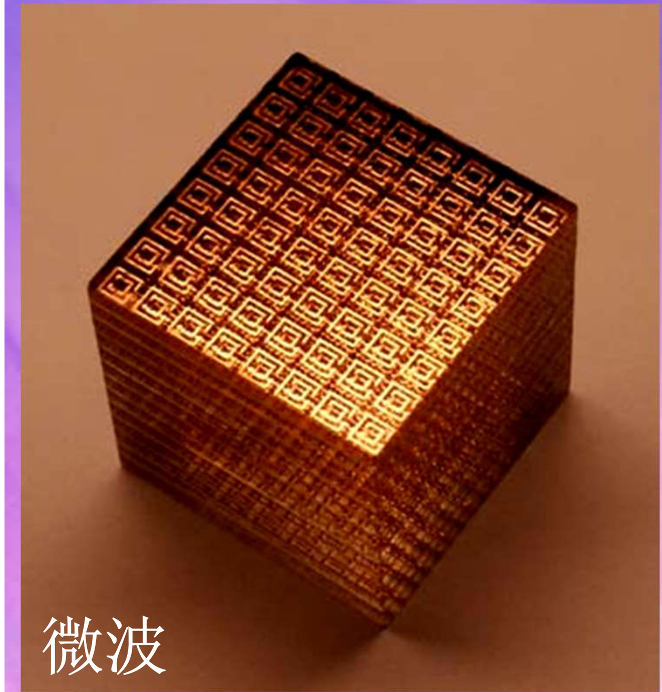
Bilkent and ISU, APL 81, 120 (2002)

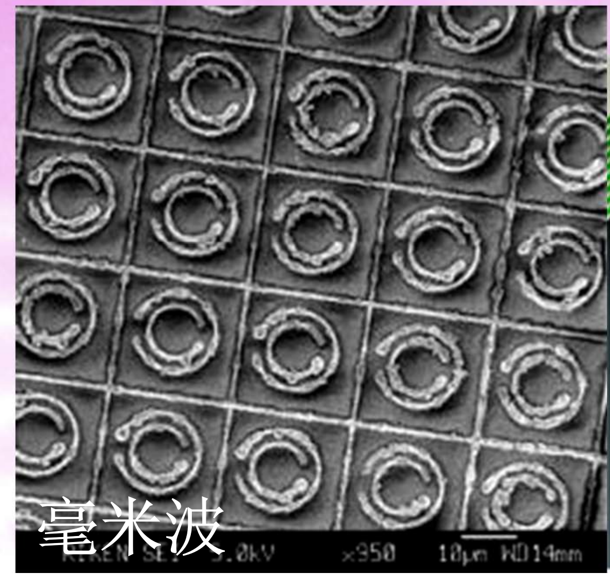
人工负磁导率材料(-μ)的构建

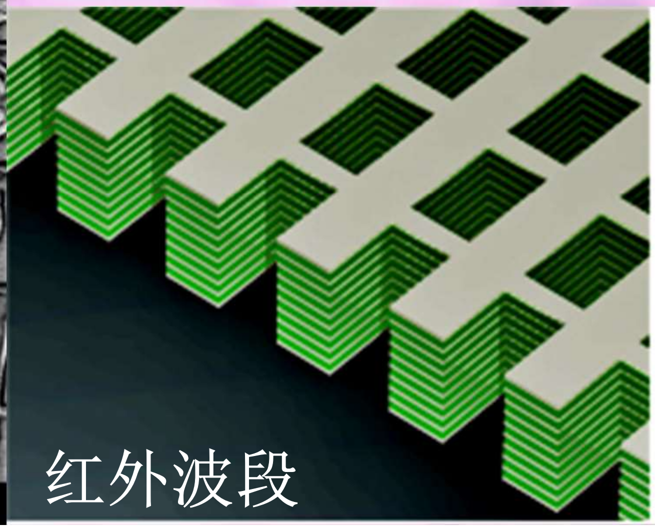


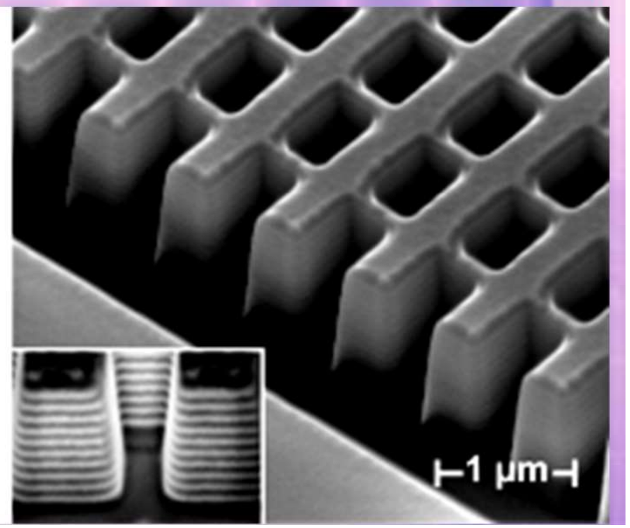
Normally, the structure consisting of multi-layers so as to form -μ.

Microwave regime



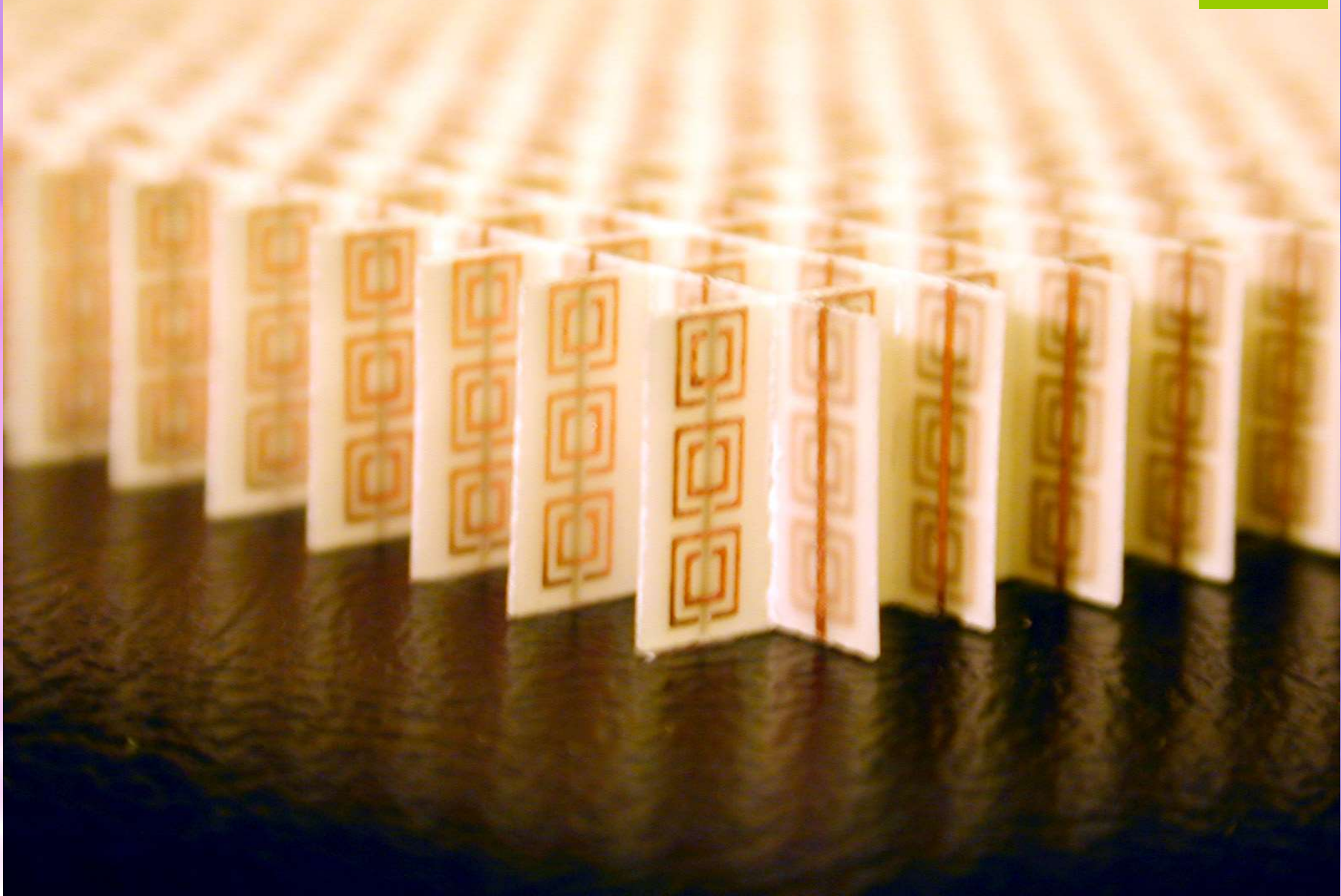






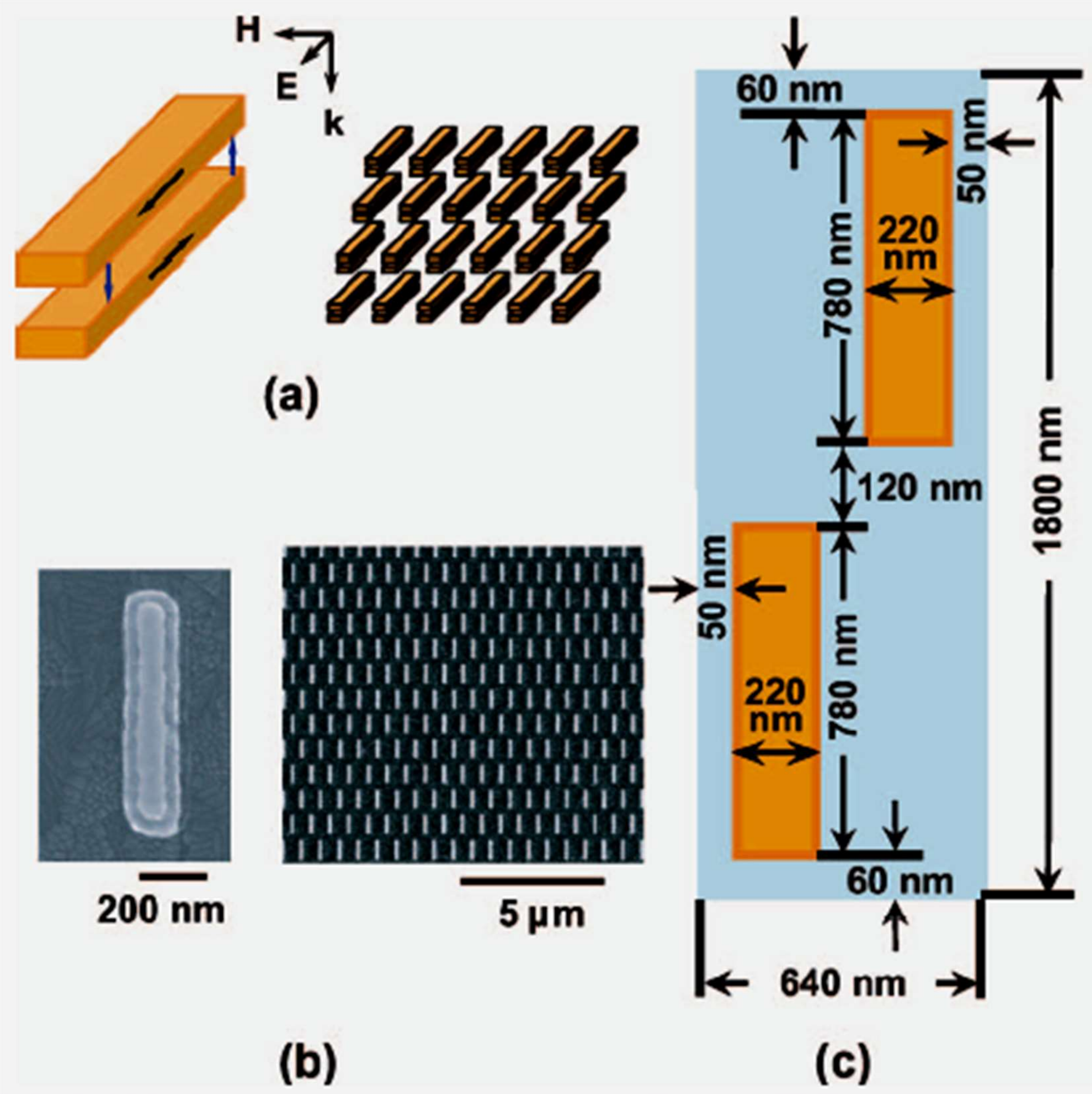
NRI在不同工作波段的结构尺度范围

微波波段，尺度范围：毫米量级



A 2-D Isotropic Structure

UCSD, APL 78, 489 (2001)



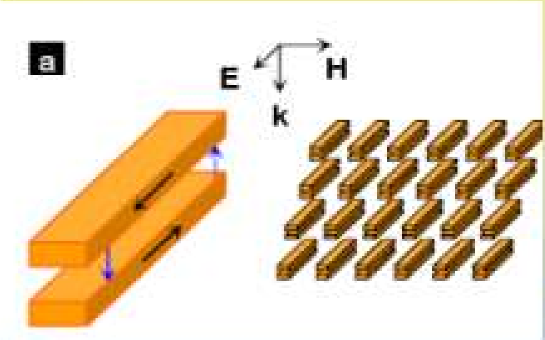
λ=1.5微米

n=-0.3±0.1

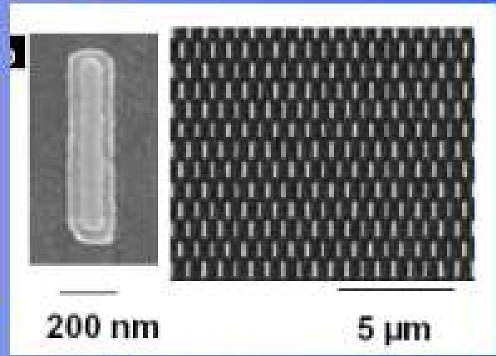
Opt. Lett. 30, 3356-3358 (2005)

Nanowires

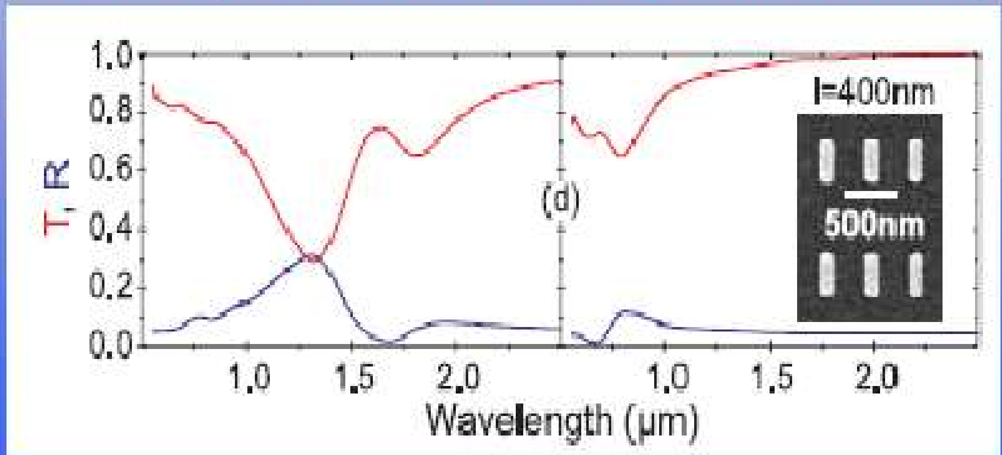
Shalaev et al. ArXiv:physics/0504091 (2005)



$Re\{ n \} = -0.3$
$\lambda = 1.5\ \mu m$



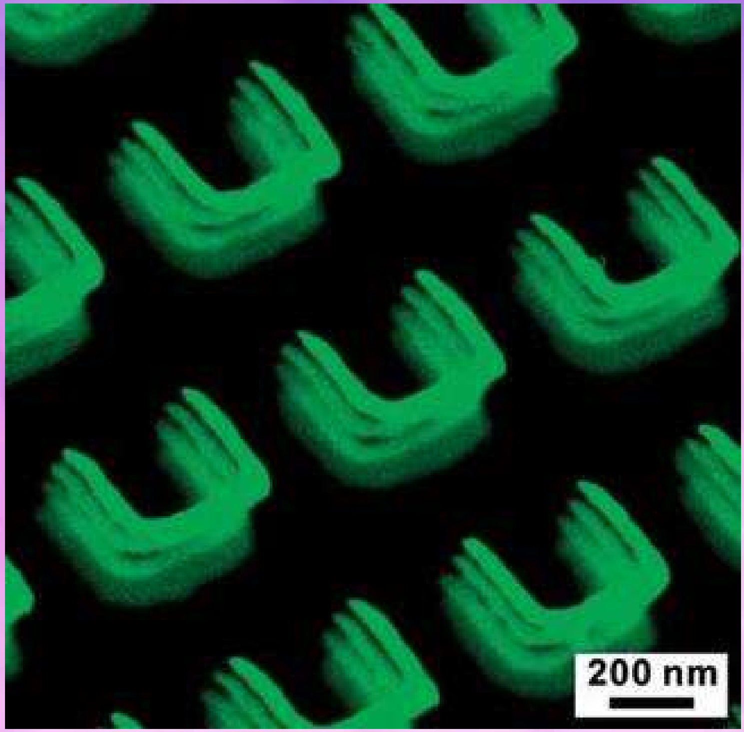
Dolling, Soukoulis et al. ArXiv:physics/0507045 (2005)

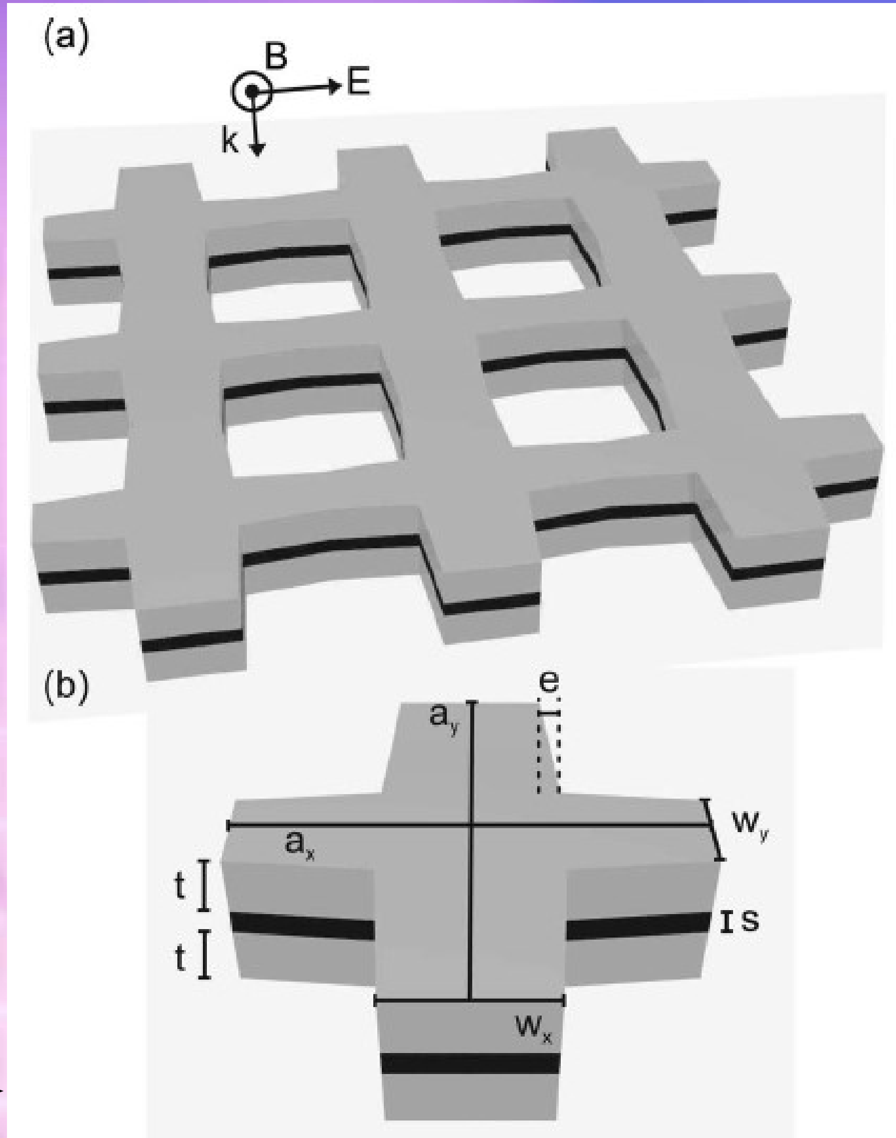


$1.3\ \mu m$

Negative permeability

两种代表性特异性材料结构

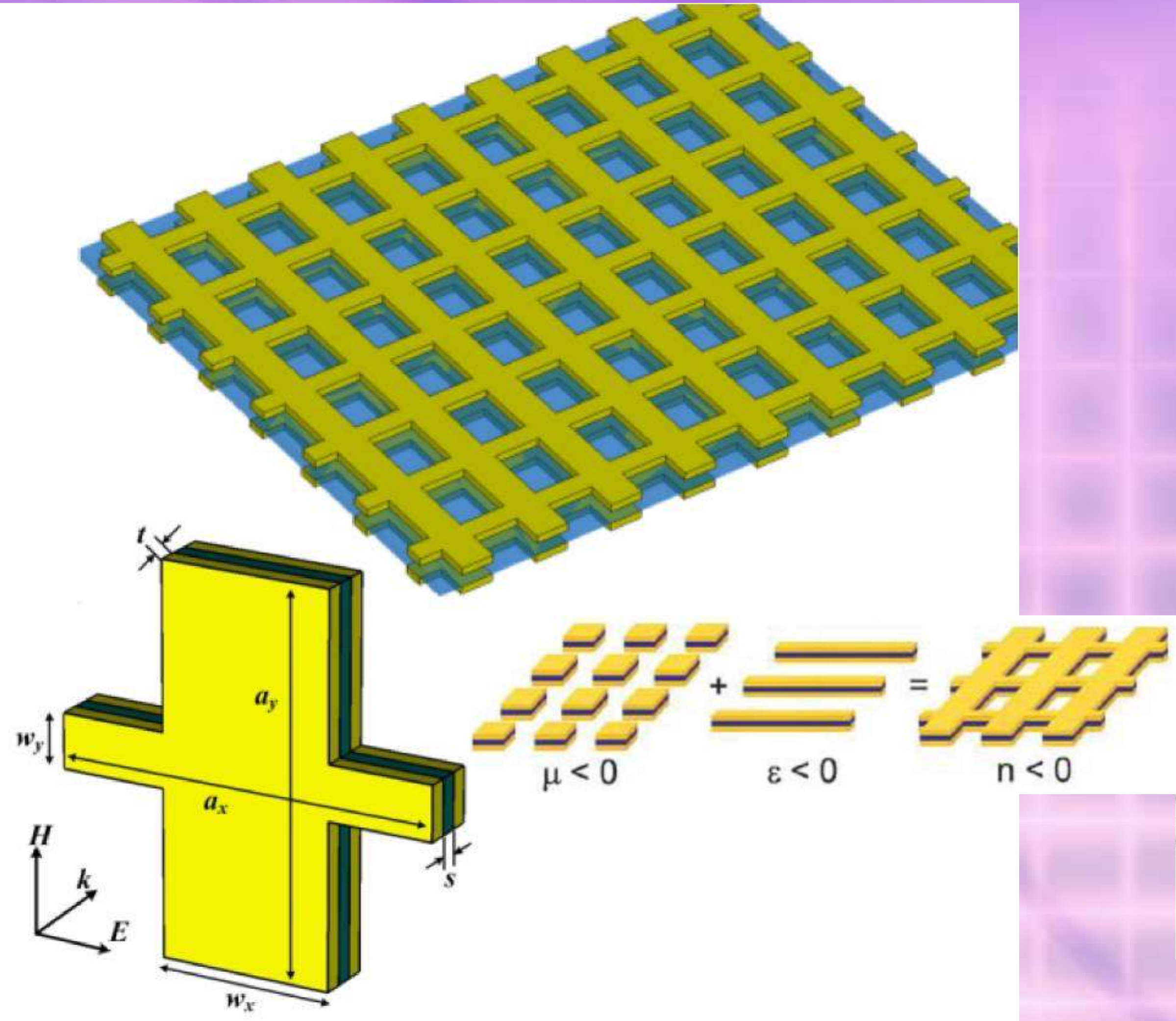


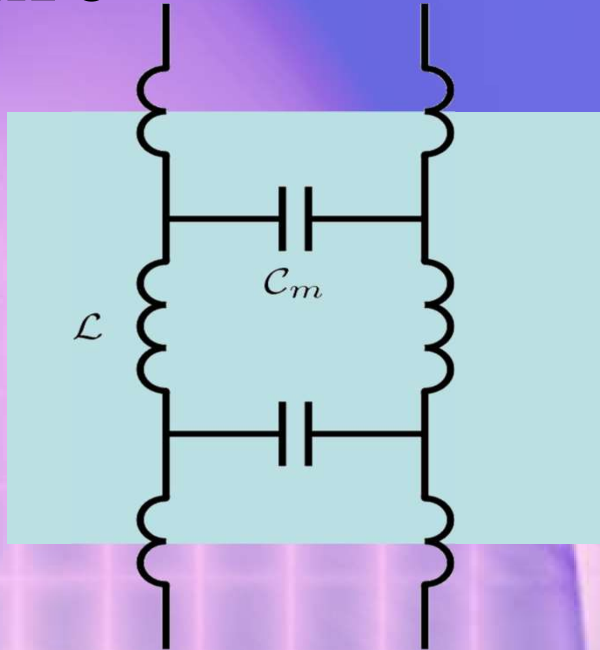


红外波段

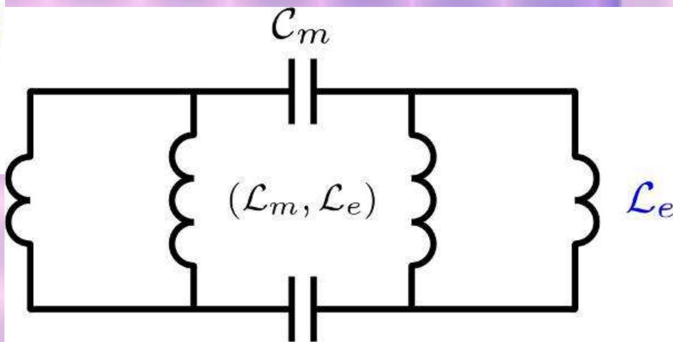
t(Au)=45nm s(MgF_2)=60nm

"Fishnet" structure





With periodicity:

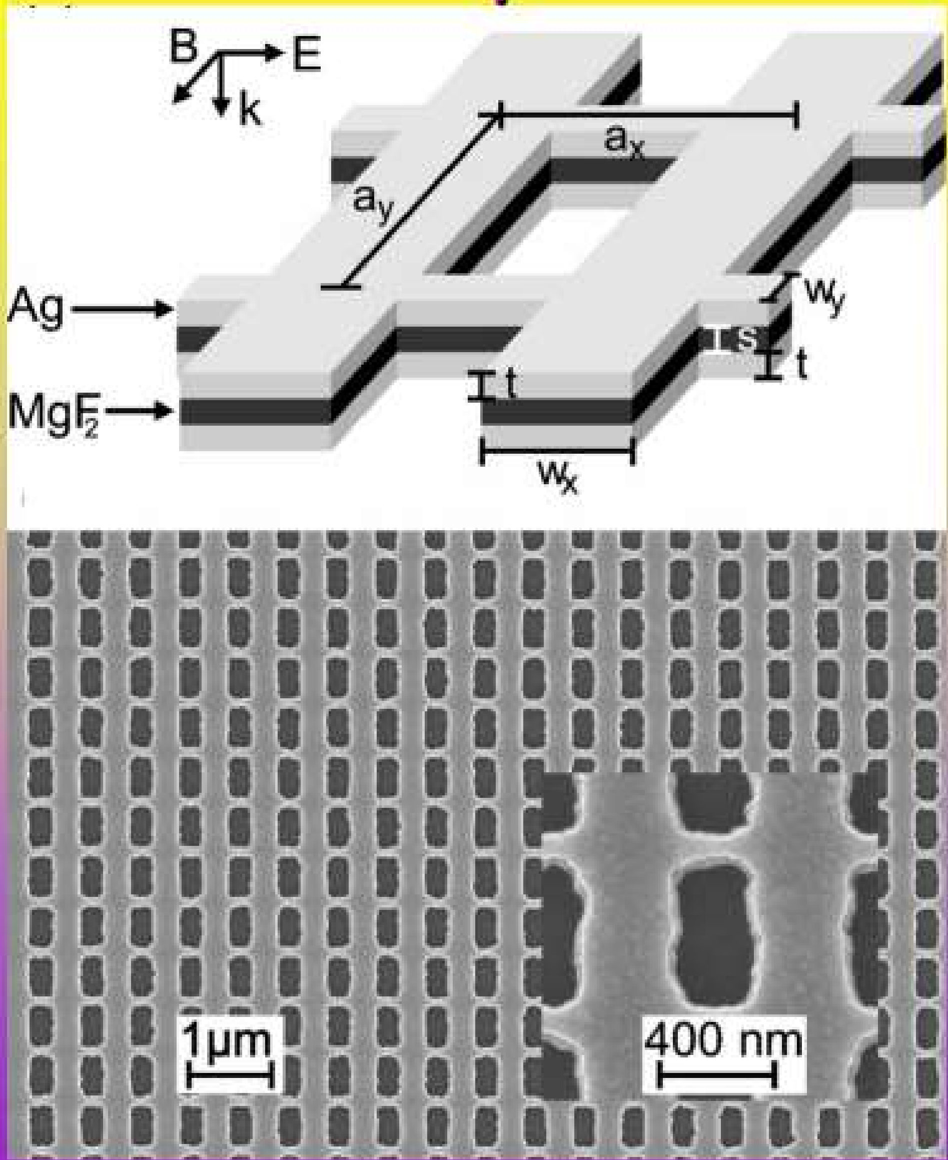


Realization n<0 at 1.5mm, Karlsruhe & ISU

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

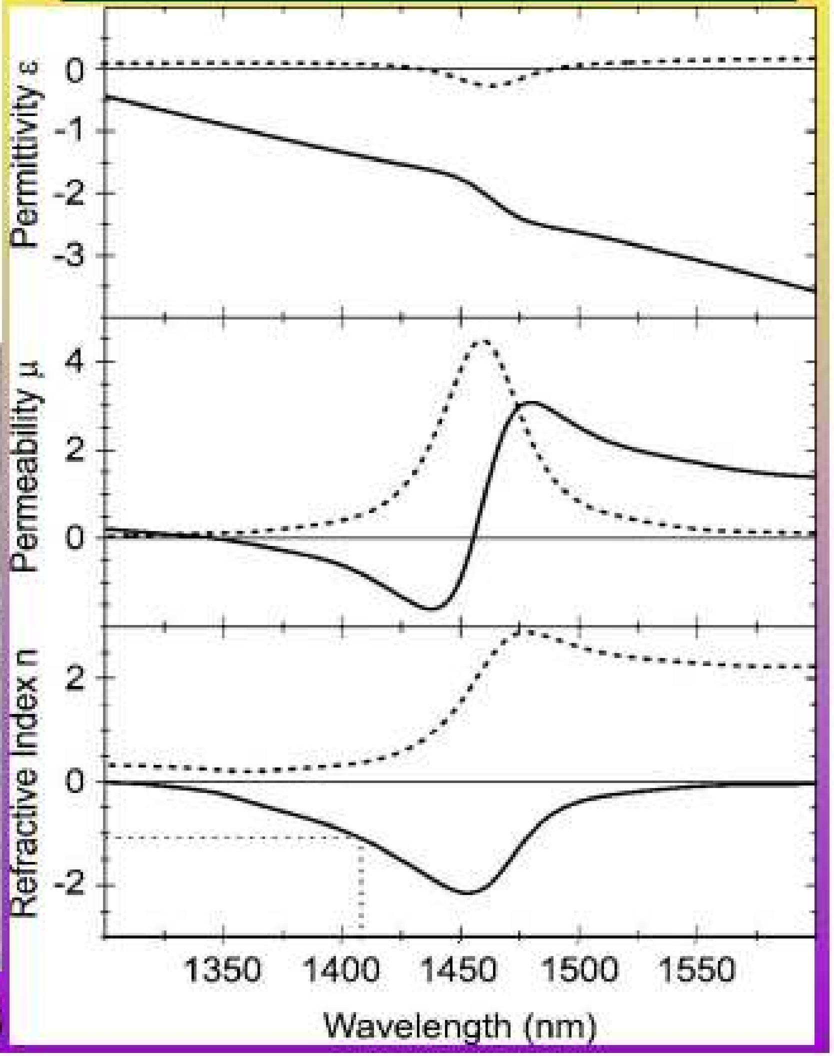
Opt. Lett. **31**, 1800 (2006).

Operates at 1.5 μm

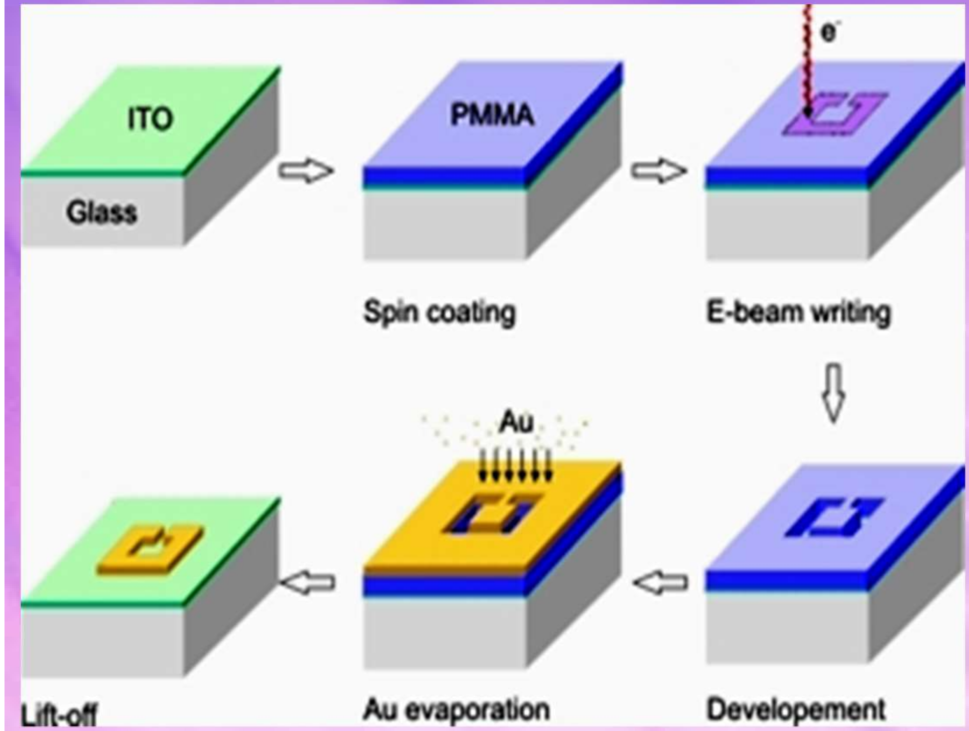


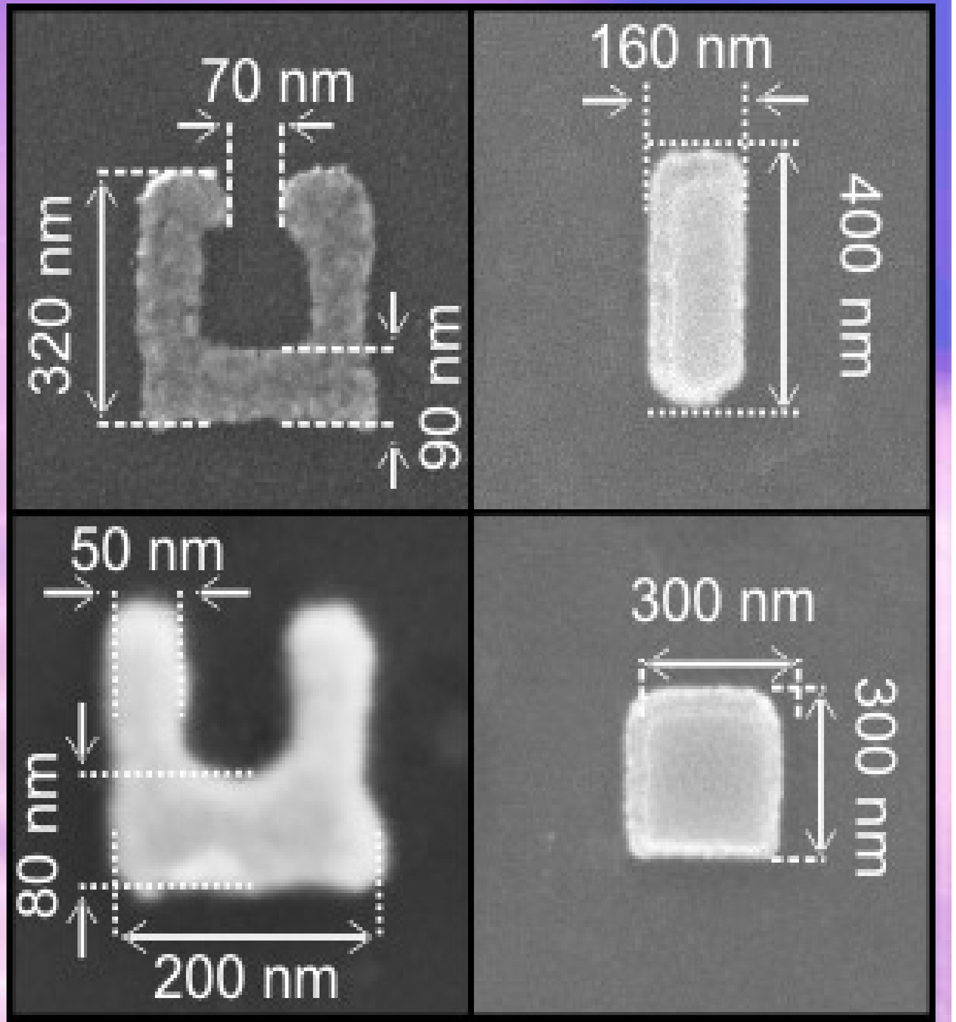
Dolling et al. Opt. Lett. **31** 1800 (2006)

Normal Incidence broad band white light



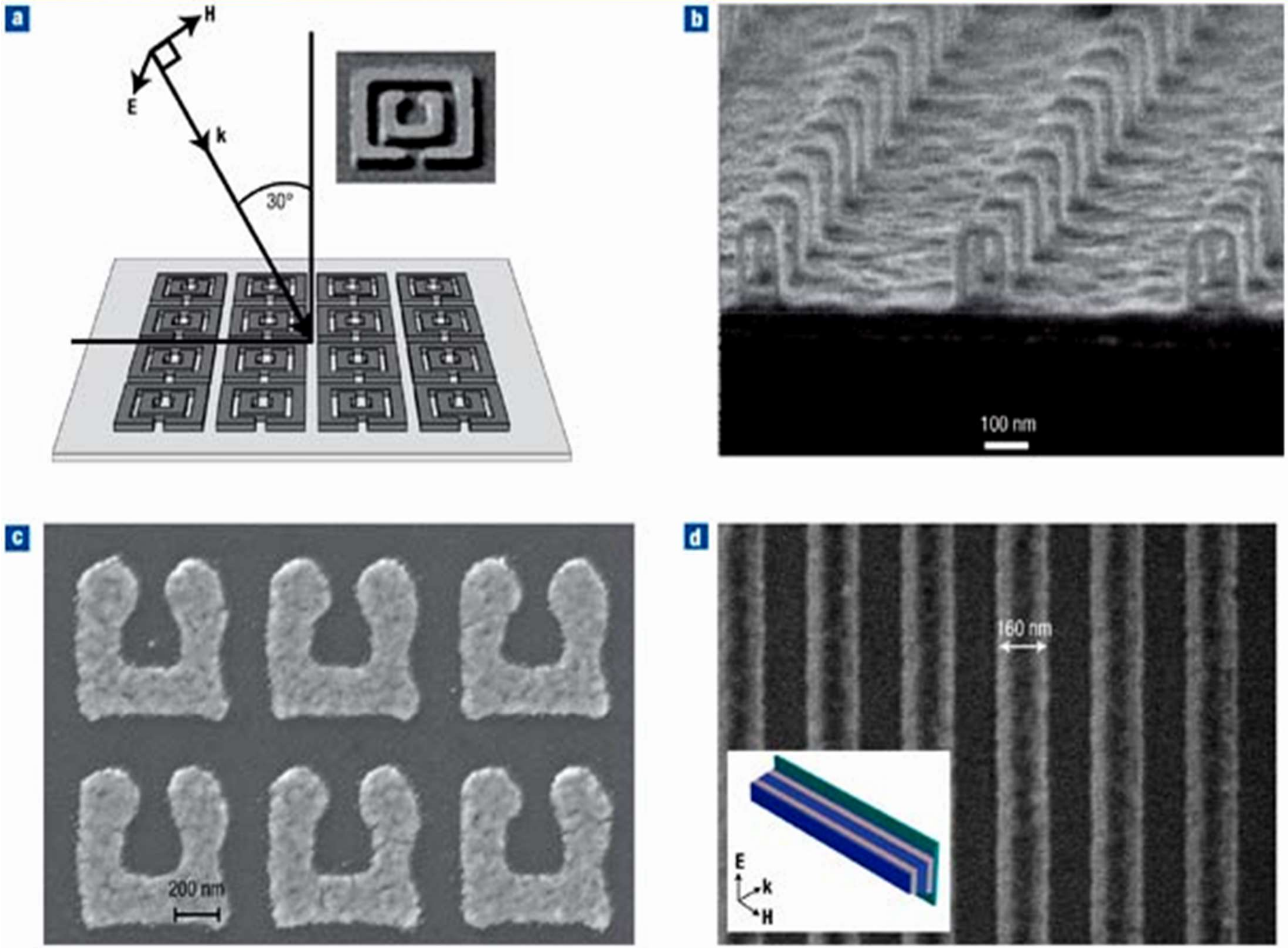
U型结构





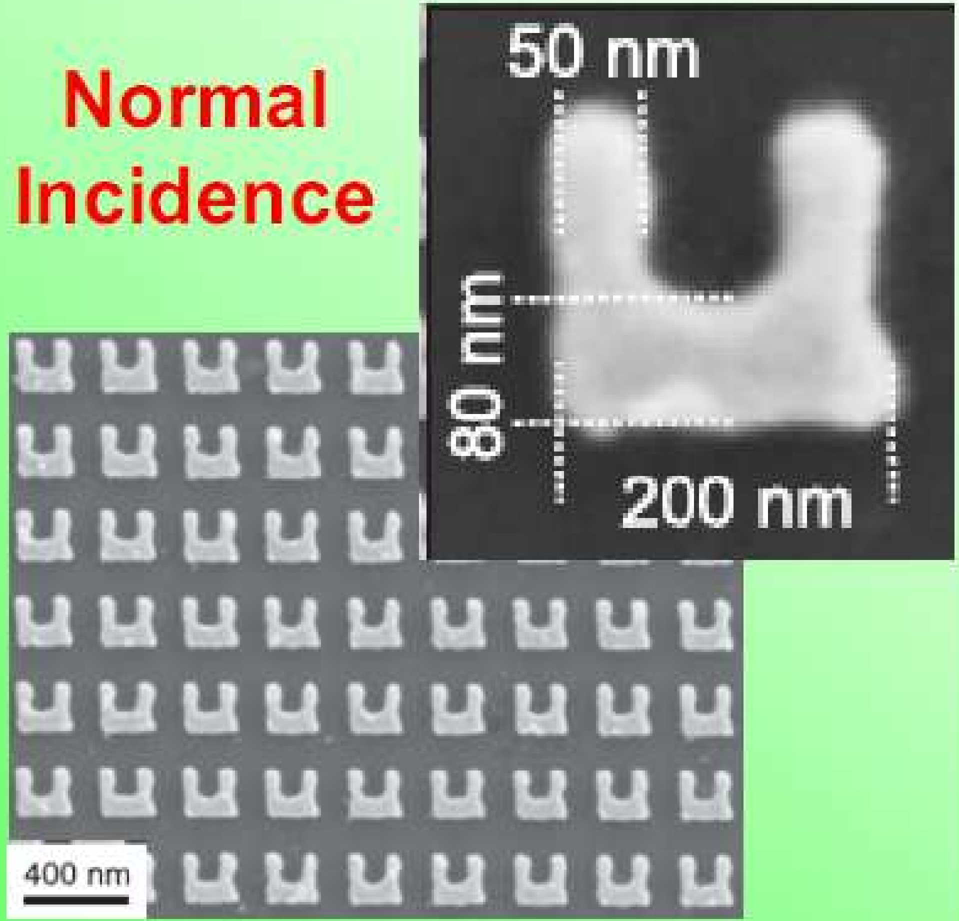
加工技术：扫描电子束刻蚀

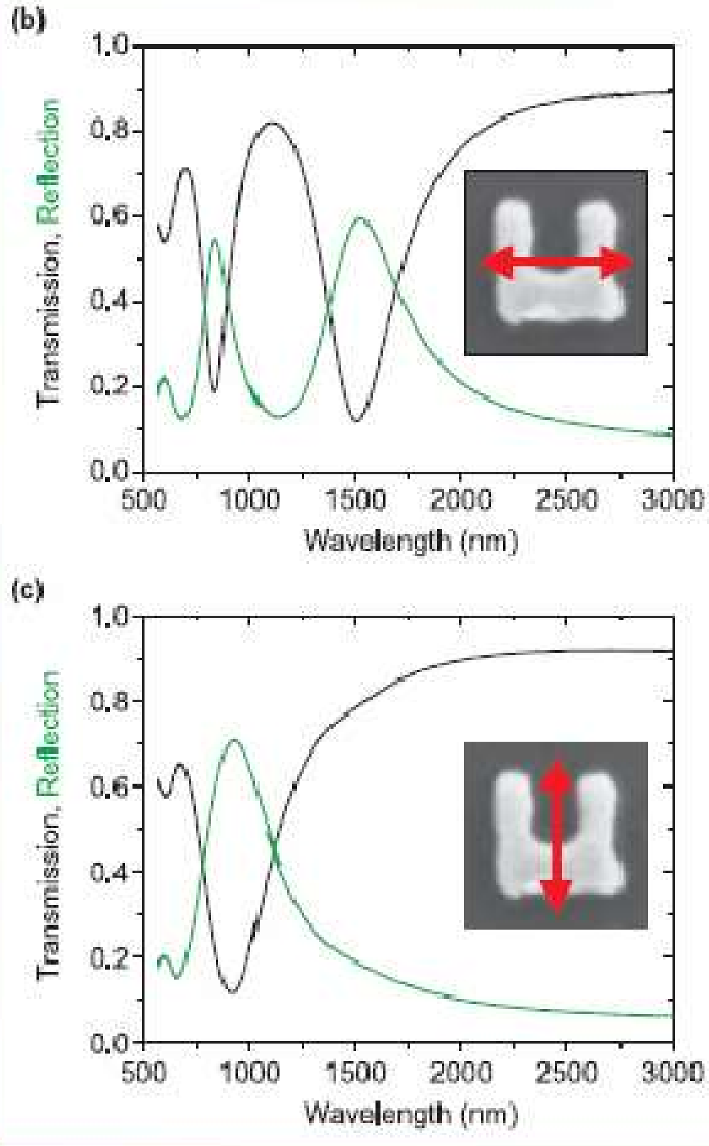
使用波段：近红外


a
H
E
k
30°
b
100 nm
c
200 nm
d
160 nm
E
k
H

Magnetic resonances at 1.5 μm

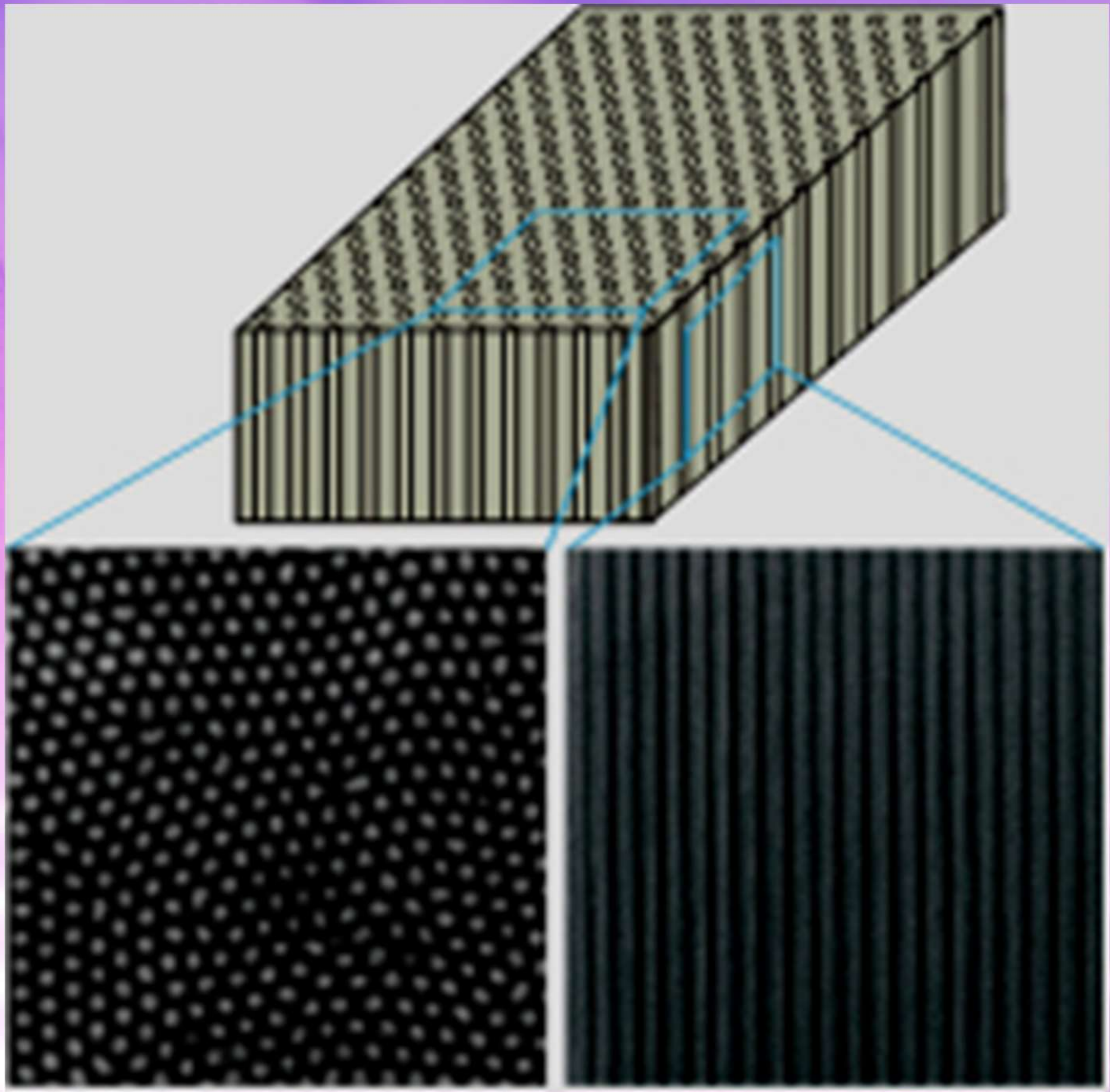
Normal Incidence





Enkrich et al. PRL **95** 203901 (2005)

应用于可见光波段的负折射率材料



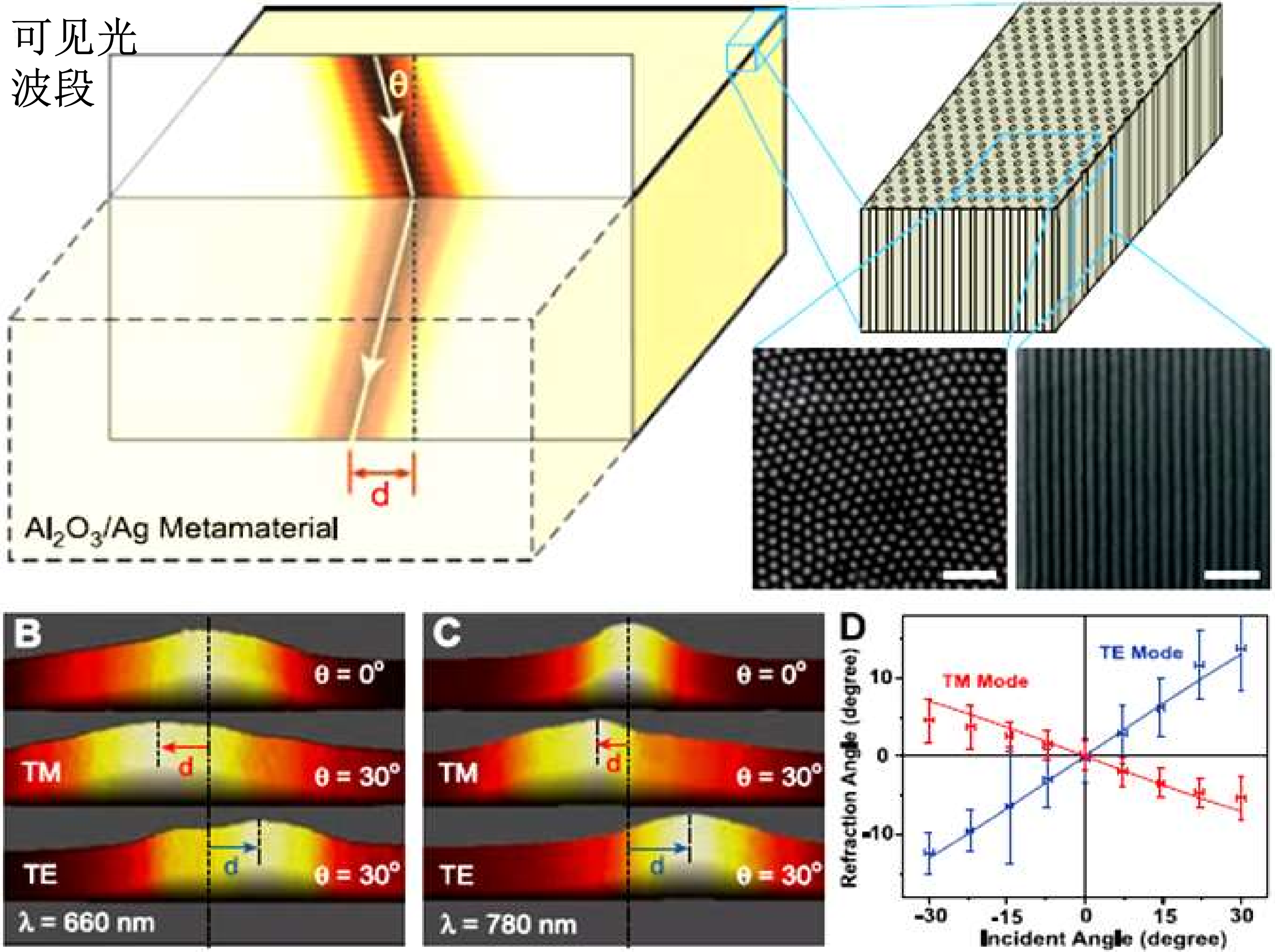
特征尺寸<100纳米

基底材料Al_2O_3

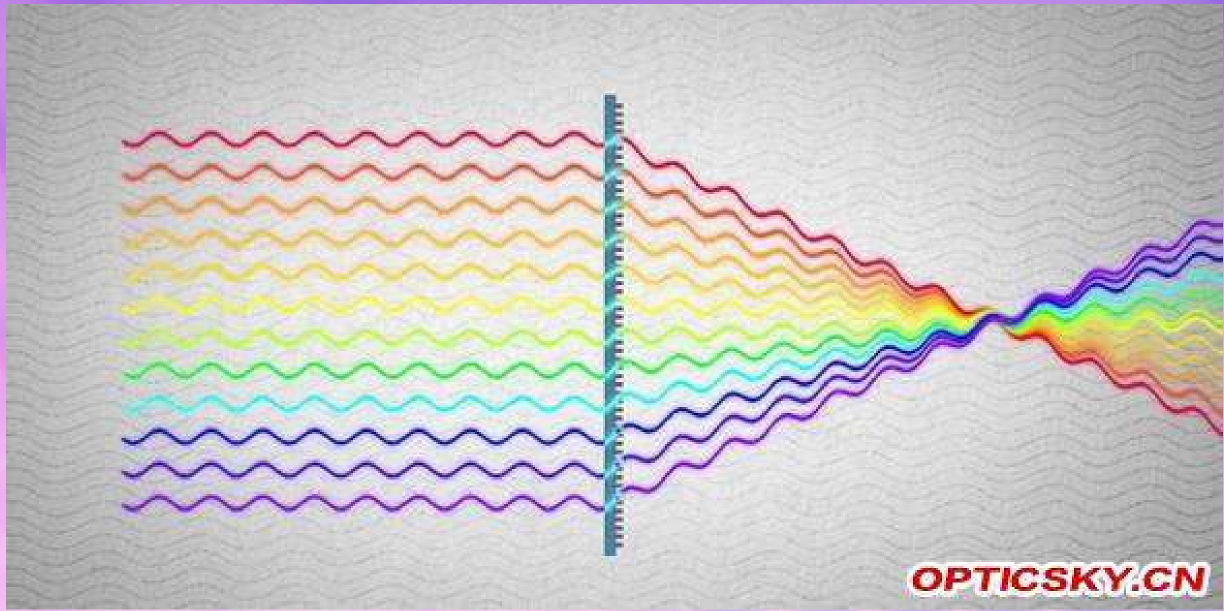
银纳米线

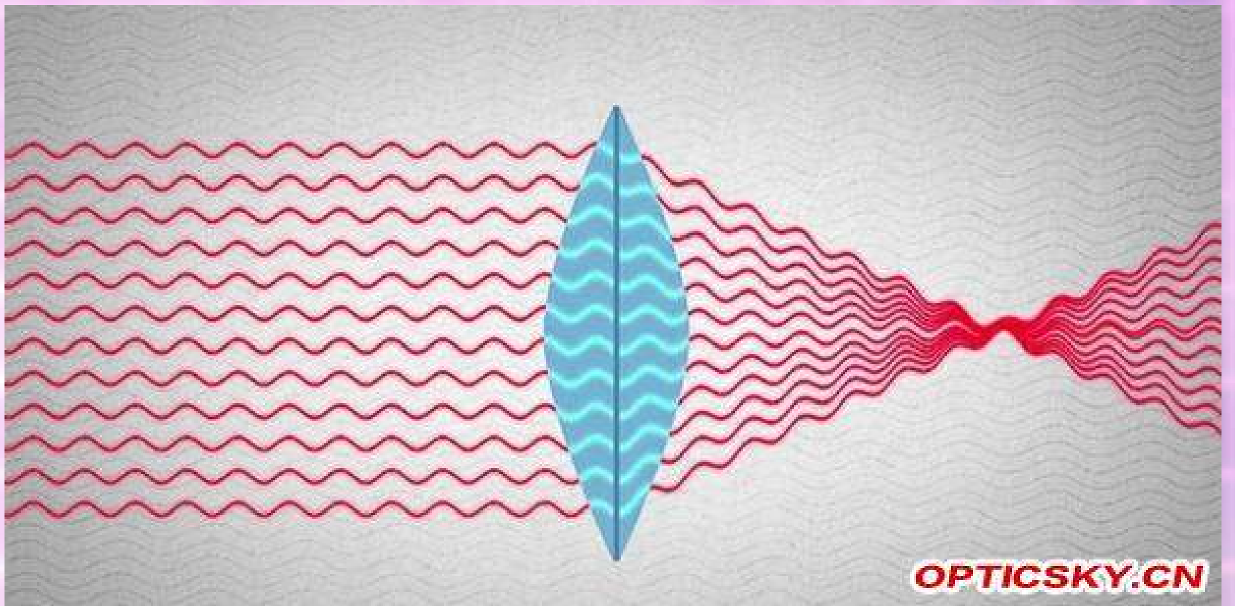
Science 321, 930 (2008).

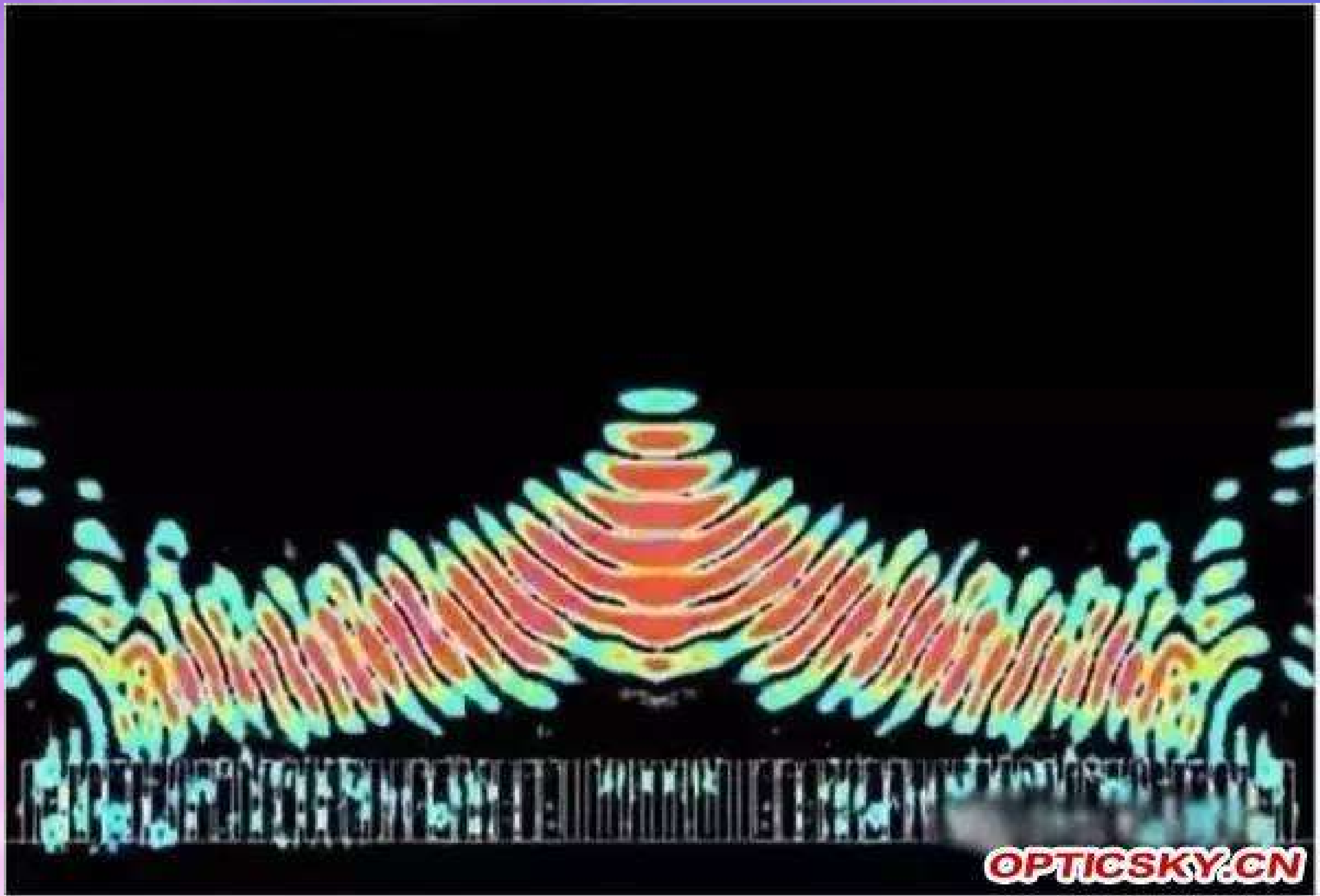
可见光
波段


θ
d
Al_2O_3/Ag Metamaterial
B
θ = 0°
TM
d
θ = 30°
TE
d
θ = 30°
λ = 660 nm
C
θ = 0°
TM
d
θ = 30°
TE
d
θ = 30°
λ = 780 nm
D
TE Mode
TM Mode
Refraction Angle (degree)
Incident Angle (degree)
10
0
-10
-30
-15
0
15
30

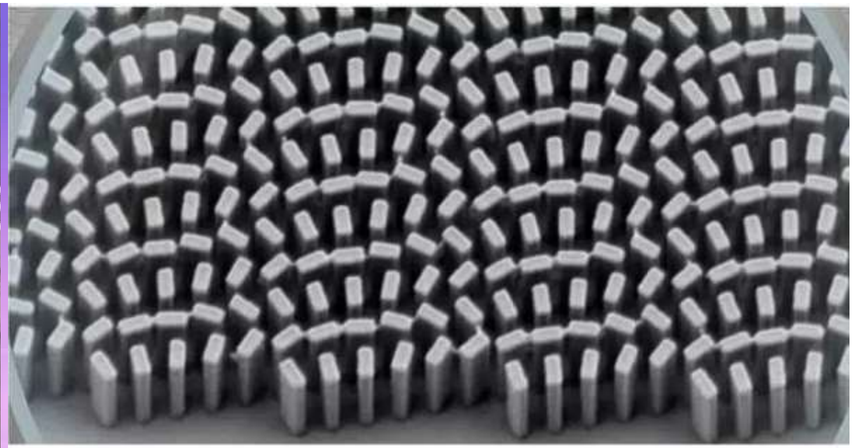
超材料透镜将彻底颠覆相机镜头

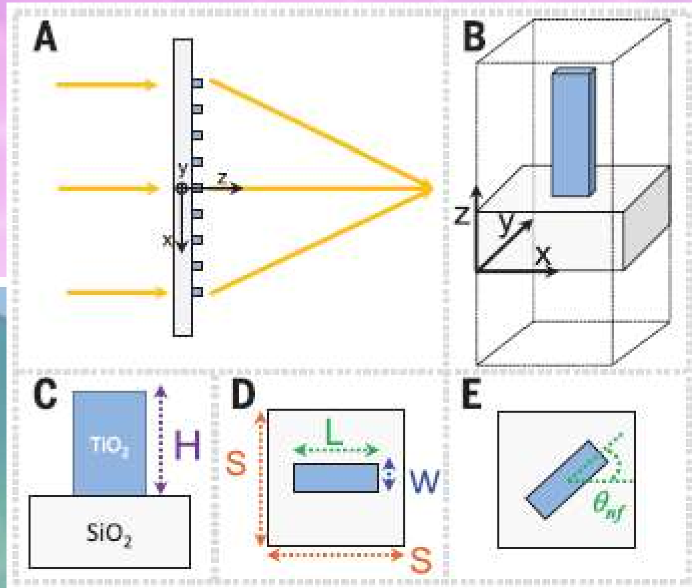


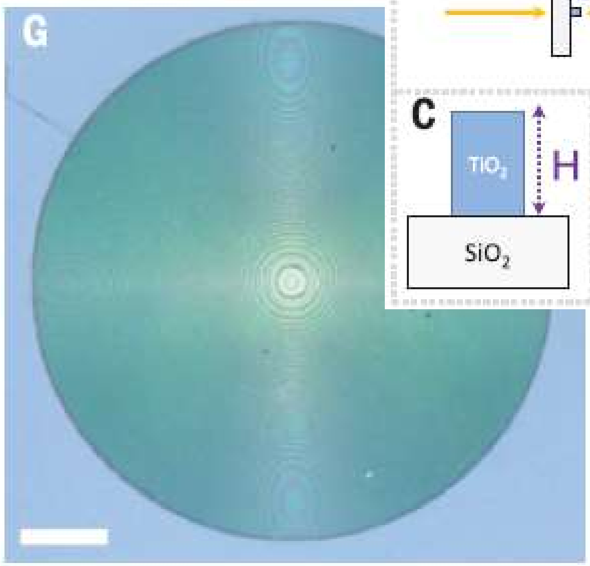


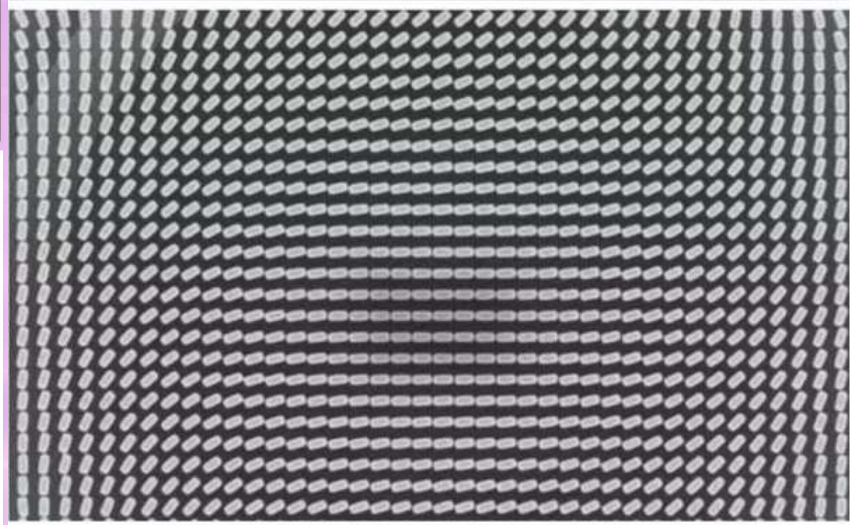


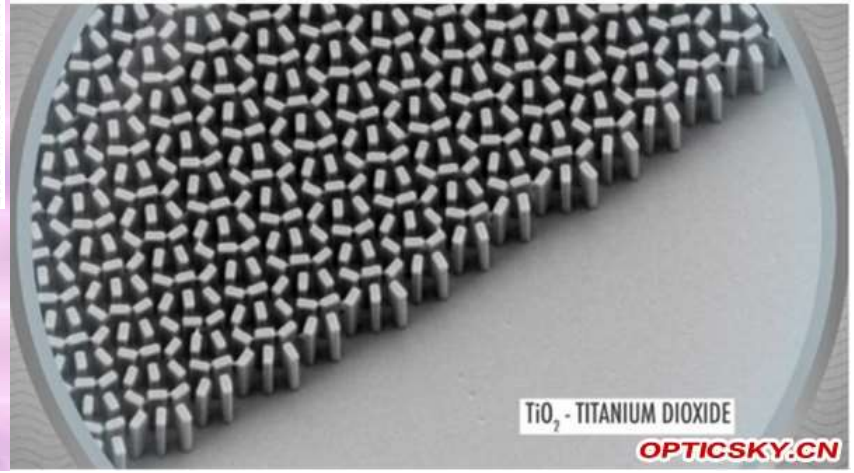
哈佛大学的这支研究团队利用高度约为600纳米的二氧化钛“纳米砖”，造出了一块完全“平整”，薄如纸片的“聚光镜片”。这块超材料镜片的有效放大倍率高达170倍，并且具备优异的成像分辨率。试验阶段的超材料镜片已能与常规光学玻璃透镜的分辨率媲美。









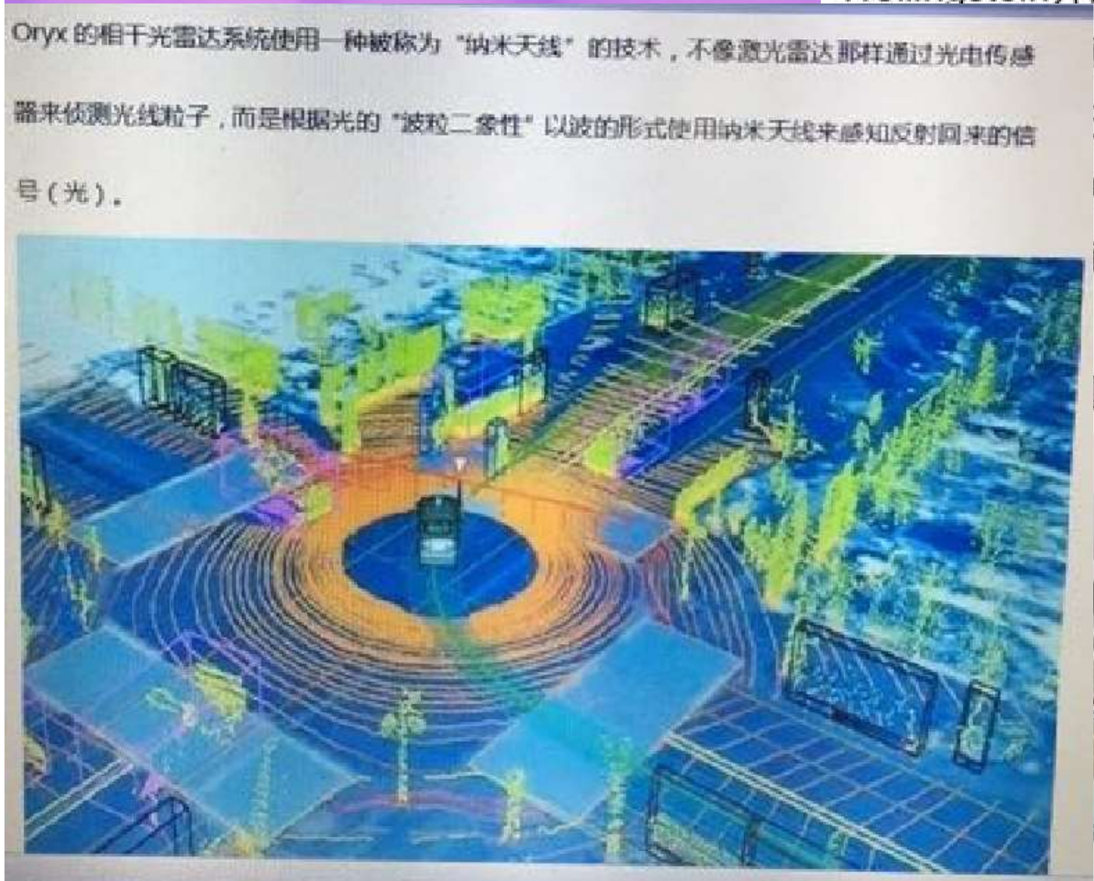


Science
352,6290(2016)

智能汽车

Oryx Vision公司CEO Rani Wellingstein近日表示，他们发明了一种“相干光雷达系统”，该系统能增强自动驾驶车辆的深度感知能力。这家崭露头角的以色列公司，刚刚完成了A轮融资，他们把自己定位为激光雷达的挑战者。

Wellingstein介绍称，传统的激光雷达依靠光电感应器来检测
|量光的能量。但是Oryx公司的雷达系统采用了
天线”的技术来接收电磁波，从而能获得更多的
中技术的优势在于增大了自动驾驶汽车对外界的
敏度，使其对周围的环境以及正在发生的事情有
Oryx天线能够接收波长为10微米的电磁波，因
烟雾，而且不像激光雷达那样会受到强光影响。


Oryx 的相干光雷达系统使用一种被称为"纳米天线"的技术，不像激光雷达那样通过光电传感器来侦测光线粒子，而是根据光的"波粒二象性"以波的形式使用纳米天线来感知反射回来的信号(光)。

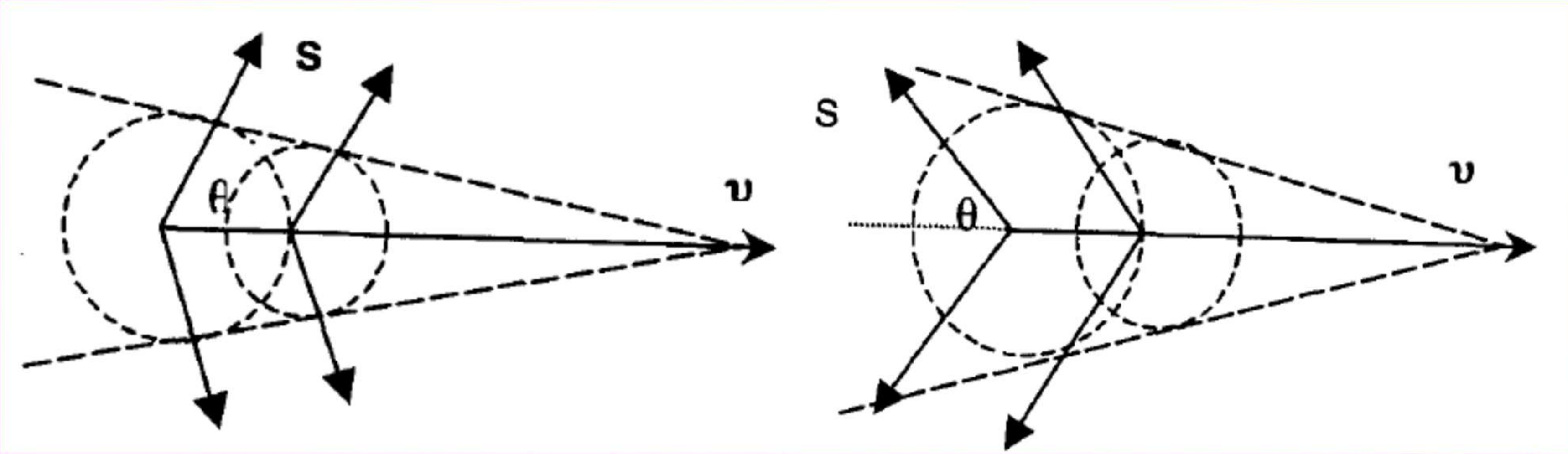
负折射率材料的特性

- 反常**Cherenkov**辐射；
- 反常**Doppler**效应；
- 反**Goos-Hanchen**位移；
- 负光压；
- 超级透镜

负折射率介质中的反常**Cherenkov**辐射

- 在真空中，匀速运动的带电粒子不会辐射电磁波。
- 在介质中，当带电粒子匀速运动时会在其周围引起诱导电流，从而在其路径上形成一系列次波源，分别发出次波。
- 当粒子速度超过介质中光速时，这些次波互相干涉，从而辐射出电磁场，称为**Cherenkov**辐射。

负折射率介质中的反常Cherenkov辐射



右手介质　　　　　　　　　　　　左手介质

干涉后形成的波前，即等相面是一个锥面。

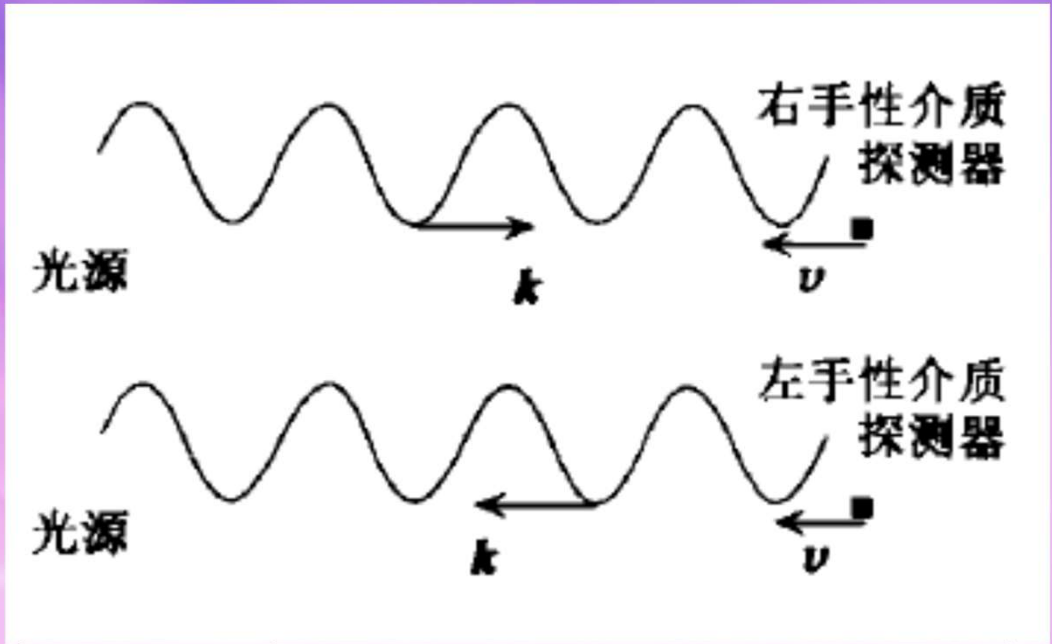
右手介质中，电磁波的能量沿此锥面的法线方向辐射出去，是向前辐射的，形成一个向后的锥角；

而在左手介质中，能量的传播方向与相速度相反，因而辐射将背向粒子的运动方向发出，辐射方向形成一个向前的锥角。

反常Doppler效应

- 声波的Doppler效应。
- 在正常材料中，波源和观察者如果发生相对移动，会出现Doppler效应：两者相向而行，观察者接收到的频率会升高;反之则会降低。
- 但在负群速度材料中正好相反，因为能量传播的方向和相位传播的方向正好相反，所以如果二者相向而行，观察者接收到的频率会降低，反之则会升高，从而出现反常Doppler频移。

反常Doppler效应



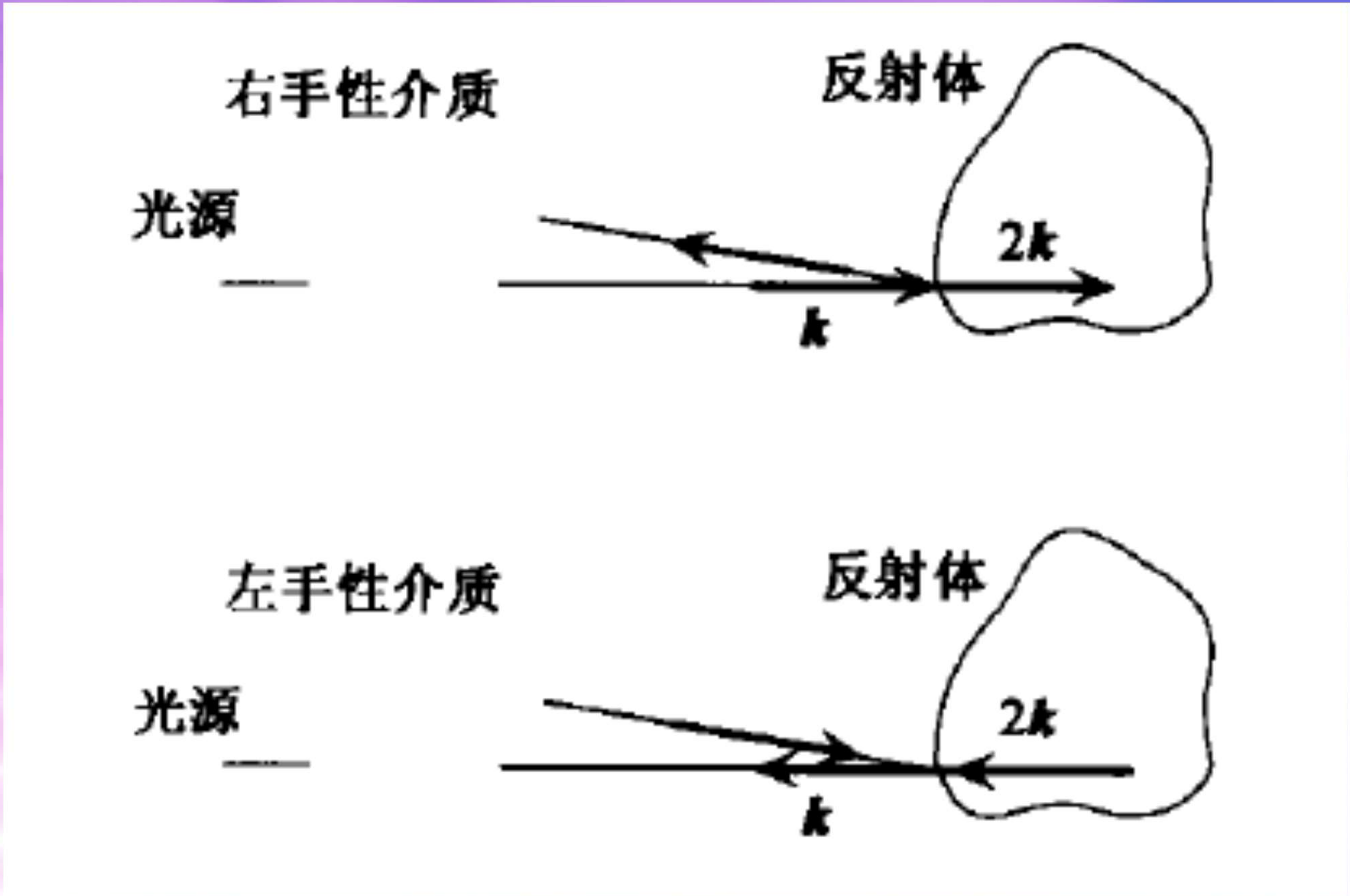
$$\omega' = \gamma\omega\left(1+\frac{\vec{n}\bullet\upsilon}{c}\right)$$，其中相对论因子 $\gamma = \left(1-\frac{\upsilon^2}{c^2}\right)^{-1/2}$

探测器向光源移动：

右手介质中，探测到的频率变高；当$n=1$时，$\omega' = \omega\sqrt{\frac{c+\upsilon}{c-\upsilon}}$，

左手介质中，探测到的频率变低。当$n=-1$时，$\omega' = \omega\sqrt{\frac{c-\upsilon}{c+\upsilon}}$，

负光压——光子动量 $\hbar k$

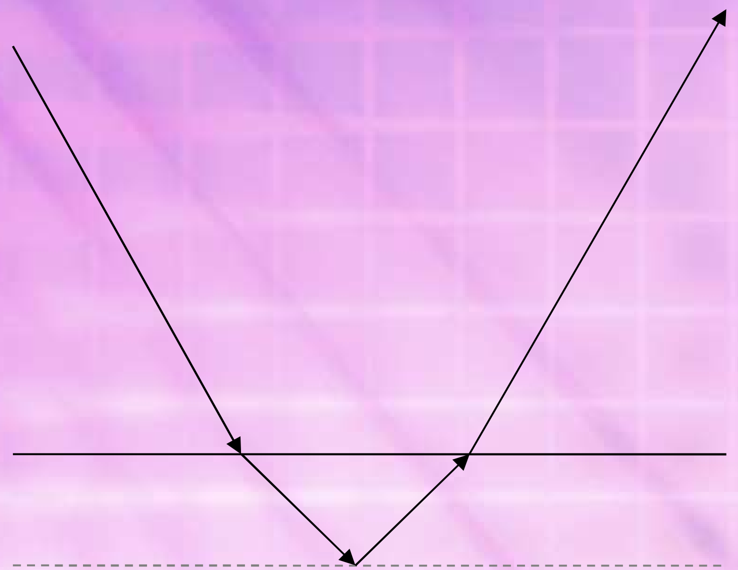


反Goos-Hanchen位移

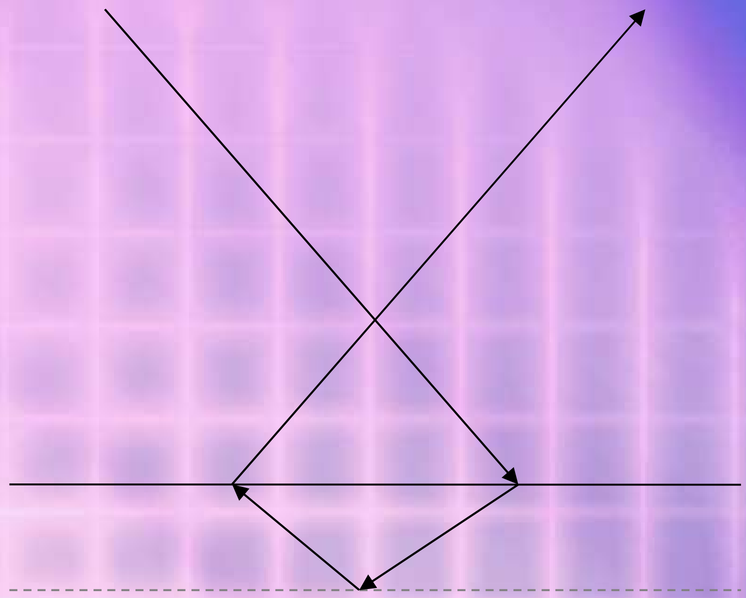
所谓的Goos-Hanchen位移是指当光波在两种介质的分界面处发生全反射时，反射光束在界面上相对于几何光学预言的位置有一个很小的侧向位移，且该位移沿光波传播的方向。

引起Goos-Hanchen位移的原因是电磁波并非由界面直接反射，而是在深入介质2的同时逐渐被反射，其平均反射面位于穿透深度处。若介质2为左手材料，则该位移沿光波传播反方向，称为反Goos-Hanchen位移。

Goos-Hanchen位移



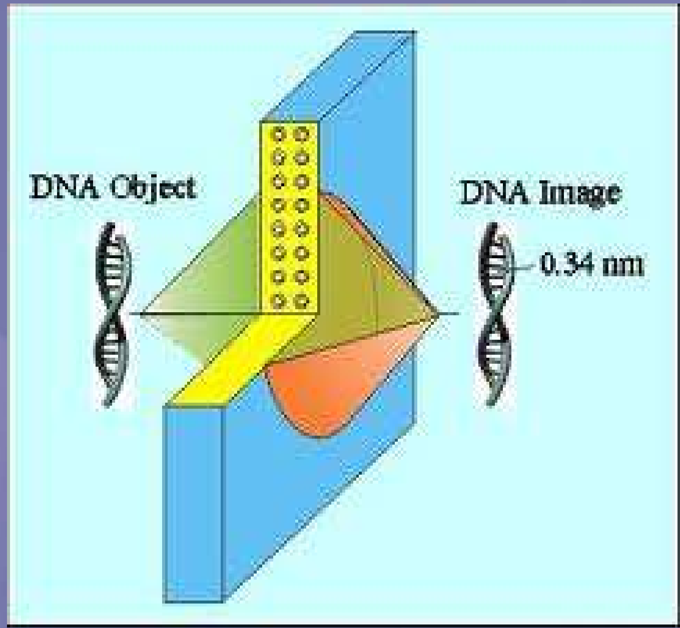
右手介质－右手介质界面



右手介质－左手介质界面

超透镜的物理机制

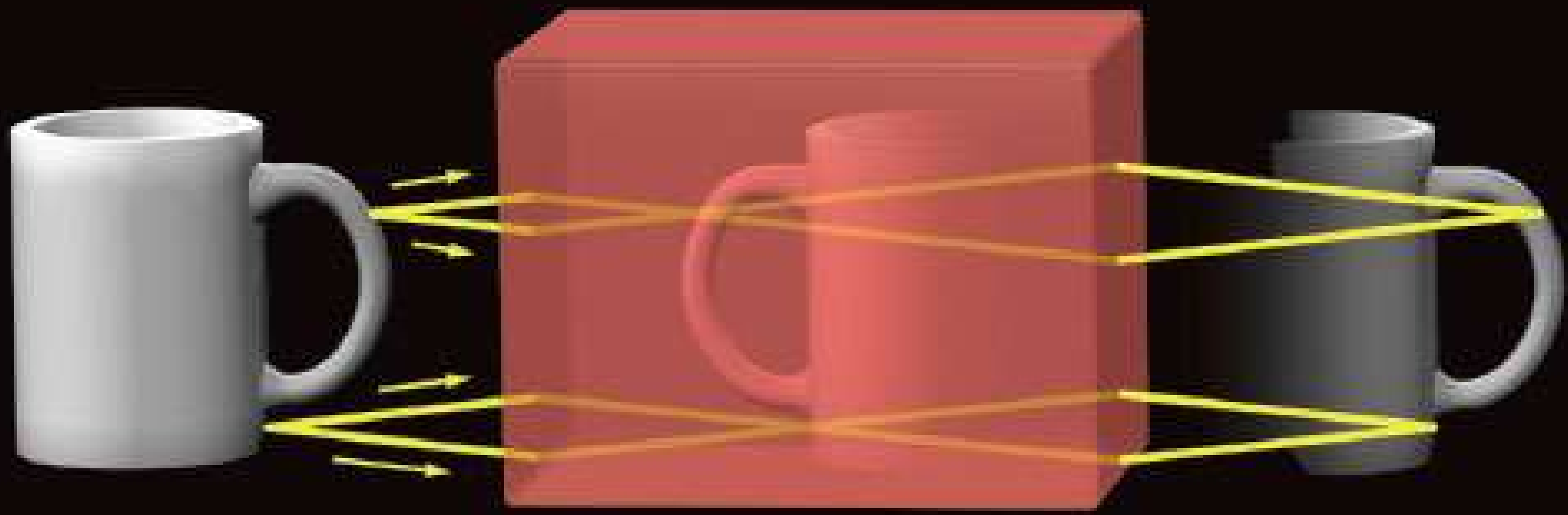
超透镜的严格定义：

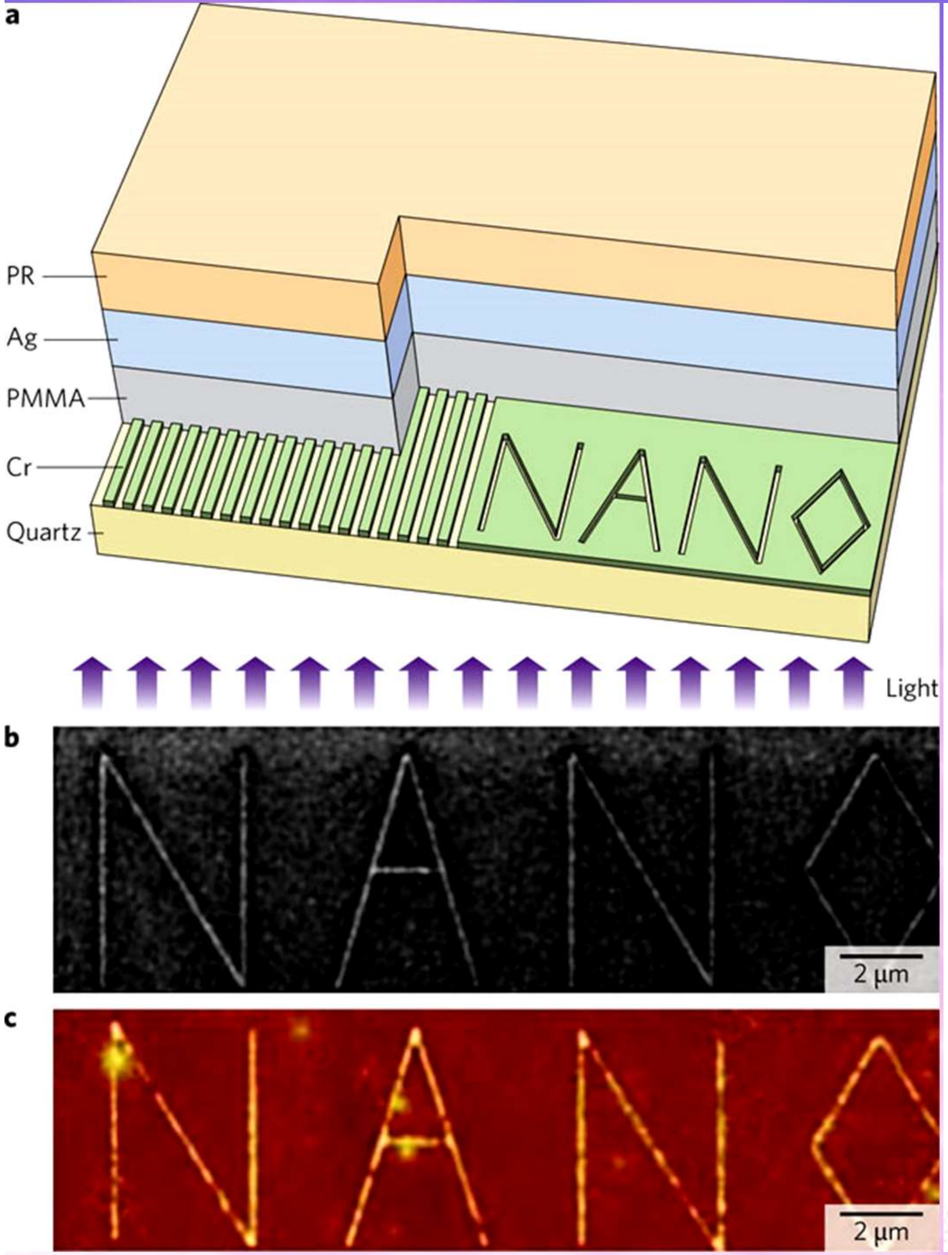


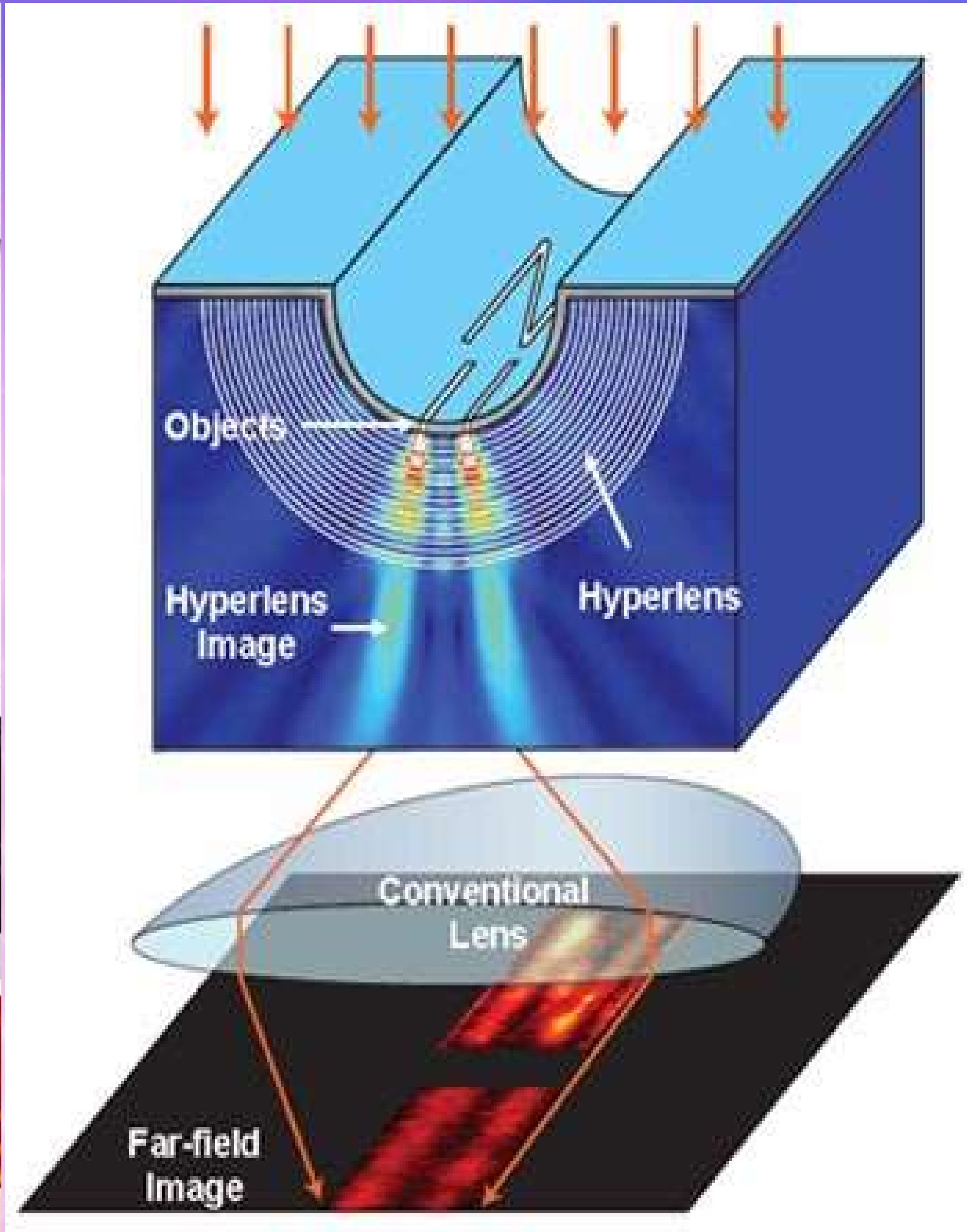
由完全负折射率材料构成的用于成像的光学元件成为超透镜(superlens)。

THE SUPERLENS

A rectangular slab of negative-index material forms a superlens. Light (*yellow lines*) from an object (*at left*) is refracted at the surface of the lens and comes together again to form a reversed image inside the slab. The light is refracted again on leaving the slab, producing a second image (*at right*). For some metamaterials, the image even includes details finer than the wavelength of light used, which is impossible with positive-index lenses.







So-called "superlens" claimed by Zhang Xiang, *et. al*.

超透镜（完美透镜）

◆Pendry在2000年提出利用负折射率材料制作“超透镜”。

◆2000与2001年所发表的关于左手征材料的研究论文数量分别是13篇与17篇，2002年60篇，2003年上升到100篇以上。

◆“超透镜”成像：

1、一块平板就能构成一块透镜；

2、所有傅立叶分量全部聚焦；

3、无衍射成像；

4、能放大倏失波。

超透镜（完美透镜）

频率为ω的偶极子，其辐射场的电场分量可以利用傅立叶级数展开为如下形式：

$$E(r,t) = \sum_{\sigma,k_x,k_y} E\sigma(k_x,k_y) \cdot \exp(\mathrm{i}k_z z + \mathrm{i}k_x x + \mathrm{i}k_y y - \mathrm{i}\omega t)$$

$$k_z = \sqrt{\omega^2 c^{-2} - k_x^2 - k_y^2},$$

当 $\omega^2 c^{-2} > k_x^2 + k_y^2$ 时, k_z 为一实数,

当 $\omega^2 c^{-2} < k_x{}^2 + k_y^2$ 时, $k_z = \mathrm{i}\sqrt{k_x^2 + k_y^2 - \omega^2 c^{-2}}$,

倏逝波衰减很快，无法参与成像，故传统光学透镜参与成像的成分为 $k_x^2 + k_y^2 < \omega^2 c^{-2}$,

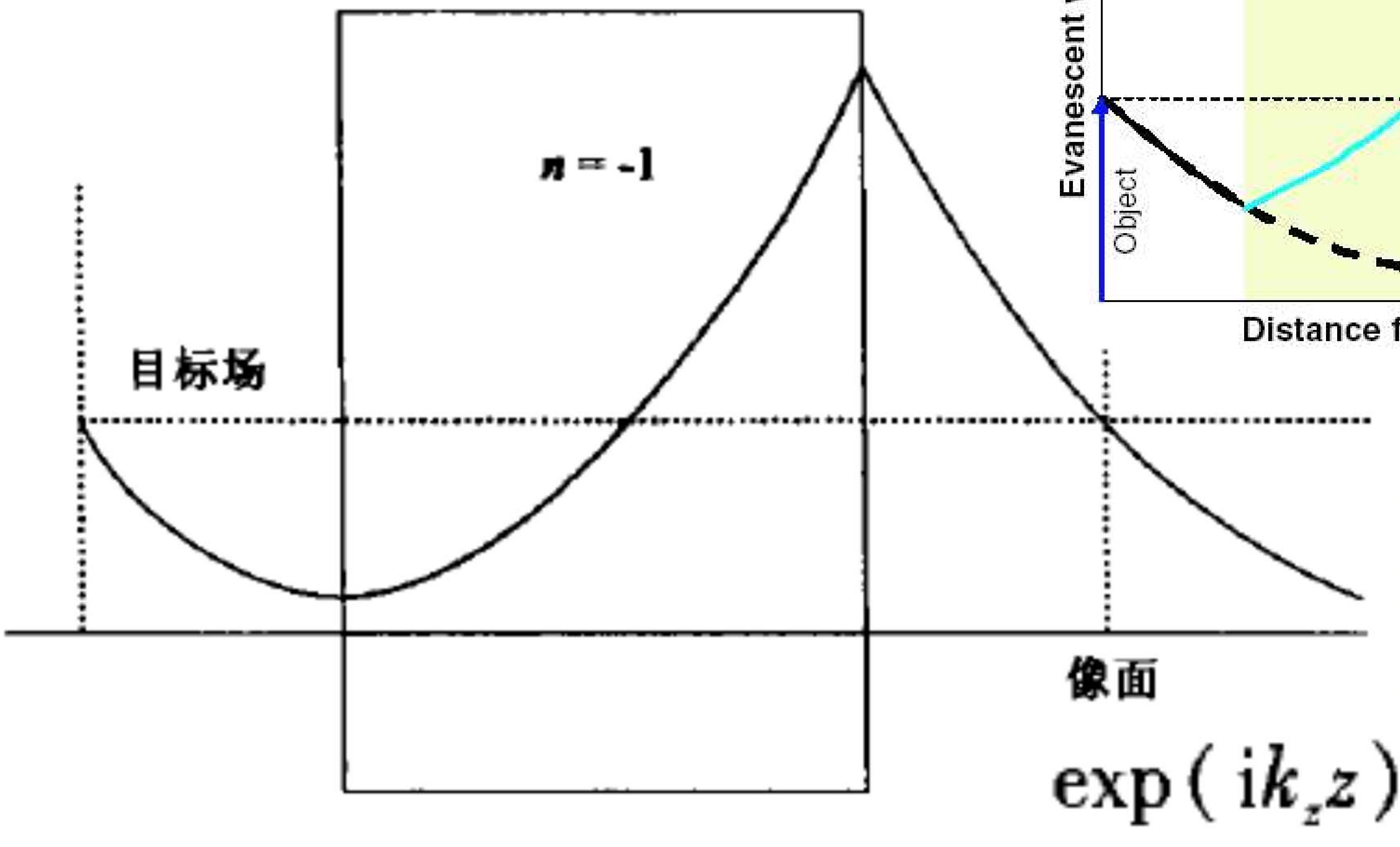
故分辨率为 $\Delta \approx \dfrac{2\pi}{k_{\max}} = \dfrac{2\pi c}{\omega} = \lambda$

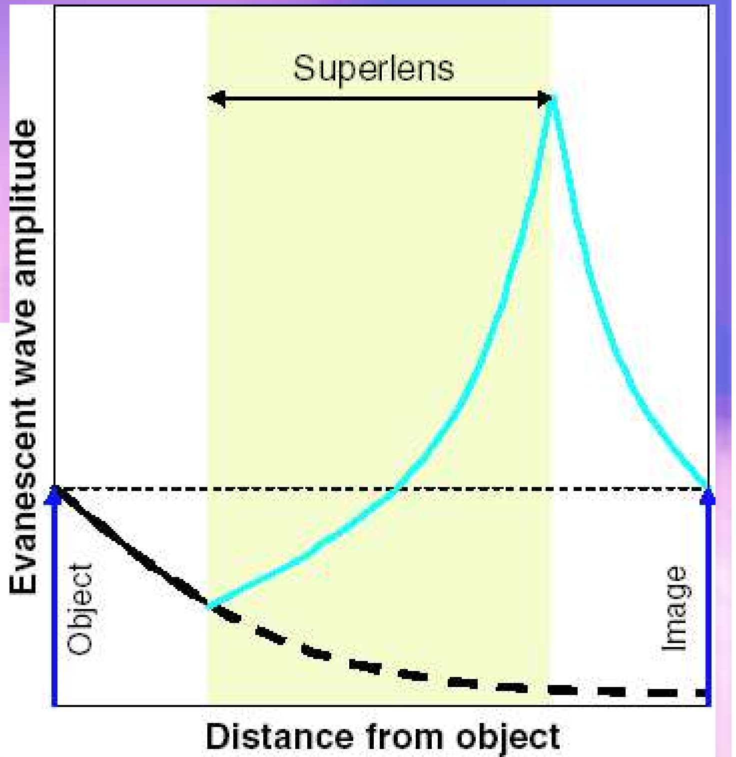
超透镜（完美透镜）

- 当 $\varepsilon=-1,\mu=-1$，即折射率 $n=-1$ 时，由菲涅尔公式得知此时反射系数为0，即传播波无损失地参与了成像。
- 波传播一段距离Z的效应相当于复振幅乘以 $\exp(ik_z z)$。对于倏逝波，相当于场的指数衰减或者增强。
- 由于左手介质和右手介质中波矢k的方向恰巧相反，所以右手介质中的衰减场进入左手介质后变为增强场；相当于左手介质对其进行放大，放大后的倏逝场经过透镜右端进入右手介质后重新衰减，最后在像平面上恢复为原来的值，参与成像。

超透镜（完美透镜）

倏逝波参与成像



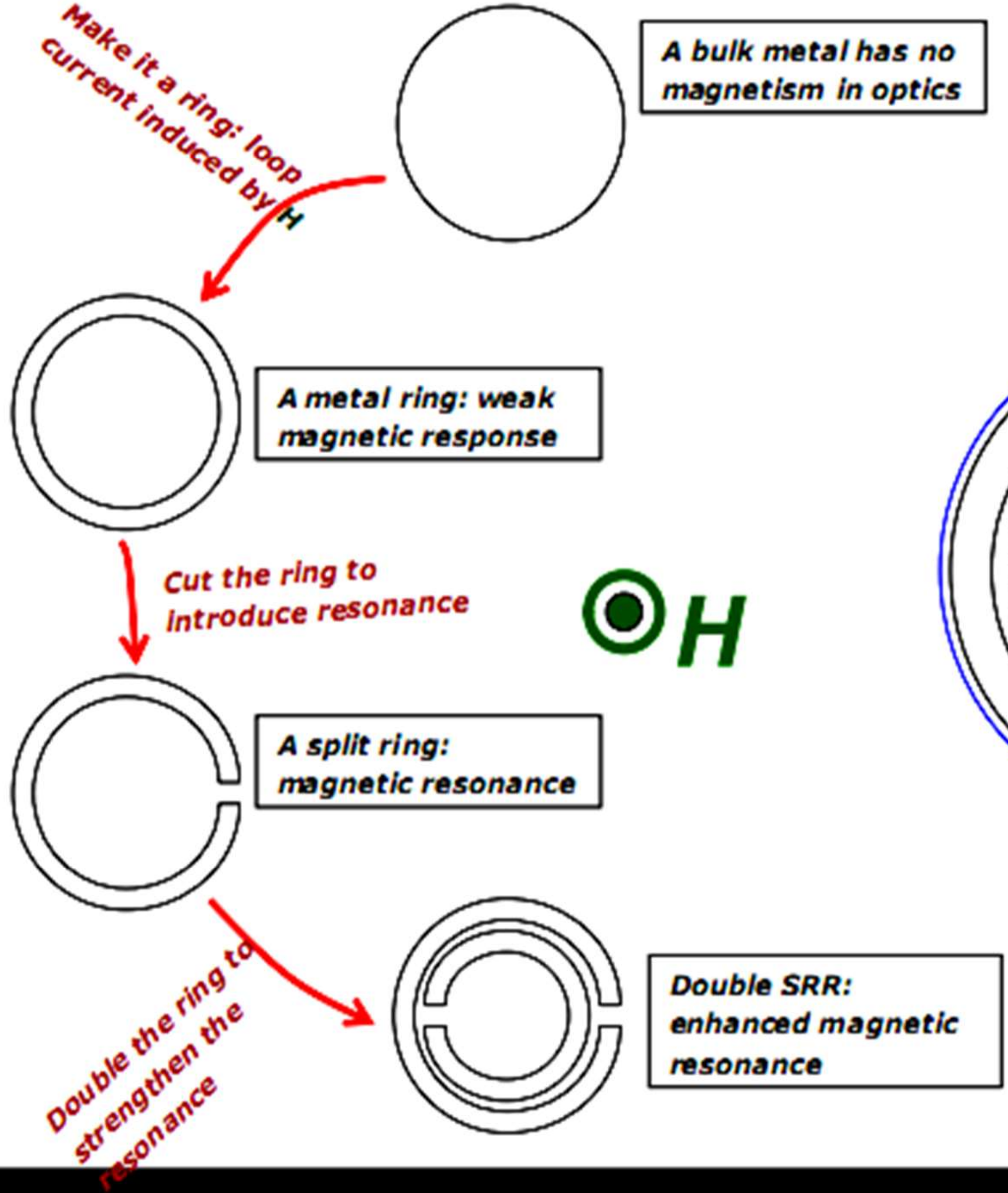


应用前景

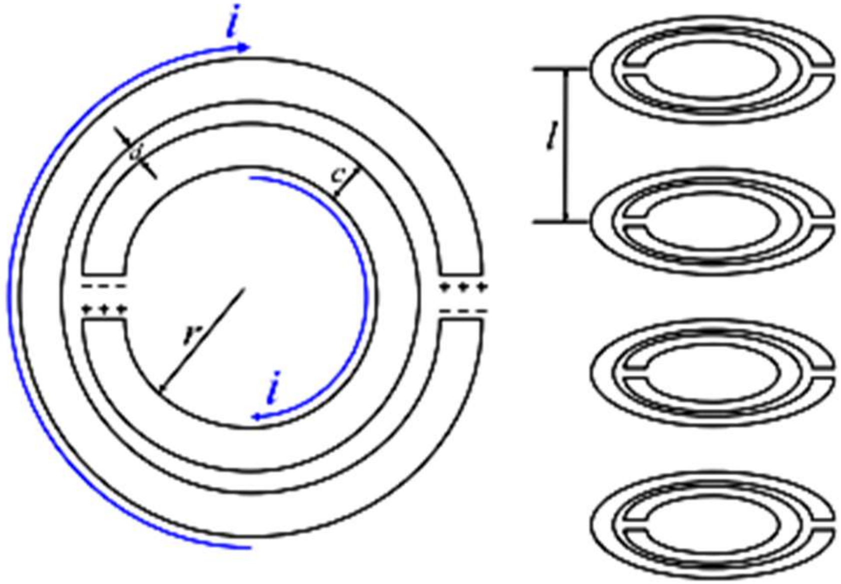
- 高方向性天线——通讯系统，如手机。
- 完美透镜——超分辨，资料储存媒介。
- 电磁波隐身——国防。

构建左手材料的物理机制

SRR: the first magnetic metamaterials



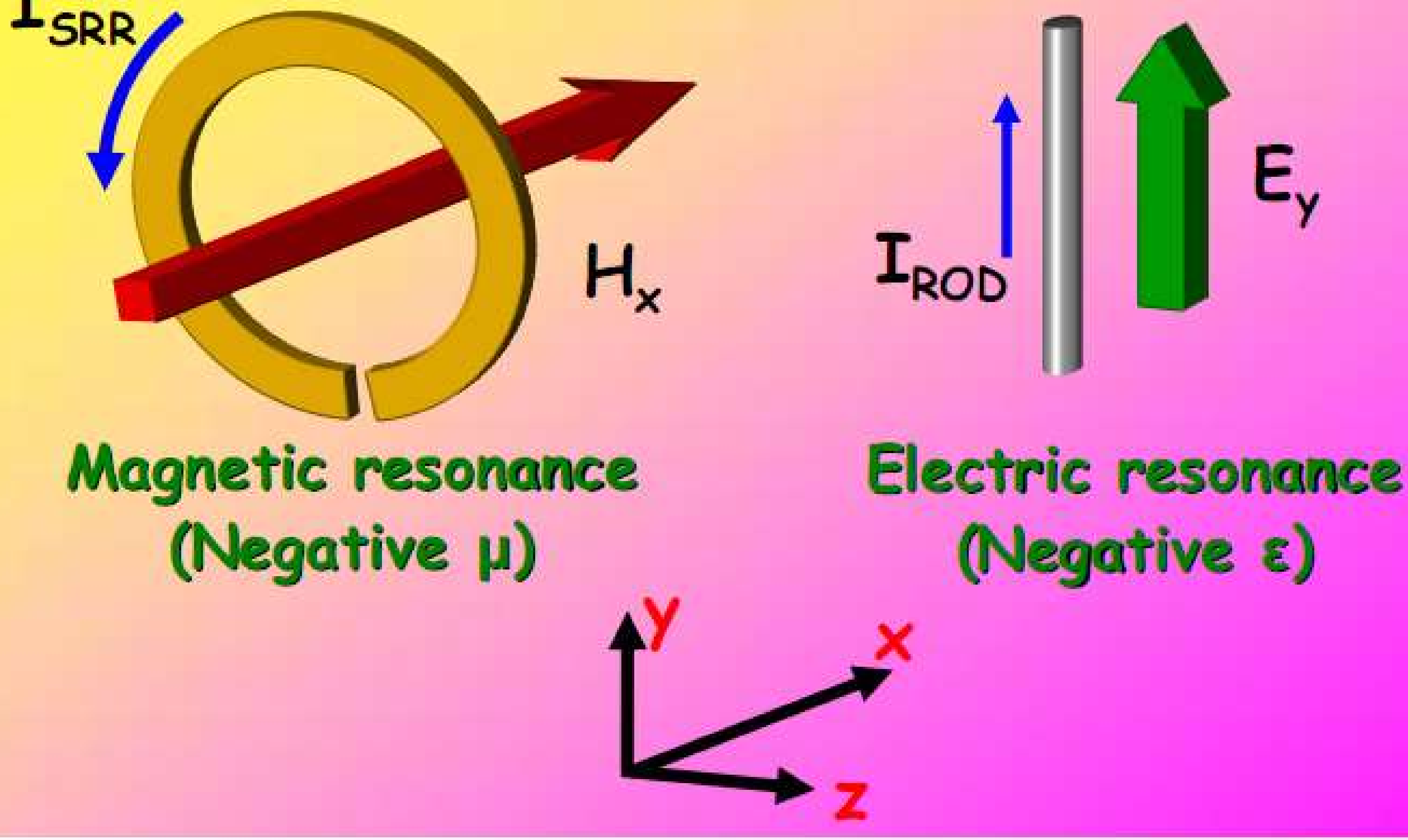
Split-ring resonator (SRR)



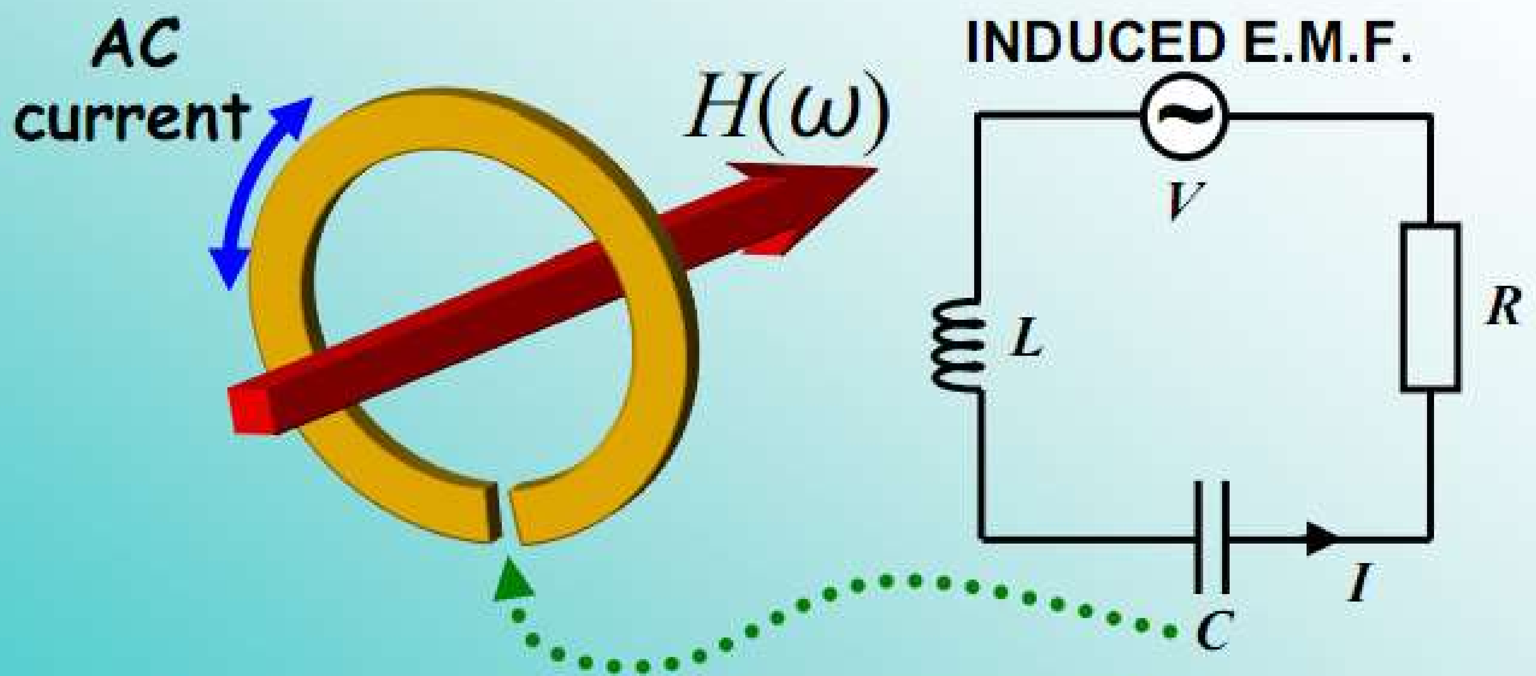
Theory: Pendry et al., 1999.

Experiment: Smith et al., 2000.

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



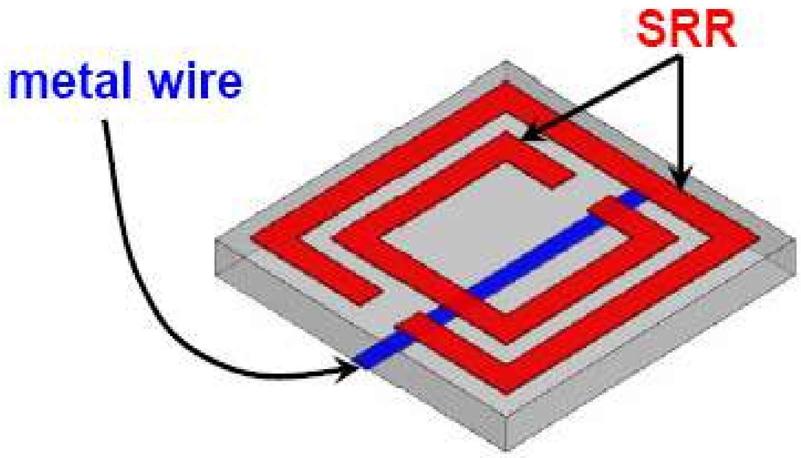
Split-Ring is an LCR Circuit



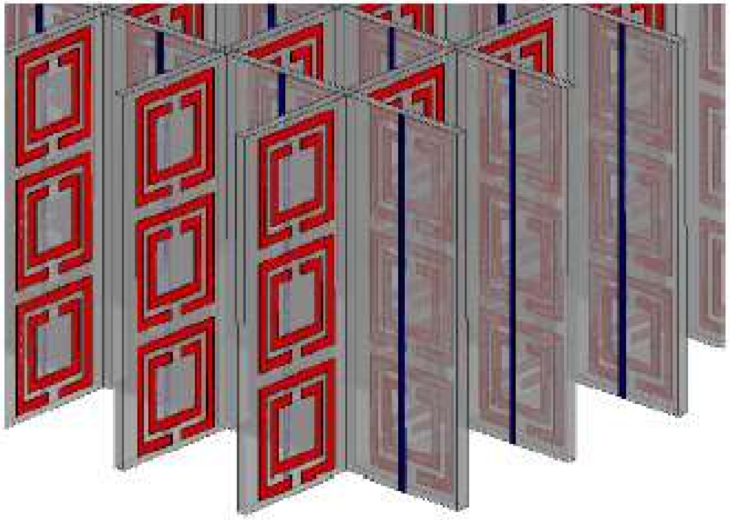
$$V = L\frac{dI}{dt} + IR + \frac{Q}{C} \rightarrow \mu(\omega)$$

LHM – Resonant Approach

- **1967**: LHM were first proposed by Russian Physicist Victor Veselago
- **2001**: LHM realized based on split ring resonators - ***Resonant Approach*** towards LHMs.



SRR-based LHM unit-cell

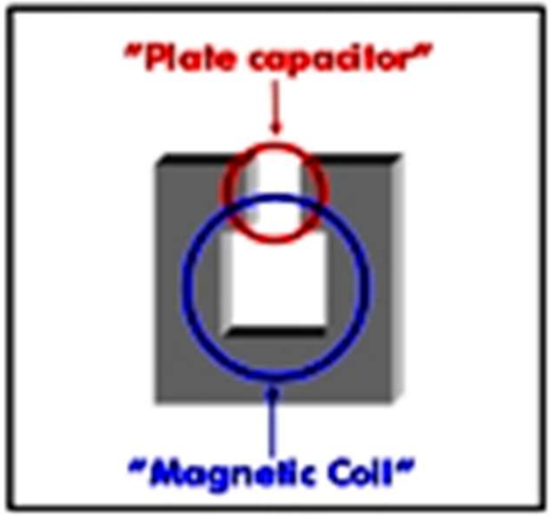


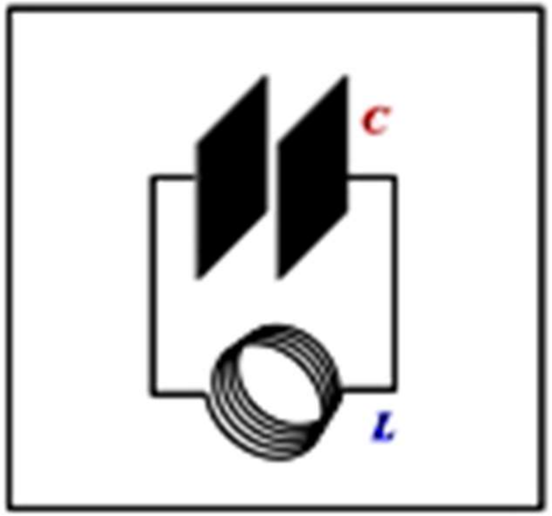
Split ring resonator SRR: at *resonance* provides $\mu<0$

metal wire: provides $\varepsilon<0$

- SRR-based metamaterials only exhibit LH properties at **resonance** - inherently ***narrow-band*** and ***lossy***.
- SRR-based LHMs are bulky - not practical for microwave engineering applications.

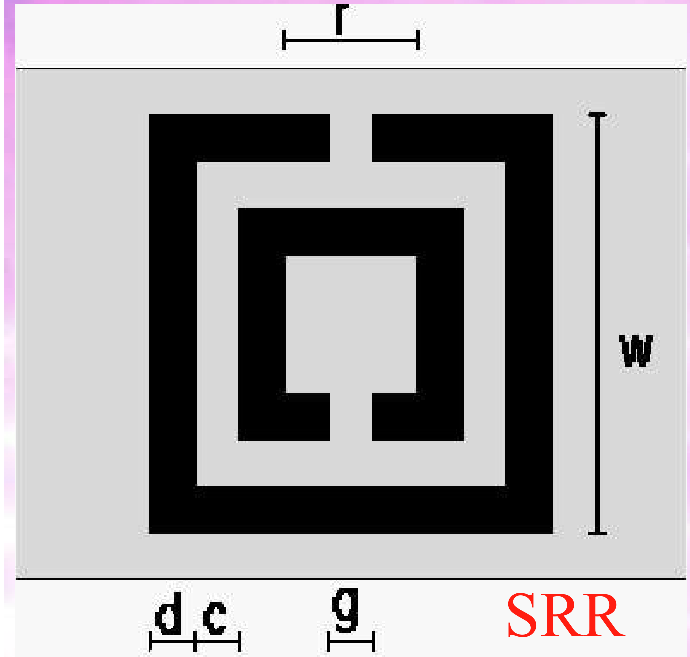
NIM physical model



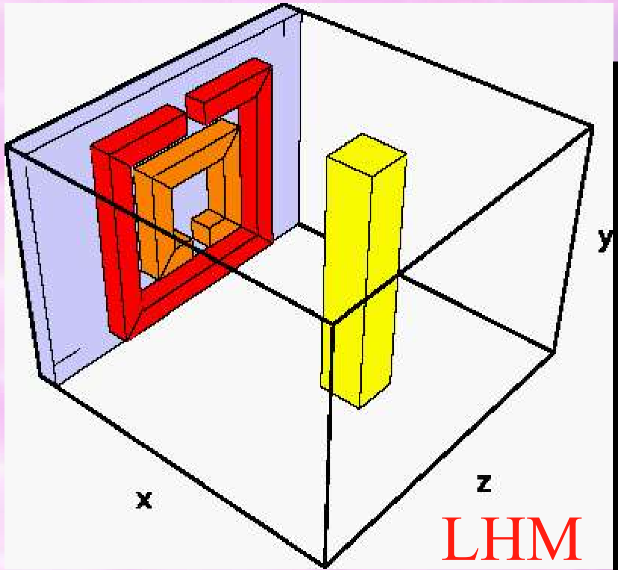


谐振频率$\omega_0 = \frac{1}{\sqrt{LC}}$

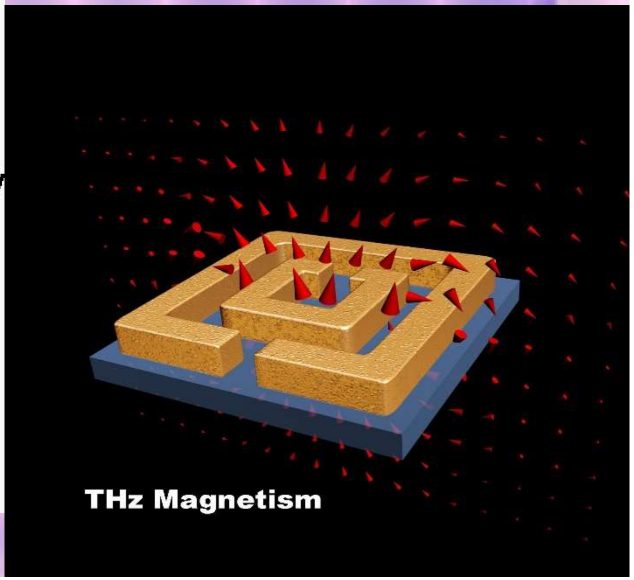
或$f_0 = \frac{1}{2\pi\sqrt{LC}}$



SRR



LHM

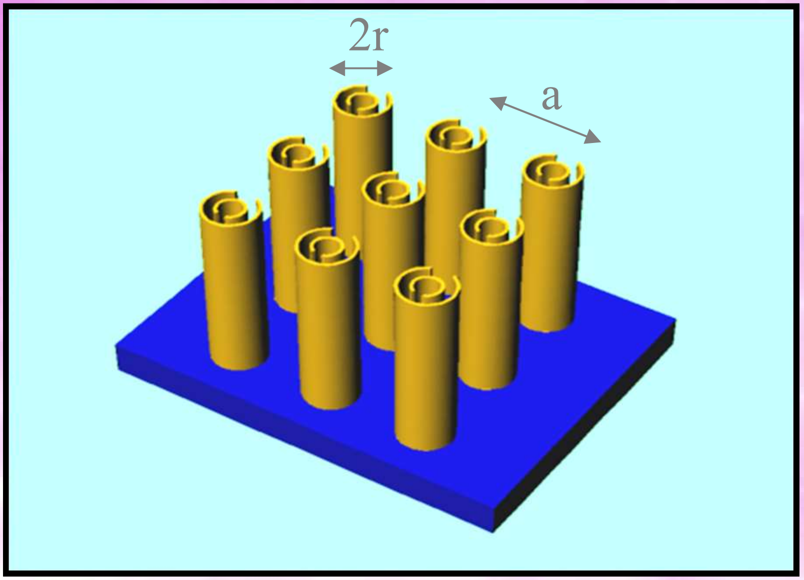


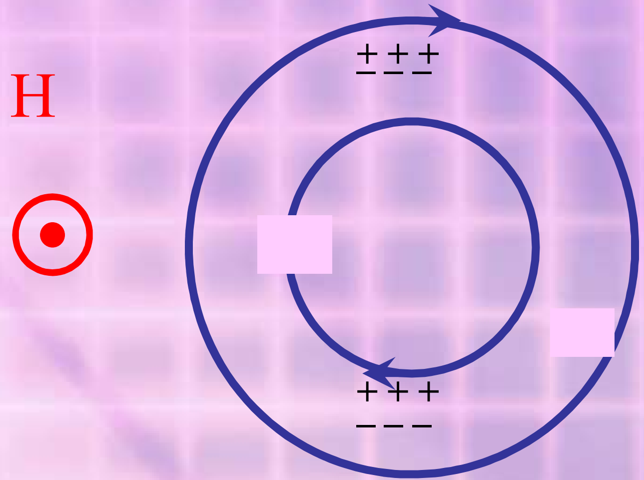
Artificial Magnetic Resonators at THz

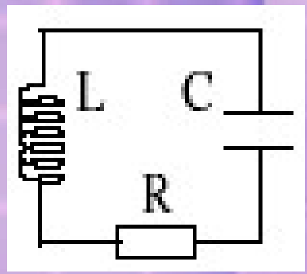
概念:

1. 磁通感应电流环形成磁偶极子

2. 内部的电导和电感将产生围绕共振频率强的顺磁性和抗磁性







Pendry J.B. *et al*, IEEE MTT 47, 2075 (1999)

等效介电常数ε_{eff}计算

当入射电磁波的电场方向平行于金属线的轴线时，在金属线上将激发感应电流，产生等效电偶极矩。这种结构的等效介电常数为

$$\varepsilon_{eff}=1-\frac{\omega_{ep}^2}{\omega^2+j\gamma\omega}=1-\frac{\omega_{ep}^2}{\omega^2+\gamma^2}+j\frac{\gamma\omega_{ep}^2}{\omega(\omega^2+\gamma^2)}$$

其中，ω_{ep}为等离子体频率，与体系中自由移动的带电粒子浓度等物理量相关，γ代表阻尼因子。从这个公式可以清楚地看到，如果 $\omega^2<\omega_{ep}^2-\gamma^2$，那么有$\mathrm{Re}(\varepsilon_{eff})<0$。一般来说，$\gamma<<\omega_{ep}$，可忽略不计，有$\varepsilon_{eff}<0$，$\omega<\omega_{ep}$。另外，由于没有磁性物质也就没有磁偶极矩产生，因此，金属细线的磁导率$\mu=\mu_0=1$。

光学成像：$\varepsilon_{eff}<0$, $\omega<\omega_{ep}$

The effective permeability can be expressed in the form

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

where F is a geometrical factor, ω_0 is the resonance frequency, Γ is the resistive loss in the resonating SRR, and μ'_{eff} and μ''_{eff} are the real and imaginary magnetic permeability functions.

5 MARCH 2004 VOL 1494, 303, SCIENCE

Artificial Magnetic Resonators at THz

$$\mu_{eff} = 1 - \frac{\dfrac{\pi r^2}{a^2}}{1 + \dfrac{2\sigma i}{\mu_0 \omega r} - \dfrac{3}{\pi^2 \mu_0 \omega^2 C r^3}}$$

Resonance frequency: $\omega_0 = \sqrt{\dfrac{3}{\pi^2 \mu_0 C r^3}}$

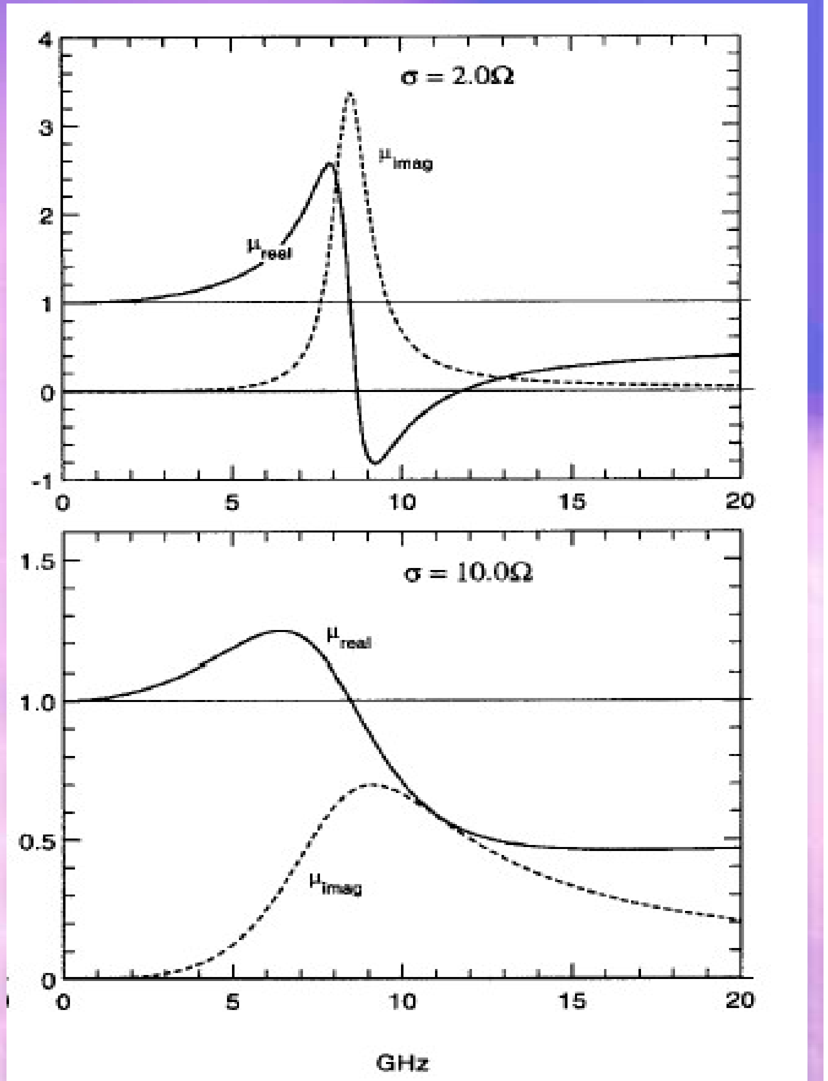
Magnetic plasma frequency:

$$\omega_{mp} = \sqrt{\frac{3}{\pi^2 \mu_0 C r^3 (1 - \pi r^2 / a^2)}}$$

Typical value: $\boldsymbol{r = 2.0\ mm}$

$$a = 5.0 \times 10^{-3} m, d = 1.0 \times 10^{-4} m$$

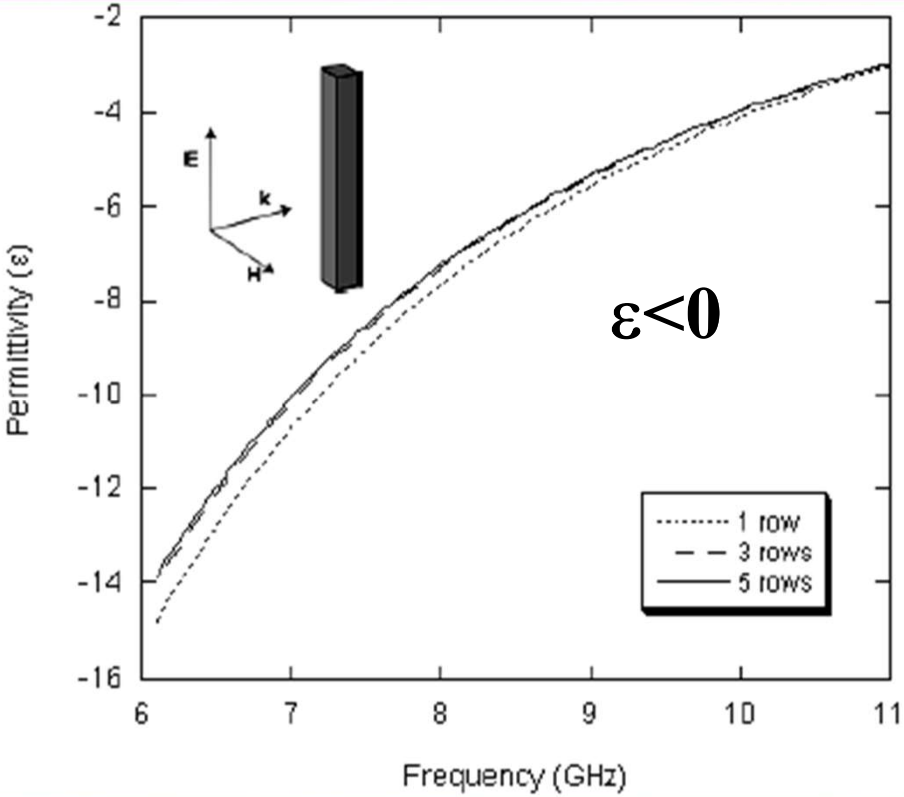
$$f_0 = 2.94 GHz, f_{mp} = 4.17 GHz$$

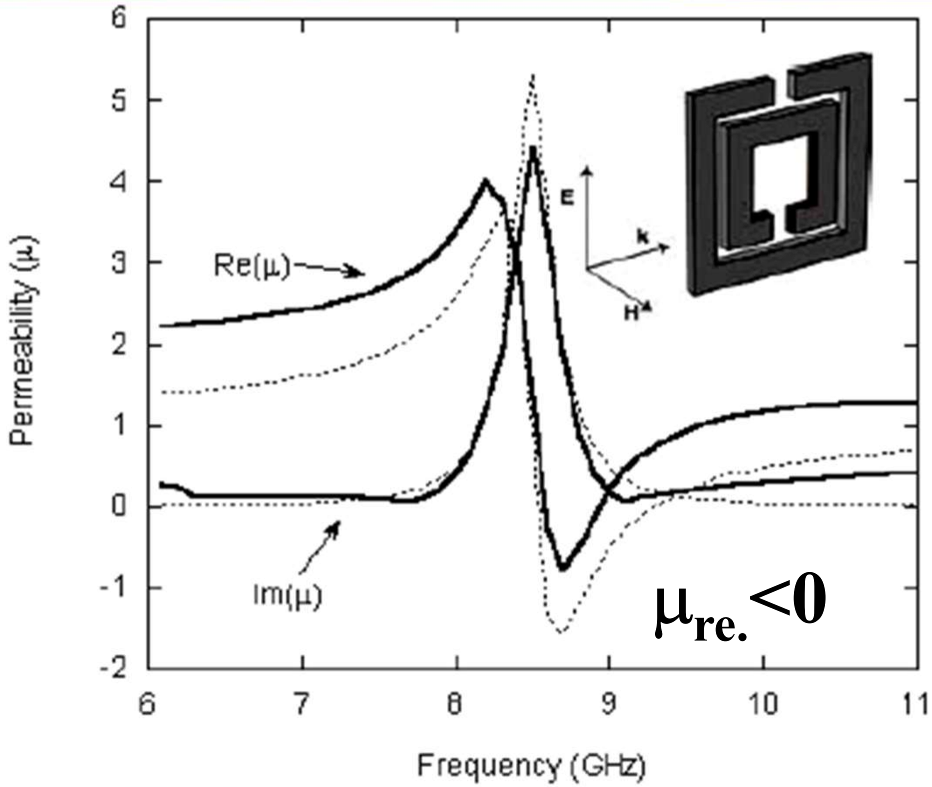


Dispersion of m_{eff} with frequency

Pendry J.B. et al, IEEE MTT 47, 2075 (1999)

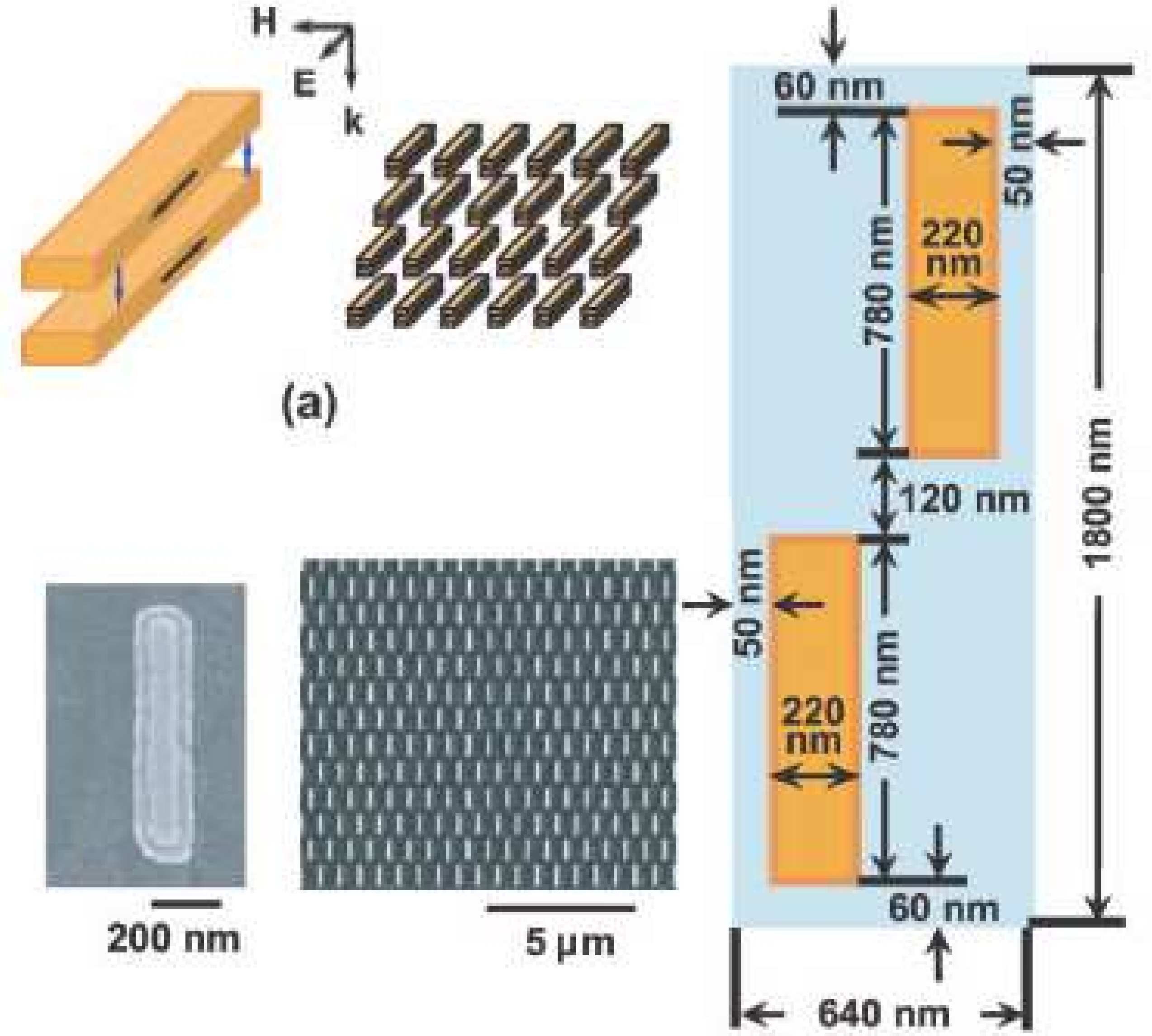
Effective permittivity $\varepsilon(\omega)$ and permeability $\mu(\omega)$ of wires and SRRs





UCSD and ISU, PRB, 65, 195103 (2002)

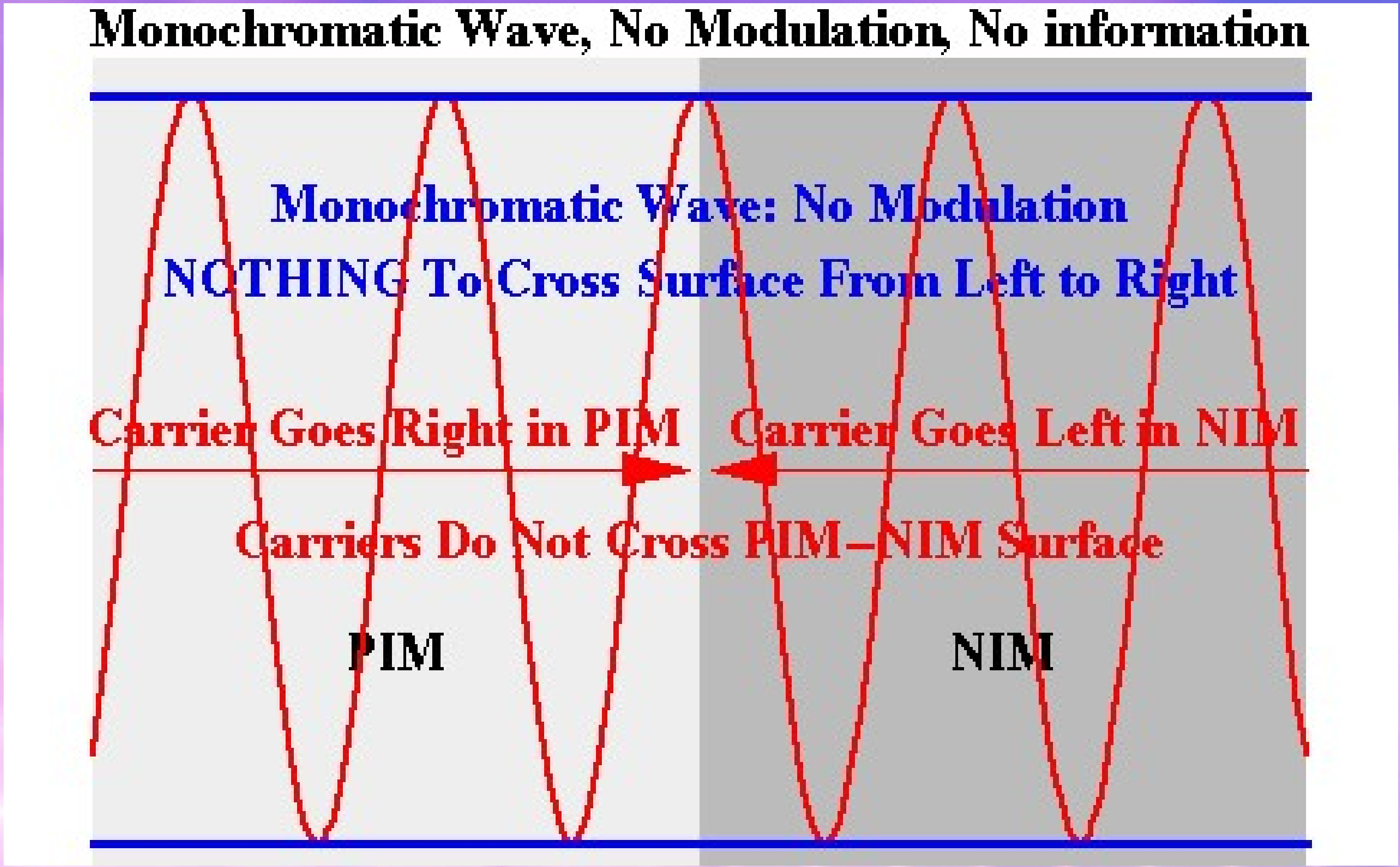
OPTICS LETTERS / Vol. 30, No. 24 / Dec. 15, 2005



$$\cos nk\Delta = \frac{1 - r^2 + n_s t^2}{(n_s + 1)t + rt(n_s - 1)},$$

n_s is the refractive index of the substrate

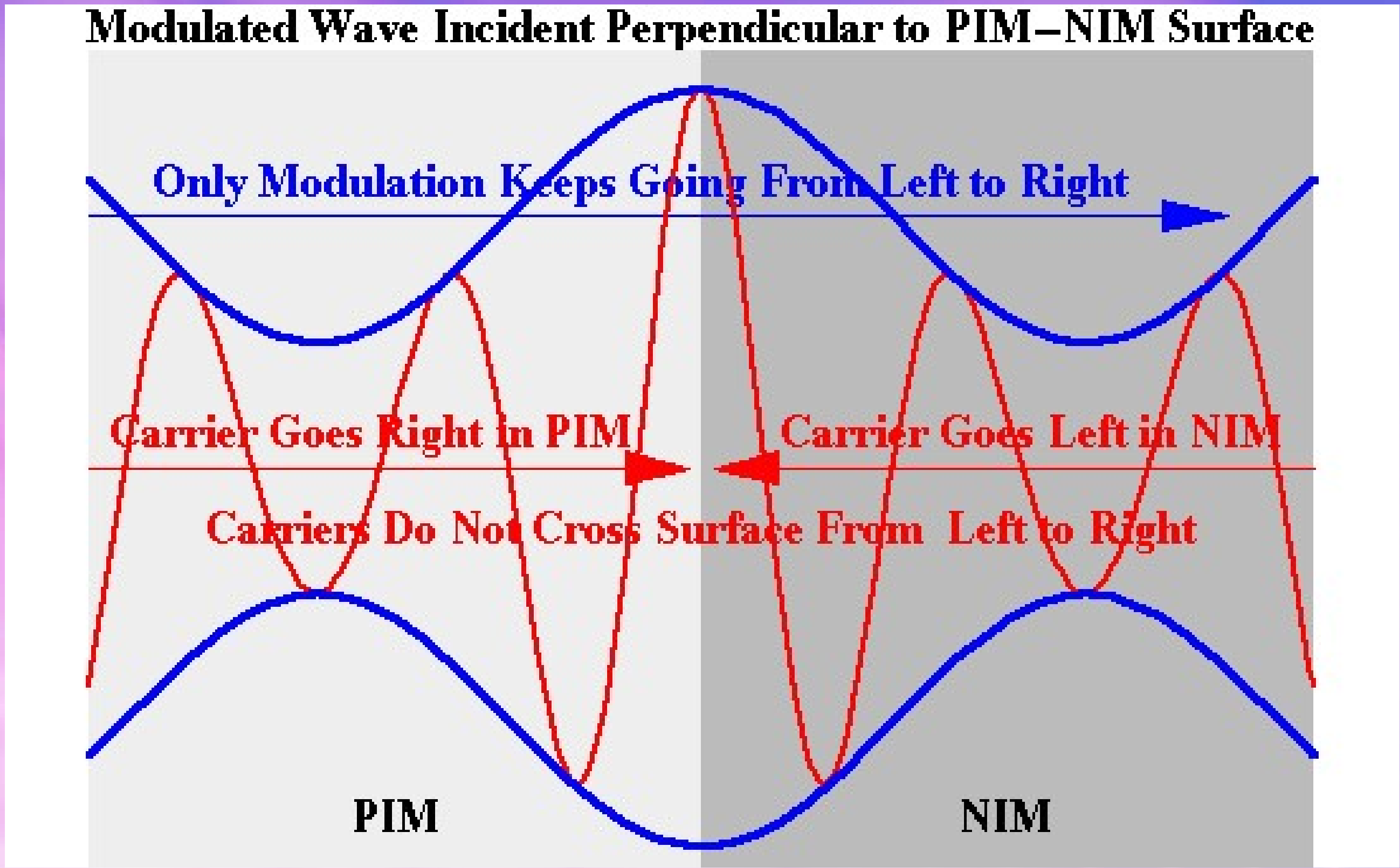
Carrier wave without modulation transports



This shows a **strictly monochromatic (single frequency) wave** (red curve) with no modulation (blue flat line, no markers). Note how the carriers go towards the PIM-NIM surface but **not across it**. Since there is no modulation present, can you see anything crossing the PIM-NIM surface from left to right? Clearly not.

So this movie cannot represent any signal or information or energy launched from left and crossing the PIM-NIM surface to right.

Modulated wave: modulation goes from left to right

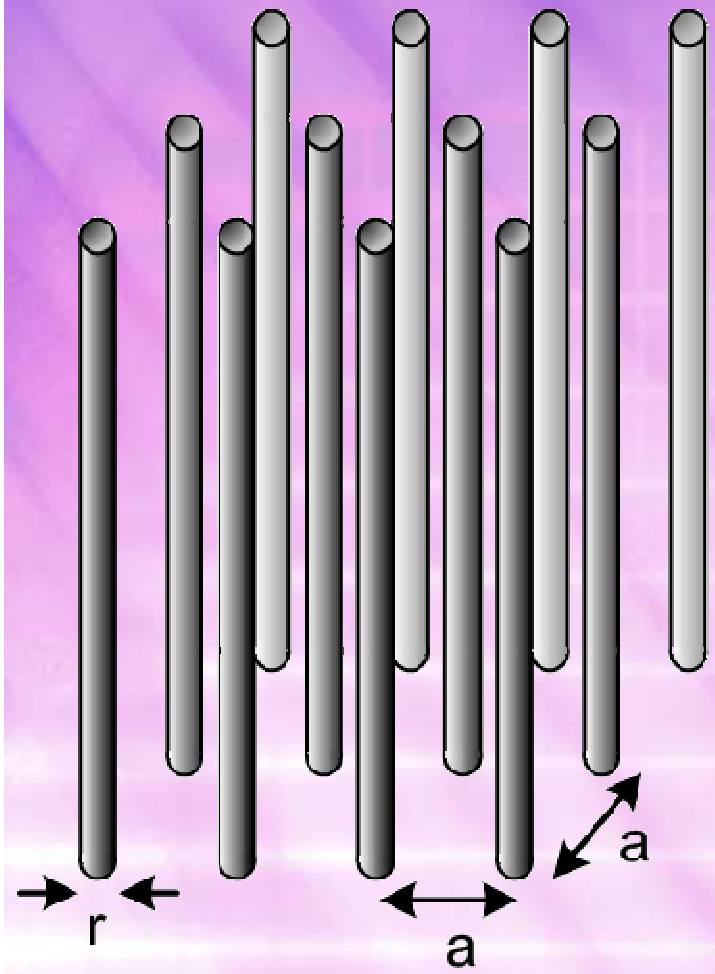


This shows a modulated wave (made of many frequencies) that starts from left. The (red curve) is the carrier, and the (blue line) is the modulation. Note how the carriers go towards the PIM-NIM surface but **not across it**. The modulation crosses the PIM-NIM surface from left to right.

In NIM, the modulations and carriers travel in opposite direction because this wave is incident perpendicular to the surface. However, this is not true when the wave is incident at an angle. Also, here the decay of the modulation after entering NIM is artificially suppressed. You will see both effects in later movies.

NIMs设计思想

How to create Metamaterials?



Thin Wires lead to Negative ε

$$\omega_P = \frac{Ne^4}{\varepsilon_0 m} = \frac{2\pi c^2}{a^2 \ln(a/r)}$$

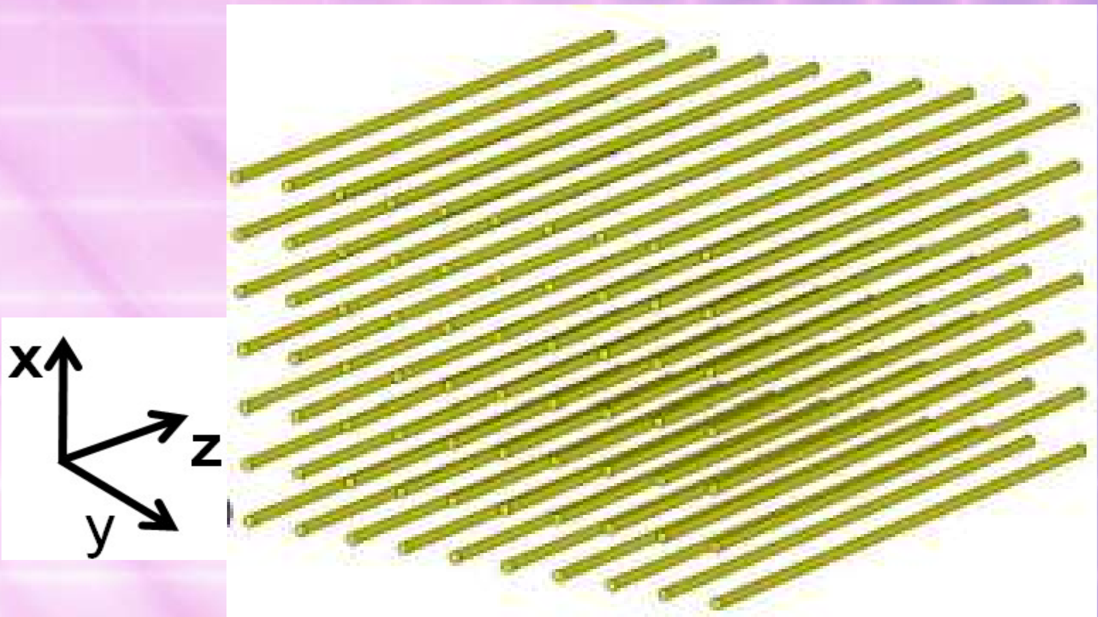
$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

3D Simulation and fabrication of metallic nanowires for NIM at visible wavelength

- **Parameters:**

Material	Incident light source	Working wavelength
Ag	Plane wave	400nm~700nm

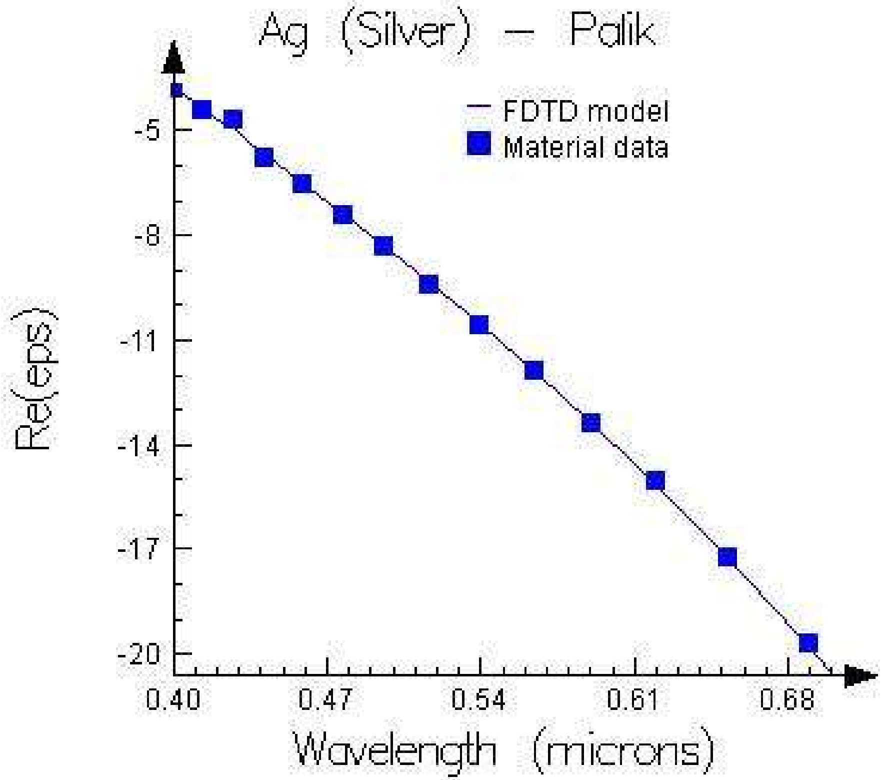
- **Model:**

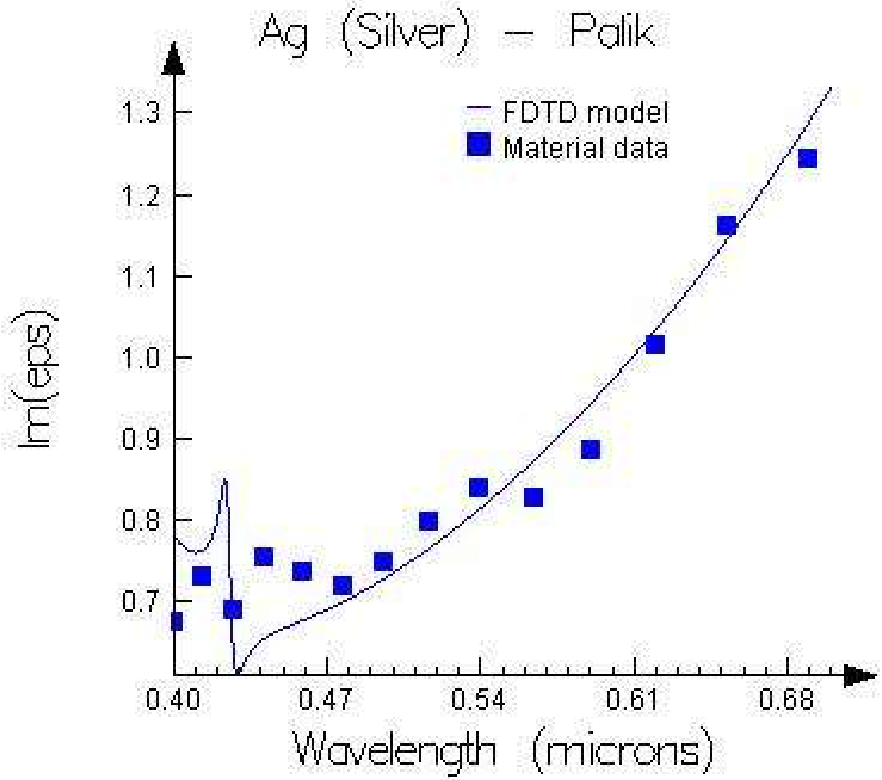


Yongqi Fu, *et. al*. ***Plasmonics***, 6:281–287 (2011).

Boundary condition：

- y-axis：Periodic boundary condition
- x-axis、z-axis：Perfect match layers
- Software：FDTD-solution
- Material：Ag-palik



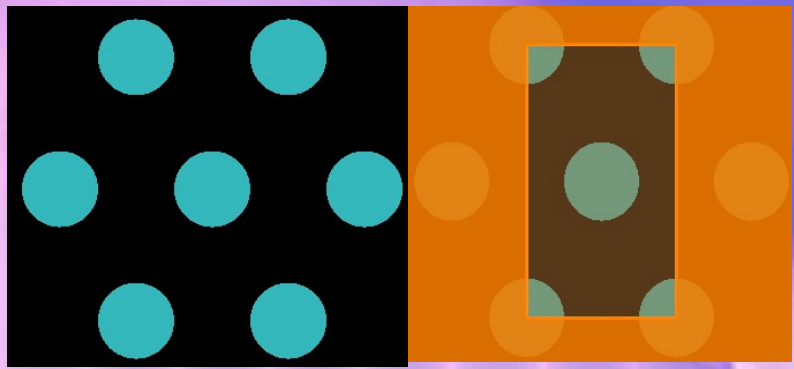


Hexagonal distribution of circular nanowires

Parameters

Plane wave	Width: 1μm
wavelength	688nm
ε(Ag)	-19.694+1.2432*i
f=S_1/S	0.1895
Lateral size	16nm
Lattice constant *L*	70nm
ε(x)	1.5306 + 0.0043i
ε(z)	-2.9215 + 0.2356i

Geometry Model

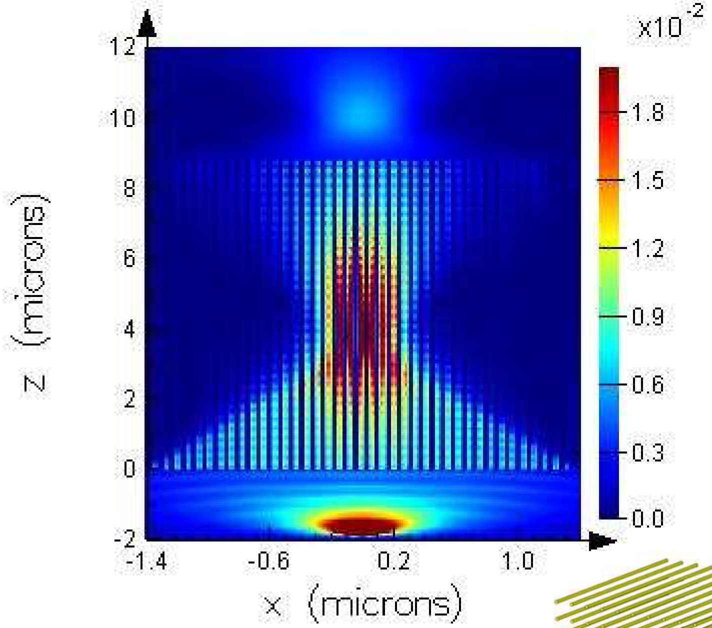


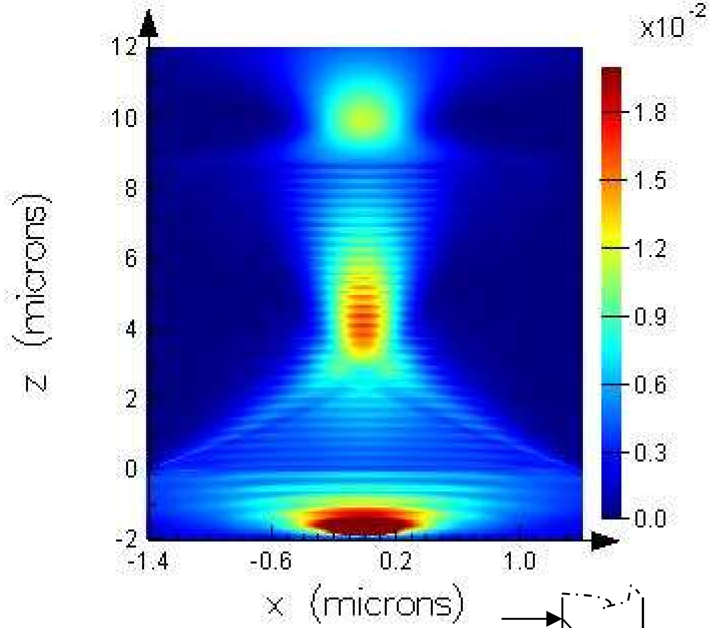
Layout of x-y cross-section

等效介质理论

$$\varepsilon_{\parallel} = \varepsilon_d \left[\frac{(1+f)\varepsilon_m + (1-f)\varepsilon_d}{(1-f)\varepsilon_m + (1+f)\varepsilon_d} \right]$$

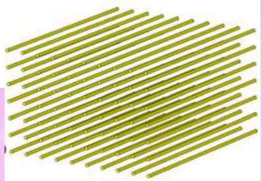
$$\varepsilon_{\perp} = f\varepsilon_m + (1-f)\varepsilon_d$$



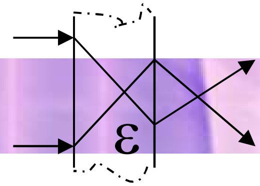


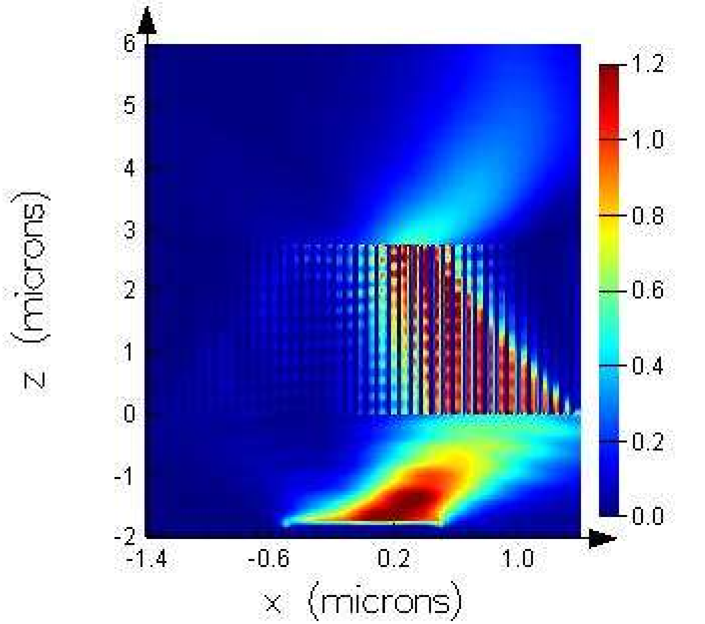
Dipole

Real structure
FDTD calculation

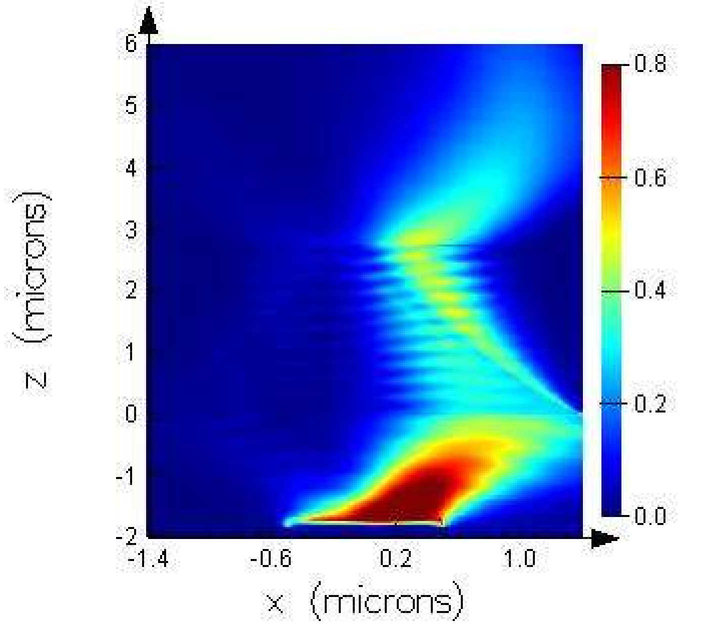


Effective ε



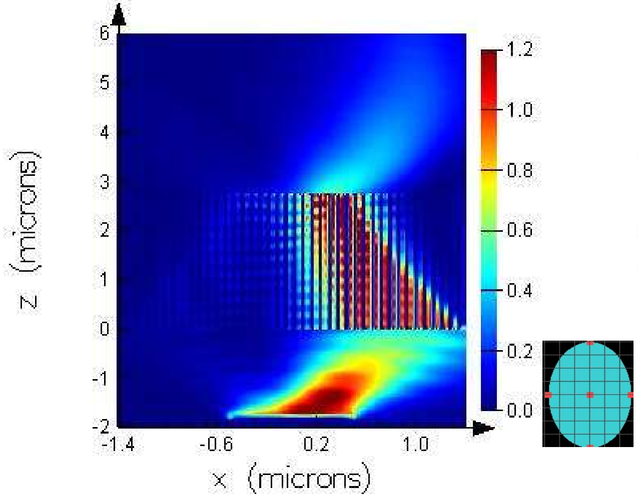


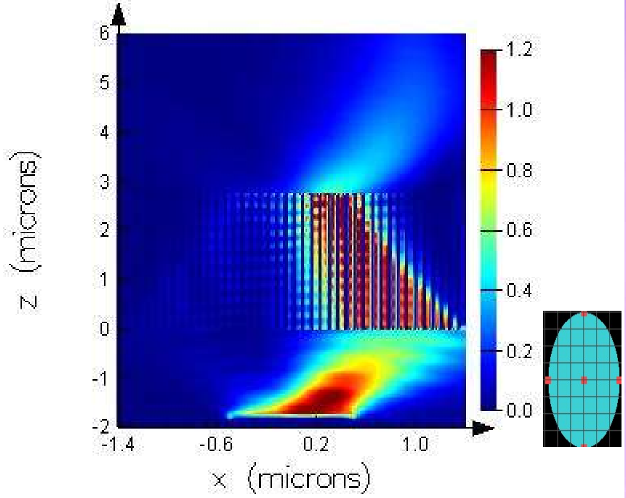
Plane wave



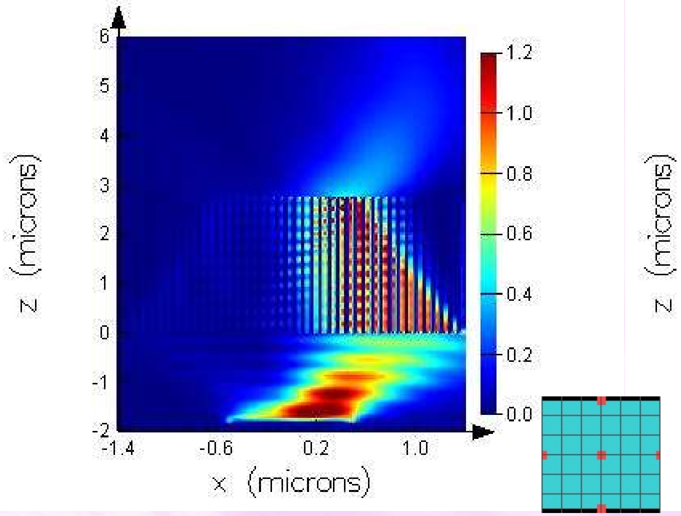
The same fill factor f=0.1895

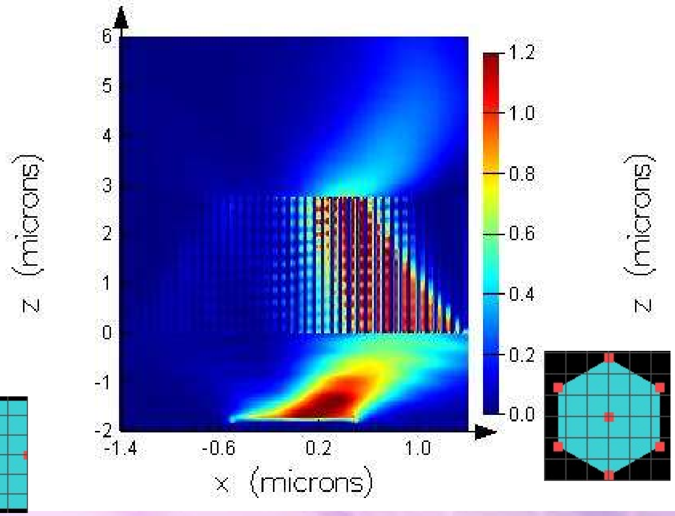
Plane wave illumination

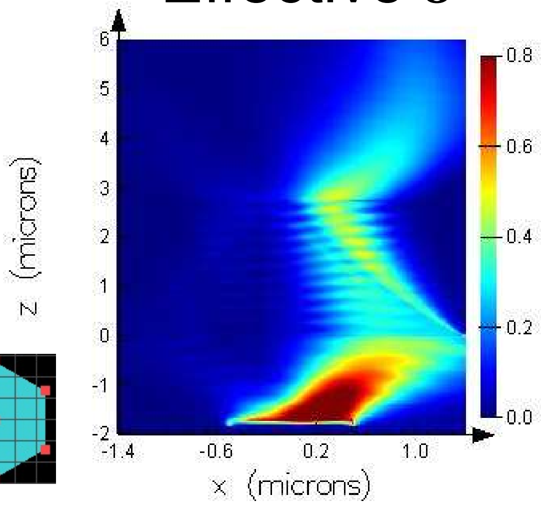


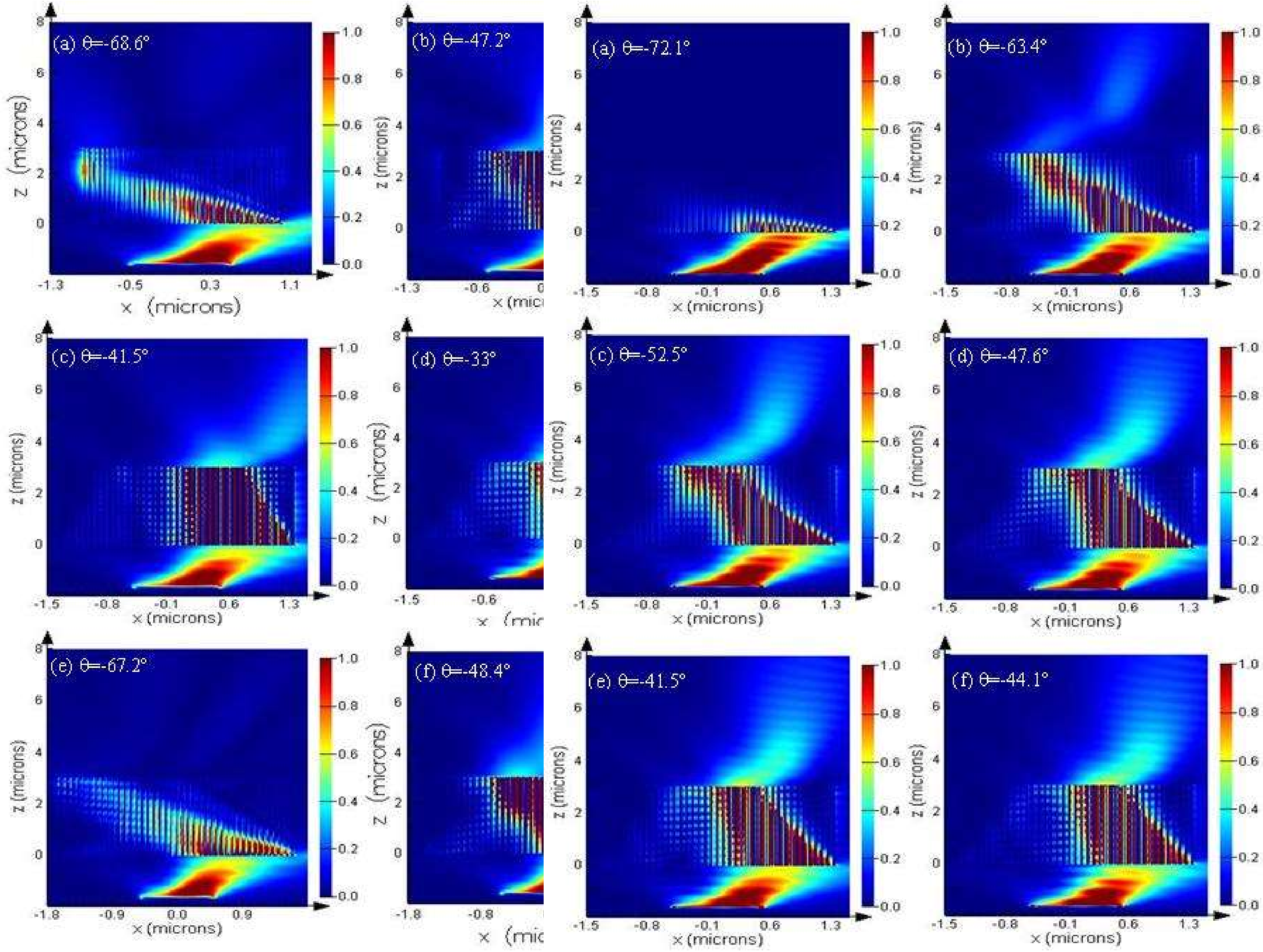


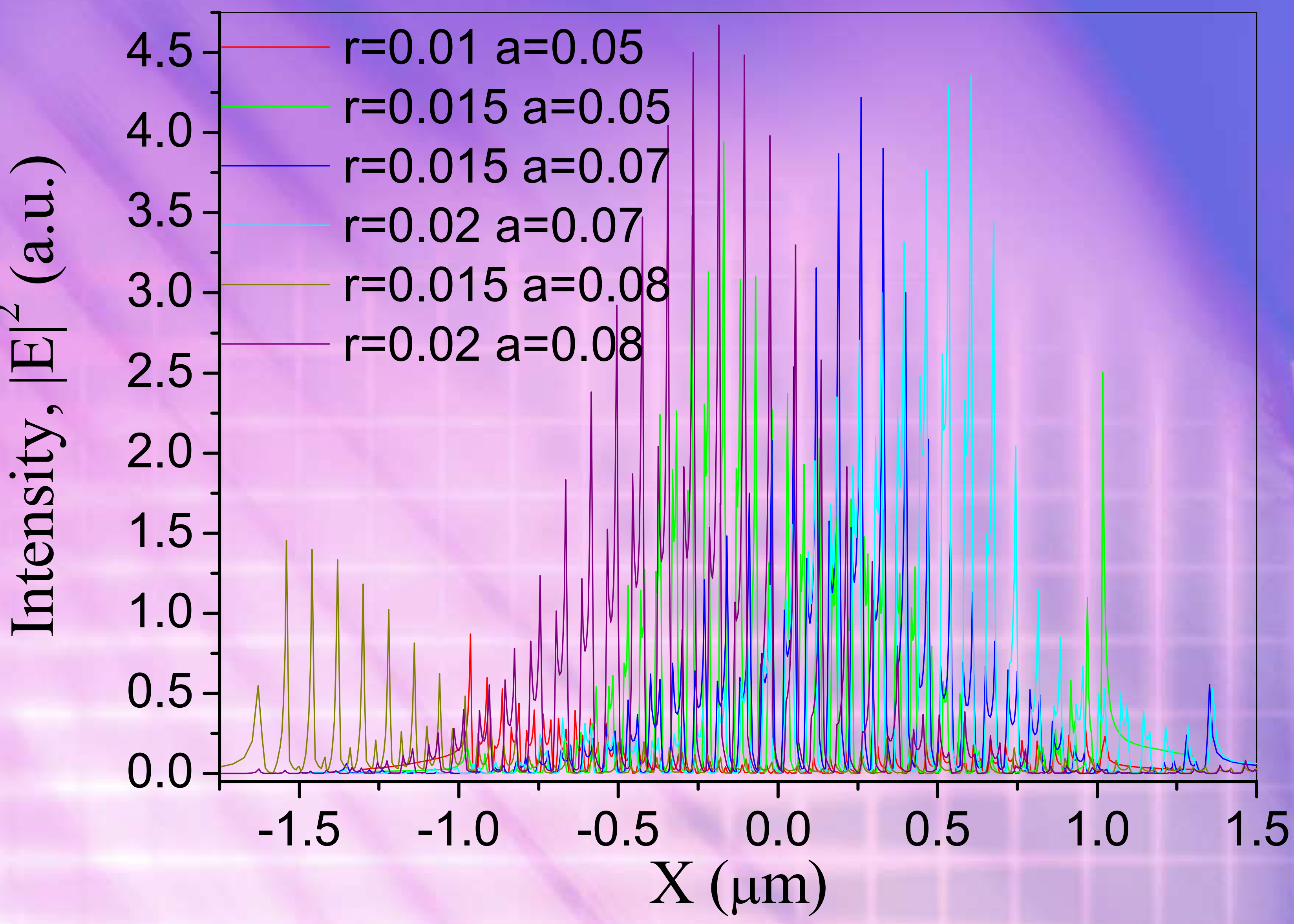
Effective ε





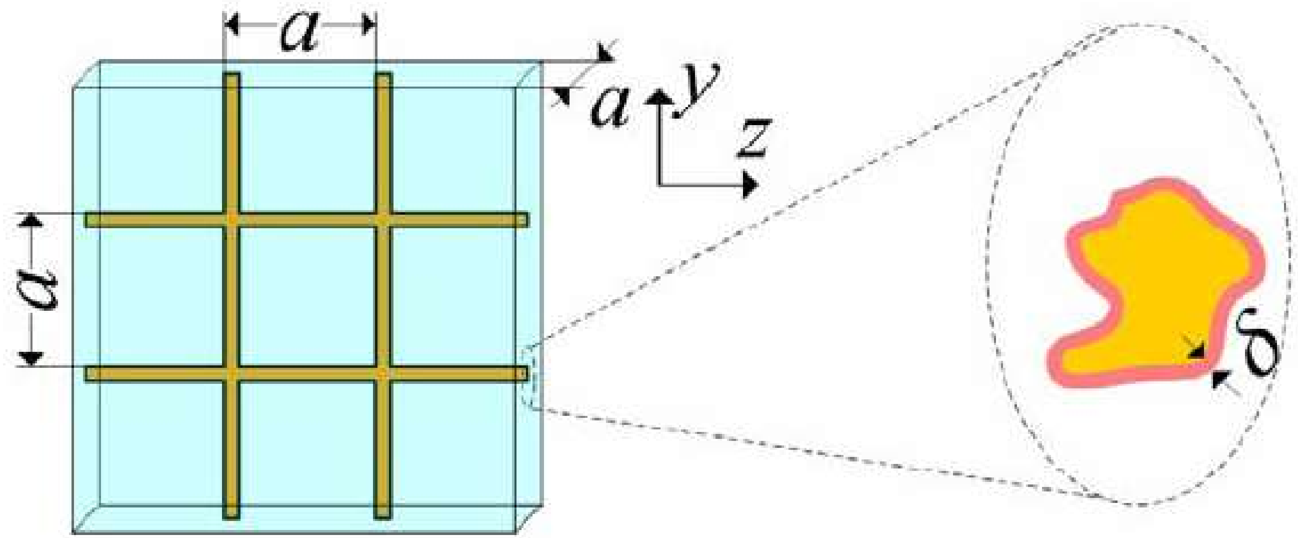



(a) θ=-68.6°
(b) θ=-47.2°
(a) θ=-72.1°
(b) θ=-63.4°
(c) θ=-41.5°
(d) θ=-33°
(c) θ=-52.5°
(d) θ=-47.6°
(e) θ=-67.2°
(f) θ=-48.4°
(e) θ=-41.5°
(f) θ=-44.1°
z (microns)
x (microns)



Yongqi Fu, *et. al*. ***Plasmonics***, (in press)

横截面为任意形状的线阵列



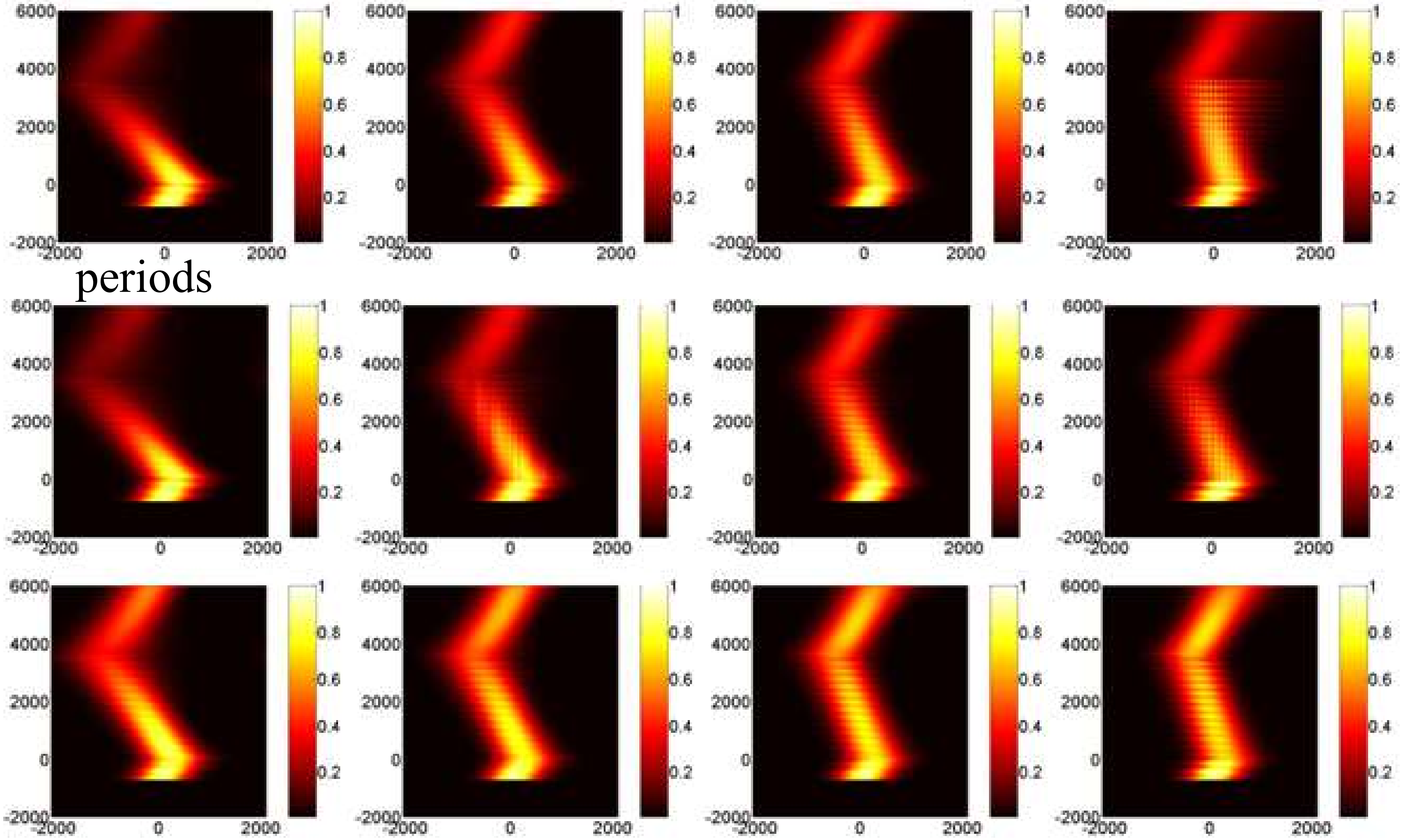
$$m_{eff} = \frac{\mu_0 \cdot l \cdot \delta \cdot n_0 \cdot e^2}{2 \cdot \pi}\left[\ln\left(\frac{l}{2 \cdot \sqrt{\pi} \cdot a}\right) - \frac{l^2}{8 \cdot \pi \cdot a^2} + \frac{1}{2}\right]$$

$$\omega_p{}^2 = \frac{2 \cdot \pi \cdot c_0{}^2}{a^2\left[\ln\left(\frac{l}{2 \cdot \sqrt{\pi} \cdot a}\right) - \frac{l^2}{8 \cdot \pi \cdot a^2} + \frac{1}{2}\right]}$$

$$\varepsilon = 1 - \frac{\omega_p}{\omega}$$

Yongqi Fu, *et. al*. ***Plasmonics***, (in press).

areas



periods

$\varepsilon_{\parallel}$=1.2282+0.0009i

$\varepsilon_{\perp}$=-0.8753+0.060i

$\varepsilon_{\parallel}$=1.2732+0.0011i

$\varepsilon_{\perp}$=1.2008+0.0711i

$\varepsilon_{\parallel}$=1.3239+0.0013i

$\varepsilon_{\perp}$=1.5525+0.0825i

$\varepsilon_{\parallel}$=1.3809+0.0016i

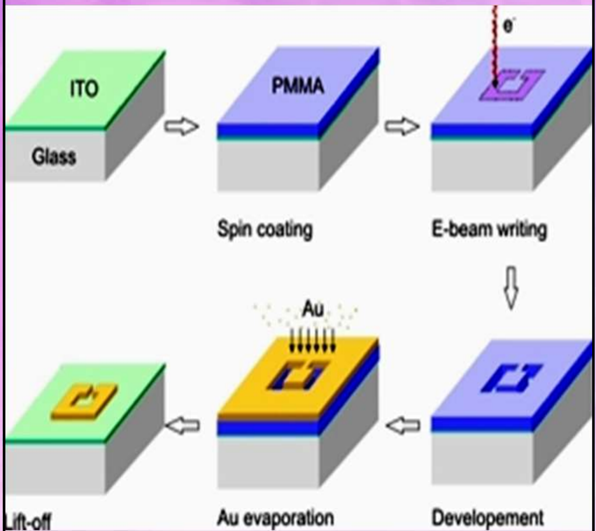
$\varepsilon_{\perp}$=-1.9301+0.094i

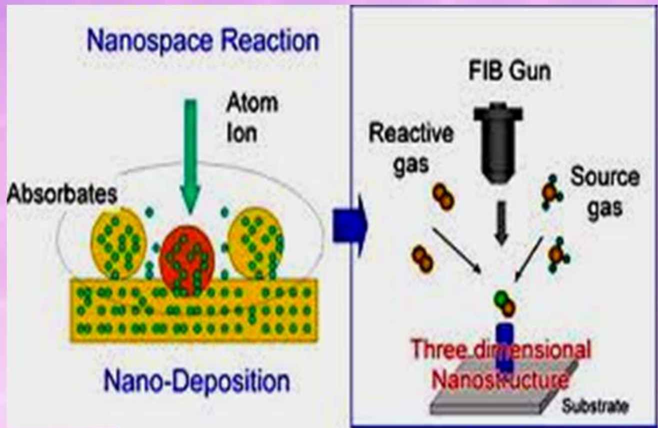
NIMs材料的制备

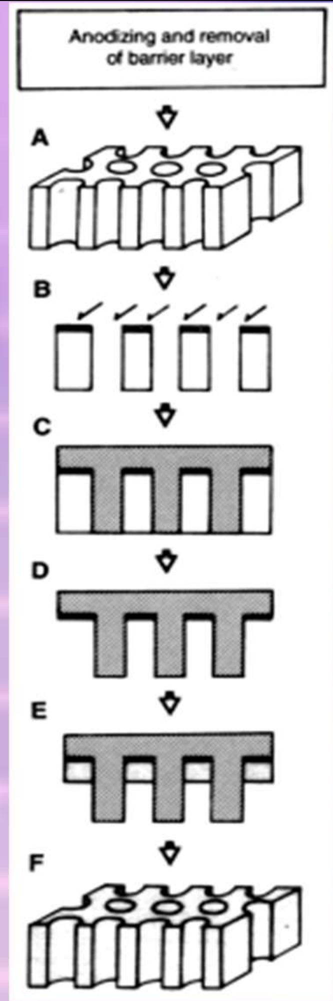
负折射率材料加工方法概述

<table>
<tr><td>应用波段</td><td colspan="2">技术手段</td></tr>
<tr><td>微波</td><td colspan="2">常规机械加工技术</td></tr>
<tr><td>毫米波</td><td colspan="2">常规机械加工技术</td></tr>
<tr><td>中远红外</td><td colspan="2">微细加工技术</td></tr>
<tr><td rowspan="2">近红外及可见光</td><td rowspan="2">纳米加工技术</td><td>物理加工方法</td></tr>
<tr><td>化学方法</td></tr>
</table>

可见光波段NRI目前主要的加工方法

<table>
<tr><th>扫描电子束曝光法</th><th>聚焦离子束一步成形法</th><th>铝模板法</th></tr>
<tr>
<td>


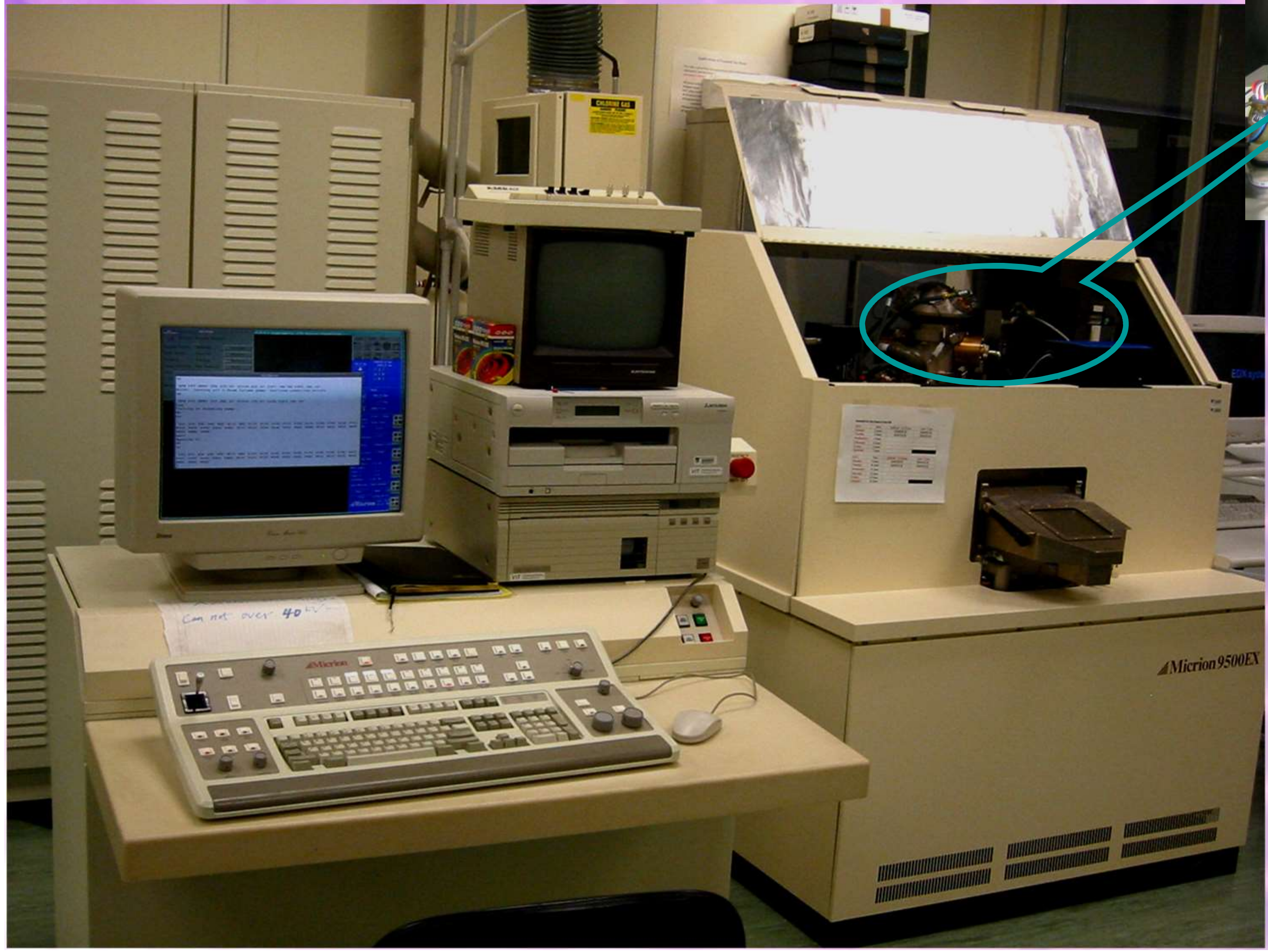
</td>
<td>


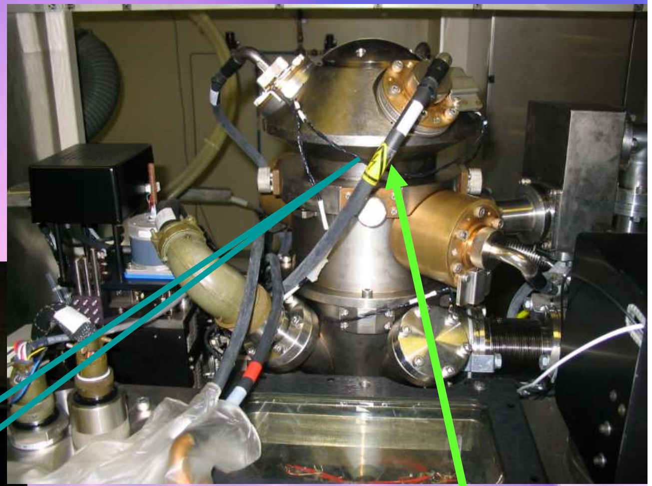
</td>
<td>


</td>
</tr>
</table>

Micrion 9500EX Dual Beam System

Equipped with Unix system and MDDL user programming function.

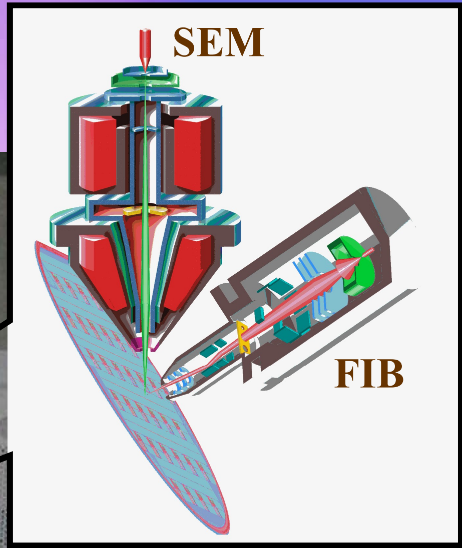


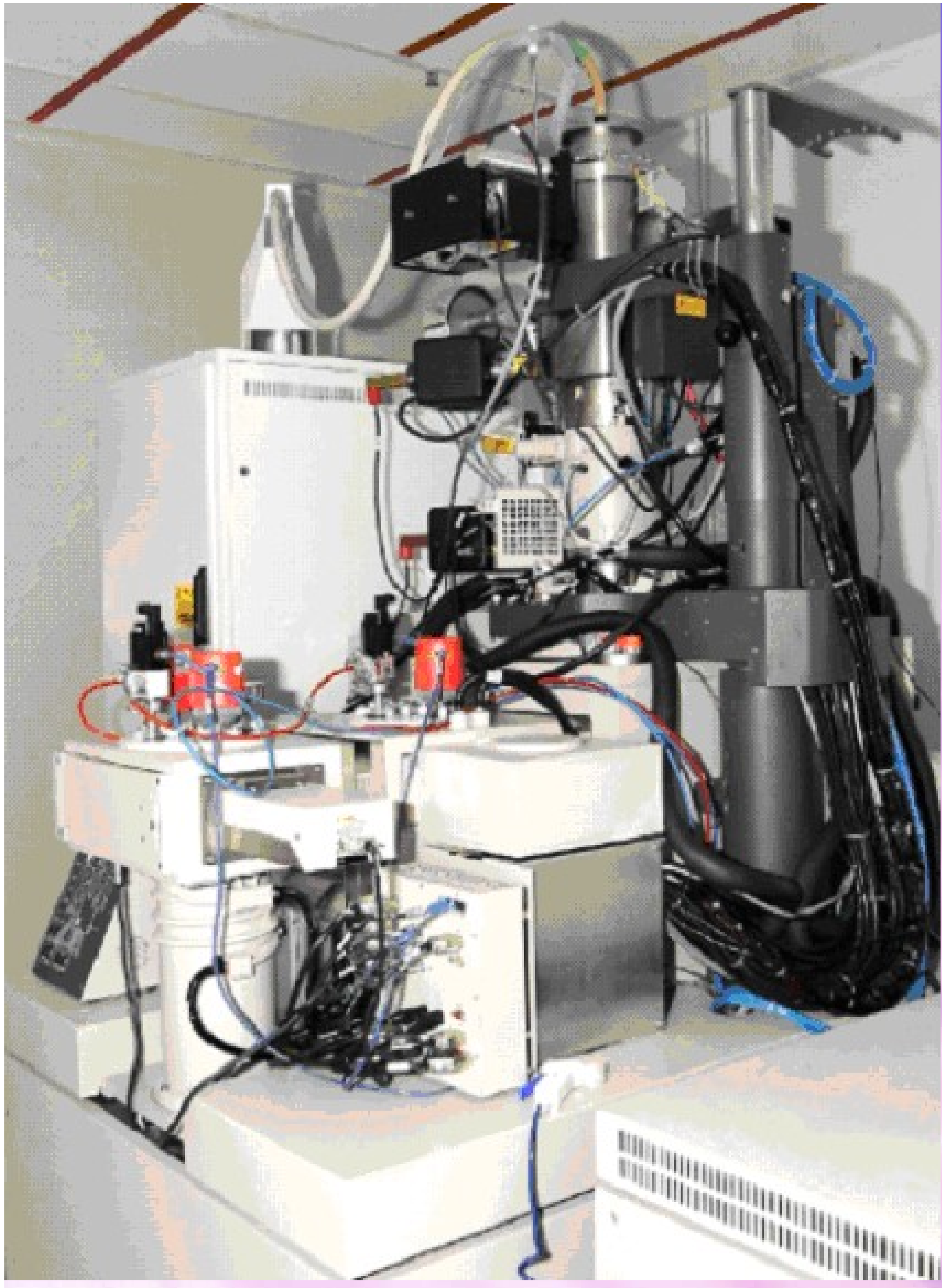


Ion column

FEI Quanta 200 3D

Equipped with Windows operation system



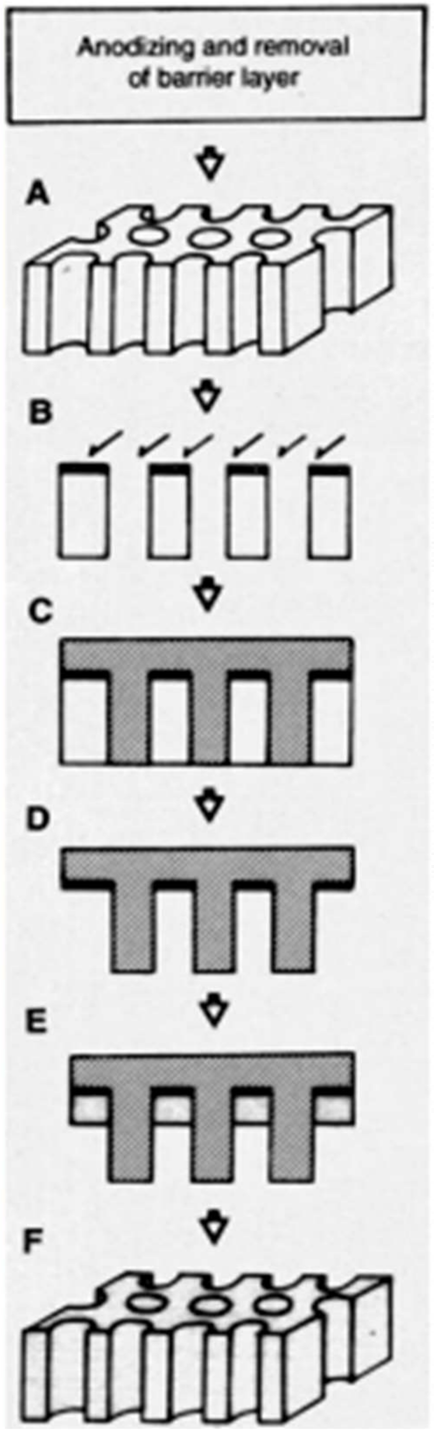


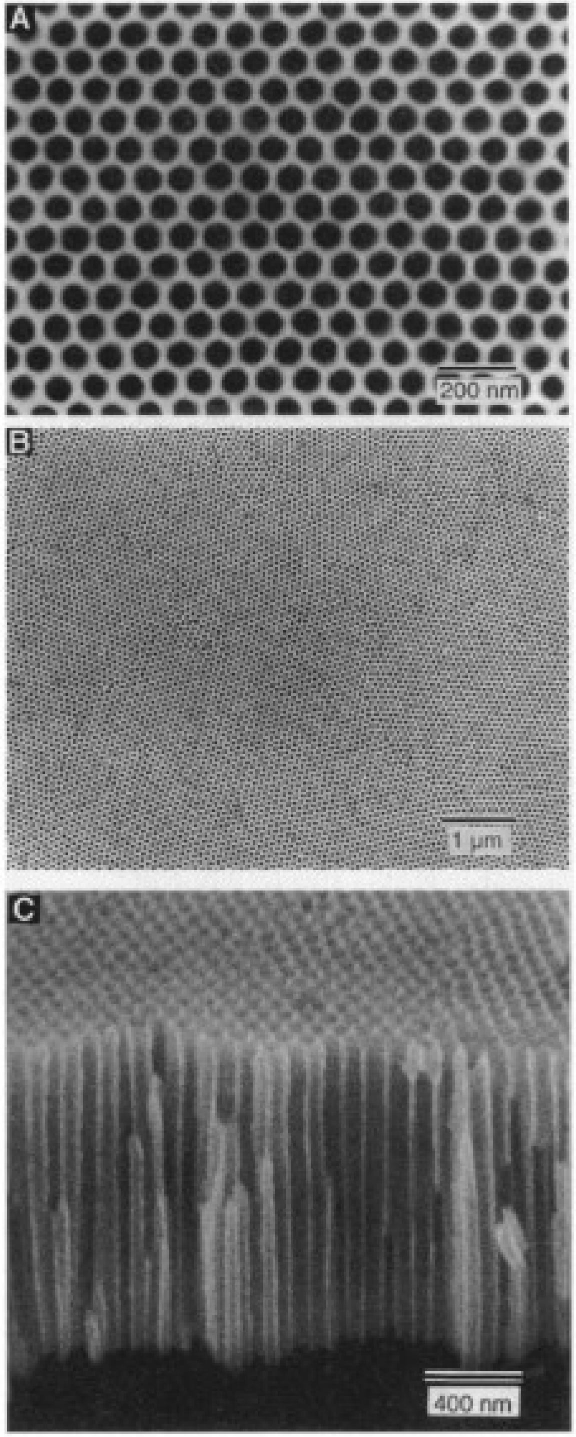
VB6 electron beam lithography machine

VB6 UHR electron beam lithography machine installed at the Cavendish Laboratory

多孔铝模板法制作过程

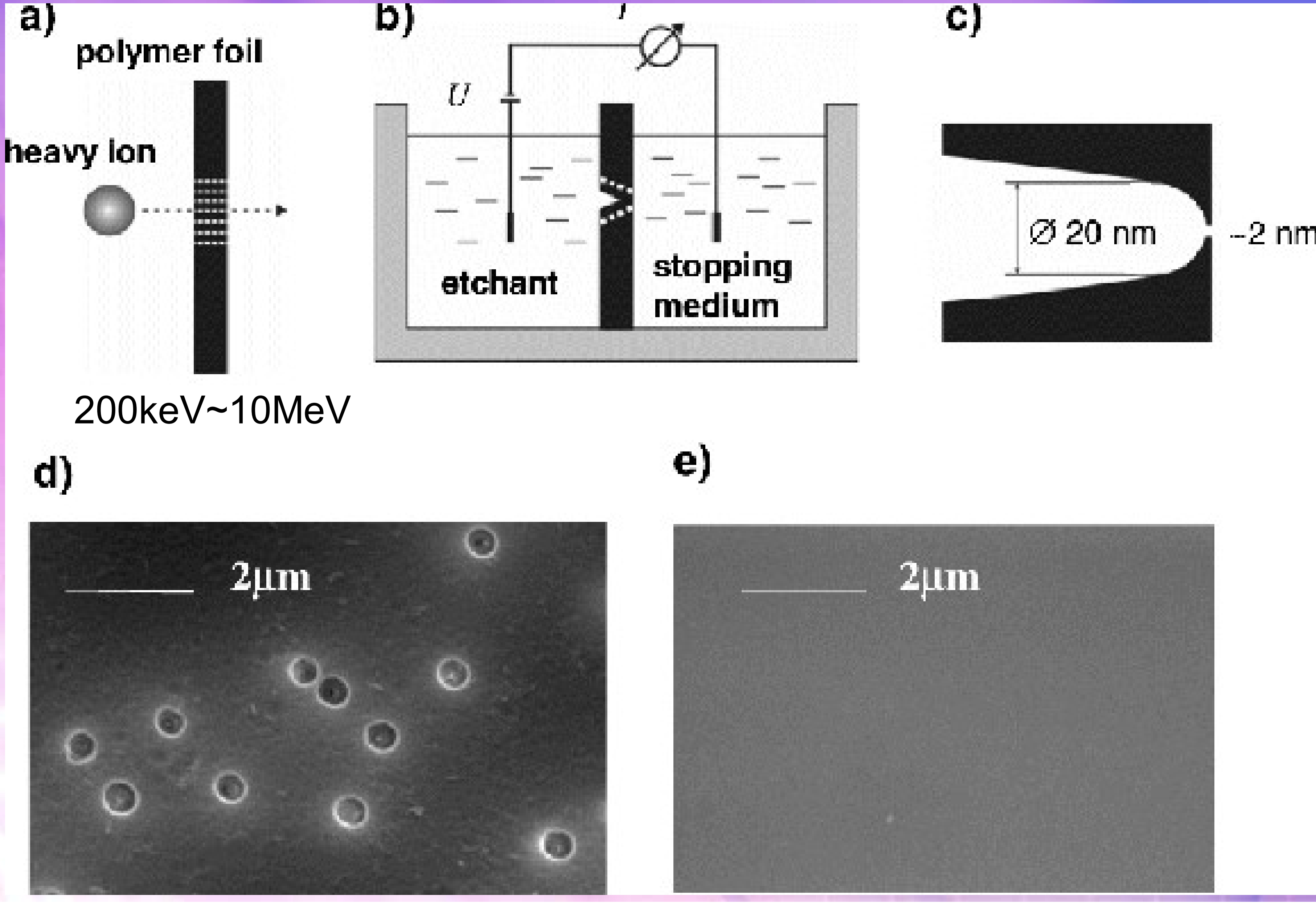
化学方法+真空蒸镀+电镀



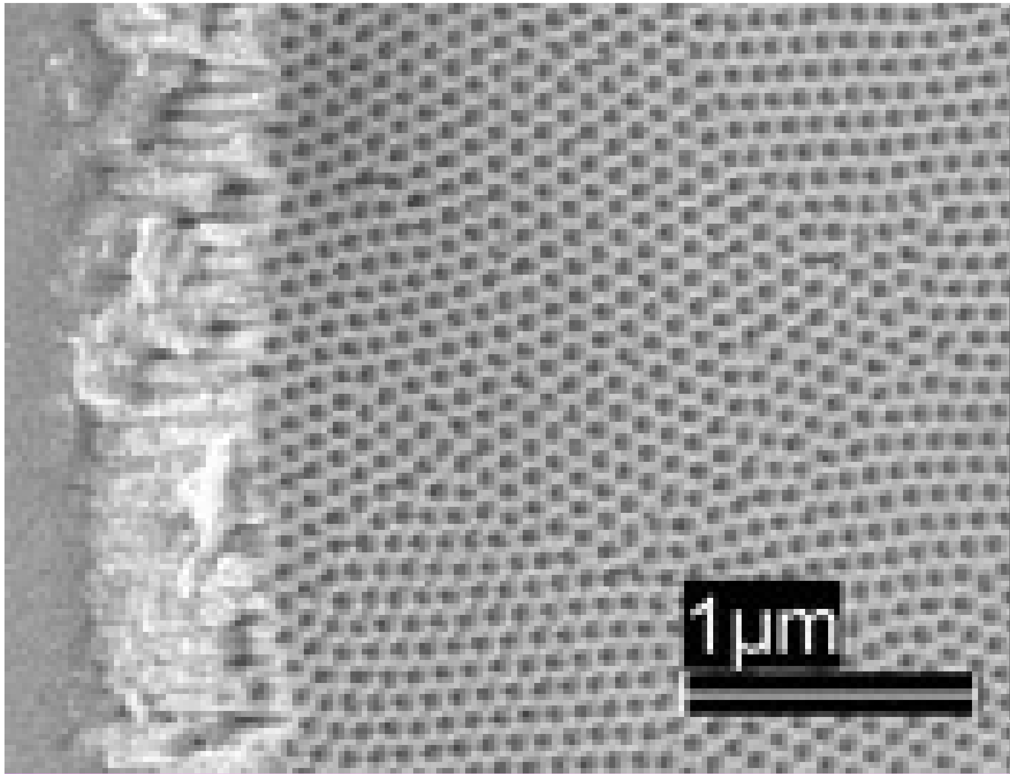


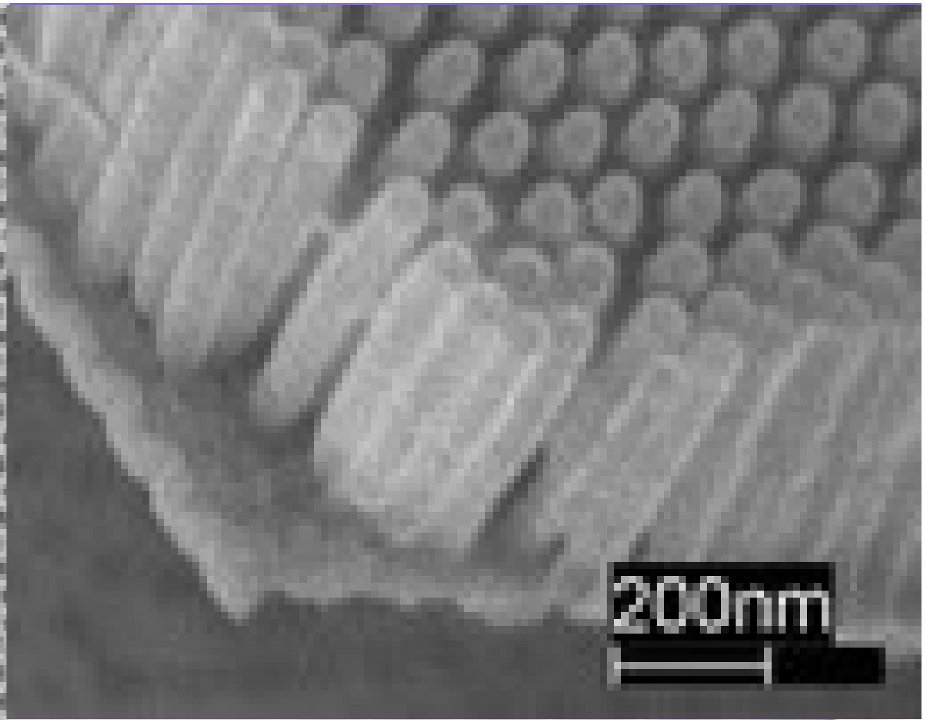
Science 268, 1466 (1995).

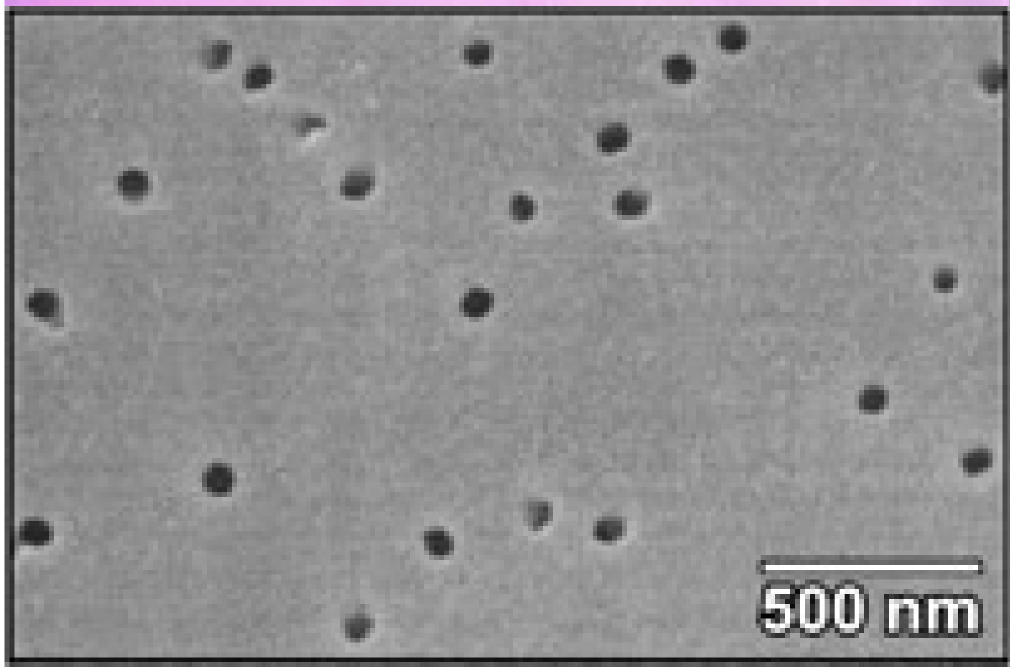
Nanofabrication: Heavy ion track etching

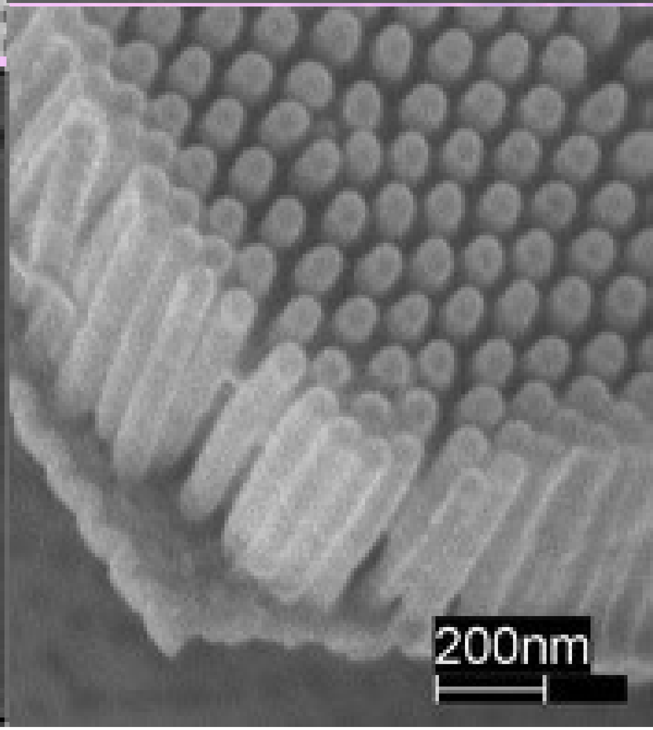


中国科学院近代物理研究所国家实验室的重离子加速器


1 µm


200nm


500 nm


200nm

THE END

PHASE & GROUP VELOCITIES

$$v_p = \frac{\omega}{k} = \frac{c}{n_p} \qquad k = \frac{\omega}{c} n_p$$

$$v_g = \frac{d\omega}{dk}$$

MEDIA	Phase index $n_p = \sqrt{\mu\varepsilon}$	Phase velocity $\bar{v}_p = \frac{c}{n_p}\hat{k}$	Group index $n_g = n_p + \omega \frac{dn_p}{d\omega}$	Group velocity $\bar{v}_g = \frac{c}{n_g}\hat{k}$
PIM	> 0	$\hat{k}$	> 0	$\hat{k}$
NIM	< 0	$-\hat{k}$	> 0	$\hat{k}$

菲涅耳（Fresnel）公式

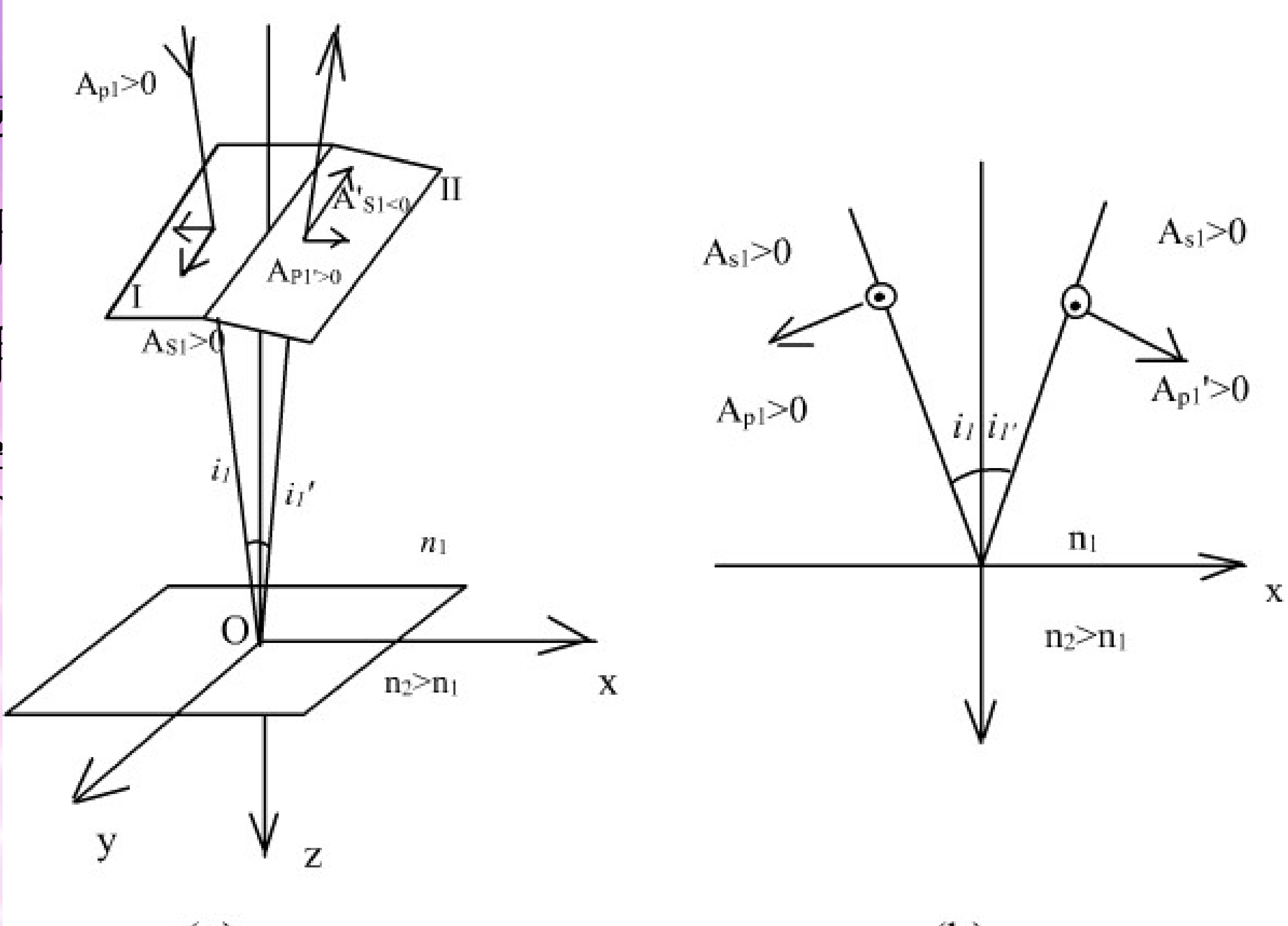
入射光在媒质界面处分为反射和折射两部分。

一．振动

和平行于

构成右手

量的正方



(a) (b)

Fresnel公式

反射、折射瞬间的电矢量与入射电矢量之间的关系。

反射光

$$\frac{E'_{s1}}{E_{s1}}=\frac{n_1\cos i_1-n_2\cos i_2}{n_1\cos i_1+n_2\cos i_2}=-\frac{\sin(i_1-i_2)}{\sin(i_1+i_2)}$$

$$\frac{E'_{P1}}{E_{P1}}=\frac{n_2\cos i_1-n_1\cos i_2}{n_2\cos i_1+n_1\cos i_2}=\frac{tg(i_1-i_2)}{tg(i_1+i_2)}$$

折射光

$$\frac{E_{s2}}{E_{s1}}=\frac{2n_1\cos i_1}{n_1\cos i_1+n_2\cos i_2}=\frac{2\sin i_2\cos i_1}{\sin(i_1+i_2)}$$

$$\frac{E_{P2}}{E_{P1}}=\frac{2n_1\cos i_1}{n_2\cos i_1+n_1\cos i_2}=\frac{2\sin i_2\cos i_1}{\sin(i_1+i_2)\cos(i_1-i_2)}$$

Assume: n_1=1, n_2=-1, then for NR have i_1=-i_2

$$\frac{E'_{sl}}{E_{sl}} = \frac{\cos i_1 + \cos i_2}{\cos i_1 - \cos i_2} = \frac{\cos i_1 - \cos i_1}{\cos i_1 - \cos i_2} = 0$$

$$\frac{E'_{pl}}{E_{pl}} = \frac{\cos i_1 + \cos i_2}{-\cos i_1 + \cos i_2} = \frac{\cos i_1 - \cos i_1}{-\cos i_1 - \cos i_2} = 0$$

Reflection coefficient:

$$r_{sl} = \frac{E'_{sl}}{E_{sl}} \qquad r_{pl} = \frac{E'_{pl}}{E_{pl}}$$

三，半波损失的解释

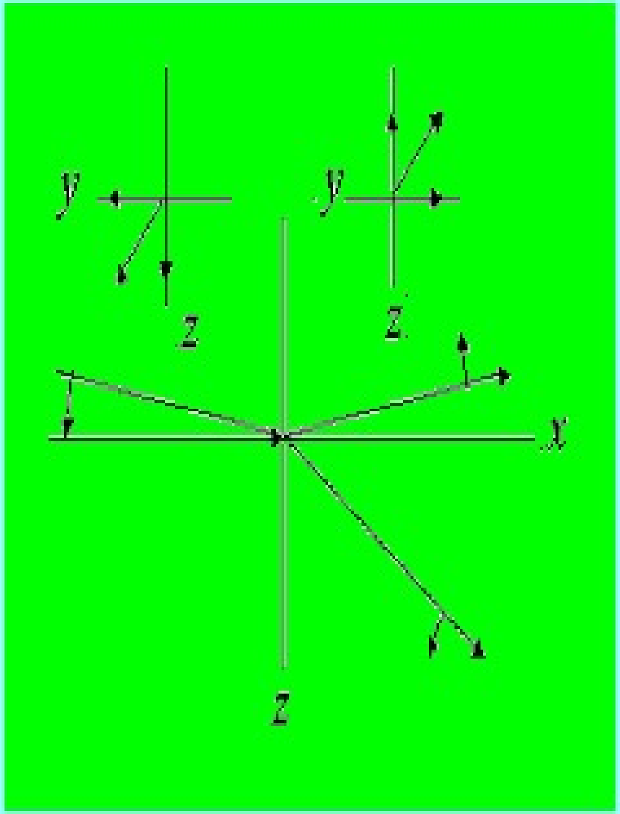
光波由光疏介质射向光密介质，n1<n2。

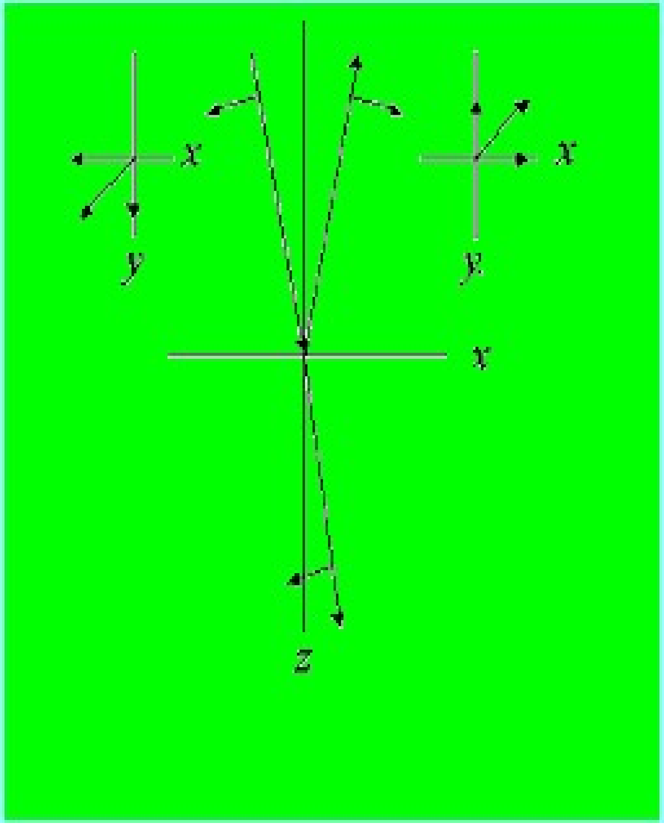
1．掠入射

$i_1 - i_2 > 0$，且 $\frac{\pi}{2} < i_1 + i_2 < \pi$，$i_1, i_2 \approx \frac{\pi}{2}$ 由Fresnel公式，可得

$\frac{E'_{S1}}{E_{S1}} < 0, \frac{E'_{P1}}{E_{P1}} < 0$，$\frac{E'_{S1}}{E_{S1}} \approx \frac{E'_{P1}}{E_{P1}}$，即 $\frac{E'_{S1}}{E'_{P1}} = \frac{E_{S1}}{E_{P1}}$ 反射光中，P，S分量的方向均在反射瞬间反转。

逆着X轴方向观察，可见振动方向反转。





2．垂直入射

$$i_1,i_2\sim 0,\quad \frac{E'_{S1}}{E_{S1}}<0,\quad \frac{E'_{P1}}{E_{P1}}>0,\quad \frac{E'_{S1}}{E_{S1}}\approx-\frac{E'_{P1}}{E_{P1}},\ \text{即}\ \frac{E'_{S1}}{E'_{P1}}=-\frac{E_{S1}}{E_{P1}}$$

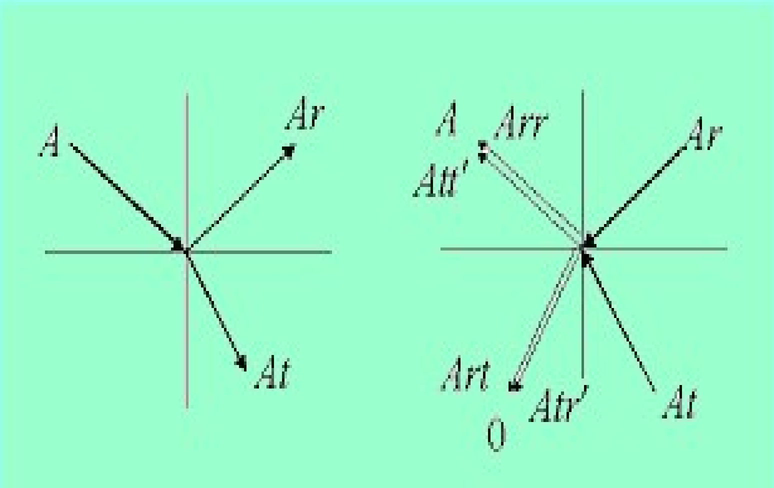
反射光中的S分量在反射瞬间反转，P分量也反转。沿Z轴方向观察，发现振动反转。

以上两种情况说明由于反射使得光的振动方向有突变，转到相反的方向，相当于光的位相突然有π的改变。对应到光程上，相当于有半个波长的突变。故称半波损失。

四．Stocks倒逆关系

r，t界面对振幅的反射率。入射波振幅为A，

$$\text{有}\begin{cases}Ar^2+Att'=A\\ Art+Atr'=0\end{cases},\ \text{即}\ \begin{cases}r^2+tt'=1\\ r+r'=0\end{cases}\qquad r=-r',|r|^2=|r'|^2$$



微结构等效介质理论：等效介质模型

$$\varepsilon_{\perp} = \frac{\boldsymbol{D}}{\boldsymbol{E}} = \frac{\varepsilon_1\varepsilon_2}{\boldsymbol{f}_1\varepsilon_2 + \boldsymbol{f}_2\varepsilon_1}$$

式中：f_1及f_2是占空比，$f_1 = \frac{\boldsymbol{t}_1}{\boldsymbol{t}_1 + \boldsymbol{t}_2}$，$f_2 = \frac{\boldsymbol{t}_2}{\boldsymbol{t}_1 + \boldsymbol{t}_2} = 1 - f_1$

t_1、t_2分别为介质和空气的厚度。

$$\varepsilon_{//} = \frac{\boldsymbol{D}}{\boldsymbol{E}} = \frac{\boldsymbol{t}_1\varepsilon_1 + \boldsymbol{t}_2\varepsilon_2}{\boldsymbol{t}_1 + \boldsymbol{t}_2} = \boldsymbol{f}_1\varepsilon_1 + \boldsymbol{f}_2\varepsilon_2$$

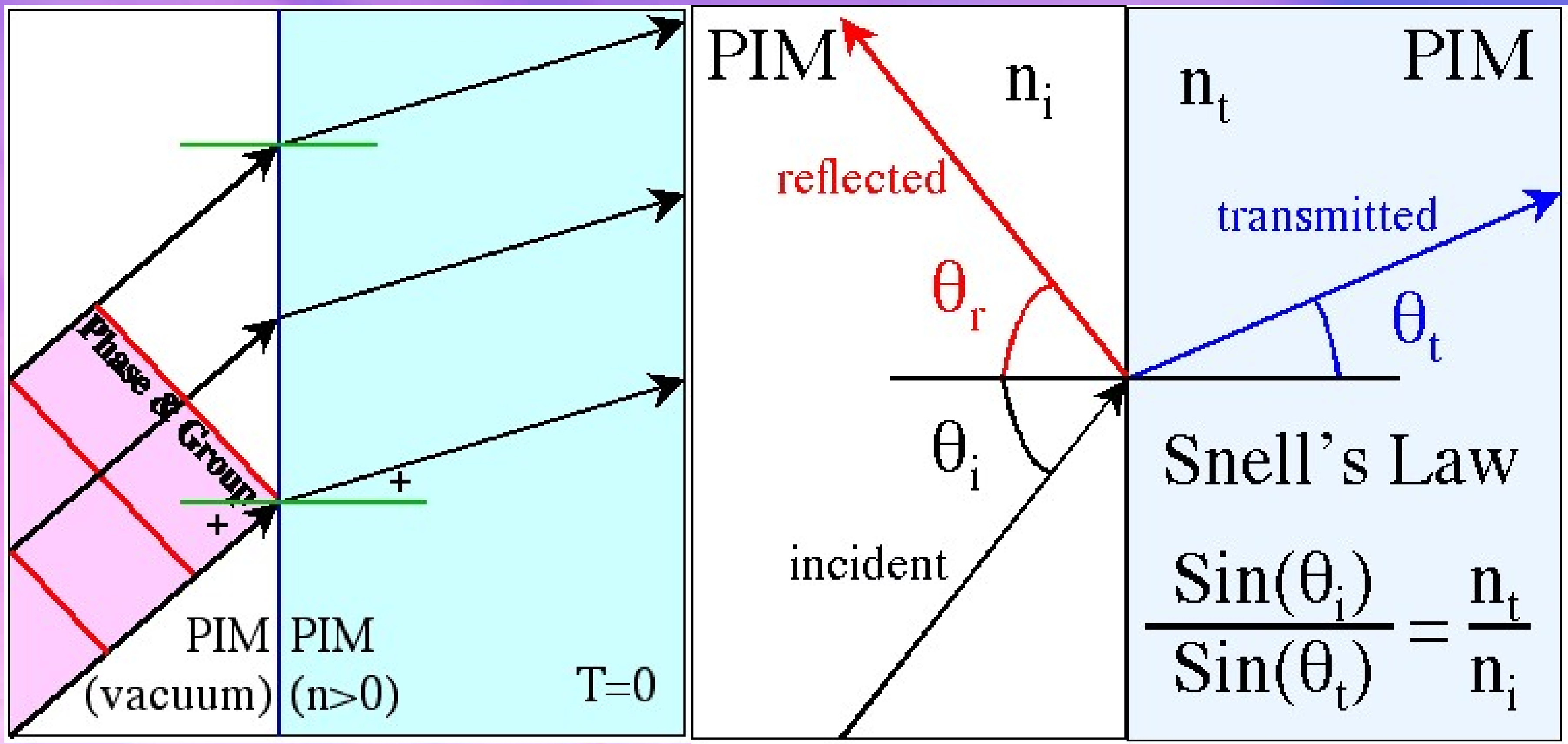
$$\mathrm{n}_{//} = \sqrt{\varepsilon_{//}} = \sqrt{\boldsymbol{f}_1\varepsilon_1 + \boldsymbol{f}_2\varepsilon_2}$$

$$\mathrm{n}_{\perp} = \sqrt{\varepsilon_{\perp}} = \sqrt{\frac{\varepsilon_1\varepsilon_2}{\boldsymbol{f}_1\varepsilon_1 + \boldsymbol{f}_2\varepsilon_2}}$$

摘自《微光学与系统》p.83

Mechanism of NRI Propagation

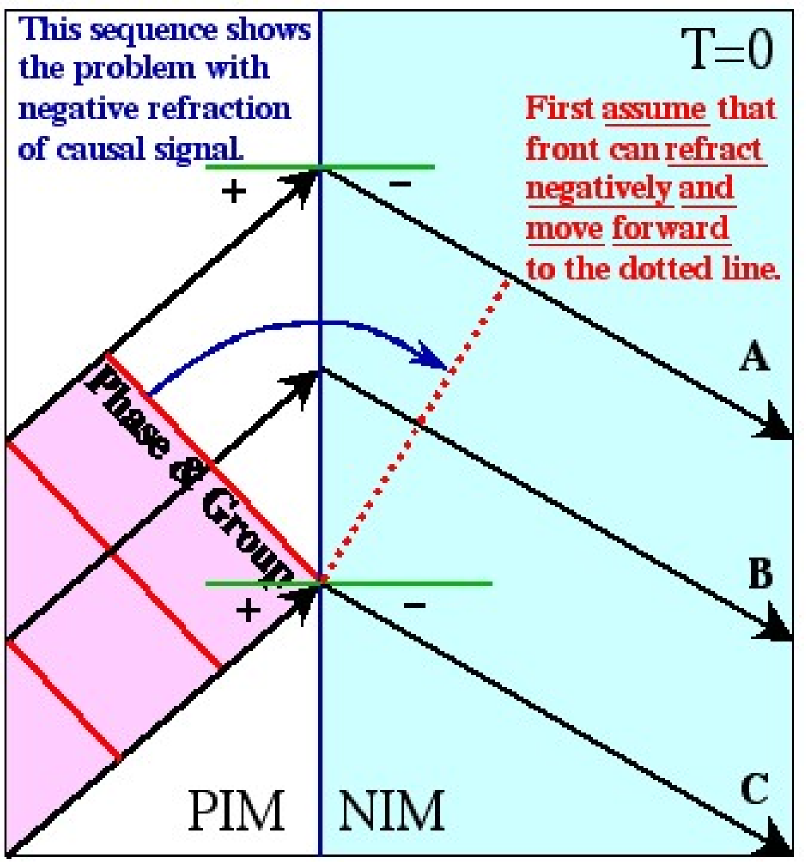
Usual positive phase and group refraction for Pim-Pim

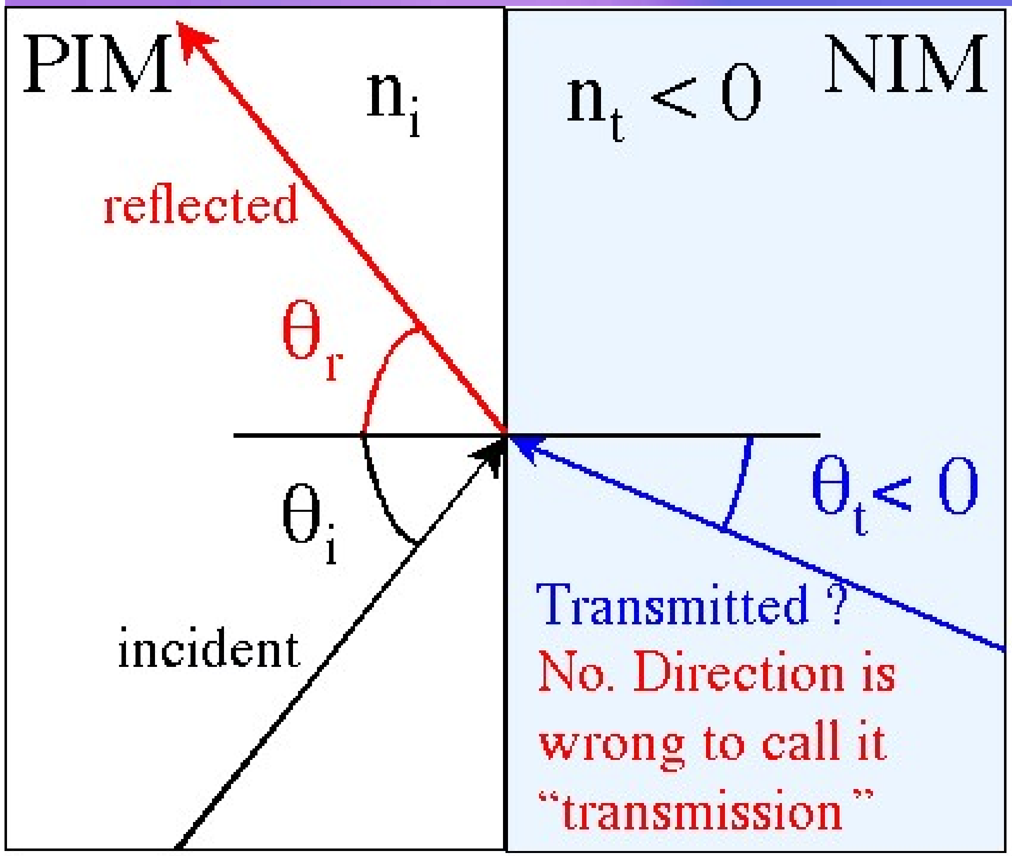


This is the familiar positive refraction. Note how the front crosses the surface in such a way that Snell's law is satisfied. No part of the front stops or goes at odd speeds.

The next movie shows how a front can never cross from PIM to NIM so as to satisfy a negative Snell's law.

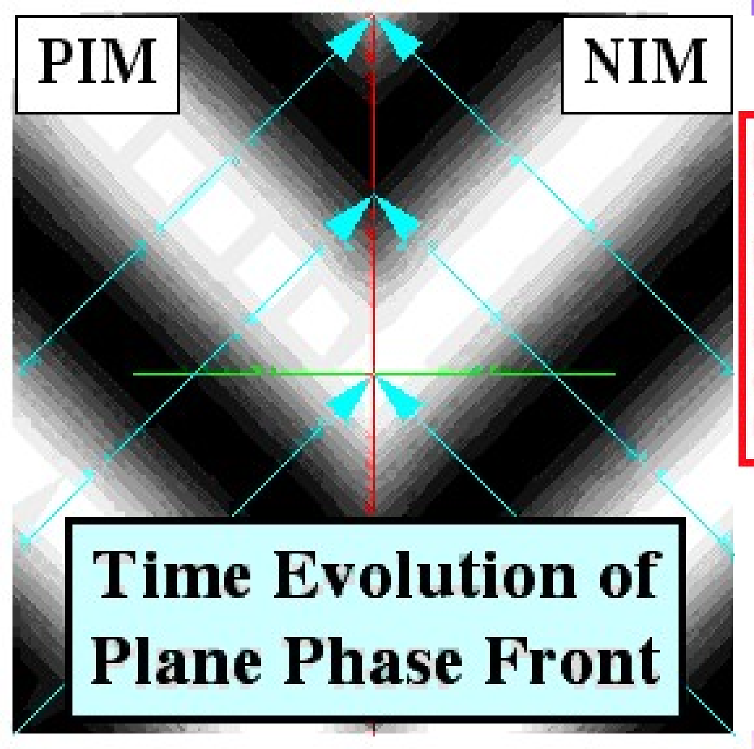
No wave front can refract in the negative fashion (PIM-NIM)





This shows why no front can bend in a negative way and keep going forward. To do this the wave front would have to pivot around the "bottom" point - the bottom point would have to stop while all others would keep going at different speeds. But the speed of each point is fixed in each medium. So this is not possible. Also, if we considered only half the beam, the "pivot" point would change. But what decides which is pivot point? Nothing. Or maybe the wave front appears on right before arriving at surface.

Negative refraction of phase fronts - no energy transport



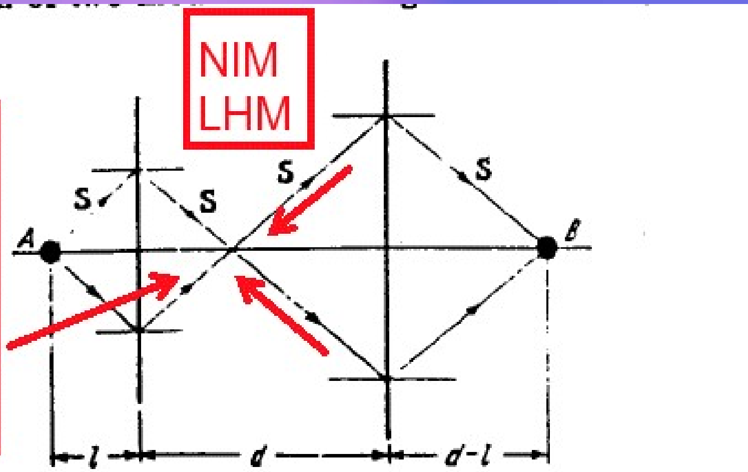
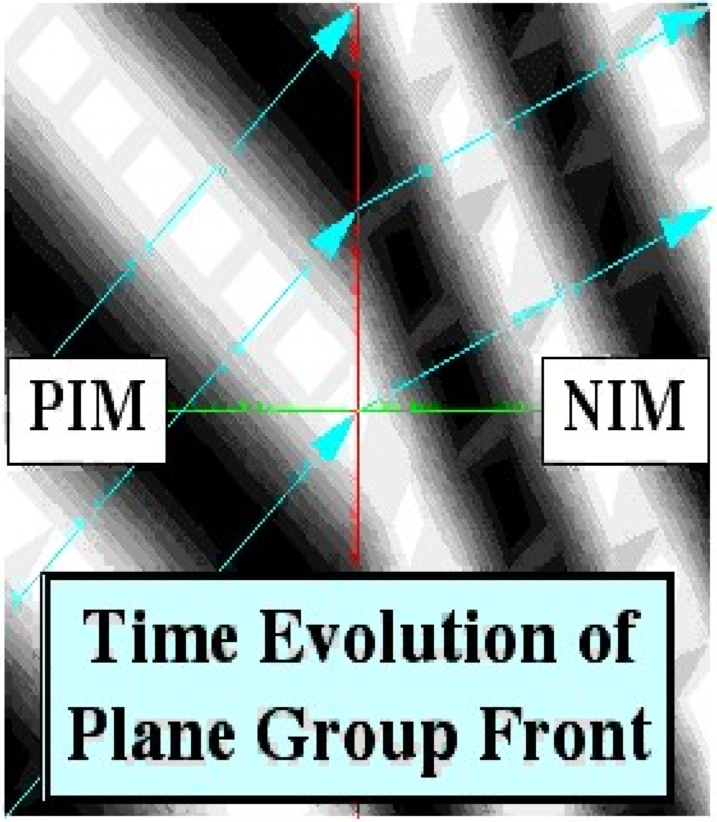


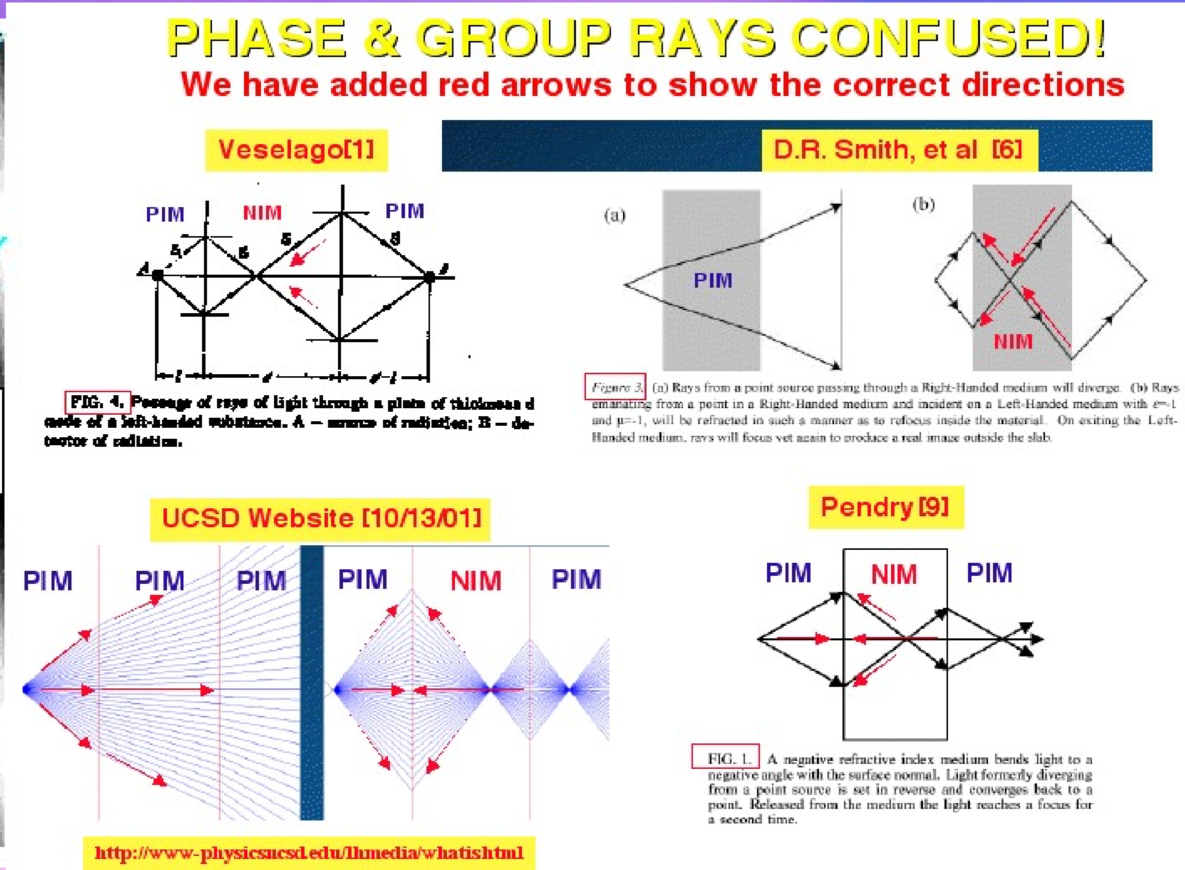
FIG. 4. Passage of rays of light through a plate of thickness d made of a left-handed substance. A – source of radiation; B – detector of radiation.

This error is copied by most later authors.

This shows how the phase fronts that satisfy a negative Snell's law come towards the PIM-NIM surface, rather than crossing it from left to right. These cannot be interpreted as anything going from left to right, *i.e.*, this does not represent causal wave front propagation along a ray as depicted by Veselago. Note that Veselago shows forward direction on arrows in NIM. That is wrong because these are phase rays. If you still do not believe how simple but true this is, try to find anything that is going from the left to the right of the surface in this movie that would correspond to the right-moving arrow on the rays shown in the figure on right.

Group fronts in PIM-NIM as well as PIM-PIM

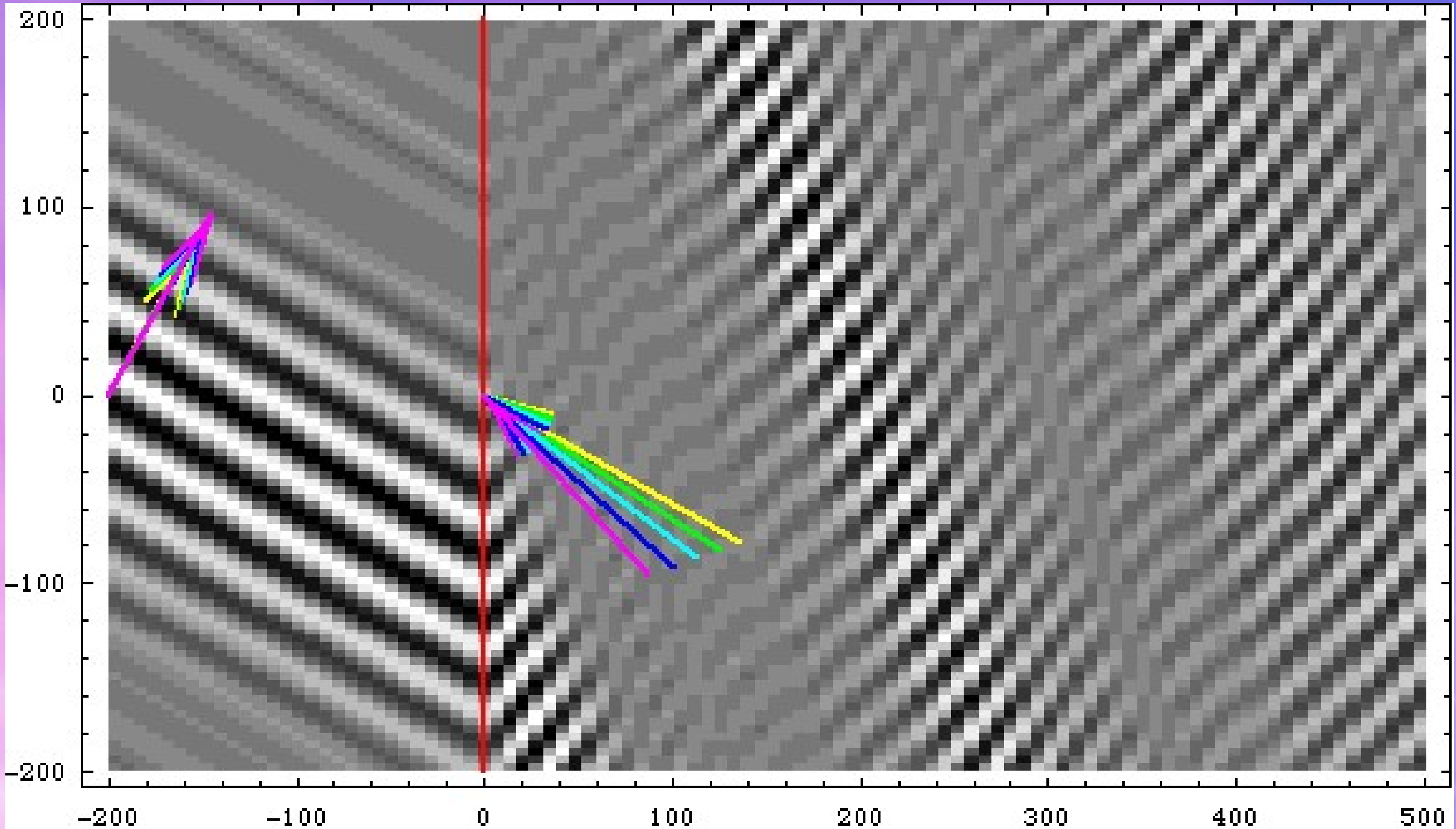




This is how the **group refracts positively (both in NIM and in PIM)**. Note how the group front crosses the surface in such a way that positive Snell's law is satisfied.

So this is the right group ray diagram with positive refraction for all media, even for NIM. The standard ray diagrams on the right are all wrong.

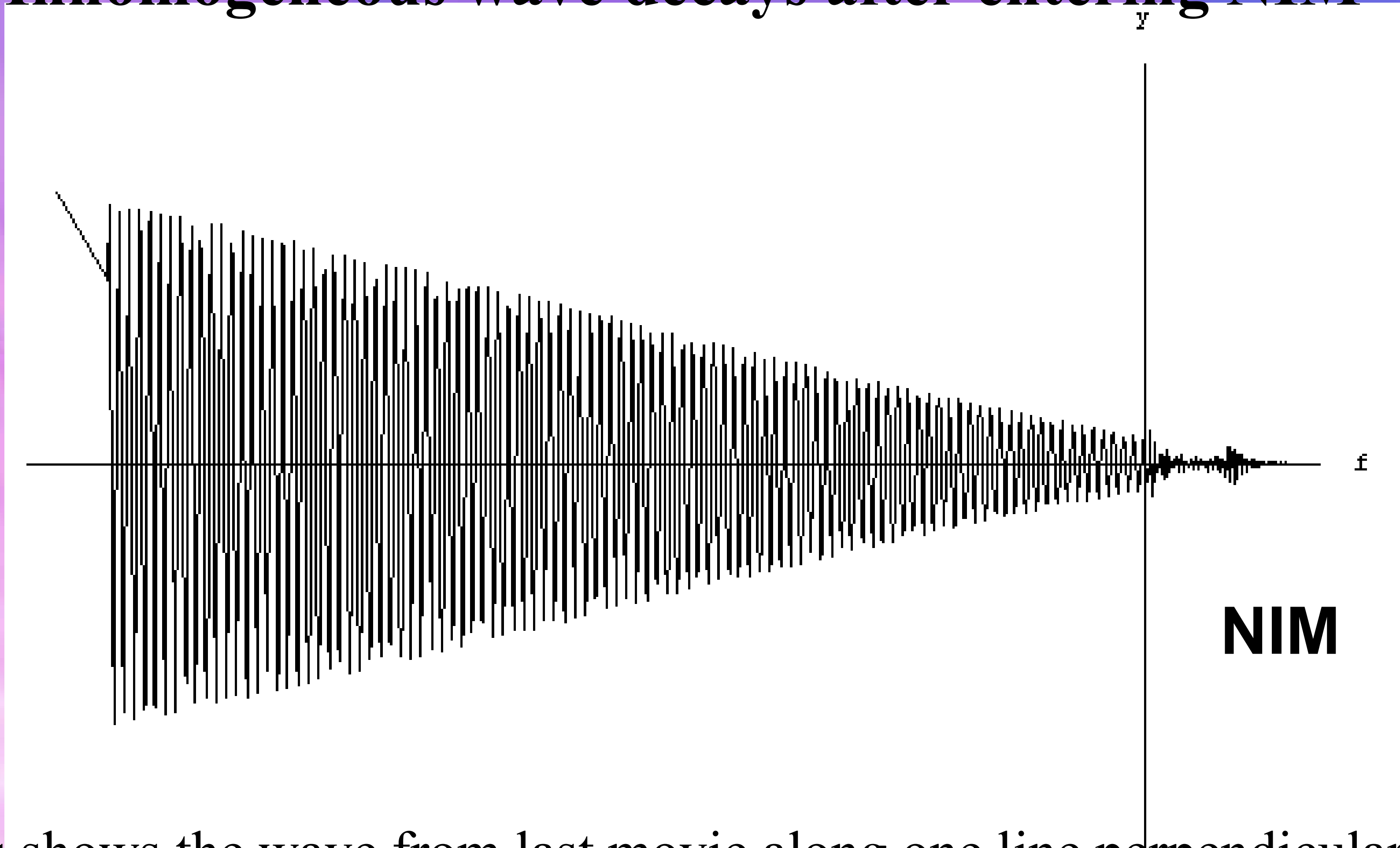
NIM inhomogenizes waves incident at an angle



When a modulated wave (made of many frequencies) is incident at an angle to PIM/NIM surface, the modulation (wide gray bands) and the carriers (sharp black-white narrow bands) **go in entirely different directions**. 倾斜入射时，调制波和载波的传播方向不同。

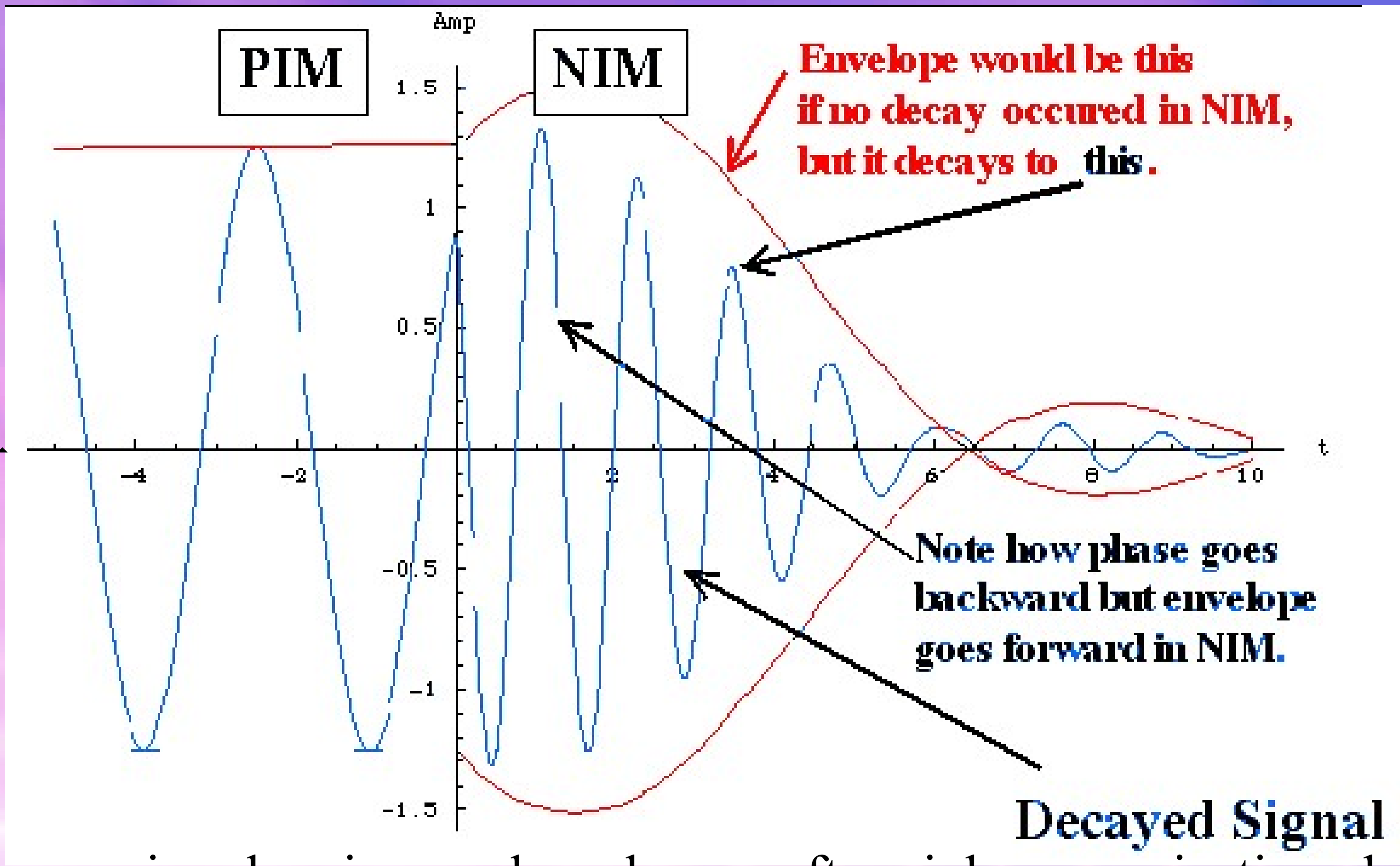
Remember how they went in opposite directions (180°) when the wave was incident perpendicular to surface? Well, here the angle between phase and group is 90~180°. Note how the **carriers go towards the PIM-NIM surface but not across it**. The modulations cross the PIM-NIM surface from left to right, and keep going upwards, *i.e.,* **modulations refract at positive angles**.

Inhomogeneous wave decays after entering NIM



This shows the wave from last movie along one line perpendicular to PIM-NIM surface. The long modulation on the incoming pulse almost **stagnates** because the group speed is so slow and positive. The large angle between the phase and group makes the pulse decay rapidly in NIM.

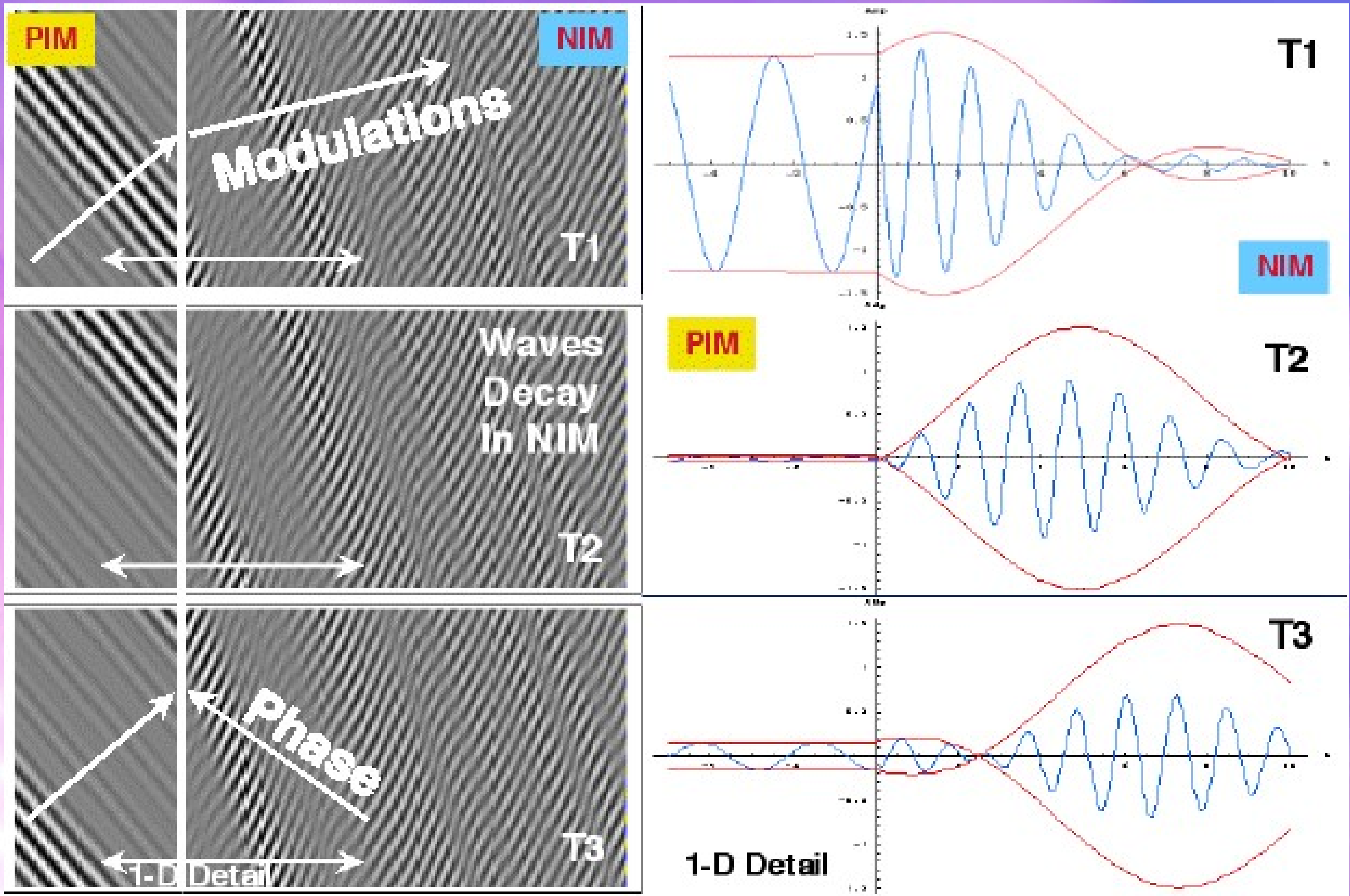
Pulse decay after inhomogenization by NIM refraction



正入射

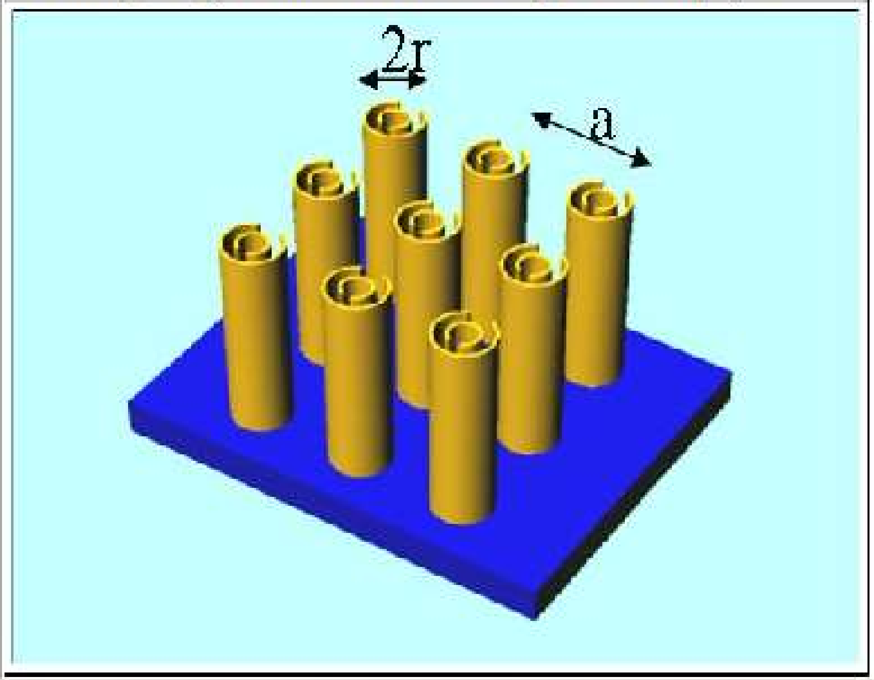
Another movie showing pulse decay after inhomogenization by NIM refraction. Here an extra envelope (modulation) is shown (red curve) that does not decay. The decay of the actual pulse can be compared to this red line: that is how big the pulse would be if it did not decay. Also see how the carriers go backwards in NIM, and how their values match at the surface but how their slopes do not match.

斜入射

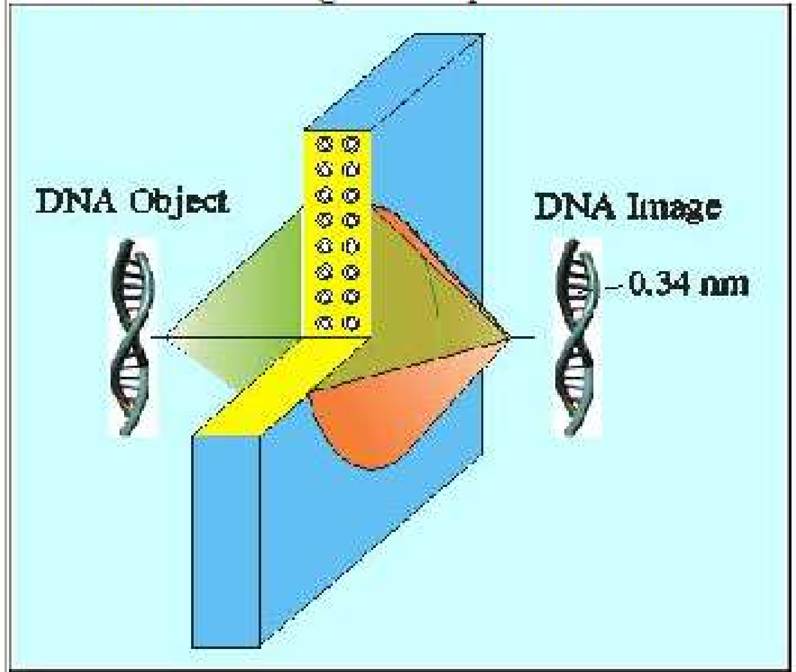


PIM
NIM
Modulations
T1
Waves
Decay
In NIM
T2
Phase
T3
1-D Detail
T1
NIM
PIM
T2
T3
1-D Detail

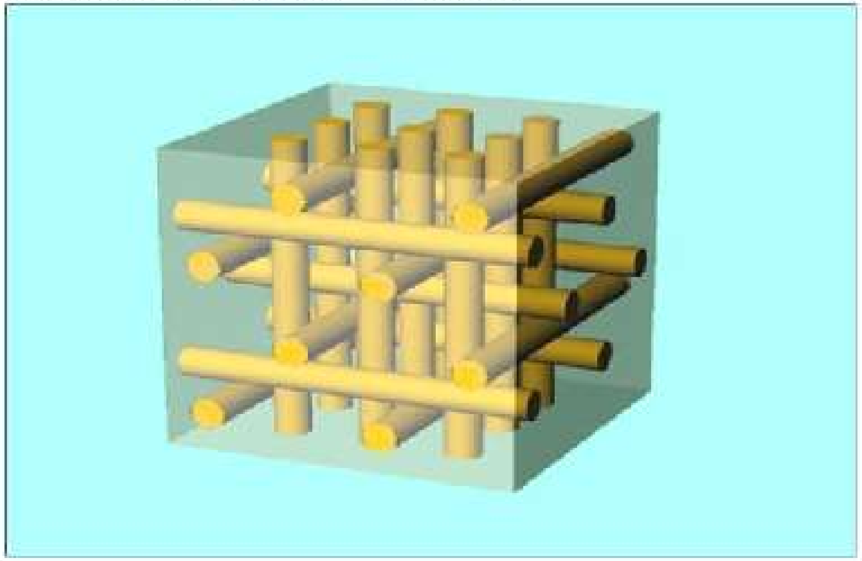
Creating Magnetism Without Magnet at High f



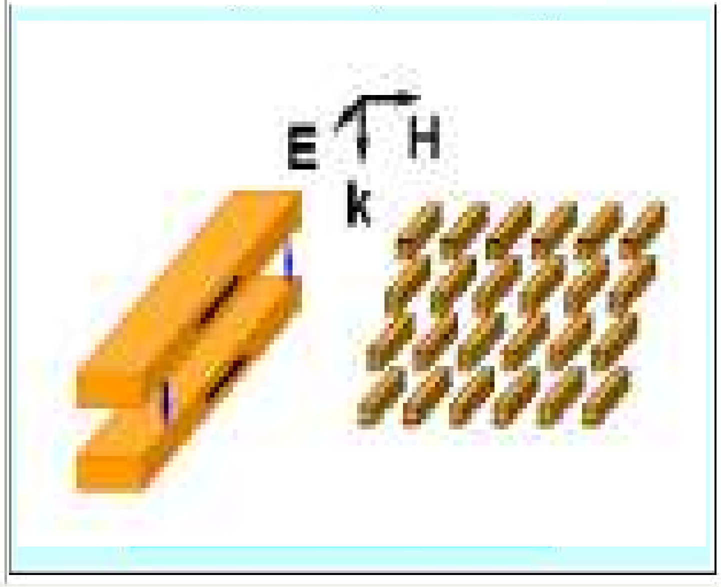
Diffraction-free Negative Superlens



Artificial Plasma with Negative ε



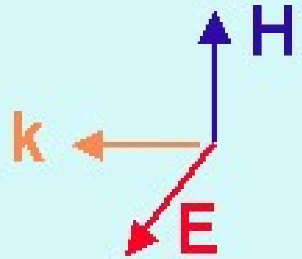
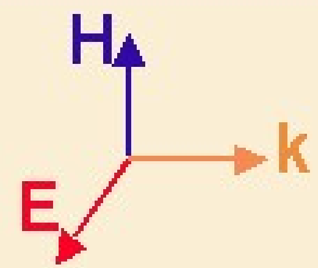
Electric metamaterial structure



PLANE WAVES IN PIM & NIM

$$\overline{k} \times \overline{E} = \omega\mu\overline{H} \qquad \overline{k} \times \overline{H} = -\omega\varepsilon\overline{E}$$

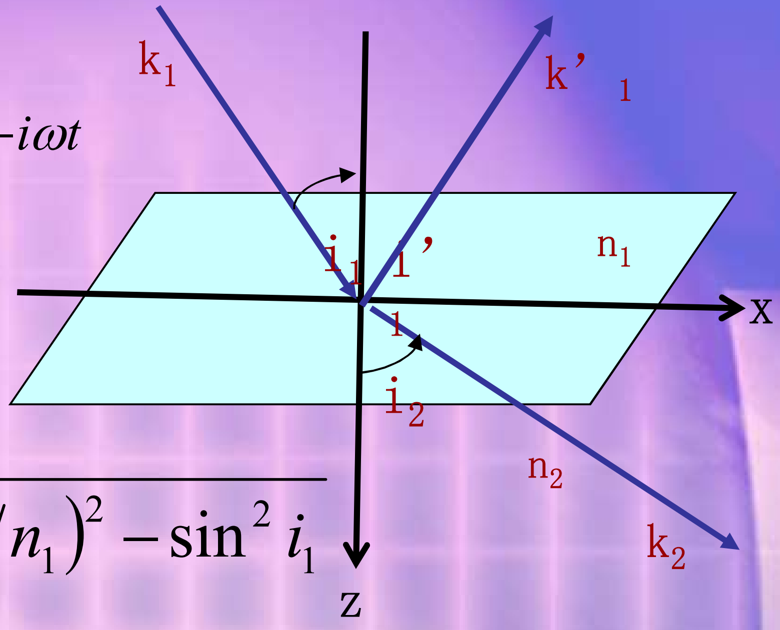
(Proof: pp. 296-7, J.Jackson,Classical Electrodynamics, 3rd Ed. 1998.)

μ	ε	$\overline{k} \times \overline{E}$	$\overline{k} \times \overline{H}$	Handednessof Medium
+	+	$\overline{H}$	$-\overline{E}$	$(\overline{E},\overline{H},\overline{k})$  Right Handed
-	-	$-\overline{H}$	$\overline{E}$	$(\overline{E},\overline{H},\overline{k})$  Left Handed

光波在界面处的传播

由边值条件，折射波的表达式

$$\vec{E}_2 = \vec{E}_{20}\exp[i(k_{2x}x + k_{2z}z)]e^{-i\omega t}$$



$$k_{2z} = \sqrt{k_2^2 - k_{2x}^2} = \sqrt{(n_2/n_1)^2 k_1^2 - k_{1x}^2}$$

$$= \sqrt{(n_2/n_1)^2 k_1^2 - k_1^2 \sin^2 i_1} = k_1\sqrt{(n_2/n_1)^2 - \sin^2 i_1}$$

$$= k_1\sqrt{\sin^2 i_c - \sin^2 i_1} = \frac{2\pi}{\lambda_1}\sqrt{\sin^2 i_c - \sin^2 i_1}$$

当$i_1 > i_c$，发生全内反射， k_{2z}为纯虚数，令 $k_{2z} = i\kappa$

$$\kappa = \frac{2\pi}{\lambda_1}\sqrt{\sin^2 i_1 - \sin^2 i_c}$$

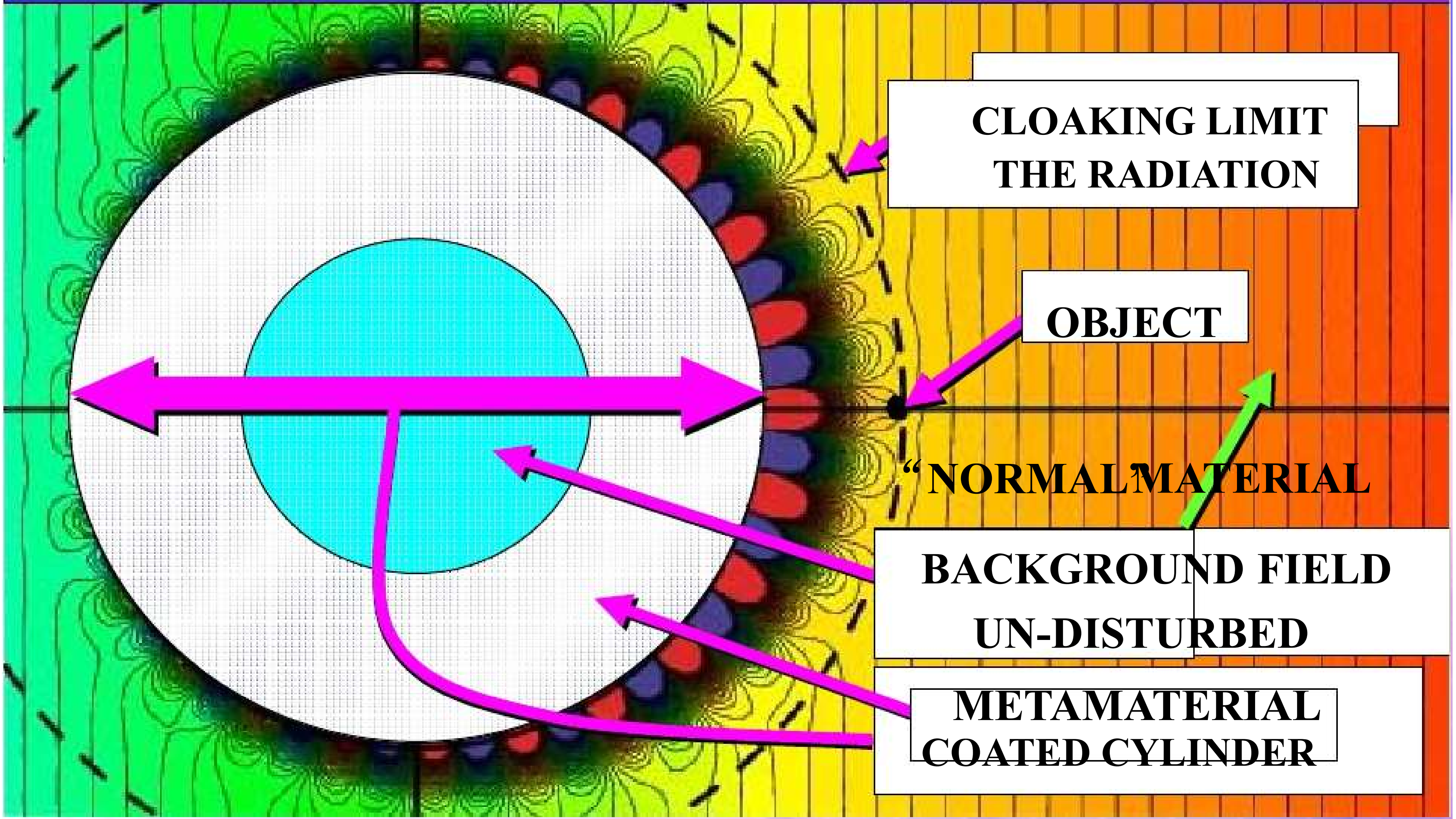
光波在界面处的传播

$$\vec{E}_2 = \vec{E}_{20}\exp[i(\vec{k}_2\cdot\vec{r}-\omega t)] = \vec{E}_{20}e^{-\kappa z}\exp[i(k_{2x}x-\omega t)]$$

- 折射波在**X**方向（沿界面）仍具有行波的形式，但沿**Z**方向（纵深方向）按指数急剧衰减。

- 全反射情况下，光仍然要进入第二介质，这并不违反能量守恒定律。入射波的能量不是在严格的界面上全反射的，而是穿透介质**2**内一定深度（即趋附深度$\delta_{\mathbf{m}}$）后逐渐反射的。

Does the object need to be inside the cloak?



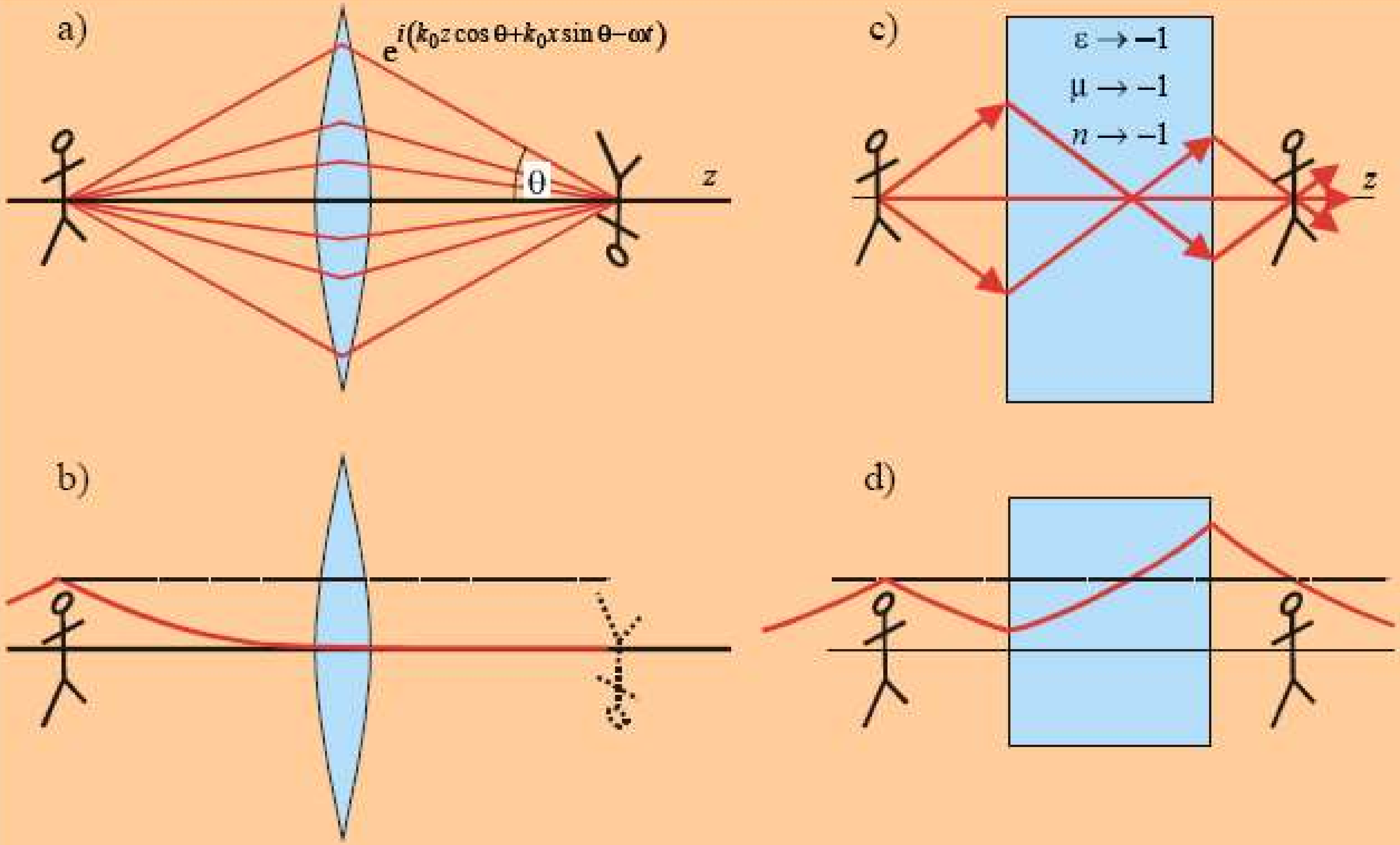
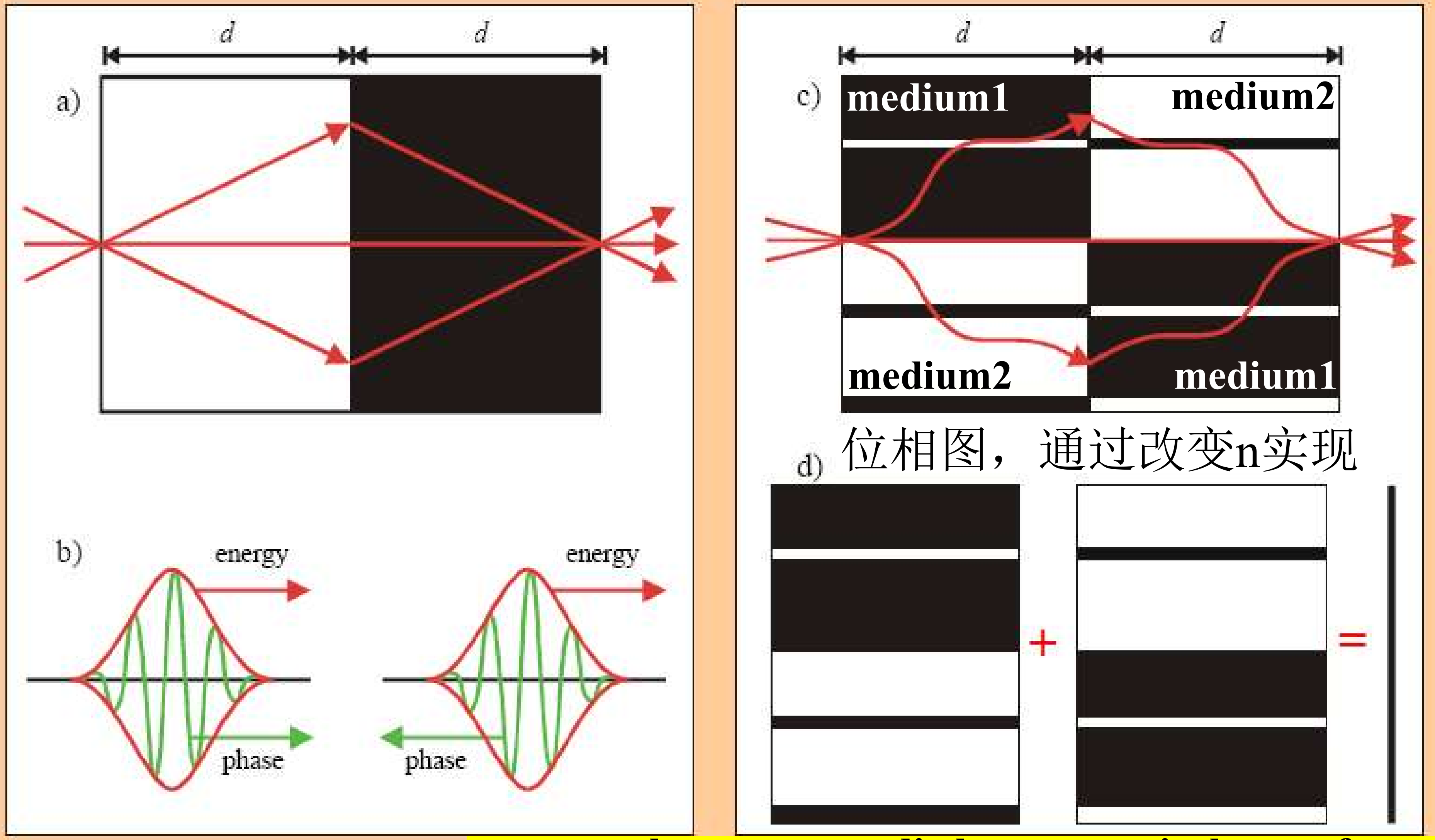


Figure 4. Limitation of resolution in lenses. a) Conventional lenses need a wide aperture for good resolution but even so are limited in resolution by the wavelength employed. b) The missing components of the image are contained in the near field which decays exponentially and makes negligible contribution to the image. c) A new lens made from a slab of negative material not only brings rays to a focus but has the capacity d) to amplify the near field so that it contributes to the image thus removing the wavelength limitation. However the resonant nature of the amplification places sever demands on materials: they must be very low loss.



two complementary media have an optical sum of zero

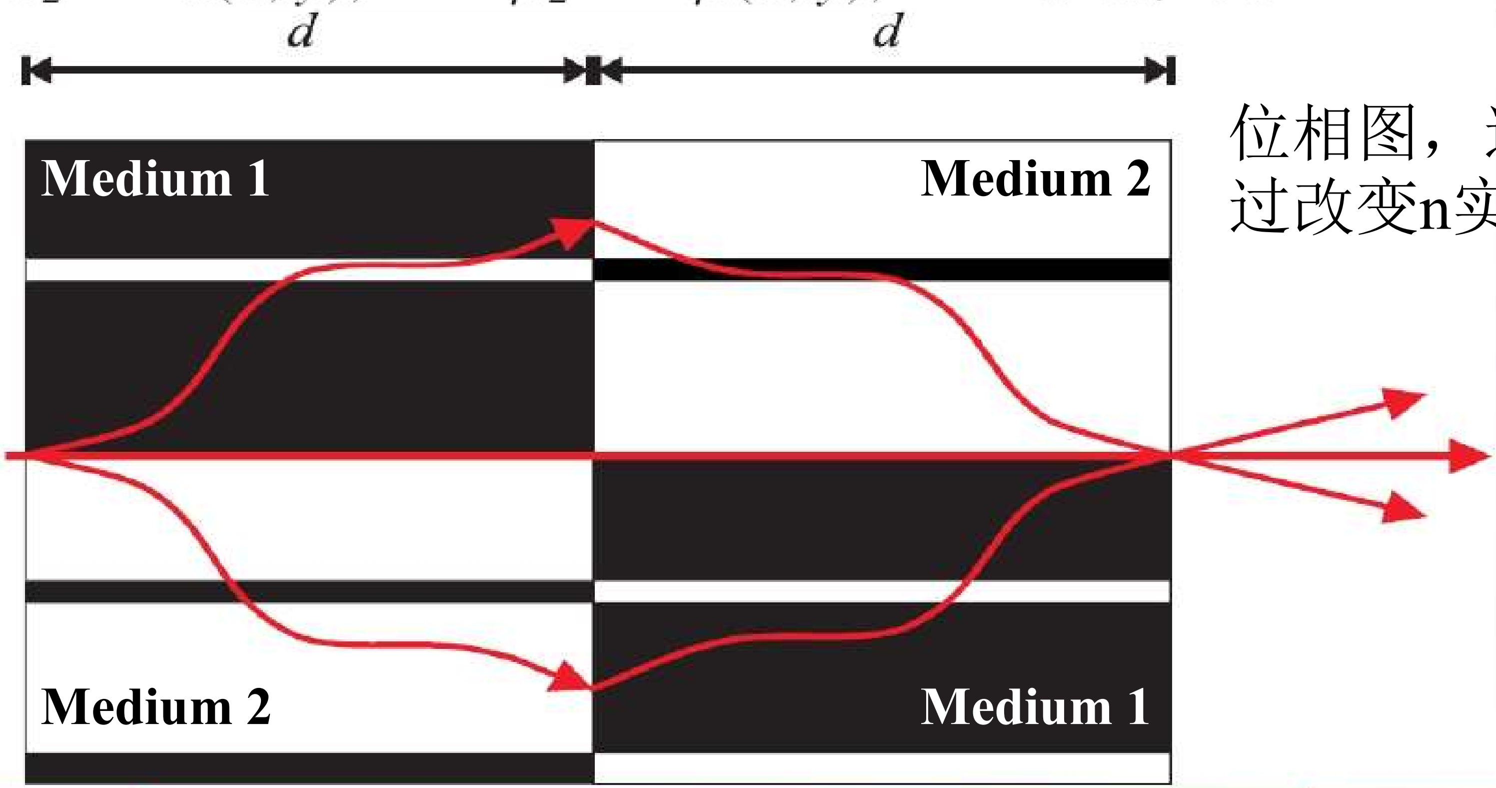
Figure 6. Generalizing the perfect lens: a) an $n = -1$ slab draws light to a perfect focus; b) shows how the focus is achieved by the negative slab 'unwinding' or negating the phase acquired in passing through free space; c) focusing can occur through two more complex objects provided that one is the inverse mirror image of the other; d) a graphical statement of the optical cancellation mirror antisymmetric regions of space optically annihilate one another. A negative medium is in effect a piece of optical antimatter.

Optical antimatter

Anti-phase or Optical Antimatter

$$\varepsilon_1 = +\varepsilon(x,y), \qquad \mu_1 = +\mu(x,y), \qquad -d < z < 0$$

$$\varepsilon_2 = -\varepsilon(x,y), \qquad \mu_2 = -\mu(x,y), \qquad 0 < z < d$$

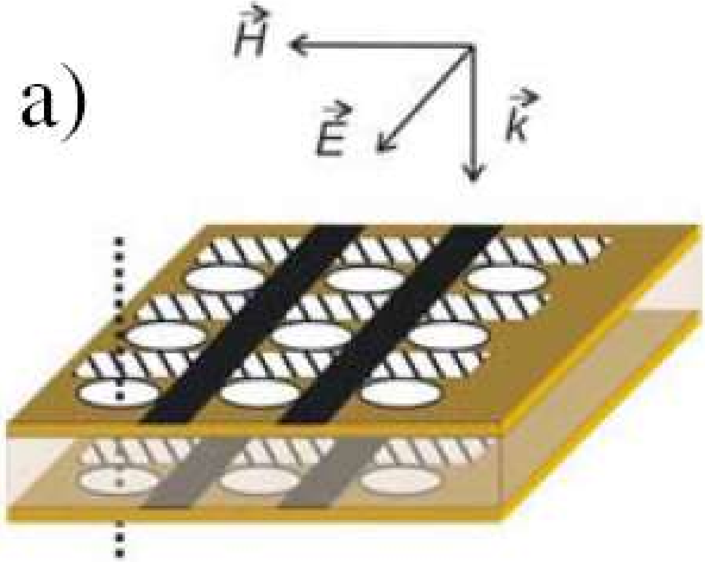


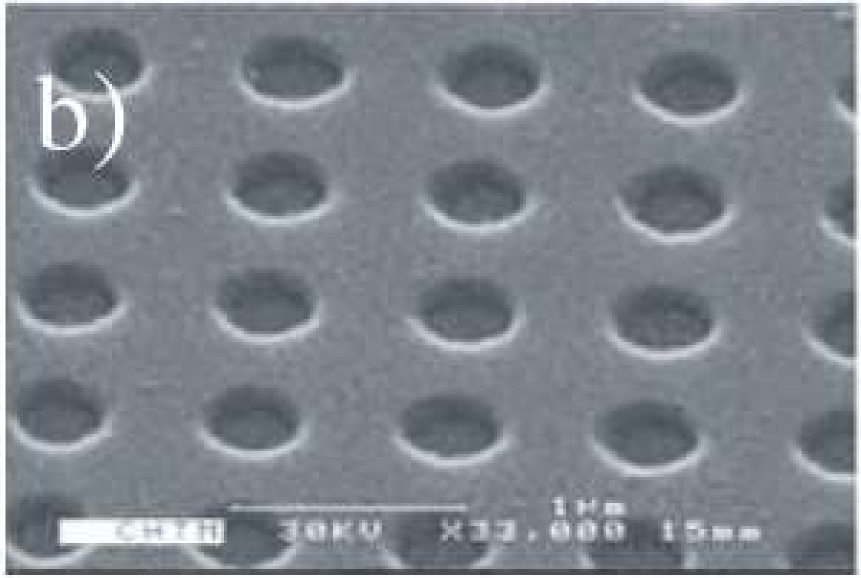
位相图，通过改变n实现

"as if section of space thickness 2d were removed"

Phase information effectively cancel each other out

Pendry & Ramakrishna J. Phys: Cond Matter **15** 6345 (2003)





$n < 0$. However, the minimum value of μ_{eff} is not negative (for both the measurement and the modeling results) as a result of the large scattering loss. The refractive index is expressed in terms of the permittivity and permeability as $n = \pm\sqrt{(\varepsilon_1\mu_1 - \varepsilon_2\mu_2) + i(\varepsilon_1\mu_2 + \varepsilon_2\mu_1)}$ and $\mathrm{Im}(n) > 0$, where $\varepsilon = \varepsilon_1 + i\varepsilon_2$ and $\mu = \mu_1 + i\mu_2$. To achieve a negative $\mathrm{Re}(n)$ with $\varepsilon_1 < 0$ and $\mu_1 > 0$, $-\varepsilon_1\mu_2$ must be larger than $\varepsilon_2\mu_1$, as is the case near the metamaterial resonance.

we show that a simple Lorentz model nicely fits the simulation. In the Lorentz model, the permeability is expressed as:

$$\mu(\omega) = \mu_\infty - \frac{f\omega_0^{\ 2}}{\omega^2 - \omega_0^{\ 2} + j\gamma\omega}, \tag{1}$$

here f is a fill factor and μ_∞ is the effective permeability for wavelengths far above the resonance.

$$\cos nk\Delta = \frac{1 - r^2 + t^2}{2t}$$

Δ is the total thickness of the sandwiched metamaterials
The transmission ($T=|t|^2$) and reflection ($R=|r|^2$) spectra are measured with a ***Lambda 950 spectrophotometer from Perkin-Elmer*** using linearly polarized light. Two different light polarizations have been used, one with the electric field parallel the nanorod pair major axis and the other with the electric field perpendicular to this axis.