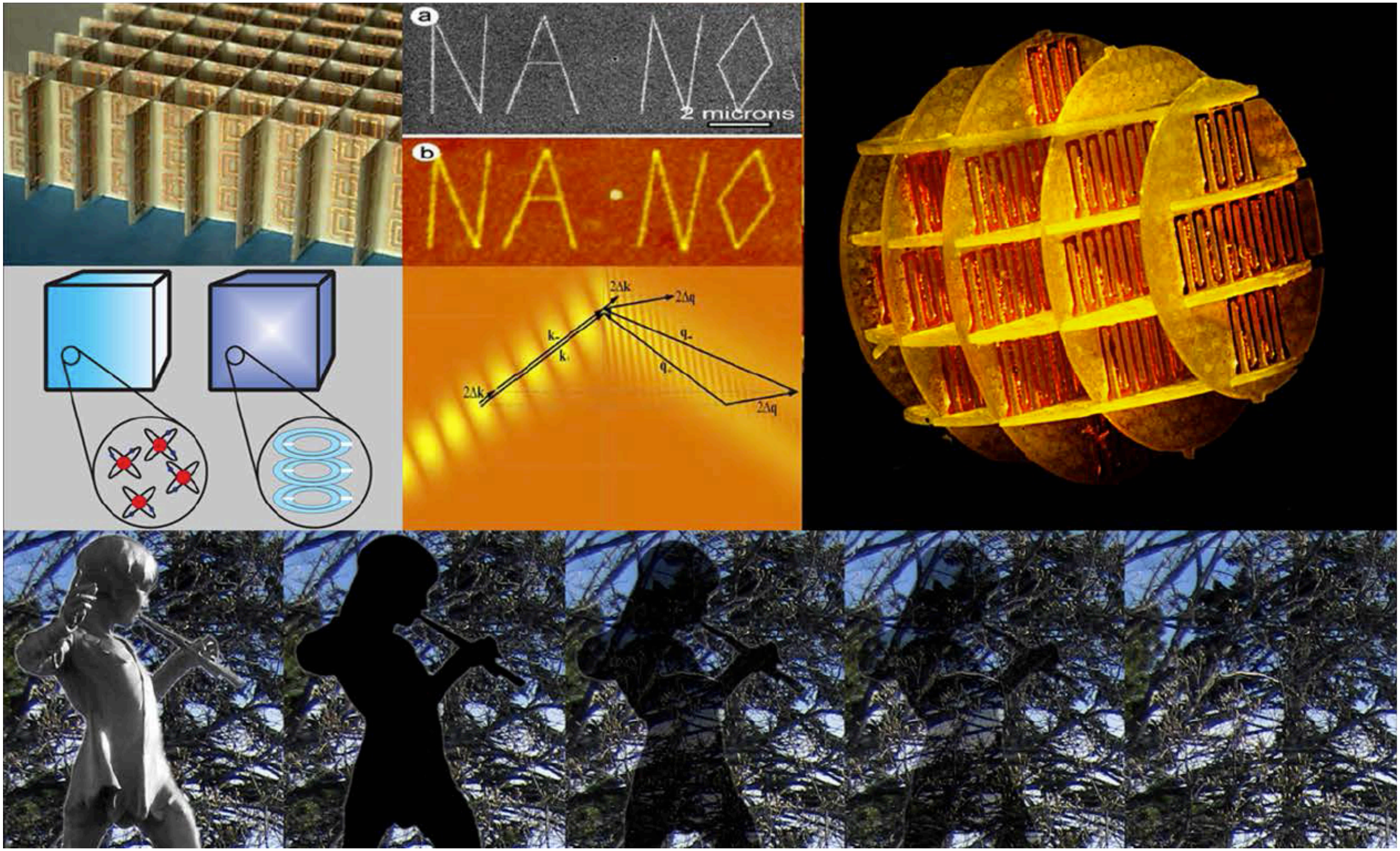
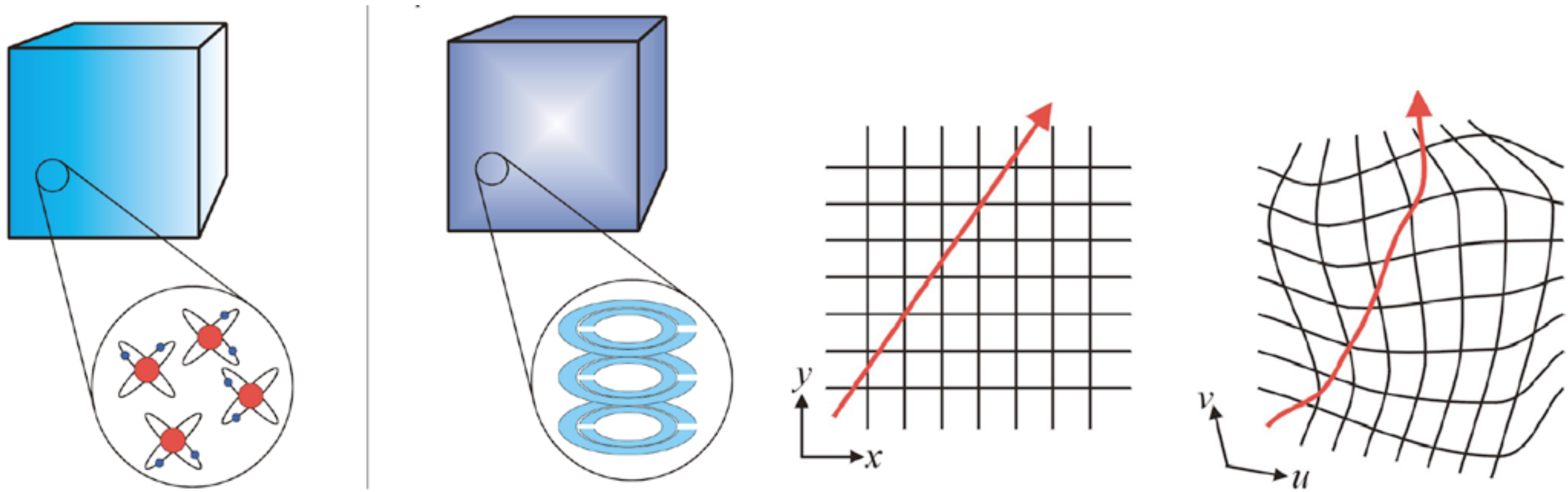
Metamaterials:
a new dimension in electromagntism

John Pendry, Imperial College London



Imperial College
London

The metamaterial concept



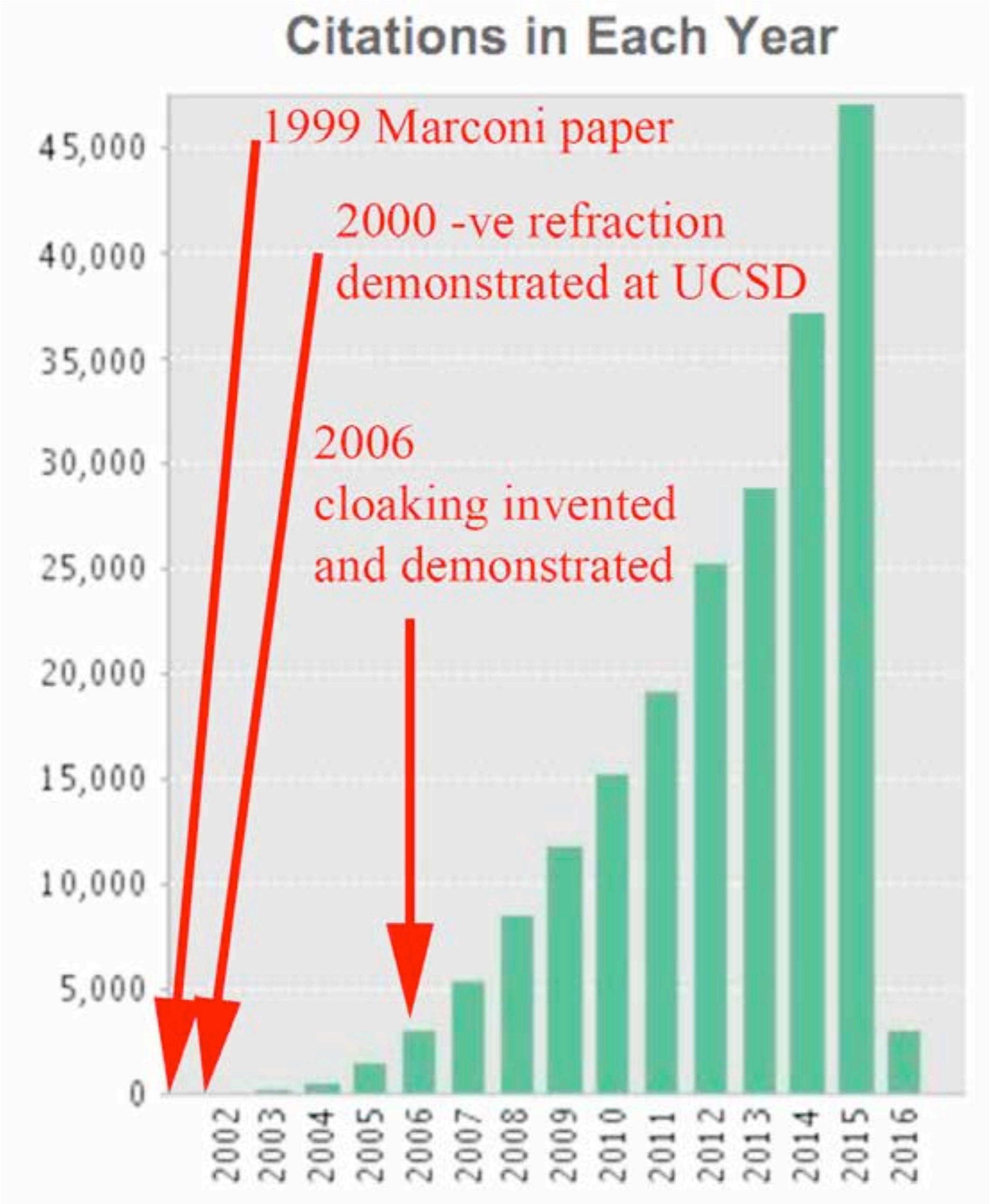
Metamaterials give access the material properties never before available.

Unlike photonic materials their properties are described by ε and μ simpifying the design process

They have enabled the new design paradigm of ‘transformation optics’

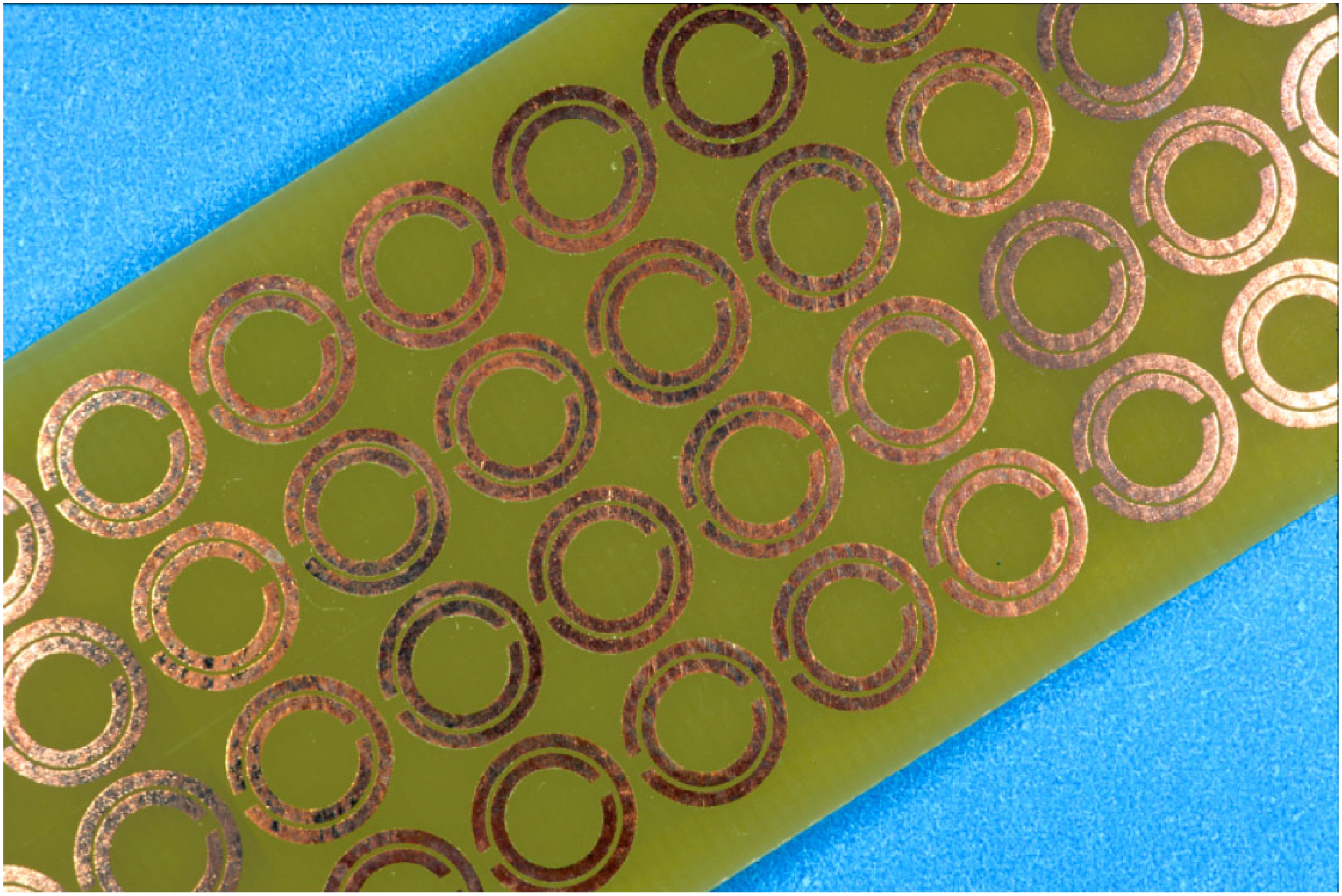
Intense concentrations of EM energy within their structures greatly enhances non linear properties – can be exploited in switching, time reversal, 4 wave mixing etc.

The rise of metamaterials

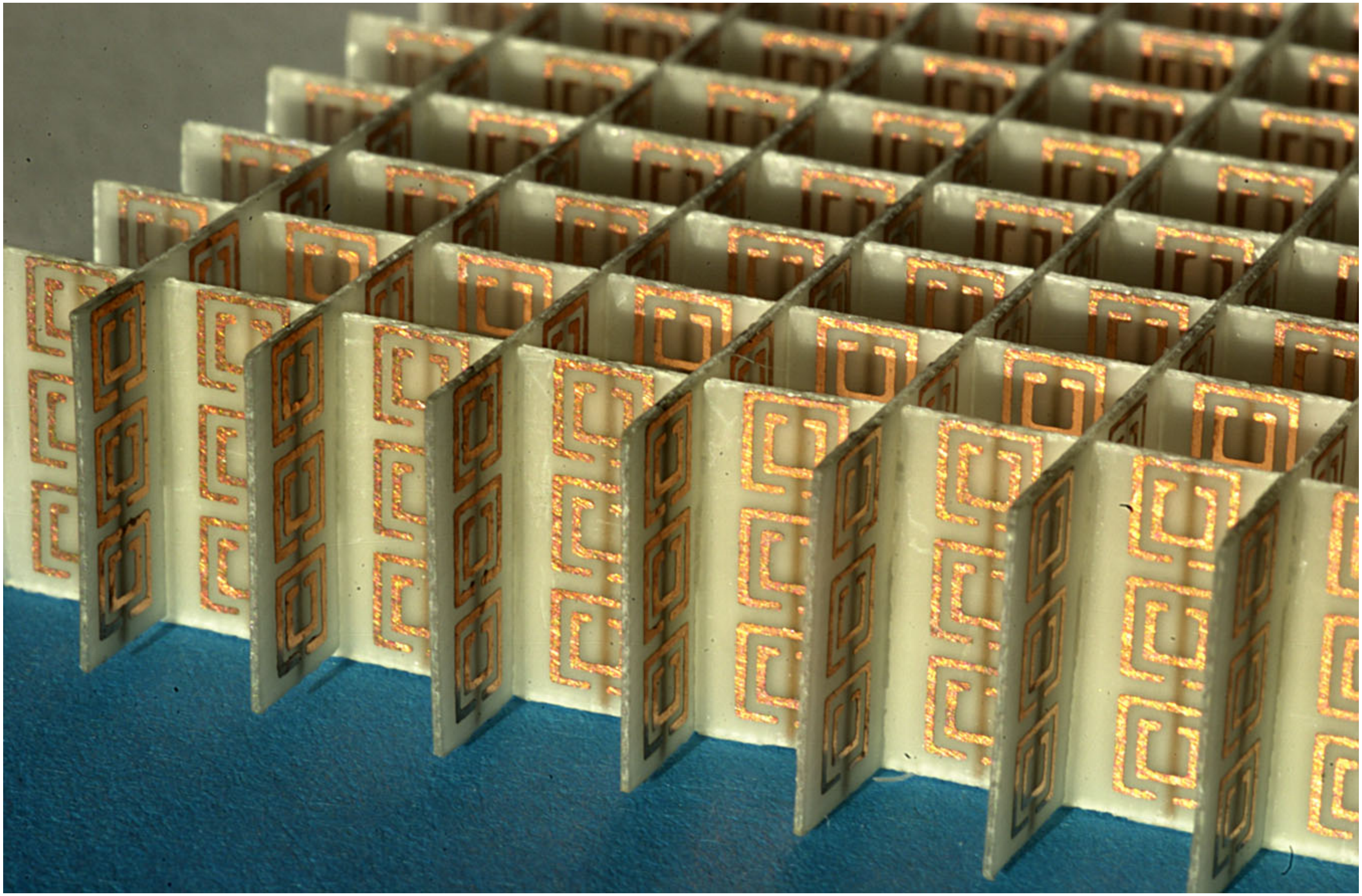


Practical realisation of the split ring structure

(Marconi: Mike Wiltshire, ca 1998)



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



Structure made at UCSD by David Smith

Negative refractive index metamaterials

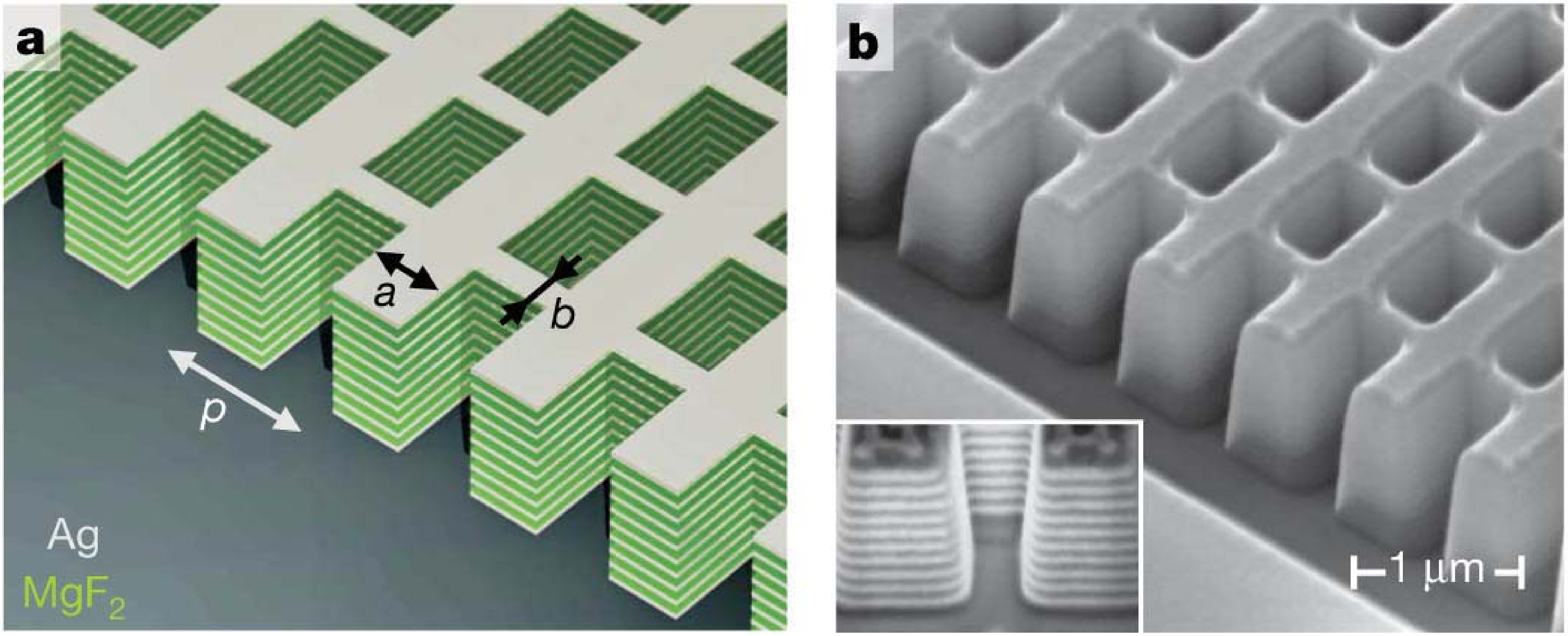


Diagram (left) and scanning electron microscope image (right) of a ‘fishnet’ structure fabricated by the Xiang group at Berkeley California. The structure consists of alternating layers of 30nm silver and 50nm magnesium fluoride.

Metamaterials – they are everywhere!

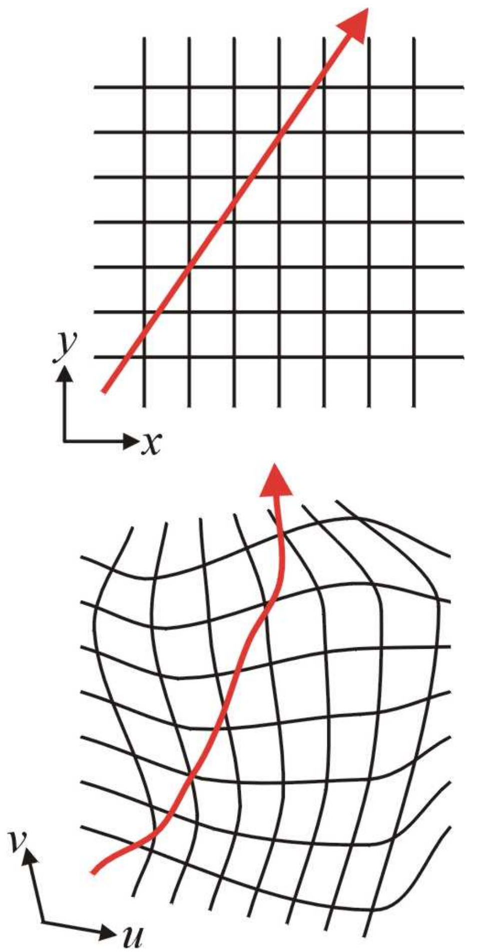
DC	giant paramagnetism
MRI	safe pick up coils (Richard Syms, IC)
RF	cell phones and satcoms (cheap and light phased array - Kymeta)
THz	enhanced cascade laser efficiency (Capasso, Harvard)
IR	control of thermal radiation, broad band absorbers
visible	plasmonics, enhanced non linear phenomena, single molecule detection, giant chirality
acoustics	sound proofing of domestic environment, stealth technology
mechanics	materials with novel mechanical properties - Vincenzo Vitelli, Leiden

Metamaterials – our recent research

- controlling light in nanoscale structures
- understanding light harvesting in plasmonic systems
- non locality in the dielectric response (with Duke)
- electron energy loss in plasmonic systems
- Van der Waals forces between complex nanostructures
- heat transfer on the nanoscale
- switchable metasurfaces

Formal theory: A. J. Ward and J.B. Pendry, *J Mod Op*, **43** 773 (1996)

also D.M. Shyroki (2003)
http://arxiv.org/abs/physics/0307029v1



Top: a ray in free space with the background Cartesian coordinate grid shown. **Bottom**: the distorted ray trajectory with distorted coordinates.

New coordinates in terms of the old: $x'^{j'}\left(x^{j}\right)$

In the new coordinate system we must use renormalized values of the permittivity and permeability, ε,μ:

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

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

where,

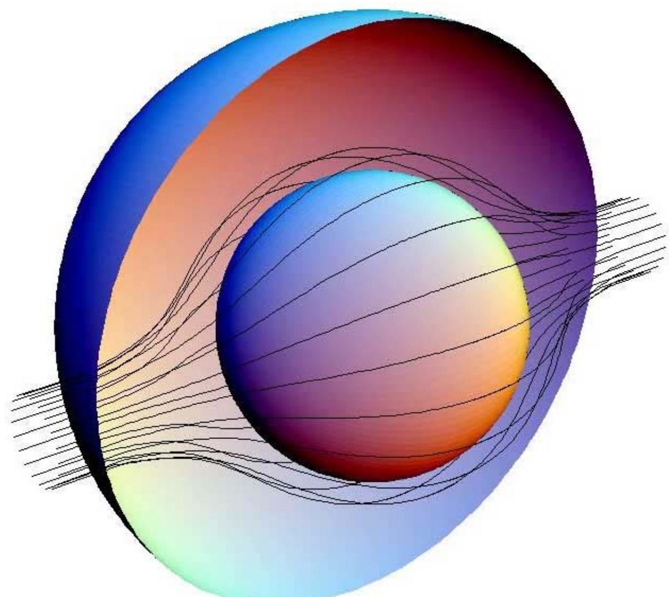
$$\Lambda_j^{j'} = \frac{\partial x'^{j'}}{\partial x^{j}}$$

For the special case of conformal transformations in 2D systems, ε, μ are unchanged.

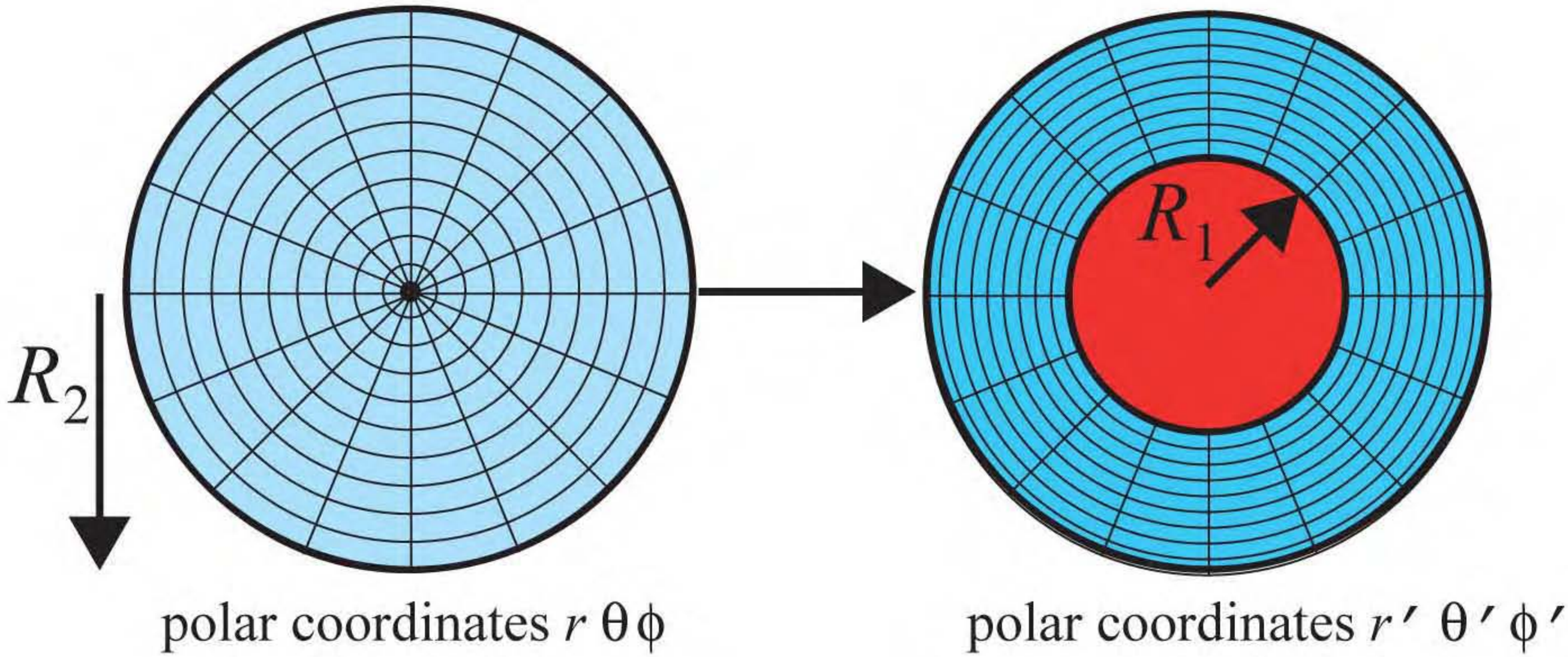
How to make something invisible using transformation optics

Science **312** 1780-2 (2006), JB Pendry, D Schurig, and DR Smith

1. define a region that is to be invisible
2. surround it with an optical medium that can bend light
3. design the medium to bend the light rays inside the cloak away from the invisible region – this ensures no one can see inside
4. check that rays outside the cloak are never disturbed – this ensures no one can detect that the cloak is present



Creating a hidden space



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

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

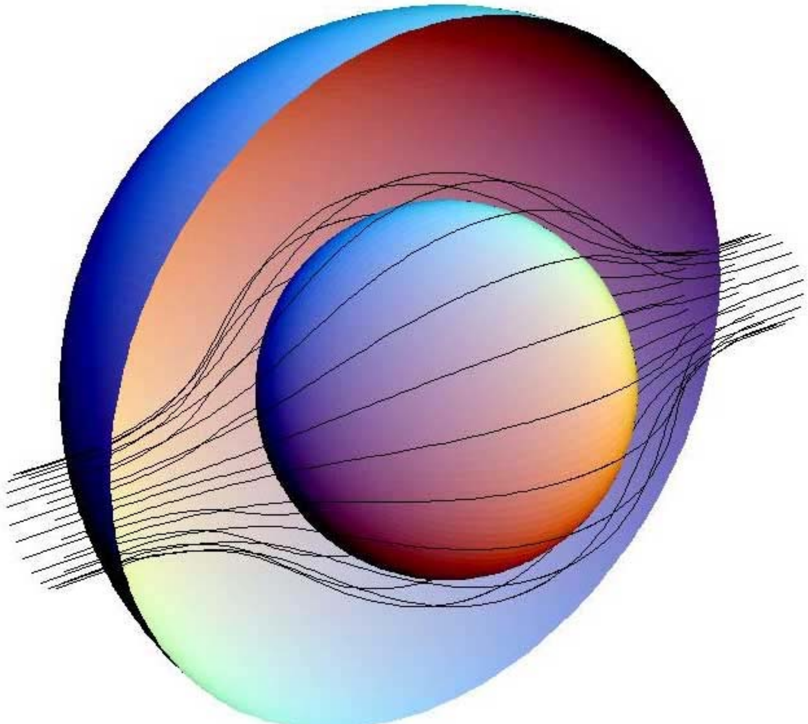
From the transformation we can find the refractive index, as a function of radius, needed to make the cloak.

Cloaking Static Magnetic Fields

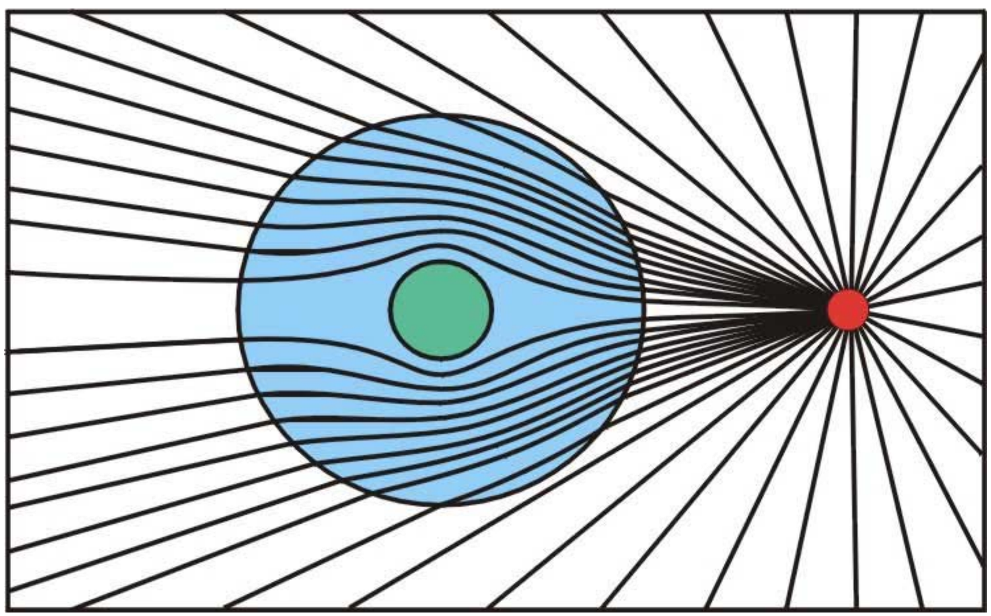
see: J. Phys.: Condens. Matter **19** (2007) 076208 (*B. Wood and JB Pendry*)

Cloaking works for fields as well as waves!

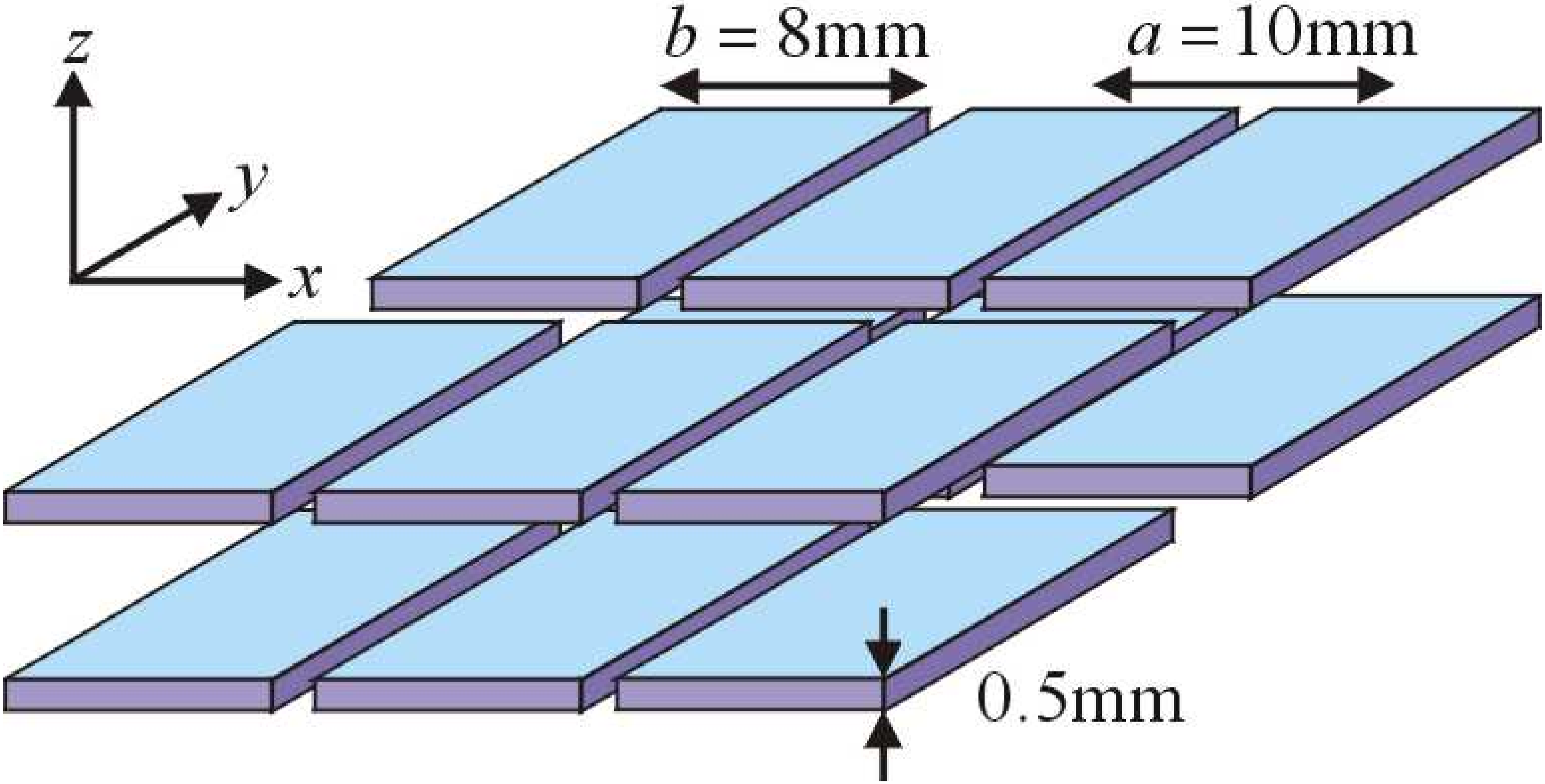
deflection of rays
(far field)



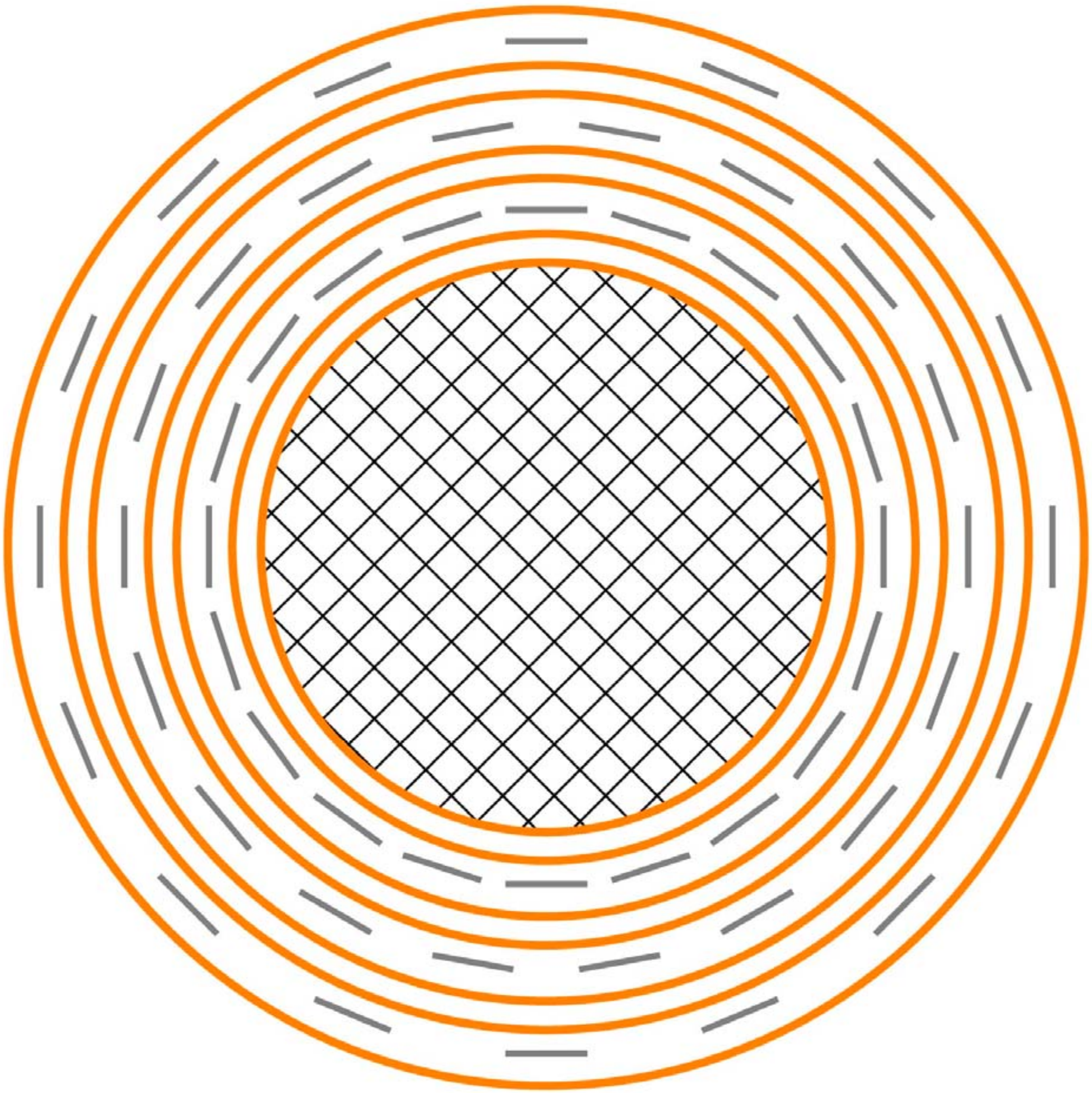
deflection of field lines
(near field)



Lattice of superconducting plates



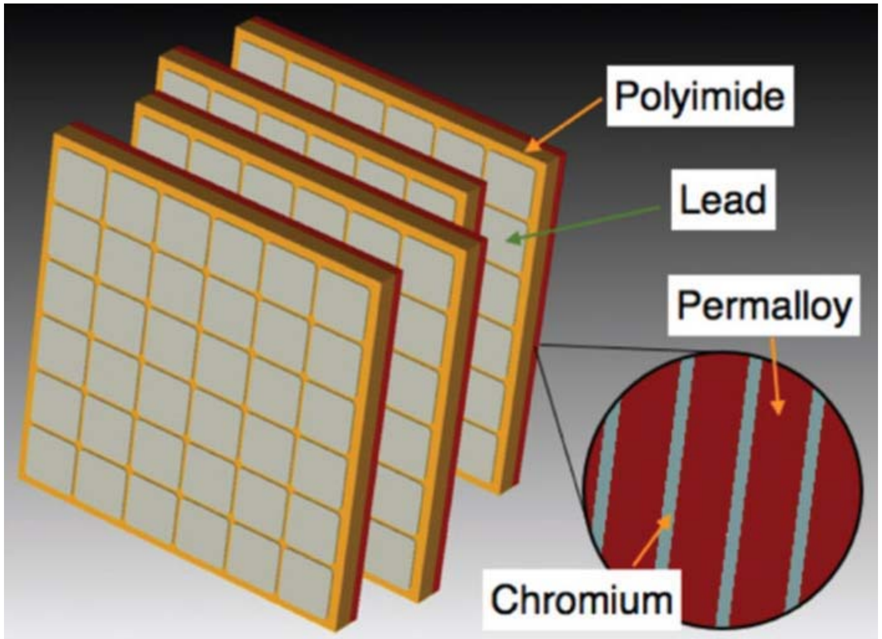
The proposed magnetic cloak



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

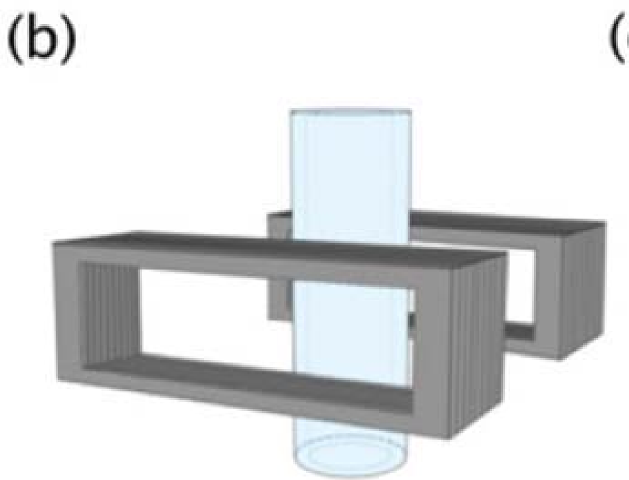
Supradeep Narayana and Yuki Sato, *Advanced Materials*, **24**, 71-74 (2012)

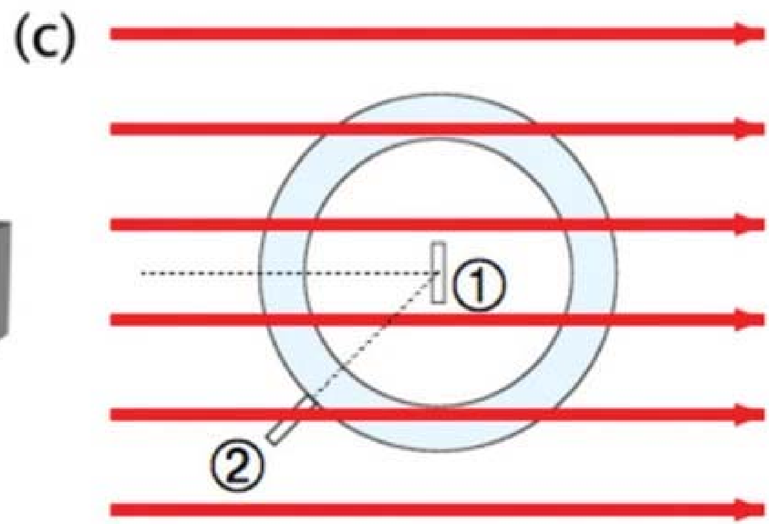


Schematic of the cloaking material consisting of an array of superconducting and soft ferromagnetic elements.

(b) Apparatus geometry.

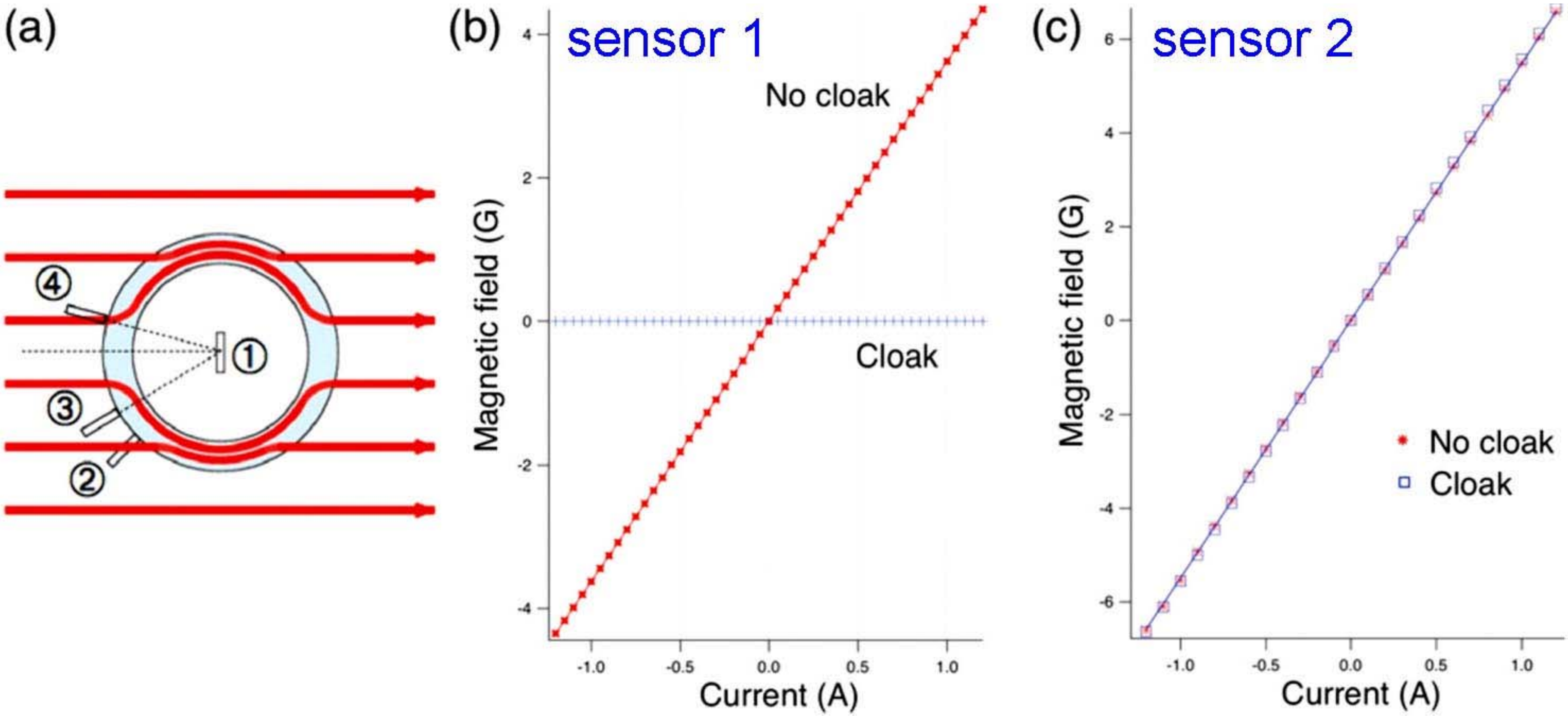
(c) Top-view schematic showing the locations of two Hall sensors and magnetic field lines in empty space. Sensor 1 detects the field that penetrates through the cloak, and sensor 2 is positioned to capture external field perturbations due to the presence of the cloak.





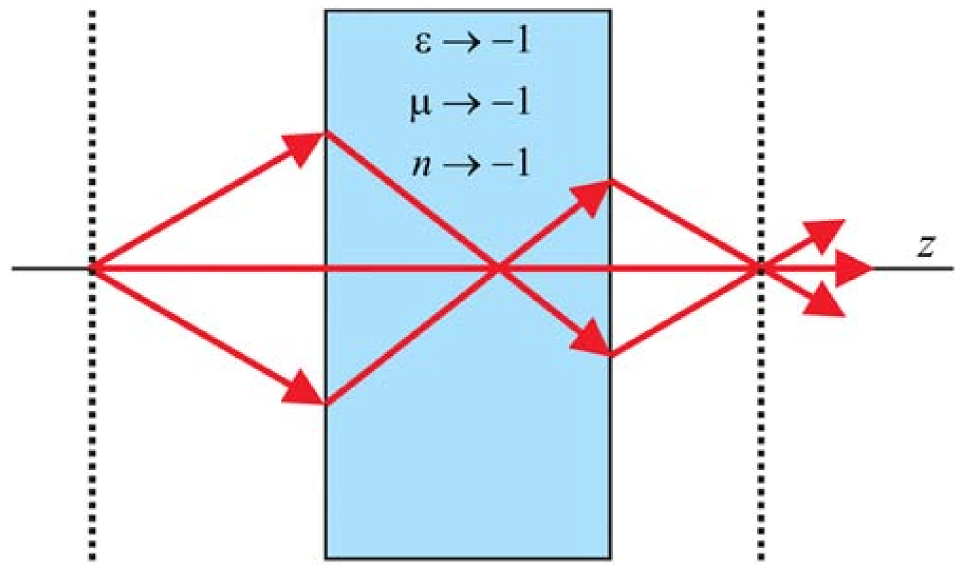
A DC magnetic cloak - 4

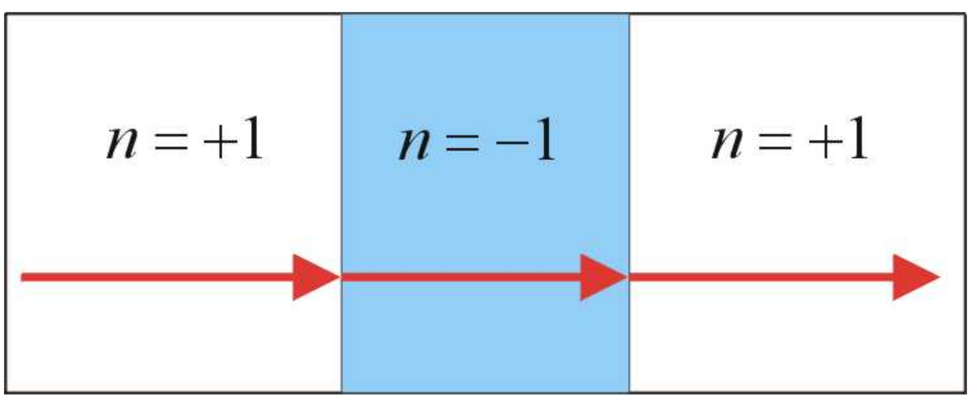
Cloaking magnetic fields using *metamaterials* excludes fields from inside the cloak, and leaves the external field undisturbed.



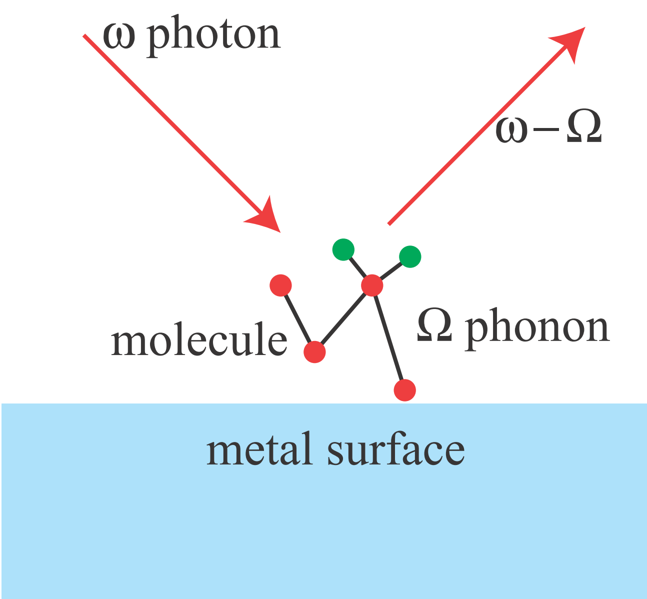
Transformation optics & negative refraction

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 exist on several manifolds:





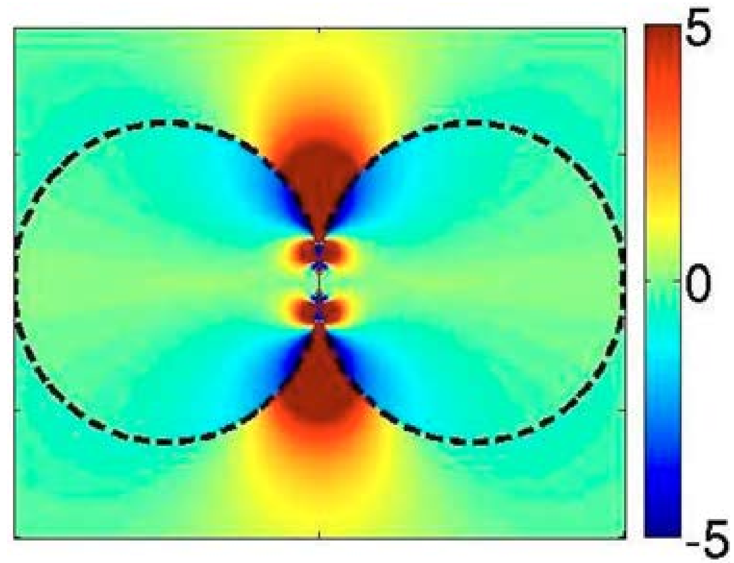
Surface plasmons ...



give rise to some extraordinary effects such as the giant Raman resonance or SERS.

Singularities in the surface geometry attract intense concentrations of fields. For example when two curved surfaces meet. The field density, $|E|^2$, can be enhanced by several orders of magnitude. The Raman signal scales as $|E|^4$ giving spectacular enhancements of the signal.

Right: simulation of light incident from above on two touching cylinders. The geometric singularity at the touching point enhances field density by a factor of around 10^4

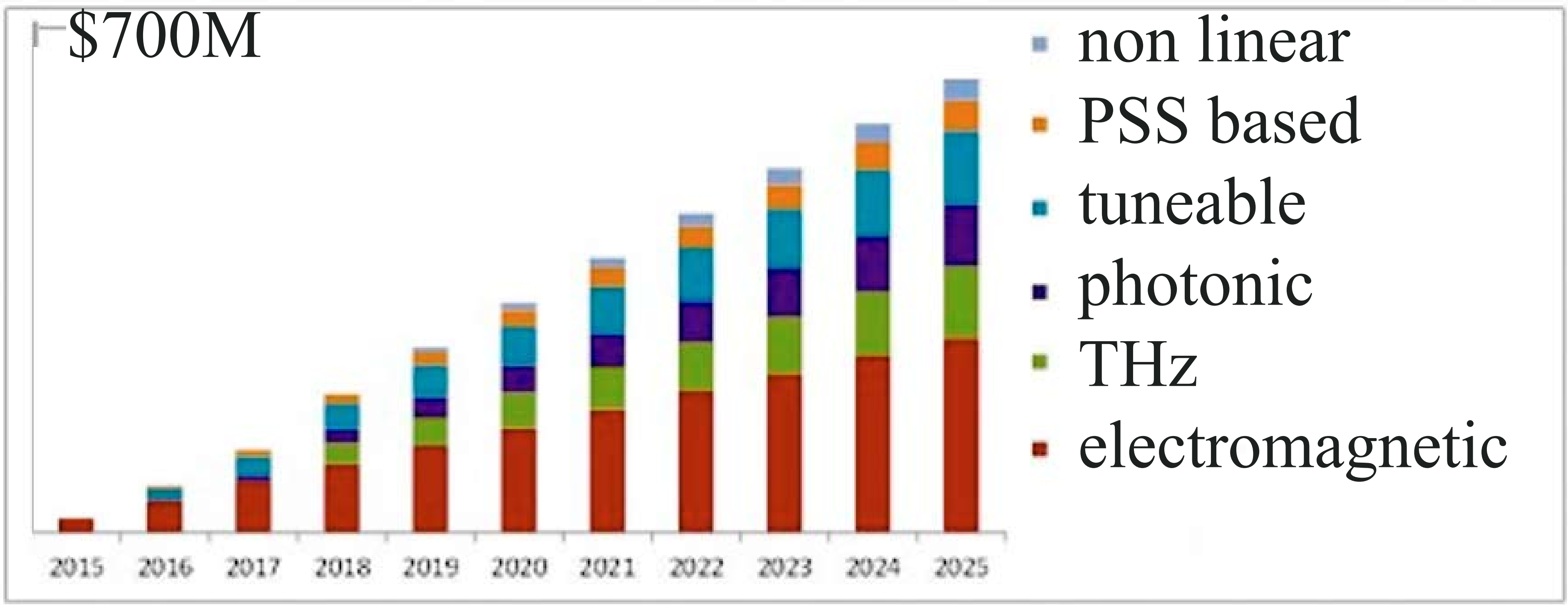


Metamaterials Market (2013-2025)

marketsandmarkets.com, April 2014, Report Code: SE 2430

"The market segmentation revolves around four verticals namely types of artificial materials,device types, application, and geography. The market is expected to grow at a CAGR of 41.25% to reach $643 million by 2025."

Metamaterials Market Value, by Type, 2013-2025 ($Millions)

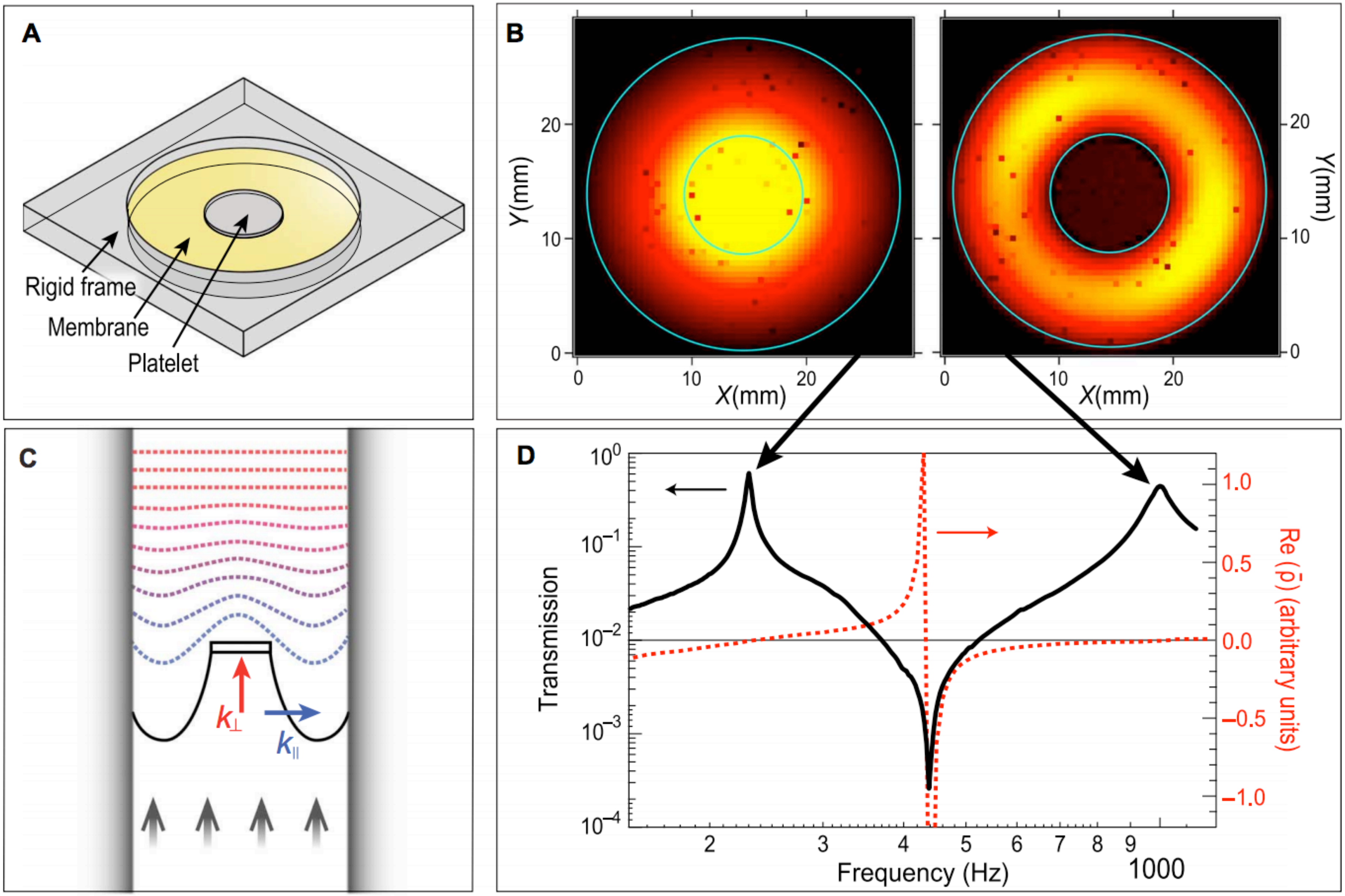


Metamaterials – UK activity

UK academic groups in the field (probably incomplete):

Birmingham	optical	Zhang, Li
Cambridge	optical	Baumberg
Exeter	RF, plasmonics, acoustics	Sambles, Hibbins, Barnes
Imperial	optical, some THz, acoustics	Hess, Maier, Syms, JBP
KCL	optical	Zayats
Liverpool	acoustic	Movchan
Loughborough	RF	Vardaxoglou
Manchester	graphene based metamaterials	Grigorenko
Oxford	RF	Grant, Shamonina
QMUL	RF	Hao, Parini
QUB	RF	Fusco
Southampton	mainly optical	Zheludev
UEA	optics	Andrews

Ping Sheng: single membrane with negative effective mass density gives a low frequency acoustic stop band.



Metamaterials and satcom – Kymeta meets Toyota

Metamaterials and satcom – Kymeta meets Toyota

In 2013, Intellectual Ventures spun out Evolv Technologies, Inc

Evolv: Commercializing new metamaterials-based imaging and detection technology for use in airports and other high-risk facilities.

Intellectual Ventures spinout Evolv gets $11.8M from Bill Gates and others, aims to transform security scanning. The second company to commercialize an invention from IV’s portfolio of metamaterials patents.

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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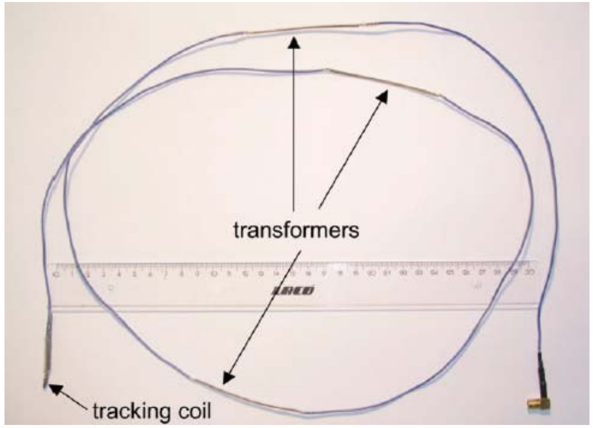
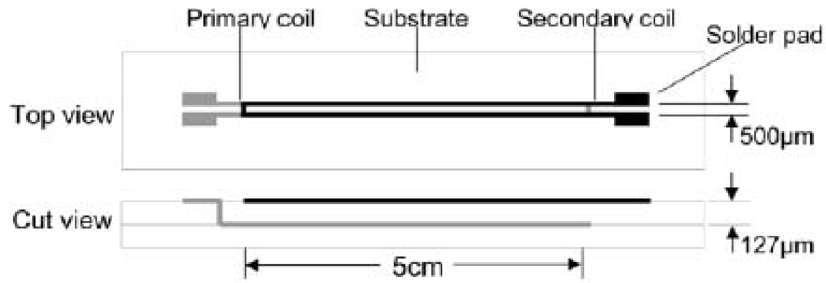
MR-Safe Cables





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

Capasso Group
Harvard School of Engineering and Applied Sciences

Gordon McKay Labs:
9 Oxford St
Rm 125
Cambridge MA 02138

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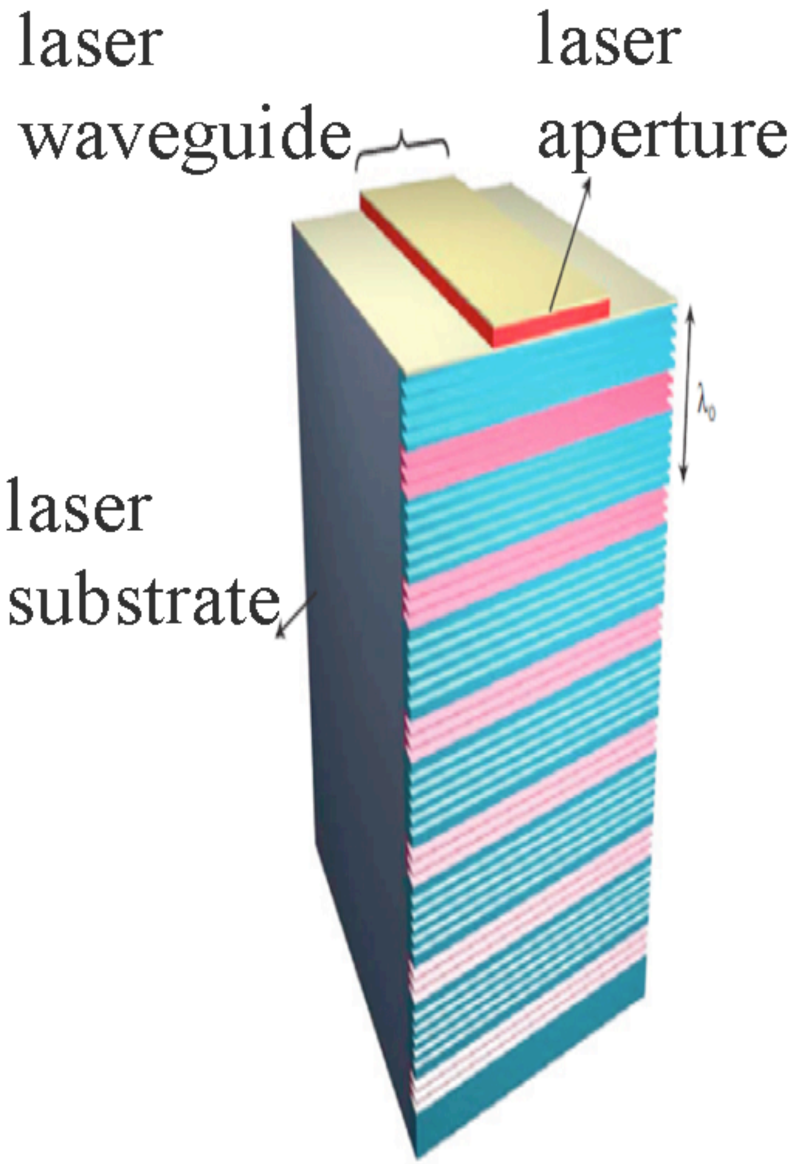

Group creates metamaterial waveguides for collimated quantum cascade laser output. The paper reports that by using a “metasurface” design to tailor the dispersion of terahertz surface plasmons, one can improve the power throughput and significantly reduce the beam divergence of terahertz quantum cascade lasers.

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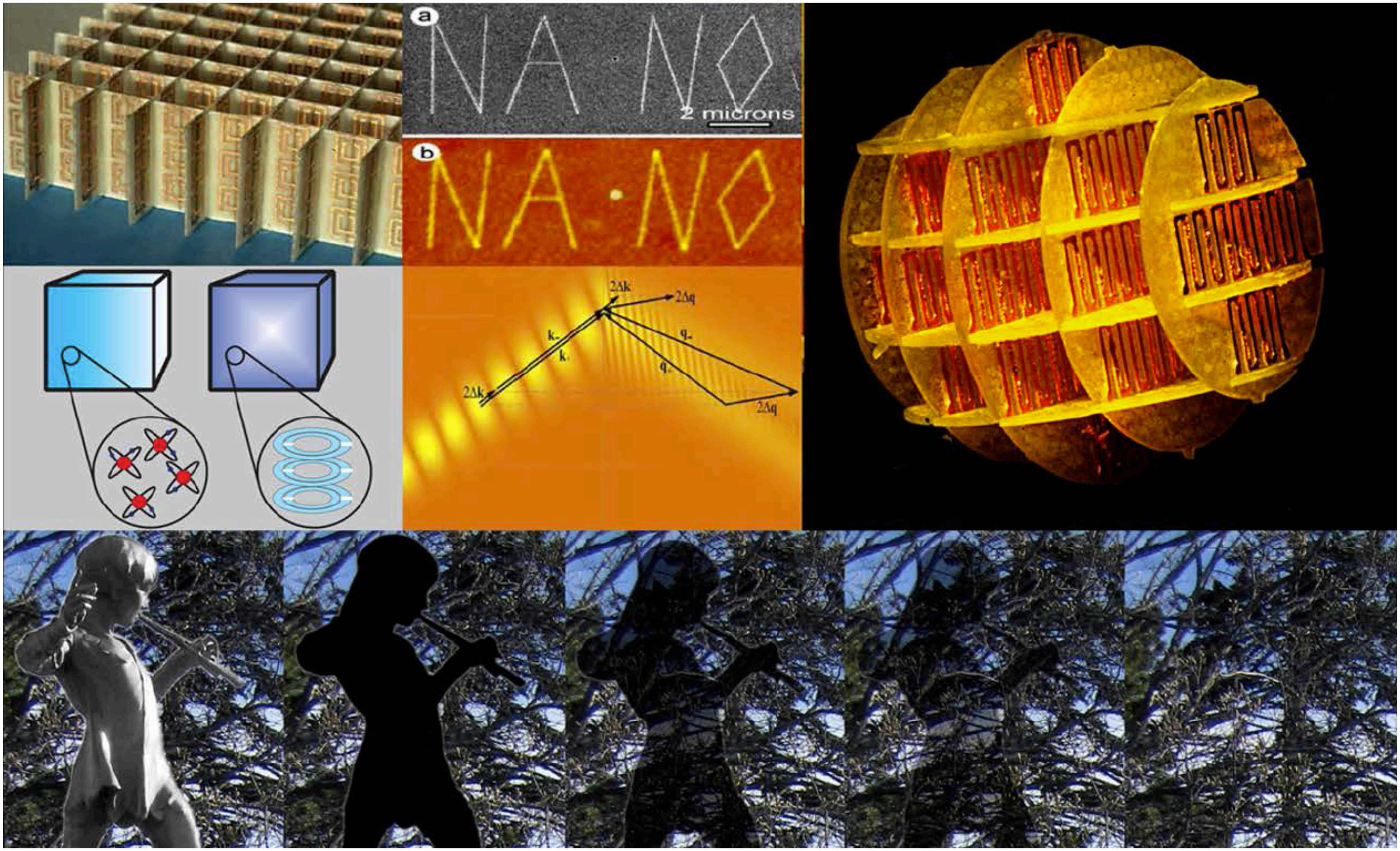

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