Metamaterials and Negative Refraction

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Some Reviews of Metamaterials

Not Just a Light Story
Nature Materials
5 755-64 (2006)

Negative Refraction
Contemporary Physics
45 191-202 (2004)

Metamaterials and Negative Refractive Index
Science
305 788-92 (2004)

Some Popular Articles

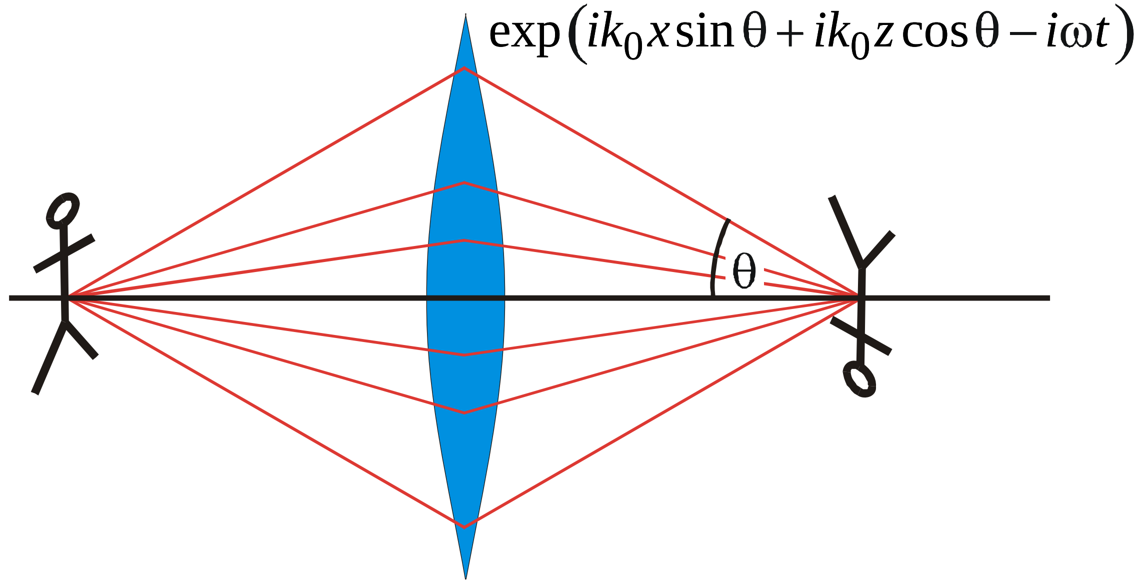
The Quest for the superlens
Scientific American
60- 67 July (2006).

Manipulating the near field with metamaterials
Optics & Photonics News
15 33-7 (2004)

Reversing Light with Negative Refraction
Physics Today
57 [6] 37-43 (June 2004)

Focussing light

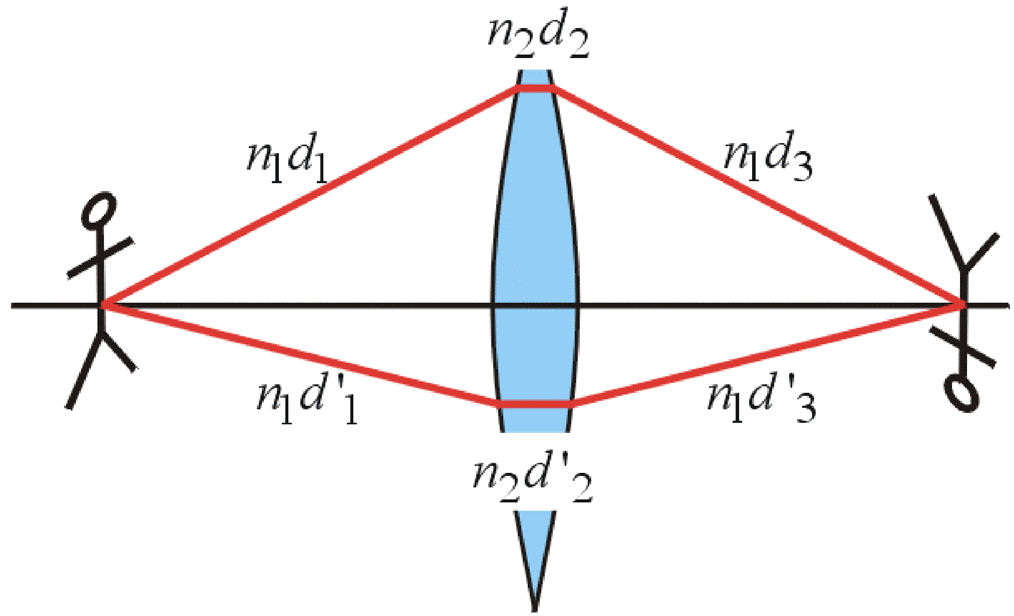
Galileo by Leoni - 1624



lens, *n.* L. *lens* lentil, from the similarity in form. A piece of glass with two curved surfaces

Fermat's Principle:

"Light takes the shortest optical path between two points"



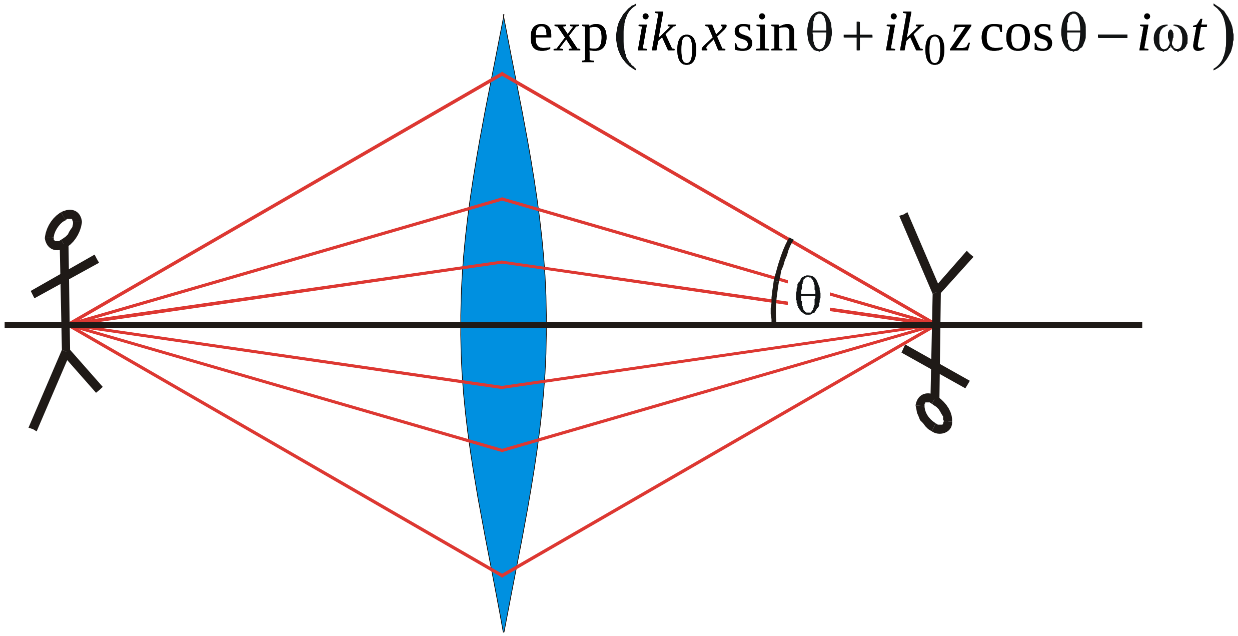
e.g. for a lens the shortest optical distance between object and image is:

$$n_1 d_1 + n_2 d_2 + n_1 d_3 = n_1 d'_1 + n_2 d'_2 + n_1 d'_3$$

both paths converge at the same point because both correspond to a minimum.

Focussing light: wavelength limits the resolution

Contributions of the far field to the image ….



….. are limited by the free space wavelength:

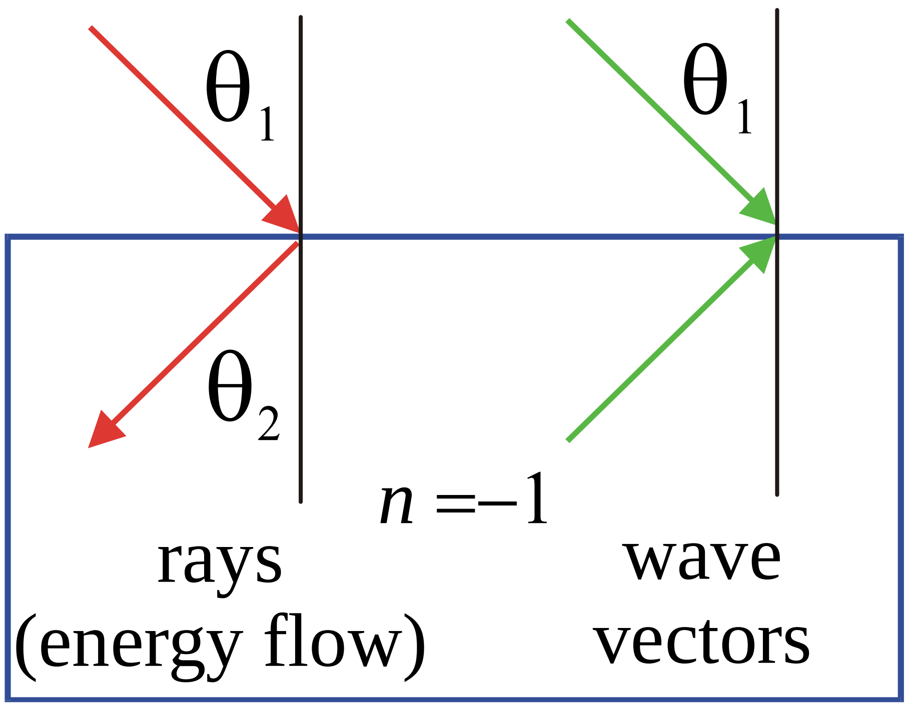
$\theta = 90^\circ$ gives maximum value of $k_x = k_0 = \omega/c_0 = 2\pi/\lambda_0$ – the shortest wavelength component of the 2D image. Hence resolution is no better than,

$$\Delta \approx \frac{2\pi}{k_0} = \frac{2\pi c}{\omega} = \lambda_0$$

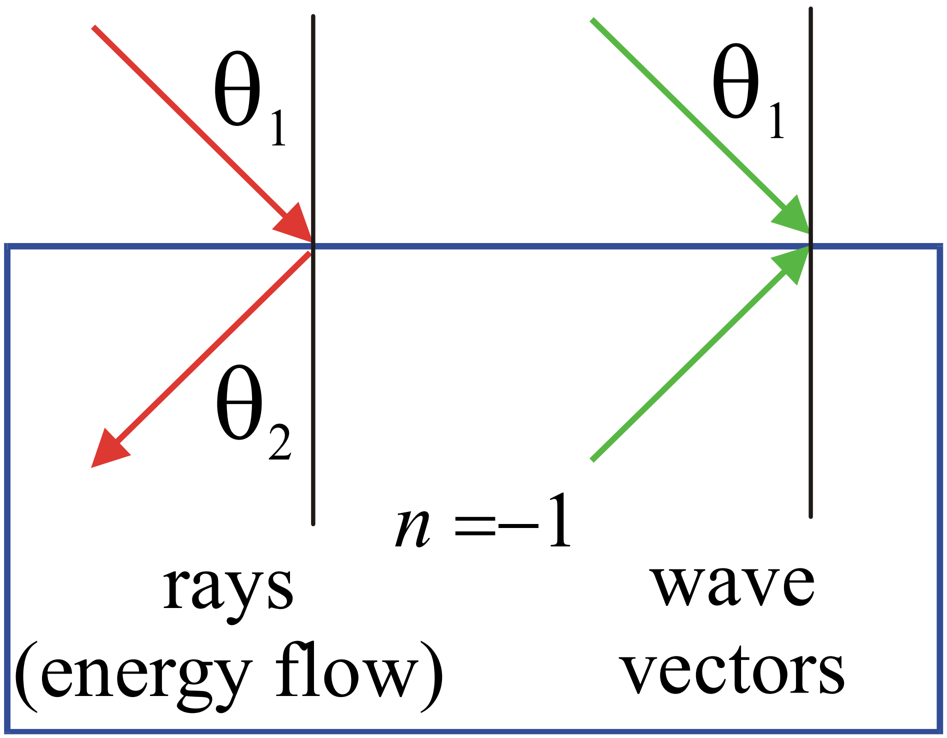
Negative Refractive Index and Snell's Law

$$n = \frac{\sin(\theta_1)}{\sin(\theta_2)}$$

Hence in a negative refractive index material, *light makes a negative angle with the normal*. Note that the parallel component of wave vector is always preserved in transmission, but that energy flow is opposite to the wave vector.



The consequences of negative refraction
1. negative group velocity



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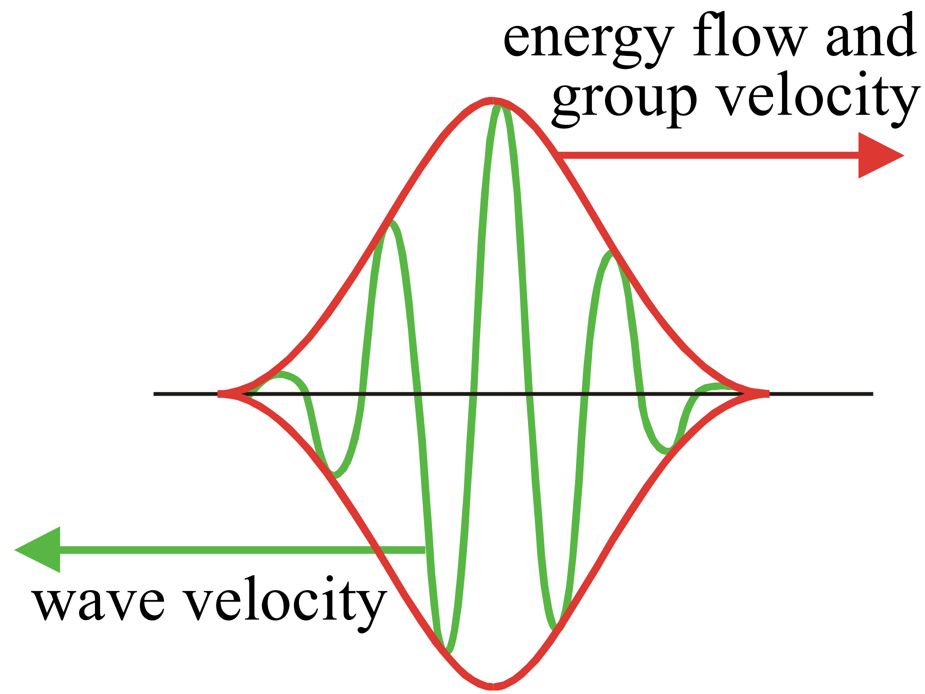
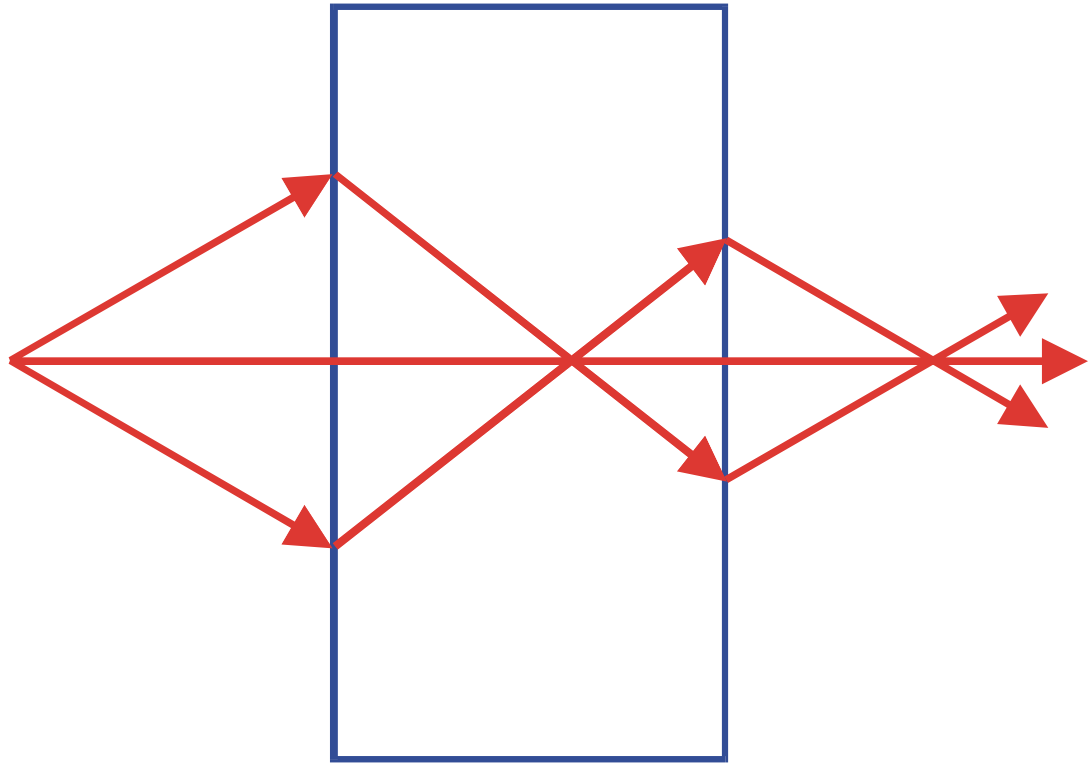


Materials with negative refraction are sometimes called ***left handed materials*** because the Poynting vector has the opposite sign to the wave vector.

Negative Refractive Index and Focussing



A negative refractive index medium bends light to a negative angle relative to the surface normal. Light formerly diverging from a point source is set in reverse and converges back to a point. Released from the medium the light reaches a focus for a second time.

Recipe for Negative Refractive Index

James Clark Maxwell showed that light is an electromagnetic wave and its refraction is determined by both:

the electrical permittivity, ε,

and the magnetic permeability, μ.

The wave vector, k, is related to the frequency by the refractive index,

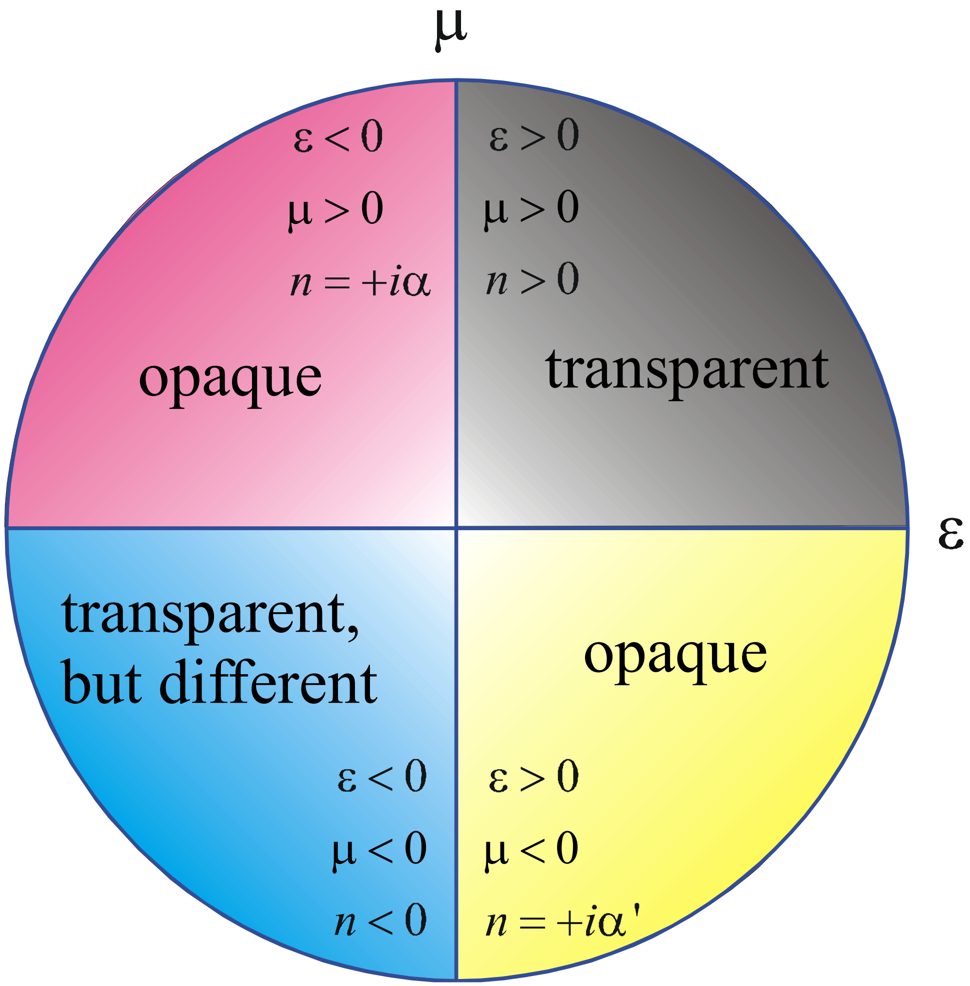
$$k = \sqrt{\varepsilon\mu}\,\omega c_0^{-1} = n\omega c_0^{-1}$$

Normally n, ε, and μ are positive numbers.

In 1968 *Victor Veselago* showed that if ε and μ are negative, we are forced by Maxwell's equations to choose a negative square root for the refractive index,

$$n = -\sqrt{\varepsilon\mu}, \quad \varepsilon < 0, \quad \mu < 0$$

Negative Refraction - $n < 0$



The *wave vector* defines how light propagates:

$$E = E_0 \exp(ikz - i\omega t)$$

where,

$$k = \omega/c \times \sqrt{\varepsilon\mu} = \omega/c \times n$$

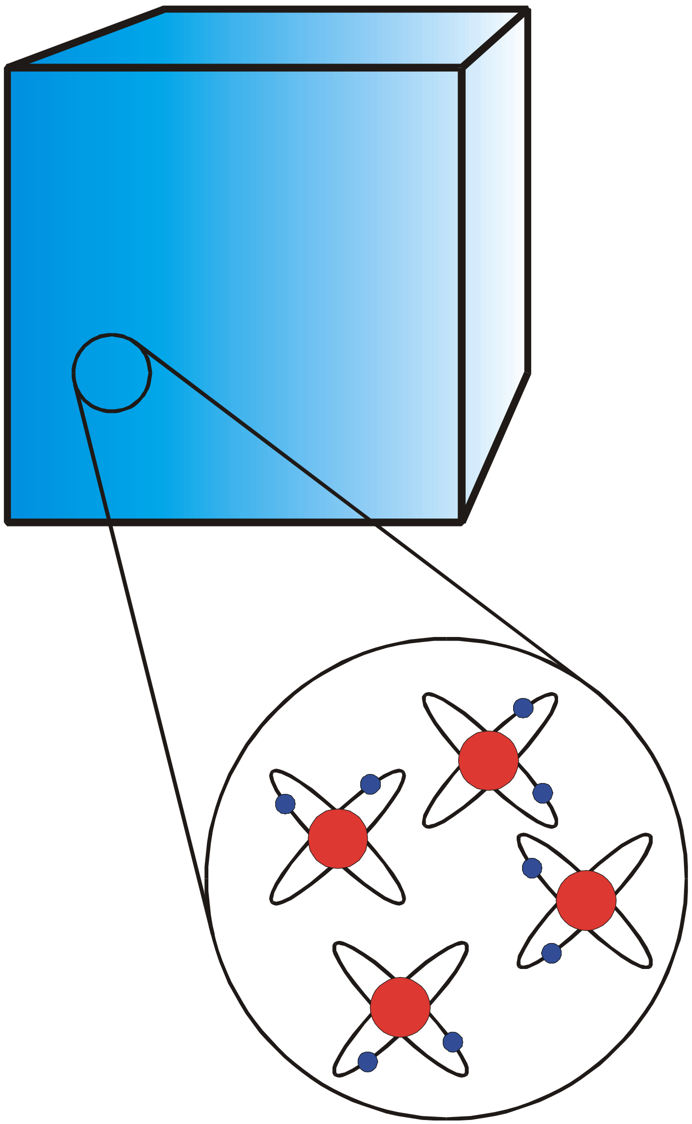
Either $\varepsilon < 0$, or $\mu < 0$, ensures that k is imaginary, and the material opaque.

If $\varepsilon < 0$ *and* $\mu < 0$, then k is real, but we are forced to choose the *negative* square root to be consistent with Maxwell's equations.

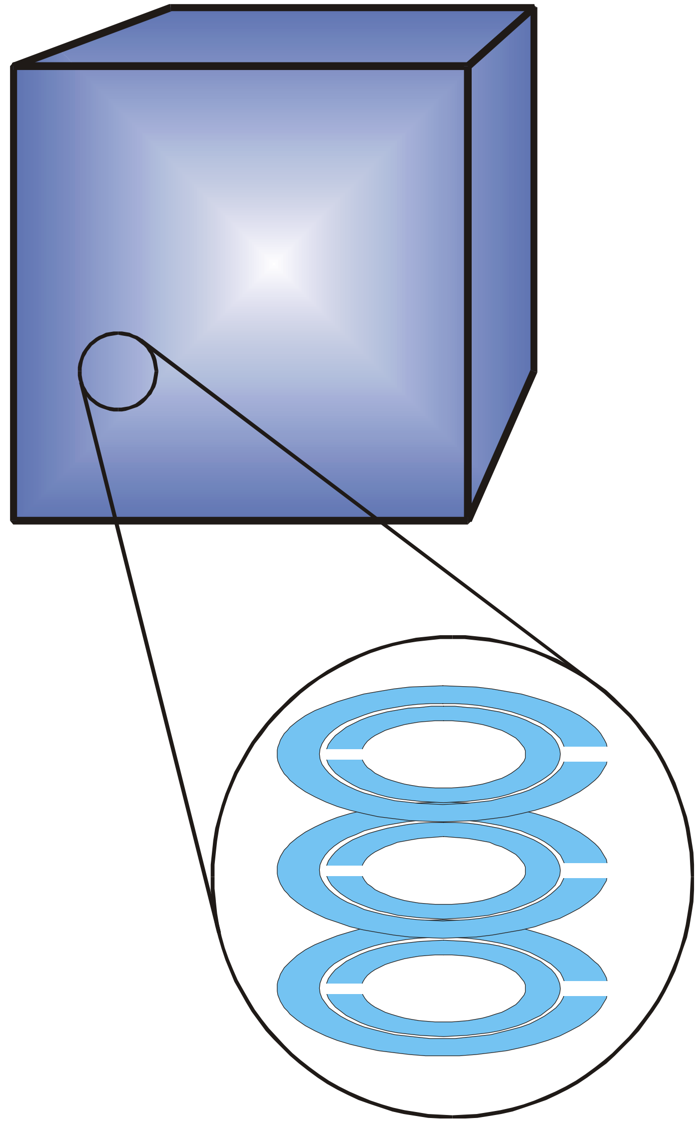
$\varepsilon < 0, \mu < 0$ means that n is negative

What is a 'metamaterial'

Conventional materials: properties derive from their constituent *atoms*.

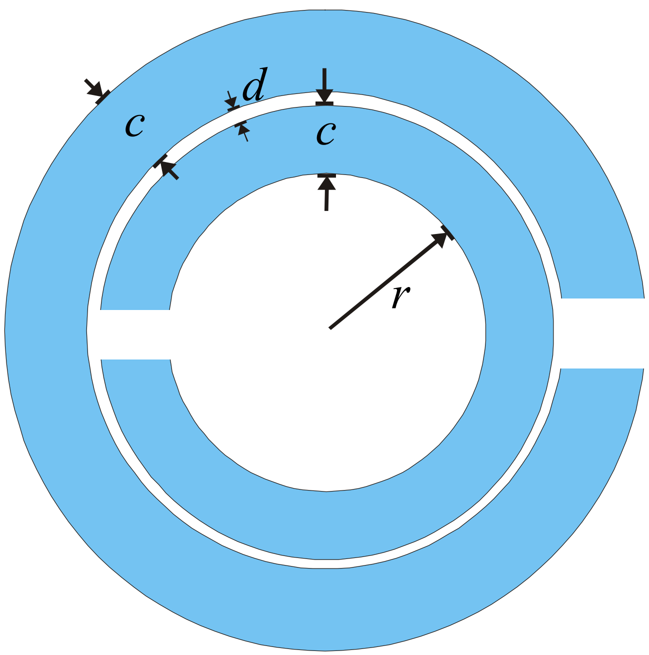


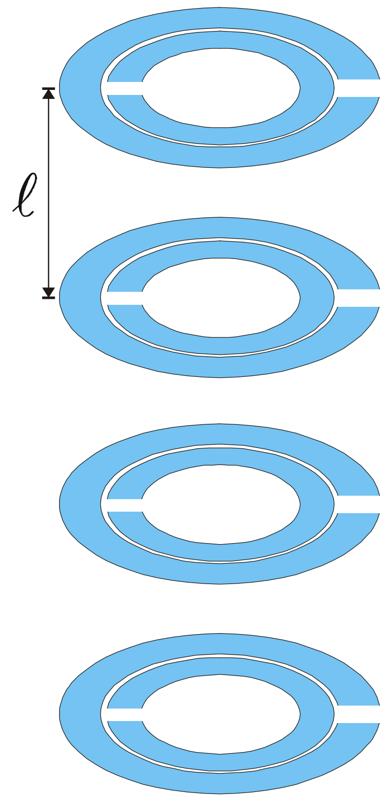
Metamaterials: properties derive from their constituent *units*. These units can be engineered as we please.



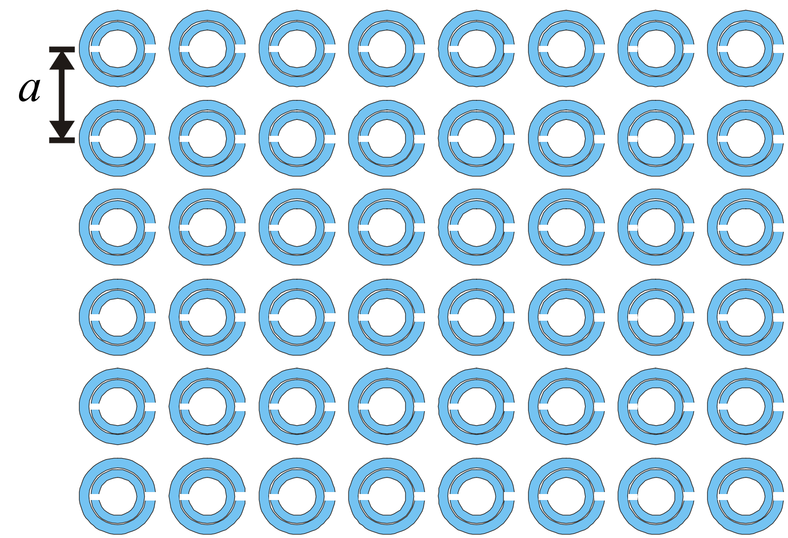
A metamaterial with μ < 0 at 10GHz

The 'split ring' structure is designed to resonate around 10GHz. The circulating currents give a magnetic response, even though the rings are made from copper.

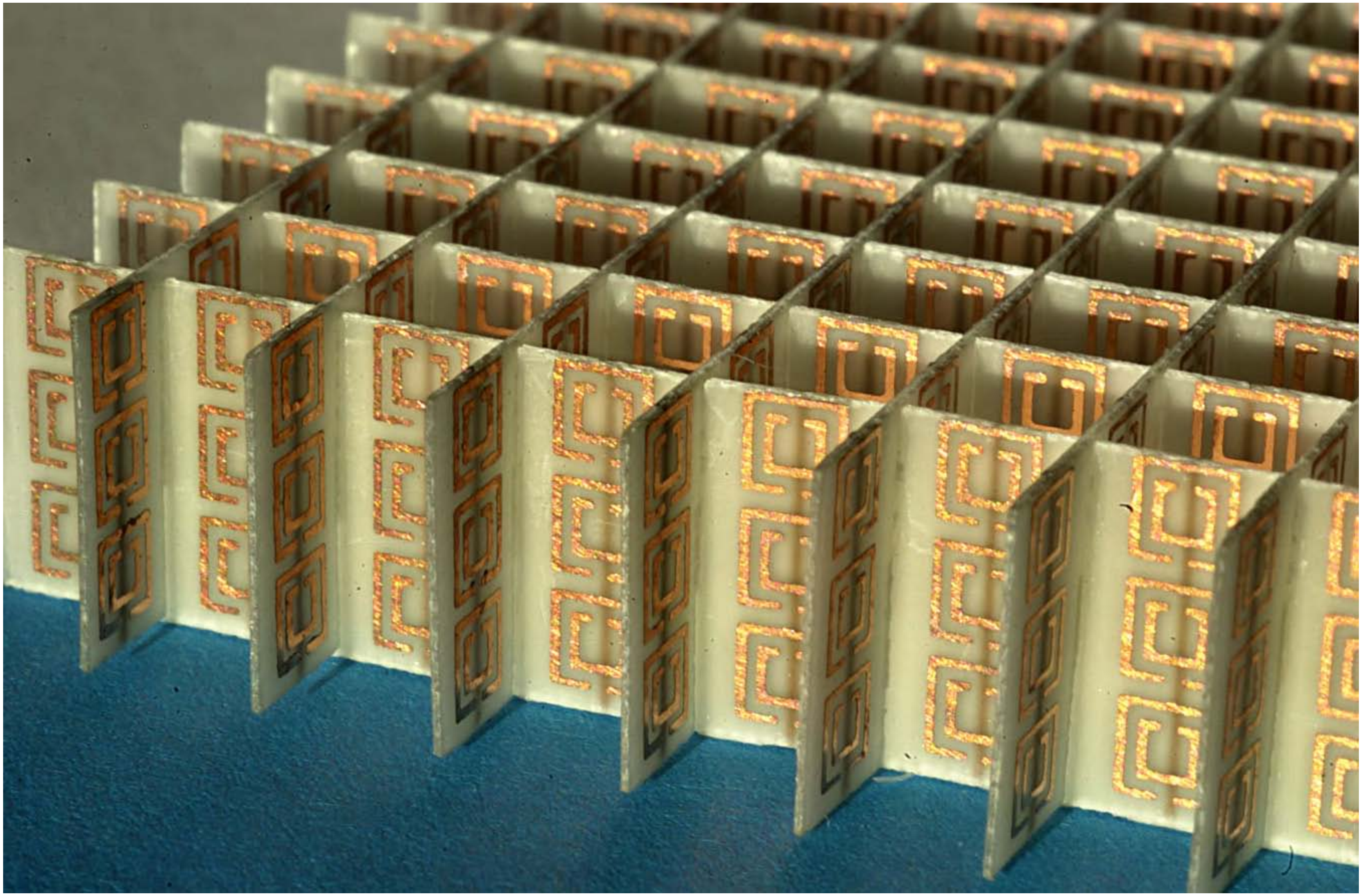




Planar split ring structure
inner radius r = 2.0mm
width of each ring c = 1.0mm
spacing between ring edges d = 0.1mm
lattice constant a = 10.0mm



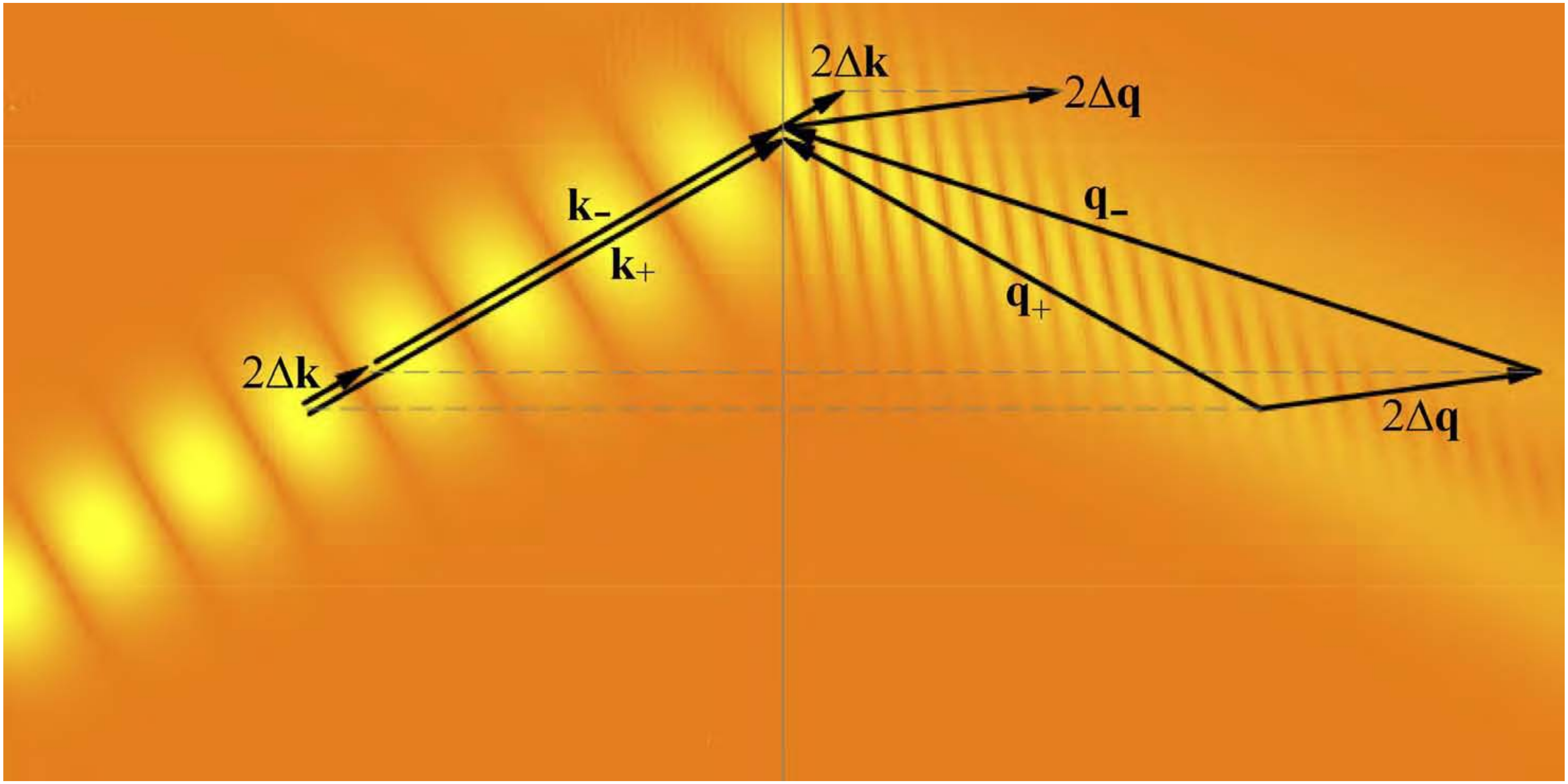
Negative refraction: $\varepsilon < 0, \mu < 0$



Structure made at UCSD by David Smith

Refraction of a Gaussian beam into a negative index medium.

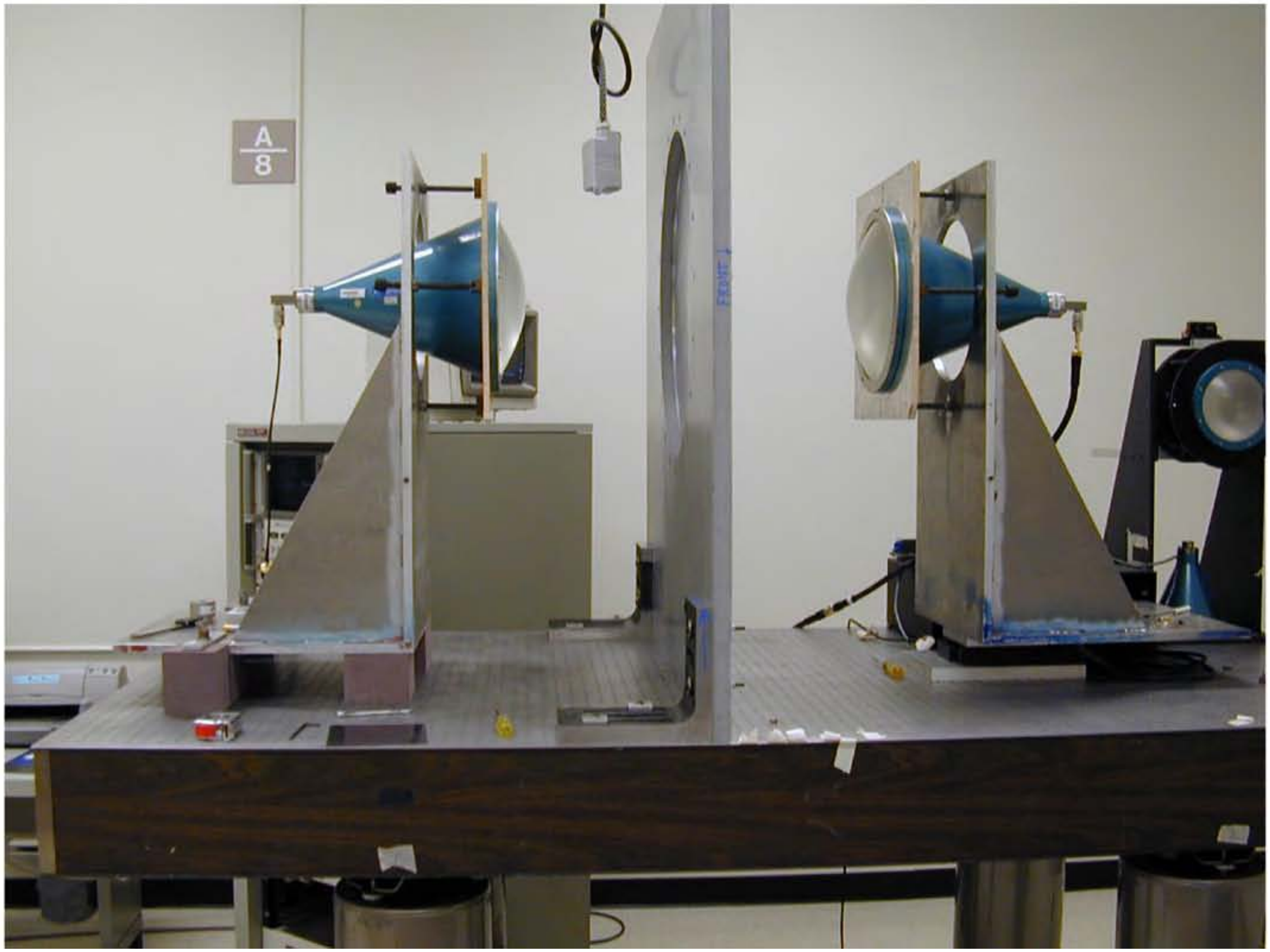
The angle of incidence is 30° (computer simulation by David Smith UCSD)



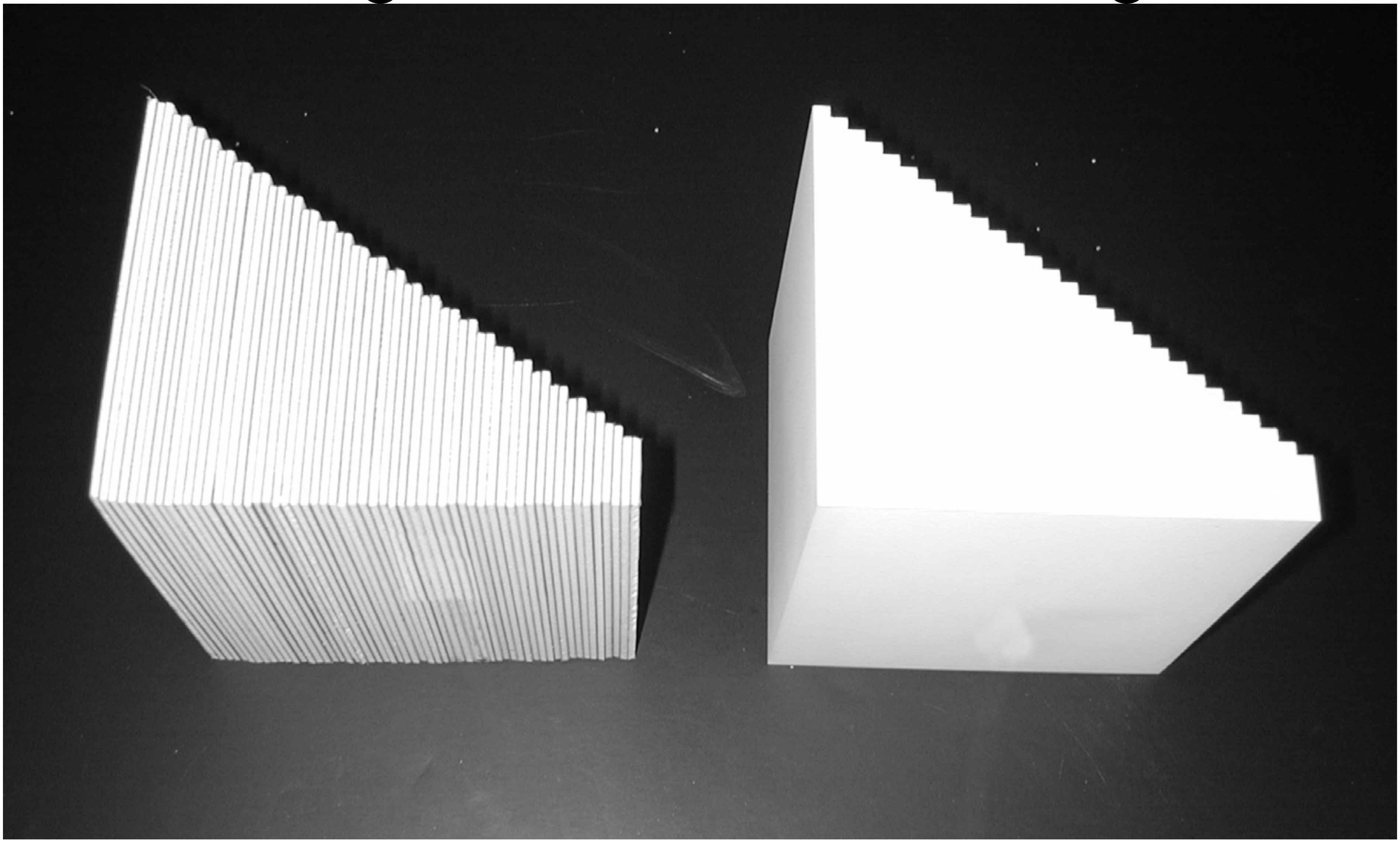
$$n(\omega_-) = -1.66 + 0.003i, \quad n(\omega_+) = -1.00 + 0.002i, \quad \Delta\omega/\omega = 0.07$$

Negative Refraction at the Phantom Works

Free-Space Experimental Set-up



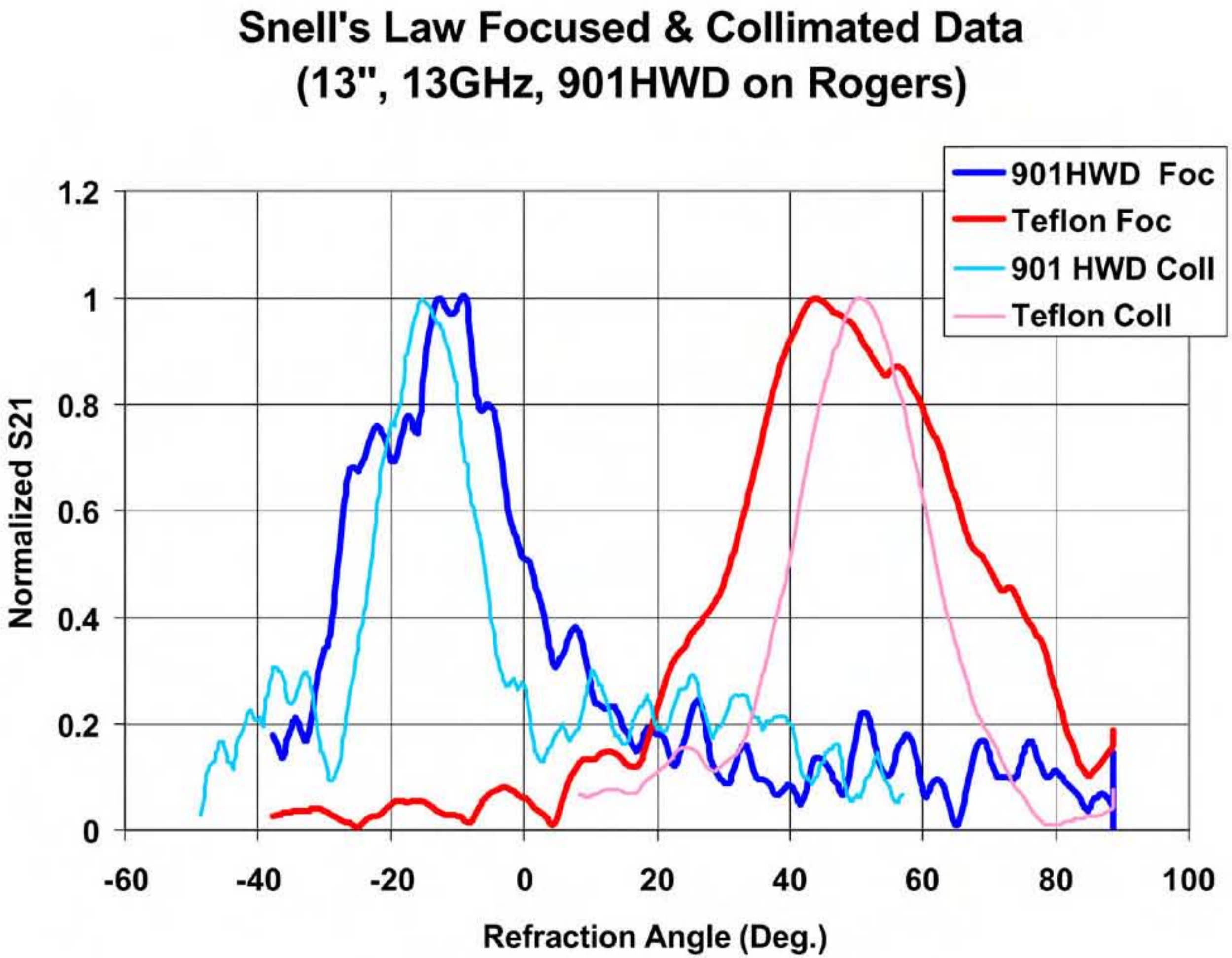
Boeing PhantomWorks 32° wedges



Left: negatively refracting sample
Right: teflon

Snell's Law Verification for n<0 in Free Space (2)

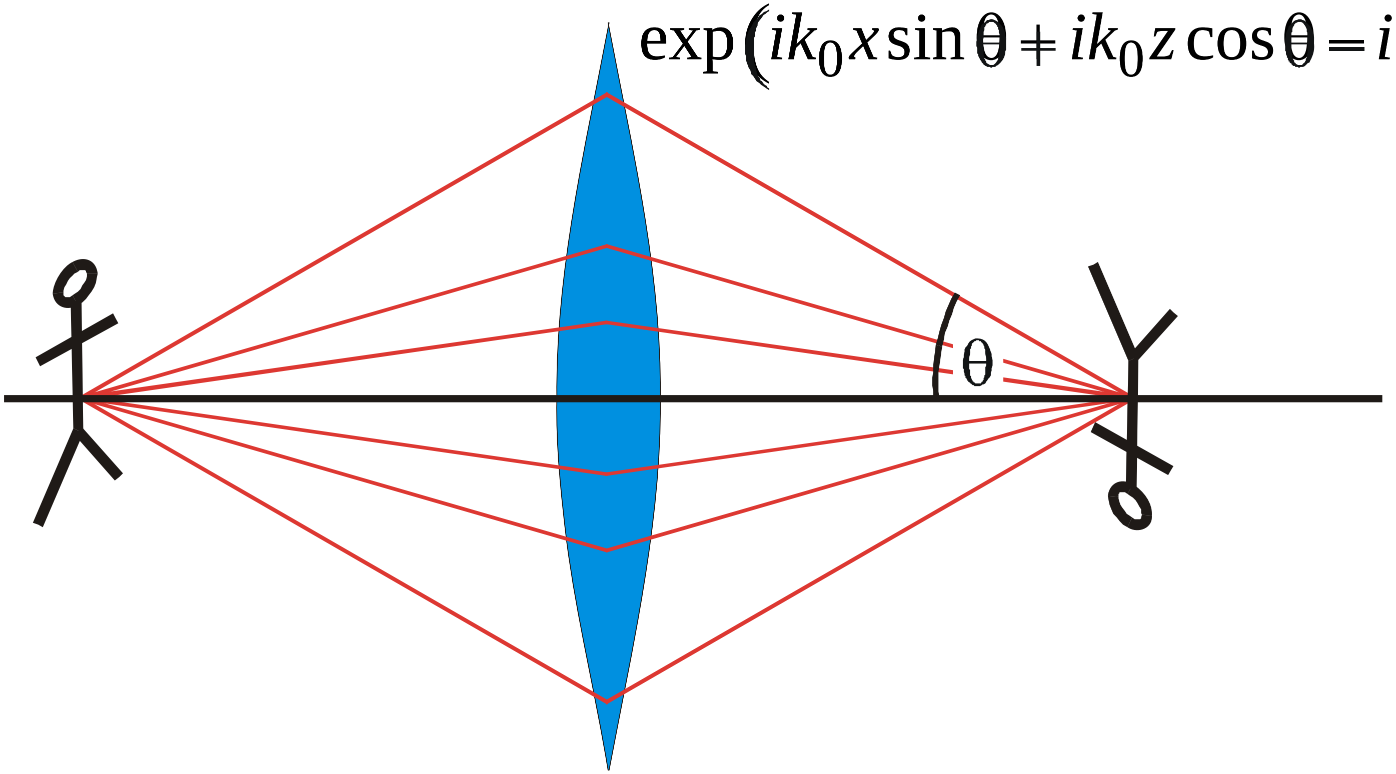
(Line plots, f=13 GHz, detector at 13", Boeing 2002)



Limitations to the Performance of a Lens

Contributions of the far field to the image …..

$$\exp\left(ik_0 x \sin\theta + ik_0 z \cos\theta - i\omega t\right)$$



….. are limited by the free space wavelength: $\theta = 90^\circ$ gives maximum value of $k_x = k_0 = \omega/c_0 = 2\pi/\lambda_0$ – the shortest wavelength component of the 2D image. Hence resolution is no better than,

$$\Delta \approx \frac{2\pi}{k_0} = \frac{2\pi c}{\omega} = \lambda_0$$

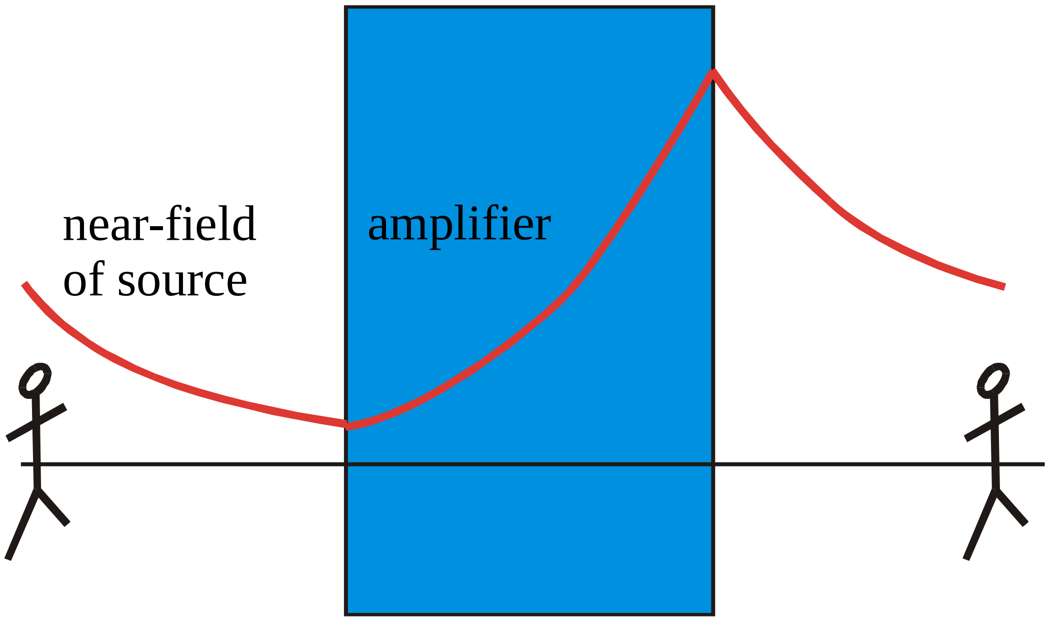
Limitations to a Conventional Lens (2)

Contributions of the near field to the image …..

come from large values of k_x responsible for the finest details in the source. Forget about ray diagrams because,

$$k_z = +i\sqrt{k_x^2 - \omega^2 c^{-2}}, \qquad \omega^2 c_0^{-2} < k_x^2$$

and 'near field' light decays exponentially with distance from the source. i.e. the near field is confined to the immediate vicinity of the source. Unless we can make an *amplifier* it is inevitable that the finest detail is lost from the image.



Attempting the impossible:
a lens for the near field,
a negative story

The consequences of negative refraction
3. *Perfect* Focussing

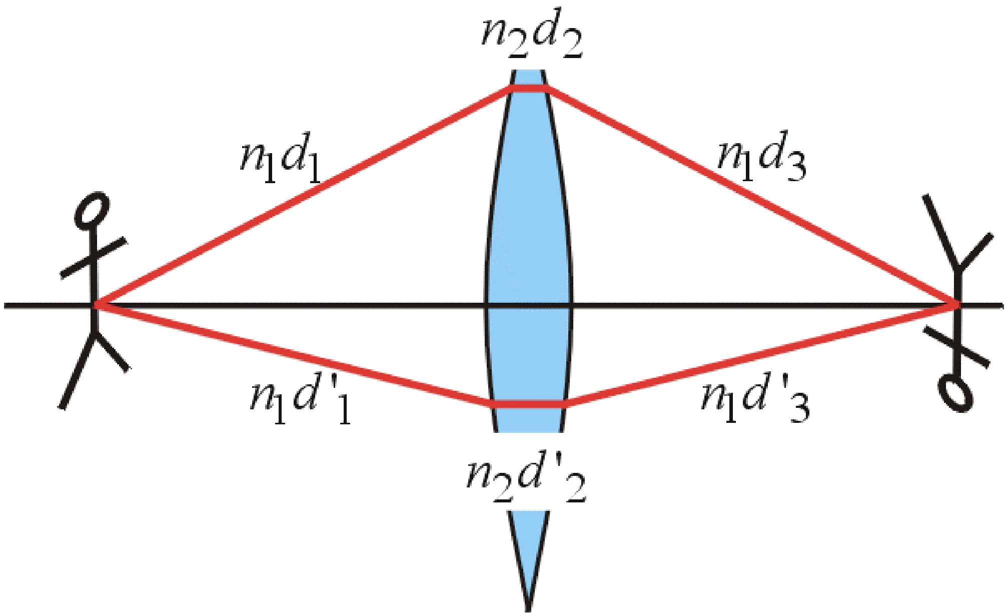
A conventional lens has resolution limited by the wavelength. The missing information resides in the near fields which are strongly localised near the object and cannot be focussed in the normal way.

The new lens based on negative refraction has *unlimited resolution* provided that the condition $n = -1$ is met exactly. This can happen only at one frequency. (Pendry 2000).

The secret of the new lens is that it can focus the near field and to do this it must *amplify* the highly localised near field to reproduce the correct amplitude at the image.

Fermat's Principle:

"Light takes the shortest optical path between two points"



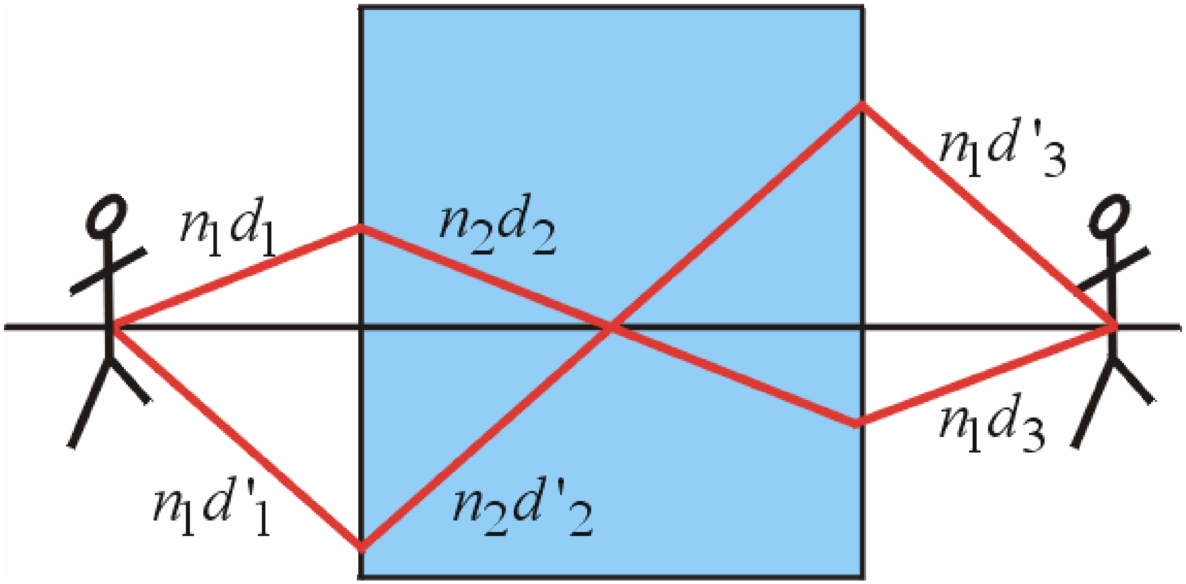
e.g. for a lens the shortest optical distance between object and image is:

$$n_1 d_1 + n_2 d_2 + n_1 d_3 = n_1 d'_1 + n_2 d'_2 + n_1 d'_3$$

both paths converge at the same point because both correspond to a minimum.

Fermat's Principle for Negative Refraction

If n_2 is negative the ray traverses **negative optical space**.



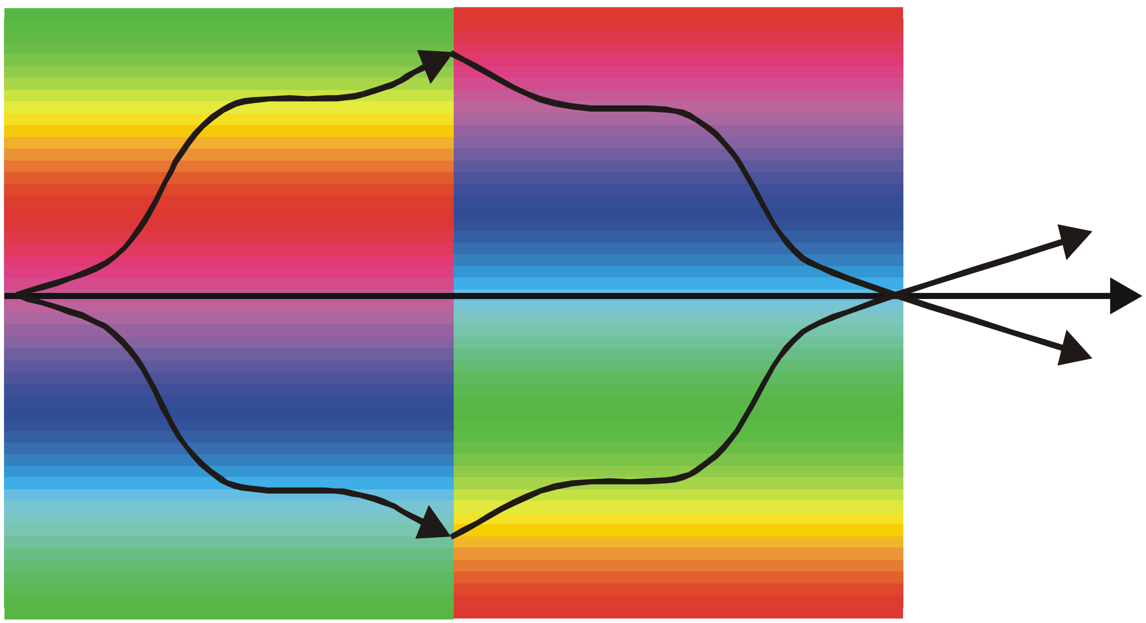
for a *perfect* lens ($n_2 = -n_1$) the shortest optical distance between object and image is **zero**:

$$0 = n_1 d_1 + n_2 d_2 + n_1 d_3$$
$$= n_1 d'_1 + n_2 d'_2 + n_1 d'_3$$

For a perfect lens the image *is* the object

Negative Space

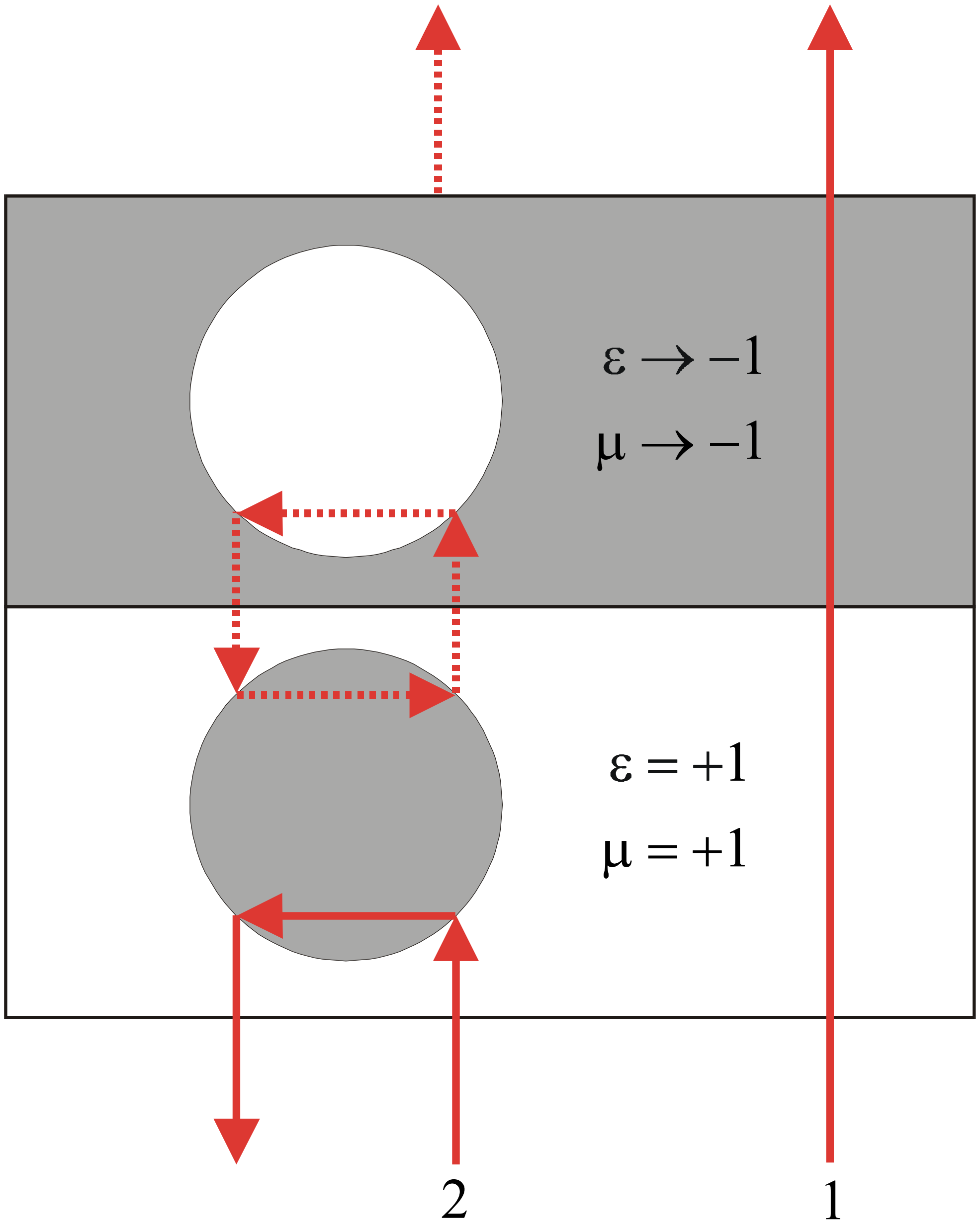
A slab of $n = -1$ material thickness d, cancels the effect of an equivalent thickness of free space. i.e. objects are focussed a distance $2d$ away. An alternative pair of complementary media, each cancelling the effect of the other. The light does not necessarily follow a straight line path in each medium:



General rule:
two regions of space optically cancel if in each region ε,μ are reversed mirror images.

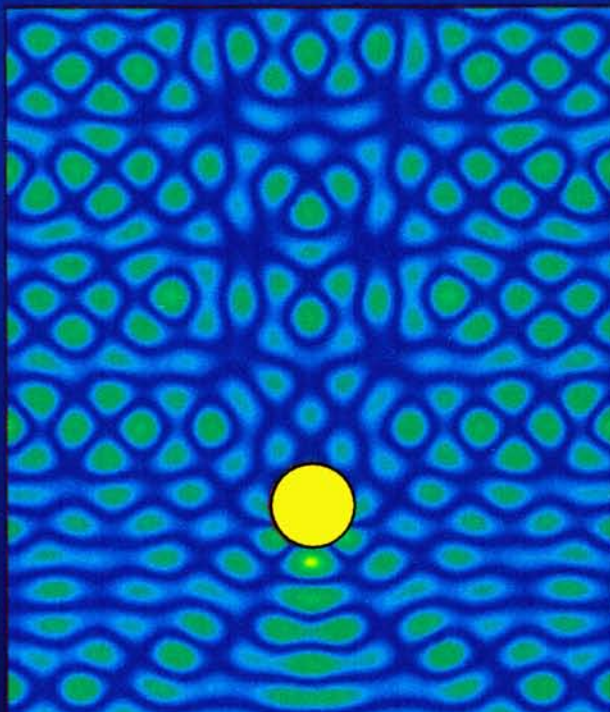
The overall effect is as if a section of space thickness $2d$ were removed from the experiment.

A Negative Paradox

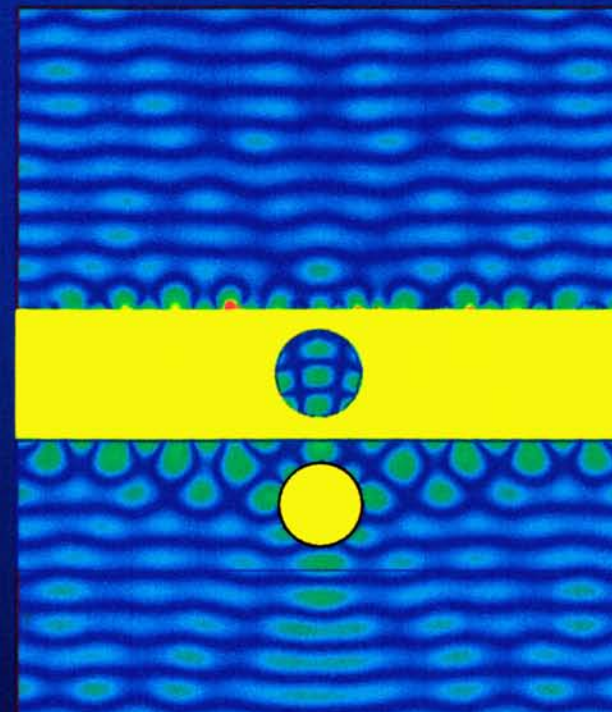


The left and right media in this 2D system are negative mirror images and therefore optically annihilate one another. However a ray construction appears to contradict this result. Nevertheless the theorem is correct and the ray construction erroneous. Note the closed loop of rays indicating the presence of resonances.

Compensation of inhomogeneous media



Scattering from a cylinder with n=-1.4



Compensation of the n=-1.4 cylinder

The ‘Poor Man’s Superlens’

The original prescription for a superlens: a slab of material with

$$\varepsilon = -1, \mu = -1$$

However if all relevant dimensions (the thickness of the lens, the size of the object etcetera) are much less than the wavelength of light, electric and magnetic fields are decoupled. An object that comprises a pure electric field can be imaged using a material with,

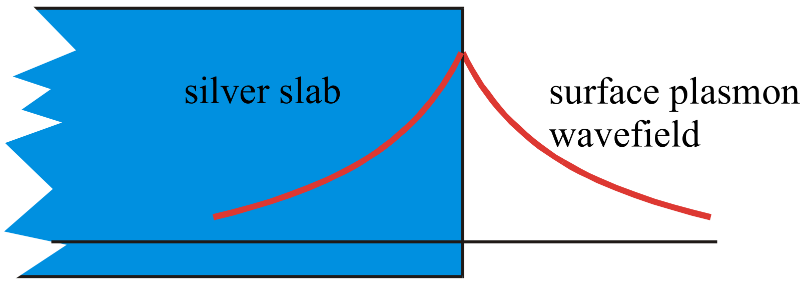
$$\varepsilon = -1, \mu = +1$$

because, in the absence of a magnetic field, μ is irrelevant.

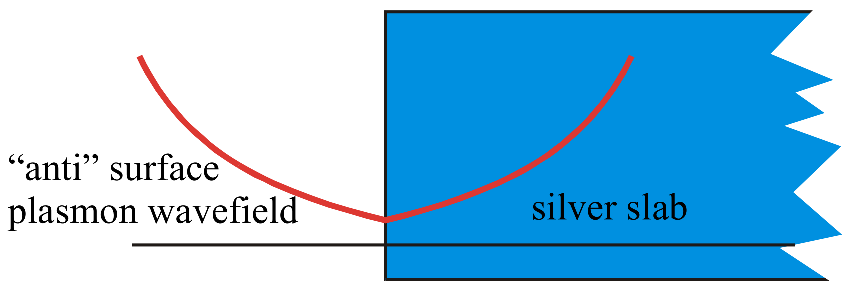
We can achieve this with a slab of silver which has $\varepsilon < 0$ at optical frequencies.

Anatomy of a Superlens

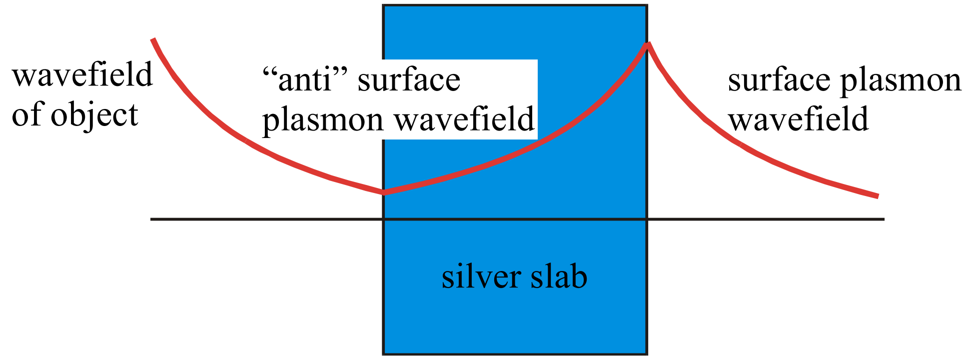
The superlens works by **resonant excitation of surface plasmons in the silver**,



At the same frequency as the surface plasmon there exists an unphysical "anti" surface plasmon - wrong boundary conditions at infinity,



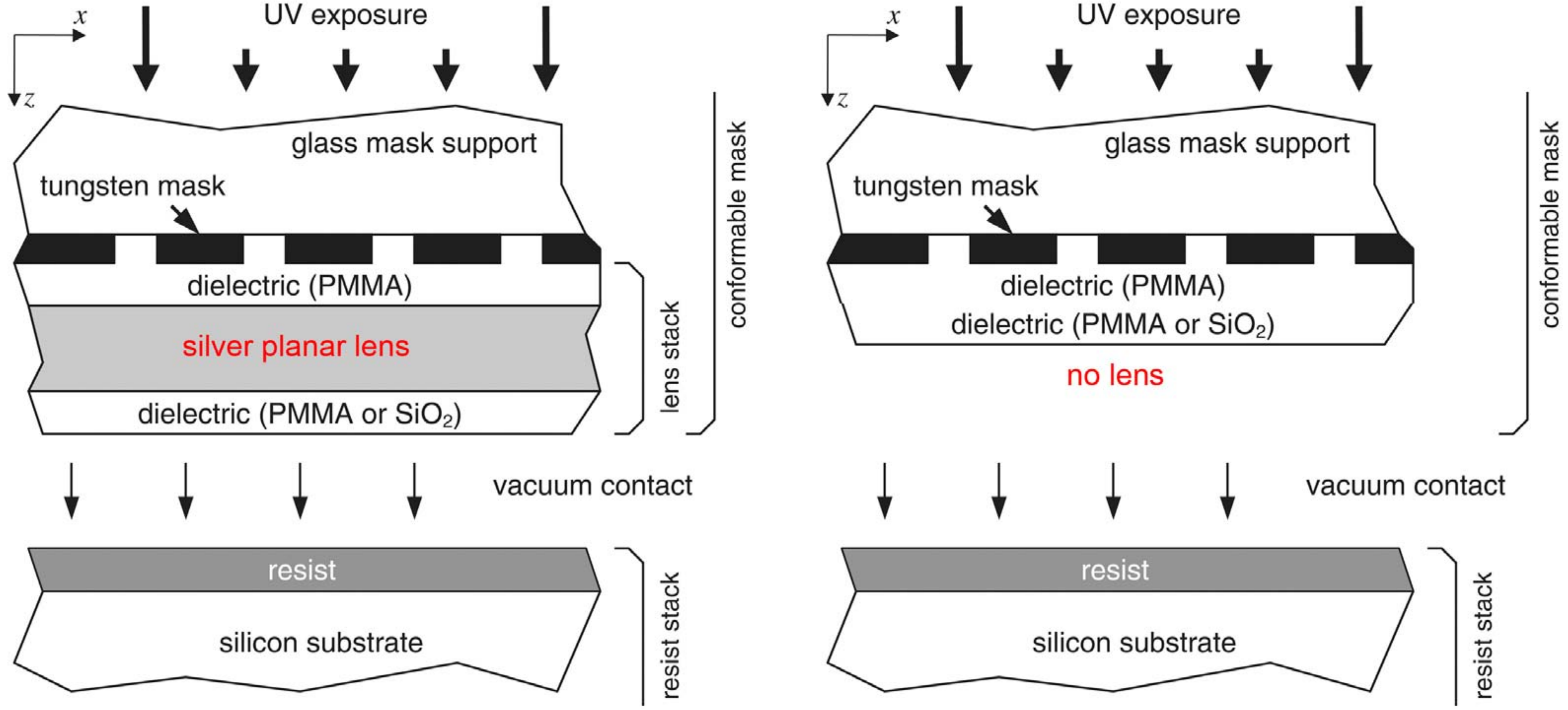
However,



Matching the fields at the boundaries selectively excites a surface plasmon on the far surface.

Near Field Superlensing Experiments

Richard Blaikie and David Melville, *J. Opt. A*, **7** S176 (2005)



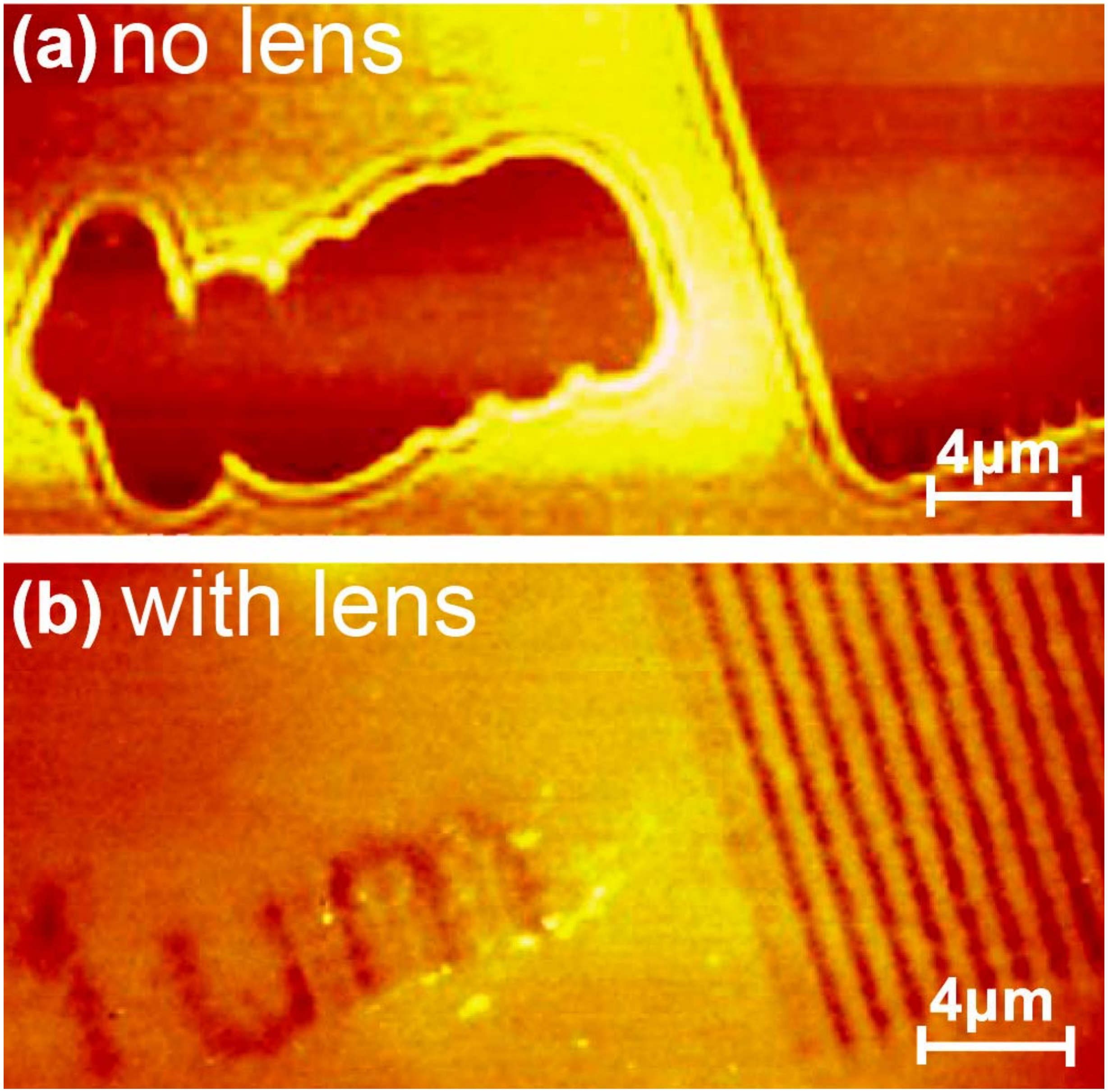
Left: experimental setup for a near field silver planar lens

Right: reference experiment excluding the lens

Imperial College London

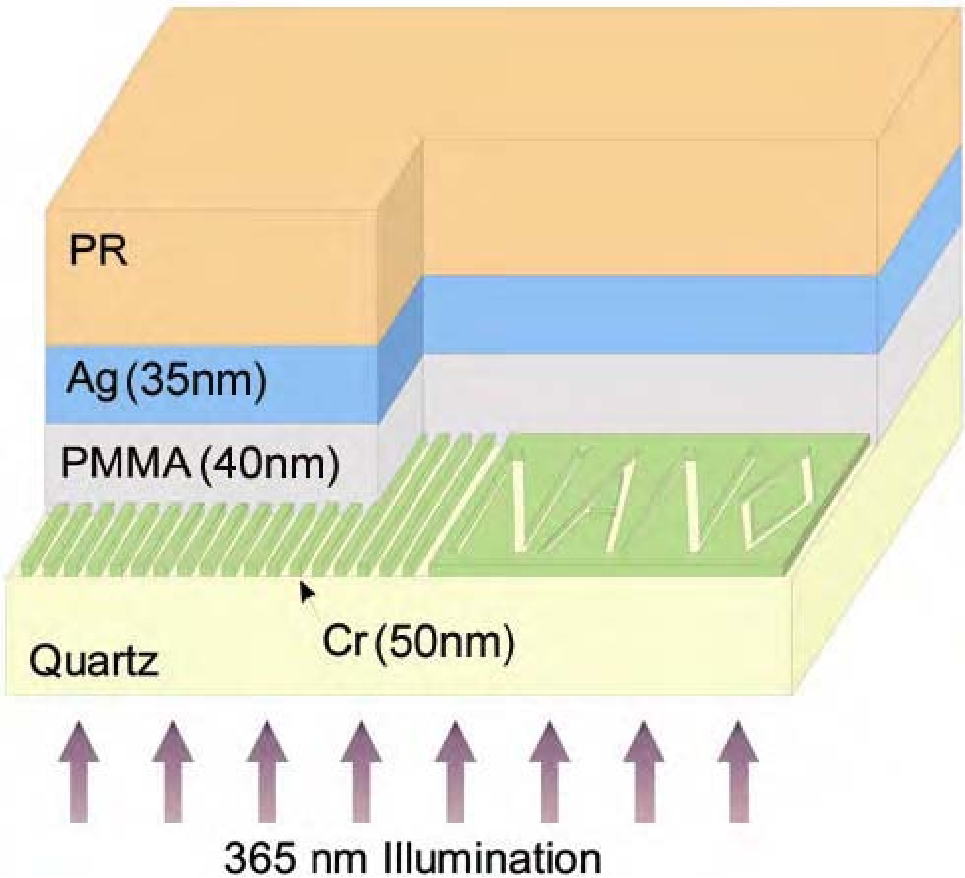
Near Field Superlensing Experiments

Richard Blaikie and David Melville, *J. Opt. A*, **7** S176 (2005)



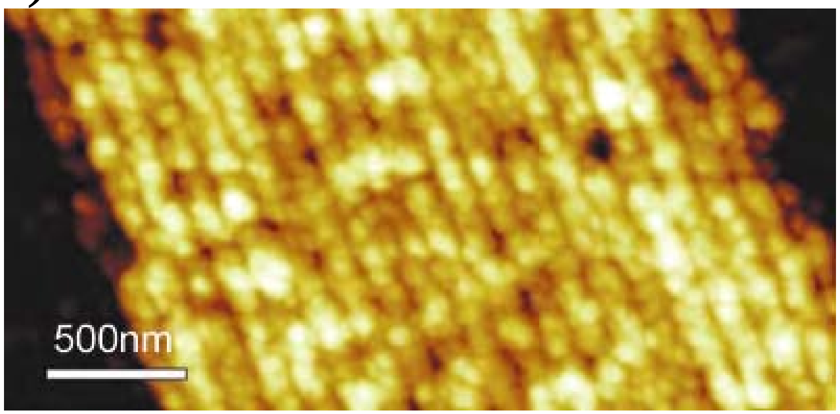
Near field superlensing experiment:

Nicholas Fang, Hyesog Lee, Cheng Sun and Xiang Zhan, UCB



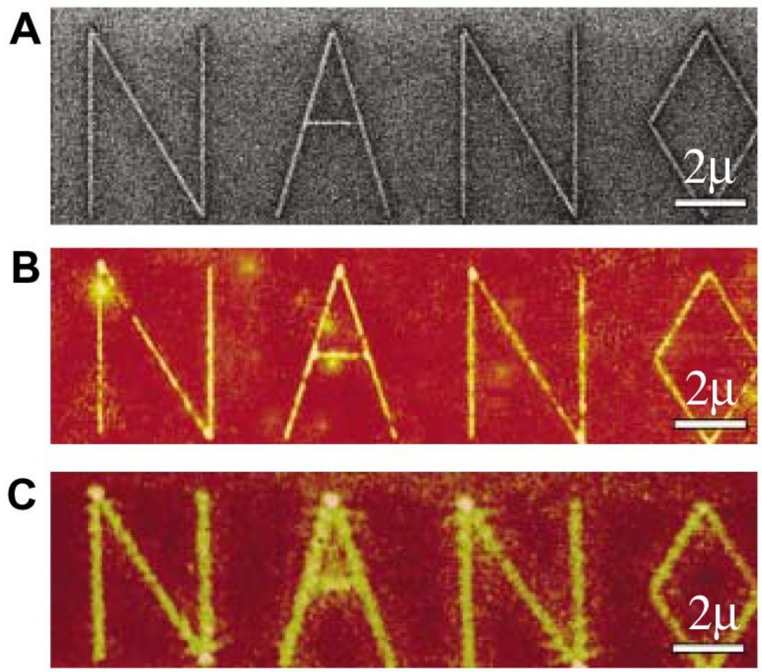
Left: the objects to be imaged are inscribed onto the chrome. Left is an array of 60nm wide slots of 120nm pitch. The image is recorded in the photoresist placed on another side of silver superlens.

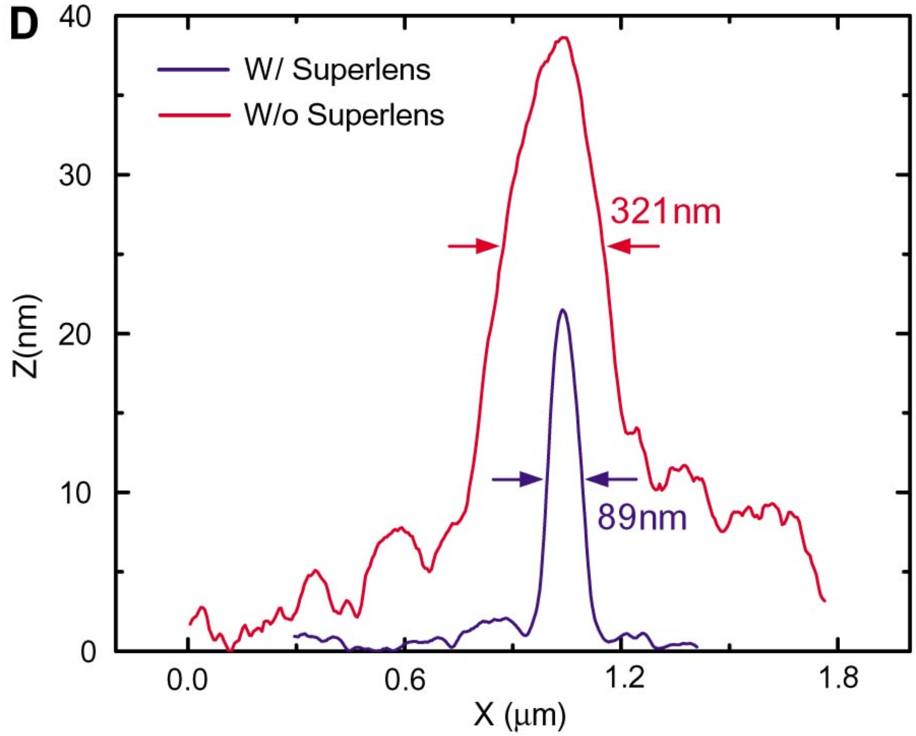
Below: Atomic force microscopy of a developed image. This clearly shows a superlens imaging of a 60 nm object ($\lambda/6$).



Imaging by a Silver Superlens.

Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang, *Science* 534 **308** (2005)





(A) FIB image of the object. The linewidth of the ‘‘NANO’’ object was 40 nm.

(B) AFM of the developed image on photoresist with a 35-nm-thick silver superlens.

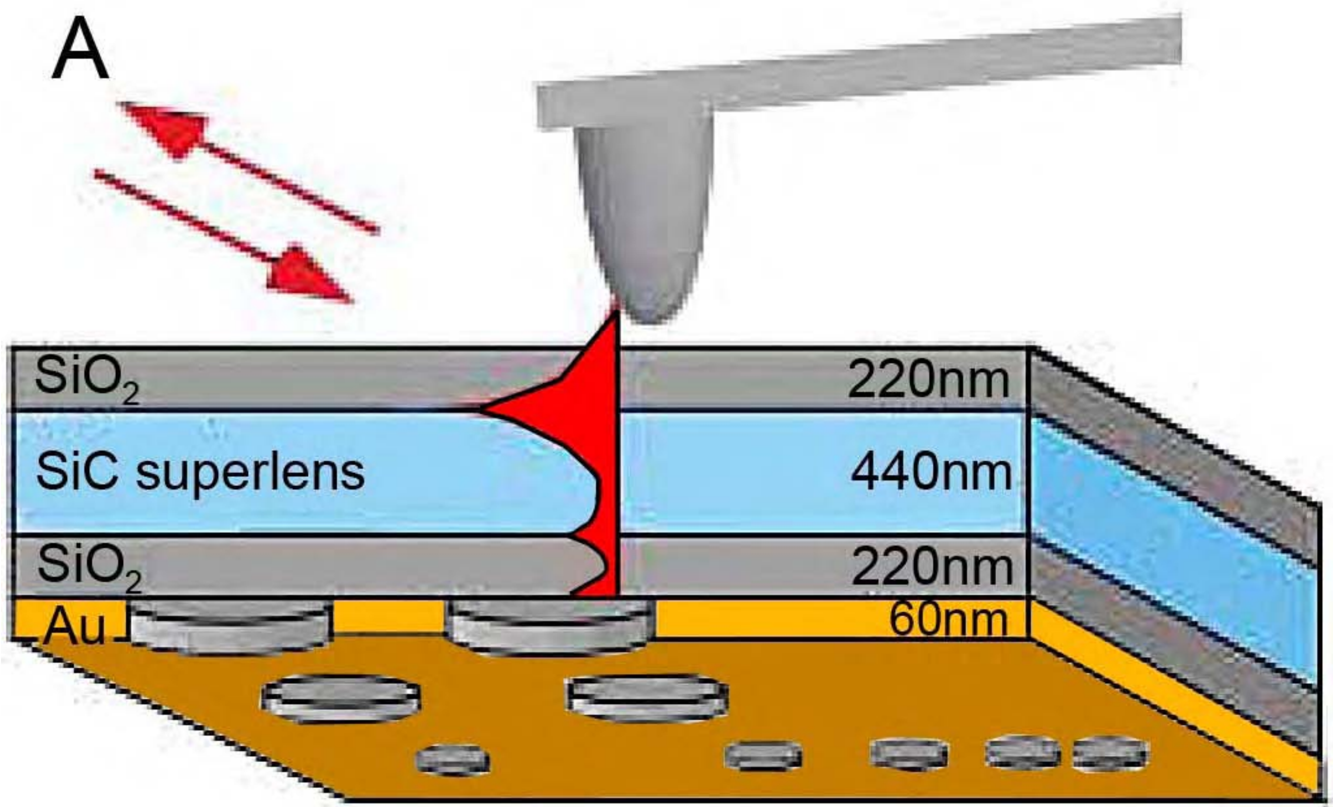
(C) AFM of the developed image on photoresist when the layer of silver was replaced by PMMA spacer as a control experiment.

(D) *blue line*: averaged cross section of letter ‘‘A’’ line width 89nm
red line: control experiment line width 321nm.

Near-Field Microscopy Through a SiC Superlens

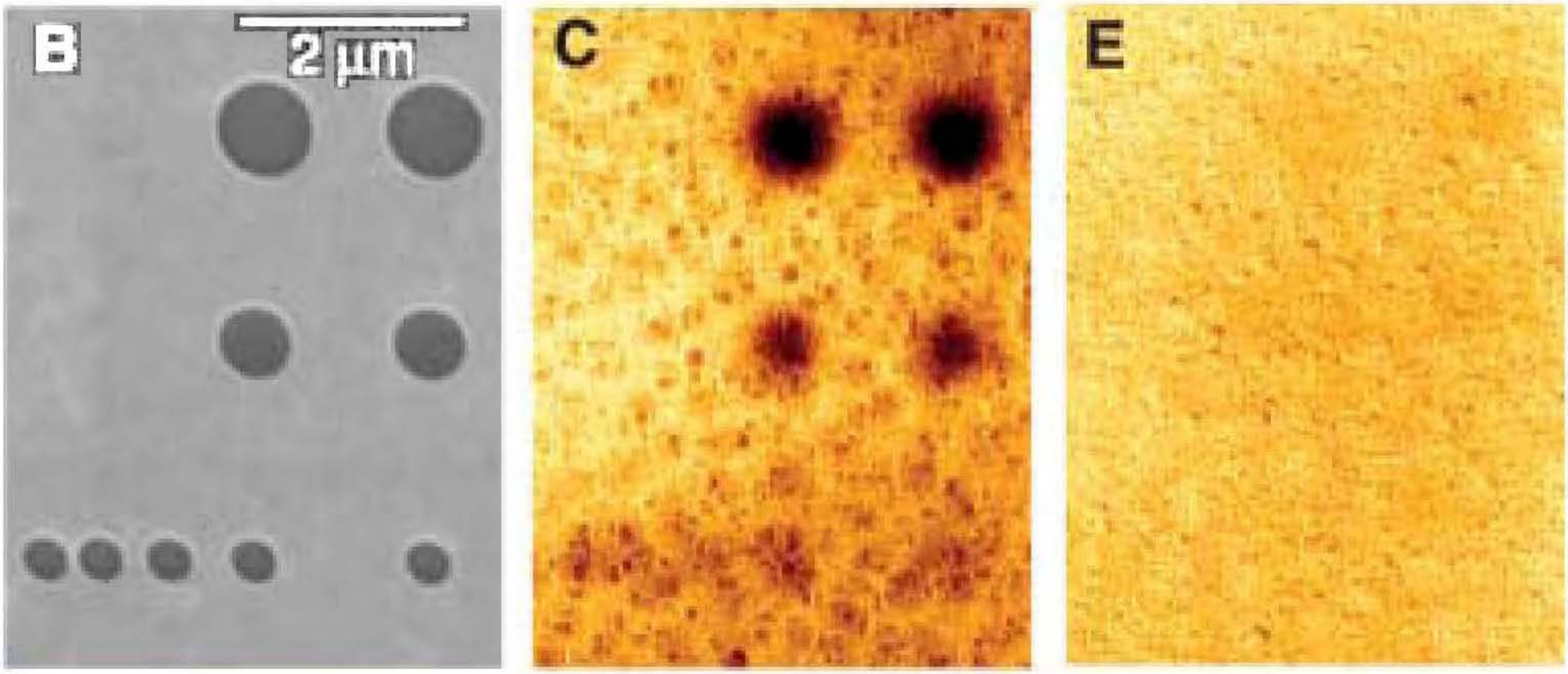
Science, **313** 1595 (2006)

Thomas Taubner, Dmitriy Korobkin, Yaroslav Urzhumov, Gennady Shvets, Rainer Hillenbrand



Near-field microscopy through a 880nm thick superlens structure: the superlens is a 440-nm-thick single-crystalline SiC membrane coated on both sides with 220-nm-thick SiO_2 layers. The two surfaces of the sandwich correspond to the object and the image planes of the lens, respectively. The object plane is covered by a Au film patterned with holes of different diameters

SiC Superlens: the Image



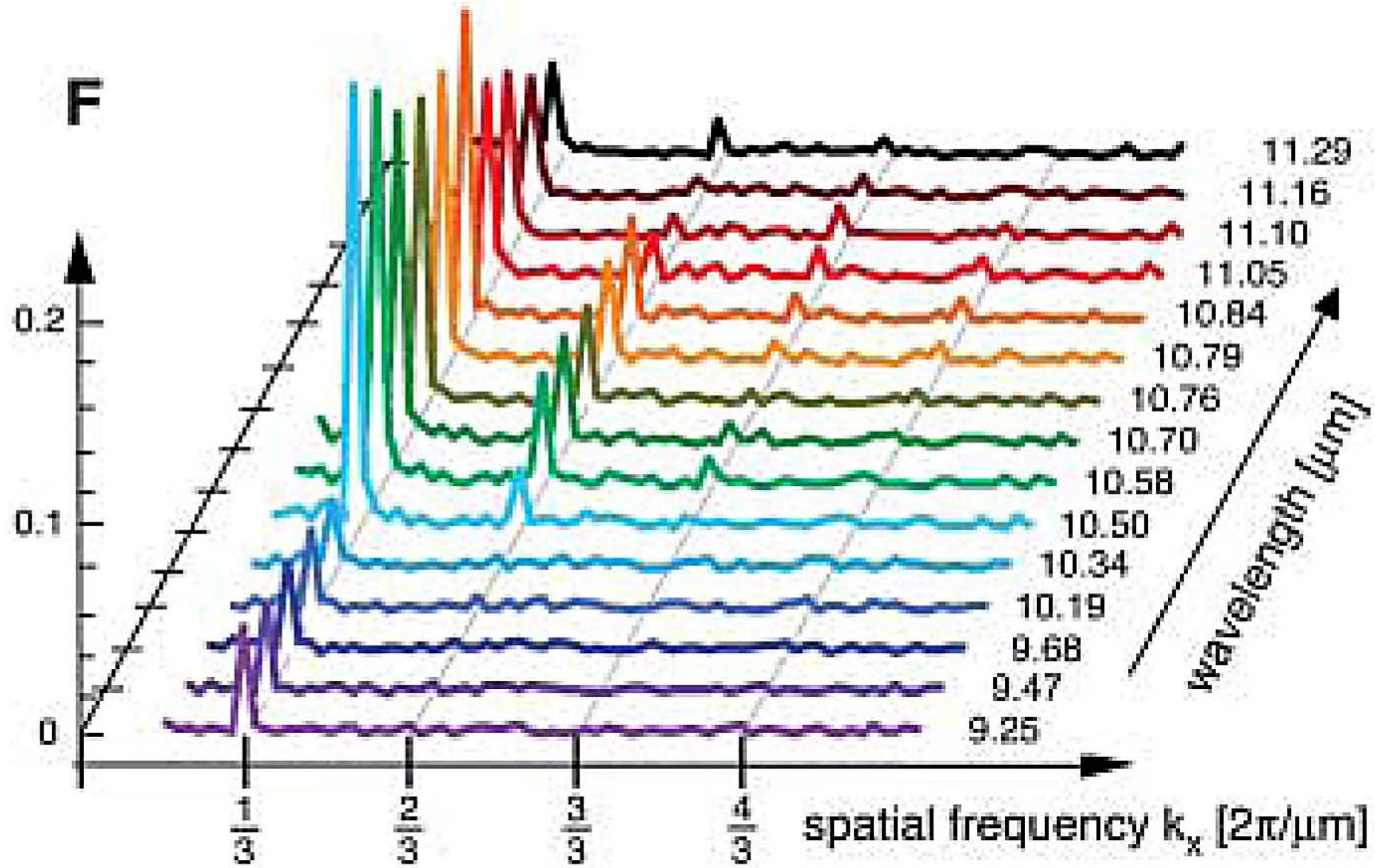
(B) Scanning electron microscope image of the object plane showing holes in a 60nm thick Au film.

(C) amplitude in the image plane at λ = 10.85μ where imaging is expected. NB the permittivity changes with frequency and hence imaging conditions are precisely met only at one frequency.

(E) Control image at λ = 9.25μ (no superlensing)

SiC Superlens:

Fourier transforms of line scans taken from images of a grating, $\lambda \approx 3\mu$ period



High spatial frequencies, up to the grating's fourth harmonic, are imaged by the superlens around $\lambda \approx 10.84\mu$ where the SiC permittivity meets the superlensing condition.

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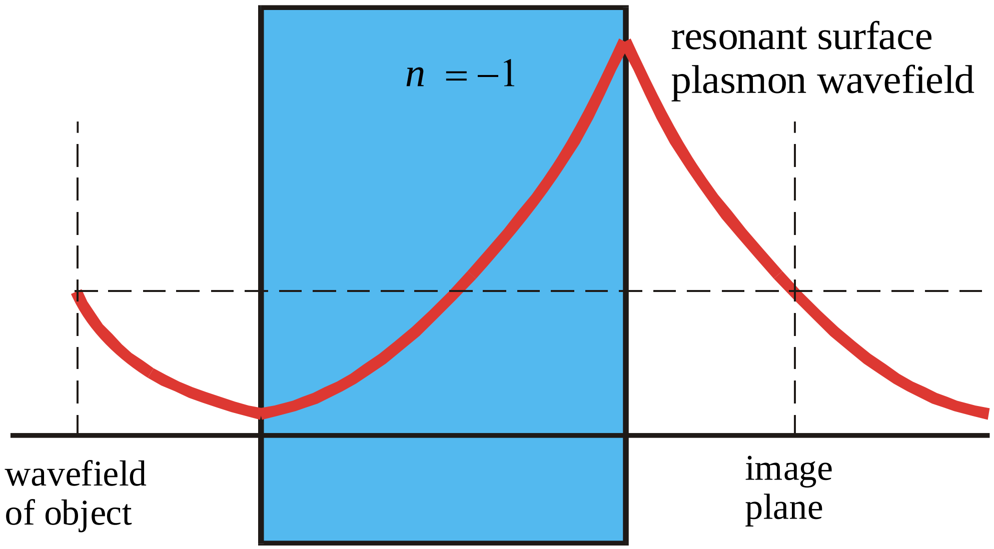
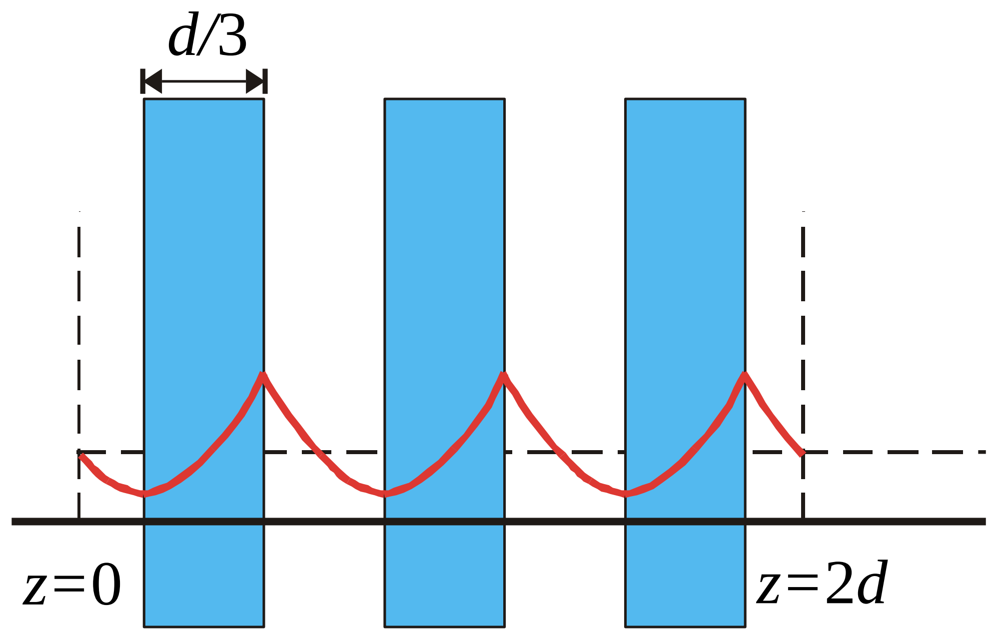
Optimising Performance: the Layered Lens (1)

Absorption is a problem because of losses in the surface plasmon resonance. Cutting the lens into several mini lenses* reduces the maximum amplitude of the wave field and hence cuts the losses which in turn enhances the resolution.





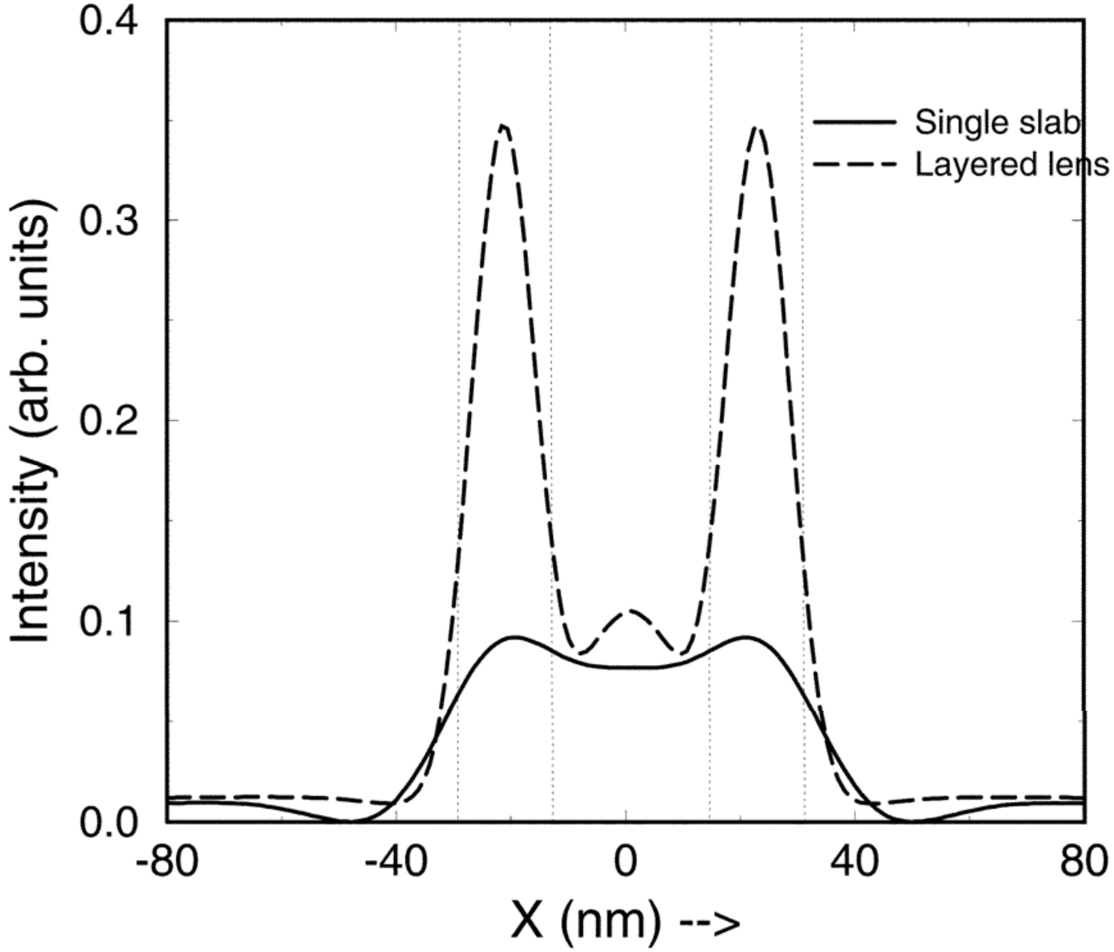
* see also:
E. Shamonina, V.A. Kalinin, K.H. Ringhofer & L. Solymar, *Electron. Lett.* **37** 1243 (2001)
S. Anantha Ramakrishna and JB Pendry, *Phys. Rev.* **B67** 201101 (2003).

Optimising Performance: the Layered Lens (2)

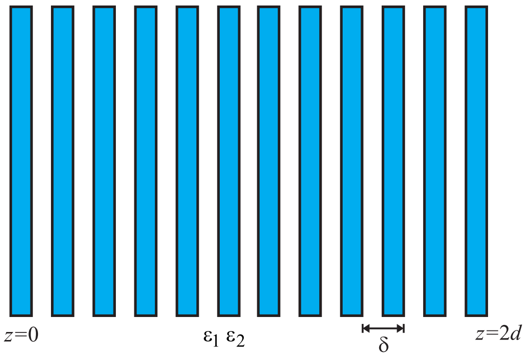
Reduced losses in the layered lens leads to enhanced resolution. The object comprises two slits of 5nm width and a peak-to-peak separation of 45 nm.

dashed curve: single slab of silver, $\varepsilon = -1 + 0.4i$, of thickness 40nm

full curve: layered stack comprising 8x5nm of silver (i.e. same total thickness).



Silver /dielectric layers as metamaterials



The near field optic fibre comprises alternate slices of positive and negative dielectric function material of equal thickness. This makes an effective medium. Averaging an electric field perpendicular to the layers gives an effective ε_z, and in the special case $\varepsilon_1 = +1, \quad \varepsilon_1 = -1,$

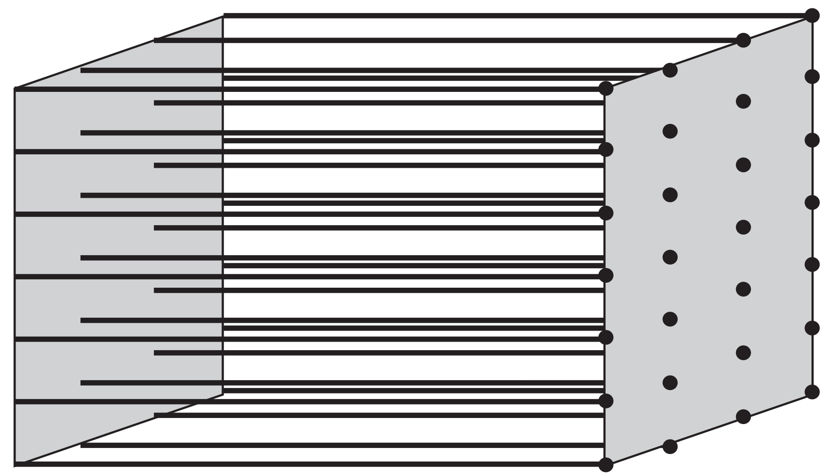
$$\varepsilon_z^{-1} = \tfrac{1}{2}\left(\varepsilon_1^{-1} + \varepsilon_2^{-1}\right) = \tfrac{1}{2}\left(\frac{1}{-1+i\delta} + 1\right) \approx -\tfrac{i}{2}\delta, \qquad \varepsilon_z \approx \infty$$

Averaging a displacement field parallel to the layers gives an effective ε_x,

$$\varepsilon_x = \tfrac{1}{2}\left(\varepsilon_1 + \varepsilon_2\right) = \tfrac{1}{2}\left(-1 + i\delta + 1\right) = \tfrac{i}{2}\delta \qquad \varepsilon_x \approx 0$$

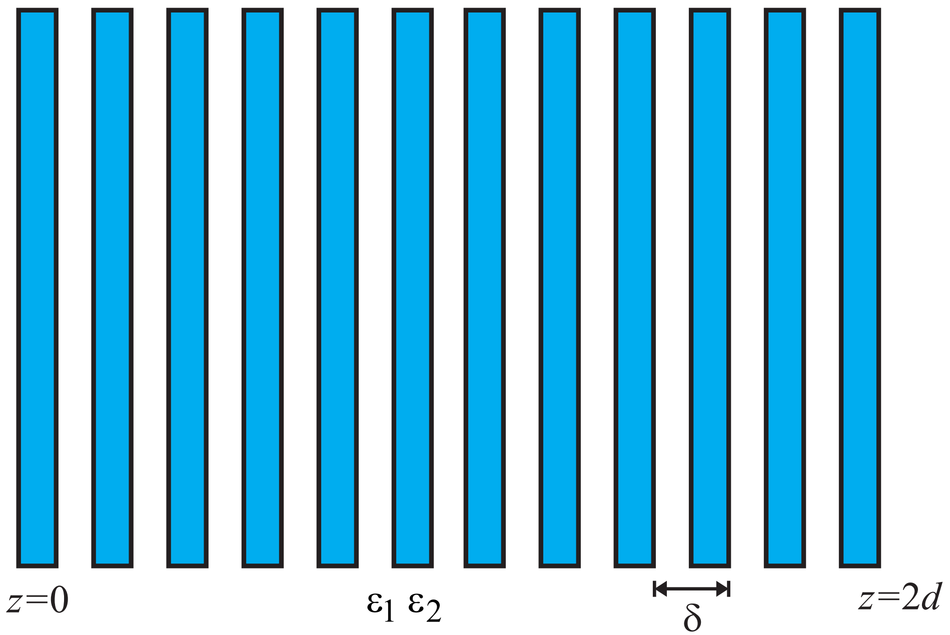
Therefore we have a *metamaterial* which resembles a set of infinitely fine, highly conducting wires aligned normal to the layers, separated by an almost perfect insulator.

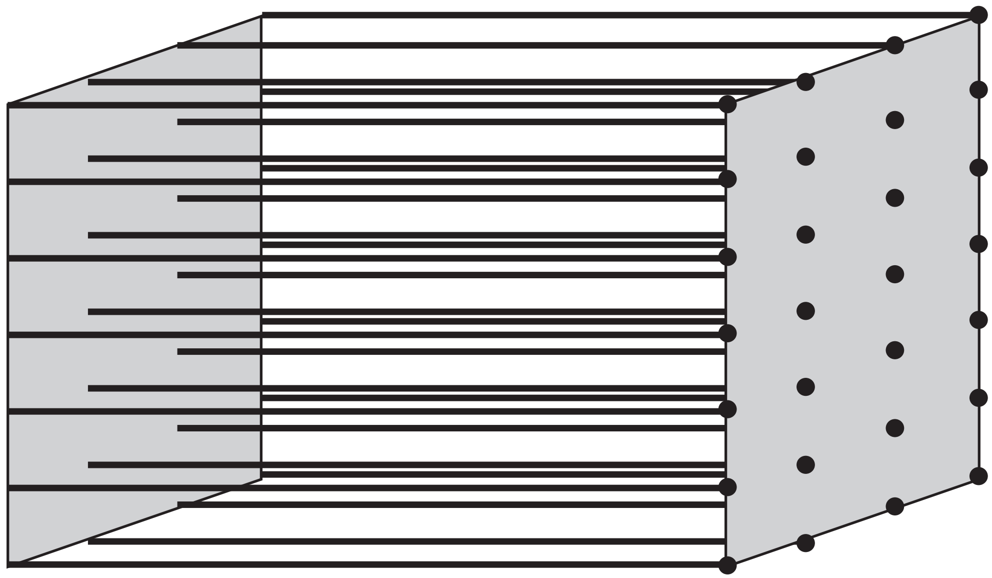
S. Anantha Ramakrishna and JB Pendry,
Phys. Rev. **B67** 201101 (2003).



Silver /dielectric layers as metamaterials

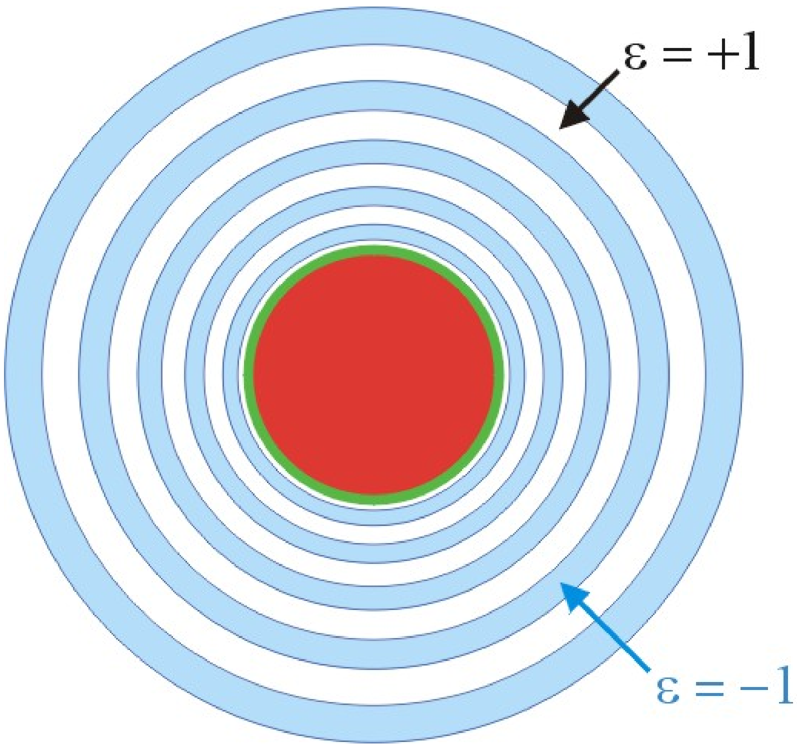
In the limit that the lens comprises many thin slices and $\varepsilon_1 = +1$, $\varepsilon_2 = -1$, a layered medium is effectively a fibre optic bundle with the unique capacity of guiding the near field. Electrical objects placed on one side of the layers are transmitted undistorted to the other side. The two sides are 'hard wired' together.



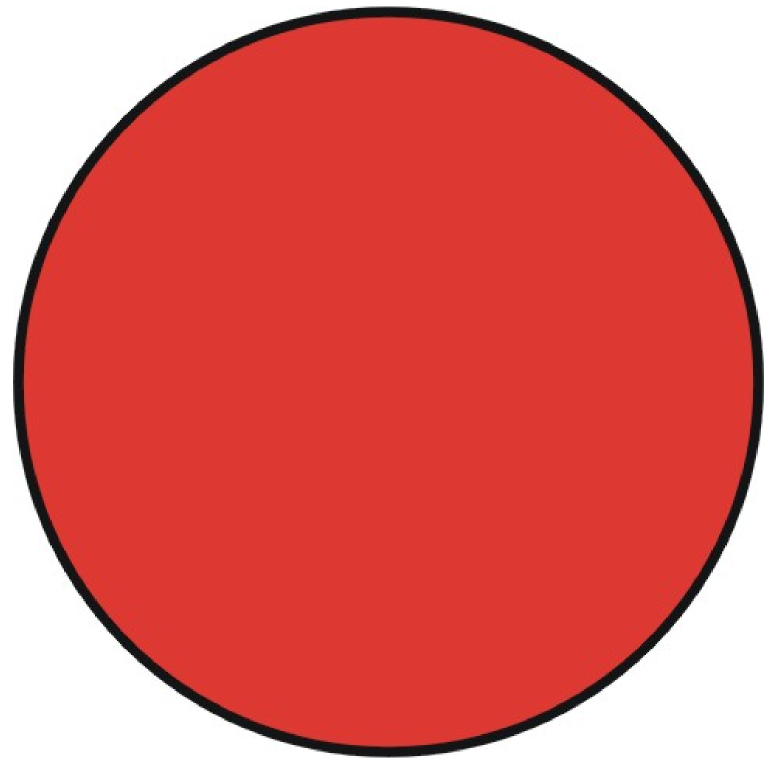


Spherical Layered Systems

Alternate flat layers of silver act like an endoscope, but the same is true of any curved surface. For example the contents of a small sphere can be magnified in this way.



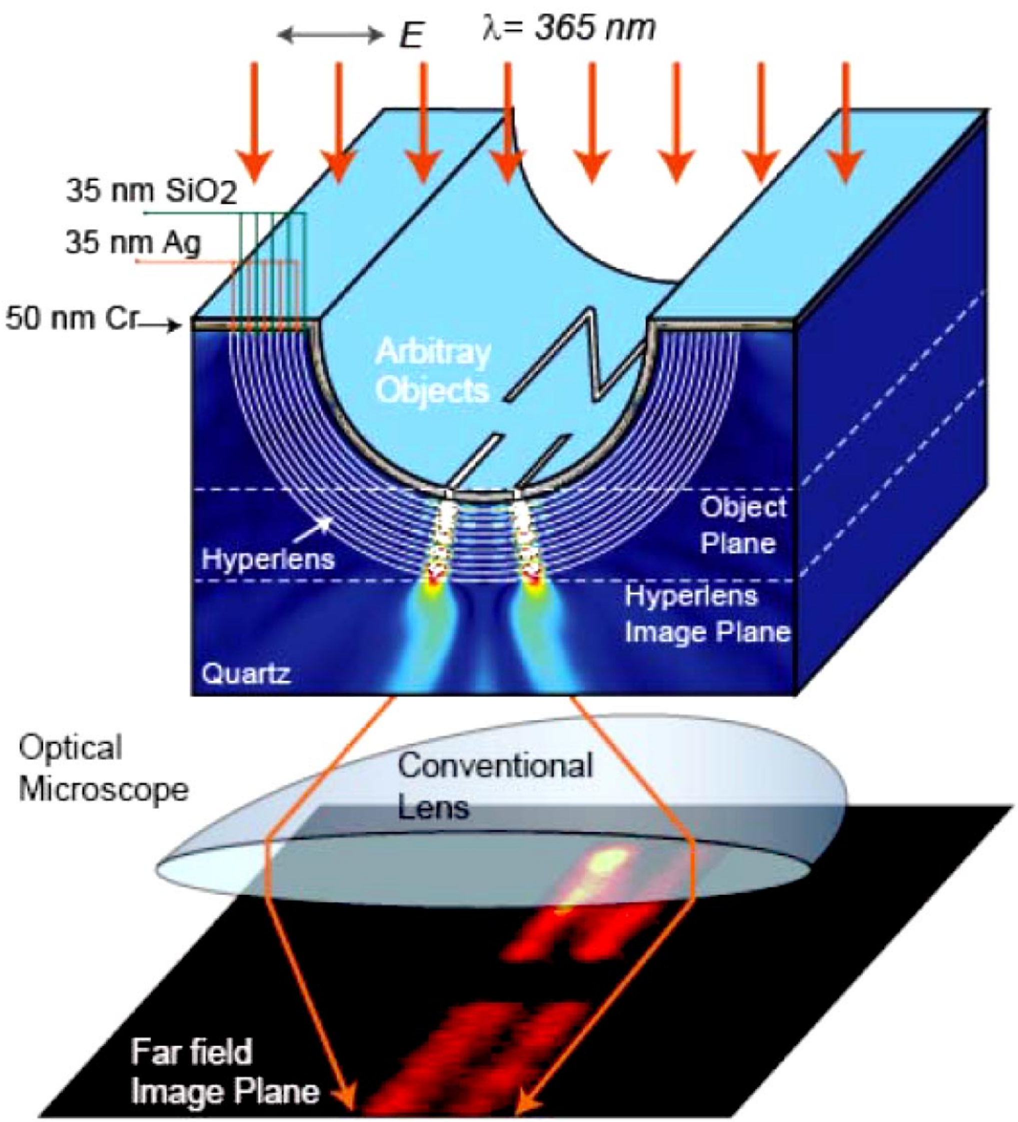
looks like



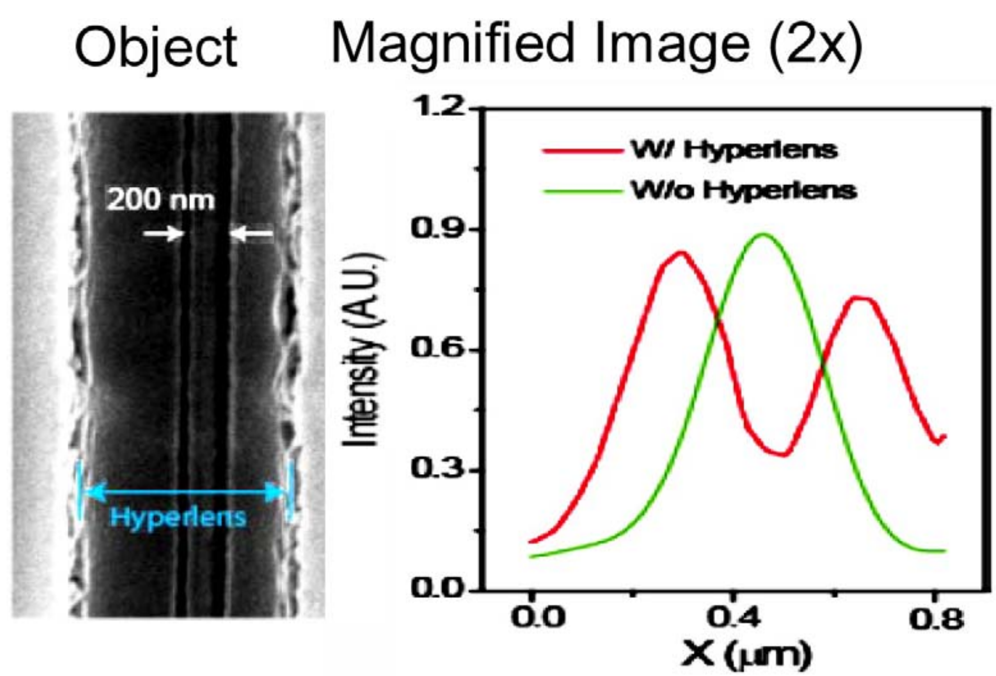
Theory: Z Jacob LV Alekseyev, E Narimanov *Optics Express* **14** 8247-8256 2006
Experiment: II Smolyaninov, YJ Hung , and CC Davis, arxiv.org/pdf/physics/0610230

A magnifying optical hyperlens

Zhang Group at UC Berkeley (submitted)



Experimental schematic setup and numerical simulation for a hyperlens made of 16 layers of Ag/SiO2 imaging a line-pair object with **line width of 35 nm and spacing of 200 nm.** The diffraction limit is 260nm



Conclusions

- Negative refraction is a radical new concept in optics
- *Metamaterials* enable negative refraction to be achieved for the first time – it never occurs in natural materials
- Using negatively refracting materials it is possible to build a ‘perfect lens’ limited only by the quality of manufacture not by physical laws
- Version of this lens have been realised first in the microwave region and now at optical band THz frequencies

Metamaterials and Negative Refraction

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http://www.cmth.ph.ic.ac.uk/photonics/

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