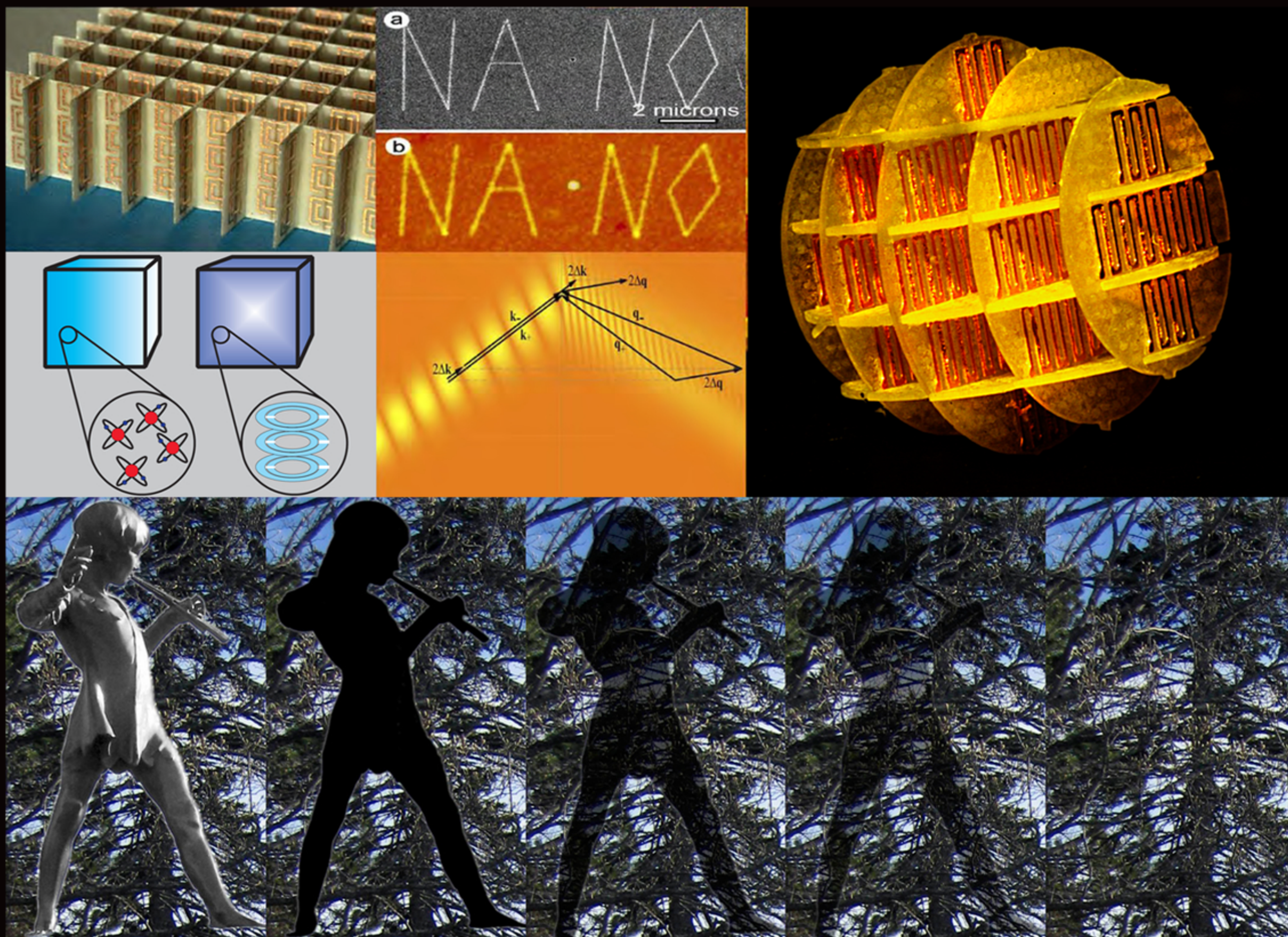
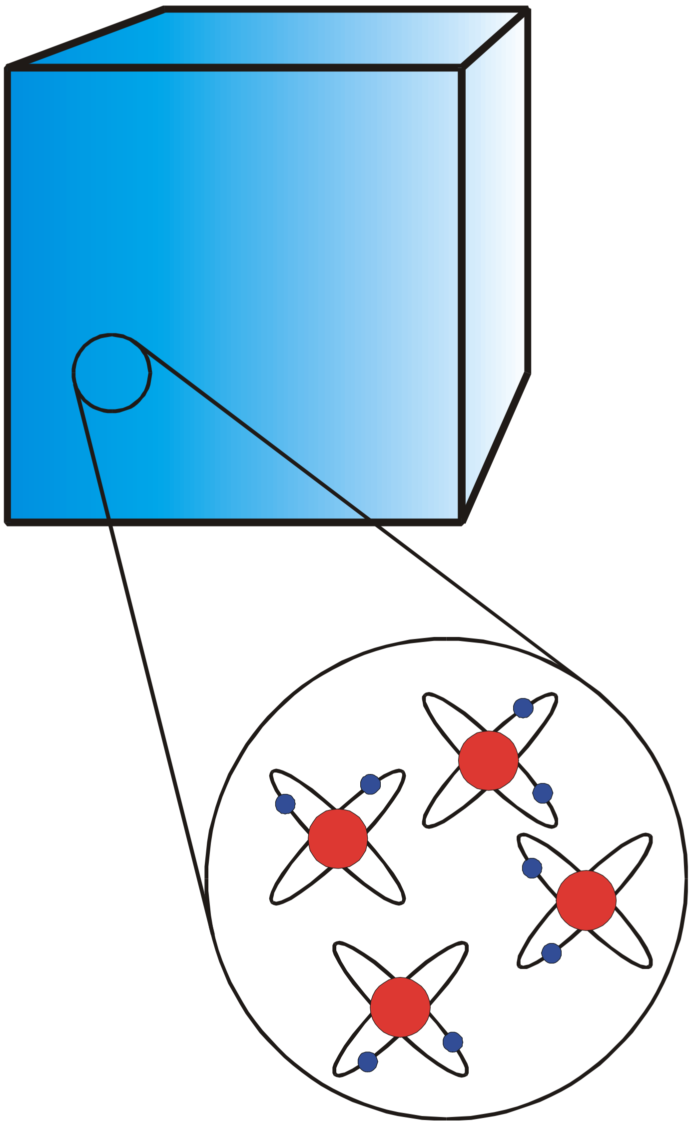
Metamaterials open new horizons in electromagnetism

John Pendry, Imperial College

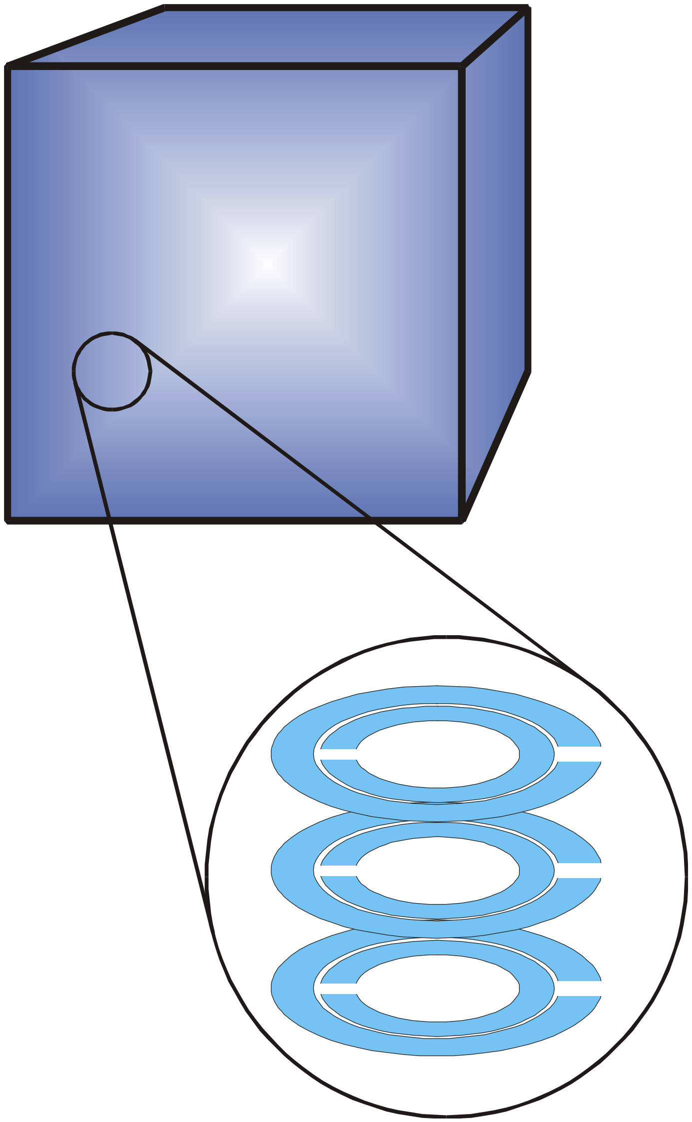


What is a 'metamaterial'

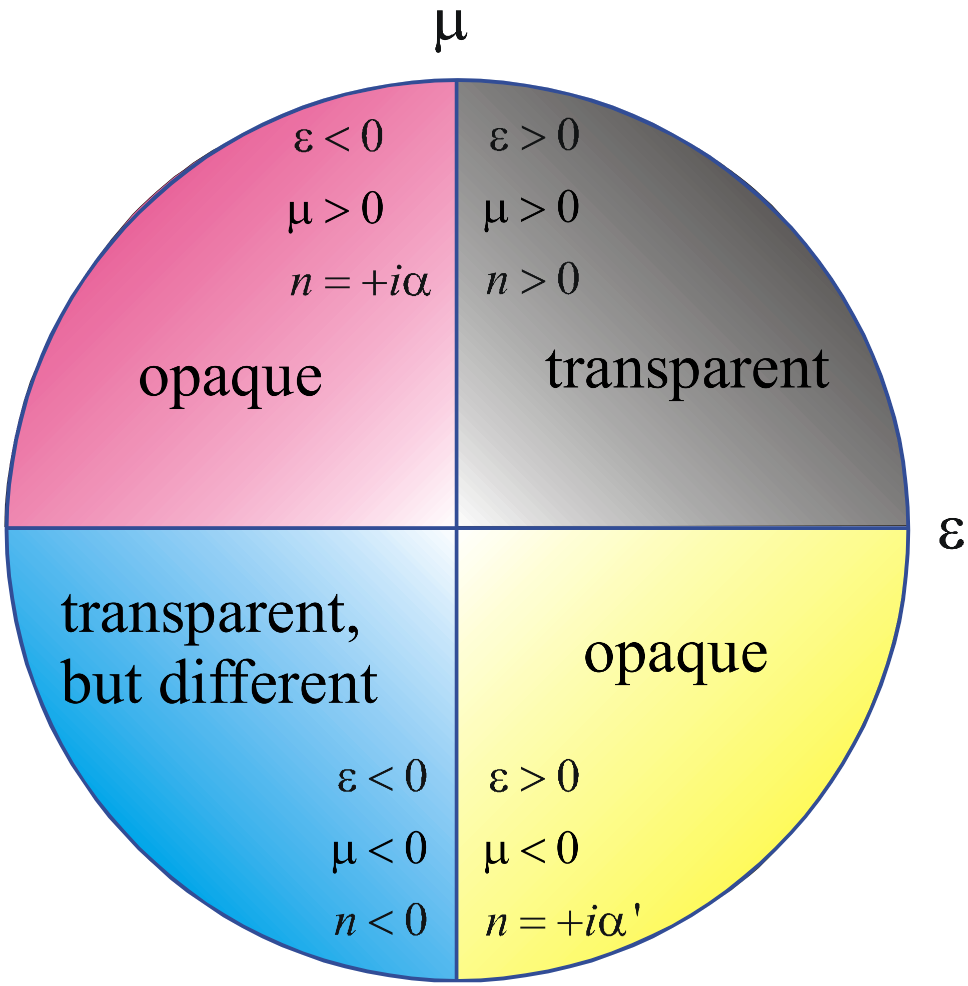
Conventional materials: properties derive from their constituent *atoms*.



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



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

Pendry (2000)

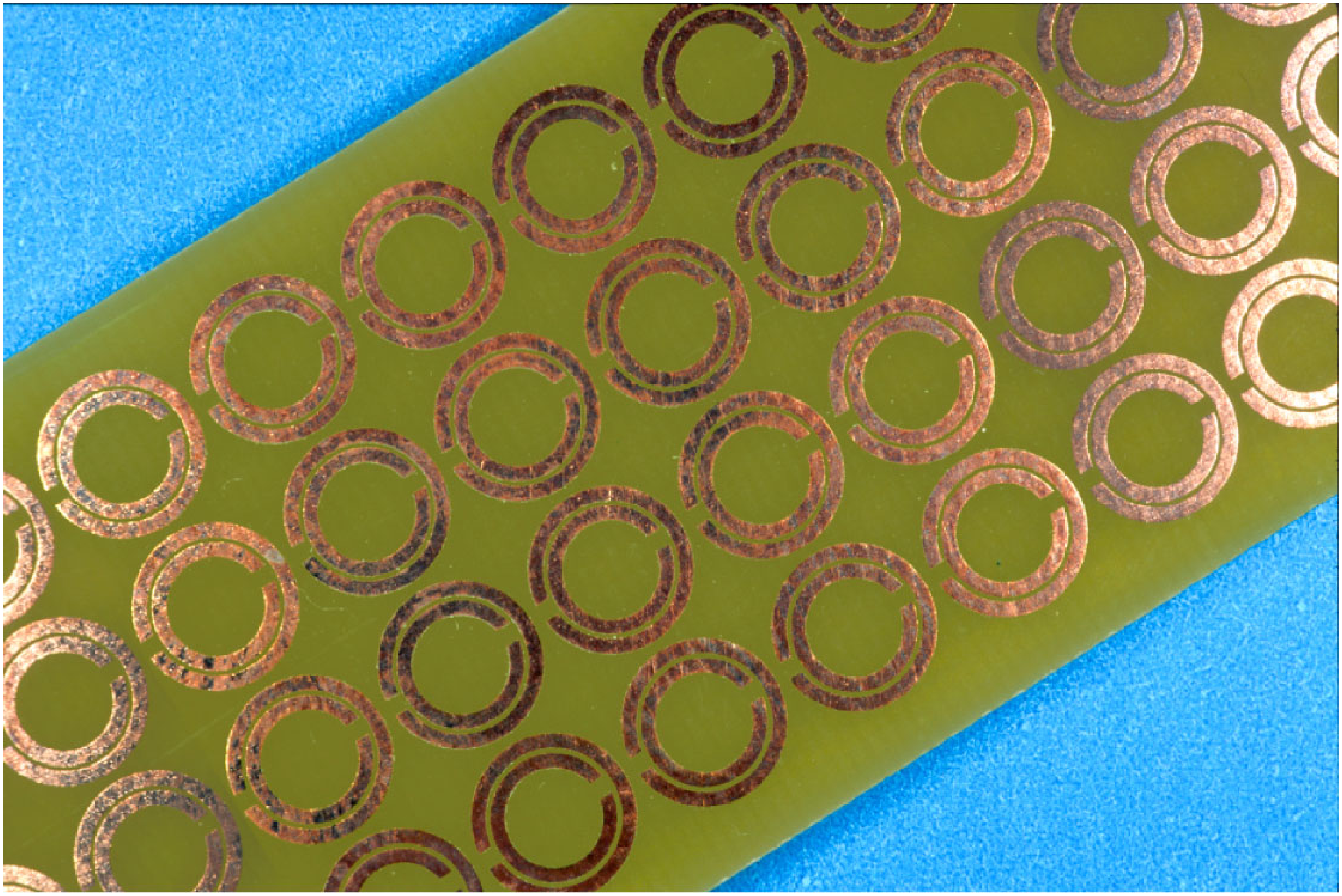
What is the point of metamaterials?

They can realise electric & magnetic properties not available in natural materials. e.g.:

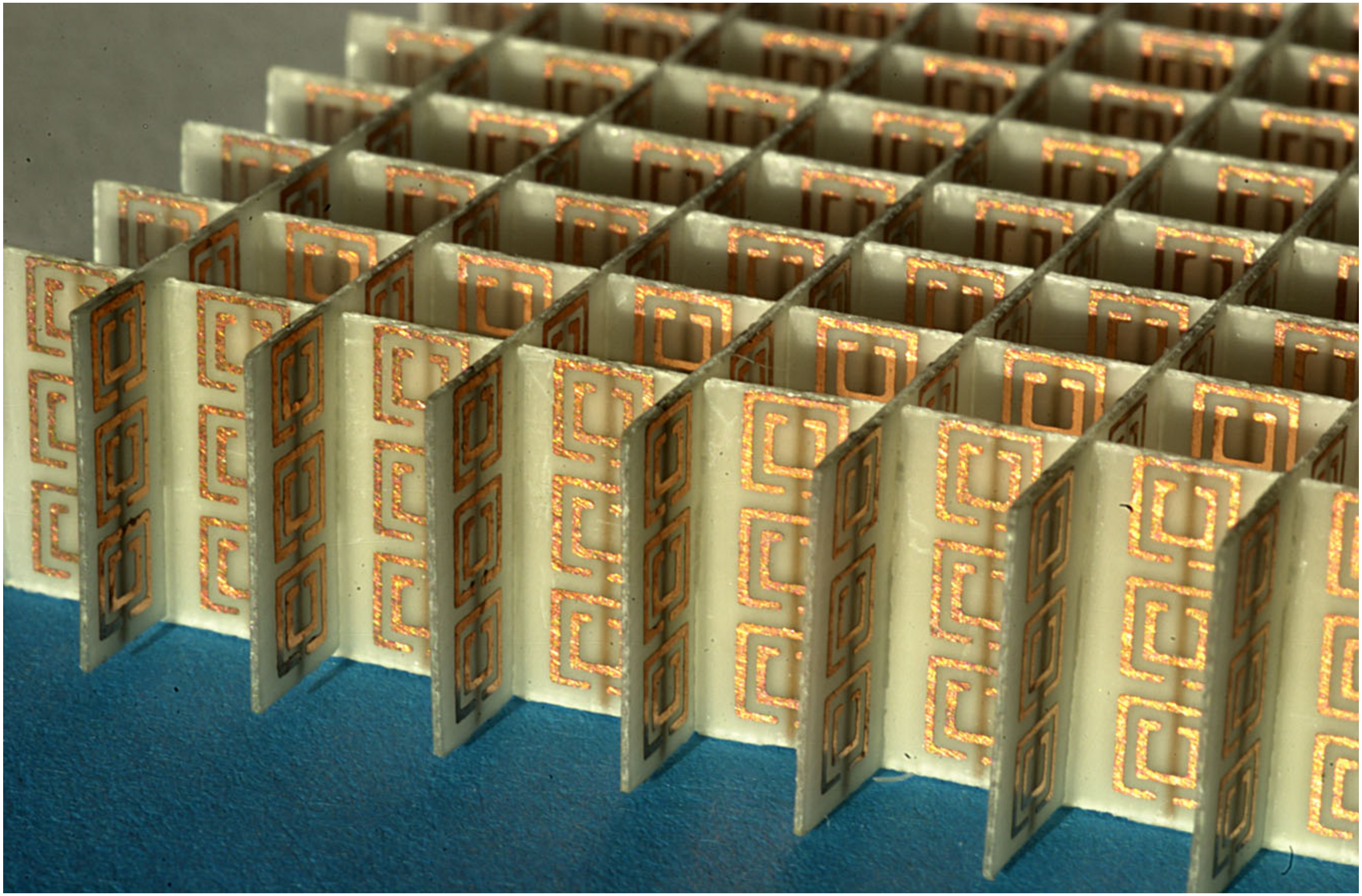
- negative refractive index
- extreme anisotropy of response to any specification
- extreme chirality
- continuously variable properties throughout the material
- magnetism at optical frequencies

Practical realisation of the split ring structure

(Marconi: Mike Wiltshire)

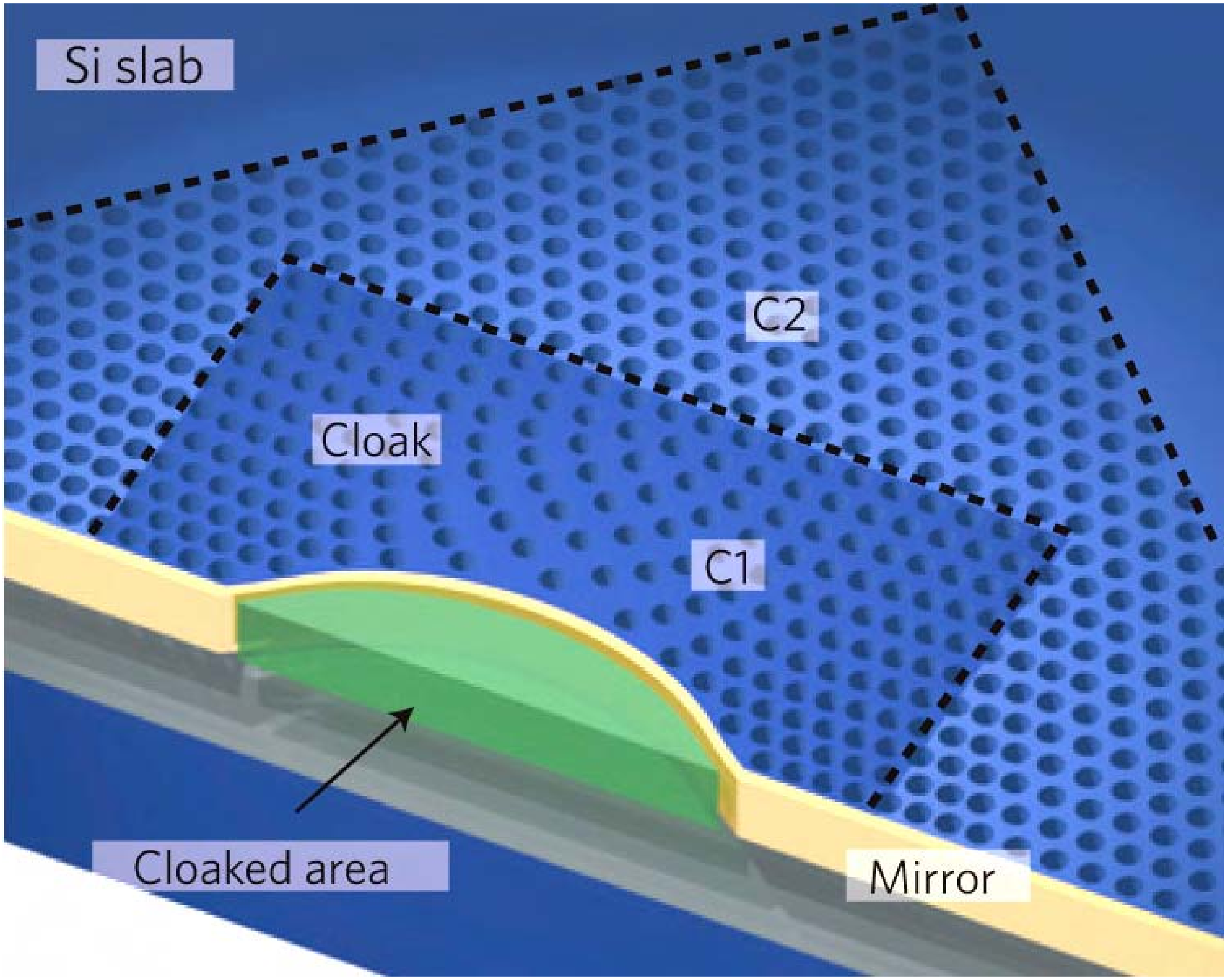


Negative refraction: $\varepsilon < 0, \mu < 0$



Structure made at UCSD by David Smith

Schematic diagram of a fabricated carpet cloak



….. showing the different regions, where C1 is the gradient index cloak and C2 is a uniform index background. The cloak is fabricated in a SOI wafer where the Si slab serves as a 2D waveguide.

The cloaked region (marked with green) resides below the reflecting bump (carpet). and can conceal any arbitrary object. The cloak will transform the shape of the bump back into a virtually flat object.

Negative refractive index metamaterials

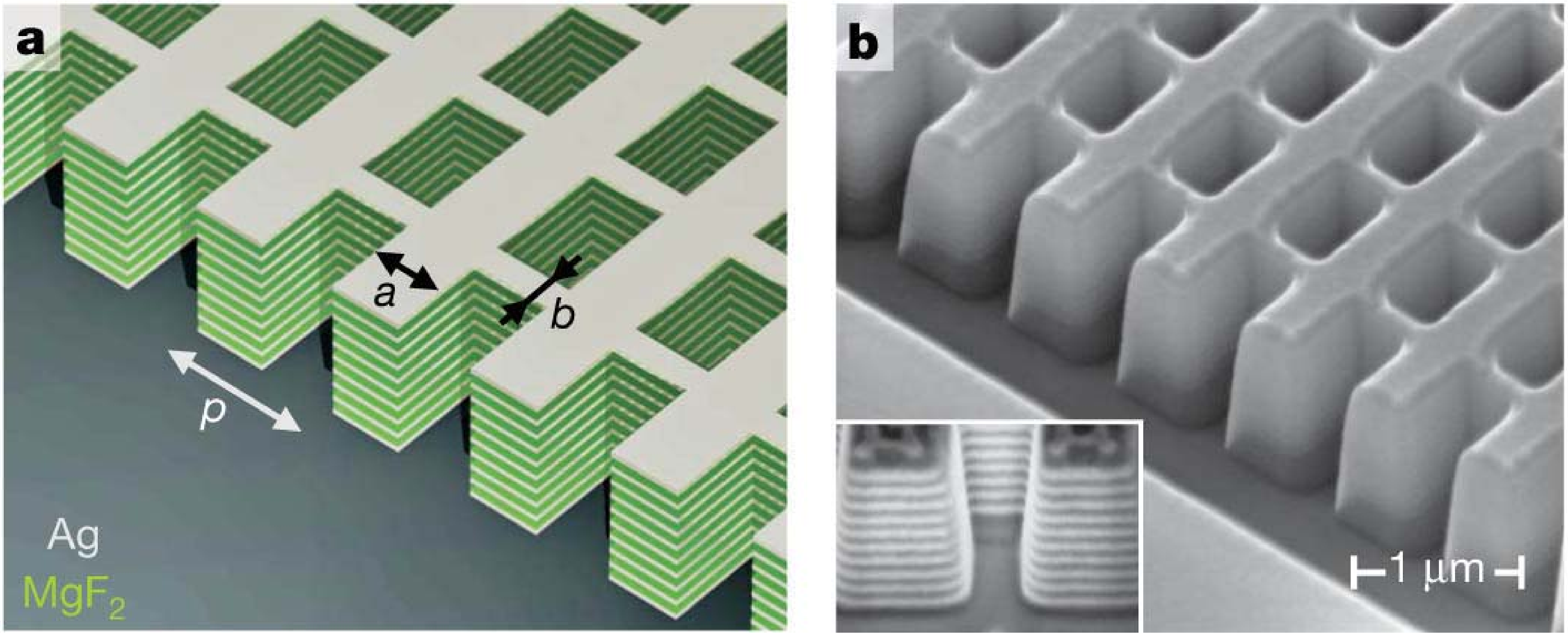
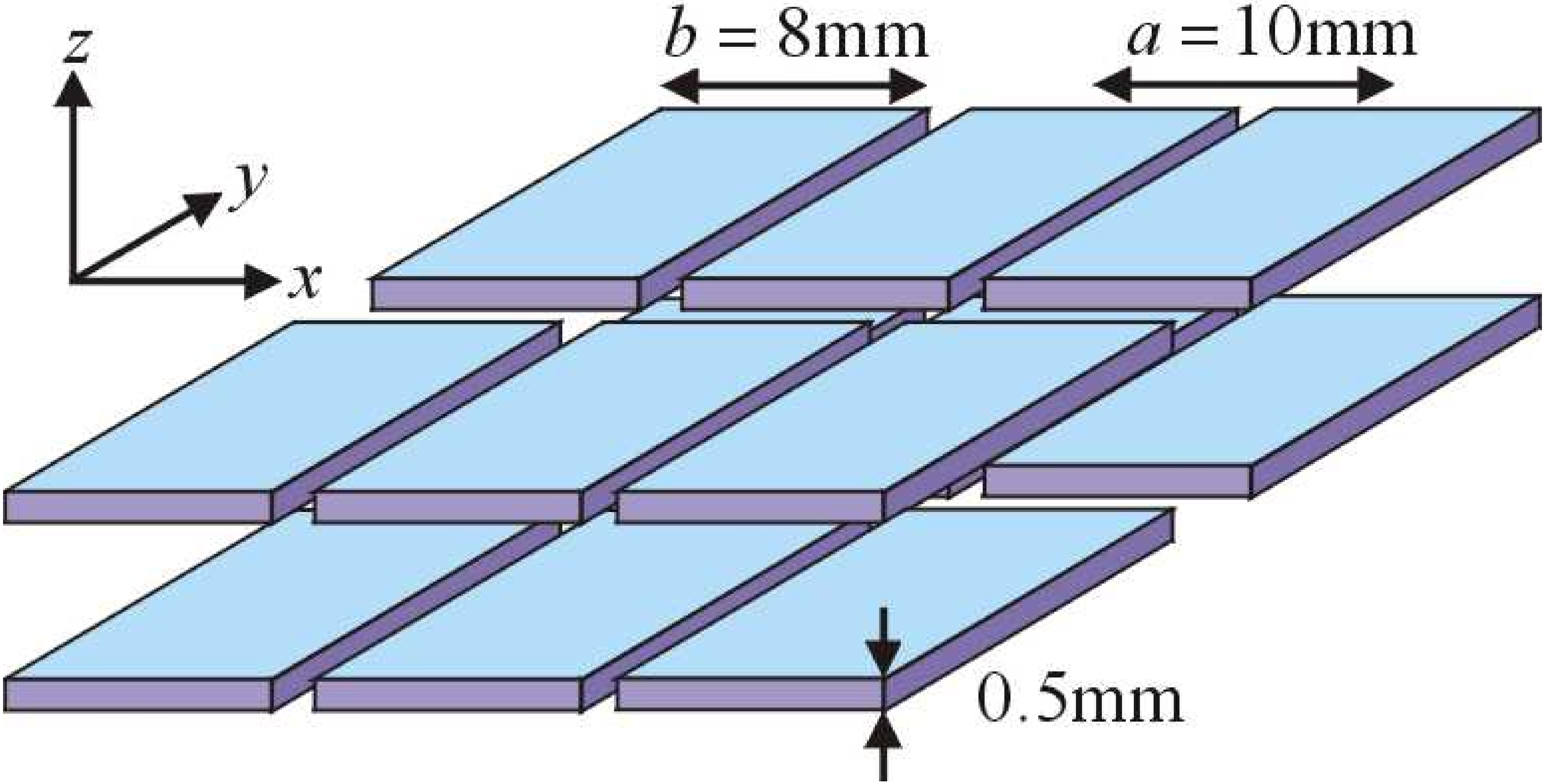
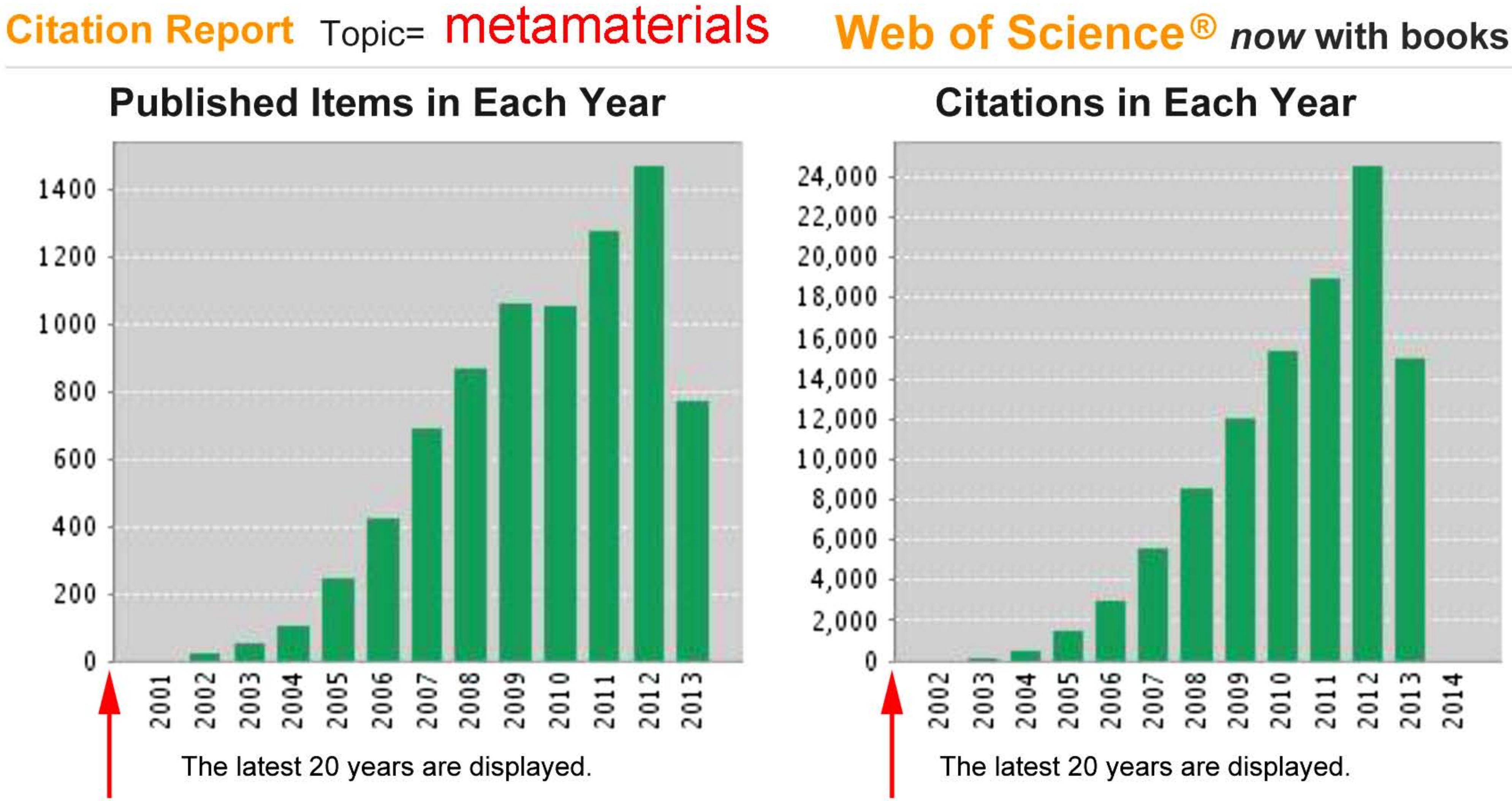


Diagram (left) and scanning electron microscope image (right) of a ‘fishnet’ structure fabricated by the Xiang group at Berkeley California. The structure consists of alternating layers of 30nm silver and 50nm magnesium fluoride.

Lattice of superconducting plates



The rise of metamaterials

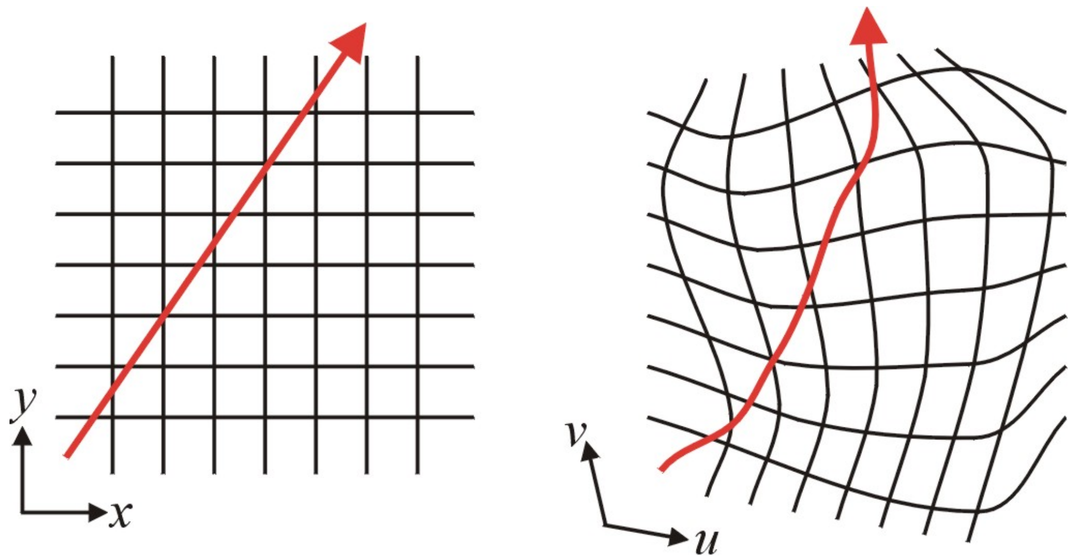


In 1999 the first metamaterial paper was published, though they were not called metamaterials at that time.

papers published in 2012: **1450**   # citations in 2012: **24,000**

Transformation optics

Distort the coordinate system, $(x,y,z) \rightarrow (u,v,w)$, and the trajectory of any rays of light as well. A coordinate transformation implies a refractive index change.



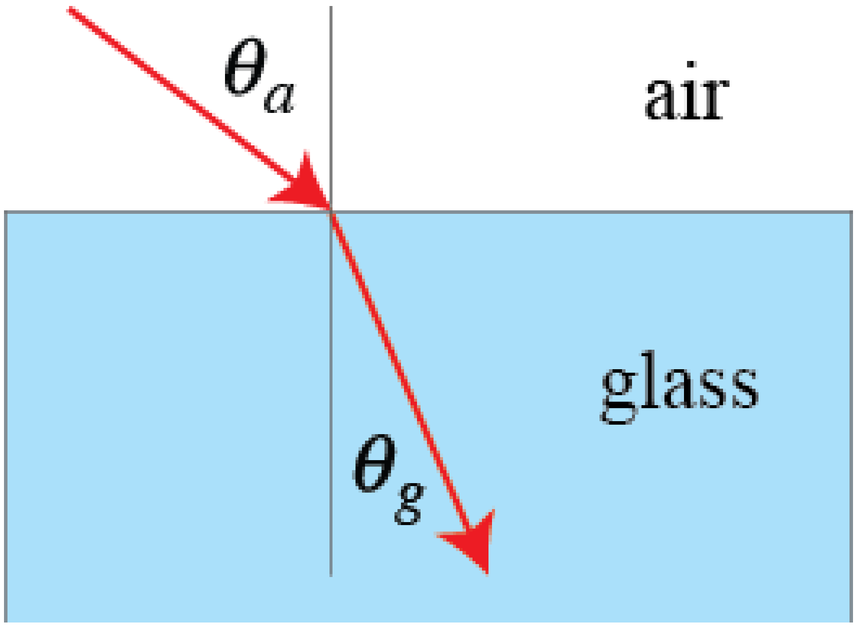
Then use transformation theory to calculate the refractive index that gives the distorted ray trajectories.

$$n' = n\, g(u,v,w)$$

where $g(u,v,w)$ is obtained from the coordinate transformation.

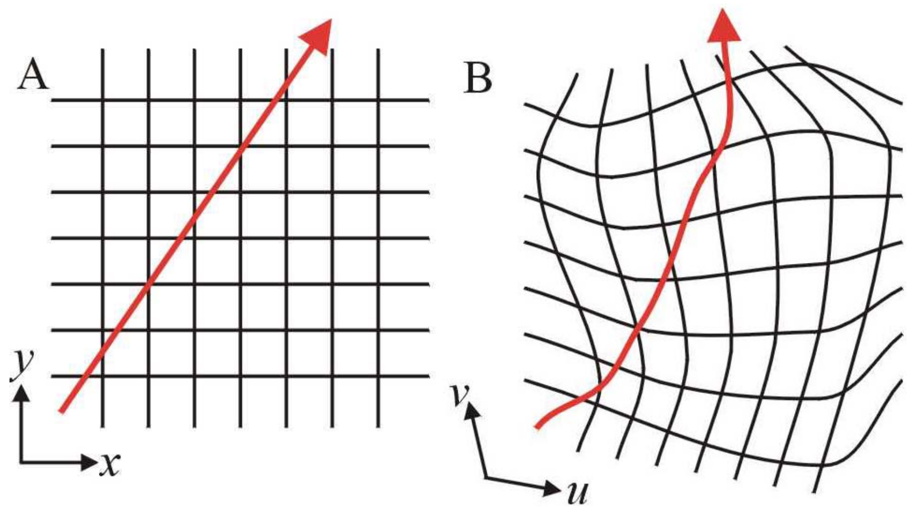
The new laws of refraction

Snell's law acts on *rays* of light



$$\frac{\sin\theta_a}{\sin\theta_g} = n$$

transformation optics acts on electric and magnetic field lines



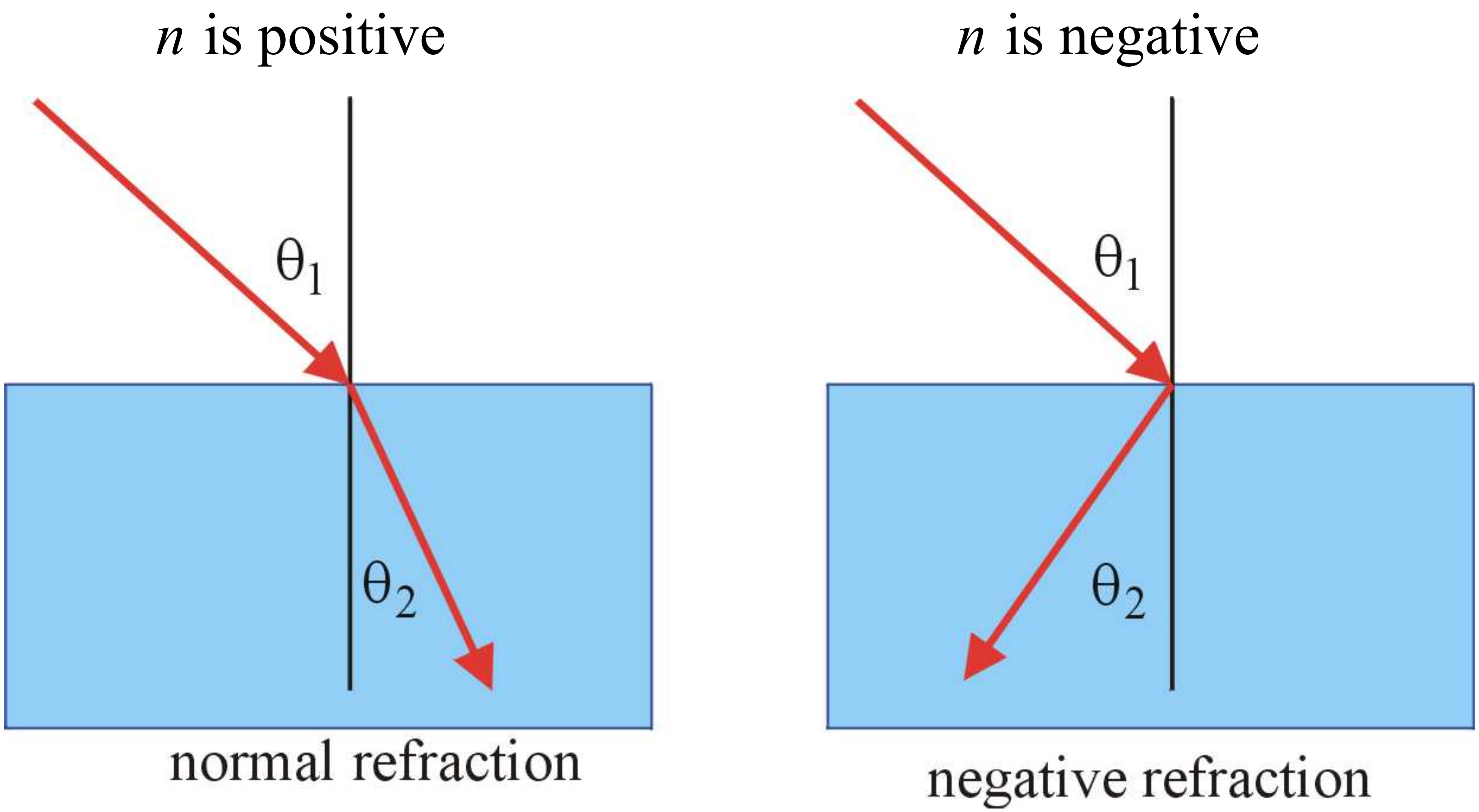
$$\varepsilon'^{i'j'} = \left[\det(\Lambda)\right]^{-1} \Lambda_i^{i'} \Lambda_j^{j'} \varepsilon^{ij}$$

$$\mu'^{i'j'} = \left[\det(\Lambda)\right]^{-1} \Lambda_i^{i'} \Lambda_j^{j'} \mu^{ij}$$

$$\Lambda_j^{j'} = \frac{\partial x^{j'}}{\partial x^j}$$

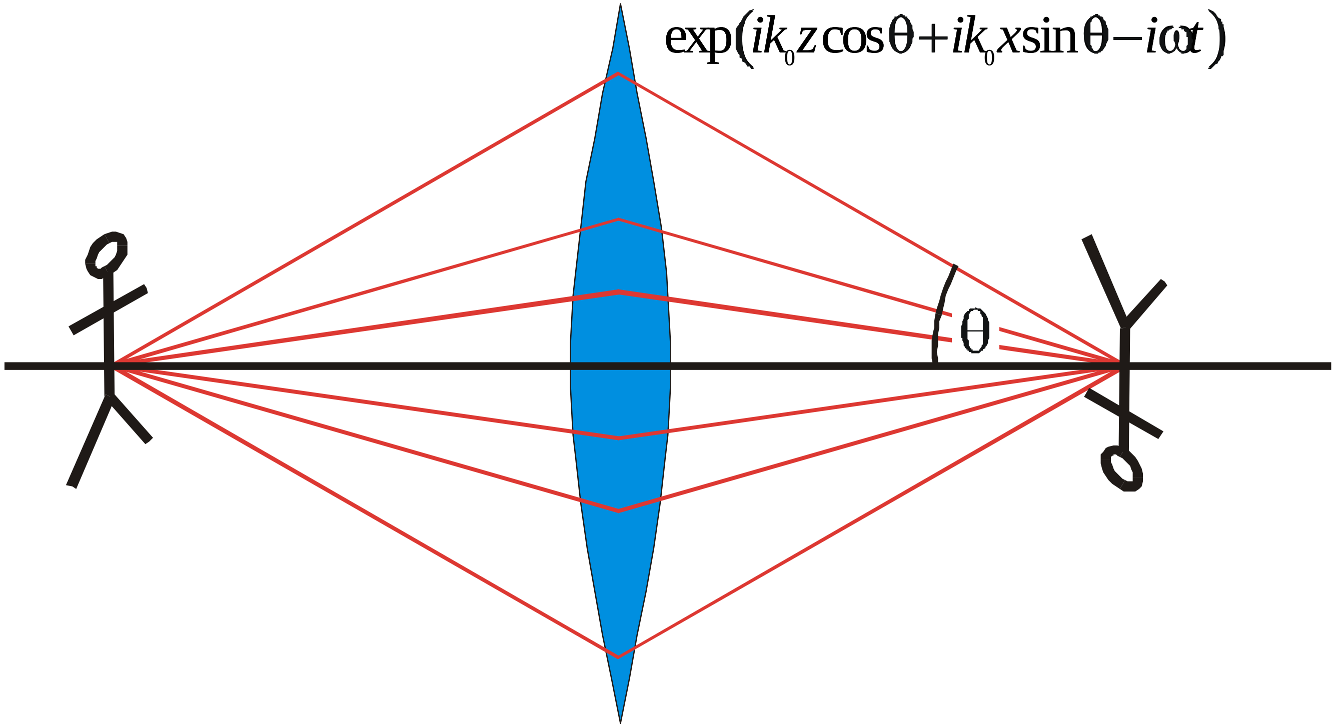
Negative refraction – Veselago

refractive index $n = \dfrac{\sin\theta_1}{\sin\theta_2}$



Limitations to the Performance of a Conventional Lens

Contributions of the far field to the image …..

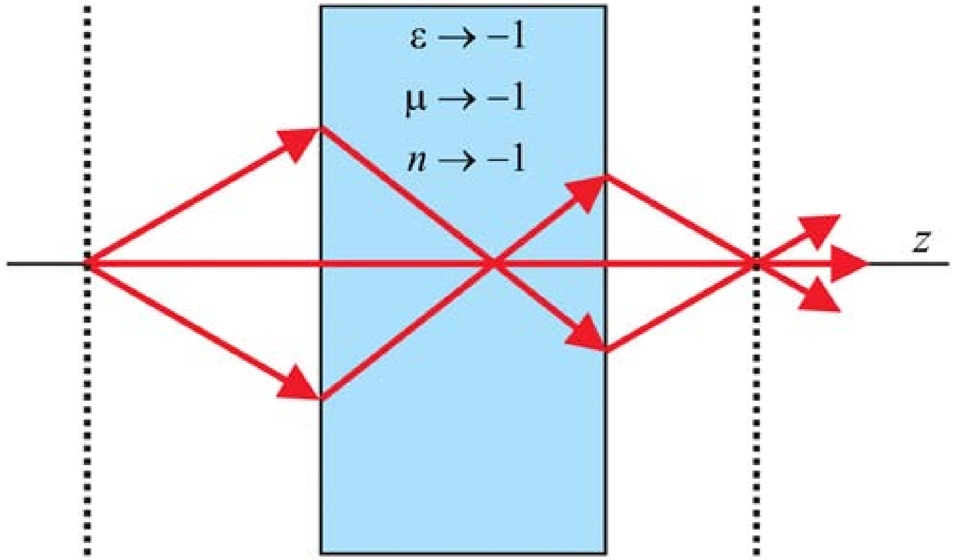


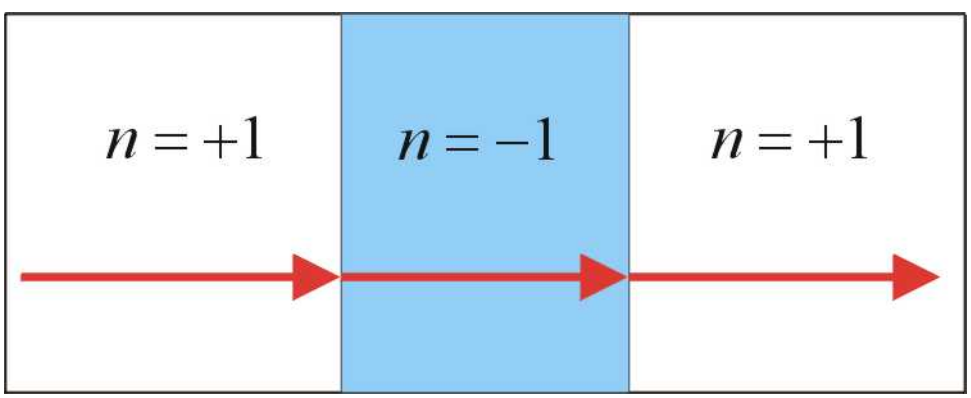
….. are limited by the free space wavelength: $\theta = 90°$ gives maximum value of $k_x = k_0 = \omega/c_0 = 2\pi/\lambda_0$ – the shortest wavelength component of the 2D image. Hence resolution is no better than,

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

Negative refraction & the perfect lens

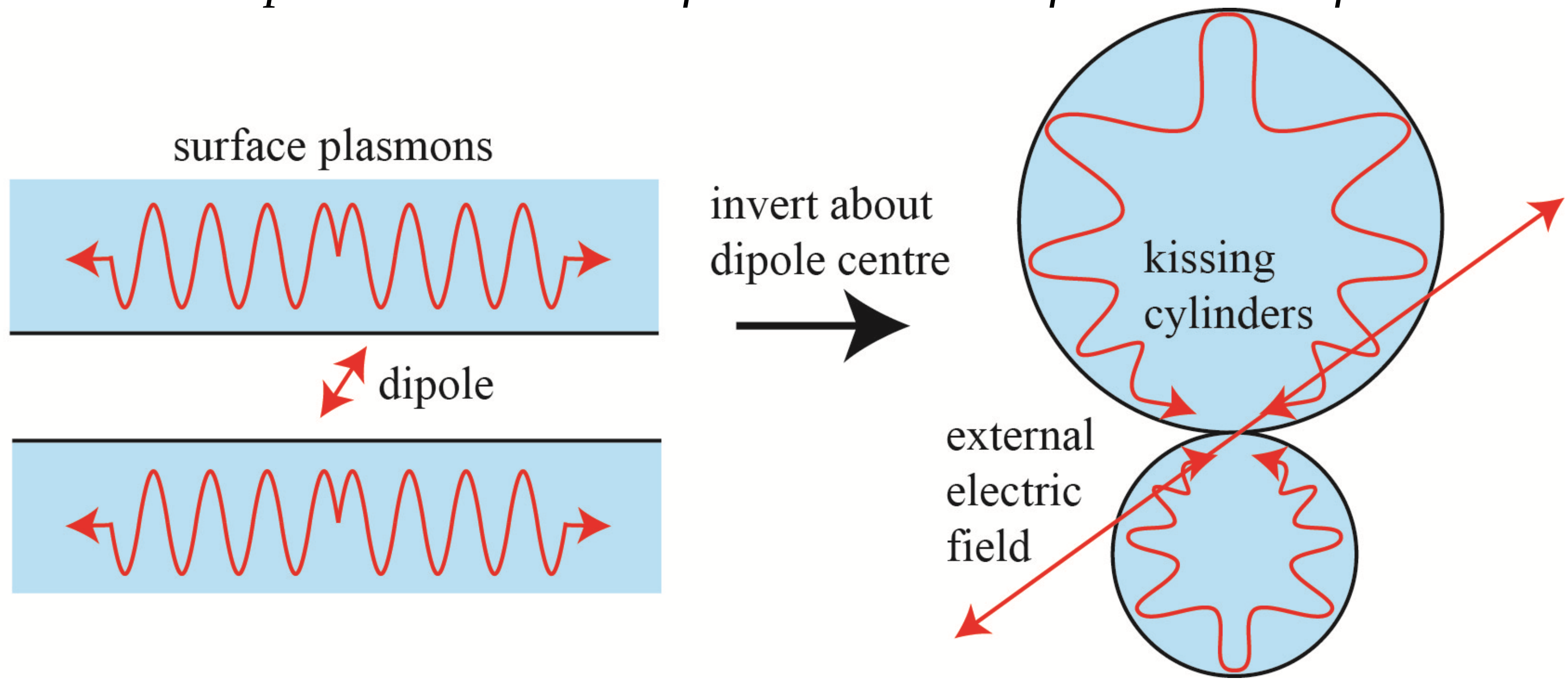
The Veselago lens can be understood in terms of transformation optics if we allow ‘space’ to take on a negative quality i.e. space can double back on itself so that a given event exists on several manifolds:





Inversion about the origin, $z' = 1/z$, converts a cavity to a pair of kissing cylinders

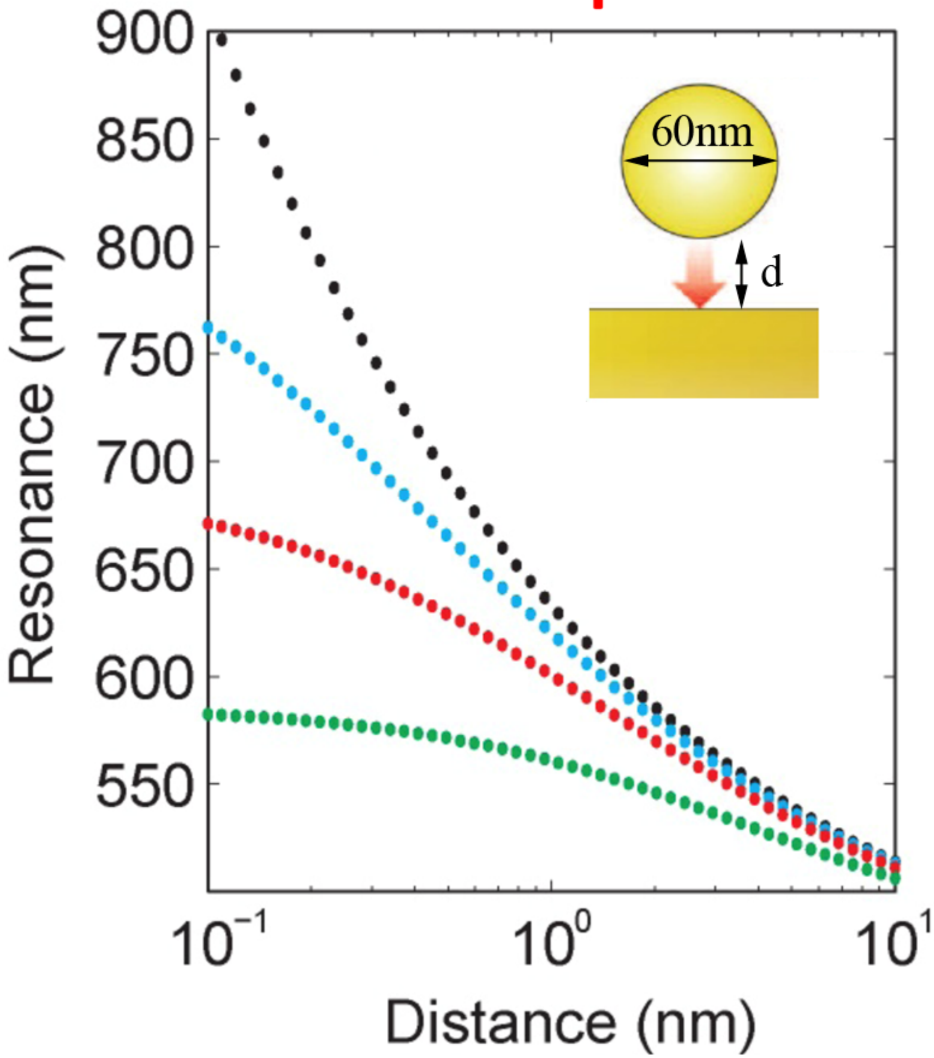
The dipole source is transformed into a uniform electric field



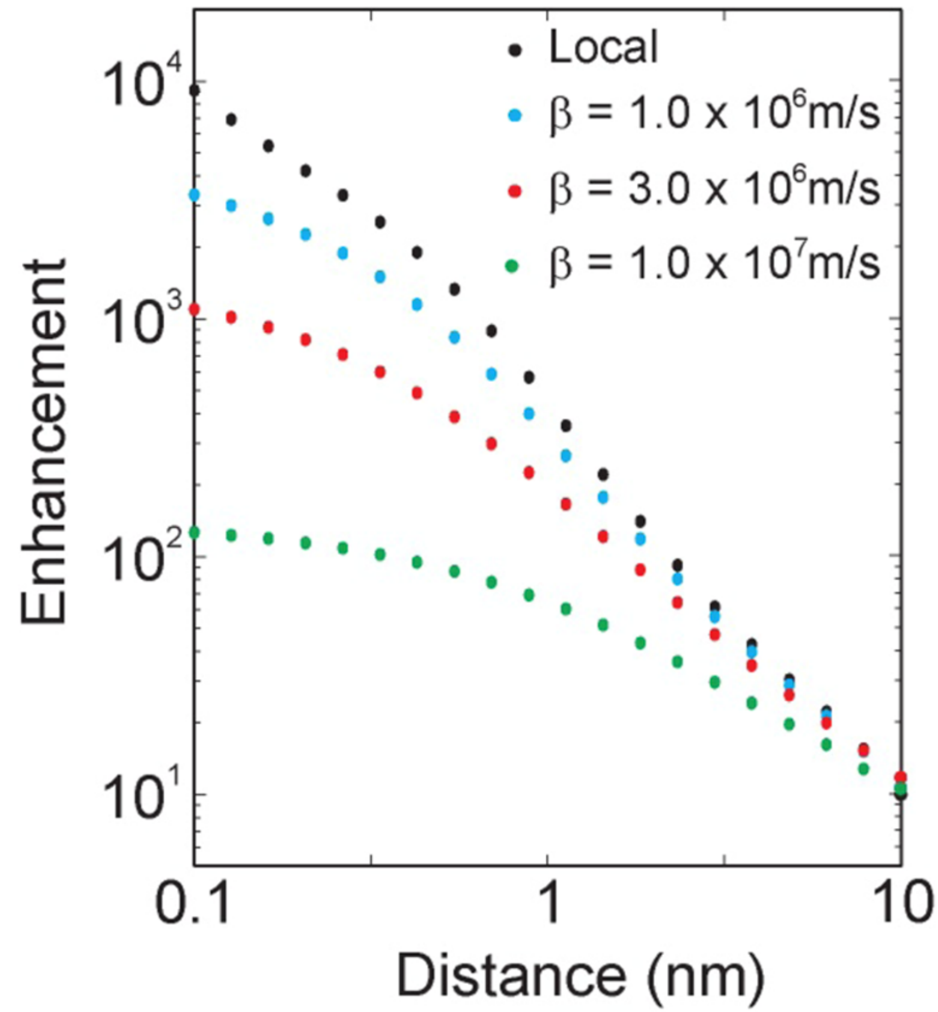
Left: a cavity supports surface plasmons that couple to a dipole source, transporting its energy to infinity. The spectrum is continuous.
Right: the transformed material now comprises two kissing cylinders. The dipole source is transformed into a uniform electric field.

Non locality: gold sphere/surface interactions

Resonance position



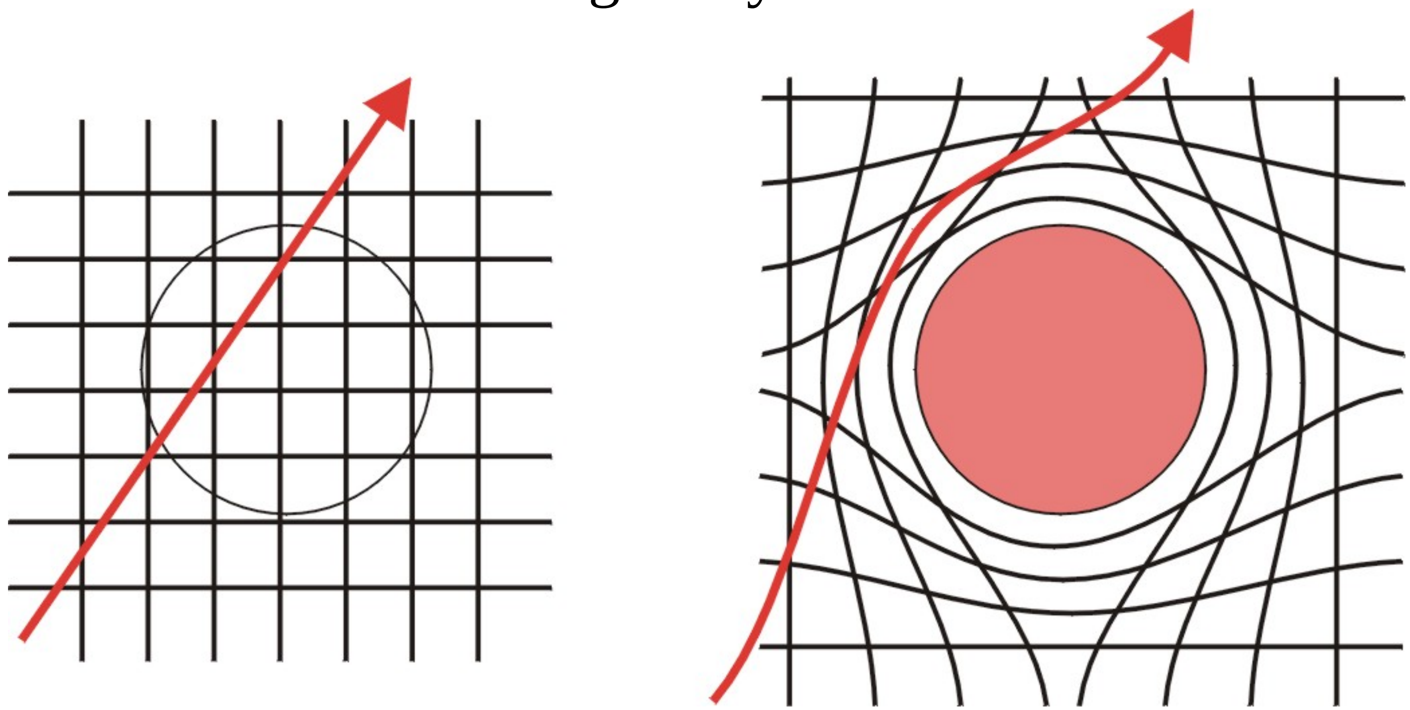
Field enhancement



The non locality parameter, β, measures penetration of the surface polarisation charge.

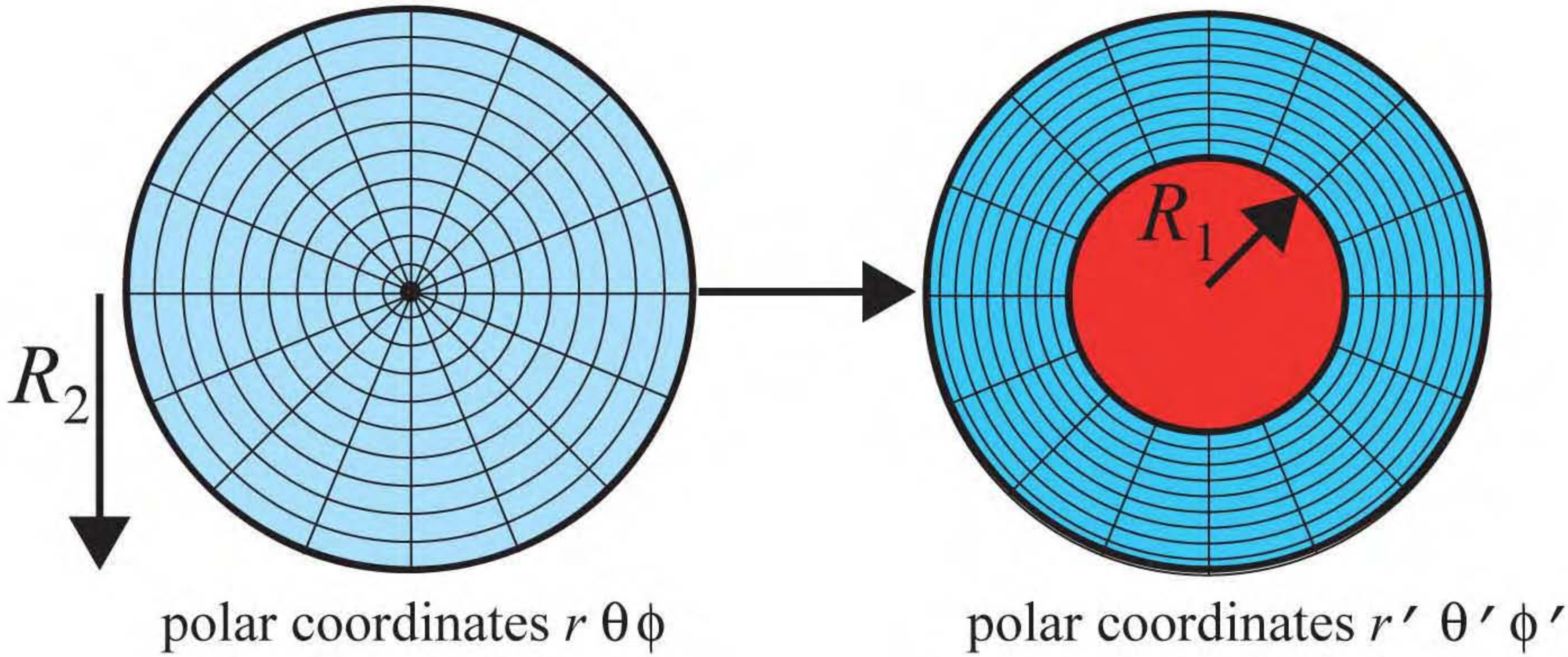
Design methodology

The challenge is to design material for the screening zone which has exactly the right refractive index to deflect radiation around the protected zone in the way we desire. In order to achieve this we need a technique for reshaping the trajectory of rays so that they avoid the objects we want to hide, but emerge from the volume of interest as though they had not been deflected.



Left: a ray in free space with the background Cartesian coordinate grid. Right: a severe distortion of the coordinate system that creates a hole within which to hide our secure zone.

Creating a hidden space



In mathematical notation the following coordinate transformation will open a hole in space,

$$r' = R_1 + r\left(R_2 - R_1\right)/R_2\,, \qquad \theta' = \theta, \qquad \phi' = \phi$$

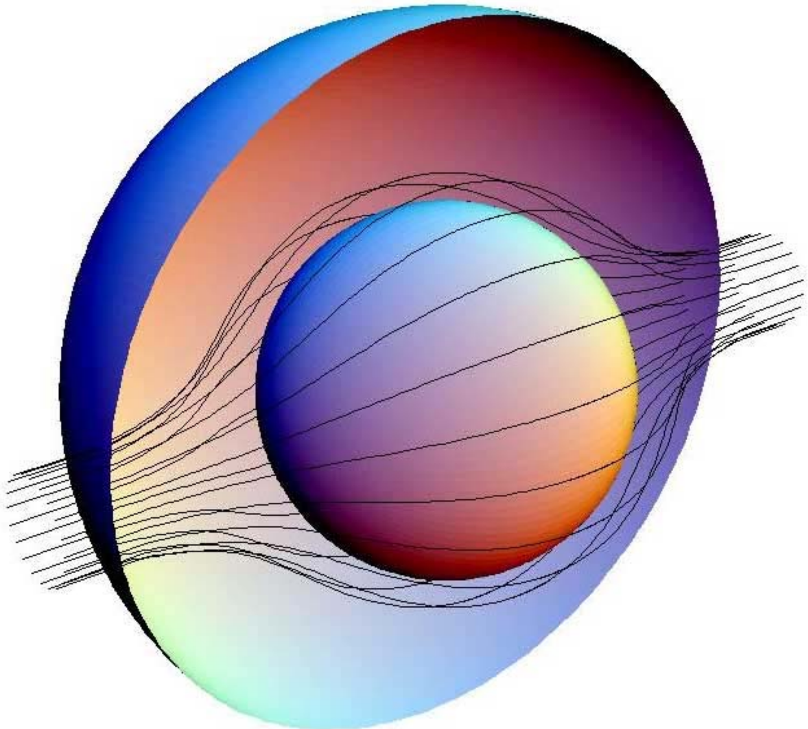
From the transformation we can find the refractive index, as a function of radius, needed to make the cloak.

Cloaking Static Magnetic Fields

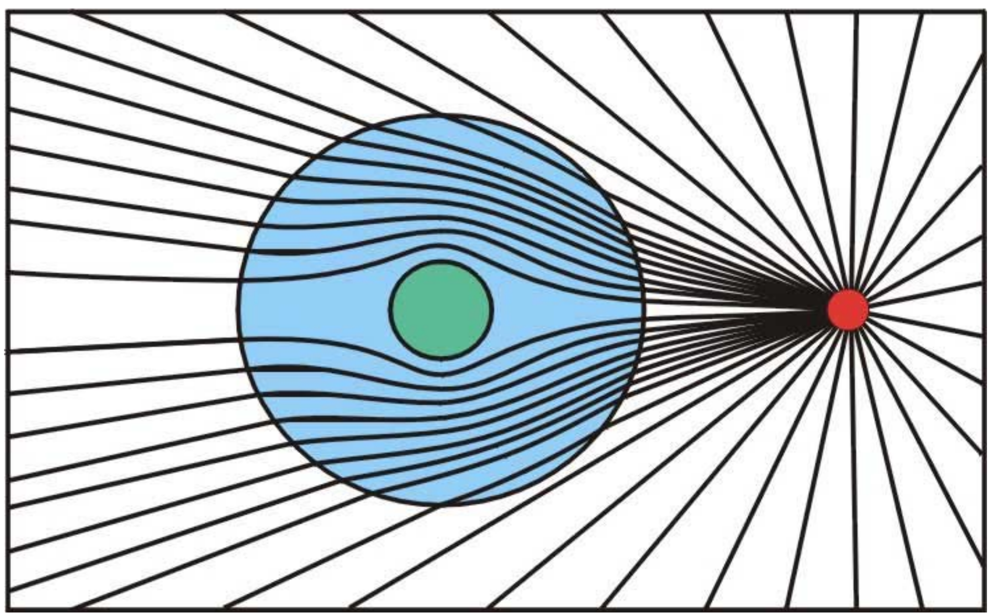
see: J. Phys.: Condens. Matter **19** (2007) 076208 (*B. Wood and JB Pendry*)

Cloaking works for fields as well as waves!

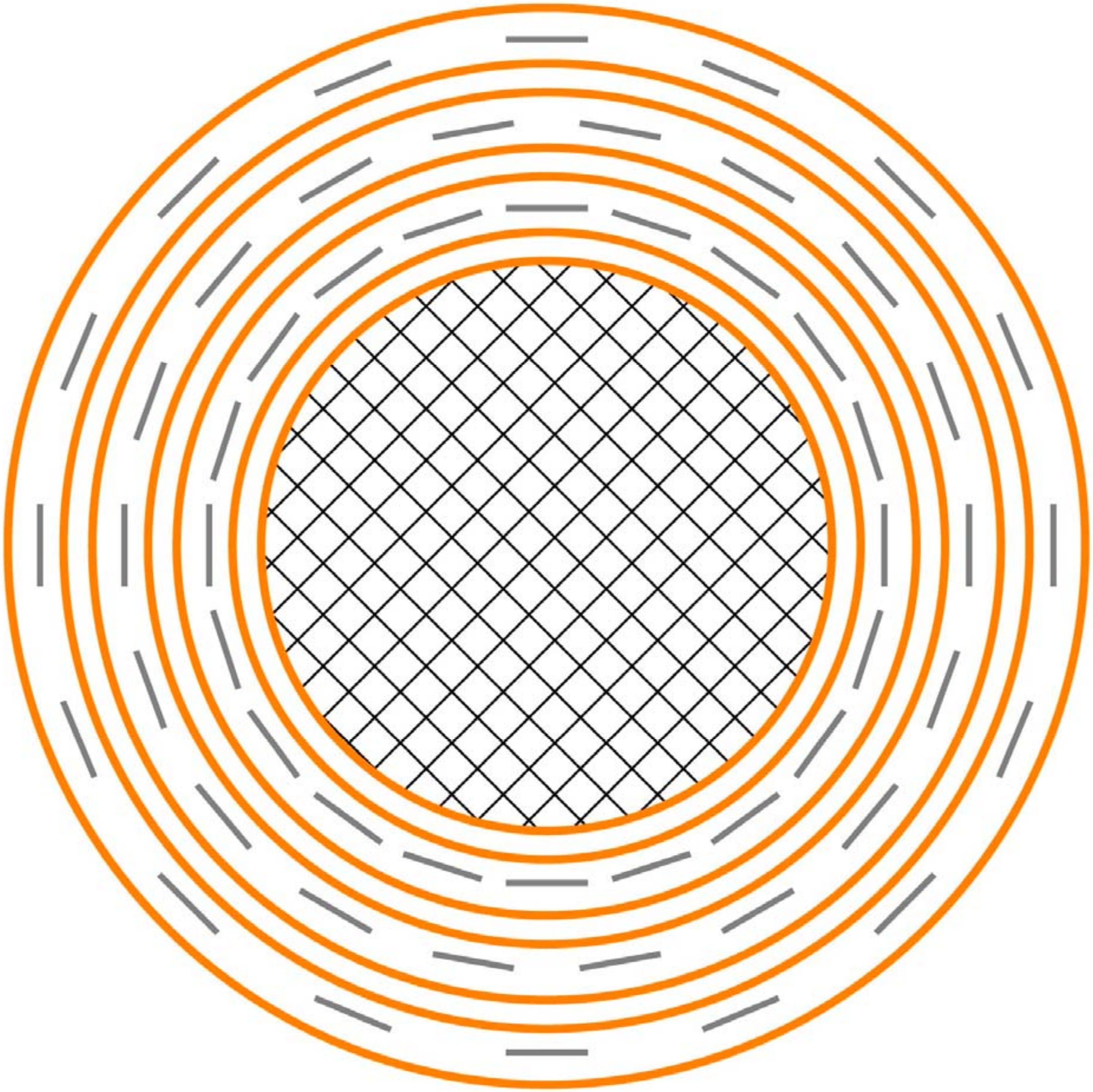
deflection of rays
(far field)



deflection of field lines
(near field)



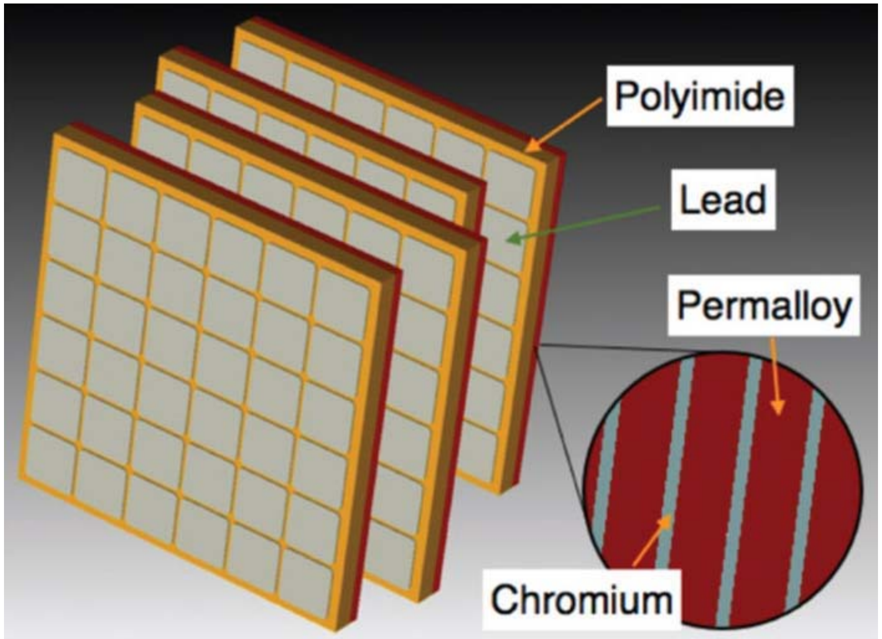
The proposed magnetic cloak



The shaded region in the centre is hidden from external magnetic fields. The plates form broken circles (in cross section); the full circles show the ferrite or amorphous metal.

A DC magnetic cloak -1

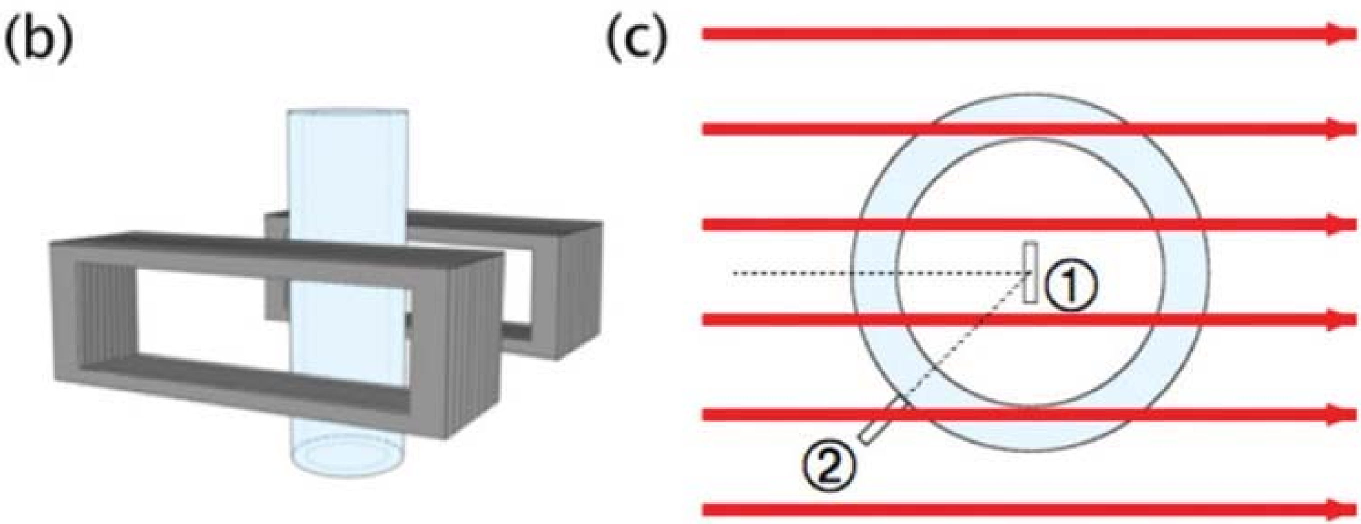
Supradeep Narayana and Yuki Sato, *Advanced Materials*, **24**, 71-74 (2012)



Schematic of the cloaking material consisting of an array of superconducting and soft ferromagnetic elements.

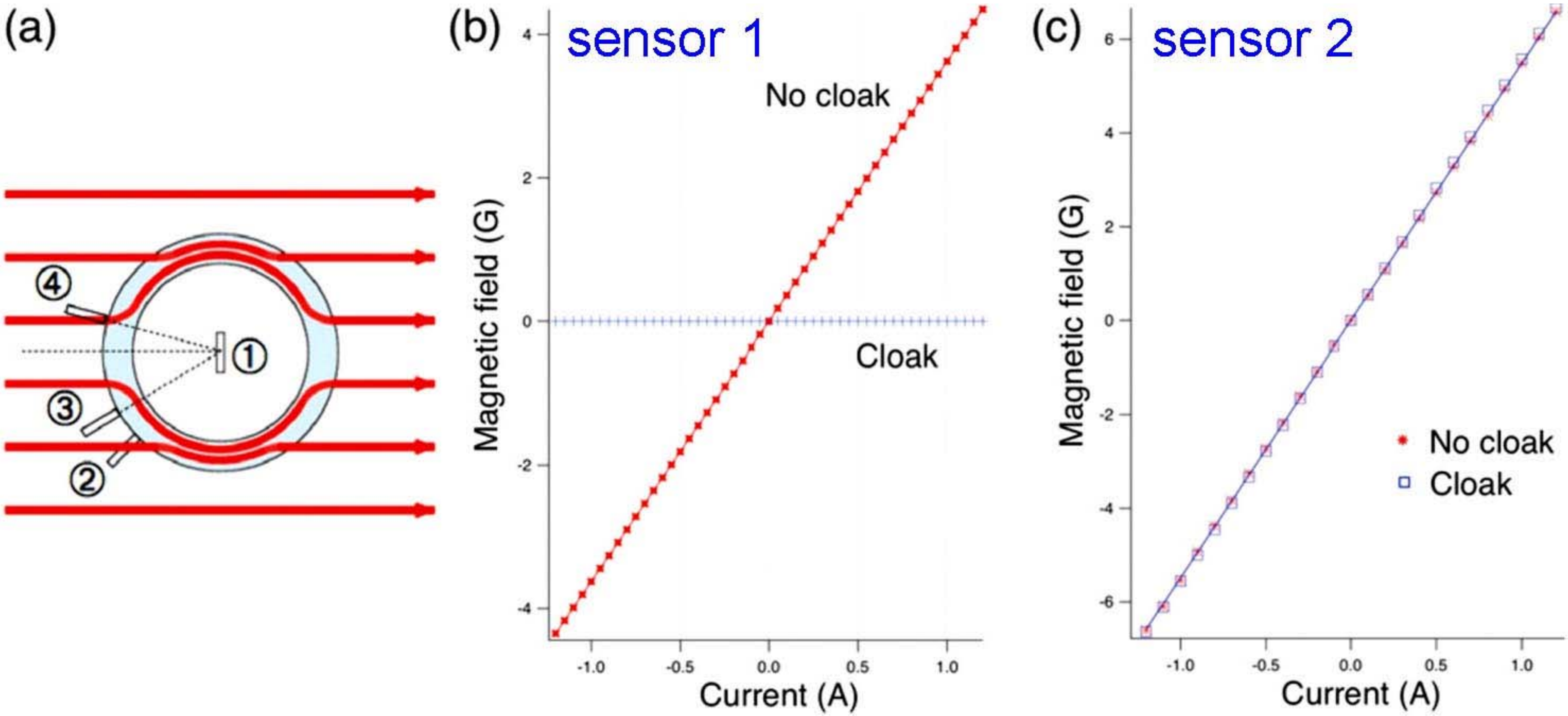
(b) Apparatus geometry.

(c) Top-view schematic showing the locations of two Hall sensors and magnetic field lines in empty space. Sensor 1 detects the field that penetrates through the cloak, and sensor 2 is positioned to capture external field perturbations due to the presence of the cloak.



A DC magnetic cloak - 4

Cloaking magnetic fields using *metamaterials* excludes fields from inside the cloak, and leaves the external field undisturbed.

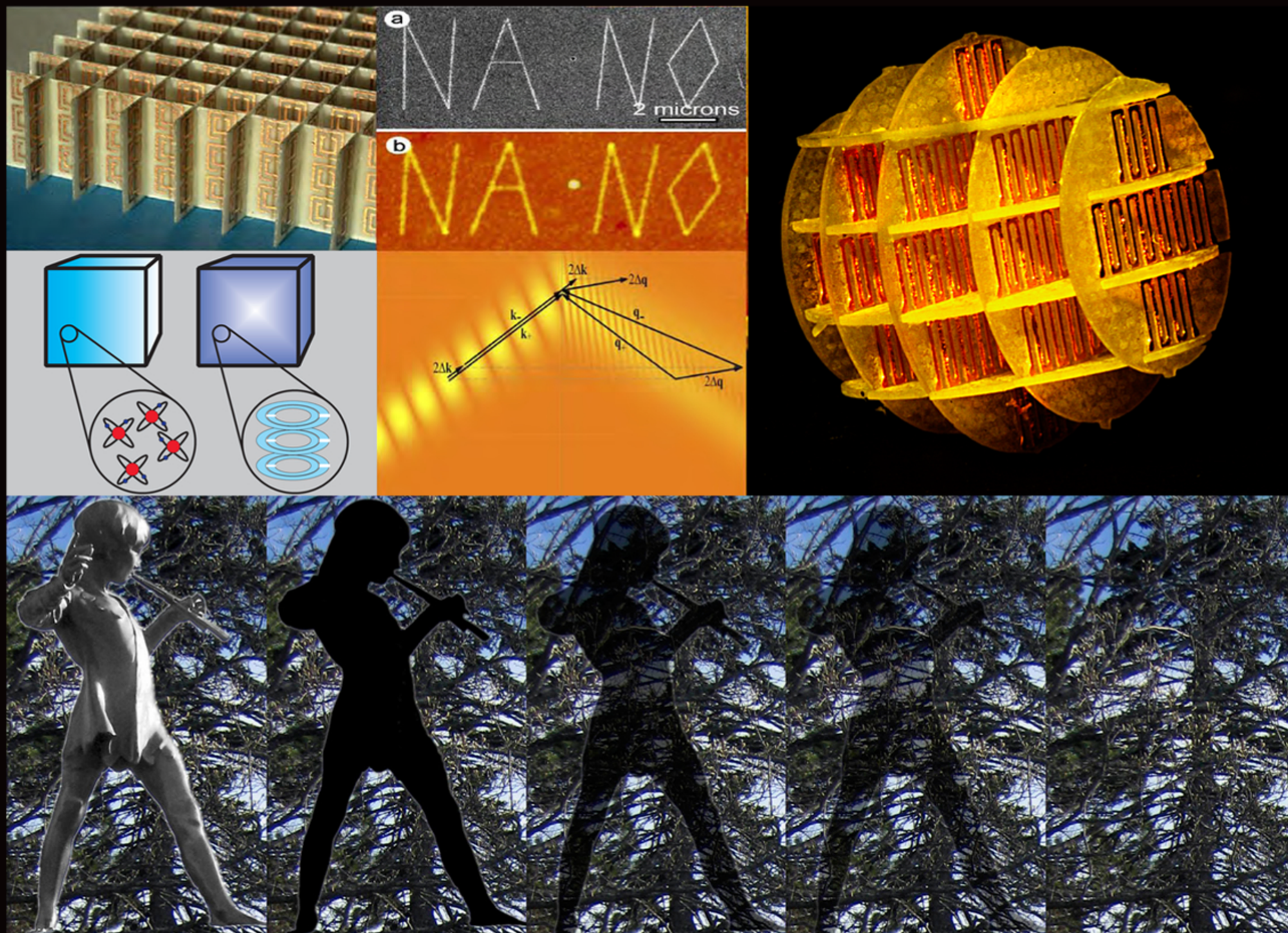


Future Directions

- The first priority is the translation of these concepts into products. This is already happening and David Smith will report on some recent activity.
- Extension of metamaterial concepts to non linear devices – RF, THz optical.
- Exploitation of plasmonic effects for single molecule biosensing at optical frequencies.
- Increased efficiency of optical gain media and lasing.
- Extension of the metamaterials concept to other fields: acoustics, heat transport, even to seismic waves!
- Exploitation of novel properties such as ultra strong paramagnetism, magnetic properties at optical frequencies, strongly chiral systems, phase conjugation, nano lasers, etc. etc.
- Transformation optics as a theoretical design tool offers rich possibilities for further novel developments.

Metamaterials open new horizons in electromagnetism

John Pendry, Imperial College



John Pendry
is professor of physics at Imperial College London. He works on the theory of metamaterials and other problems in electromagnetism

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Dan Hooper
DARK MATTER
5 February

THE BIG CHALLENGE
REALISING OUR DREAMS

The advent of metamaterials has inspired renewed interest in the fundamentals of electromagnetism. In part our dreams of what can be achieved with these materials have been realised, but to some extent they have outrun our capacity to make them happen. What are the stumbling blocks?

Fundamental to the metamaterial concept is the ability to structure a material on a scale less than the wavelength of the radiation you want to manipulate. This is not a problem with the microwaves used for mobile phone signals, with a wavelength of around 30 centimetres, which is why much of the early experimental work was with mircrowaves.

Visible light presents a greater challenge: whereas traditional technologies used to manufacture mirrors and glass lenses have required tolerances of better that 1 micrometre, metamaterials have to be constructed to nanometre-scale accuracy. Though technologies such as ion beam etching can do this, they are expensive and handle only small samples. Further progress will require Investment in nano-manufacturing.

The performance of a metamaterial is ultimately determined by the characteristics of the ingredients from which it is made. Metallic metamaterials perform well at the frequencies used by mobile phone networks but not at visible wavelengths, where metals tend to absorb visible light.

One approach is to compensate for such losses by introducing an amplifying medium, such as dye molecules or an array of quantum dots.

What is not in doubt is the excitement created by the new metamaterial world, which has liberated theorists to dream of that which was previously thought impossible and challenged experimentalists to make it happen.

RECOMMENDED READING

A selection of articles at both advanced and popular level can be found at my website (bit.ly/cBXmF4) and at David Smith's site (bit.ly/bmFgh7).

Optical Metamaterials: Fundamentals and applications by W. Cai and V. Shalaev (Springer)

Physics and Applications of Negative Refractive Index Materials by S. Anantha Ramakrishna and Tomasz M. Grzegorczyk (CRC Press)

Cover image
XMM-Newton/ESA/NASA

METAMATERIALS
John Pendry

New Scientist 8 January 2011

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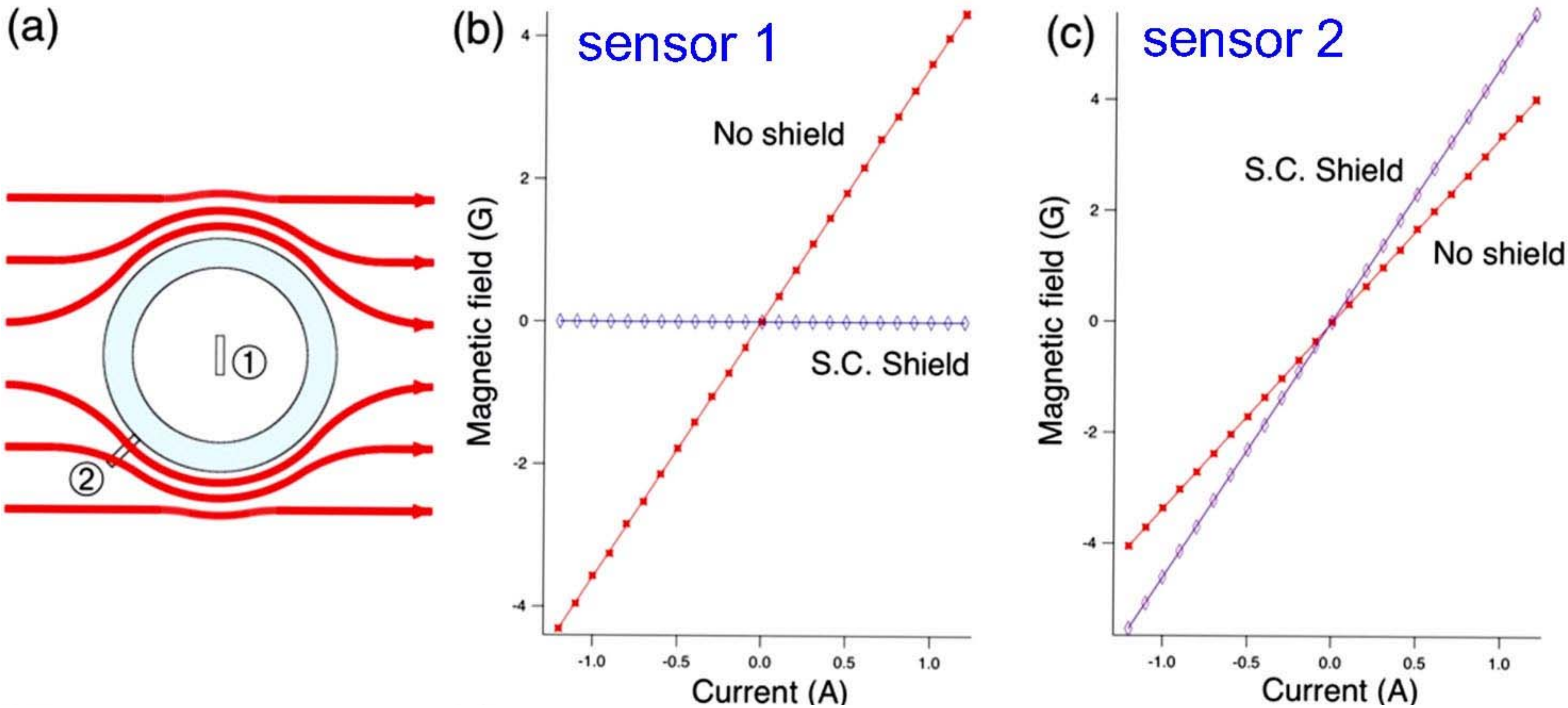
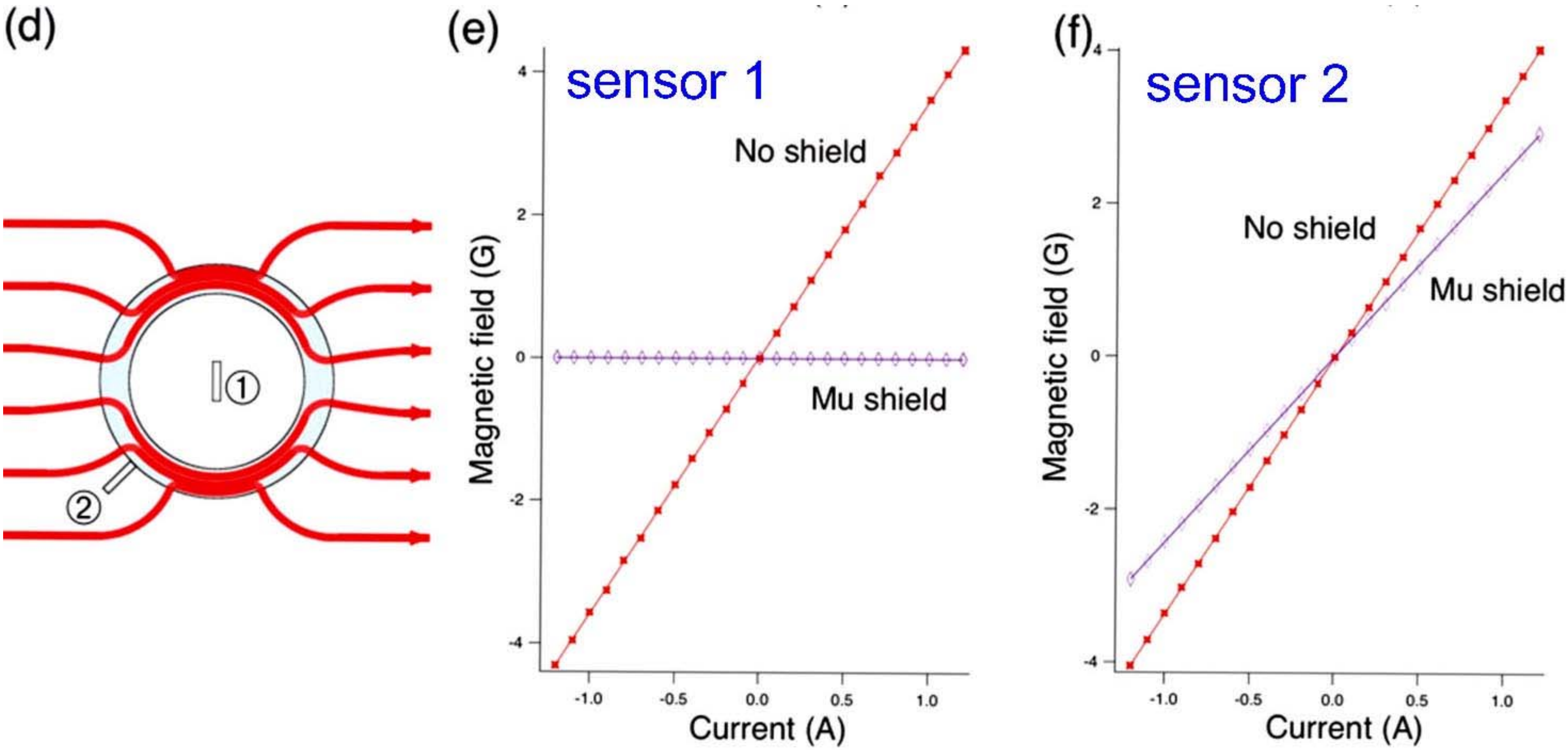
A DC magnetic cloak - 2

Screening magnetic fields using a *superconductor* excludes fields from inside the screen, but creates a massive dipole field externally.

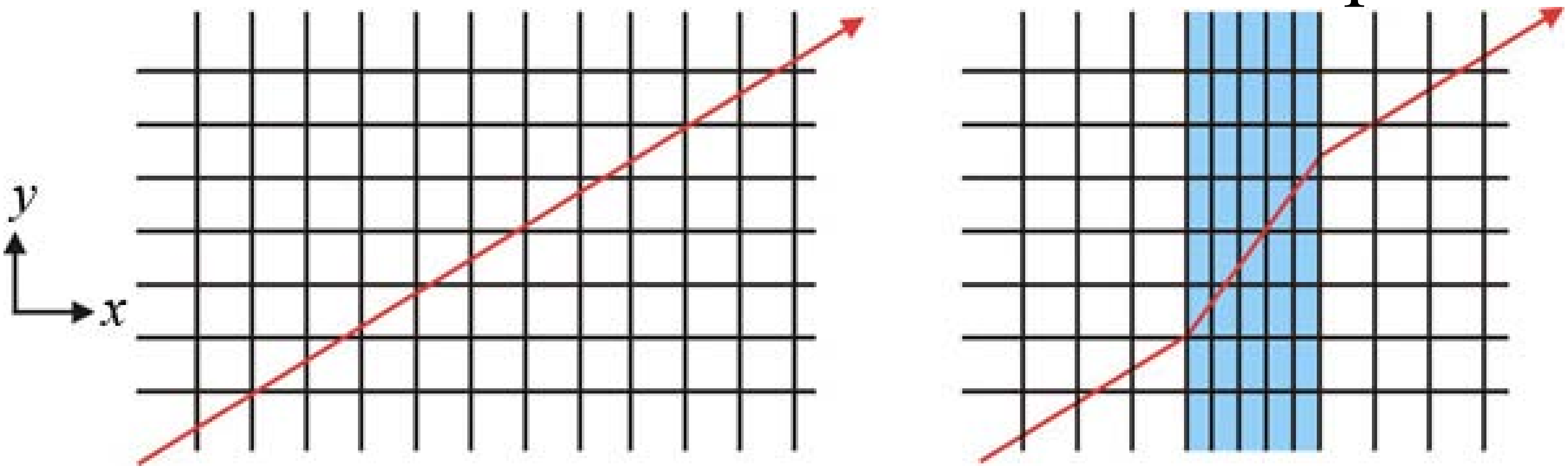


A DC magnetic cloak - 3

Screening magnetic fields using *mu metal* excludes fields from inside the screen, but creates a massive dipole field externally.



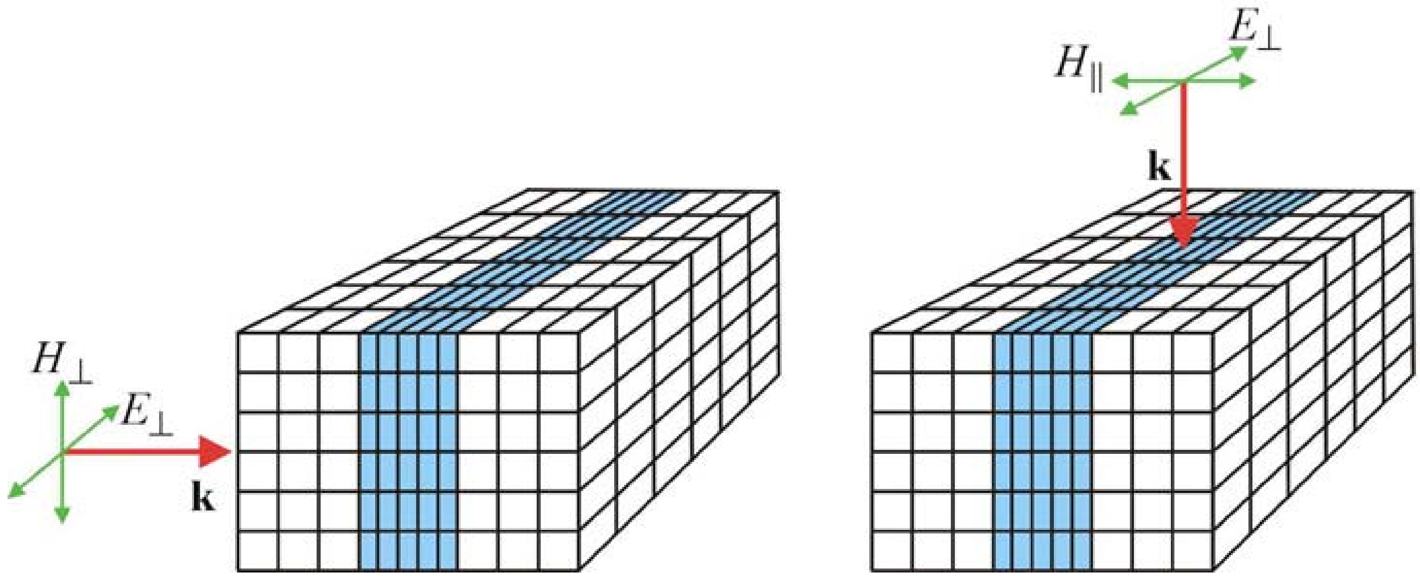
A Geometric view of transformation optics



Imagine the simplest possible distortion of space shown above. We probe the compressed region with two rays in order to find the values of $\boldsymbol{\varepsilon}(\mathbf{r})$ and $\boldsymbol{\mu}(\mathbf{r})$ that would give rise to the ray trajectory shown. We recognize that:

- $\boldsymbol{\varepsilon}(\mathbf{r}), \boldsymbol{\mu}(\mathbf{r})$ are tensors because we have singled out the *x*-axis,
- in the uncompressed regions there is no change so $\boldsymbol{\varepsilon}(\mathbf{r}) = \boldsymbol{\mu}(\mathbf{r}) = 1$,
- $\boldsymbol{\varepsilon}(\mathbf{r})$ and $\boldsymbol{\mu}(\mathbf{r})$ appear on the same footing because of E / H symmetry.

It follows from the last assertion that $\boldsymbol{\varepsilon}(\mathbf{r}) = \boldsymbol{\mu}(\mathbf{r})$.



Rays propagating *parallel* to the $x-$axis arrive at the far side of the compressed region with the same phase as in the uncompressed system. We require,

$$\varepsilon_y = \mu_y = m^{-1}$$

On the other hand rays propagating perpendicular to the $x-$axis must take the free space value if the correct phase evolution is to be followed. In this case,

$$\varepsilon_y \mu_x = \varepsilon_x \mu_y = 1$$

hence,

$$\varepsilon_x = \mu_x = m$$

Length of side of plates	Number of layers	plate spacing	permeability (predicted)	permeability (measured)
133	9	34	0.64	0.58 ± 0.04
153	6	14	0.48	0.49 ± 0.05
163	9	4	0.23	0.31 ± 0.06
167	9	0	0.0	0.04 ± 0.06

Endoscopically Compatible MR-Safe Magneto-inductive Imaging Catheter

R.R.A. Syms[1], I.R.Young[1], M.M.Ahmad[1],
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Imperial College London

7th Int. Cong. on Advanced Electromagnetic Materials in Microwaves
and Optics - Metamaterials 2012, Bordeaux, France, 16-21 Sept. 2013

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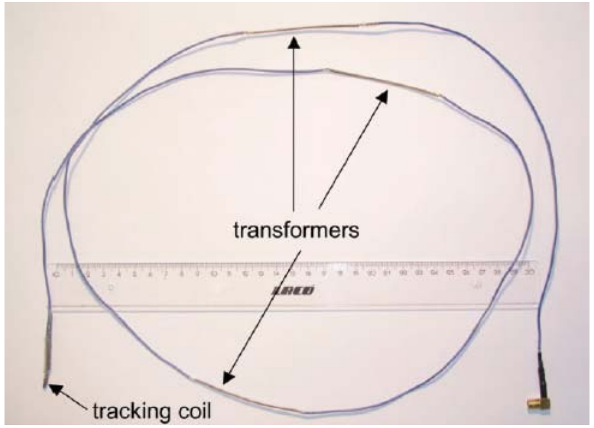
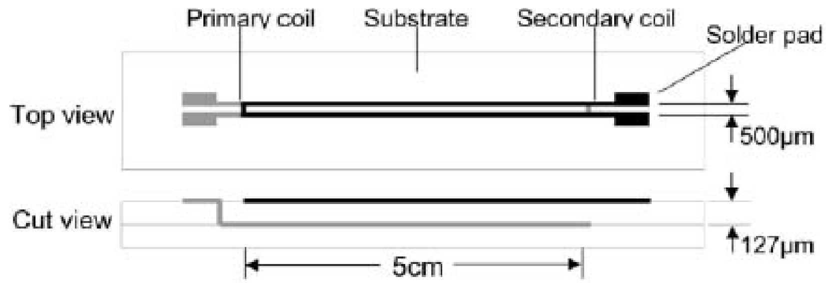
MR-Safe Cables



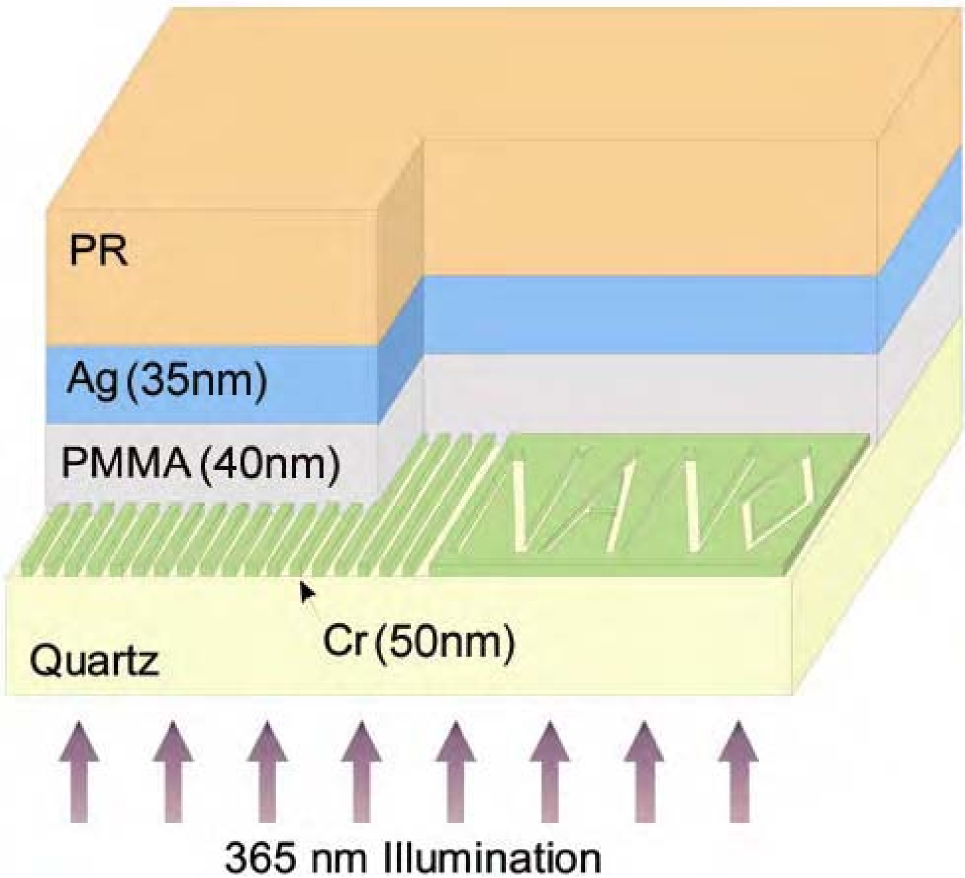


Weiss et al.
"Transmission line for improved RF safety of interventional devices"
MRM 54, 182-189 (2005)

- Solution to subdivide cable using transformers
  - Each segment then too short to support external standing waves
- Periodic nature of structure generally ignored
  - Actually magneto-inductive waveguide

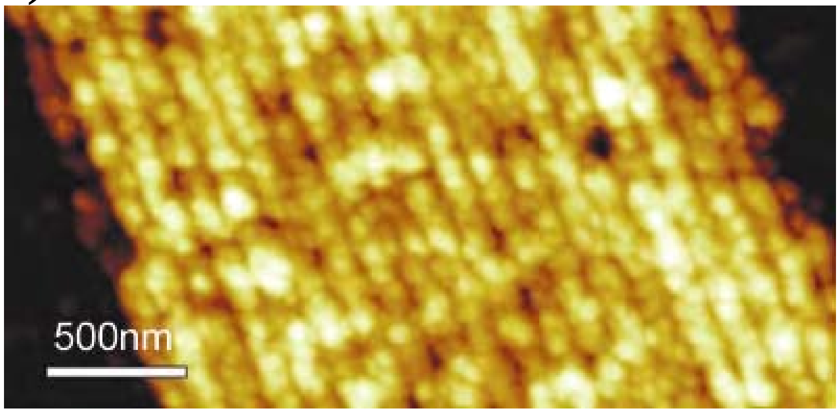
Near field superlensing experiment:

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



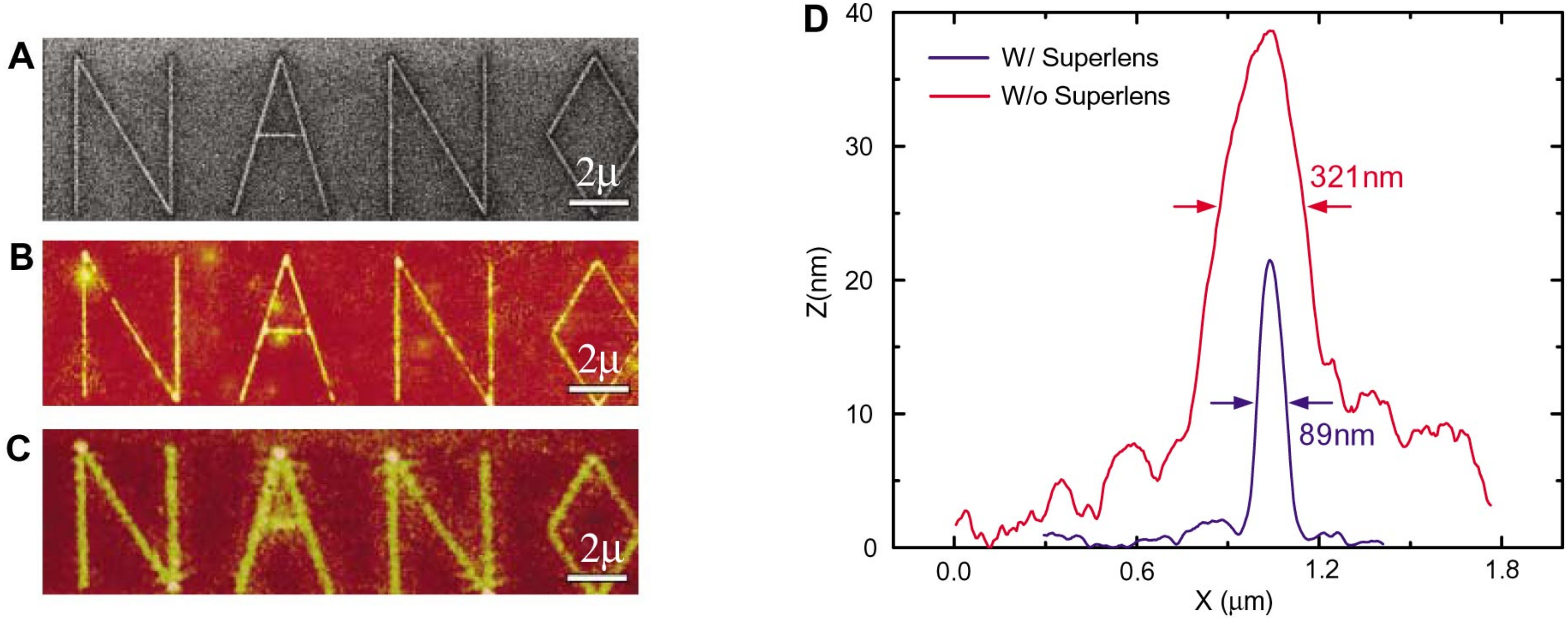
Left: the objects to be imaged are inscribed onto the chrome. Left is an array of 60nm wide slots of 120nm pitch. The image is recorded in the photoresist placed on another side of silver superlens.

Below: Atomic force microscopy of a developed image. This clearly shows a superlens imaging of a 60 nm object (λ/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.