科技与幻想：电磁超材料技术与应用

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一些有趣的科学梦想

一叶遮目

Harry Potter, Invisible Cloak

Star Trek, cloaking devices

Outlines

一、超材料 (metamaterials)

-什么是超材料？

-超材料领域的历史与发展

二、负折射率超材料

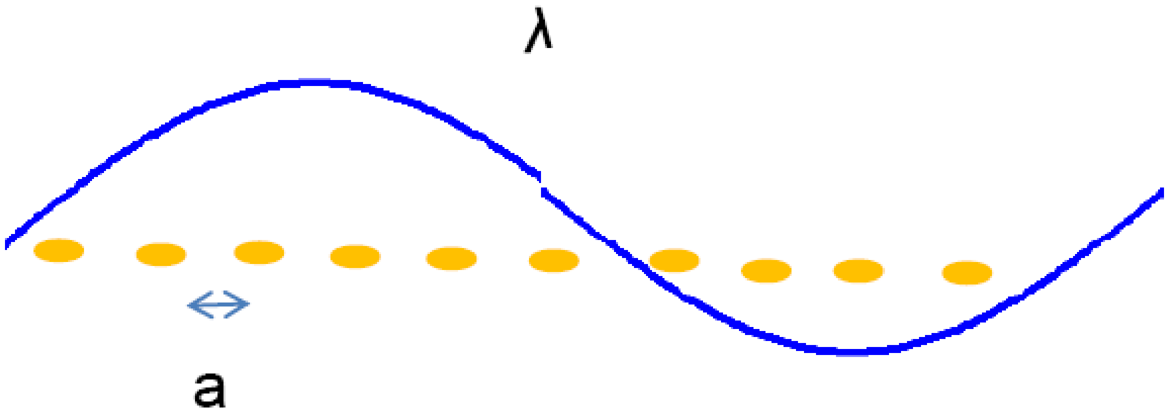
三、超透镜

四、完美隐身

五、超构表面

六、超材料未来研究方向

光与材料的相互作用



•Microscopic EM fields (**e,b**) to what we are familiar with macroscopic (**E,B**)

•Averaging over length scale larger than atomic length scale but below wavelength

•Leads to electromagnetic material parameters εand μ

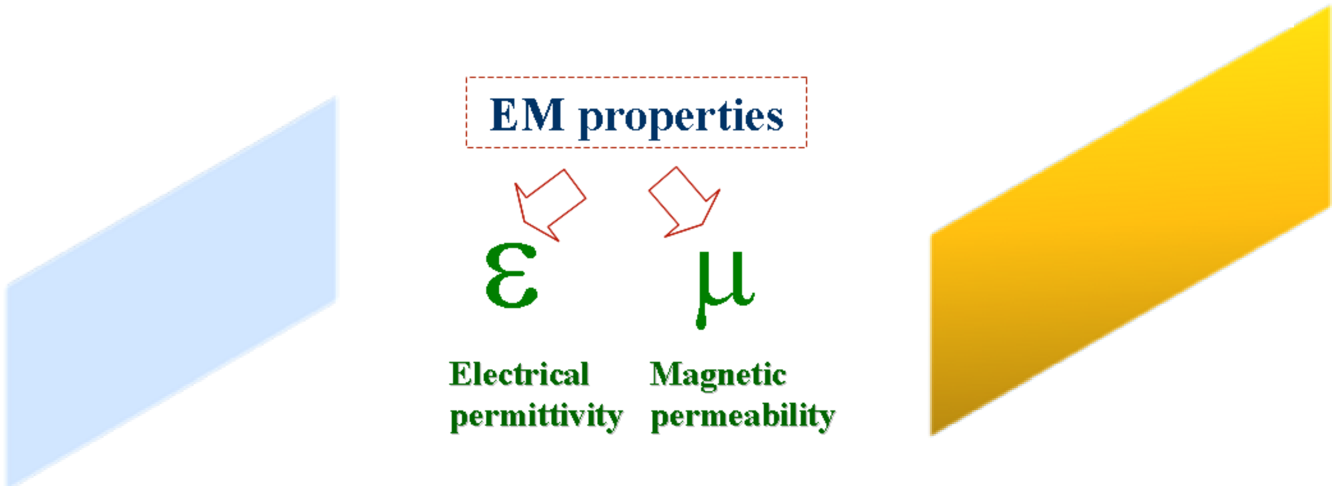
自然界材料

Transparent media

Eg: Vacuum, Dielectrics (ε> 0)

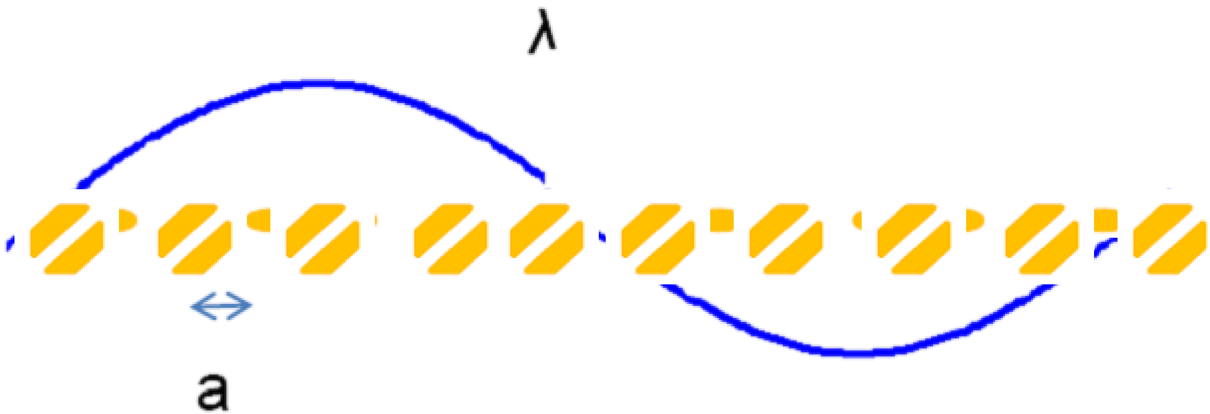
Reflective media

Eg: Metals (ε< 0)



We doun’t have materials with negative magnetic permeabilities.

人造原子



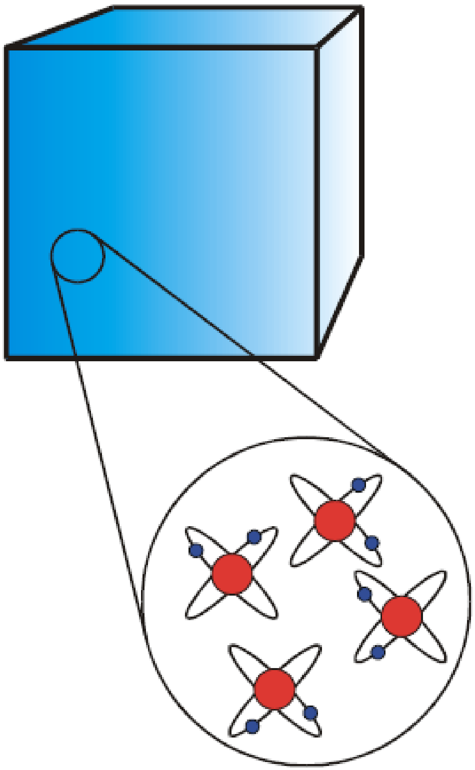
Nano-inclusions/meta-atoms ~ 10 nm

•Tailor mechanical, thermal and electromagnetic properties for interesting physics and devices

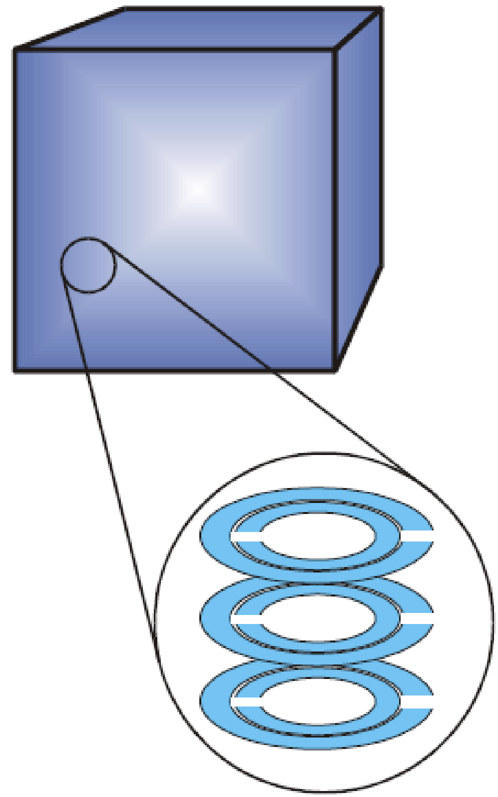
•Unprecedented control over light

什么是超材料？

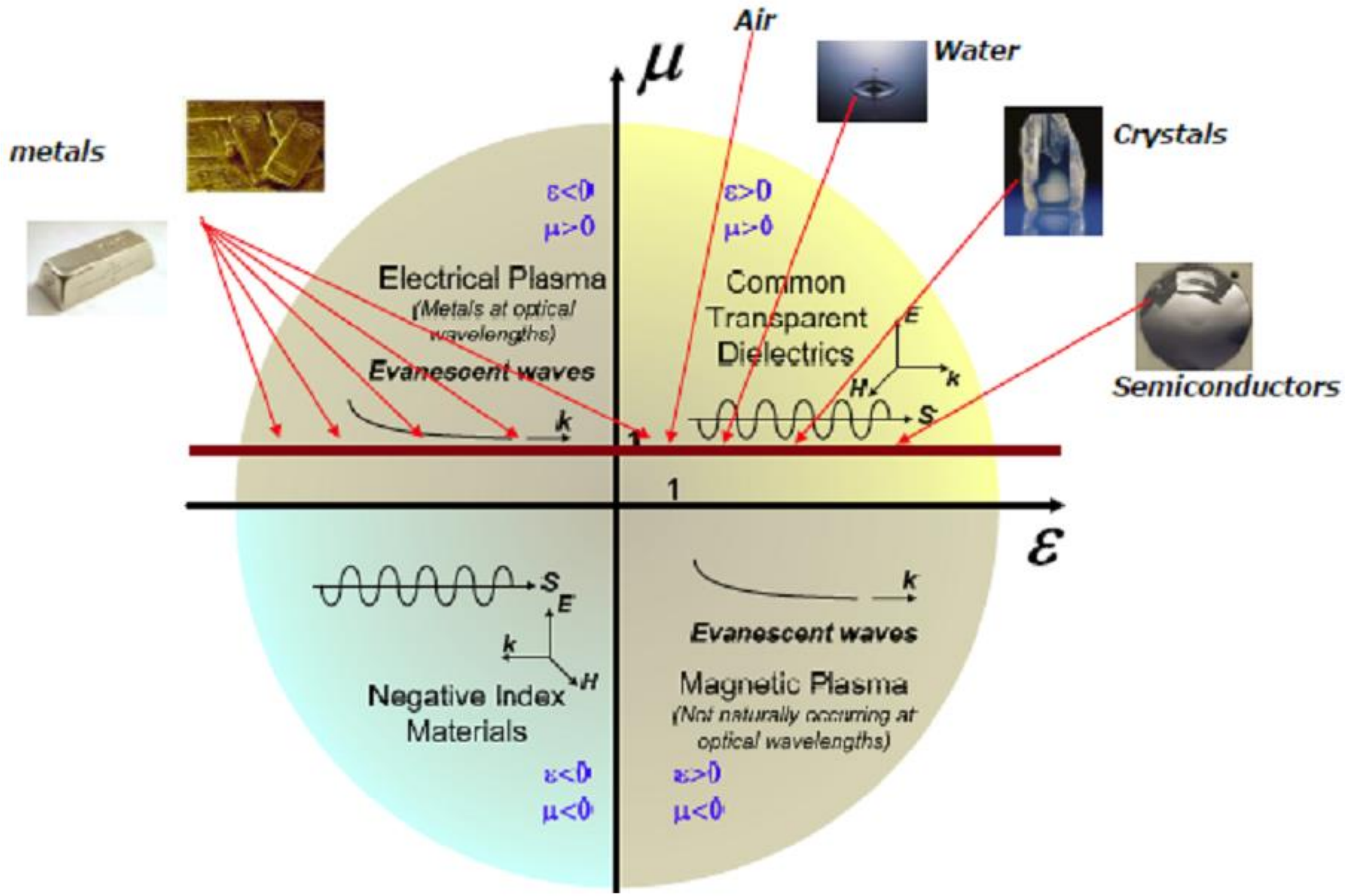
Conventional materials: properties derive from their constituent atoms.



Metamaterials: properties derive from their constituent *units*. These units can be engineered as we please.



超材料的研究对象


Air
Water
Crystals
metals
Semiconductors
μ
ε
ε<0
μ>0
Electrical Plasma
(Metals at optical wavelengths)
Evanescent waves
k
ε>0
μ>0
Common Transparent Dielectrics
E
k
H
S
1
1
S
E
k
H
Negative Index Materials
ε<0
μ<0
k
Evanescent waves
Magnetic Plasma
(Not naturally occurring at optical wavelengths)
ε>0
μ<0

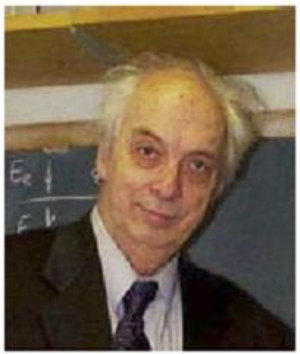
超材料的历史


Sir Arthur Schuster   Sir Horace Lamb

... energy can be carried forward at the group velocity but in a direction that is anti-parallel to the phase velocity...
Schuster, 1904

Negative refraction and backward propagation of waves
Mandel'stam, 1945

L. I. Mandel'stam



V. G. Veselago

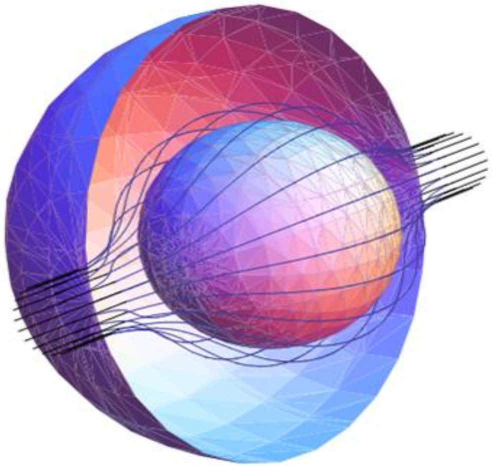
Left-handed materials: the electrodynamics of substances with simultaneously negative values of ε and μ
Veselago, 1968

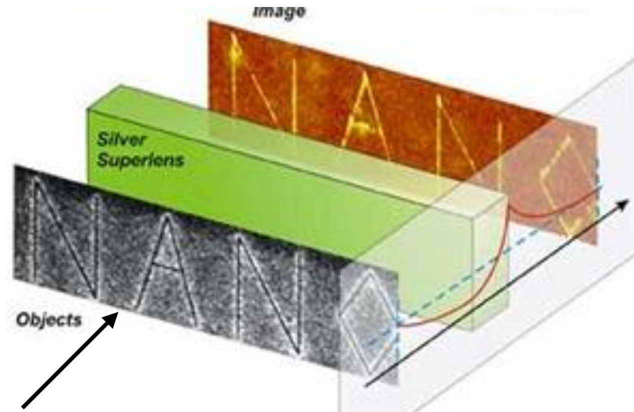
Pendry, the one who whipped up the recent boom of NIM researches

Perfect lens (2000)
EM cloaking (2006)

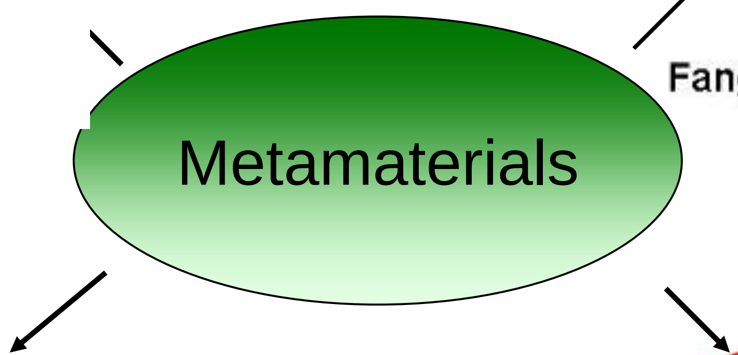
Sir John Pendry

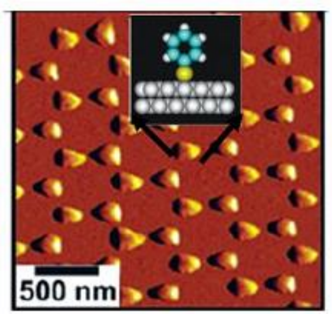
超材料的应用



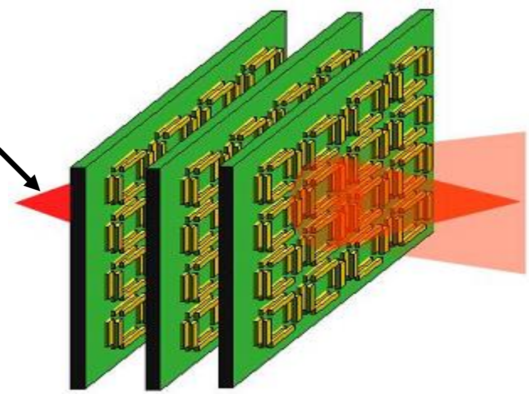


Fang *et al.*, Science, 2005





Van Duyne *et al.*, MRS bulletin, 2005



Loges *et al.*, Appl. Phys. A, 2007

超材料的迅速发展

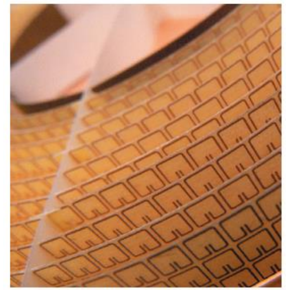
#8 About-face. After 2 years of debate, work this year confirmed that certain oddball materials are capable of bending light in the wrong direction. Materials bend light and other types of electromagnetic radiation according to a property known as their index of refraction. The bigger a material's index, the slower light travels through it, and the more light bends. A change in refractive index is why a straw in a glass appears to have a kink where it enters the water. In natural materials, light always bends at a positive angle with respect to the angle at which it entered.

See Web links on left-handed materials

In 1964, a Russian physicist theorized that researchers could tailor materials to reverse the way they manipulate passing electromagnetic radiation. Two years ago, researchers created such "left-handed" materials. They beamed microwaves at a composite of copper rings and wires, which steered microwaves out at a negative instead of a positive angle. Last year other teams challenged those results, but this year definitive proof came from multiple camps.

2003，Top Ten Scientific Breakthroughs

The top ten advances in materials science **INSIGHT**



The metamaterial structure of an invisibility cloak that hides objects from microwave radiation. (Credit: David Schurig, Duke University.)

But the surprising optical properties don't arise from the material's composition as its structure. The first metamaterial was a composite of metal wires and split rings assembled on a lattice of printed circuit boards. It was an example of a metamaterial – an artificial structure of repeated micro-sized elements designed for specific properties.

"Metamaterials derive their properties as much from their internal structure as from their chemical composition," explains John Pendry of Imperial College London, UK. "Adding structure to chemistry as an ingredient greatly increases the range of properties that we can access. There is a new realization that

2008，The Top Ten Advances in Materials Science Over the Last 50 Years

5 THE ULTIMATE CAMOUFLAGE

Science veered toward science fiction this year as physicists cobbled together the first rudimentary invisibility cloak. Although far from perfect—the ring-shaped cloak is invisible only when viewed in microwaves of a certain wavelength traveling parallel to the plane of the ring—the device could usher in a potentially revolutionary approach to manipulating electromagnetic waves.

See Web links on cloaking technology

The disappearing act began in May, when two independent analyses predicted that it should be possible to ferry electromagnetic waves around an object to hide it. All that was needed was a properly designed shell of "metamaterial," an assemblage of tiny metallic rods and c-shaped rings. The waves churn the electrons in the rods and rings, and the sloshing affects the propagation of the waves. Both analyses specified how to sculpt the properties of the metamaterial and left it to experimenters to design the materials to meet those specs.

In October, the team that made one of the predictions did just that—almost. Physicists at Duke University built a ring instead of an all-concealing sphere. They made some approximations that rendered the cloak slightly reflective. Still, the thing whisked microwaves around a plug of copper, proving that the method works. Cloaks for visible light are likely years off, as researchers must figure out how to make metamaterials that work at such short wavelengths. Even then, the cloak would be a bust for spying because it would be impossible to see out of it.

View larger version:
» In this page » In a new window

The real breakthrough may lie in the theoretical tools used to make

2006，Top Ten Scientific Breakthroughs

INSIGHTS OF THE DECADE

Now you see it. Metamaterials make it possible to steer light around an object, creating an artificial blind spot (*below*). A disk version works with microwaves (*left*).

a few years later, other teams reported initial success in making a superlens and related devices called hyperlenses.

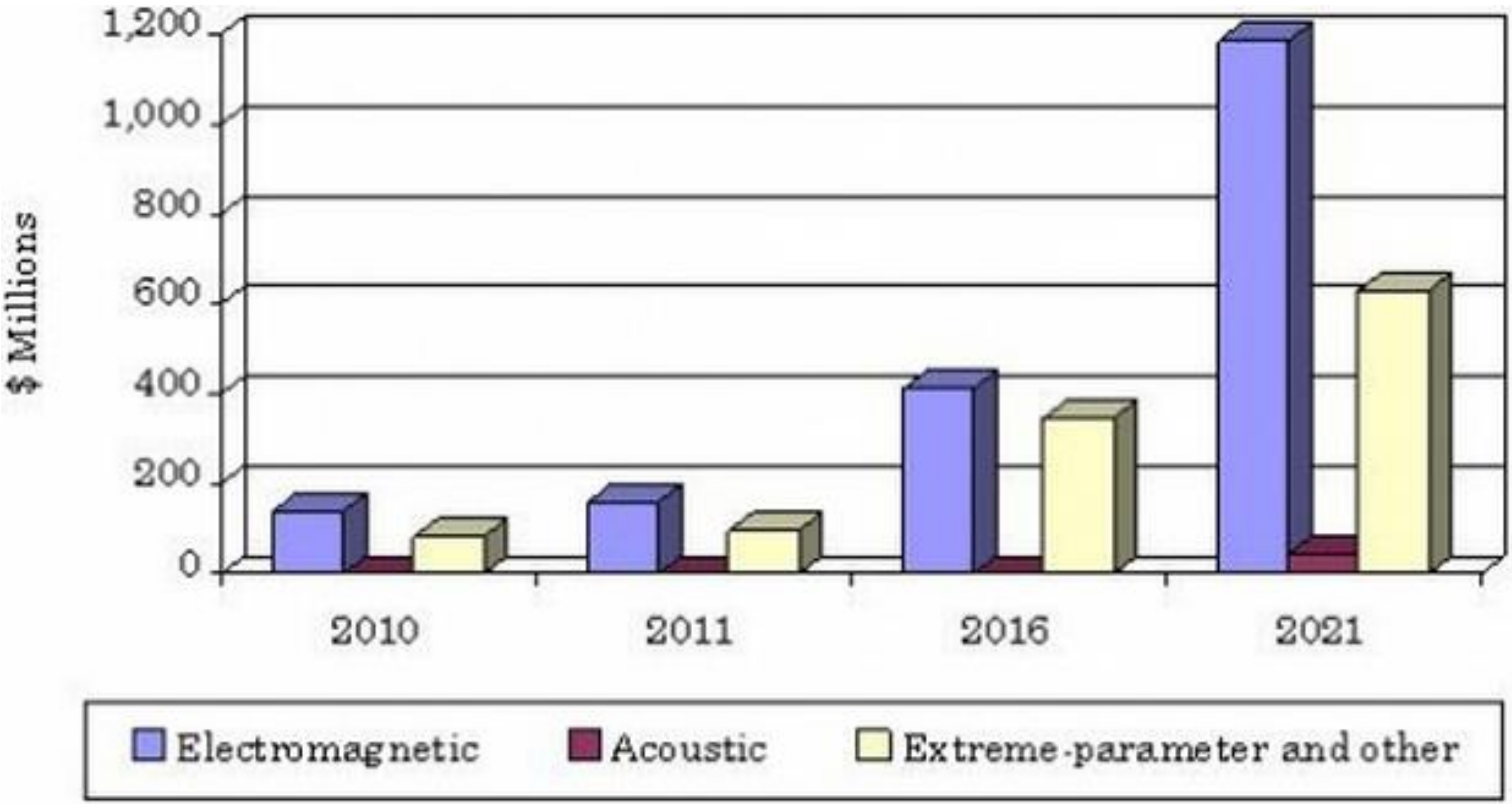
Then things got really strange. In May 2006, Pendry and colleagues and, independently, Ulf Leonhardt, a theorist at the University of St. Andrews in the United Kingdom, reported that metamaterials could be used to render an object invisible by steering light around it the way water streams around a boulder. Just 5 months later, Smith, his postdoc David Schurig (now at North Carolina State University in Raleigh), and other colleagues unveiled such a ring-shaped cloaking device.

The device wasn't perfect; it worked only

2010，Insights of the Decade

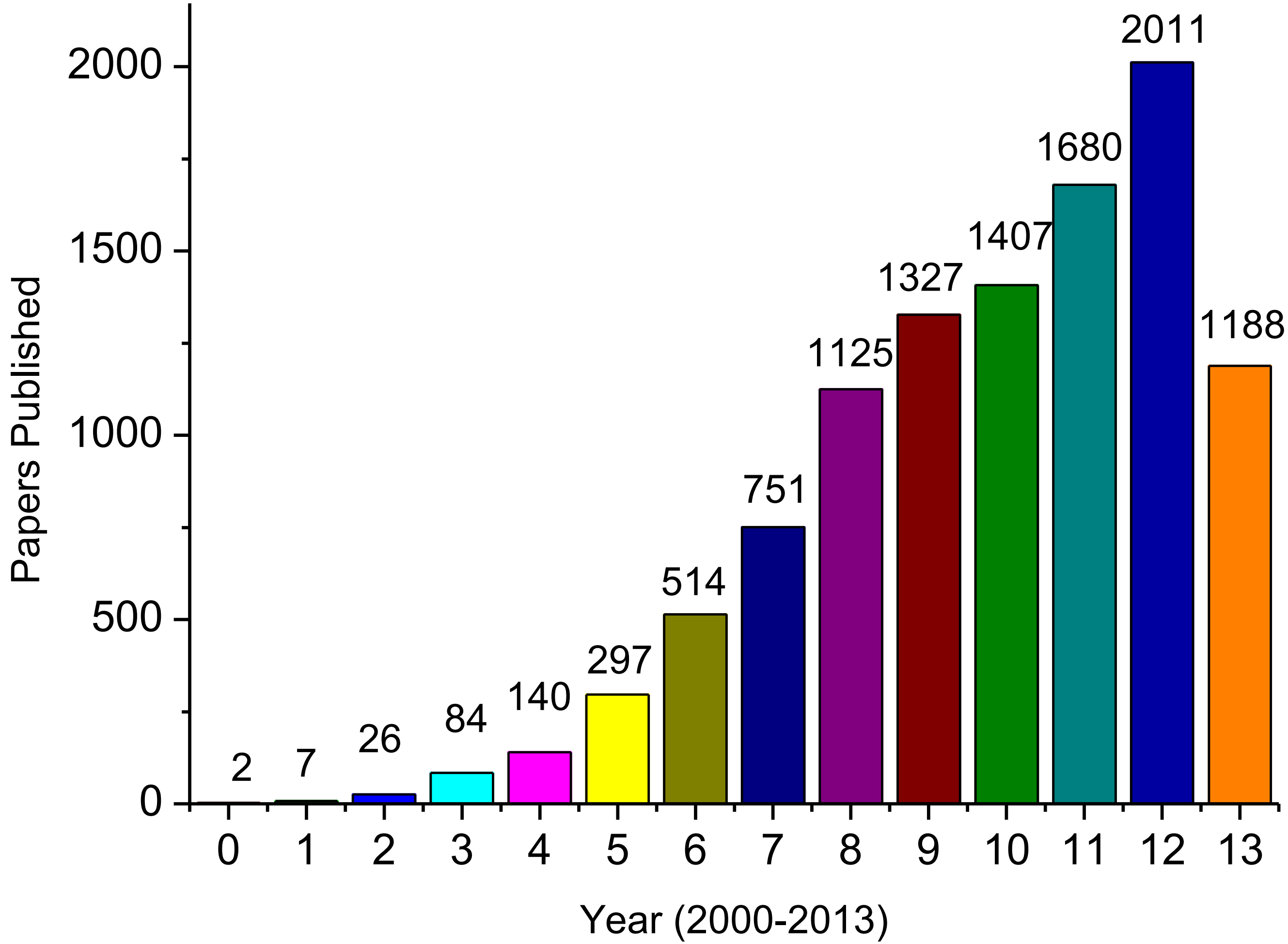
哈爾濱工業大學
HARBIN INSTITUTE OF TECHNOLOGY

超材料的迅速发展



1,200
1,000
800
600
400
200
0
$ Millions
2010
2011
2016
2021
Electromagnetic
Acoustic
Extreme-parameter and other

超材料的迅速发展


Papers Published
2000
1500
1000
500
0
2
7
26
84
140
297
514
751
1125
1327
1407
1680
2011
1188
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Year (2000-2013)

Outlines

一、超材料

二、负折射率超材料

-电谐振和磁谐振超材料

-负折射率超材料

三、超透镜

四、完美隐身

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材料的折射率

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

In naturally exiting substances permittivity and permiability are positve (except the cases of noble metals like gold silver etc where permitivitty is negative for certain range of frequency).

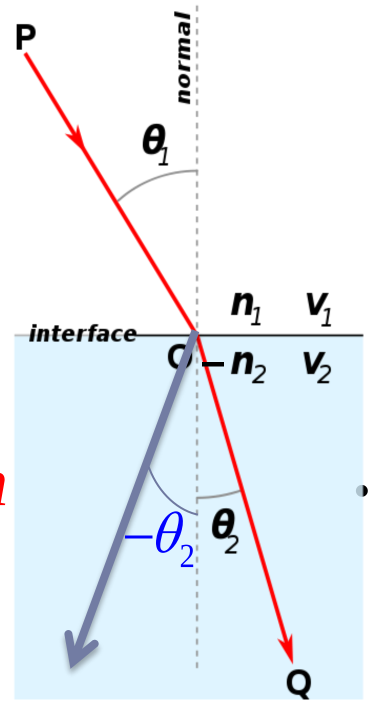
Now lets consider that :

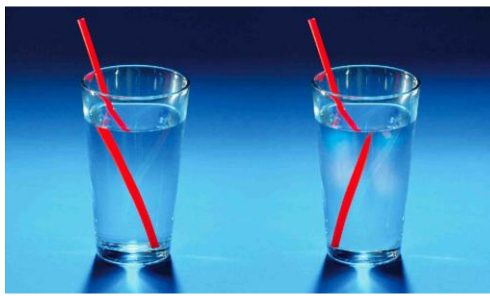
$$\mu < 0$$

$$\varepsilon < 0$$

$$n_{eff} = \sqrt{(-|\varepsilon|)(-|\mu|)} = -\sqrt{|\varepsilon\mu|} = -n$$

$$\vec{k} = \frac{\vec{k}_{LHM}}{n_{LHM}}$$





- Snell`s law is still valid

电谐振超材料

Drude model for permittivity:

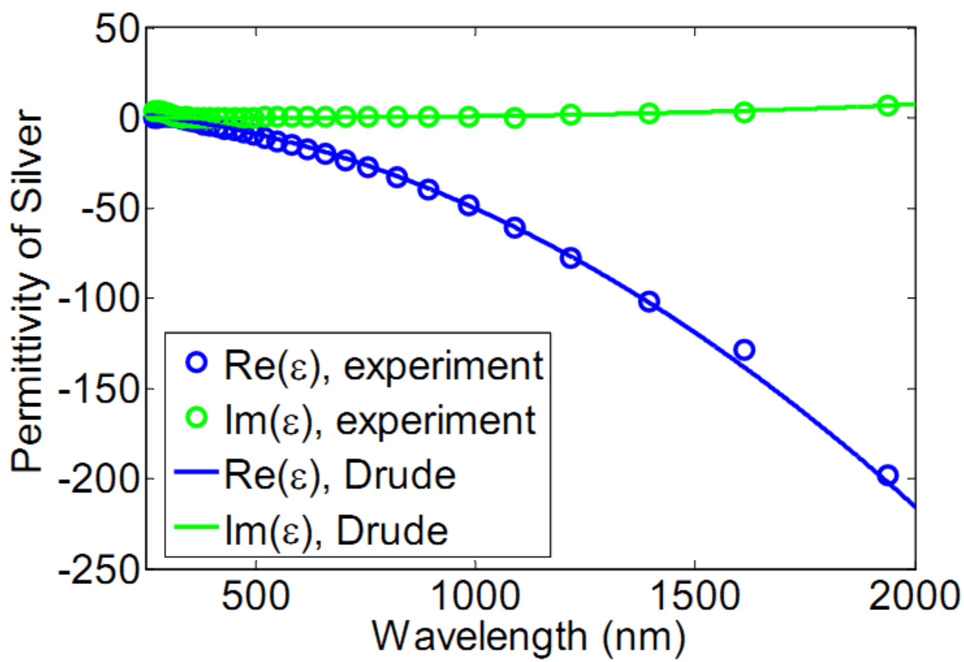
$$\varepsilon(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$$

Silver parameters:

$\varepsilon_0 = 5.0$

$\omega_p = 9.216 \quad eV$

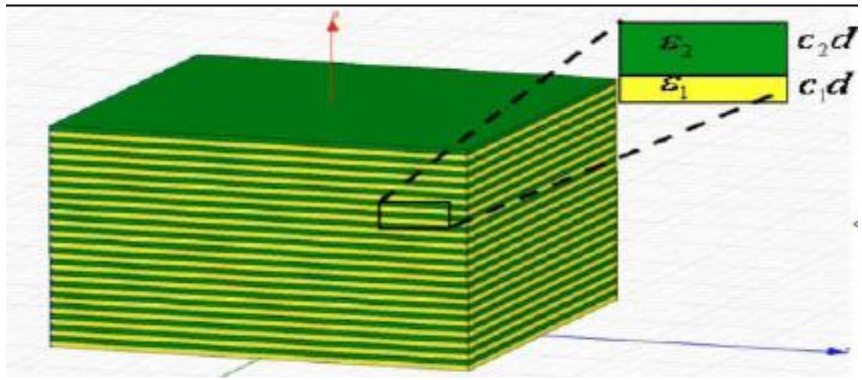
$\Gamma = 0.0212 \quad eV$

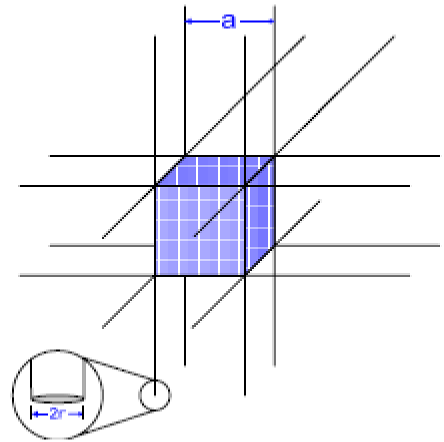


Experimental data from Johnson & Christy, PRB, 1972

电谐振超材料

Negative ε' : metal with negative ε' and dielectric with ε' positive composite (dilute metal)





Random mixing metal particles in dielectric host

A periodic stack of metal/dielectric layers

A periodic array of thin metal wires in lattice

By carefully adjusting the ratio of metal to dielectric, the effective permittivity can be changed.

早期电谐振超材料

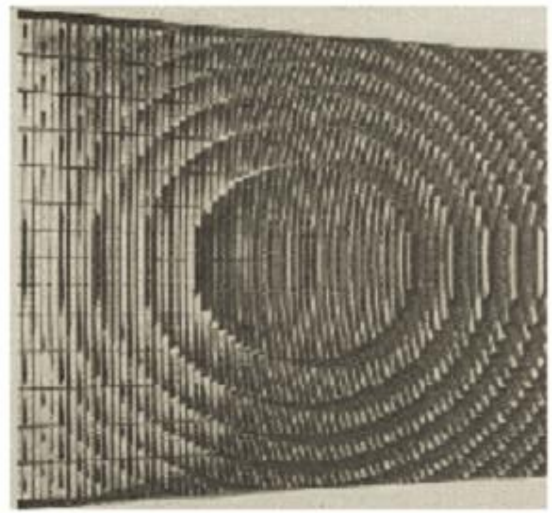
Periodic metal-dielectric plates with <u>effective index of less than 1</u>

828 *Proceedings of the I.R.E. and Waves and Electrons* November

Metal-Lens Antennas*

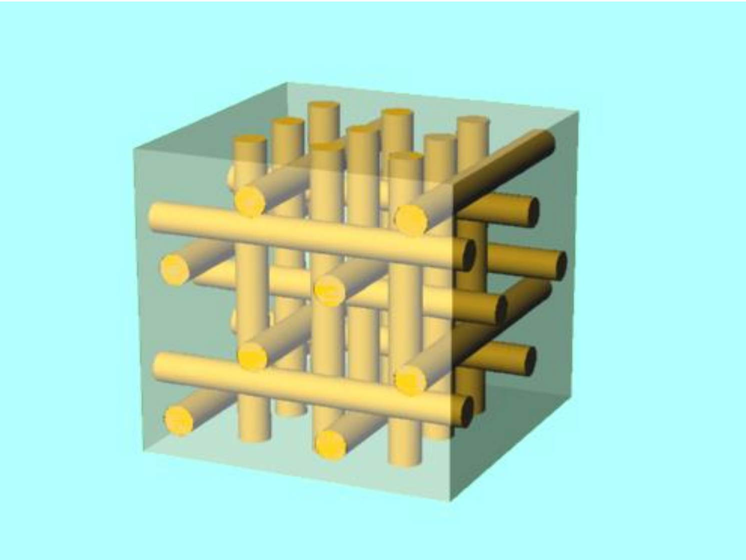
WINSTON E. KOCK†, SENIOR MEMBER, I.R.E.

velocity.[1] This same property is acquired by waves confined between conducting plates which are parallel to the electric vector and spaced apart a distance greater than one half wavelength. A row of such parallel plates accordingly constitutes a refractive medium with index of refraction less than unity. Such a medium, when cut to the proper profile, can be used to produce a focusing or lens effect in a manner similar to that of a dielectric lens.

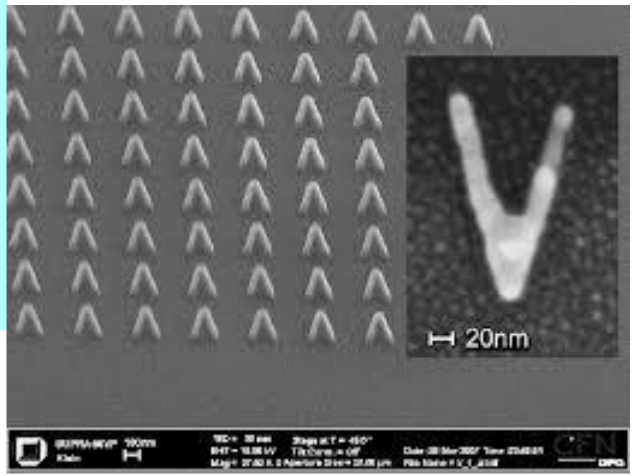


W. E. Kock, *Proc. IRE*, Vol. 34, 1946

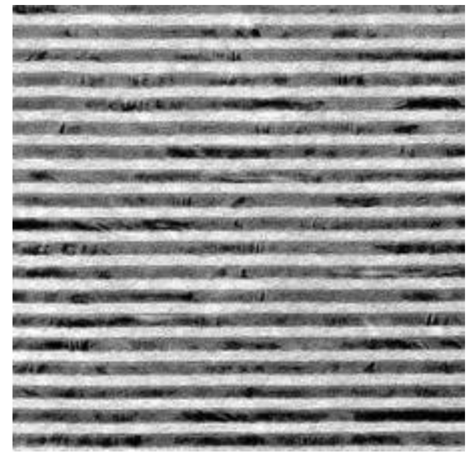
现代电谐振超材料



3D



2D



1D

磁谐振超材料

Magnetic coupling to an atom: ~ $\mu_B = e\hbar / 2m_e c = \alpha e a_0$ ***(Bohr magneton)***

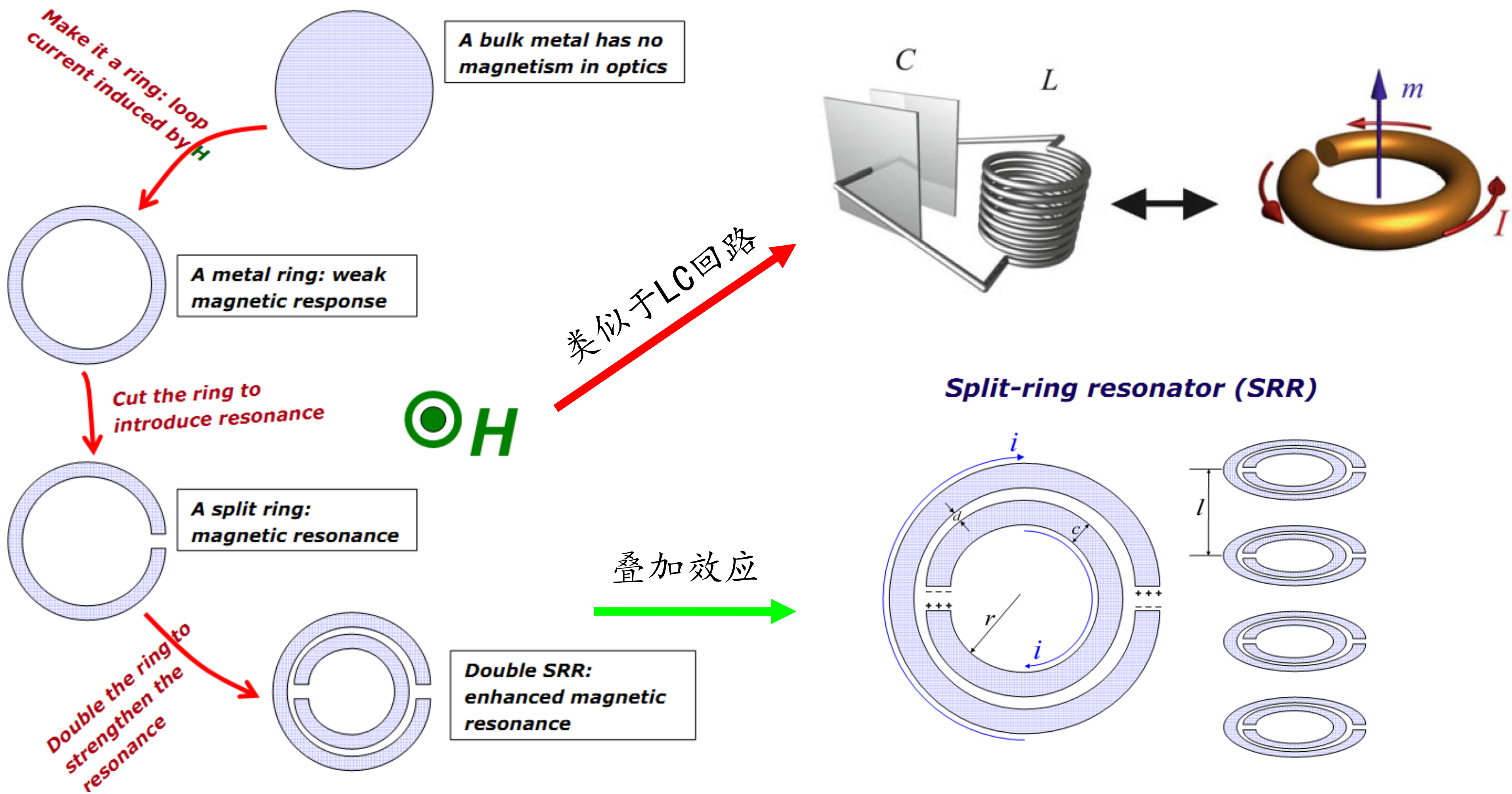
Electric coupling to an atom: ~ $e a_0$

Magnetic effect / electric effect $\approx \alpha^2 \approx (1/137)^2 < 10^{-4}$

"... the magnetic permeability μ(ω) ceases to have any physical meaning at relatively low frequencies...there is certainly no meaning in using the magnetic susceptibility from optical frequencies onwards, and in discussion of such phenomena we must put μ=1."

Landau and Lifshitz, ECM, Chapter 79.

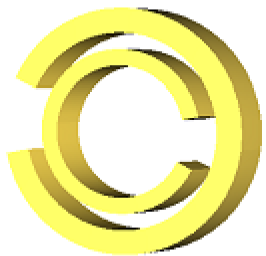
磁谐振超材料



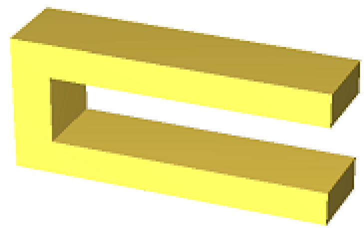
Make it a ring: loop current induced by H
A bulk metal has no magnetism in optics
A metal ring: weak magnetic response
Cut the ring to introduce resonance
A split ring: magnetic resonance
Double the ring to strengthen the resonance
Double SRR: enhanced magnetic resonance
H
类似于LC回路
C
L
m
I
叠加效应
Split-ring resonator (SRR)
i
a
c
r
l

磁谐振超材料

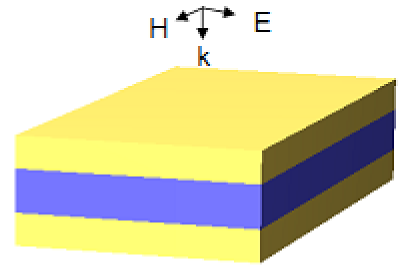
Modern magnetic units for optical metamagnetism:



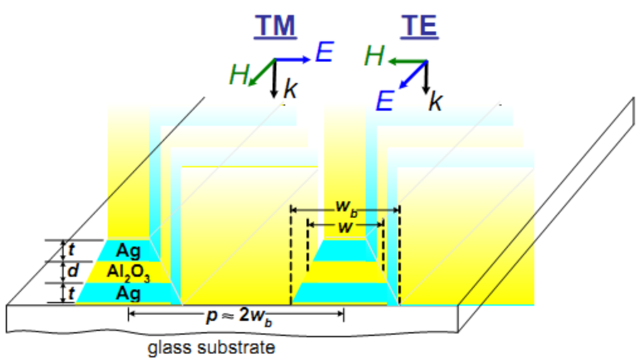
SRR



C-shaped Rod

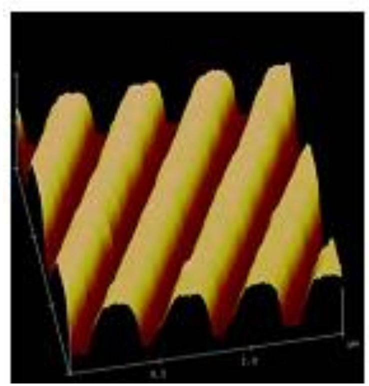


Nanostrip (or nanorod) Pair

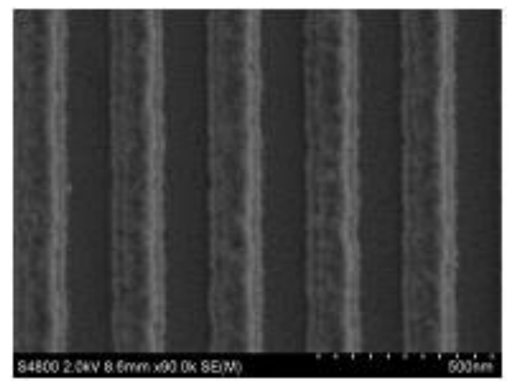


$t = 35\ nm \quad d = 40\ nm \quad p \approx 2w_b$

Visible range design



AFM image

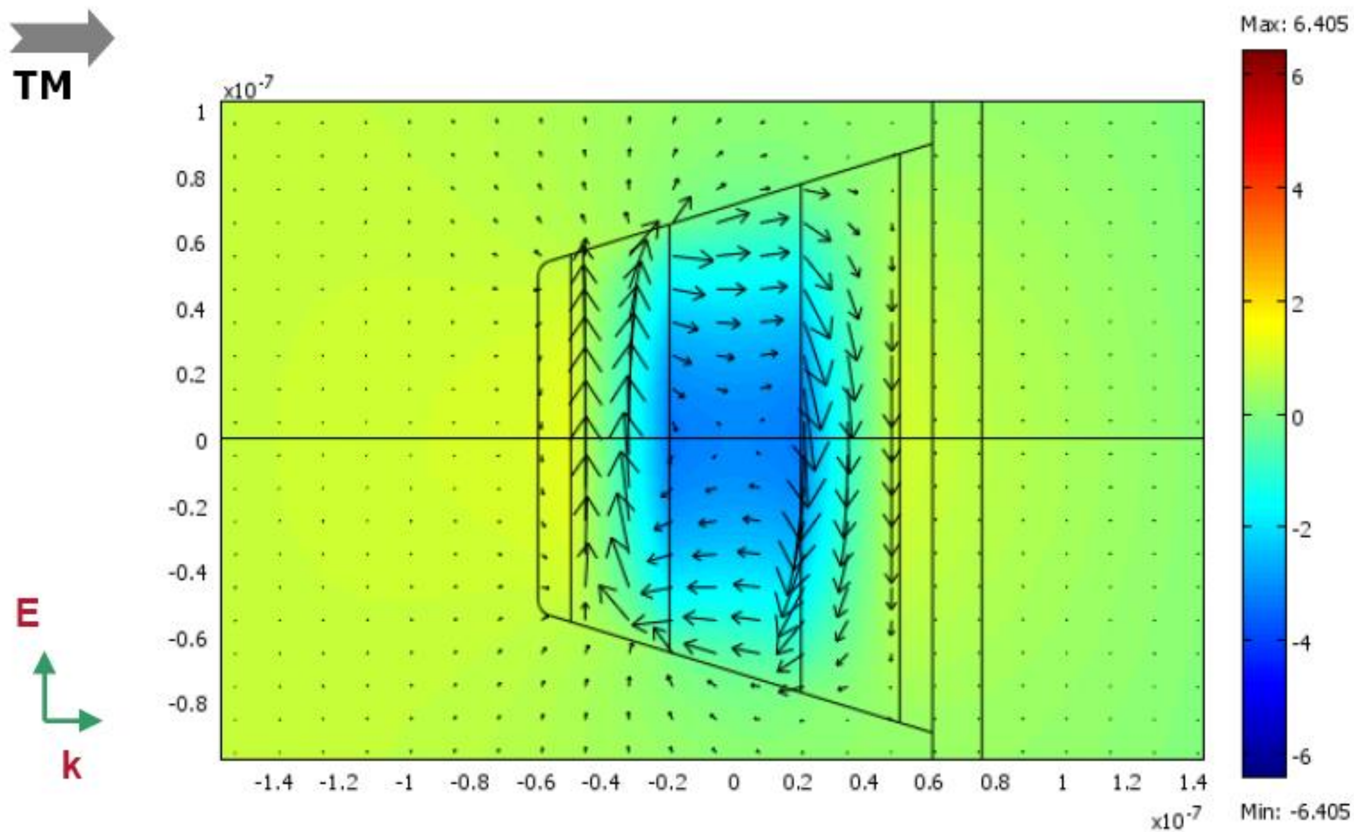


SEM image

磁谐振超材料

Magnetic field distribution: negative response

Electric displacement forms a loop and work as a magnetic dipole



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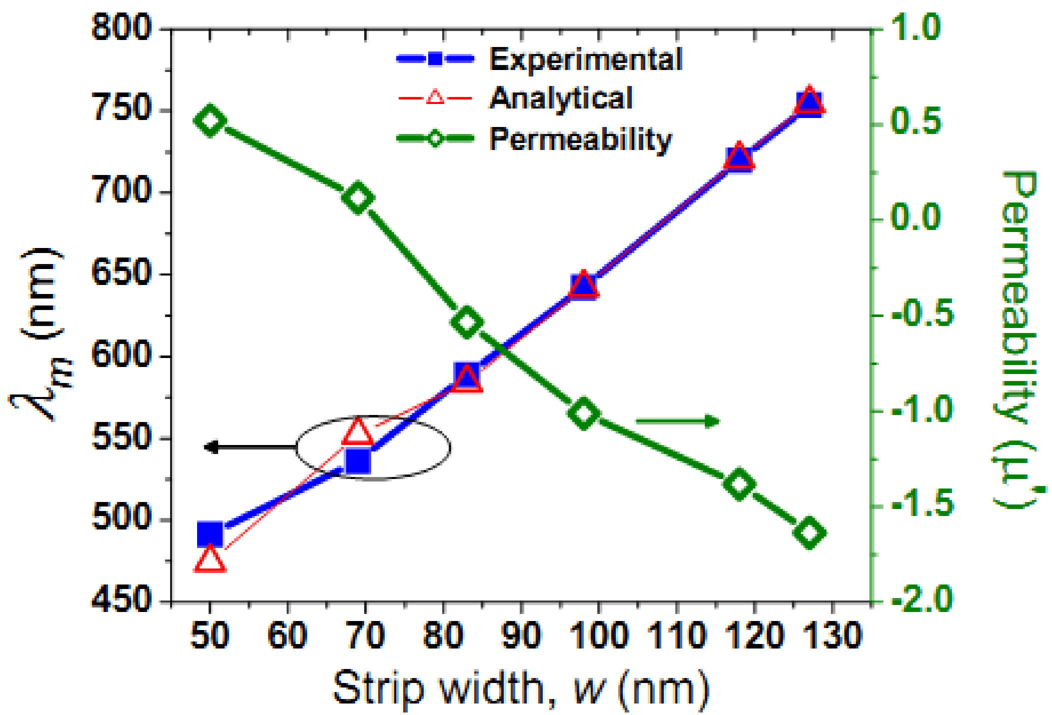
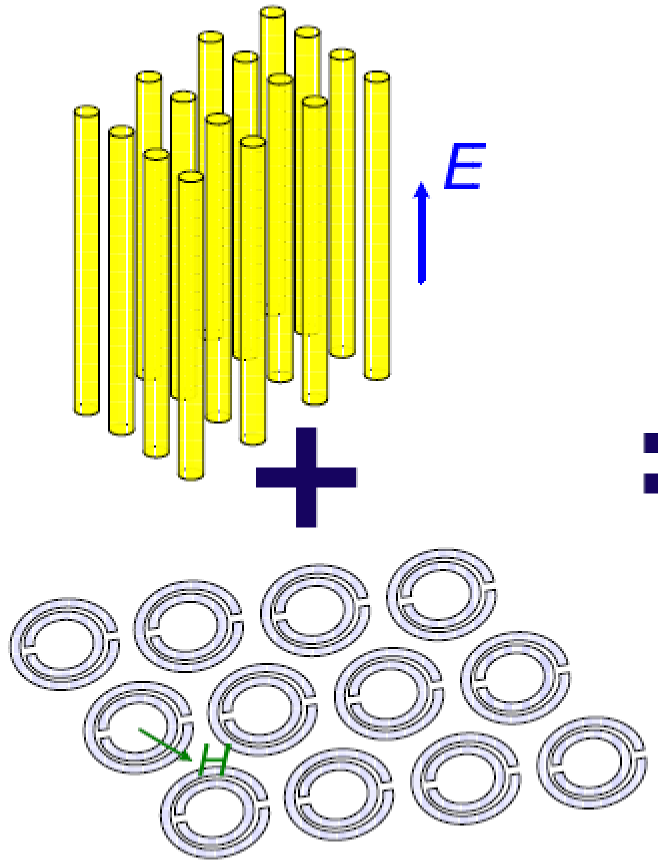


λ_m as a function of strip width "w": experiment vs. theory
Negligible saturation effect on size-scaling (as opposed to SRRs)

负折射率材料

Negative electrical metamaterial + Negative magnetic metamaterial = Negative index metamaterial



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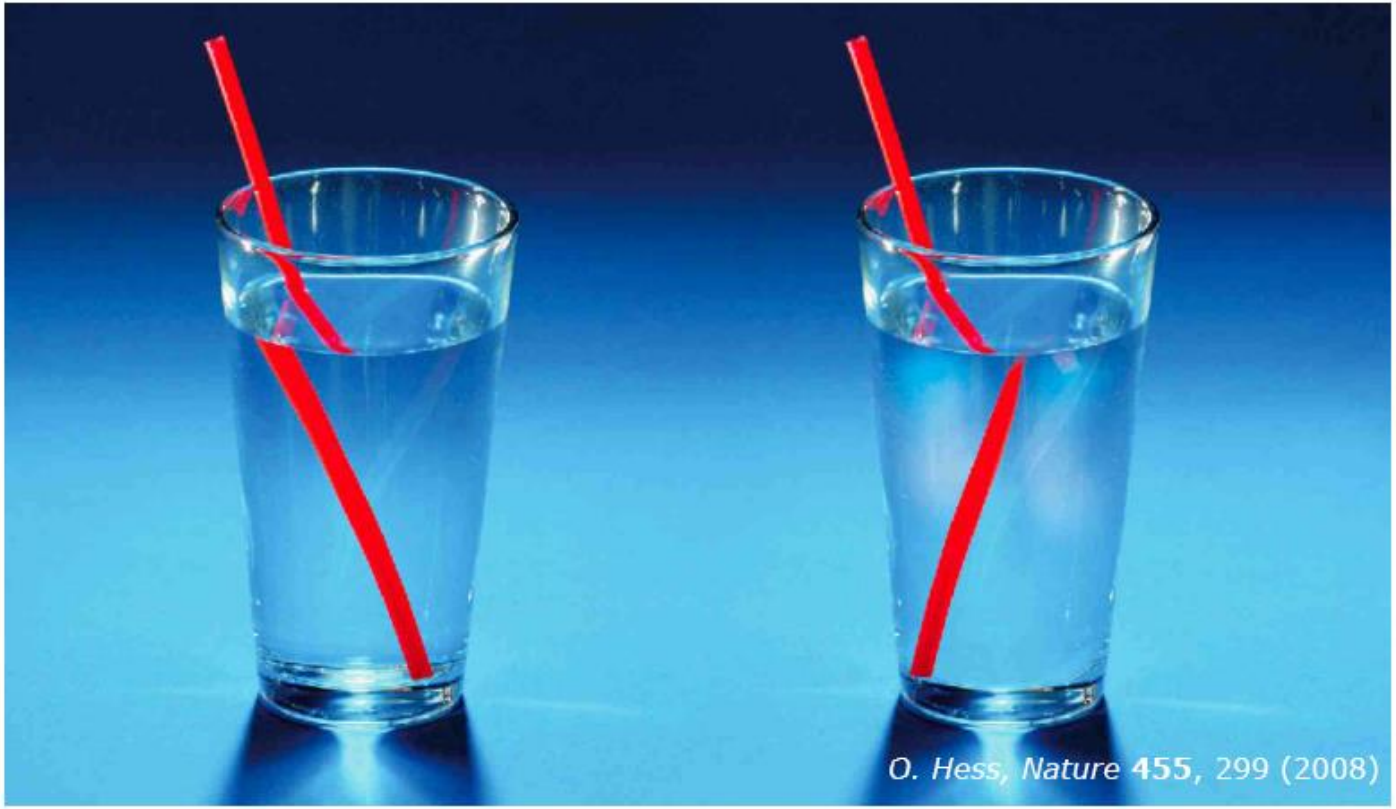
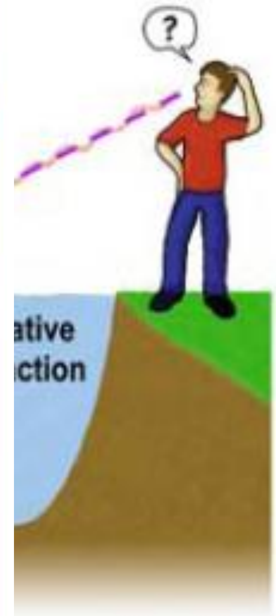
Smith, et al., UCSD, PRL (2000)

有趣现象

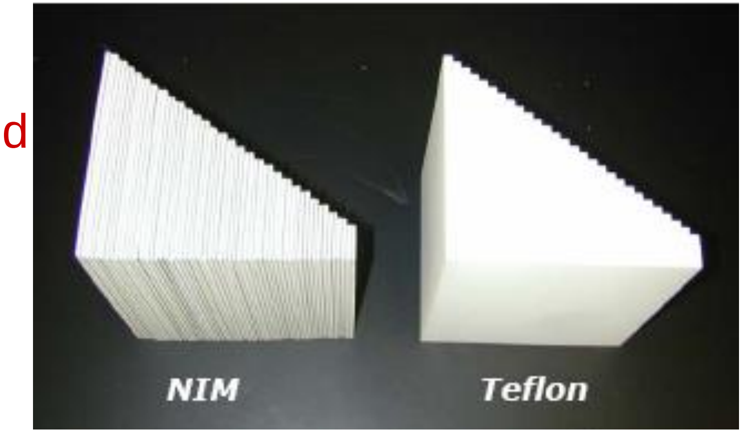




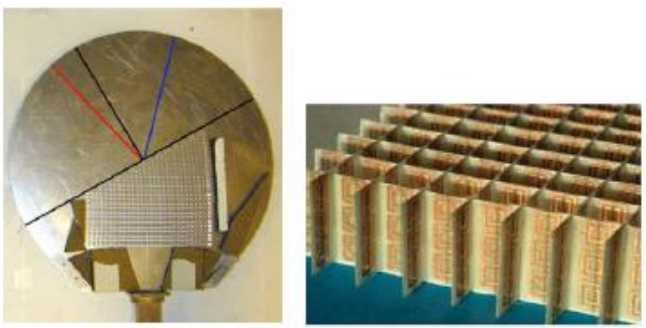
Negative Refractive effect

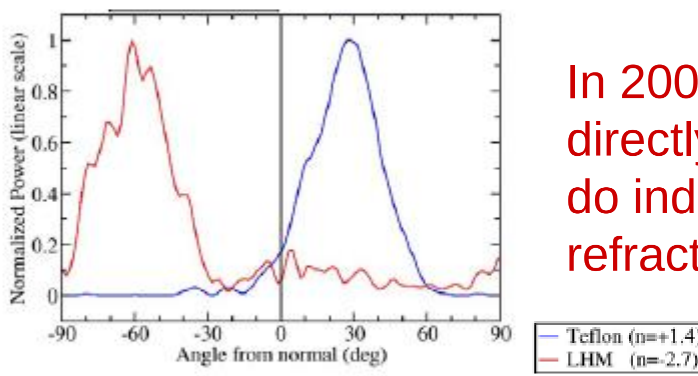
负折射率材料（微波）

In 2000, SRR structure combined + metal wire provides negative refractive index. (@5GHz)



2D waveguide



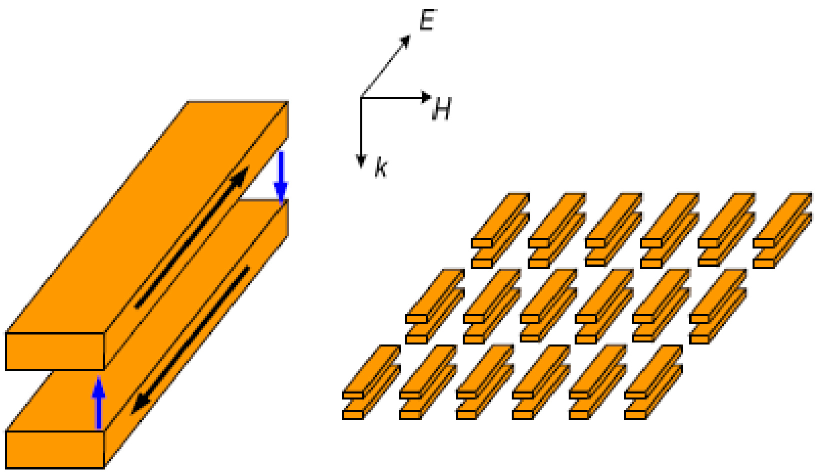


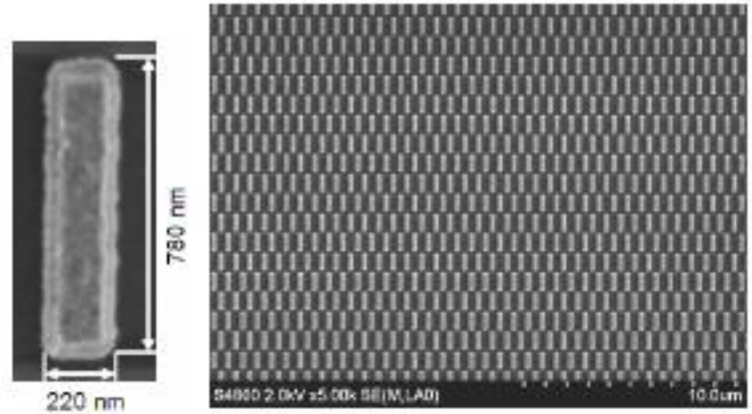
In 2001, experiments directly confirm that LHMs do indeed exhibit negative refraction.(@10.5GHz)

Smith, et al., UCSD, PRL (2000)
Shelby， et al., UCSD, Science (2001)

负折射率材料（光波）

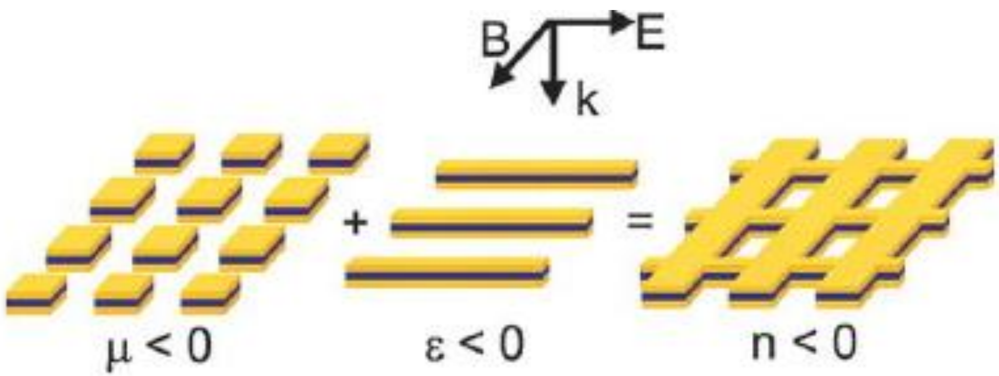
Nanorod arrays support both electrical and magnetic resonances （@1.5um）

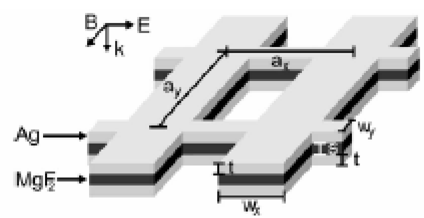


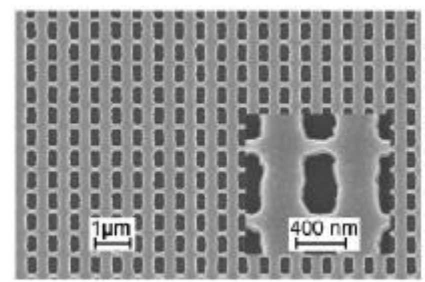


SEM

Nano-plate pairs + thin metal wire pairs = “optical fishnet” (@500nm-2um)

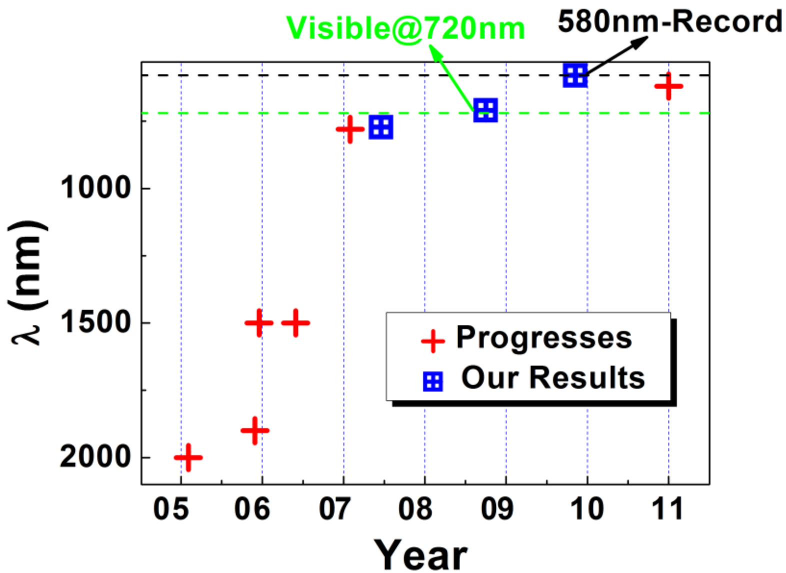




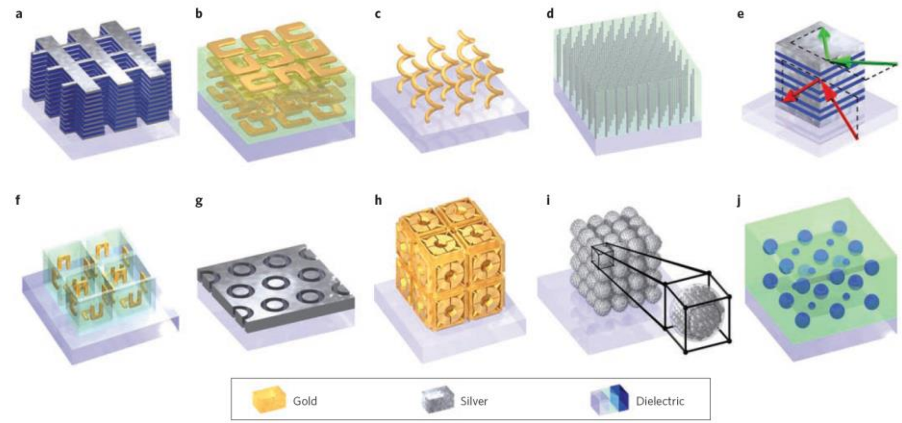


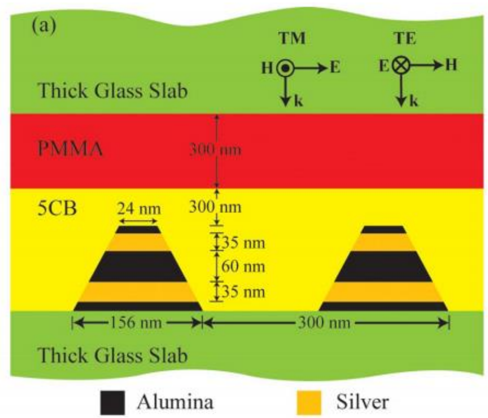
负折射率材料发展现况

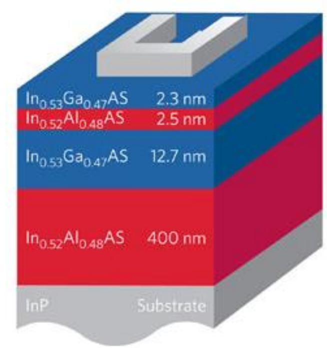
1. Wavelength goes down to visible.



2. Structure goes up to 3D







3. Tunable and loss free is realized.

Outlines

一、超材料

二、负折射率超材料

三、超透镜

-超透镜的原理

-实验和拓展

四、完美隐身

五、超构表面

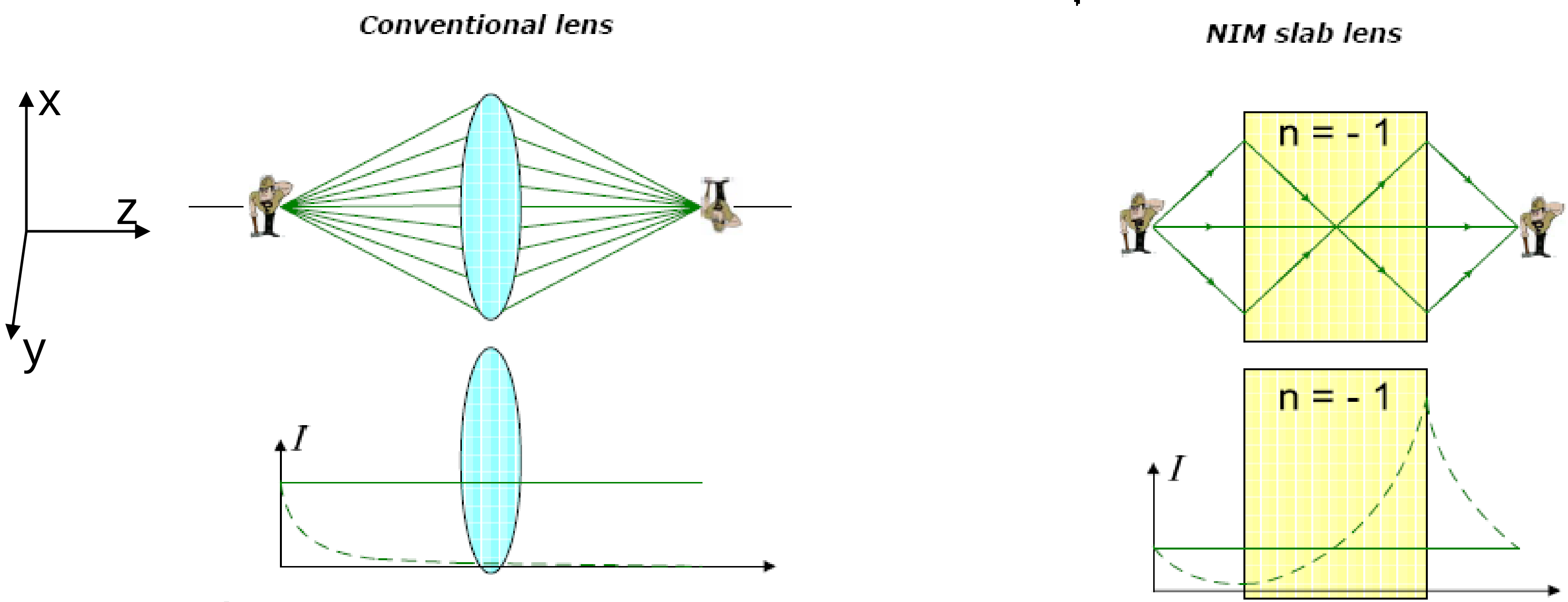
六、超材料未来研究方向

超透镜的原理

Waves scattered by an object have all the Fourier components： $k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}$

The propagating waves are limited to: $k_t = \sqrt{k_x^2 + k_y^2} < k_0 \quad \Rightarrow \quad \Delta > (\lambda_t = \frac{2\pi}{k_t}) > (\frac{2\pi}{k_0} = \lambda)$

To resolve features Δ, we must have ： $\Delta < \lambda \Rightarrow k_t = \sqrt{k_x^2 + k_y^2} > k_0 \Rightarrow k_z^2 < 0$



$E = E_0 e^{ink_z z}$

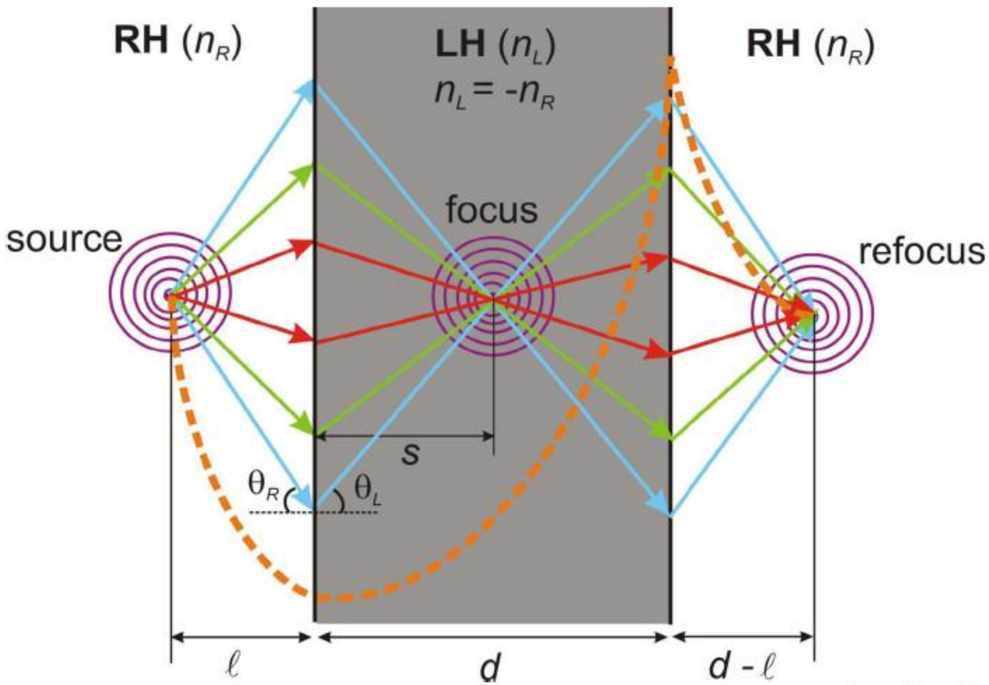
Propagating waves

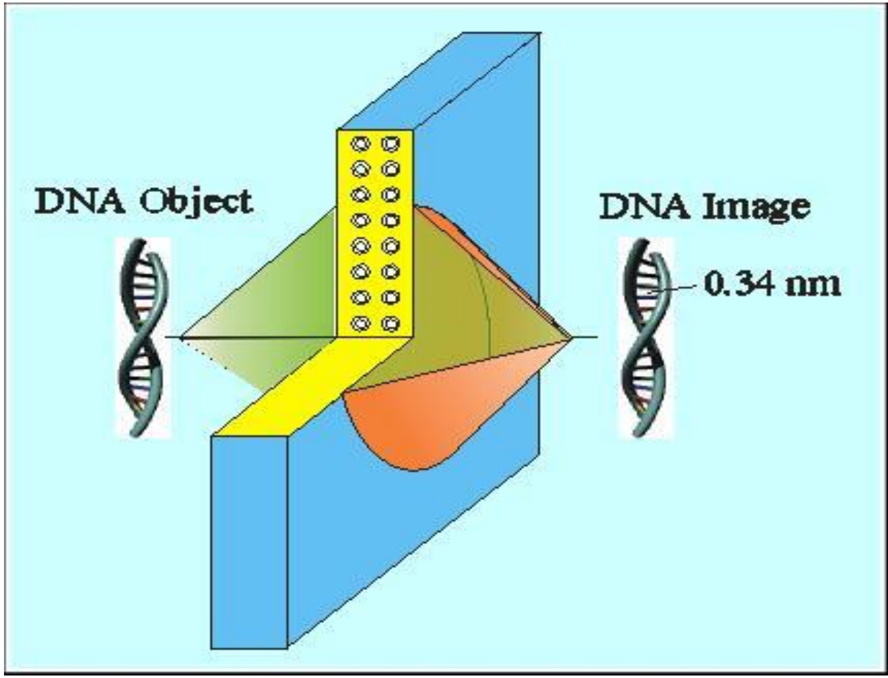
Evanescent waves

Pendry, PRL, 2000

超透镜的工作方式

$$E = E_0 e^{ink_z z}$$



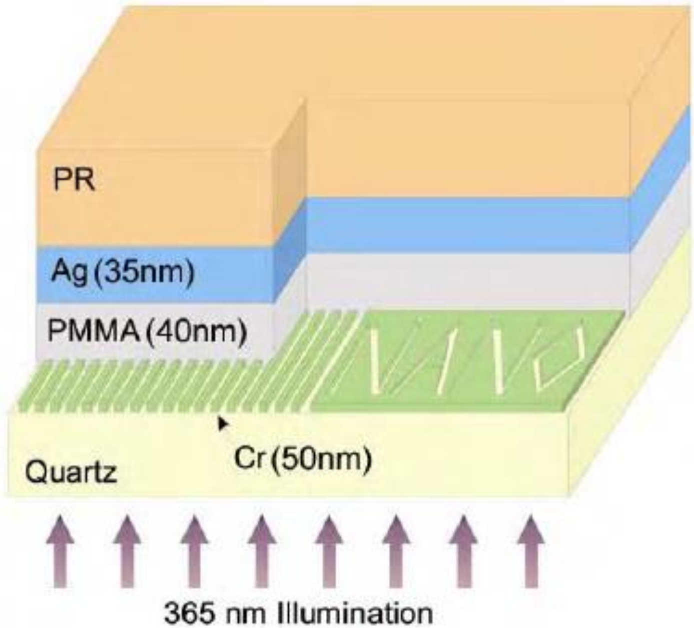


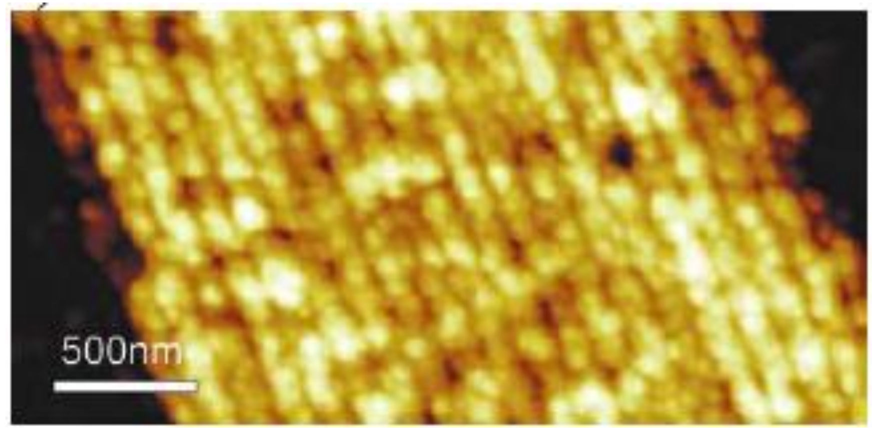
O. Hess, University of Surrey

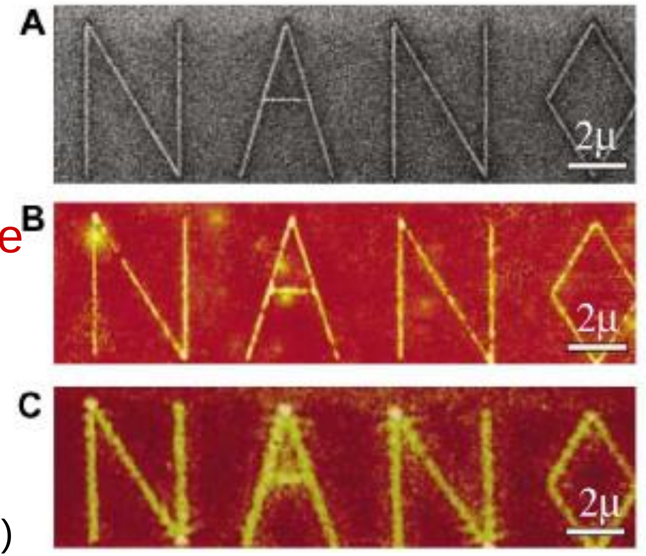
Amplification of Evanescent Waves Enables sub-λImage

This has led to the desire to view live biological cell interactions in a real time, natural environment, and the need for subwavelength imaging.

超透镜的实验实现





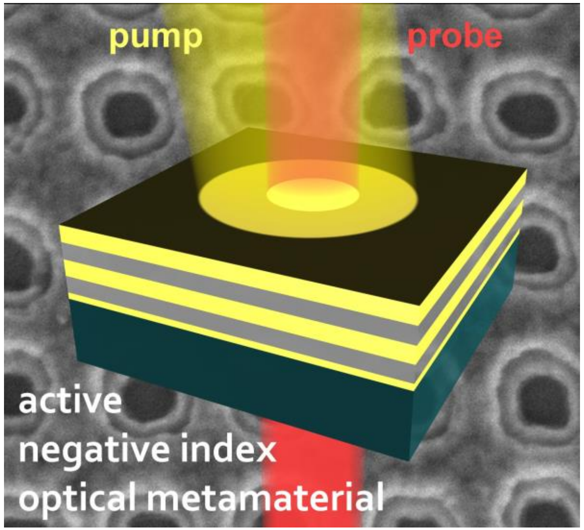


Left: An array of 60nm wide slots of 120nm pitch. The image is recorded in the photoresist placed on another side of silver superlens.

Right: Atomic force microscopy of a developed image. Superlens imaging of a 60 nm object (λ/6).

N. Fang *et al*., Science (2005)

低损耗超透镜的实现和应用

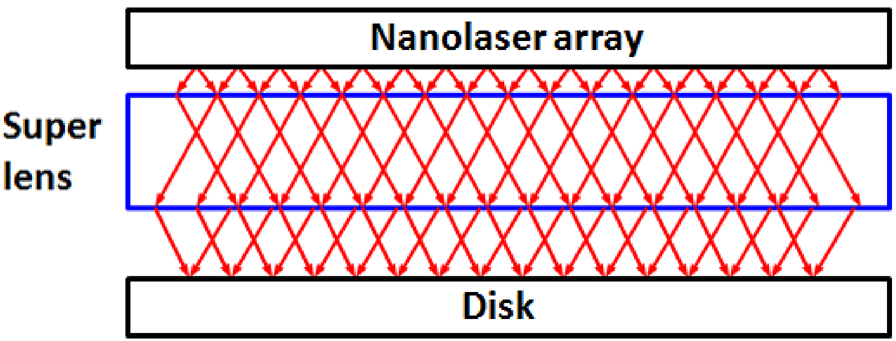


Surface Roughness and loss are two big issues.

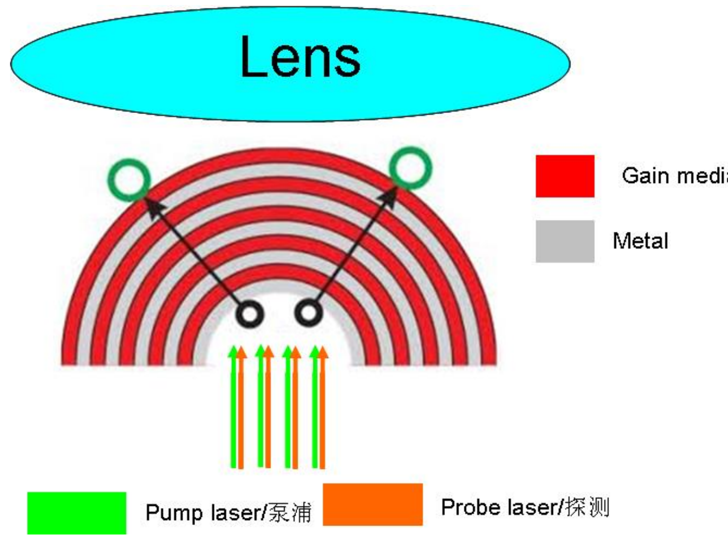
Gain media is used to compensate the loss of metal.

The resolution can be reduced to $\lambda/50$.

Can be used for sensing and data storage.



Optical storage device design



Diagnosis for pathological changes

Outlines

一、超材料

二、负折射率超材料

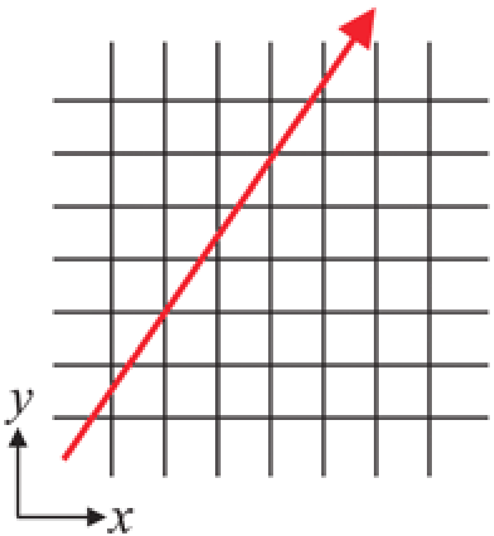
三、超透镜

四、完美隐身

五、超构表面

六、超材料未来研究方向

变换光学



Straight field line in Cartesian coordinate

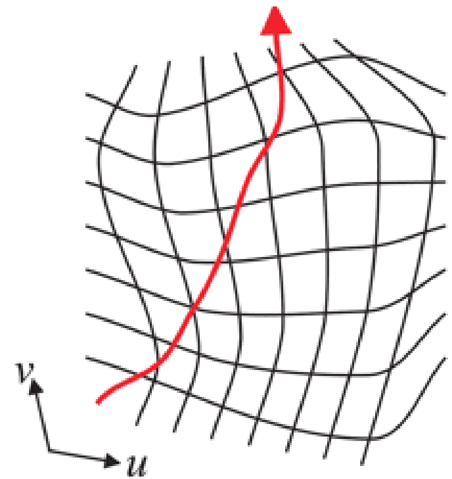
Fermat:

$\delta \int n\,dl = 0$

$n = \sqrt{\varepsilon(r)\,\mu(r)}$

"curving"

optical space



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

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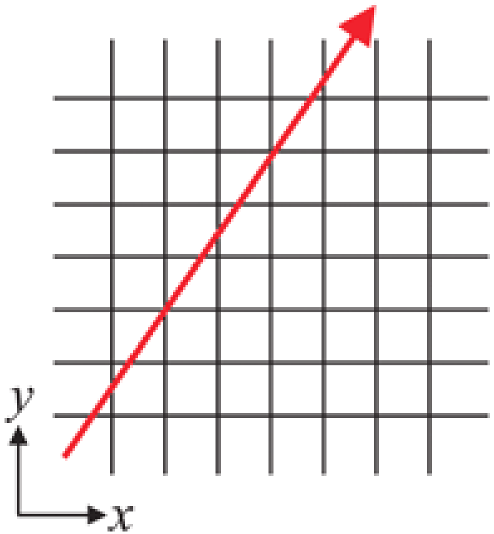
变换光学

C (x, y, z) 虚空间



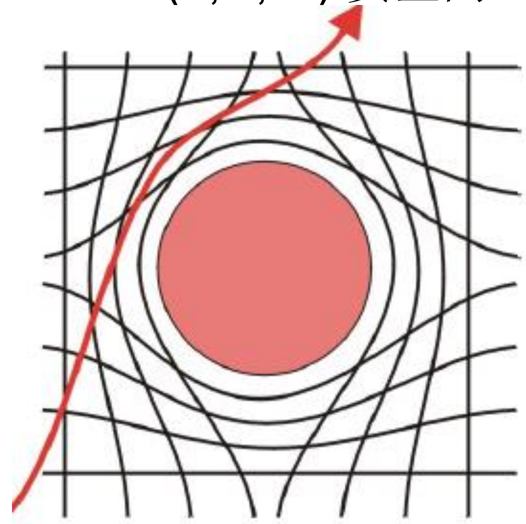
黎曼度量

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

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

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

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

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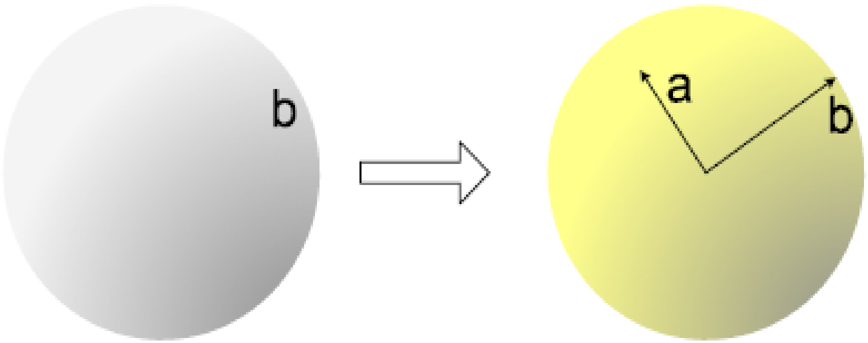
实验实现（微波）

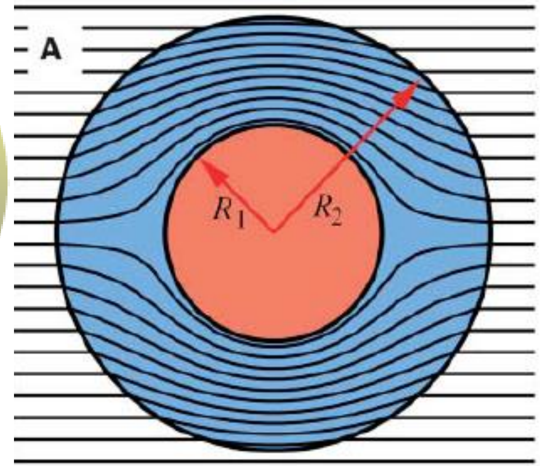


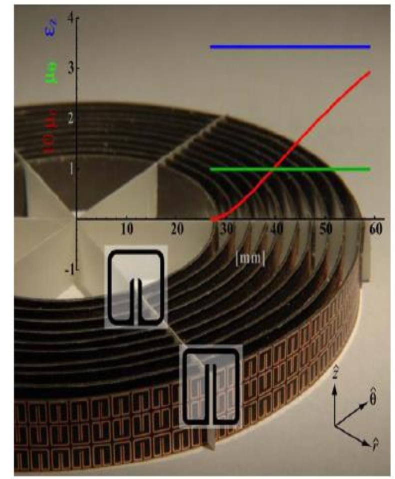
The coordinate transformation that compresses a cylindrical region b into a concentric cylindrical shell a <r<b.

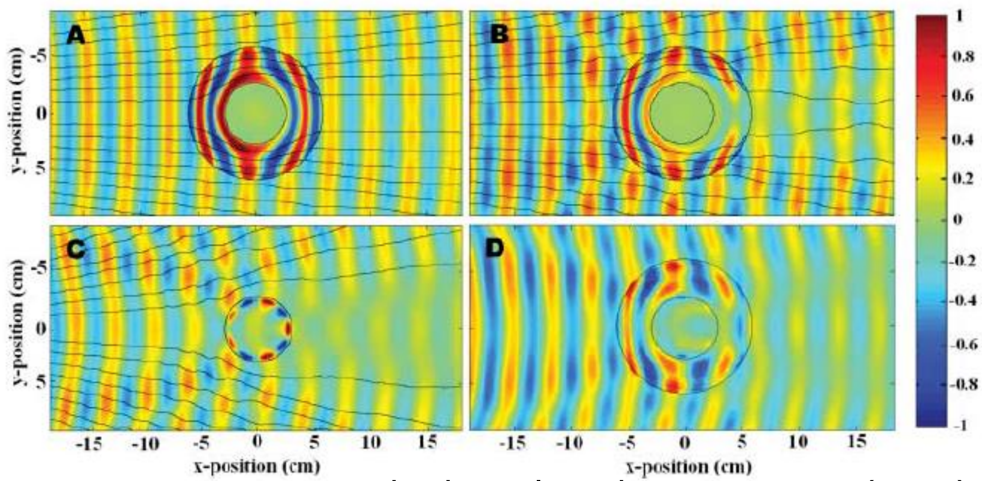
$$0 < r < b \longrightarrow a < r' < b$$

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

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

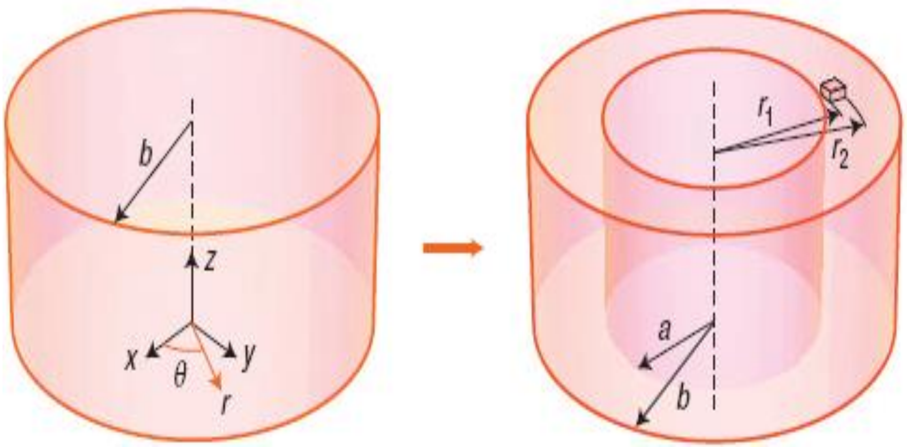






D. Schuriget al., Science Express (2006)

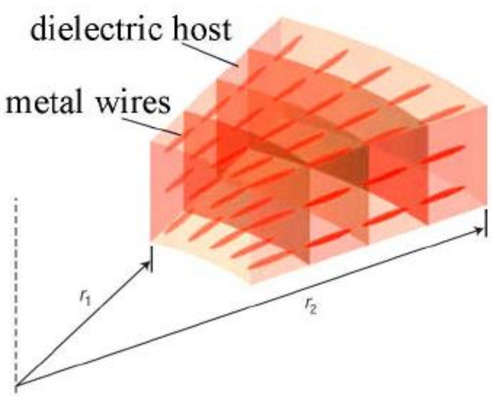
光学隐身的实现

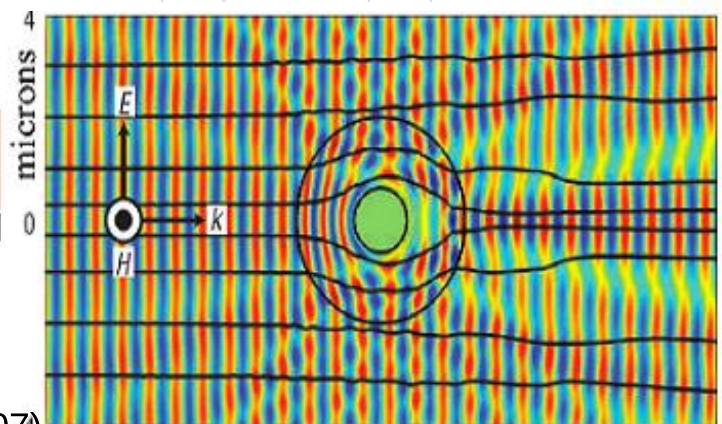


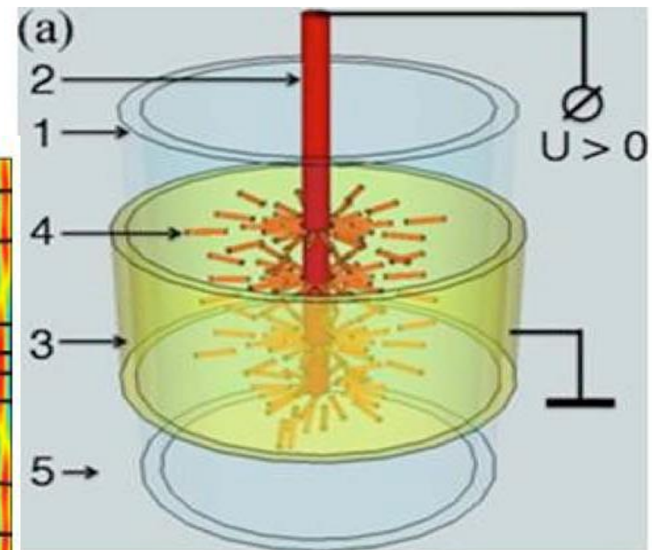
Metallic wires oriented along the radii provide the necessary graded refractive index.

A dispersion of gold Au nanorods in an isotropic dielectric fluid can achieve tunable effect.

$$\mu_z = 1, \quad \varepsilon_\theta = \left(\frac{b}{b-a}\right)^2, \quad \varepsilon_r = \left(\frac{b}{b-a}\right)^2 \left(\frac{r-a}{r}\right)^2$$



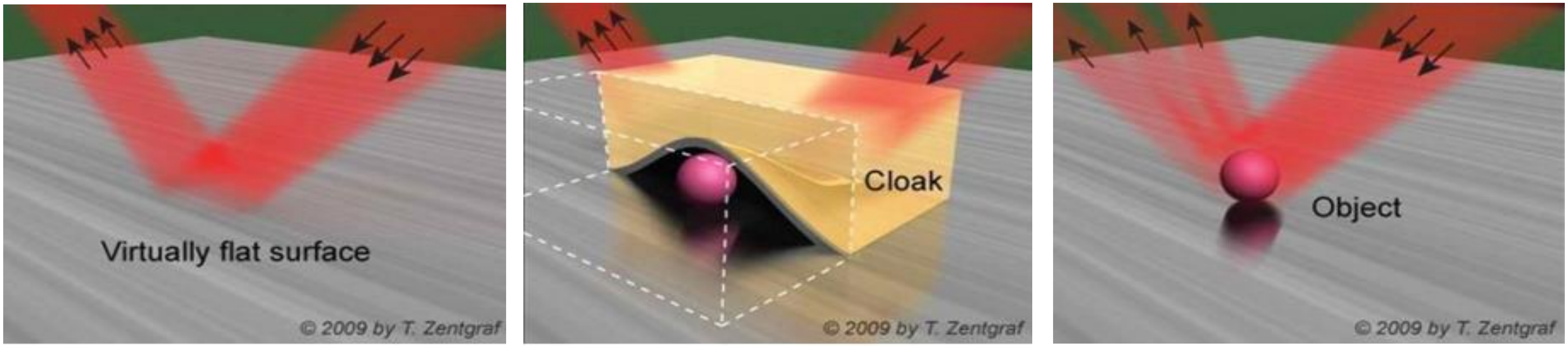




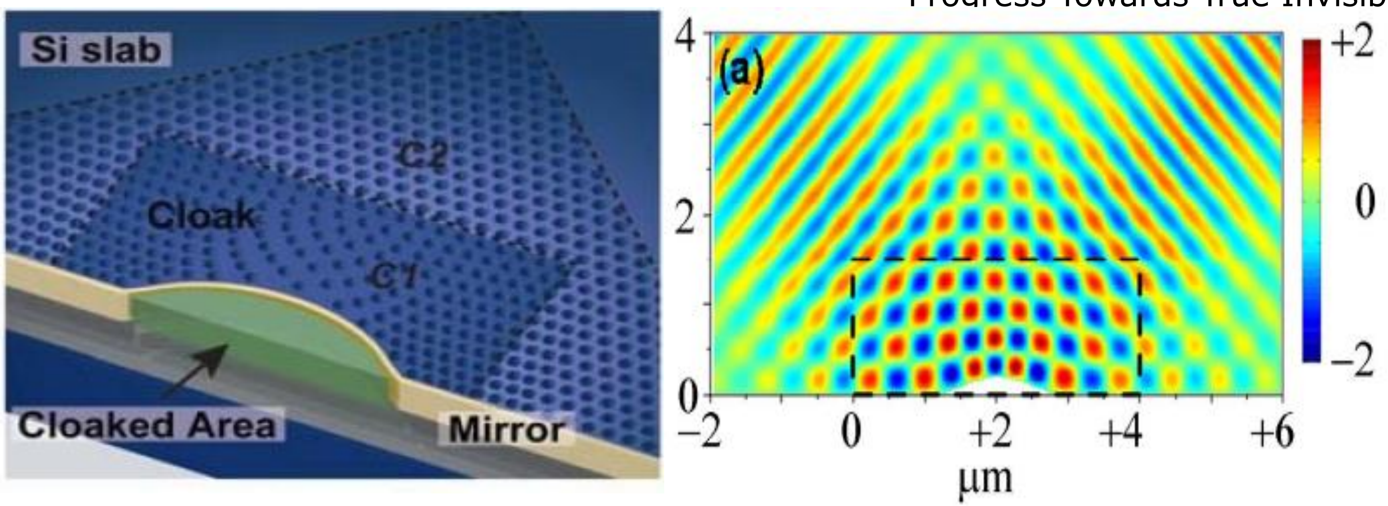
W. Cai *et al*., Nature Photonics (2007)

Golovin *et al*., Applied Physics Letter (2009)

地毯式隐身



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

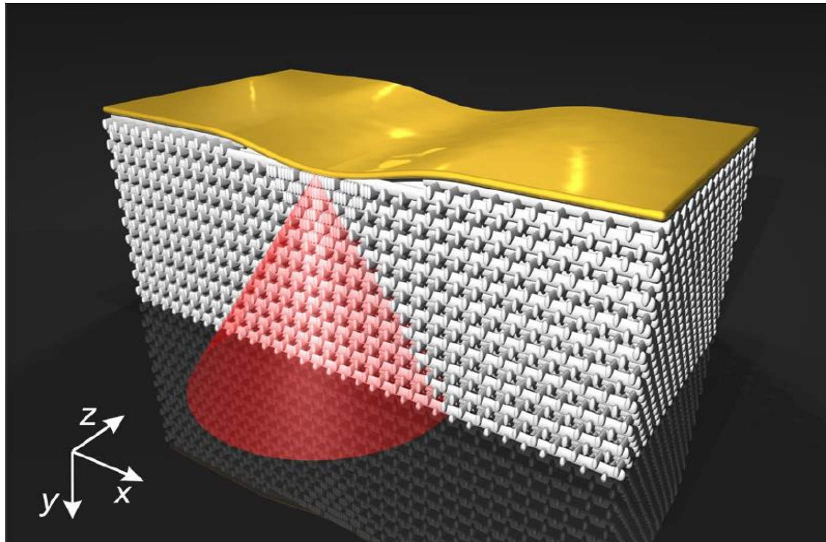


C1 is the gradient index cloak and C2 is a uniform index background.
The cloak will transform the shape of the bump back into a virtually flat object.

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

三维光学隐身

Operation wavelength:
1.4 μm to 2.7 μm
Viewing angle: 60 degrees

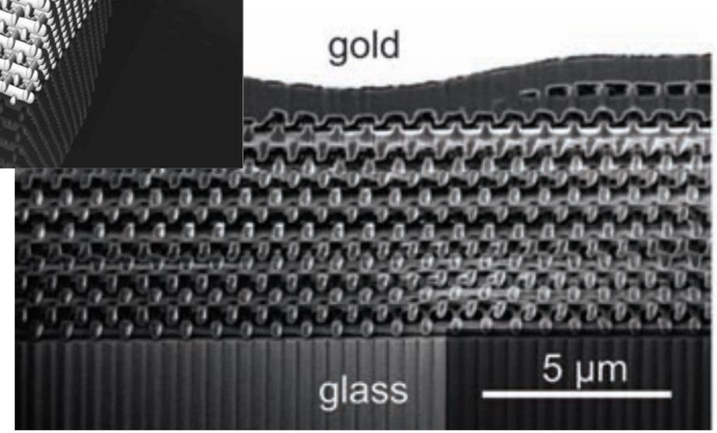


Bump:

$$y(x) = h\cos^2(\pi x / w)$$

for $|x| \le w/2$

height of the bump : h=1 μm
full width of the bump: w=13 μm



Cloak:
26 μm in x direction
10 μm in y direction

Inside the cloaking, the local effective refractive index is controlled by the volume filling fraction of polymer.

Tolga Ergin et al (Wegener group)., Science express 2010

光学幻象技术

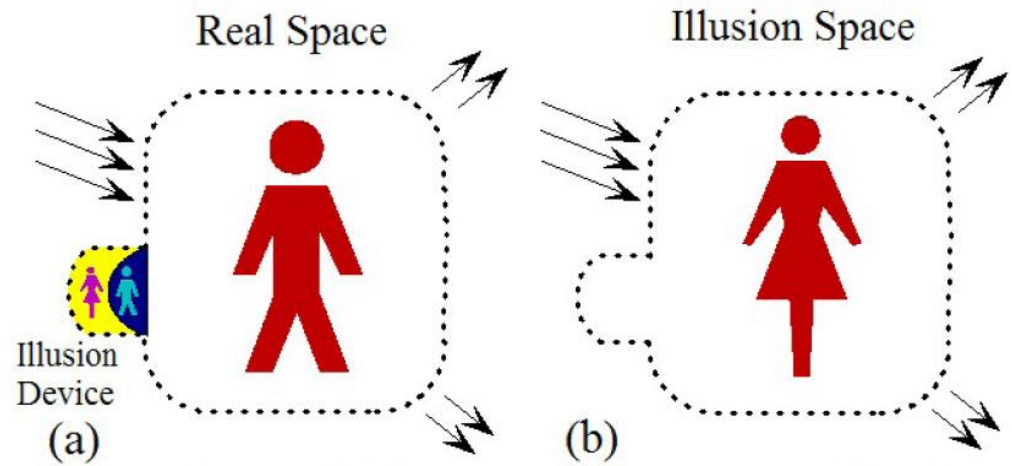
Illusion device can remotely change the optical response

region 1
restoring medium

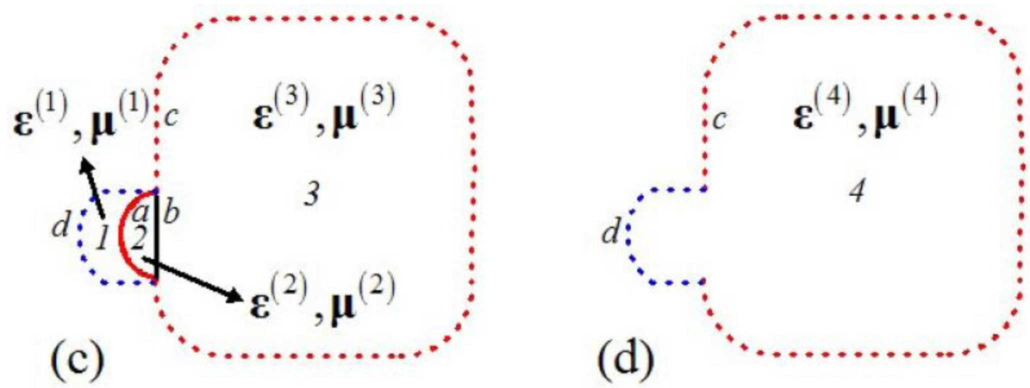
region 2
complementary medium

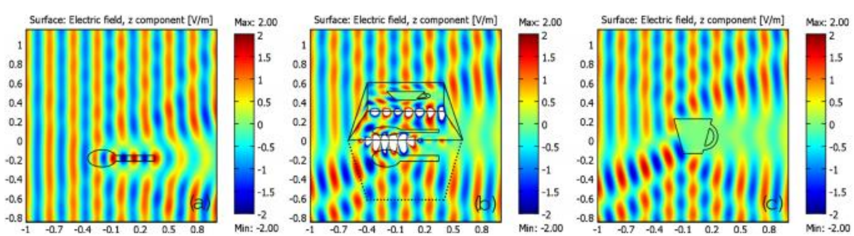
region 3
folding region including the man

region 4
compressing region including the woman



a man (object)   a woman (illusion)





Yun Lai et al., PRL(2009)

实际应用例子

Allows:

- Invisibility cloaks (隐身斗篷)
- Stealth paint on planes（隐身飞机涂料）
- See through gloves for surgeons（帮助外科手术）
- Take away blind spots for drivers in cars （扫除汽车视线盲点）
- Virtually anything in the military ranging from clothes for soldiers to invisible planes（光学幻象机）

A person wearing a real "invisibility cloak" made of metamaterials

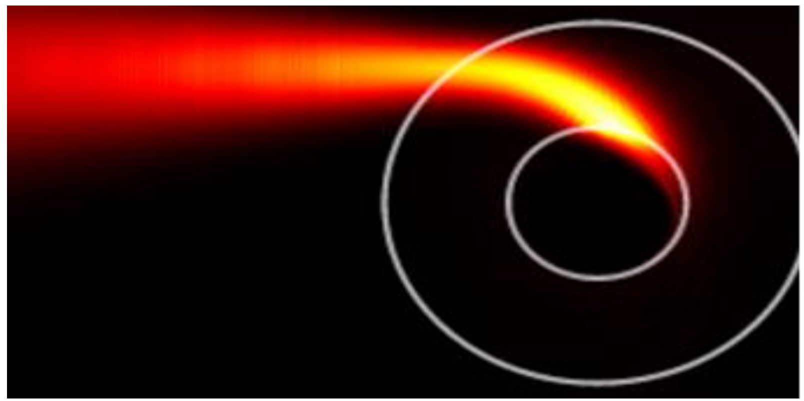
The type of plane that would benefit from metamaterial cloaking; stealth attacks and landing would be much easier and safer.

变换光学的应用

Fermat: $\delta \int n dl = 0$

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

curving optical space

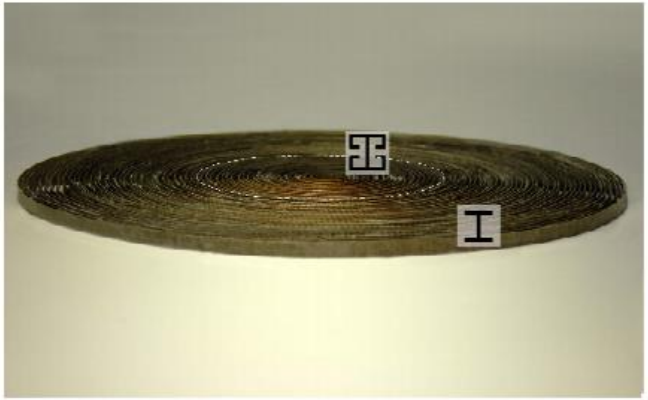


Light Concentrator
(also, Schurig et al)

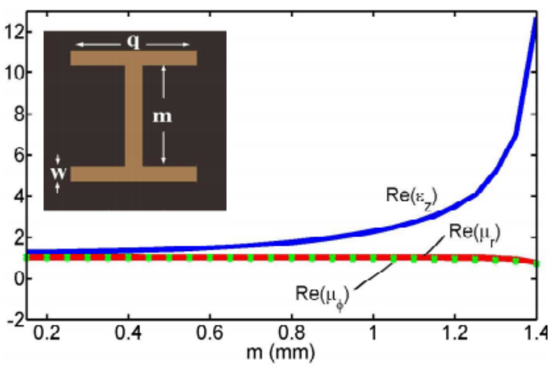
Optical Black Hole
(Zhang group; Narimanov,Kildishev)

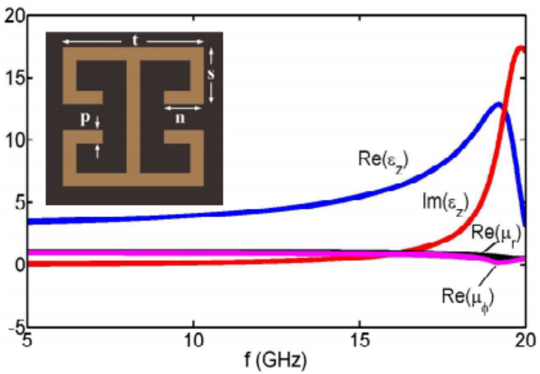
R=20μm, Rc=8.4μm, λ=1.5 μm

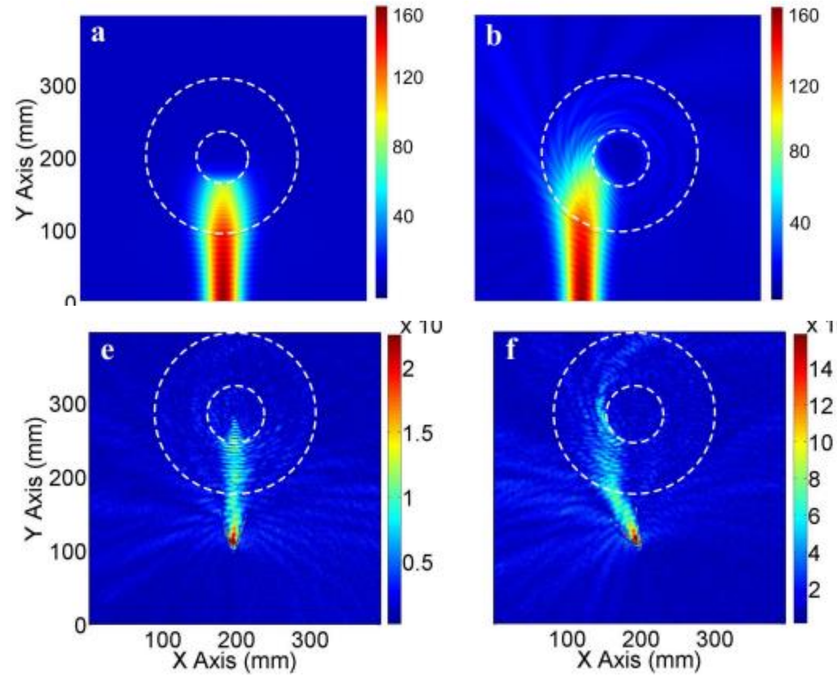
黑洞的实现（微波）



Lossy circular inner core—ELC resonator (20 layers)
Lossless circular shell—I-shaped metamaterials (40 layers)







Gaussian beam :Absorbing rate 99.94%, 98.72%

Other sources also can work!

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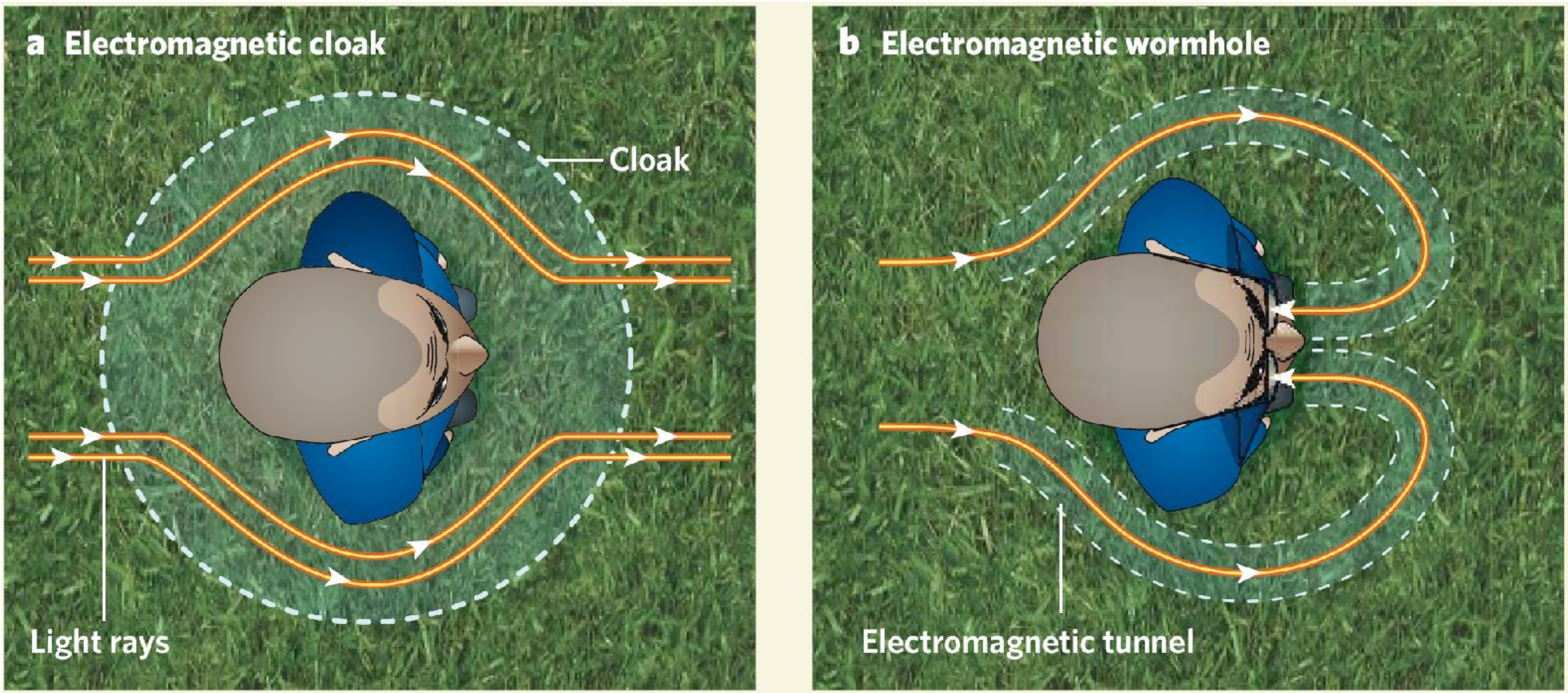
变换光学的应用-电磁虫洞

Watching your back !! ➡ 眼观六路，耳听八方！！



Greenleaf et al., PRL(2007)

Outlines

最小作用量原理

Pierre Louis Maupertuis (1698-1759)

Maupertuis felt that “Nature is thrifty in all its actions”, and applied the principle broadly:

“The laws of movement and of rest deduced from this principle being precisely the same as those observed in nature, we can admire the application of it to all phenomena. The movement of animals, the vegetative growth of plants are only its consequences …”

莫佩尔蒂于1744年发表了最小作用量原理。这原理阐明，对于所有的自然现象，作用量趋向于最小值。他定义作用量为物体的质量，移动距离，与移动速度的乘积。同年他又指出光选择的传播路径，作用量最小。他定义作用量为移动速度与移动距离的乘积。

欧拉公式

Leonhard Euler (1707-1783)

The action functional from point A to point B is

$$S_0 = \int_A^B \mathbf{p} \cdot \mathrm{d}\mathbf{q}$$

where **p** is the momentum, and **q** is the coordinate.

From the *principle of least action* the true path of a system from point A to point B is a **stationary point** of the functional.

It works for any physical system!

最小作用原理→费马最小光程原理

"Fermat's principle applied to phase waves is identical to Maupertuis' principle applied to the moving body; the possible dynamic trajectories of the moving body are identical to the possible rays of the wave."

Pierre de Fermat

Maupertuis' principle

$$\delta S_0 = \delta \int_A^B \mathbf{p} \cdot \mathrm{d}\mathbf{q} = 0$$

Fermat's principle

$$\delta \Phi = \delta \int_A^B \mathbf{k} \cdot \mathrm{dl} = 0 \rightarrow \delta \int_A^B \mathrm{dl} \cdot \mathbf{n} = 0$$

p = ħ**k**

$$\int_A^B d\varphi = 0$$

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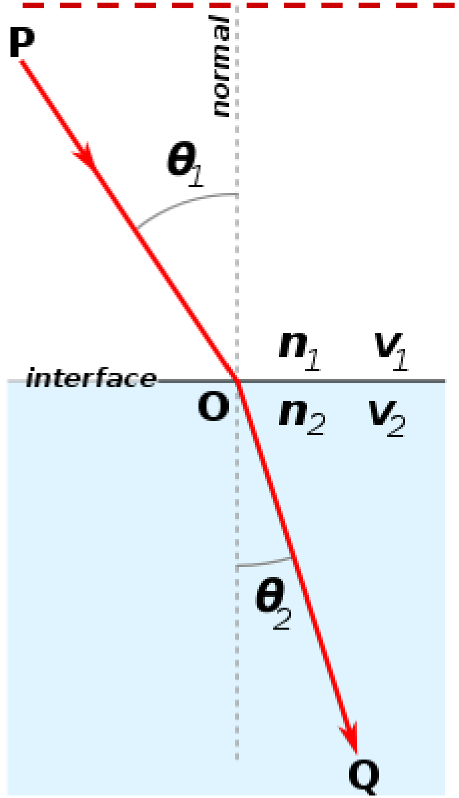
Snell 定理



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

折射光和入射光没有相位的突变。

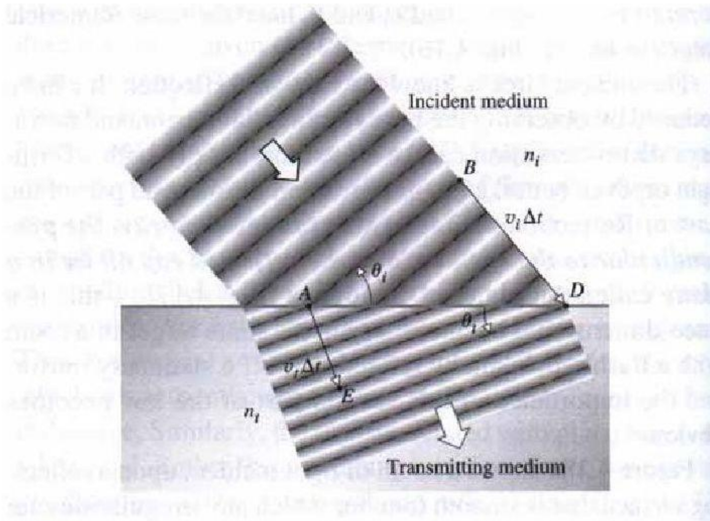
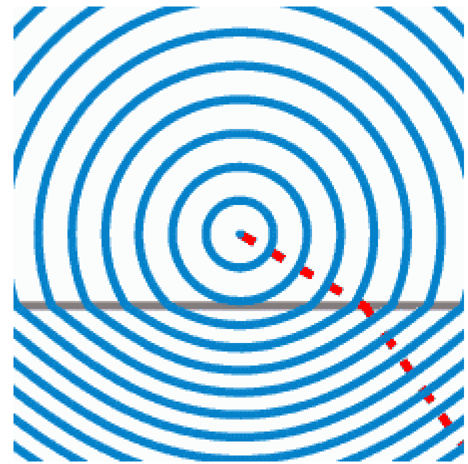


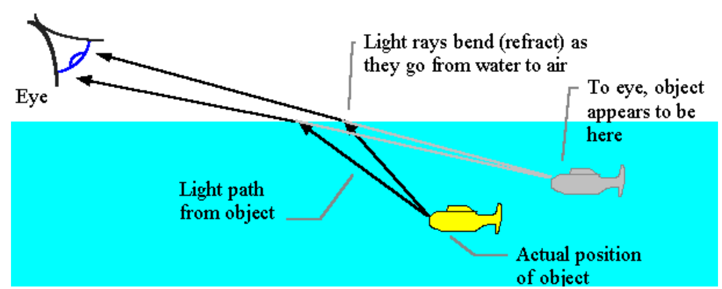
Figure 4.19 The refraction of waves. The atoms in the region of the surface of the transmitting medium reradiate wavelets that combine constructively to form a refracted beam.

折射不会改变平面光的波前形状，所以不会聚焦。

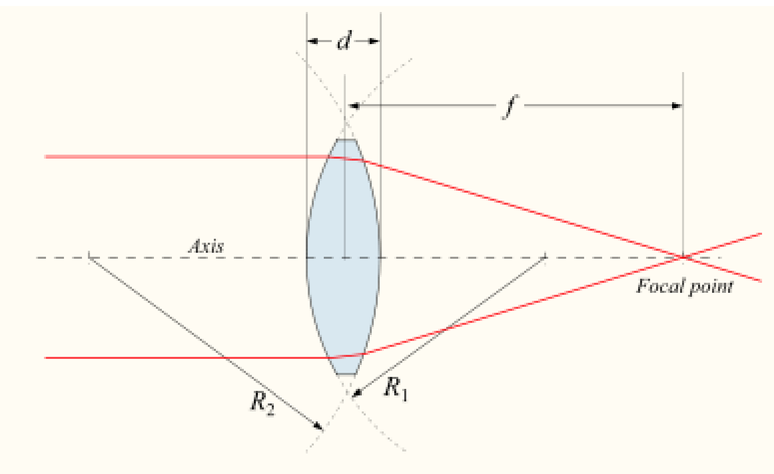


折射不会改变点光源发出光的波前形状，所以不会成像

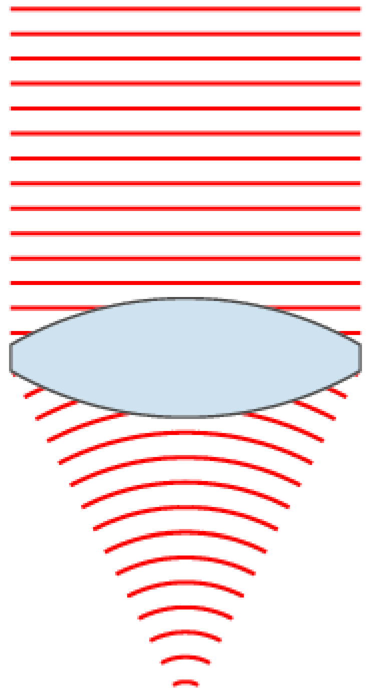
Refraction at Surface of Water



透镜

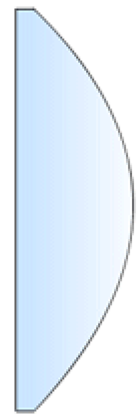


Positive (converging) lens



通常用的透镜厚度比较厚，一方面比较重，应用不方便，另外对于数值孔径比较大的透镜，由于边缘和中心位置厚度的差别比较大，会出现严重的像差。虽然利用菲涅尔透镜虽然解决了这些问题，但是这种镜子制备非常麻烦

这是普通凸透镜



Fresnel lens

为了使平行光线在通过界面时折射角能发生变化，引进了弯曲的表面，也就是透镜，同时也改变了光的波前。

广义（Generalized） Snell's Law

$$\int_A^B d\varphi = 0$$

$$[k_o n_i \sin(\theta_i) dx + (\Phi + d\Phi)] - [k_o n_t \sin(\theta_t) dx + \Phi] = 0$$

For reflection

$$\sin\theta_r - \sin\theta_i = n_i^{-1} k_0^{-1} \nabla\Phi$$

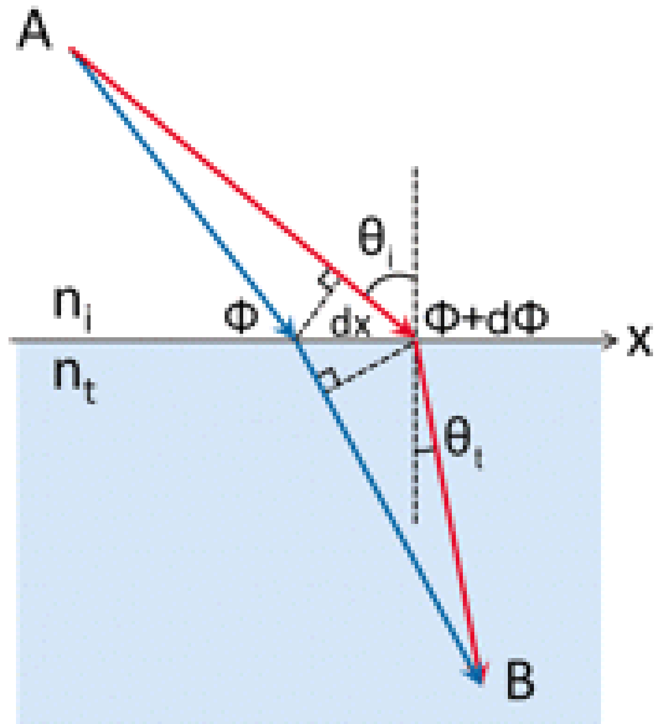
For refraction

$$n_t \sin\theta_t - n_i \sin\theta_i = k_0^{-1} \nabla\Phi$$

$$\theta_c = \arcsin\left(\pm\frac{n_t}{n_i} - \frac{\lambda_o}{2\pi n_i}\frac{d\Phi}{dx}\right)$$

$$\theta_c' = \arcsin\left(1 - \frac{\lambda_o}{2\pi n_i}\left|\frac{d\Phi}{dx}\right|\right)$$

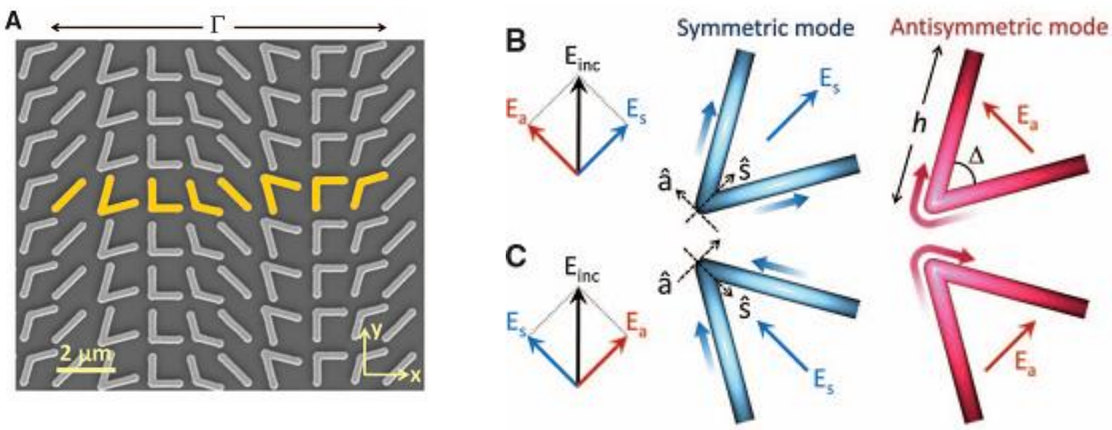
Principle of least action → The momenta difference between blue and red path is zero



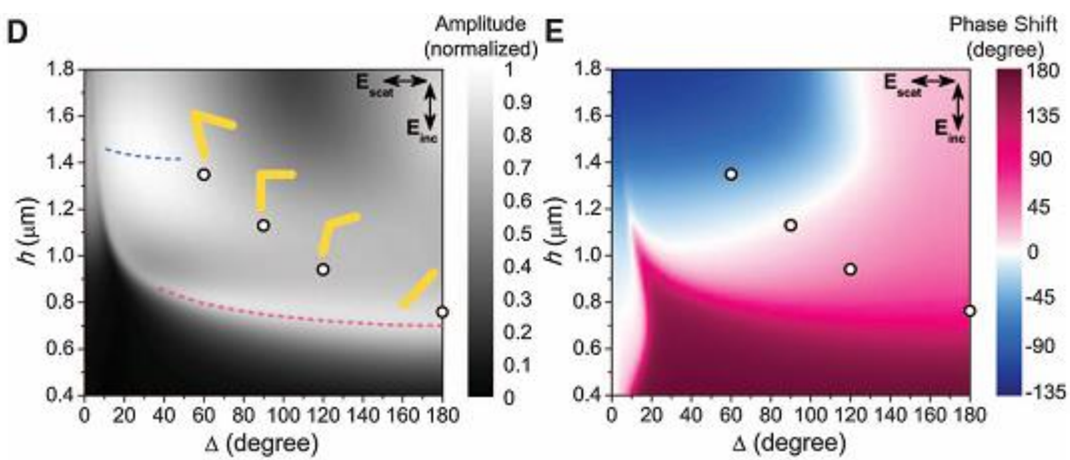
当平面具有相位突变的时候，根据最小相位，可以得到折射角和反射角和相位变化率有关。

N. Yu, et al. Science, 2011 (Capasso Group)

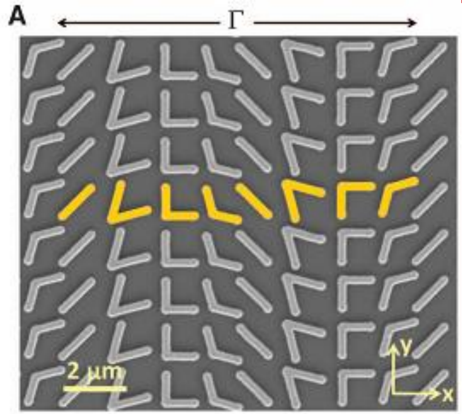
超构表面

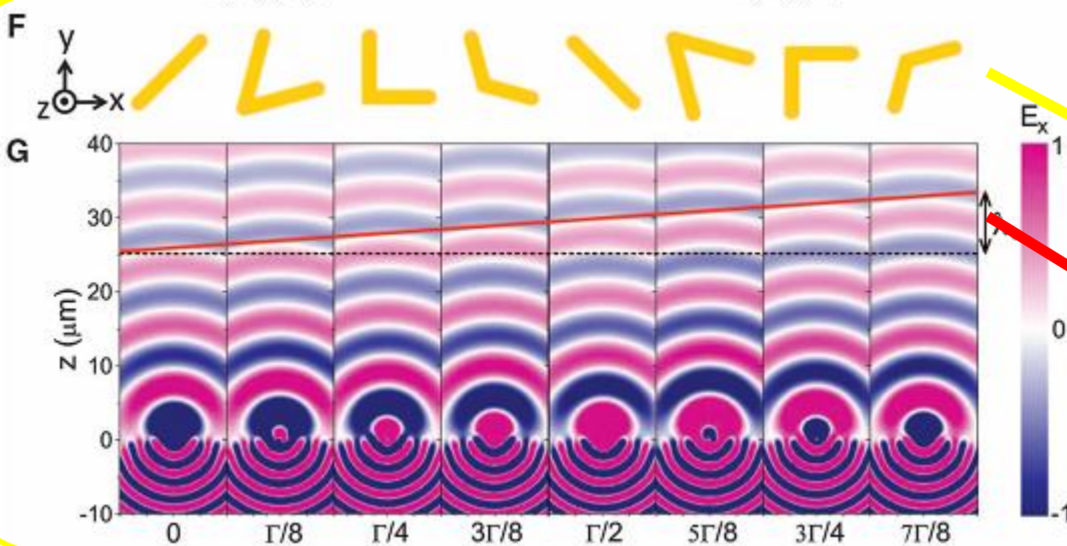


利用朝向和角度变化的V形纳米天线可以获得对入射光波一个突变的相位叠加，根据V形纳米天线朝向的不同，相位的突变从0-2π，把8个纳米天线按照一定的间距排列起来，能够获得平面上随着位置的不同，相位出现从0-360的线性渐变,相位变化梯度为：$2\pi/\Gamma$



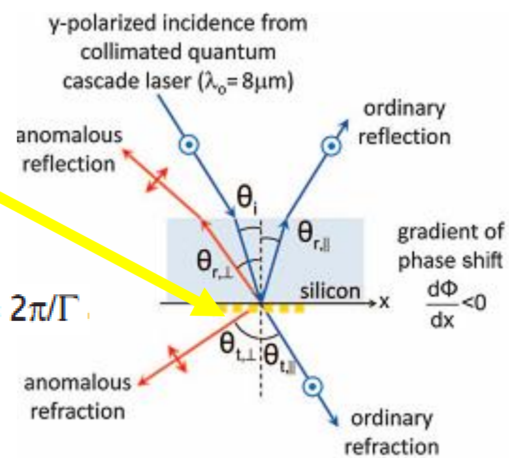
超构表面





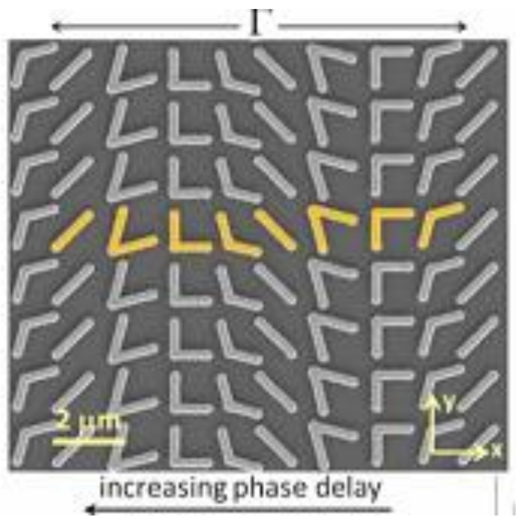
利用朝向变化的V形纳米天线可以获得对入射光波一个突变的相位叠加，根据V形纳米天线朝向的不同，相位的突变从0-2 ，把8个纳米天线按照一定的间距排列起来，能够获得平面上随着位置的不同，相位出现从0-360的线性渐变，相位变化梯度为： $2\pi / \Gamma$

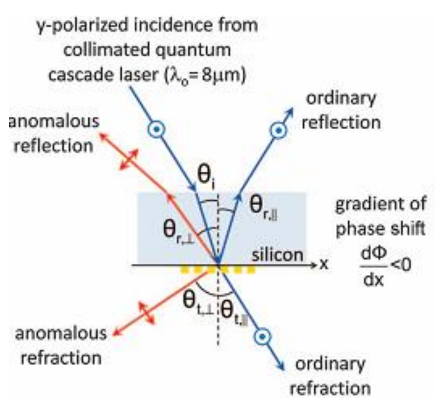
$$|d\Phi/dx| = 2\pi/\Gamma$$



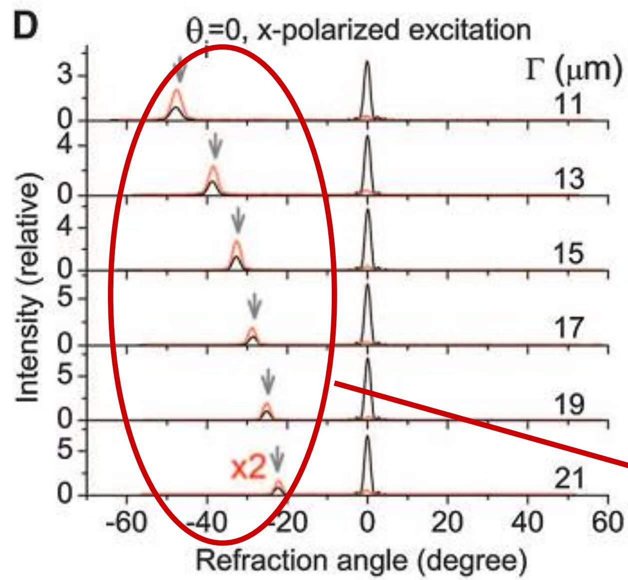
N. Yu, et al. Science, 2011 (Capasso Group)

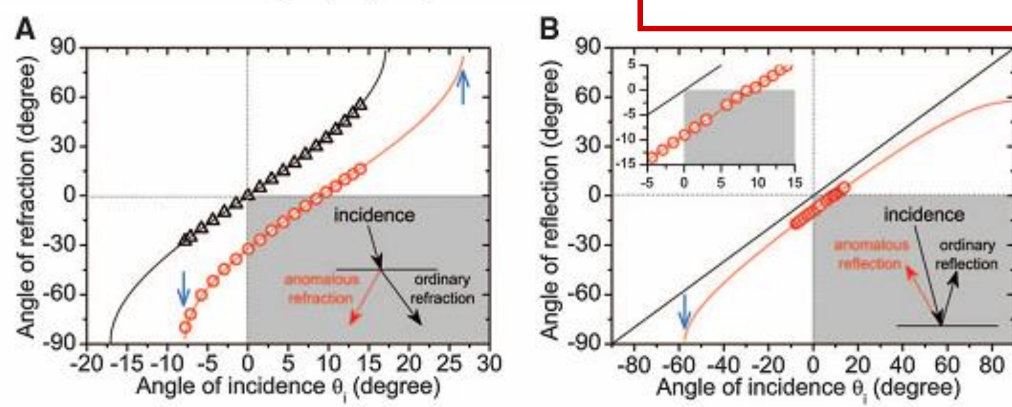
实验实现





N. Yu, et al. Science, 2011 (Capasso Group)





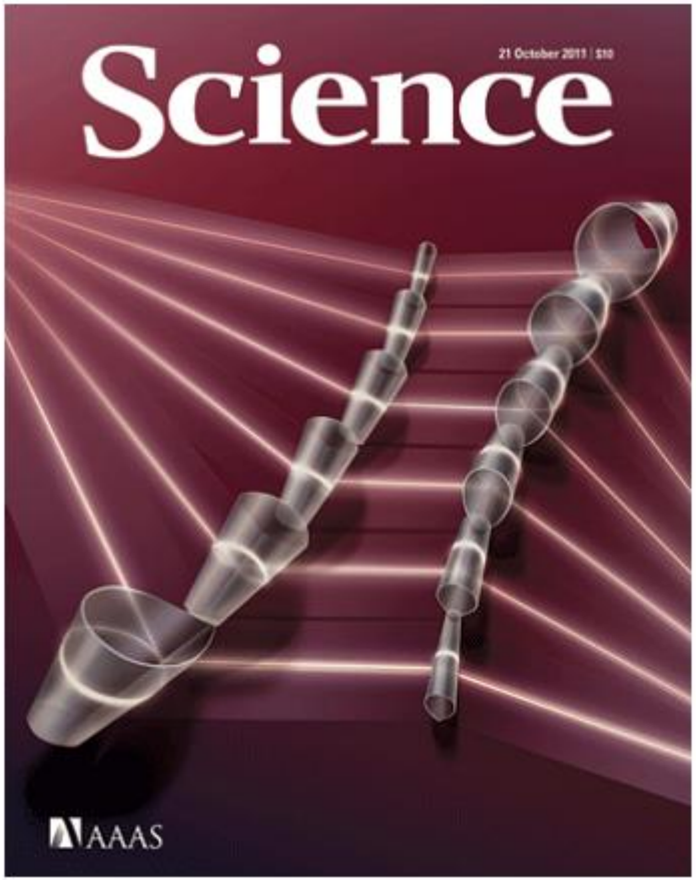
@ 8um，在正入射的情况下，观察到了随着周期的变化折射角变化，出现了异常反射和折射现象；

随着入射角的变化，折射角也发生变化，而且不对称

$$\frac{d\varphi}{dx} = -\frac{2\pi}{\Gamma}$$

$$\theta_{t,\perp} = \arcsin[n_{Si}\sin(\theta_i) - \lambda_o/\Gamma]$$

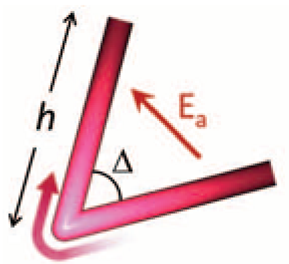
V-形天线阵列



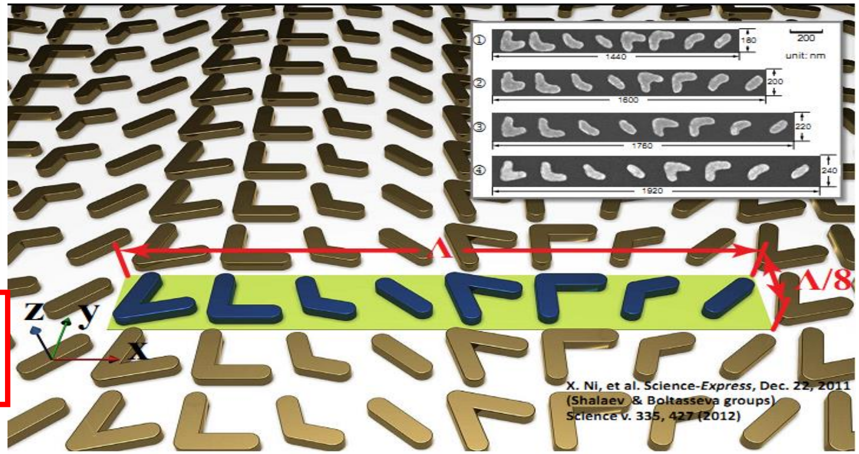
V型纳米天线可以看成是一个平面微腔，入射的光被耦合到微腔内部，变成了内部电子的有序运动（等离子体运动），而后再发射出带有纳米天线相位特征的折射光出来。

N. Yu, et al. Science, 2011 (Capasso Group)

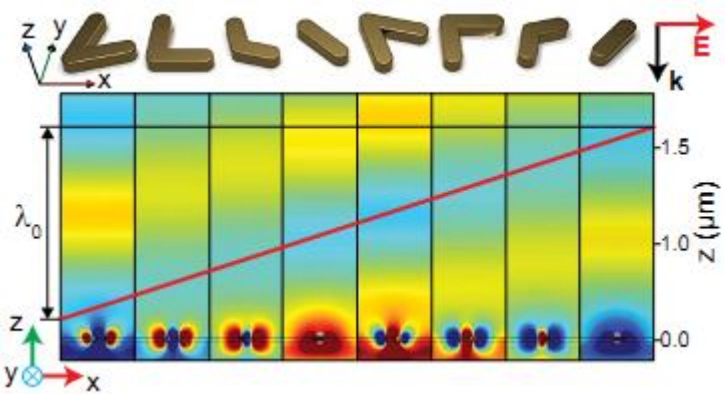
光学天线

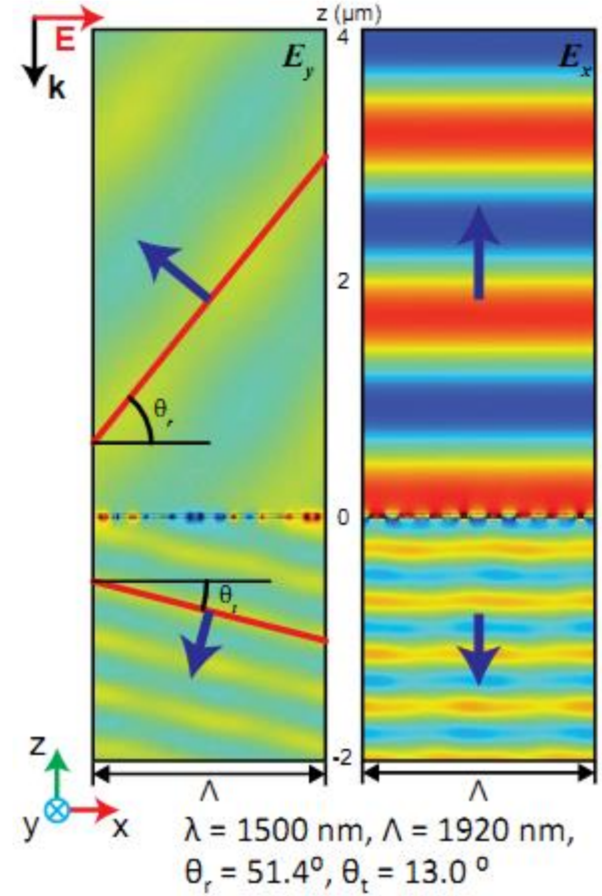


$$h = \lambda_{eff} / 4$$



2012年，Purdue小组通过缩小纳米天线的尺寸，将工作波长缩小到1.5微米

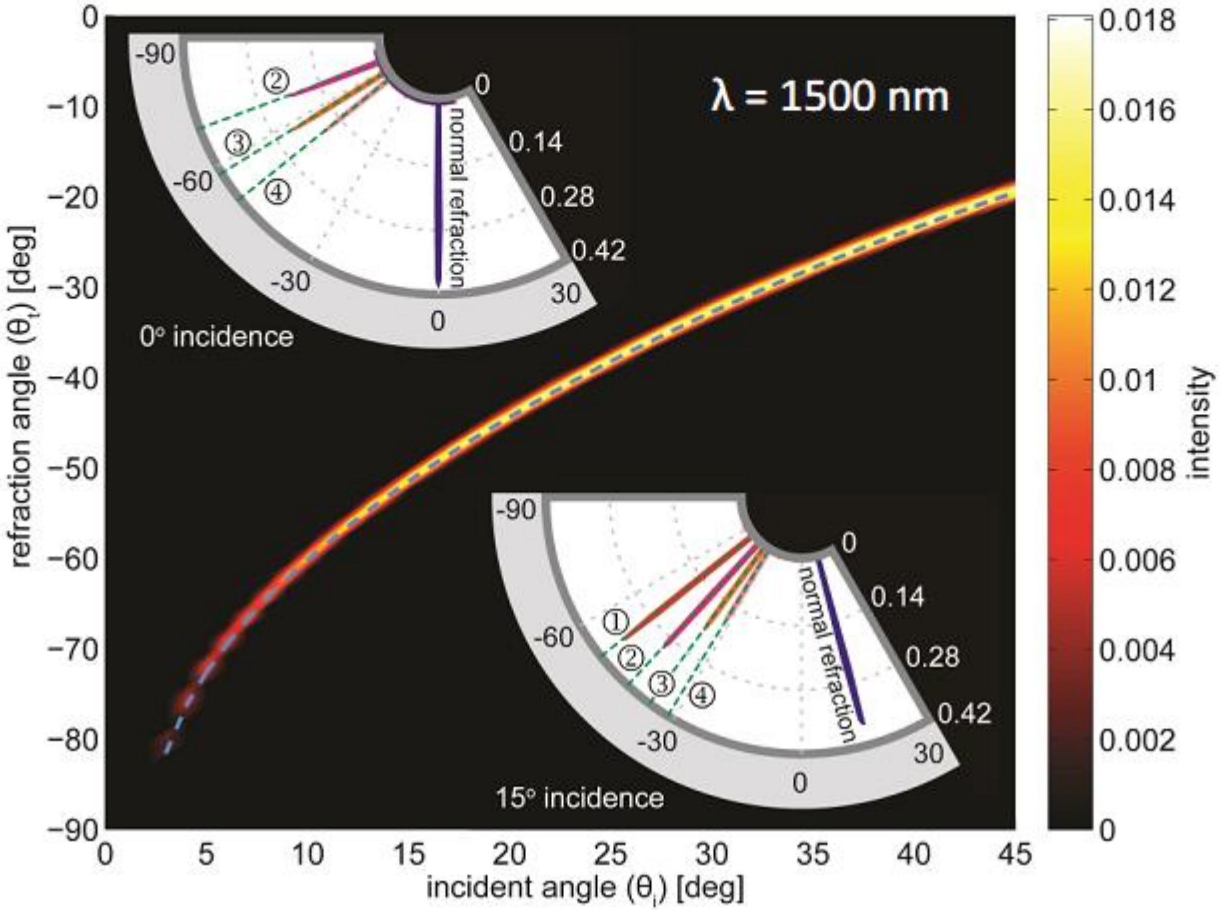




X. Ni et al. Science (2012) Shalaev Group

哈爾濱工業大學 HARBIN INSTITUTE OF TECHNOLOGY

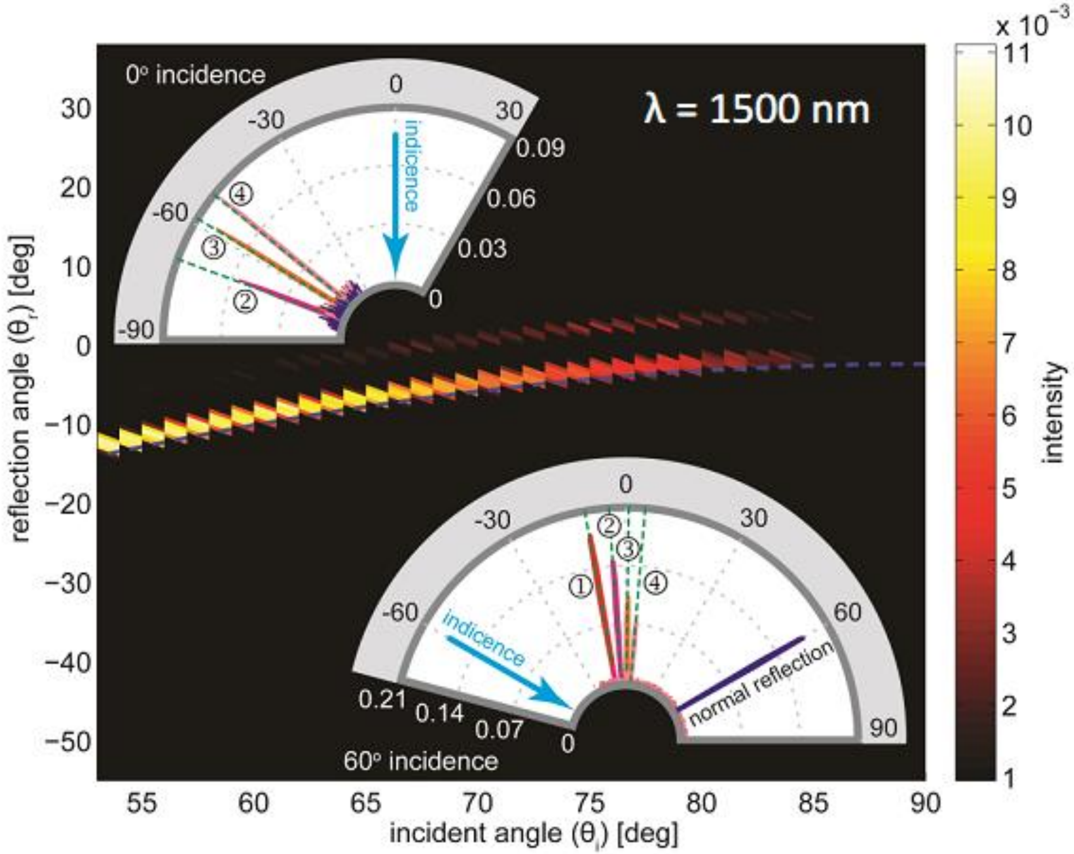
异常光折射实验



异常光折射现象：对于垂直入射的光，折射角出现了负值，而且随之相位梯度的减小折射角绝对值也出现了减小，另外还出现了当梯度变化大于1时，由于没有角度解，所有的波转换成了倏逝波

X. Ni et al. Science (2012) Shalaev Group

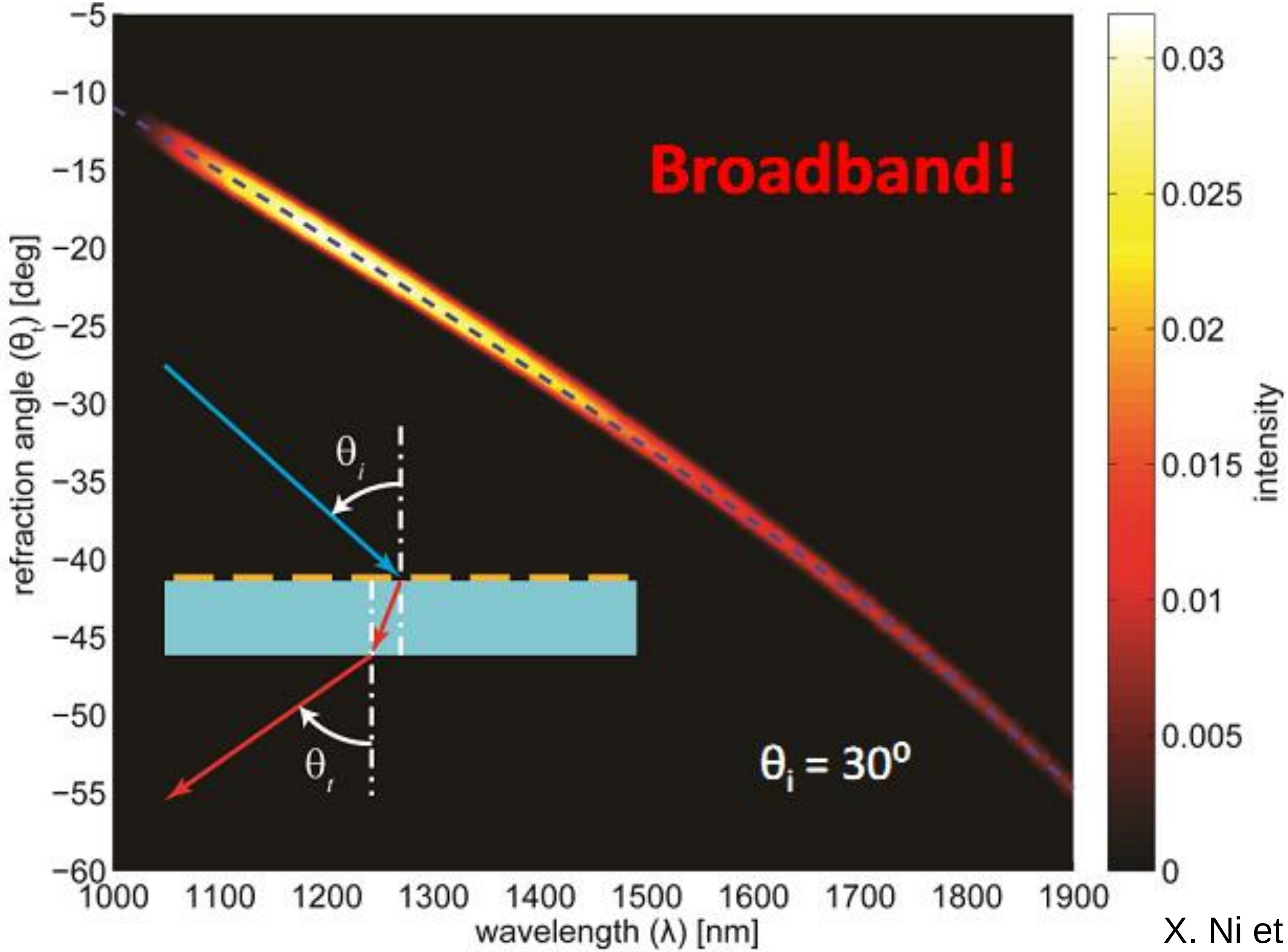
异常光反射实验



异常反射现象：对于垂直入射的光，反射角出现了负值，而且随之相位梯度的减小折射角绝对值也出现了减小，另外还出现了当梯度变化比较大时，由于没有角度解，所有的波转换成了倏逝波

X. Ni et al. Science (2012) Shalaev Group

超宽工作频率



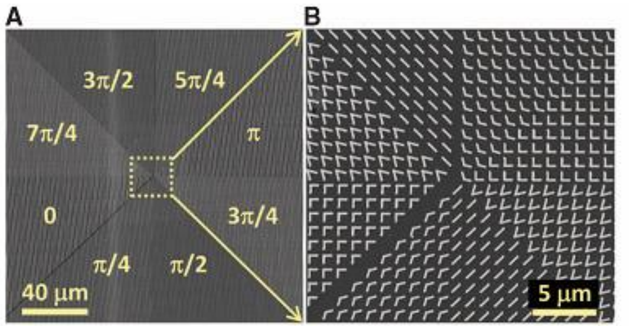
通过模拟发现波长从

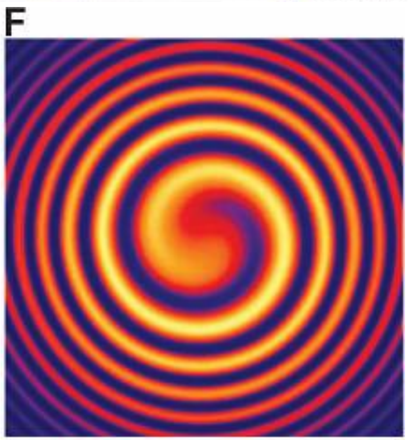
$$\lambda = 1\mu m - 2\mu m$$

在V纳米天线所在的平面上都会出相位梯度，从而都能出现入射光的非寻常折射和反射

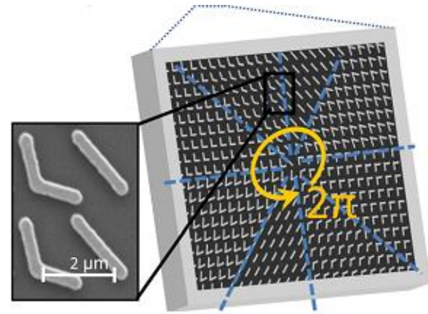
X. Ni et al. Science (2012) Shalaev Group

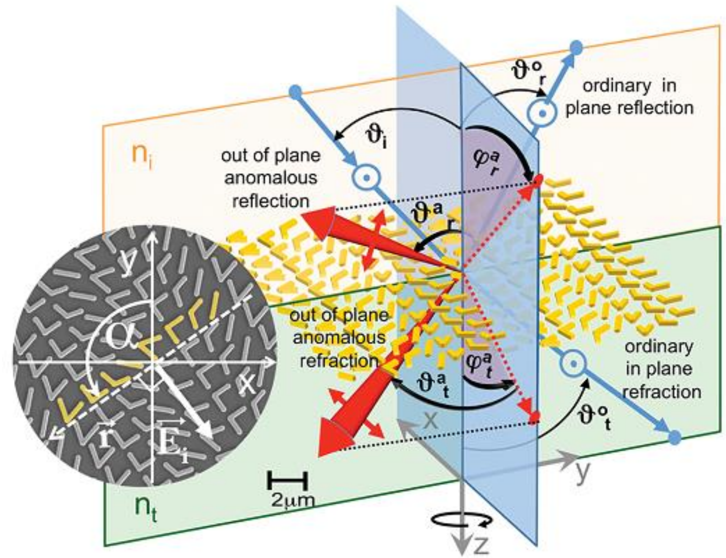
利用V-形天性进行波前整形





$$\exp(il\varphi)$$
$$L = l\hbar$$





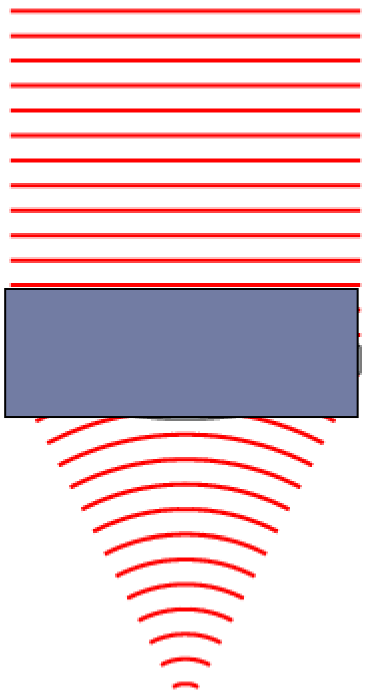
N. Yu, et al. Science, 2011 (Capasso Group)

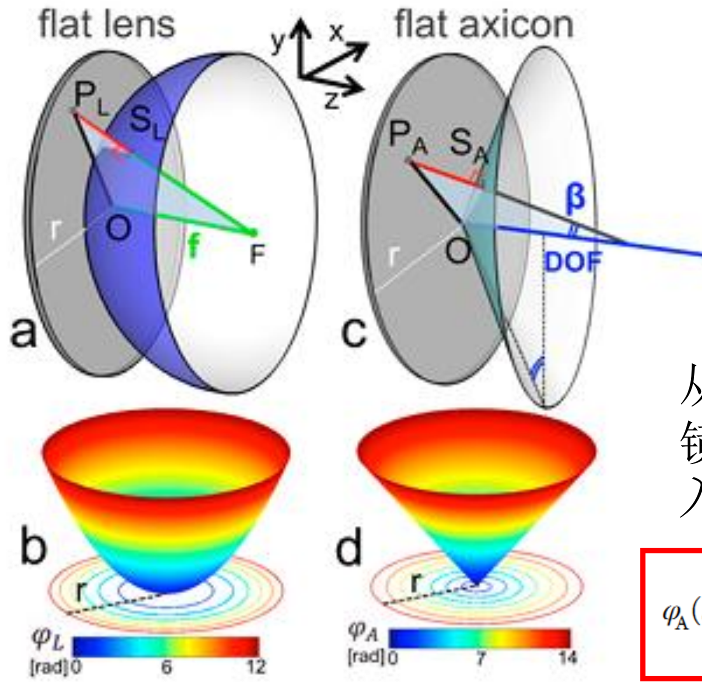
P.Genepet *et al*. App. Phys. Lett. (2012)

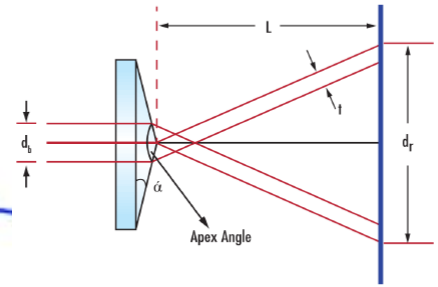
F. Aeita *et al.* Nano Letter (2012)

利用V形纳米天线可以实现对于光波的波前形貌整形，观察到螺旋波束，面外折射和反射等异常现象。

梯度变化超构表面能实现平面聚焦效应







从位相上看，轴锥透镜是利用几何尺寸引入了线性的相位渐变。

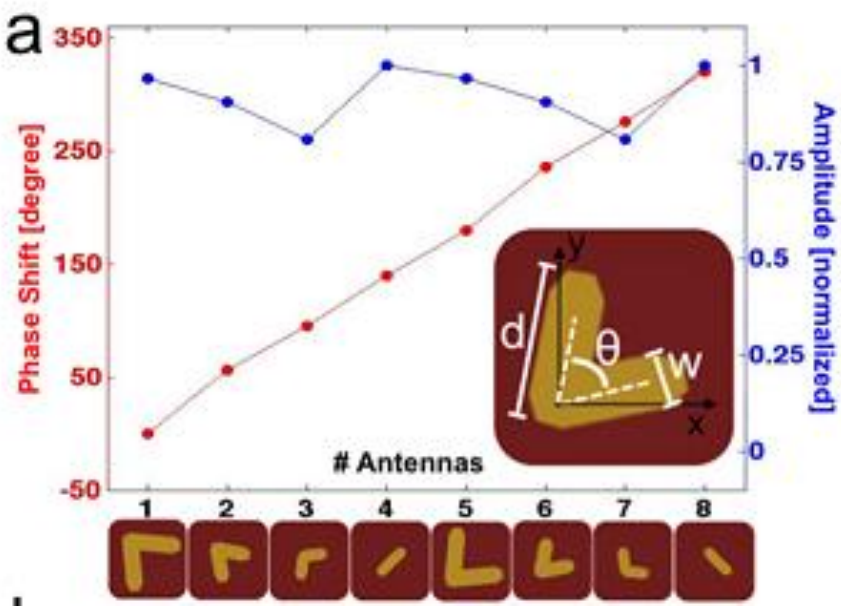
$$\varphi_A(x,y)=\frac{2\pi}{\lambda}\overline{P_A S_A}=\frac{2\pi}{\lambda}\sqrt{x^2+y^2}\sin\beta$$

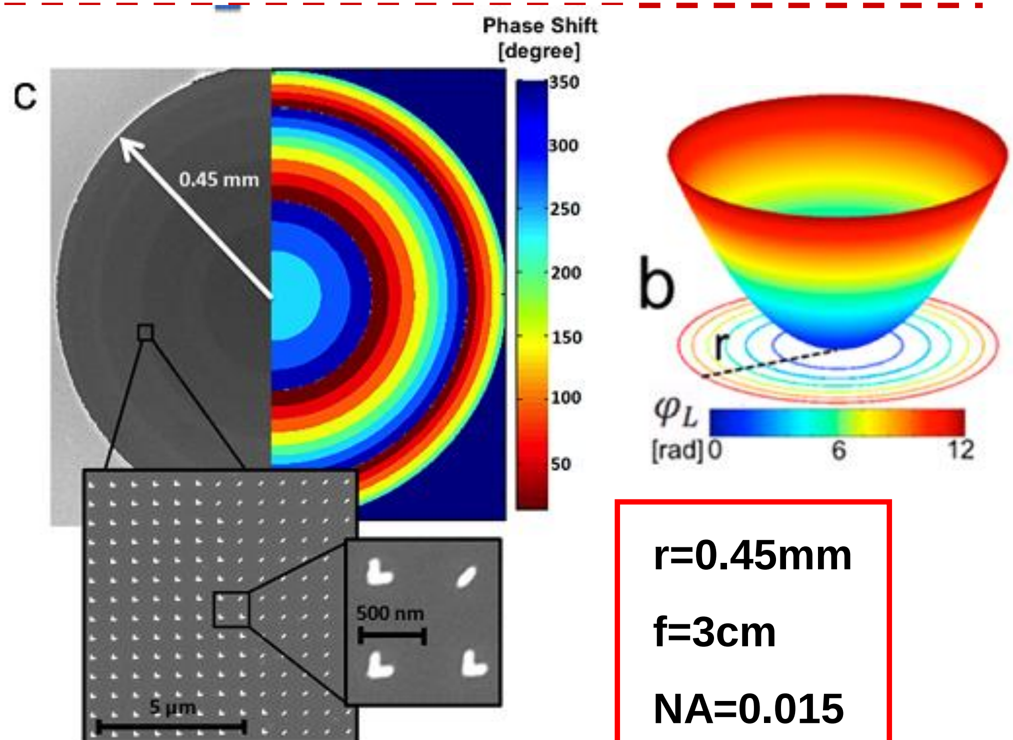
透镜是利用一个渐变的表面使得垂直入射的平行光在表面不同位置出现渐变的折射角，从而实现聚焦的功能。

从位相上来说，透镜可以看成是利用渐变的几何尺寸来获得位相变化，由于光的传播方向垂直于等相面（波前），所以发射折射聚焦，而相位随坐标的关系服从双曲线分布：

$$\varphi_L(x,y)=\frac{2\pi}{\lambda}\overline{P_L S_L}=\frac{2\pi}{\lambda}\left(\sqrt{(x^2+y^2)+f^2}-f\right)$$

利用天线构建梯度平面





r=0.45mm

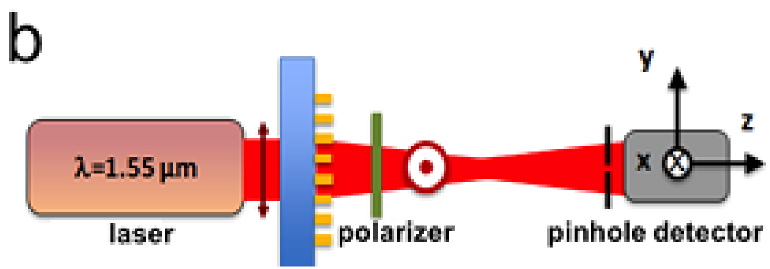
f=3cm

NA=0.015

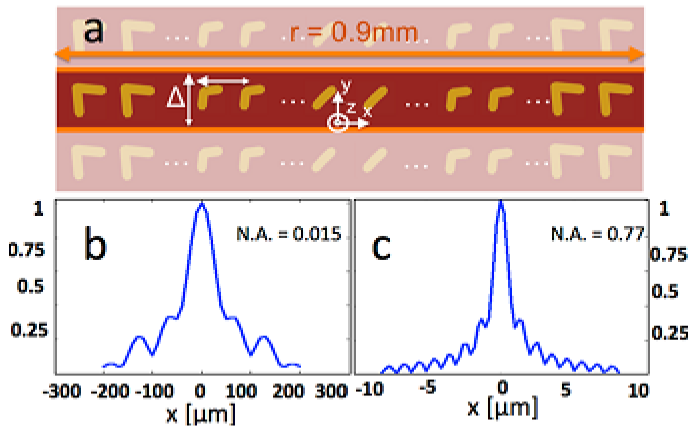
从前面我们可以看出，利用朝向不同的V形纳米天线可以实现对偏振入射光的相位产生0-360的控制，这使得我们可以随意调节界面上任意点的相位

将不同朝向的纳米天线在平面上按照同心圆层状的排列起来，使得在界面上的相位分布和通常透镜由于球面形貌带来的相位变化相似。

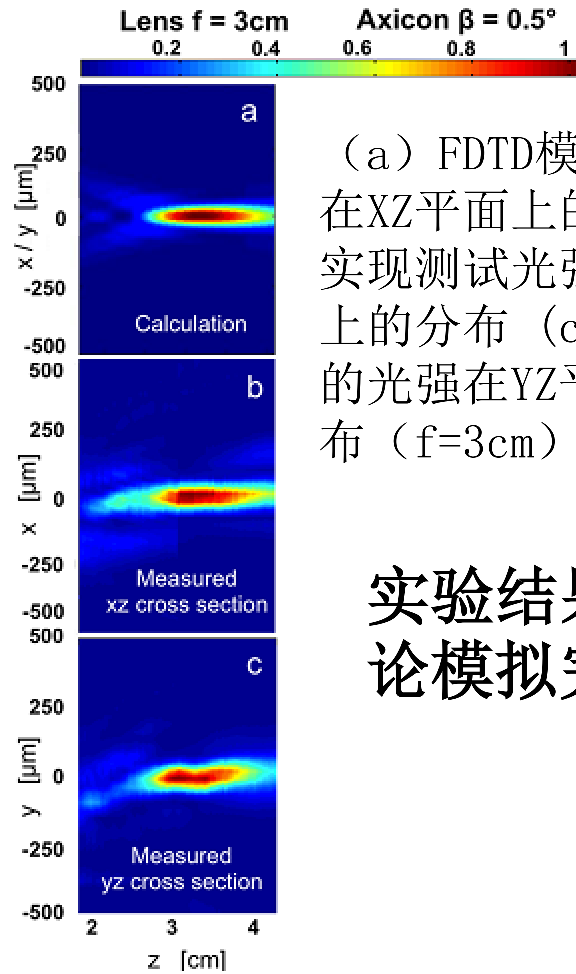
平面聚焦效应



1.55微米激光，利用CCD成像聚焦光斑



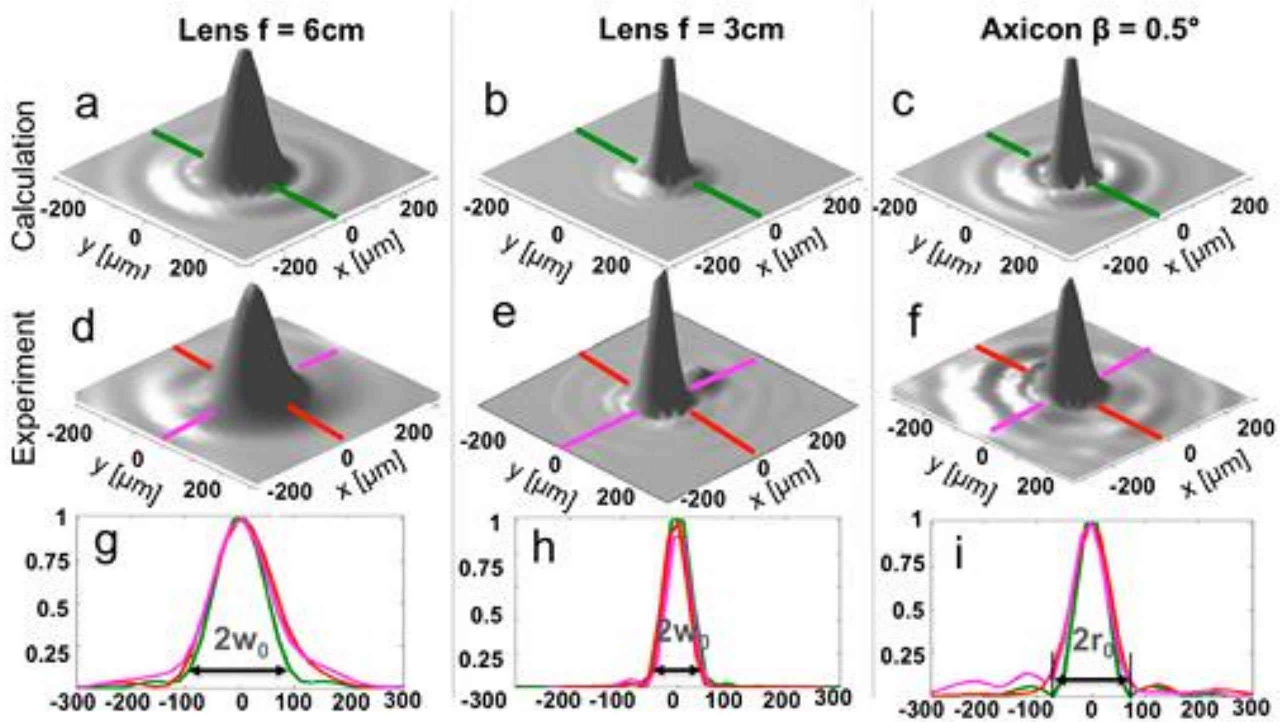
利用FDTD计算得到：利用渐变界面制备的平面透镜可以实现高数值孔径



（a）FDTD模拟的光强在XZ平面上的分布；（b）实现测试光强在XZ平面上的分布（c）实验测试的光强在YZ平面上的分布（f=3cm）。

实验结果几乎和理论模拟完全符合！

光斑质量



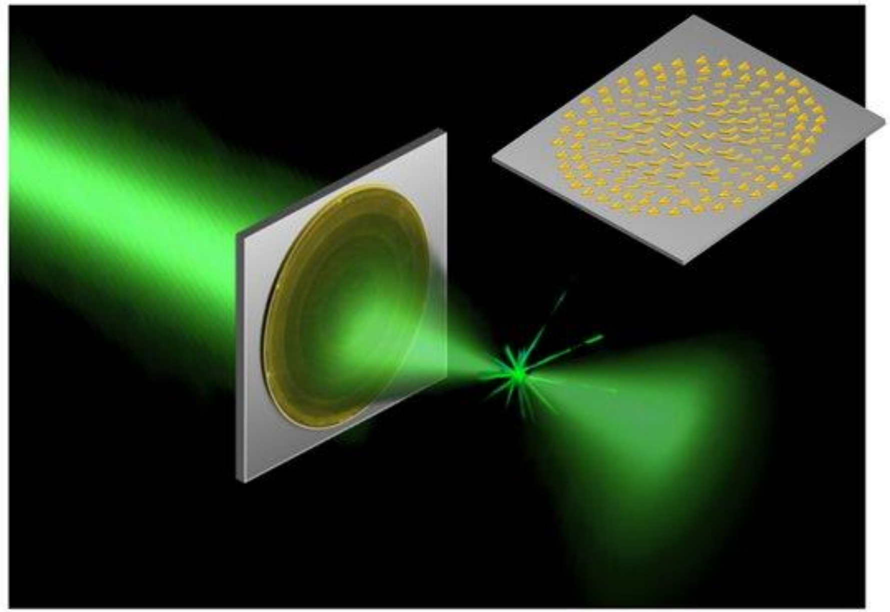
从横截面光强分布来看，实验结果和理论模拟基本符合，从而肯定了利用相位渐变的人造表面能够获得高数值孔径聚焦透镜、轴锥透镜等。另外由于界面是个完美的平面，所以这种透镜不具有通常透镜由于球面带来的单色像差（球差、慧差、畸变等）

优势和应用

1、无通常透镜具有的单色像差

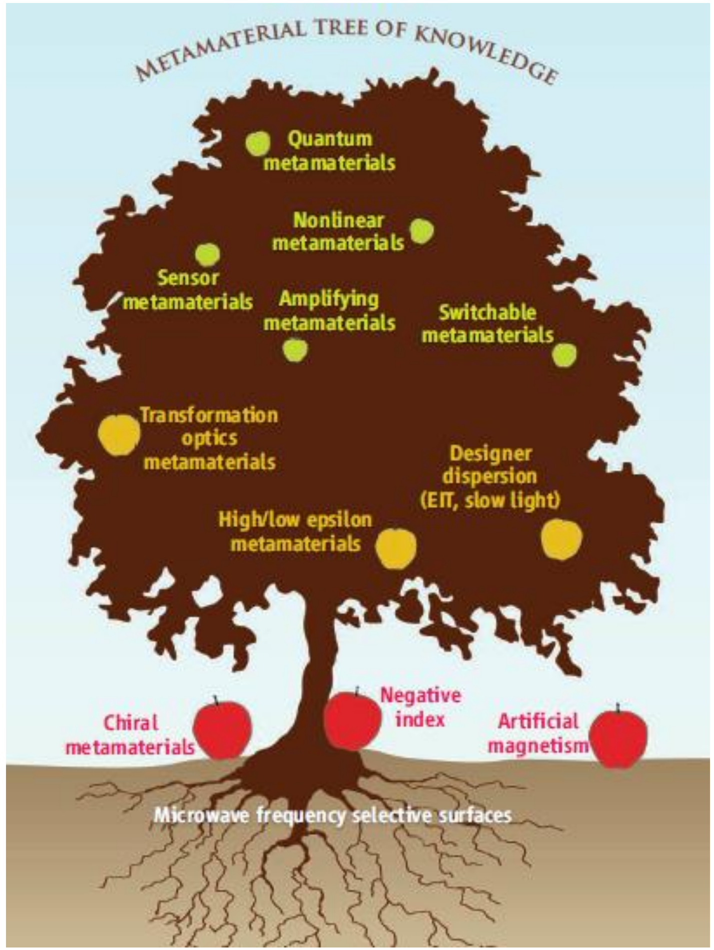
2、超轻、超薄（50万倍），成本低（纳米压印技术）、集成度高

3、最明显的用途为摄影及显微术，也能应用于信息存储等，或者是任何能取代传统透镜的地方，因为这种平面透镜只有几十纳米厚，重量也非常的轻，对于航天飞行器中成像技术的革新具有非常重要的意义。

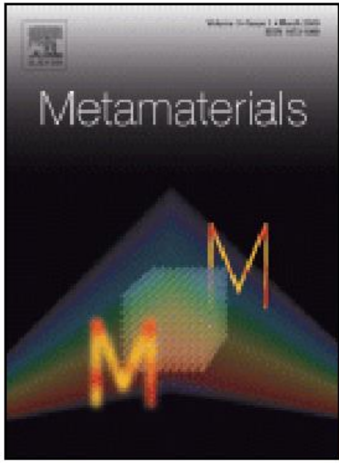


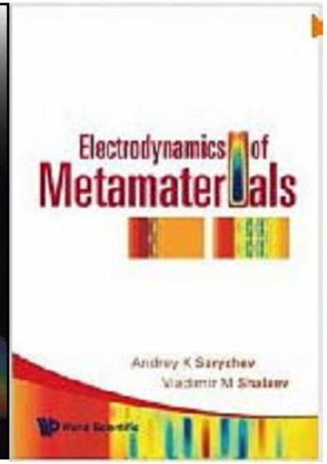
Outlines

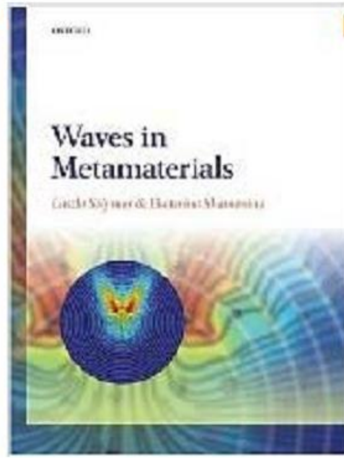
超材料领域的未来发展

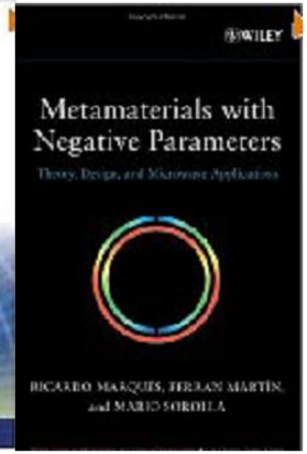

METAMATERIAL TREE OF KNOWLEDGE
Quantum metamaterials
Nonlinear metamaterials
Sensor metamaterials
Amplifying metamaterials
Switchable metamaterials
Transformation optics metamaterials
Designer dispersion (EIT, slow light)
High/low epsilon metamaterials
Chiral metamaterials
Negative index
Artificial magnetism
Microwave frequency selective surfaces

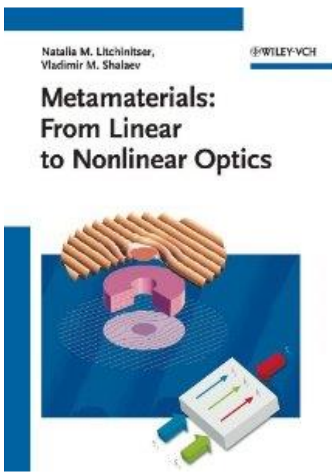
参考文献

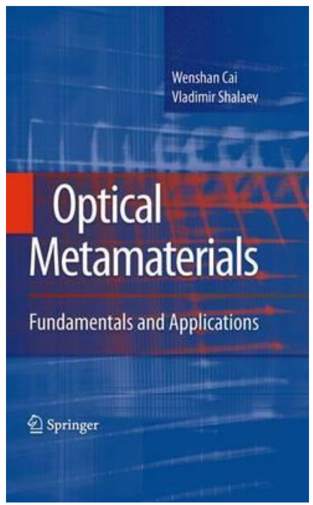












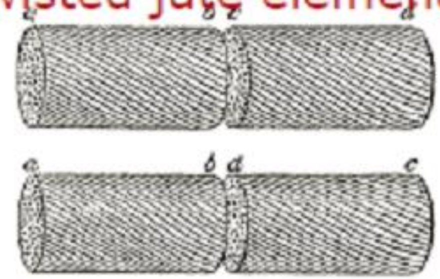
许许多多的文章……

Thank you

& Questions？

超材料的历史

Twisted jute elements



Artificial chiral molecules

In order to imitate the rotation produced by liquids like sugar solutions, I made small elements or " molecules " of twisted jute, of two varieties, one kind being twisted to the right (positive) and the other twisted to the left (negative). I now interposed a number of, say, the positive variety, end to end, between the crossed polariser and analyser; this produced a restoration of the field. The same was the case with the negative variety. *I now mixed equal numbers of the two varieties, and there was now no restoration of the field, the rotation produced by one variety being counteracted by the opposite rotation produced by the other.*

Jagadis C. Bose, *Proceeding of Royal Soc. London*, 1898
"On the Rotation of Plane of Polarization of Electric Waves by a Twisted Structure"

变换光学

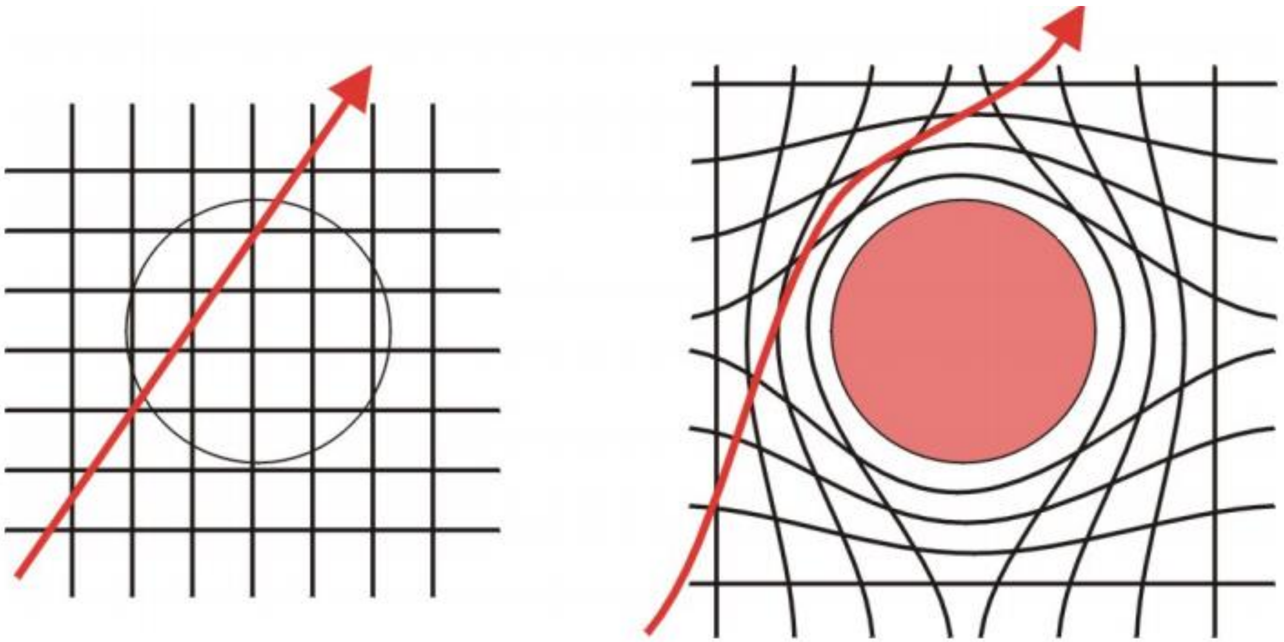
Fermat:

$$\delta \int n\,dl = 0$$

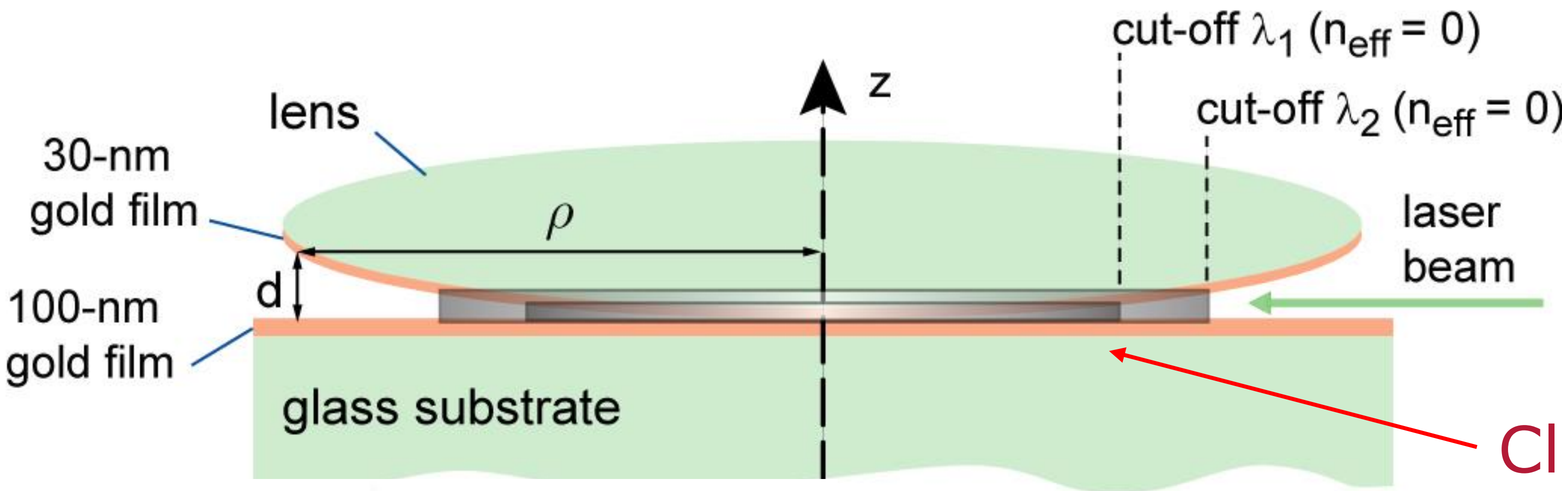
$$n = \sqrt{\varepsilon(r)\mu(r)}$$

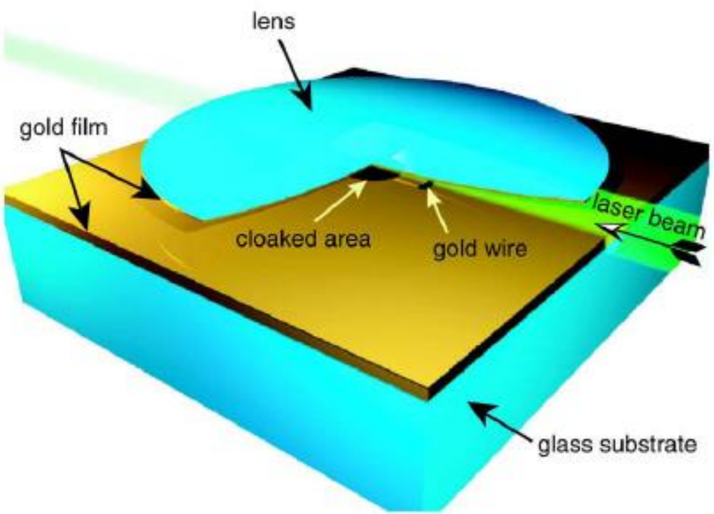
“curving”

optical space



其他传输光学办法





Cloaking is achieved by guiding light around the hidden region. This can be achieved using a smoothly varying refractive index – difficult in practice.

A waveguide has an effective refractive index determined by its height. Varying the height tunes the refractive index – a much simpler procedure.

Smolyaninov, *et al.*, Physical Review Letters (2009)

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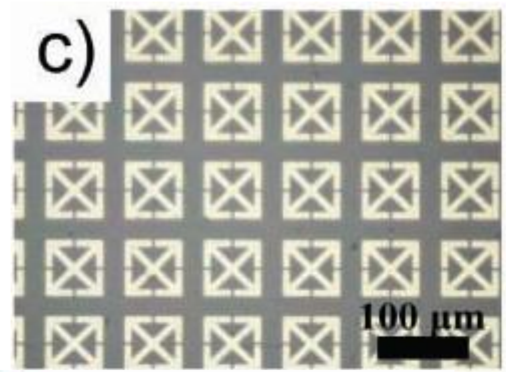
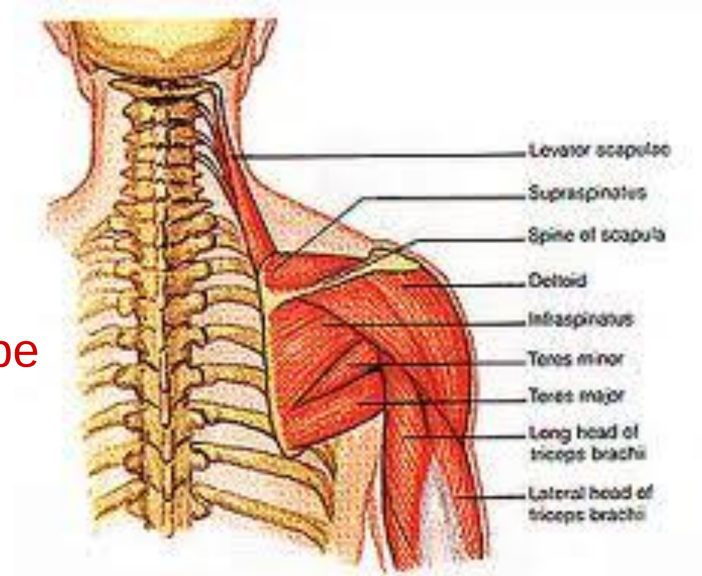
HARBIN INSTITUTE OF TECHNOLOGY

变换光学的应用-医学

"Stenciling" 10,000 gold resonators onto a 1 cm square of silk





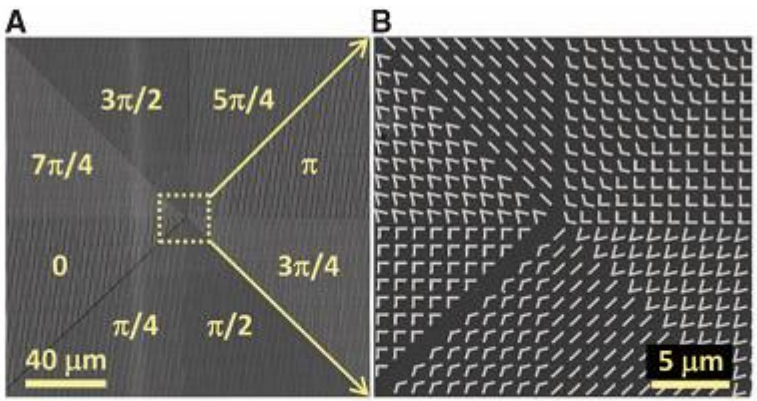
Just work at terahertz range, but not optics range.

Silk is compatible to metamaterials. Other materials would be rejected by the human body, but not silk-based implants.

Invisible silk allows radiologists and doctors to wrap various organs or tissues and see through them.

http://www.huffingtonpost.com/2010/08/11/invisibility-cloak-made-f_n_679170.html

涡旋光束整形

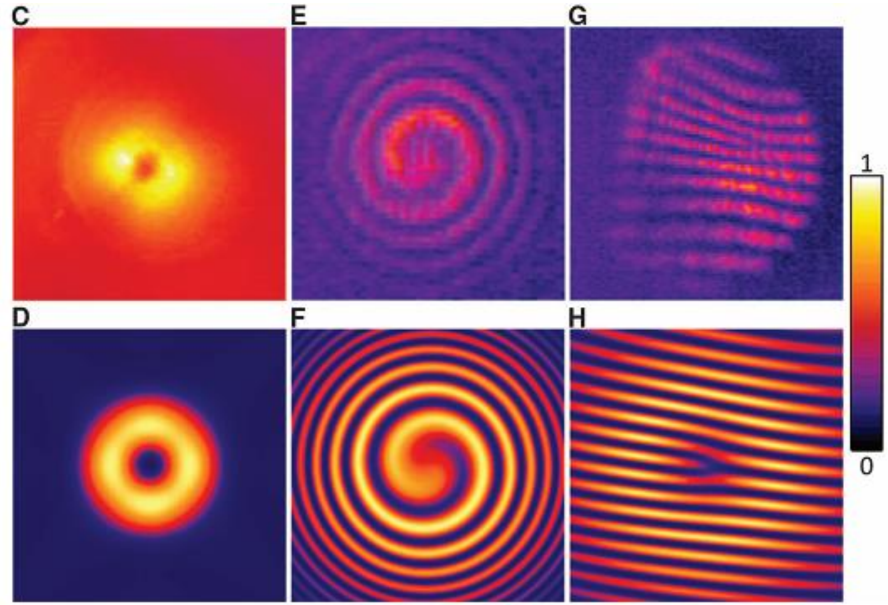


随着方位的不同出现相位的变化，空间的相位形成了一个类螺旋的形貌，

$$\exp(il\varphi)$$

$$L = l\hbar$$

V形纳米天线能够在入射光通过一层很薄的表面时附加上一个突变的相位。而随着天线朝向的不同，出现了0-360度的相位叠加。所以可以利用其对光波的相位进行控制，从而控制光波的波前。



Fig（C、E、G）实验结果，而Fig（D、F、H）模拟结果

利用螺旋分布的相位表面对平面入射的光进行波前整形，使得通过其的光线具有螺旋形相位分布，利用高斯光和他发生干涉以后出现螺旋干涉条纹，小角干涉揭示了l=1。

N. Yu, et al. Science, 2011 (Capasso Group)