Metamaterials, transformation optics, & cloaks of invisibility

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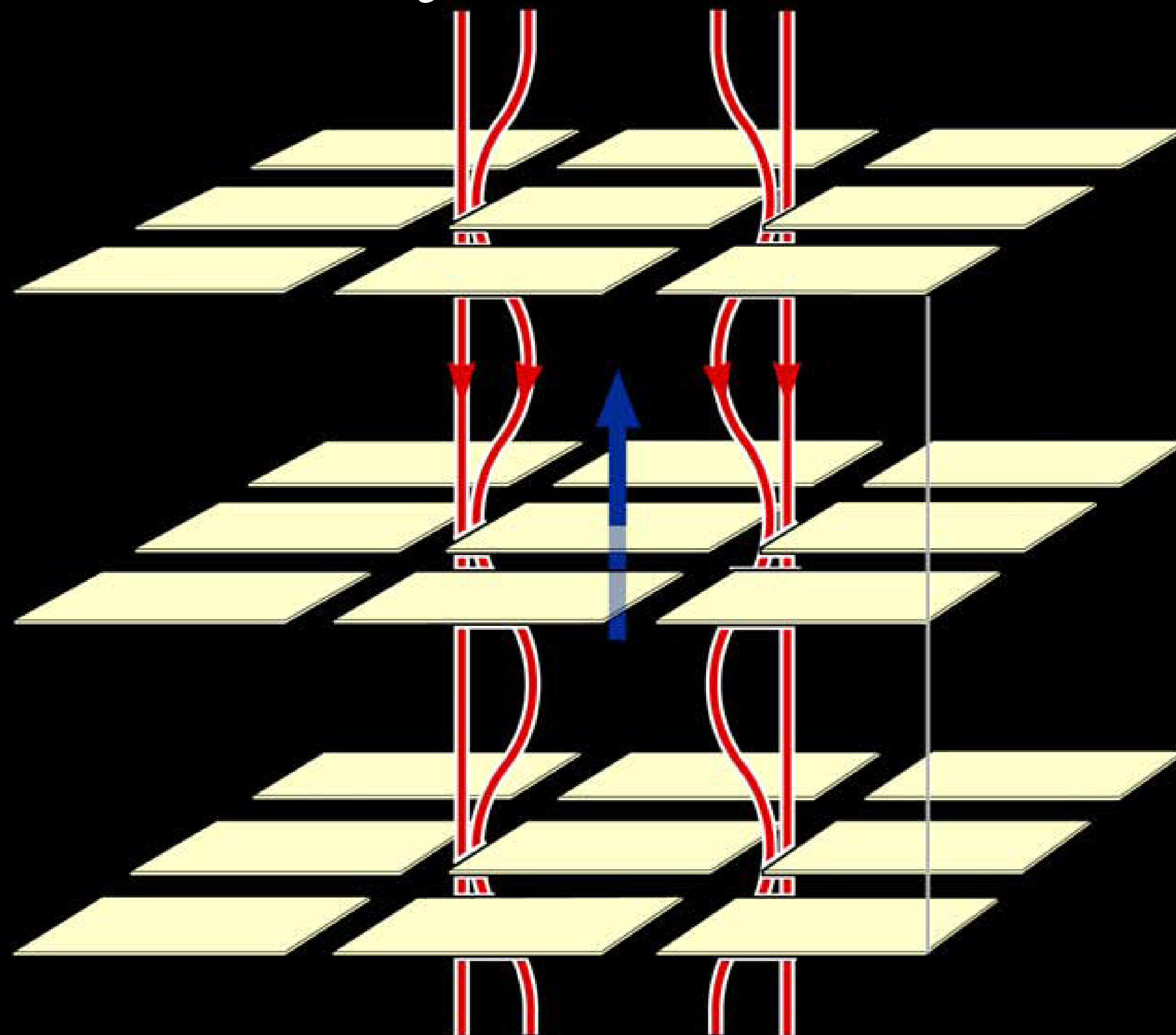
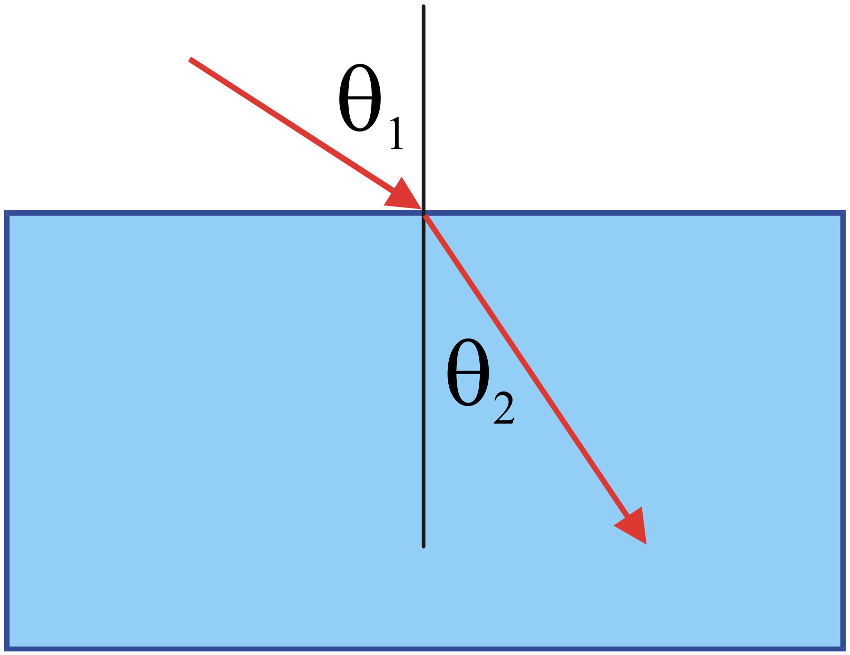


Refraction of Light – Snell/Descartes



The Snell-Descartes law of refraction:

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

where n is the refractive index of the material

Willebrord Snell van Roijen (or Snellius) (1580- 1626)

René Descartes (1596 –1650)

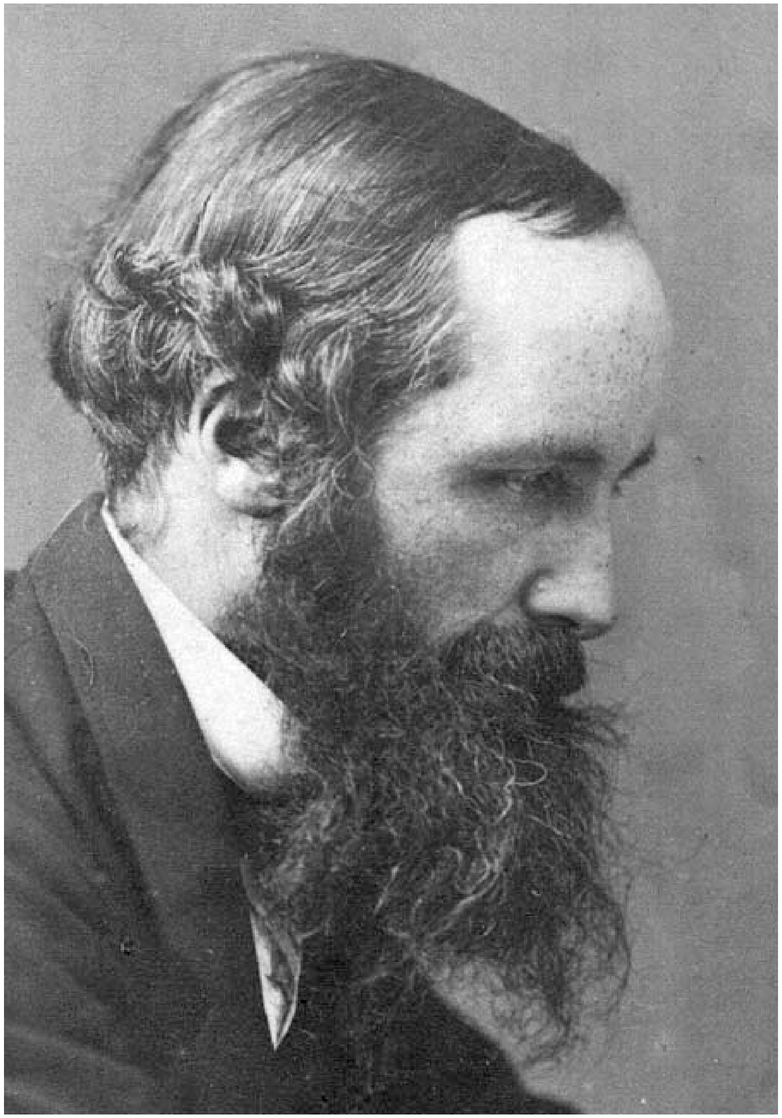
Maxwell's Equations

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$

$$\nabla \times \mathbf{H} = +\partial \mathbf{D} / \partial t$$

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$



James Clerk Maxwell
(1831–1879)

Maxwell and Faraday

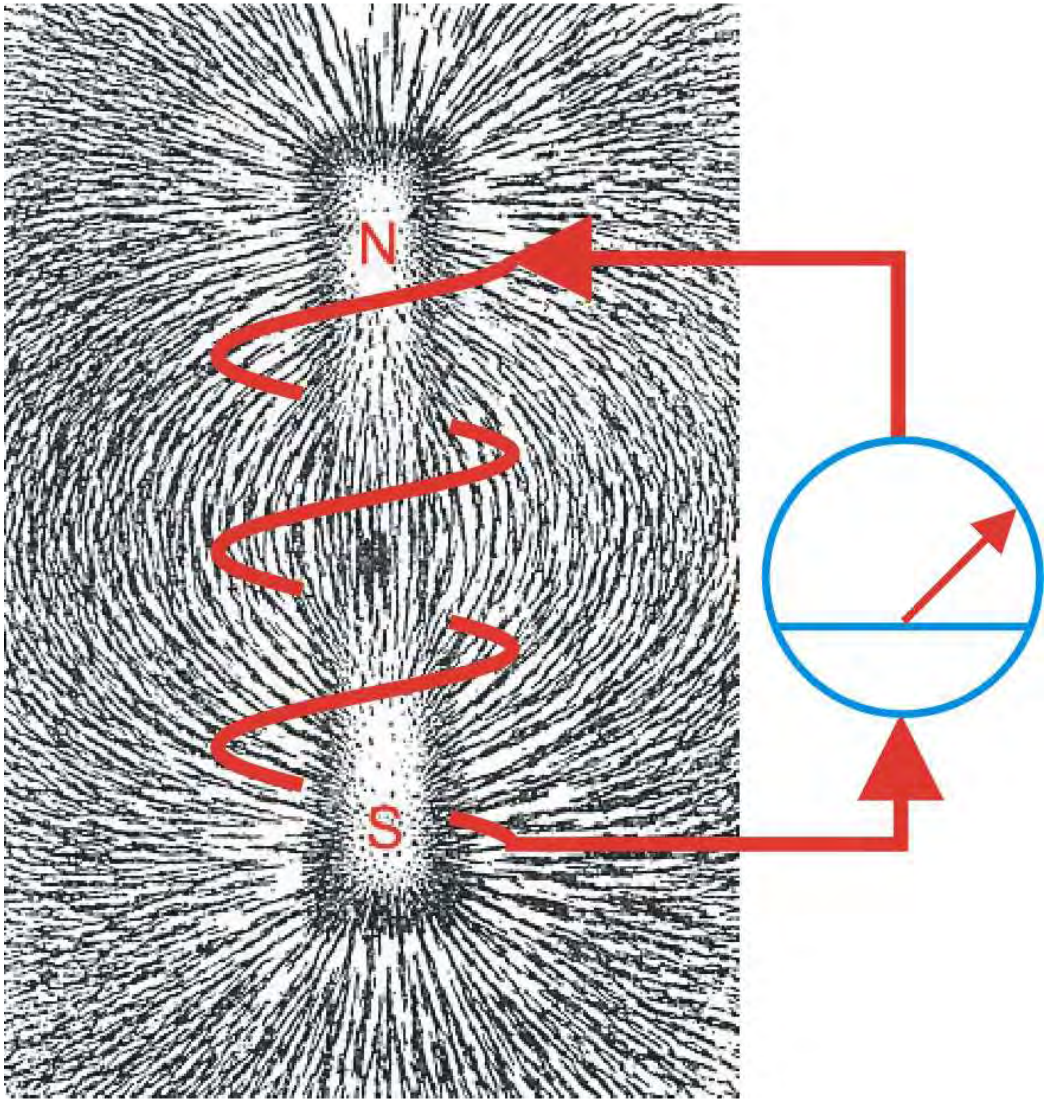
Maxwell's equations are largely the mathematical rationalisation of Michael Faraday's *lines of force.*

The magnetic **B**-field is represented by lines that begin and end on magnetic poles. They are otherwise continuous; their density represents the strength of the field and their orientation the direction.

Similarly the electric **D**-field is represented by lines that begin and end on electrical charges.

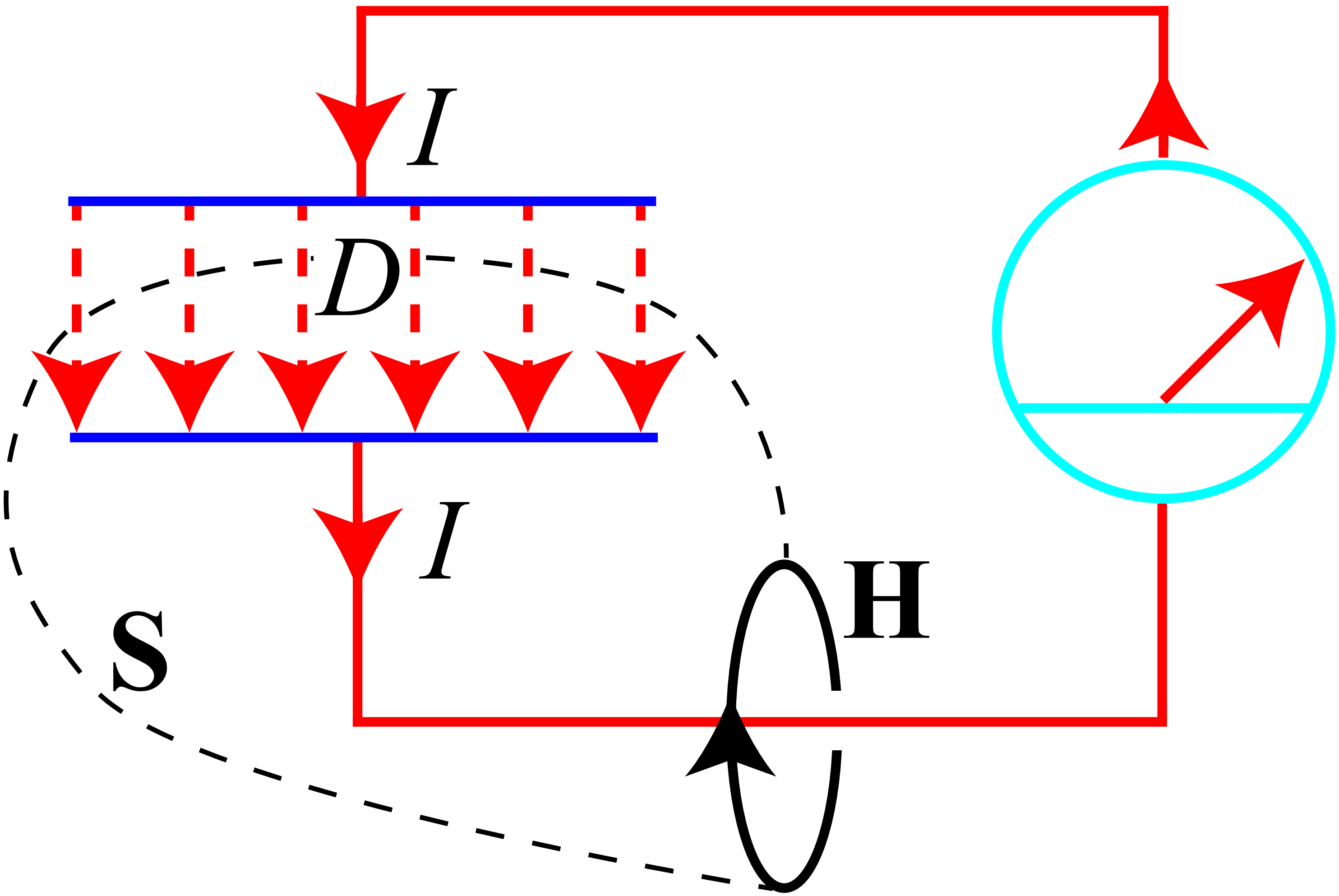
If we can manipulate these lines of force we have total control over electromagnetic phenomena.

Faraday's Laws of Induction



Michael Faraday
(1791–1867)

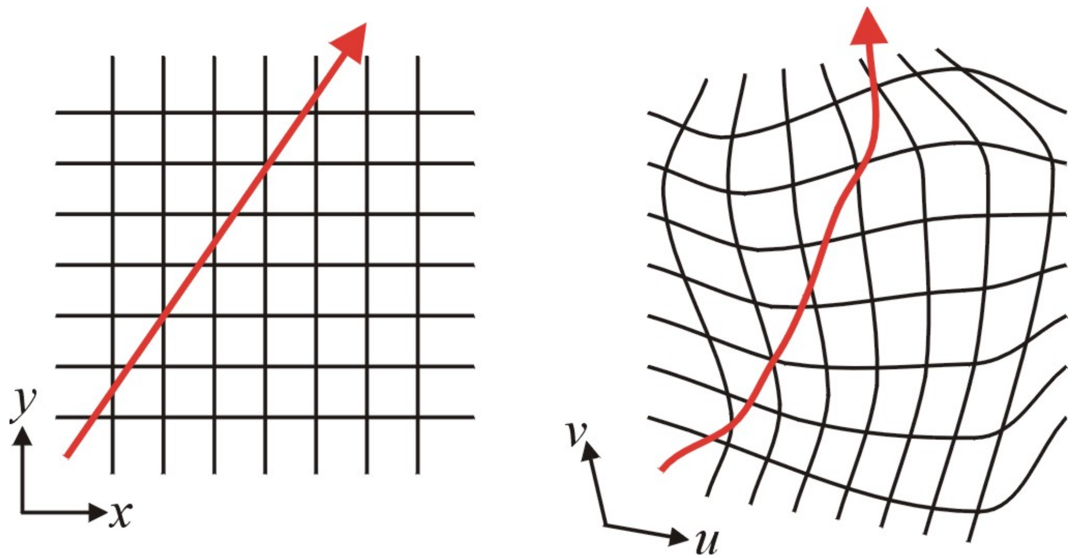
Maxwell's displacement current



$$\oint \mathbf{H} \cdot d\ell = \int I \cdot d\mathbf{S} = \int \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{S}$$

Making Light Flow Like Water

Distort the coordinate system, $(x,y,z) \to (u,v,w)$, 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.

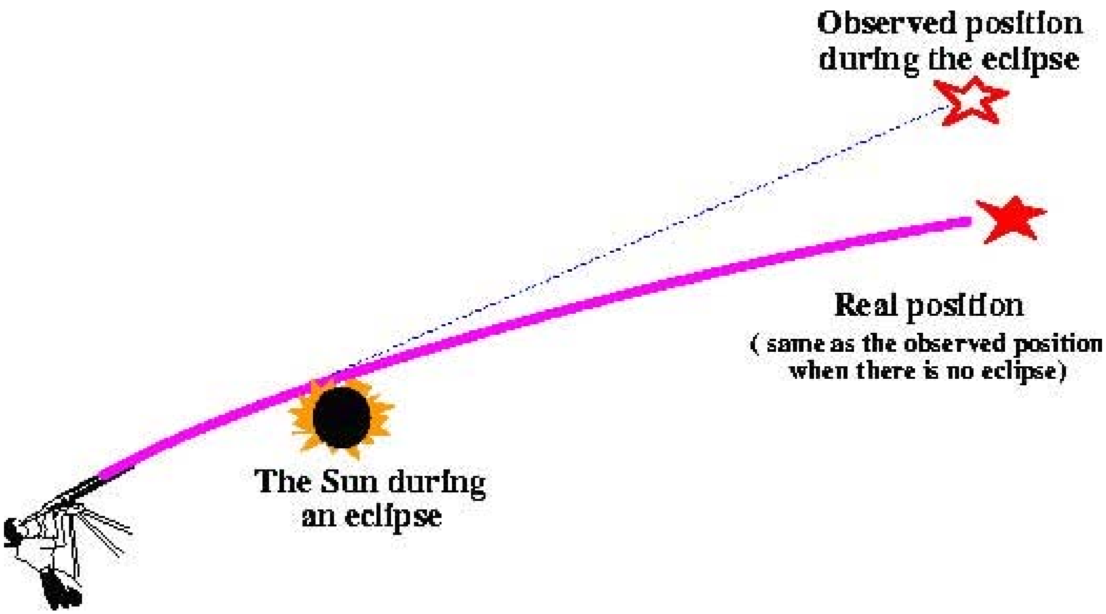
$$n' = n\, g(u,v,w)$$

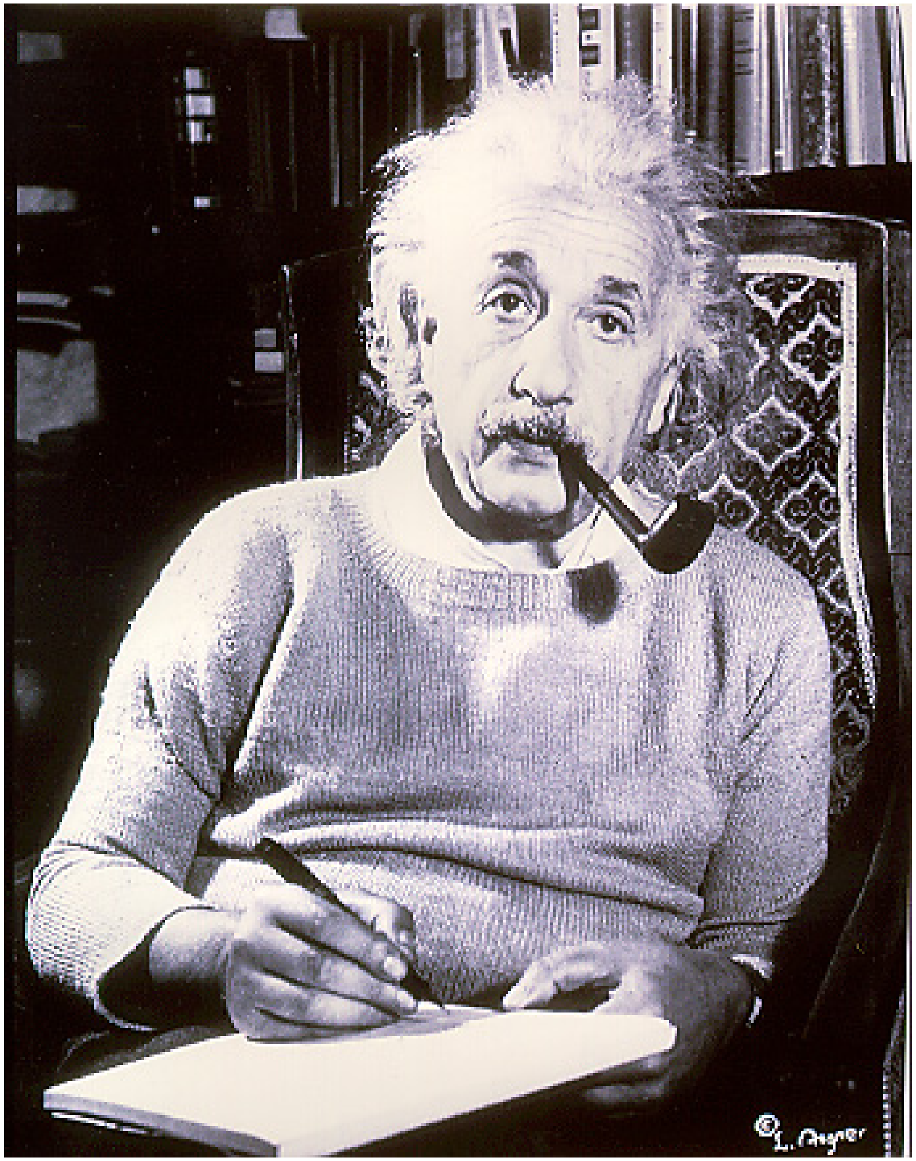
where $g(u,v,w)$ is obtained from the coordinate transformation.

Einstein, Light, and Geometry – the theory

The general theory of relativity: gravity changes geometry.

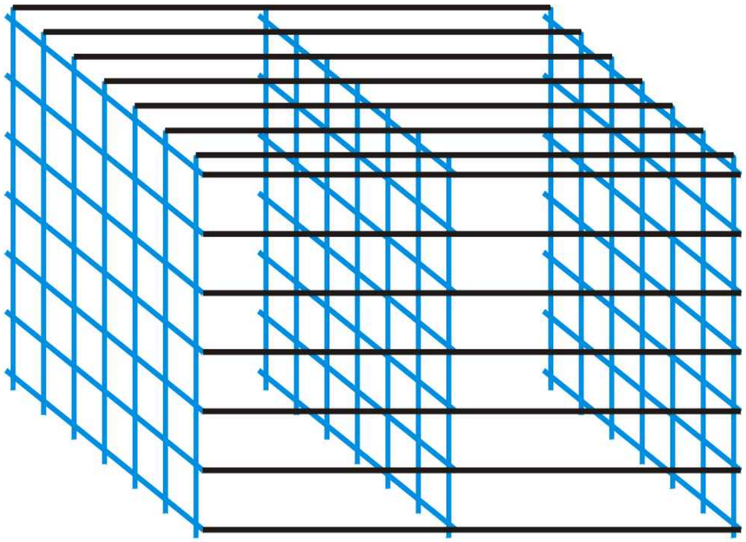
Therefore gravity should bend light



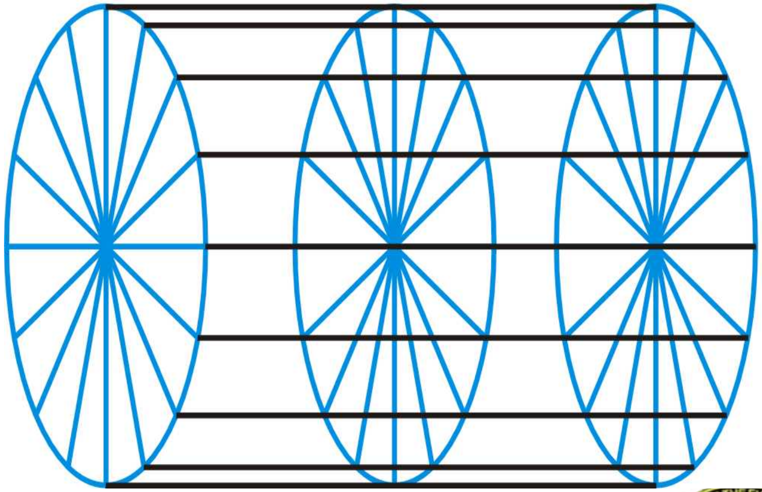


Where it all started:

FDTD calculations in Cartesian geometry…



… can be applied to cylindrical geometry, e.g. an optical fibre, simply by changing the values of ε, μ used in the calculation.



A J Ward & J B Pendry *Journal of Modern Optics*, **43** 773-93 (1996)

step 1: make a coordinate transformation,

$$q_1(x,y,z), \quad q_2(x,y,z), \quad q_3(x,y,z)$$

step 2: rewrite Maxwell's equations in the new coordinate system –
the *form* of Maxwell's equations does not change,

$$\nabla\times\tilde{\mathbf{E}} = -\tilde{\mu}\mu_0\partial\tilde{\mathbf{H}}/\partial t, \qquad \nabla\times\tilde{\mathbf{H}} = -\tilde{\varepsilon}\varepsilon_0\partial\tilde{\mathbf{E}}/\partial t$$

step 3: Calculate the new values of ε, μ,

$$\tilde{\varepsilon}_i = \varepsilon_i \frac{Q_1 Q_2 Q_3}{Q_i^2}, \qquad \tilde{\mu}_i = \mu_i \frac{Q_1 Q_2 Q_3}{Q_i^2}$$

where,

$$Q_i^2 = \left(\frac{\partial x}{\partial q_i}\right)^2 + \left(\frac{\partial y}{\partial q_i}\right)^2 + \left(\frac{\partial z}{\partial q_i}\right)^2, \quad \tilde{E}_i = Q_i E_i, \qquad \tilde{H}_i = Q_i H_i$$

conclusion: We can transform solution of Maxwell's equations into new geometries where the surfaces are curved, but we must change ε, μ.

Maxwell’s equations – a curious property

Cartesian coordinates:

$$\frac{\partial E_3}{\partial x_2}-\frac{\partial E_2}{\partial x_3}=-\frac{\partial(\mu\mathbf{H})_1}{\partial t},\qquad \frac{\partial H_3}{\partial x_2}-\frac{\partial H_2}{\partial x_3}=+\frac{\partial(\mu\mathbf{D})_1}{\partial t}$$

$$\frac{\partial E_1}{\partial x_3}-\frac{\partial E_3}{\partial x_1}=-\frac{\partial(\mu\mathbf{H})_2}{\partial t},\qquad \frac{\partial H_1}{\partial x_3}-\frac{\partial H_3}{\partial x_1}=+\frac{\partial(\mu\mathbf{D})_2}{\partial t}$$

$$\frac{\partial E_2}{\partial x_1}-\frac{\partial E_1}{\partial x_2}=-\frac{\partial(\mu\mathbf{H})_3}{\partial t},\qquad \frac{\partial H_2}{\partial x_1}-\frac{\partial H_1}{\partial x_2}=+\frac{\partial(\mu\mathbf{D})_3}{\partial t}$$

Arbitrary coordinates:

$$\frac{\partial E'_3}{\partial x'_2}-\frac{\partial E'_2}{\partial x'_3}=-\frac{\partial(\mu\mathbf{H}')_1}{\partial t},\qquad \frac{\partial H'_3}{\partial x'_2}-\frac{\partial H'_2}{\partial x'_3}=+\frac{\partial(\varepsilon'\mathbf{D}')_1}{\partial t}$$

$$\frac{\partial E'_1}{\partial x'_3}-\frac{\partial E'_3}{\partial x'_1}=-\frac{\partial(\mu'\mathbf{H}')_2}{\partial t},\qquad \frac{\partial H'_1}{\partial x'_3}-\frac{\partial H'_3}{\partial' x_1}=+\frac{\partial(\varepsilon'\mathbf{D}')_2}{\partial t}$$

$$\frac{\partial E'_2}{\partial x'_1}-\frac{\partial E'_1}{\partial x'_2}=-\frac{\partial(\mu'\mathbf{H}')_3}{\partial t},\qquad \frac{\partial H'_2}{\partial x'_1}-\frac{\partial H'_1}{\partial x'_2}=+\frac{\partial(\varepsilon'\mathbf{D}')_3}{\partial t}$$

The *form* of Maxwell’s equations is the same in any system of coordinates only ε, μ change.

The Transformations

If the distorted system is described by a coordinate transform $x'^{j'}\left(x^{j}\right)$ we define,

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

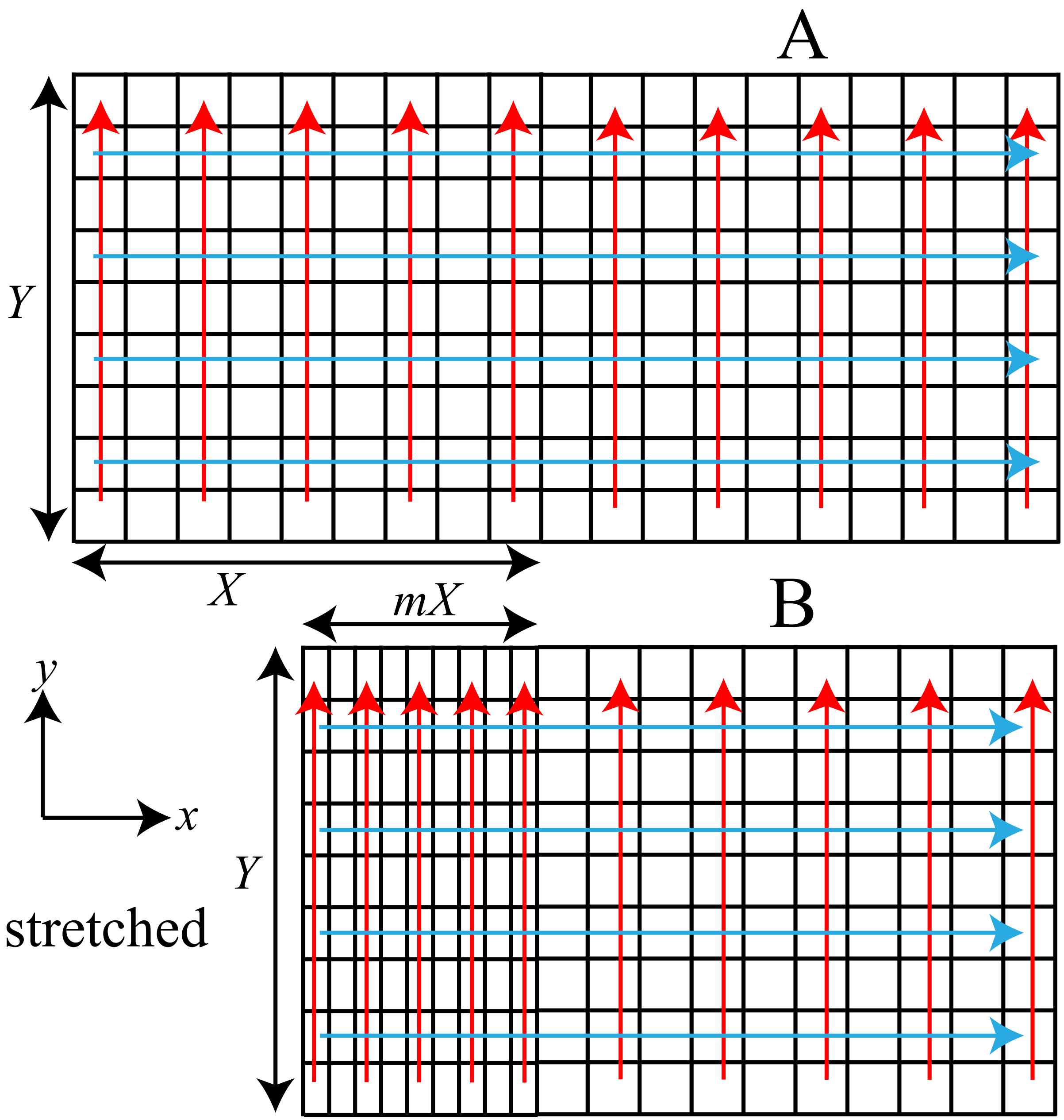
Then in the new coordinate system we must use modified values of the permittivity and permeability to ensure that Maxwell's equations are satisfied,

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

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

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

A Geometric view of transformation optics



System A: displacement field, D_x, parallel to the $x-$axis is shown in cyan; displacement field D_y, parallel to the $y-$axis is shown in red.

System B: after compression by a factor m the fields become D'_x, D'_y.

We argue that field lines of **D** are conserved, but may be stretched or compressed under the transformation.

Deriving ε_x

Lines of **D** parallel to x (cyan) are compressed lengthwise, but not pushed closer together therefore,

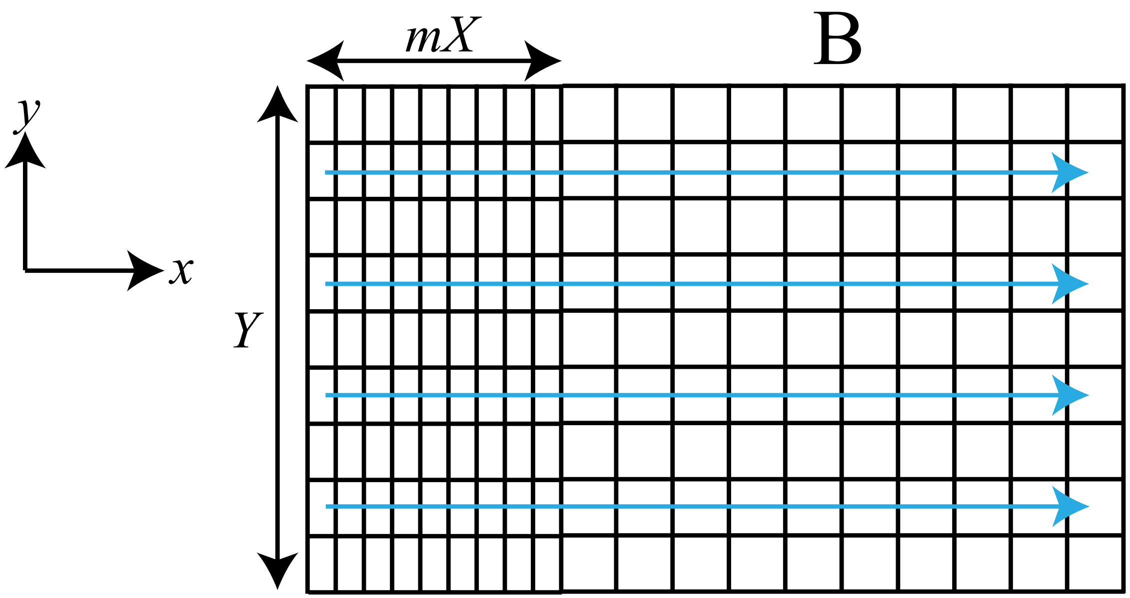
$$D'_x = D_x$$

and hence:

$$E_x = \varepsilon_x^{-1} D_x$$

$$E'_x = \varepsilon'^{-1}_x D'_x = \varepsilon'^{-1}_x D_x$$

Note that the work done by a test charge, q, passing from one side of the compressed region to the other is unaltered by the compression.



$$qXE_x = qmXE'_x$$

Hence, $\boxed{\varepsilon'_x = m\varepsilon_x}$

Deriving ε_y

Lines of **D** parallel to y (red) are pushed closer together therefore,

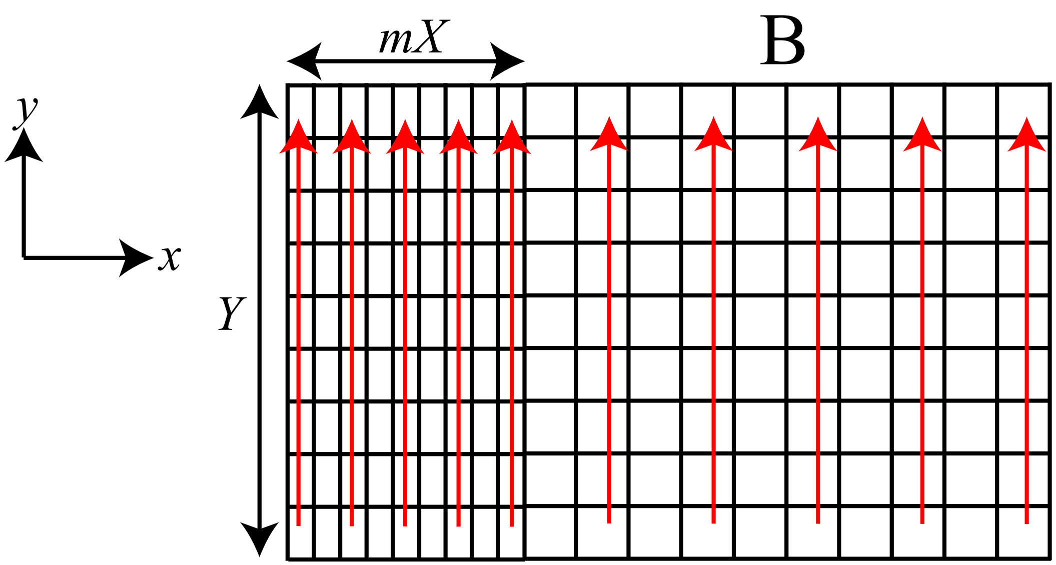
$$D'_y = m^{-1} D_y = m^{-1} \varepsilon_y E_y$$

However E_y is continuous across the boundary:

$$E'_y = E_y$$

Combining these equations gives,

$$m^{-1} \varepsilon_y^{-1} D_y = \varepsilon'^{-1}_y D'_y = E'_y = E_y = \varepsilon_y^{-1} D_y$$



Hence, $\varepsilon'_y = m^{-1} \varepsilon_y$

General rule:

Under a compression m:

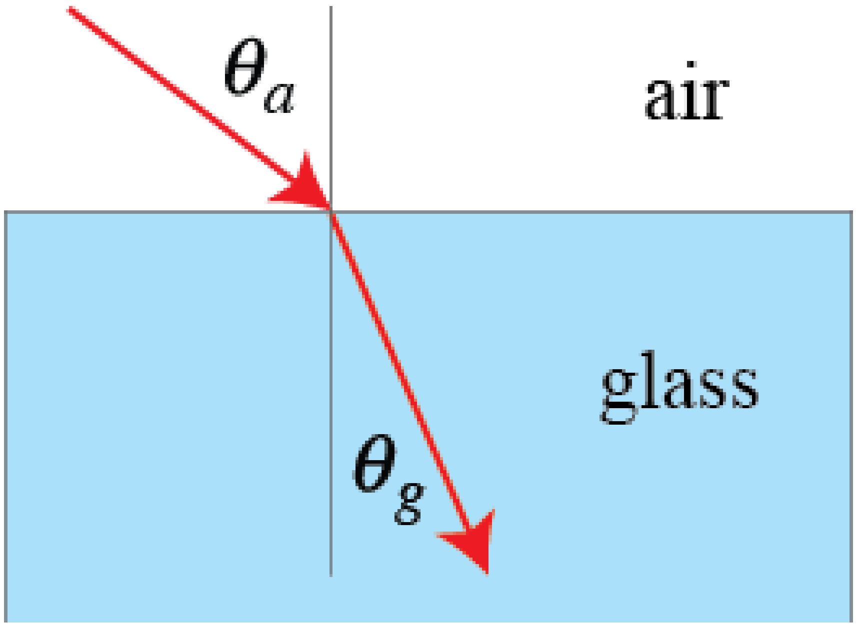
In the direction parallel to the compression $\varepsilon_{||}, \mu_{||}$ both *decrease* by a factor m,

In the direction perpendicular to the compression $\varepsilon_{\perp}, \mu_{\perp}$ both *increase* by a factor m,

Thus the effect of any distortion of the coordinates can be calculated by noting the changed orientation of the coordinate frame and applying the rule to all three directions.

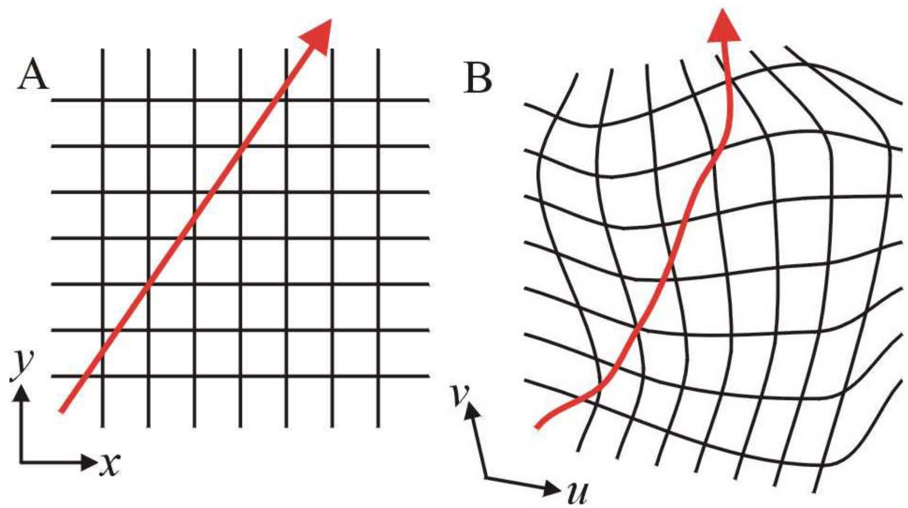
The new laws of refraction - move over Snellius!

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



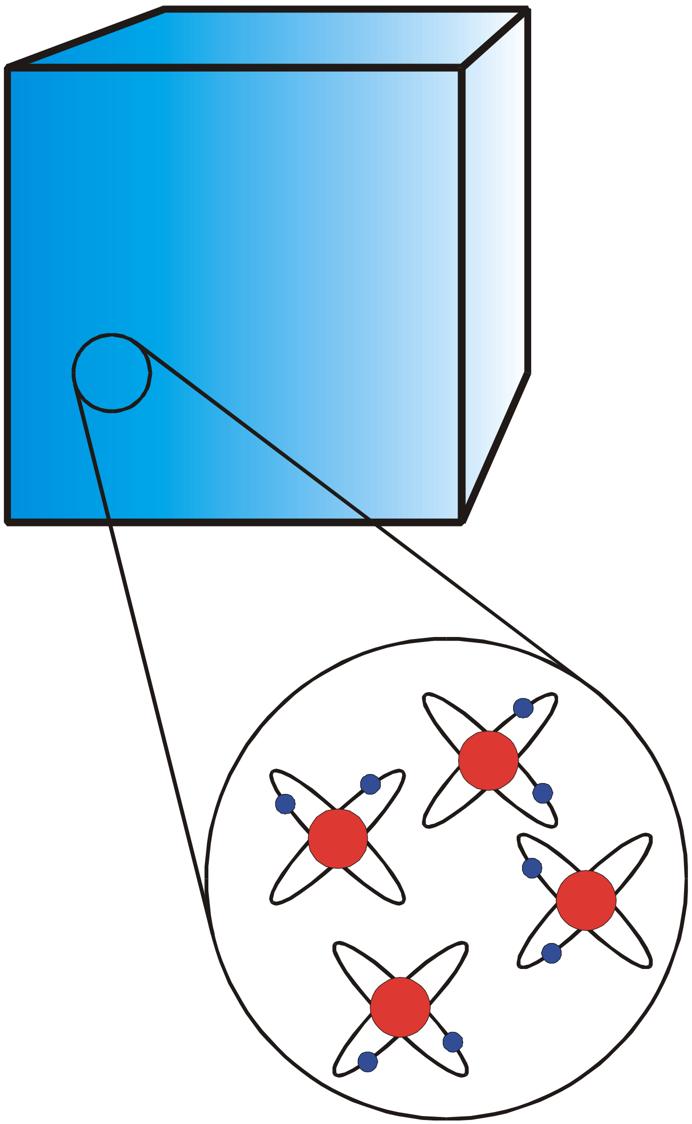
$$\varepsilon'^{i'j'} = \left[\det(\Lambda)\right]^{-1} \Lambda_i^{i'} \Lambda_j^{j'} \varepsilon^{ij}$$

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

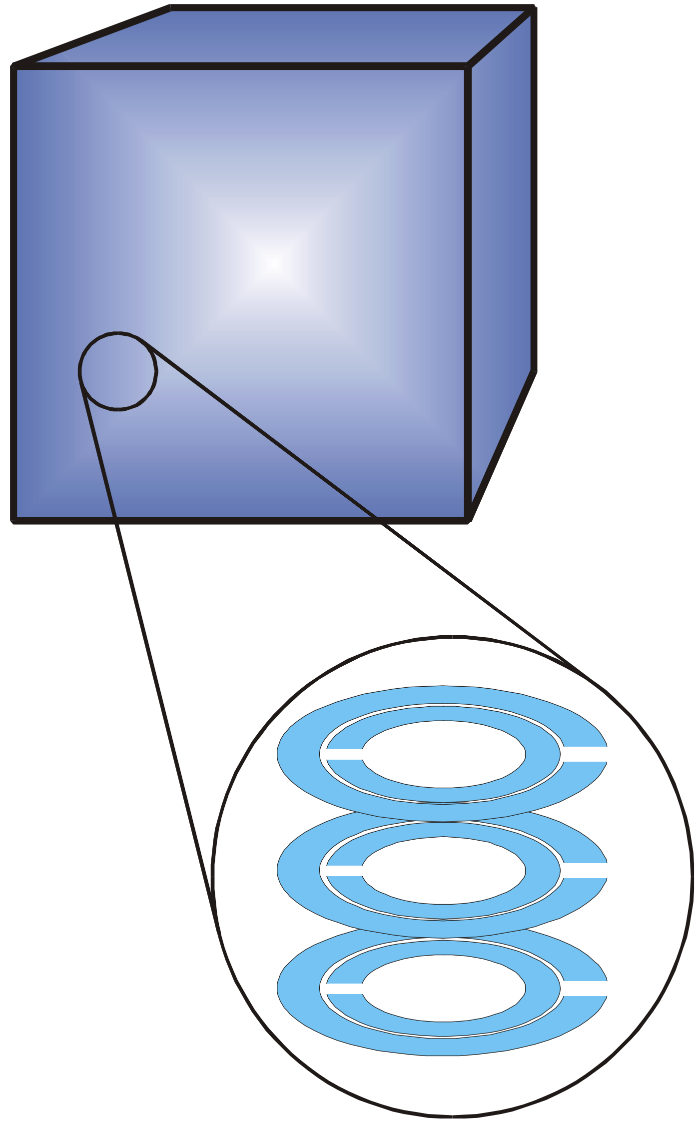
$$\Lambda_j^{j'} = \frac{\partial x^{j'}}{\partial x^j}$$

What is a 'metamaterial'

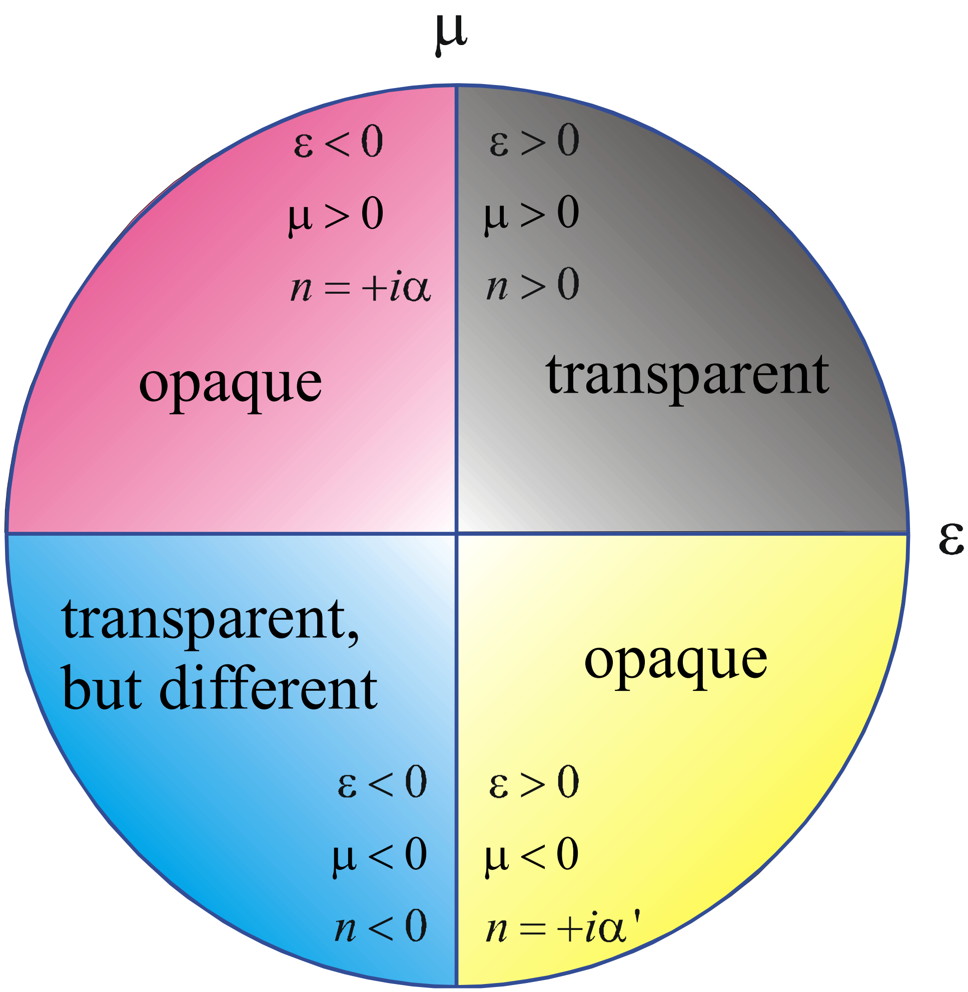
Conventional materials: properties derive from their constituent *atoms*.



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)

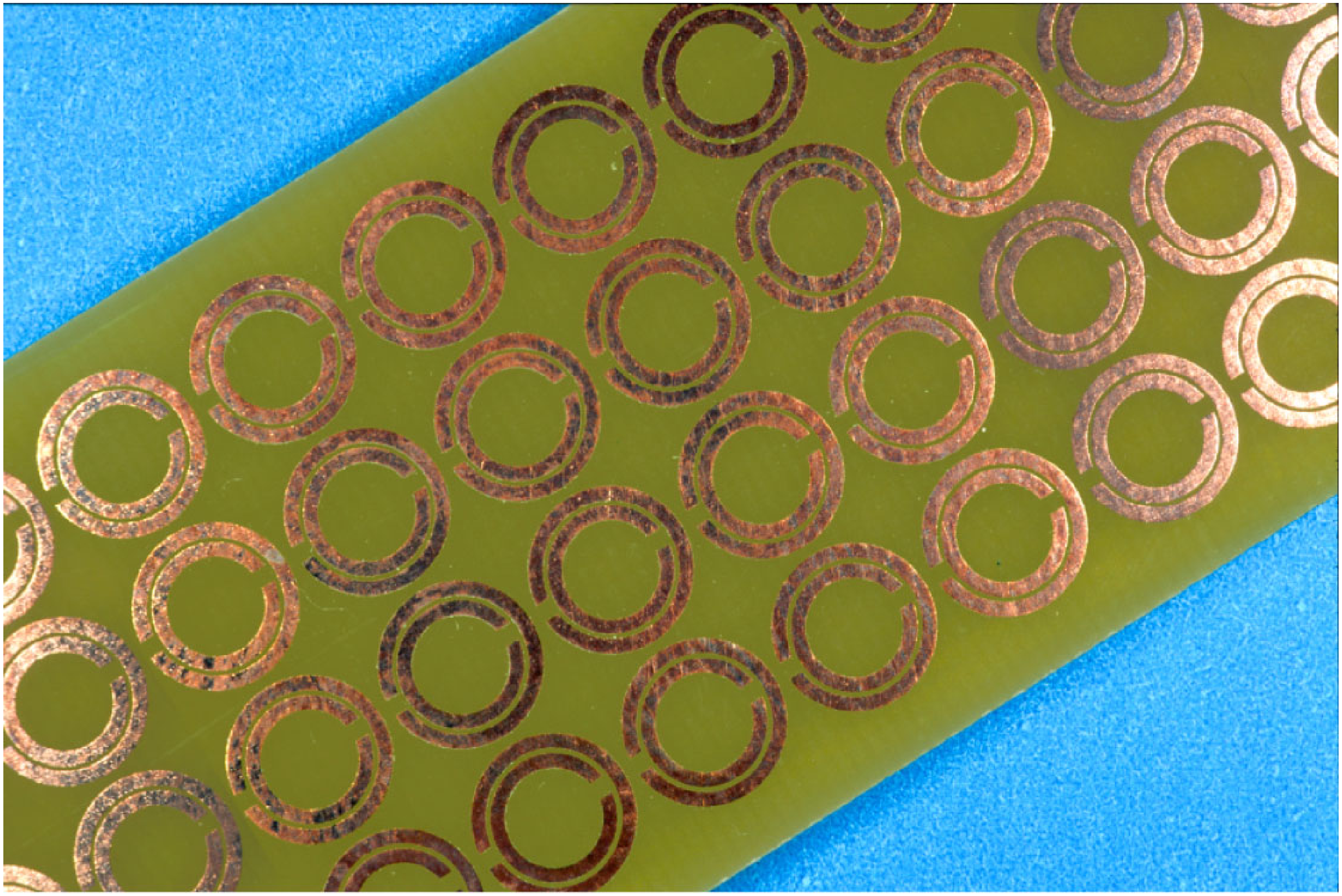
What is the point of metamaterials?

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

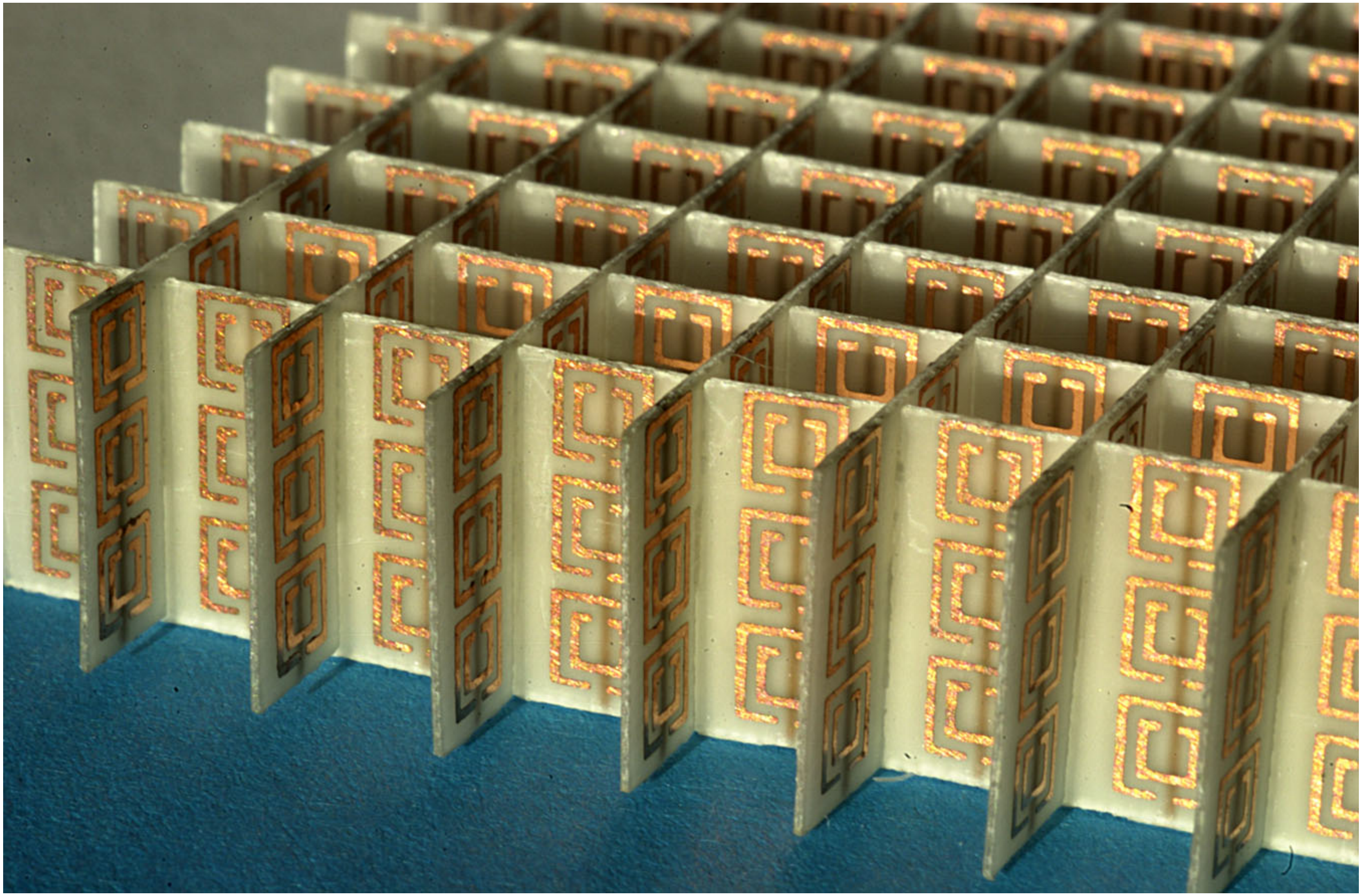
- negative refractive index
- extreme anisotropy of response to any specification
- extreme chirality
- continuously variable properties throughout the material
- magnetism at optical frequencies

Practical realisation of the split ring structure

(Marconi: Mike Wiltshire)



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

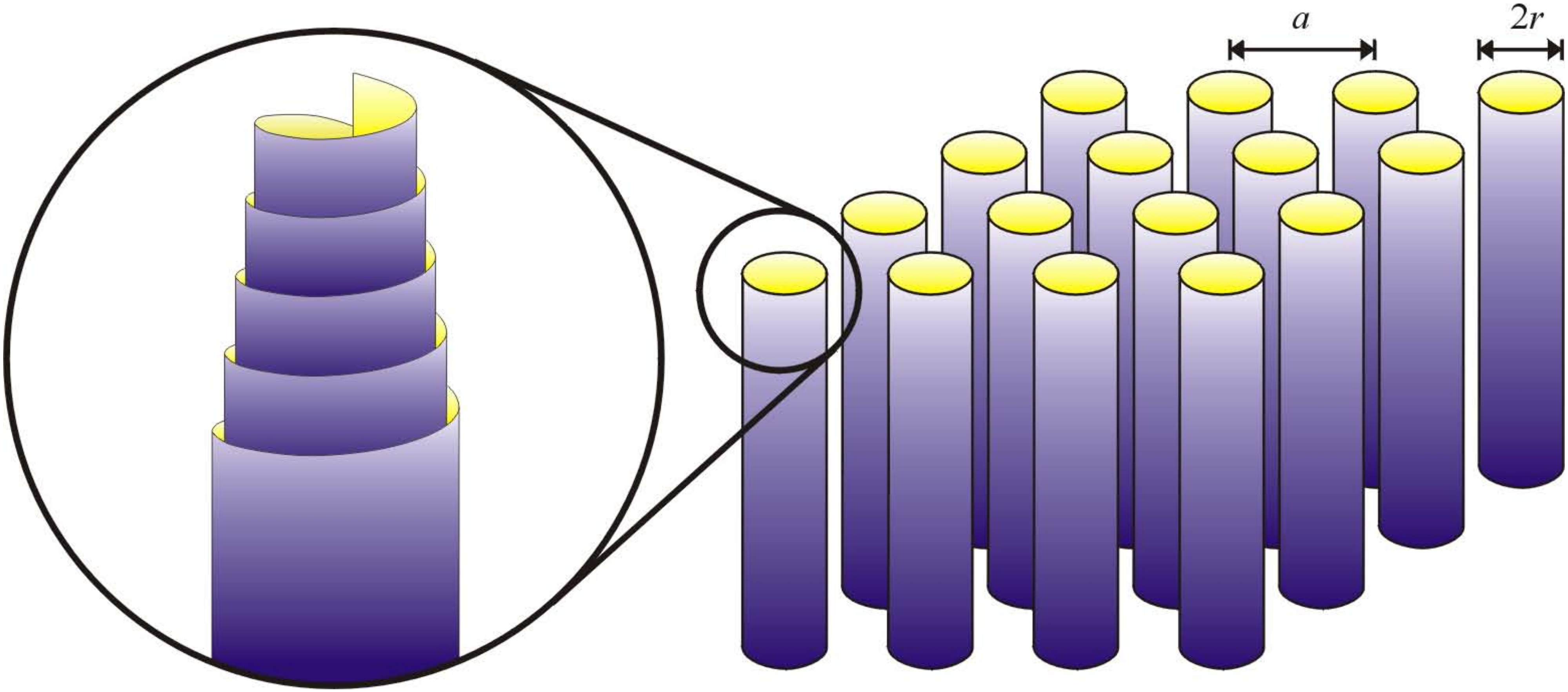


Structure made at UCSD by David Smith

The Swiss Roll:

A metamaterial with $\mu < 0$ at 21MHz

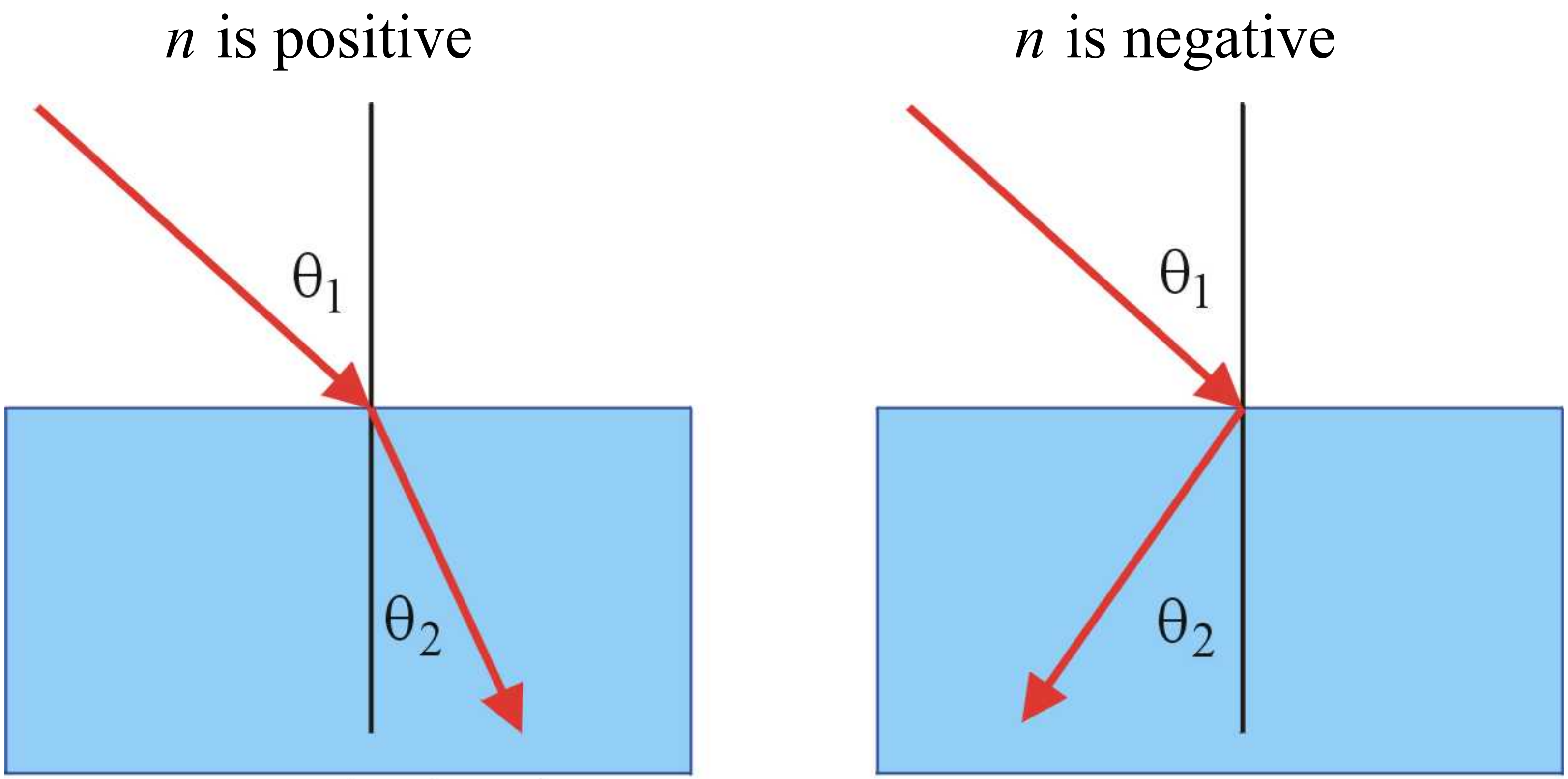
The 'Swiss roll' structure comprises rolls of insulated copper sheets. The rolls are typically around 1cm in diameter and resonate around 21MHz. The circulating currents give a magnetic response.



The Swiss roll is an excellent metamaterial: $\lambda/a \approx 10^3$ - as good as glass!

Negative refraction – Veselago

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



normal refraction

negative refraction

Negative refractive index metamaterials

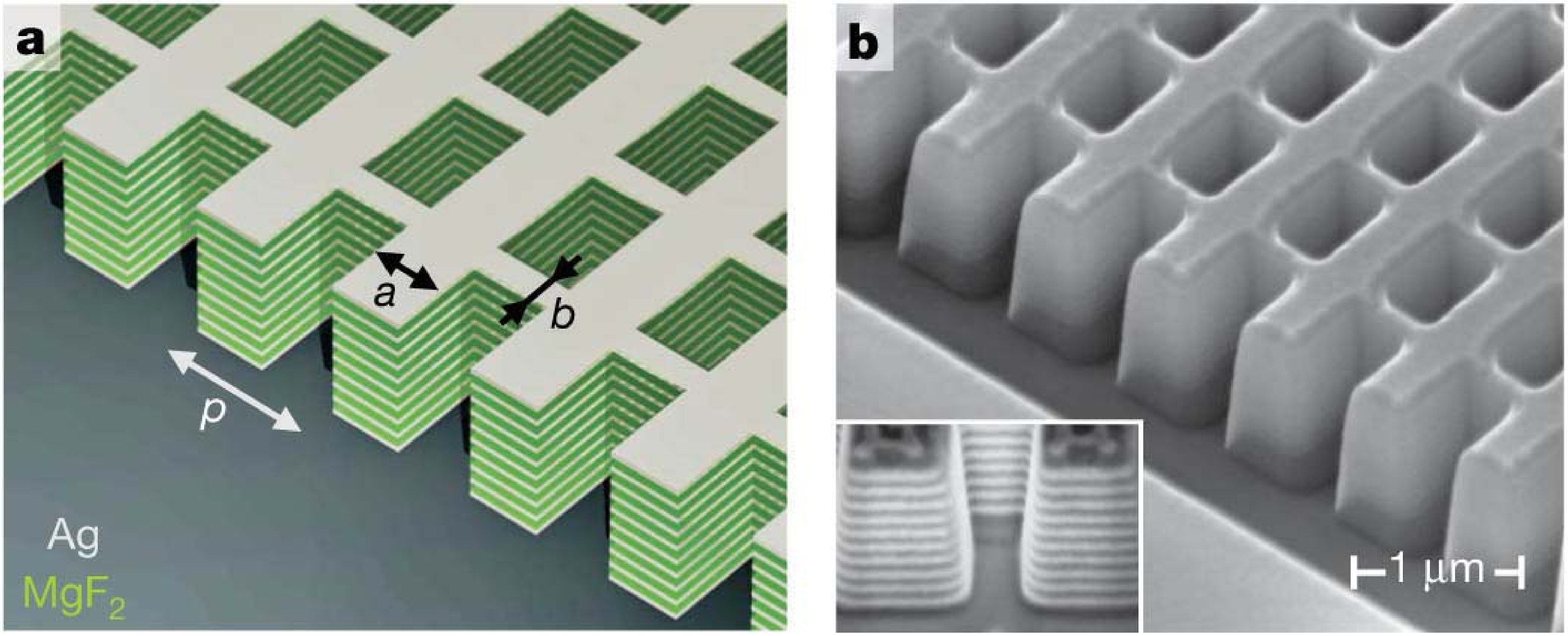


Diagram (left) and scanning electron microscope image (right) of a ‘fishnet’ structure fabricated by the Xiang group at Berkeley California. The structure consists of alternating layers of 30nm silver and 50nm magnesium fluoride.

Peter Pan loses his shadow – black is not enough!

Peter Pan loses his shadow – going, going – gone

75% Peter 50% Peter 0% Peter

How They Built
Platform 9¾ at King's Cross Railroad Station

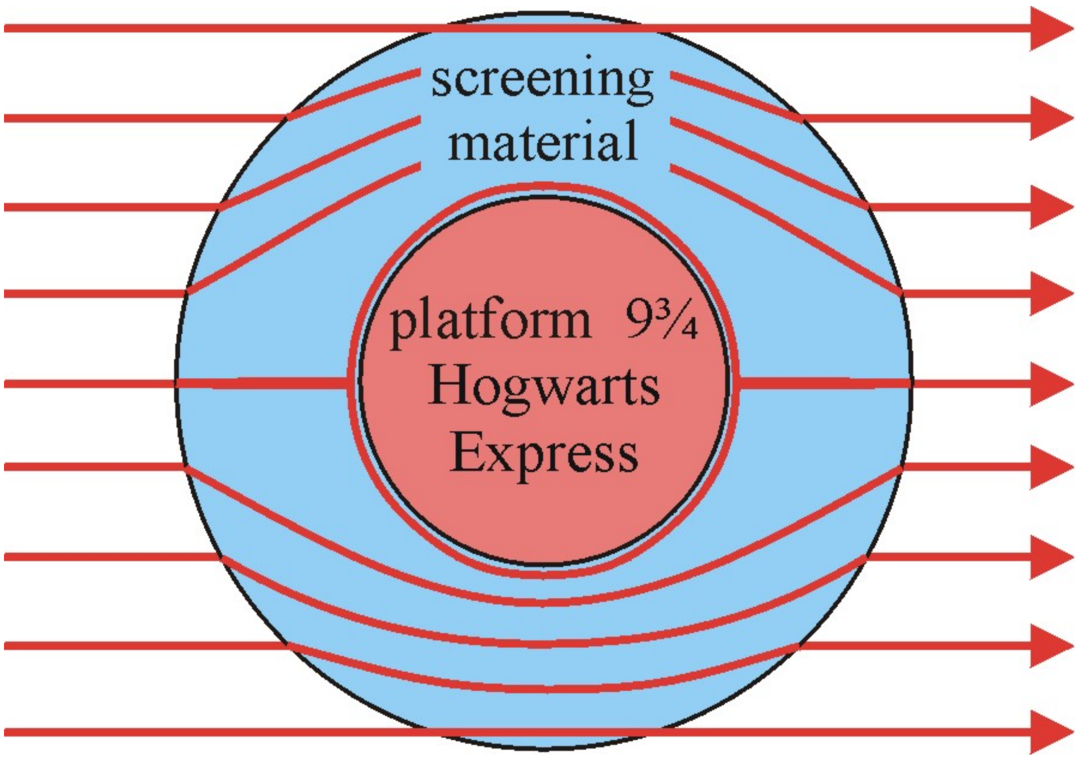
(Harry Potter fans only)

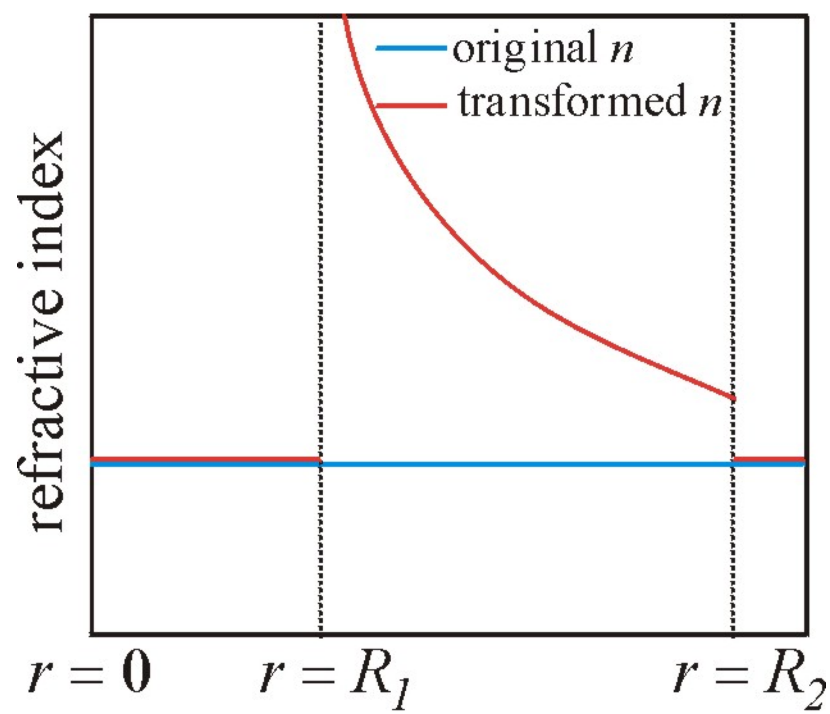
The challenge: to create a volume of space such that

a) the contents are invisible to the outside world **b) no one can detect that the space exists**

Solution: introduce a transformation $r' = R_1 + r\left(R_2 - R_1\right)/R_2$ which compresses the sphere $r < R_2$ into the shell $R_1 < r < R_2$ leaving an optically unreachable void inside the sphere $r < R_1$.

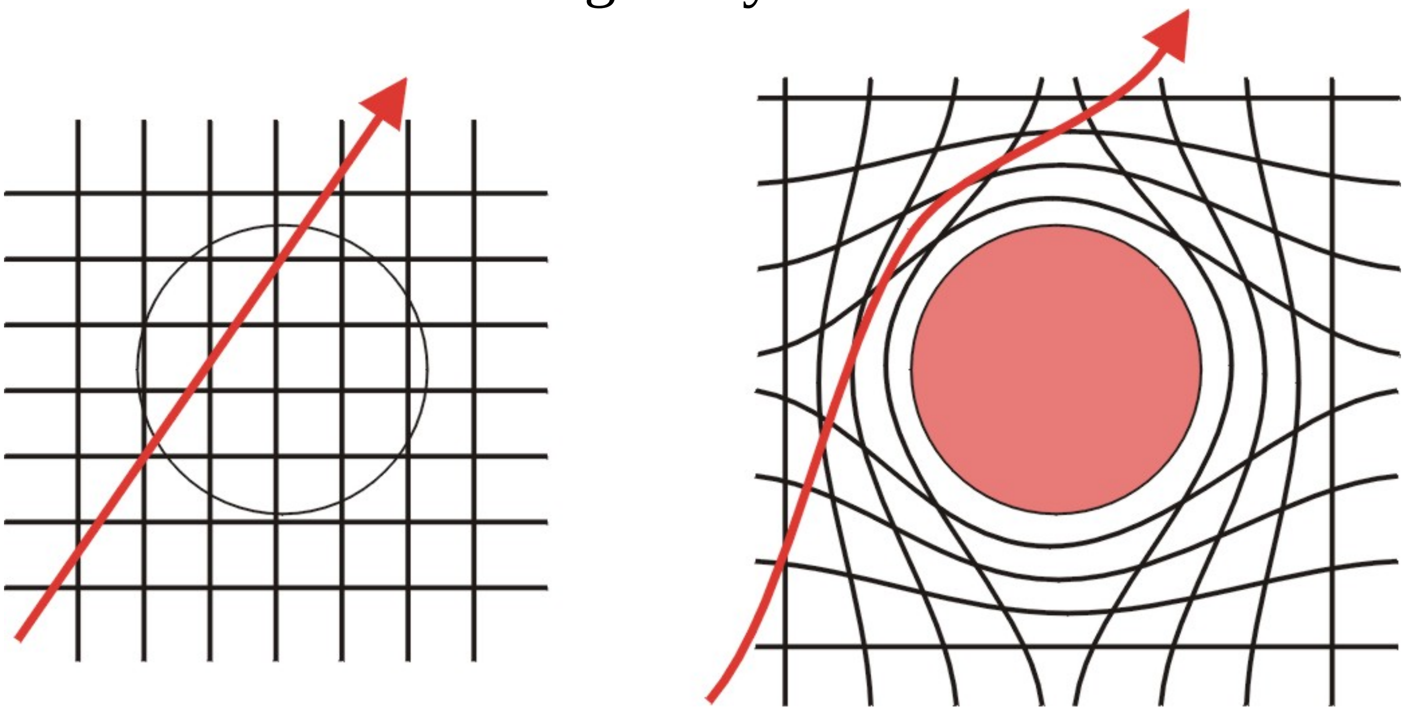
Then use transformation theory to calculate the refractive index that gives the distorted ray trajectories.





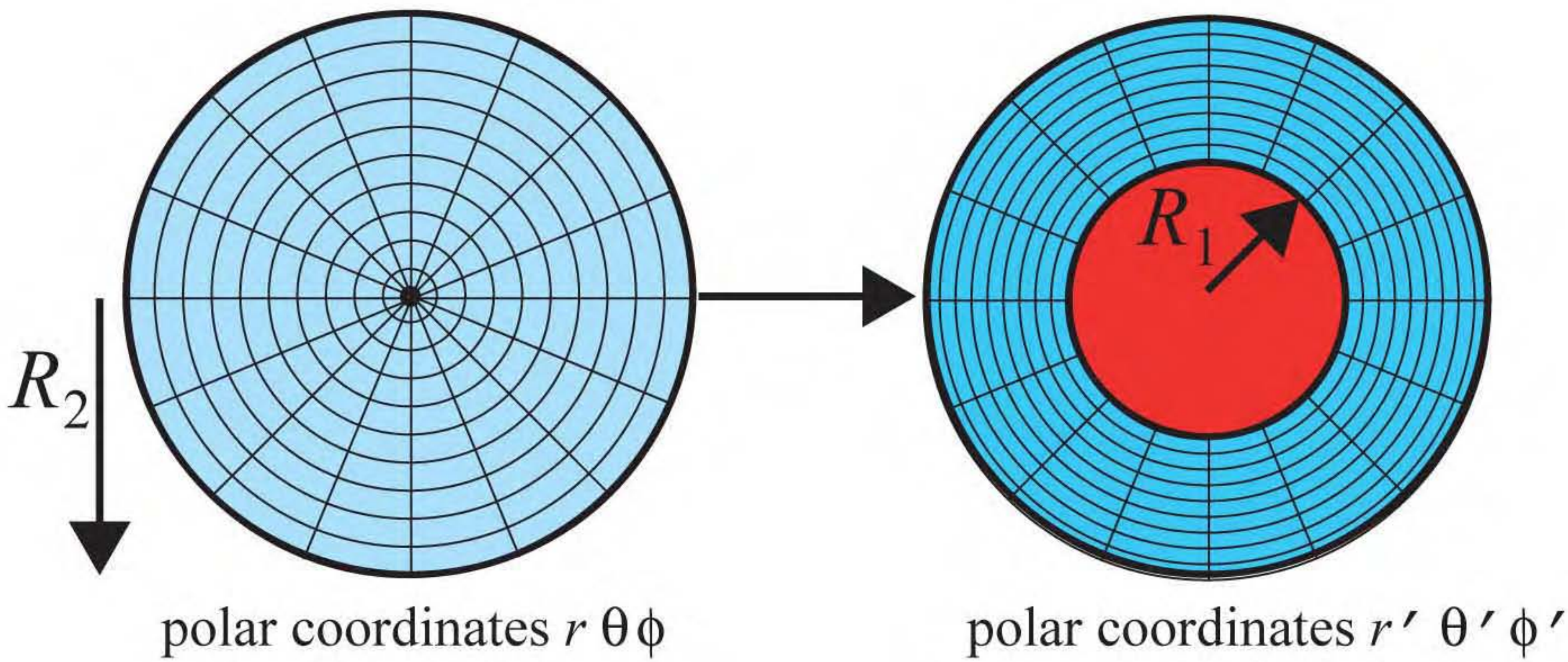
Design methodology

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

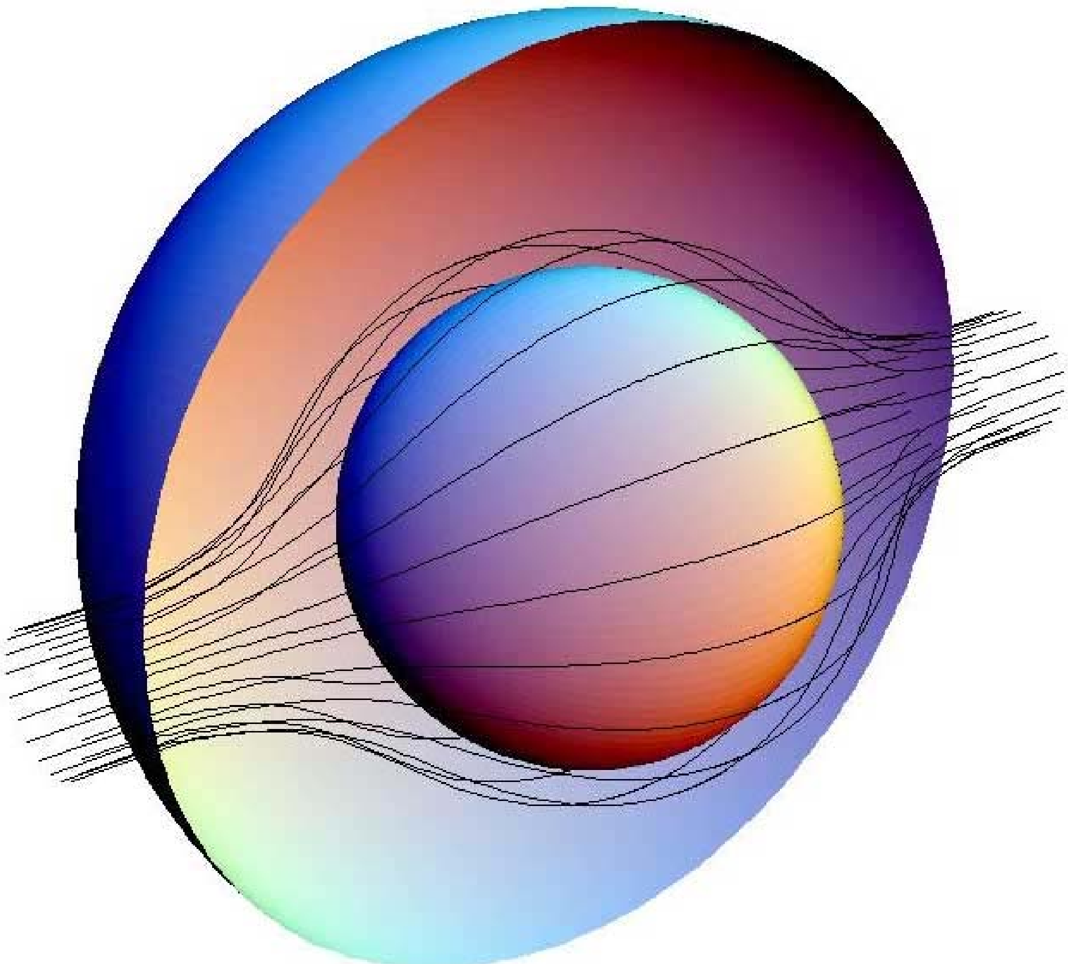


In mathematical notation the following coordinate transformation will open a hole in space,

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

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

Strategy for cloaking

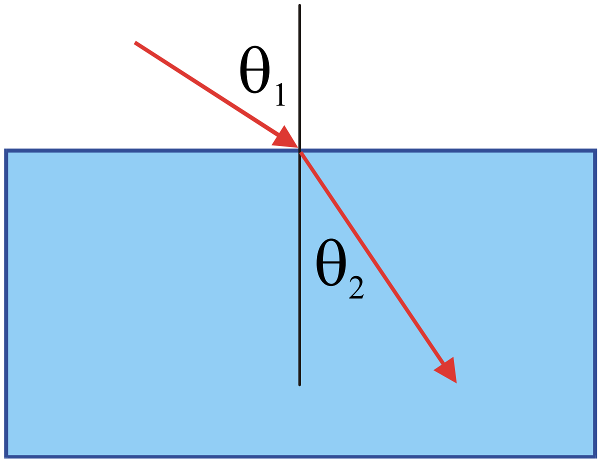


We are going to hide an object behind a *mirage,* bending light around the object, just like a road mirage. We do this by grading the index of refraction in the cloak so as to bend the light by exactly the right amount.

Ordinary materials like glass are not adequate for this task and we have had to invent a new class of materials, *metamaterials*, whose properties can be tailored virtually at will.

How to bend Light

A simple example: refraction at a surface

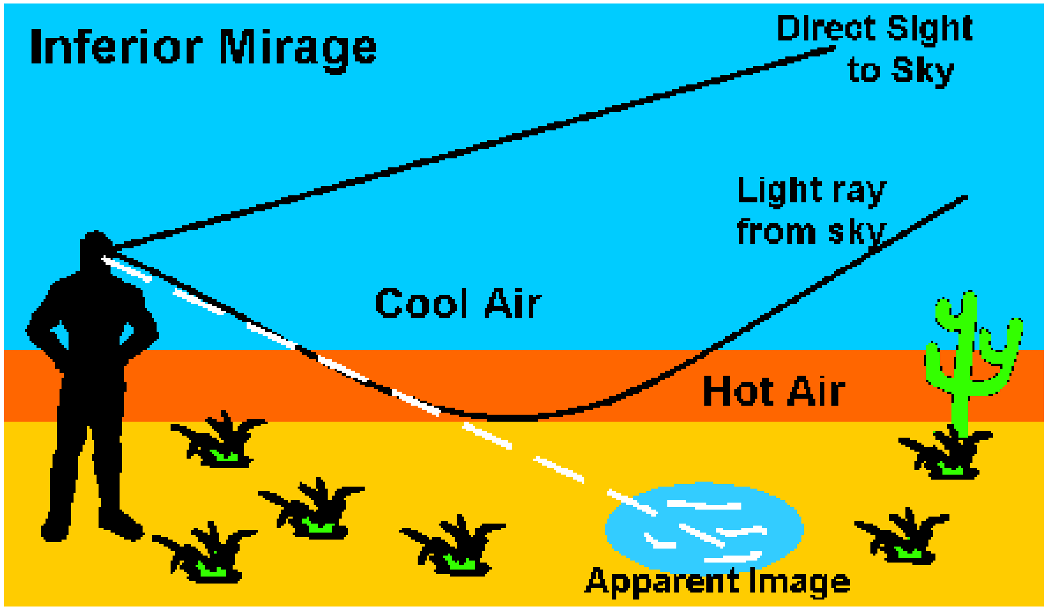


Snell's law states:

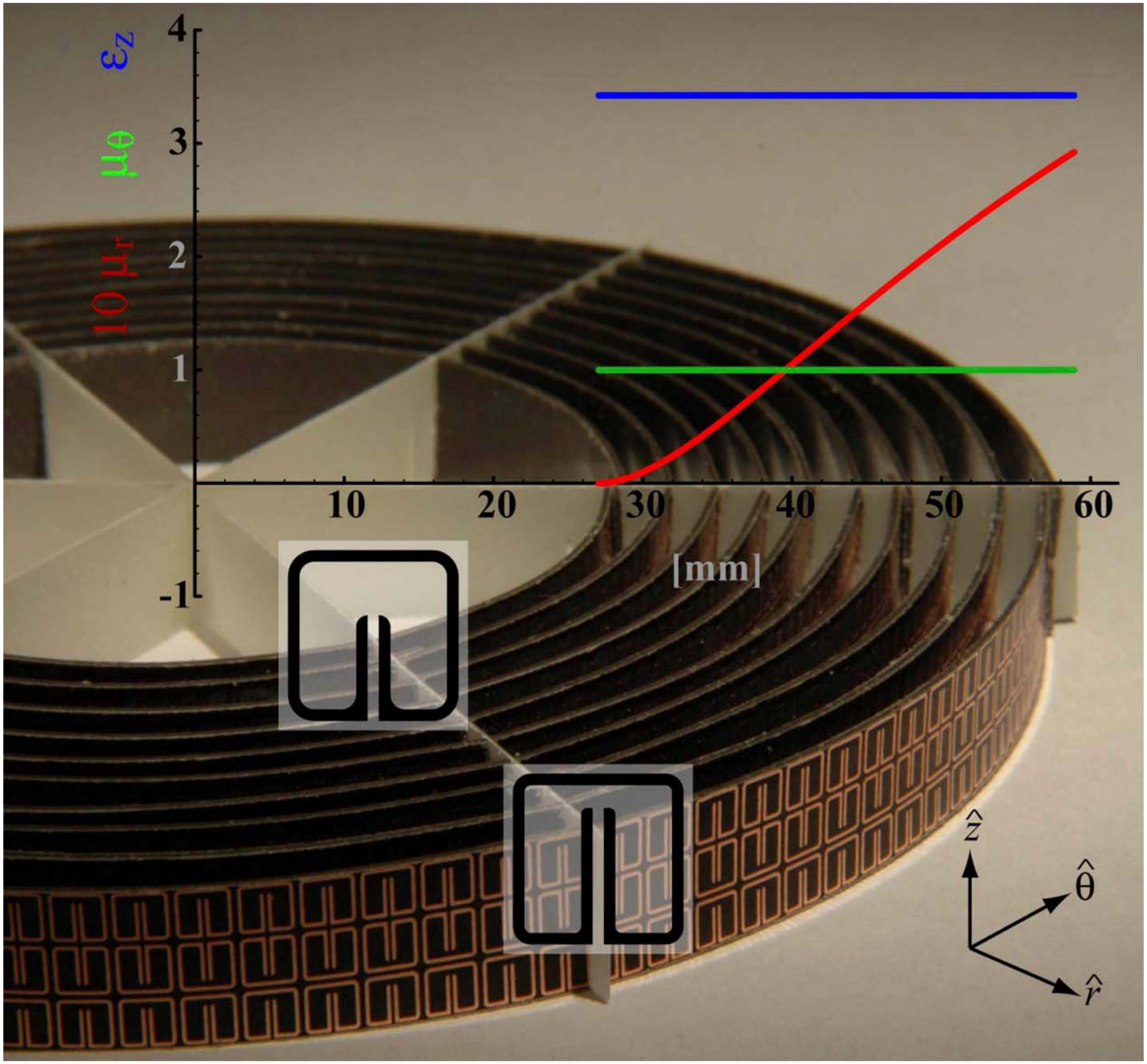
$$n = \frac{\sin\theta_1}{\sin\theta_2}$$

where n is the *refractive index* of the material

A Mirage – the *refractive index* varies continuously near the road surface



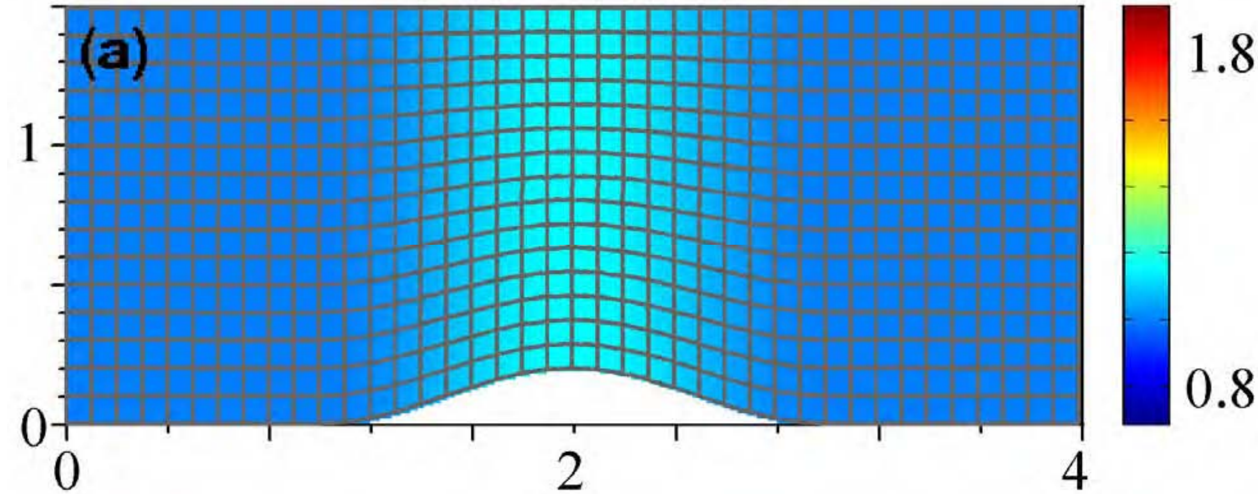
A Metamaterial Cloak



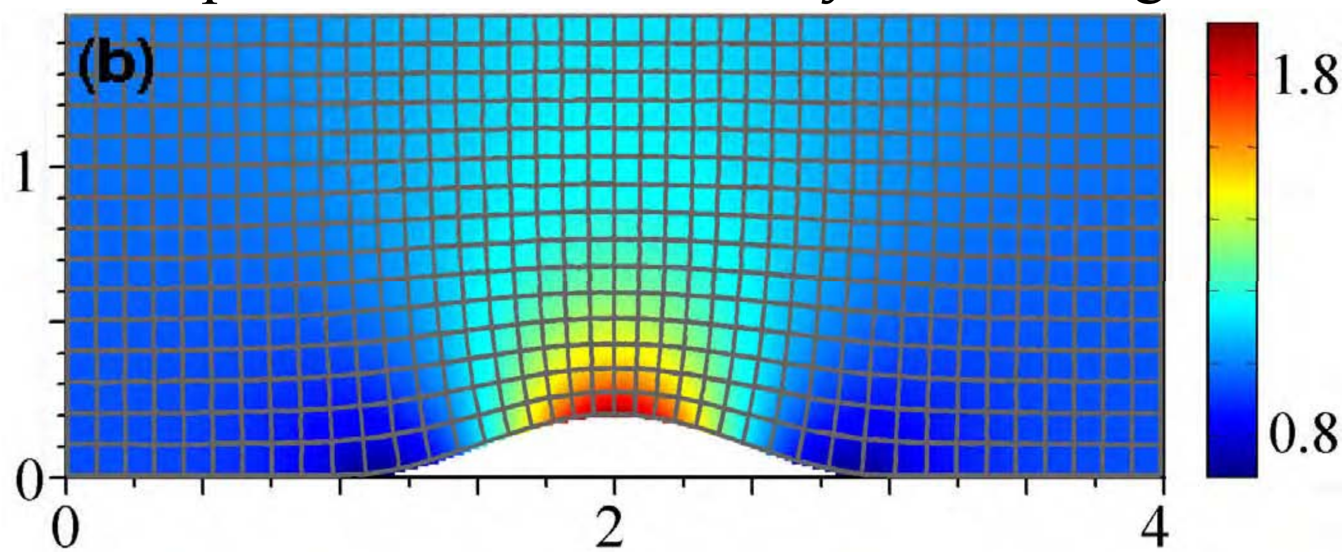
Science: to appear Nov

D. Schurig
J. J. Mock
B. J. Justice
S. A. Cummer
J. B. Pendry
A. F. Starr
D. R. Smith

Optimising the refractive index profile

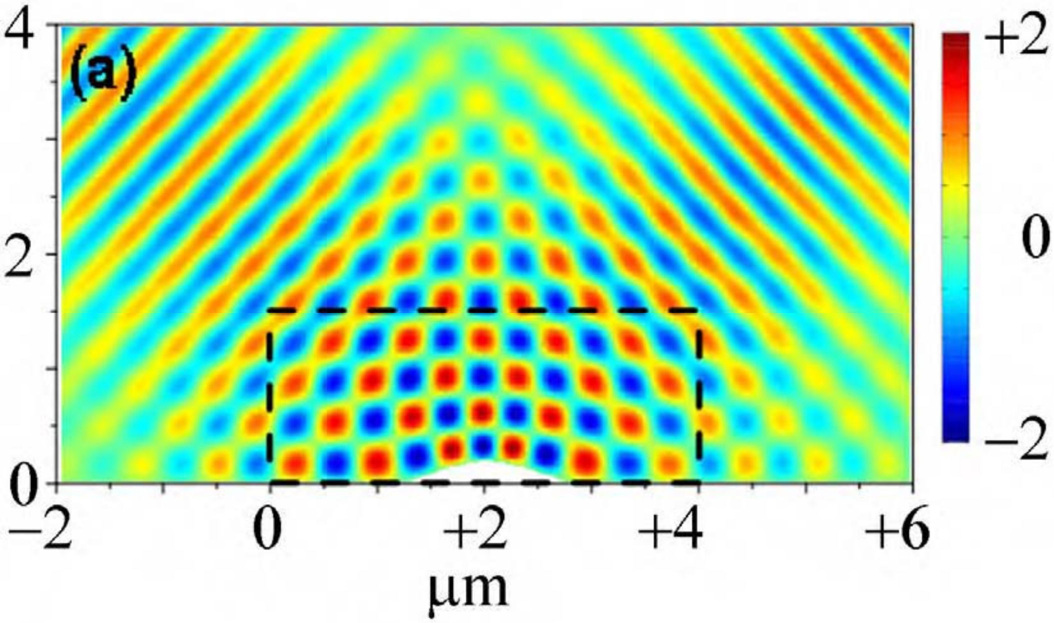


Cavity opened by compressing the *y*- coordinate to give anisotropic cells. The colour bar shows the profile in n^2. The *x* and *y* scales are given in μm.

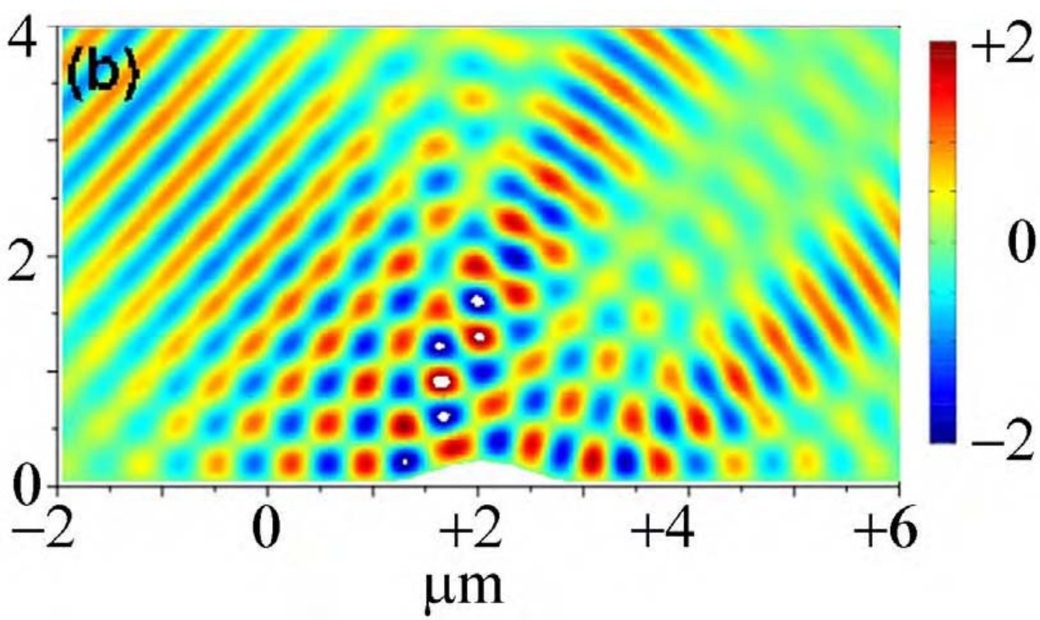


Quasiconformal grid gives almost isotropic cells, but a greater index contrast.

Cloaking an arbitrary cavity on a conducting surface



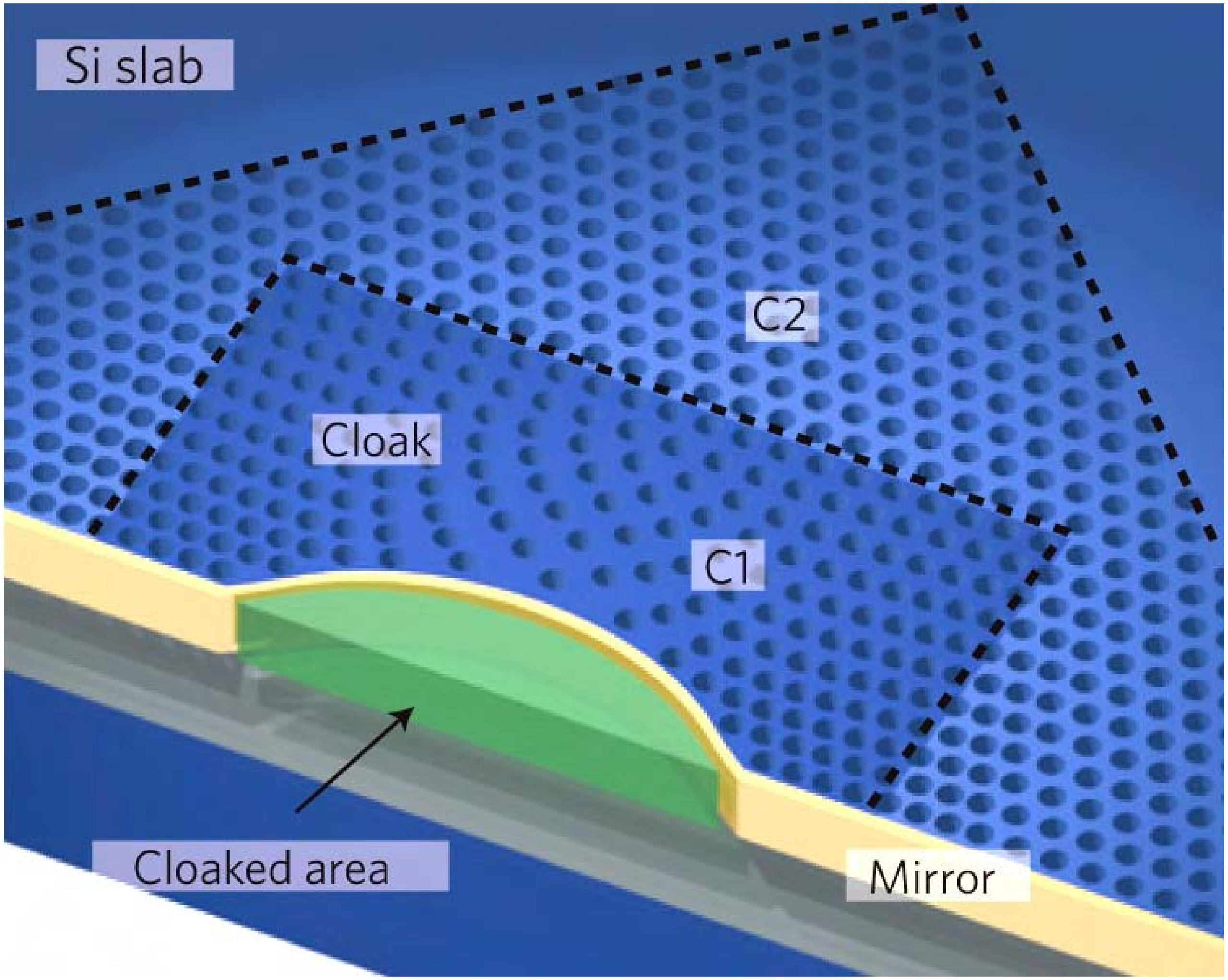
Left: computed E-field pattern with the cloak located within the rectangle in dashed line when a Gaussian beam is launched at 45° towards the ground plane from the left.



Left: computed E-field pattern when only the object is present without the cloak.

The width of the beam is around 4µm at a wavelength of 750nm. The medium above the ground plane and outside the cloak is SiO_2 of $n = 1.5$

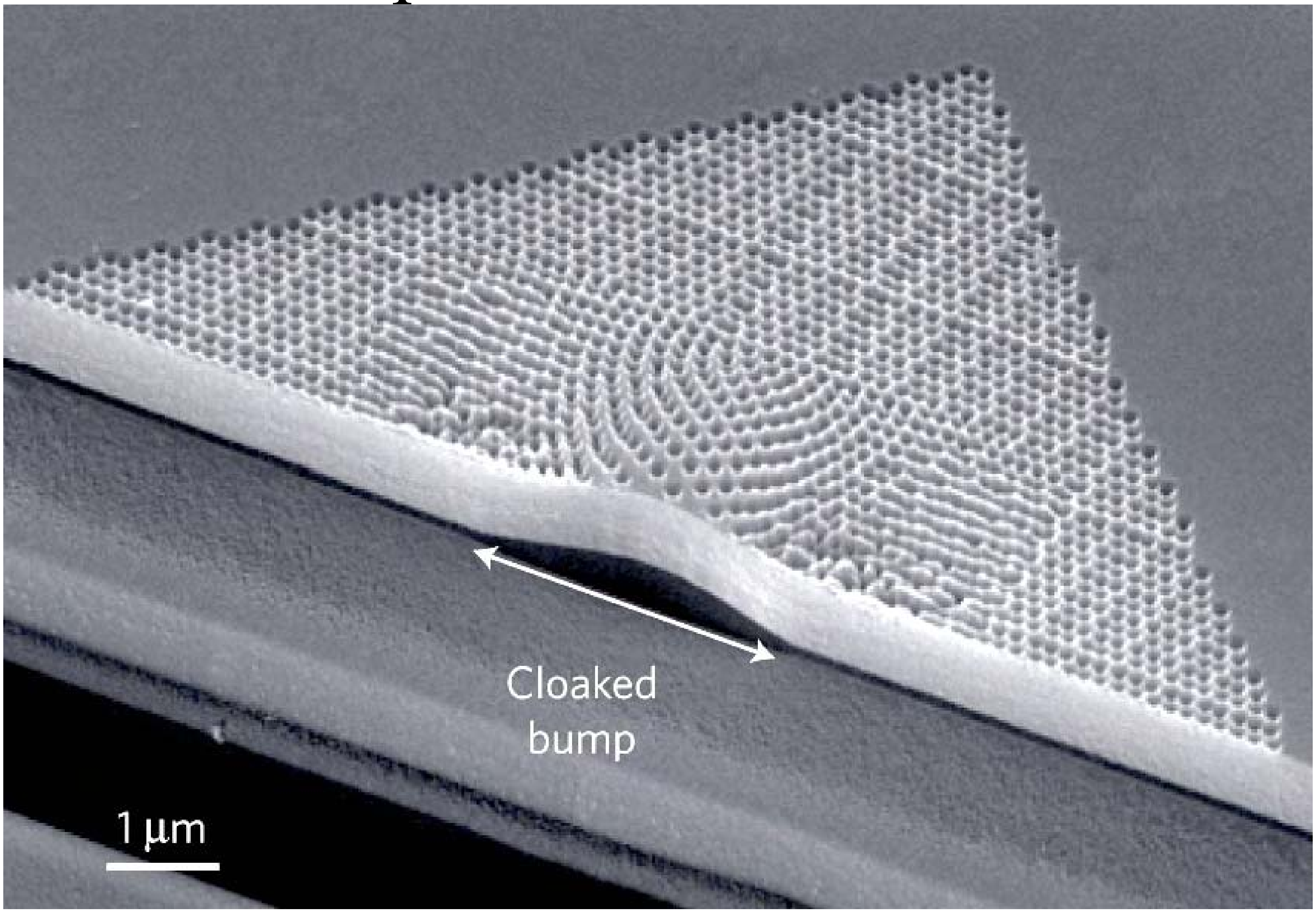
Schematic diagram of a fabricated carpet cloak



….. 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.

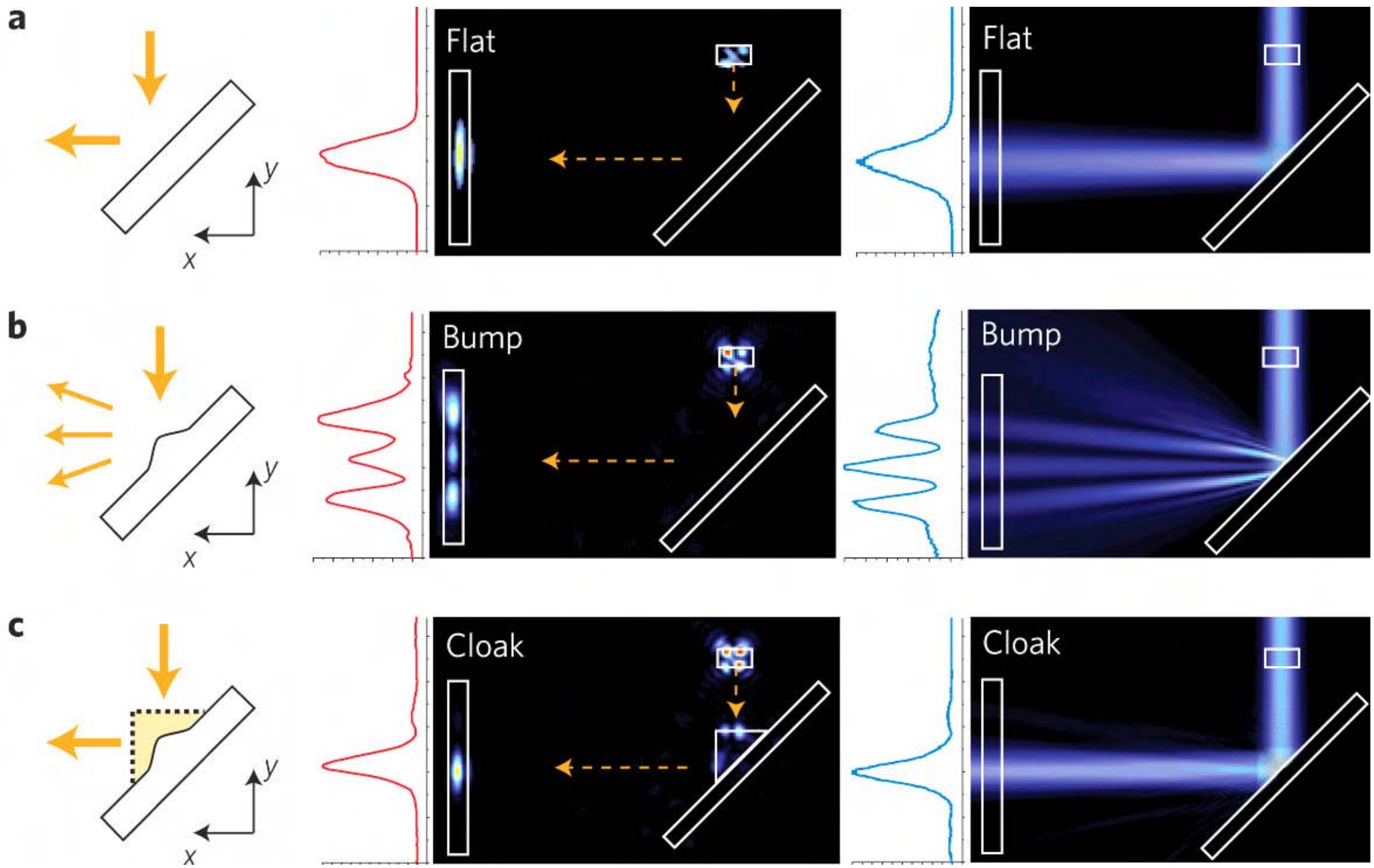
The cloaked region (marked with green) resides below the reflecting bump (carpet). and can conceal any arbitrary object. The cloak will transform the shape of the bump back into a virtually flat object.

Scanning electron microscope image of a fabricated carpet cloak



The width and depth of the cloaked bump are 3.8 μm & 400 μm, respectively.

The optical cloaking experiments



(**a**) Gaussian beam reflected from a flat surface

(**b**) a curved (without a cloak) surface

(**c**). and the same curved reflecting surface with a cloak

Left column: the schematic diagrams; right column: optical microscope images

red curves: experimental intensity profile

blue curves: computer simulations

Cloaking big objects

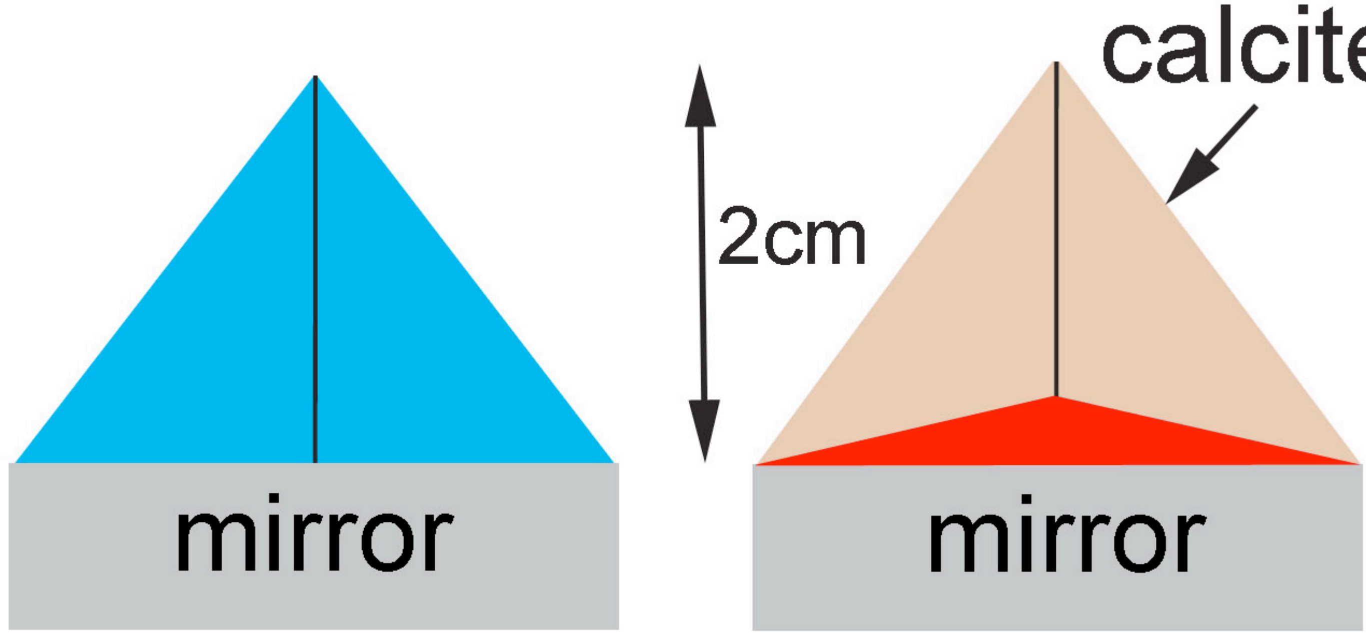
Two recent papers show that it is possible to build a cloak several centimetres across, that is broadband, and works for visible light.

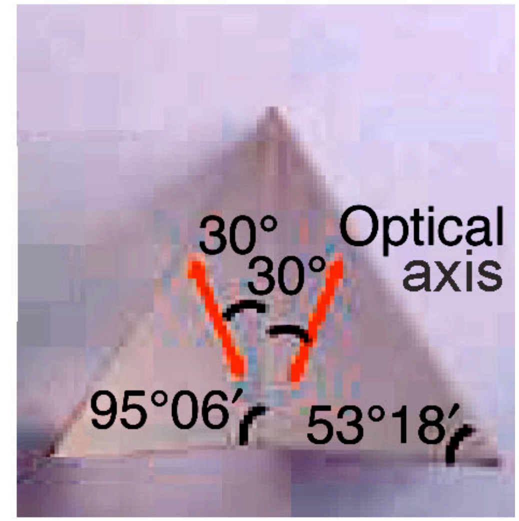
Shuang Zhang's team at Birmingham University, UK, in collaboration with Yu Luo at Imperial College: 'Macroscopic invisibility cloaking of visible light' Xianzhong Chen, Yu Luo, Jingjing Zhang, Kyle Jiang, John B. Pendry, & Shuang Zhang, *Nature Communications*, **2**, 176, (2011)

and from the Singapore-MIT Alliance for Research and Technology (SMART) Centre: 'Macroscopic Invisibility Cloak for Visible Light', Baile Zhang, Yuan Luo, Xiaogang Liu, and George Barbastathis, *Physical Review Letters* **106**, 033901, (2011)

These cloak work only for one polarization of light but nevertheless achieve macroscopic dimensions for the first time.

The Birmingham calcite cloak





Left: transformation optics starts from a triangular region of free space and a reflecting surface.

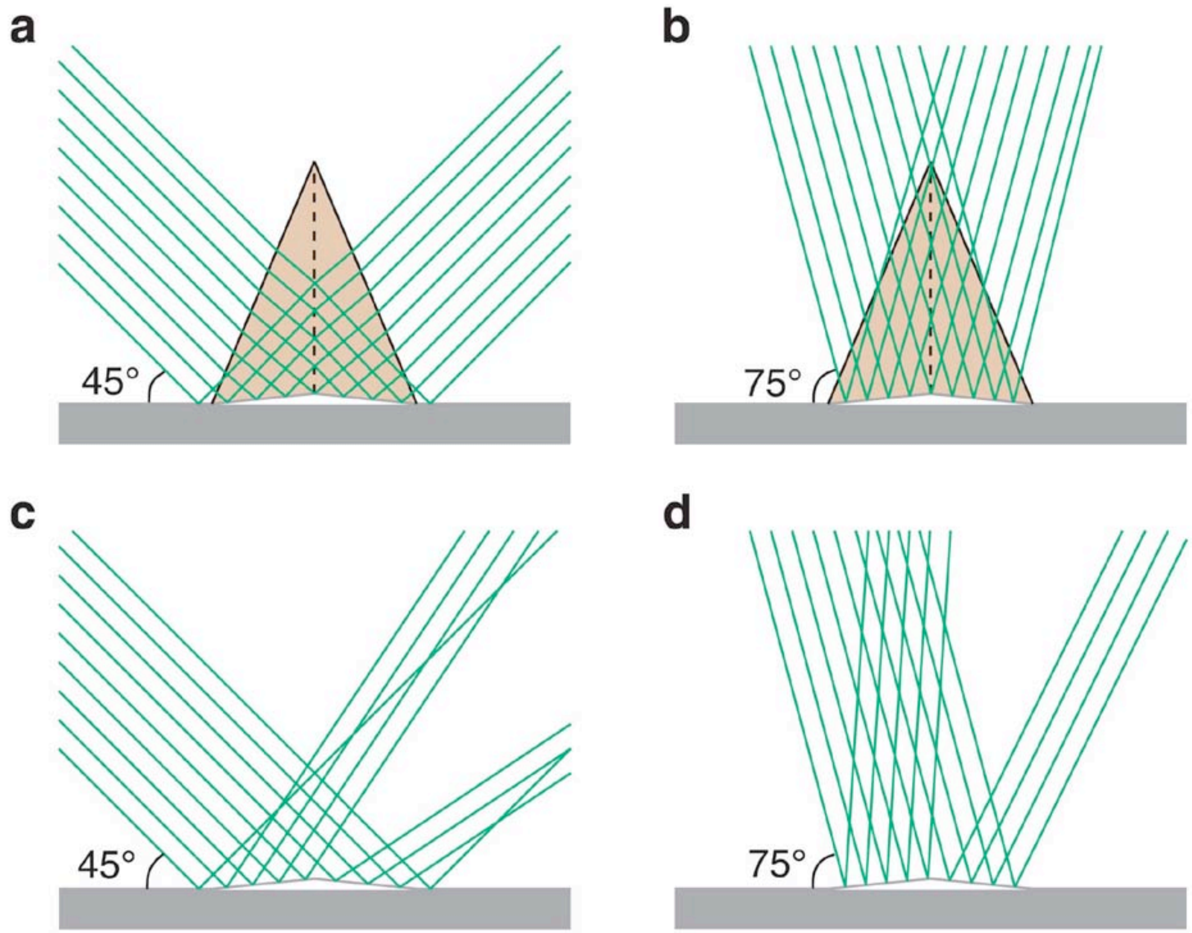
Centre: then compresses the upper region to make a hidden triangle.

Right: two calcite crystals can be used to realize the cloak.

Viewed externally the cloaked region appears to be a flat mirror.

Dimensions: approximately 2cm x 2 cm.

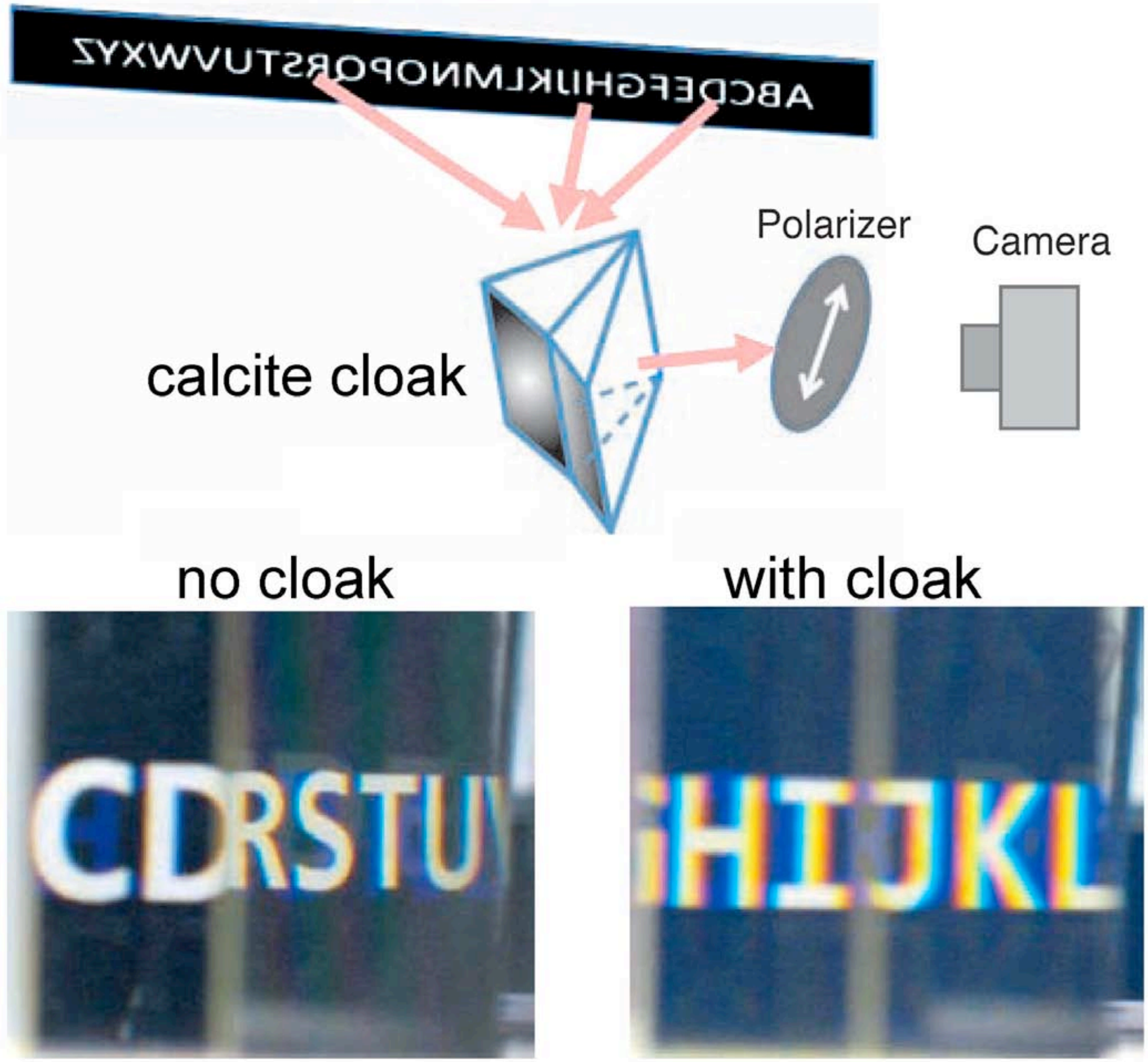
Trajectories of rays through the calcite cloak



Top: ray trajectories with the cloak in place

Bottom: ray trajectories without the cloak

The alphabet viewed through the calcite cloak

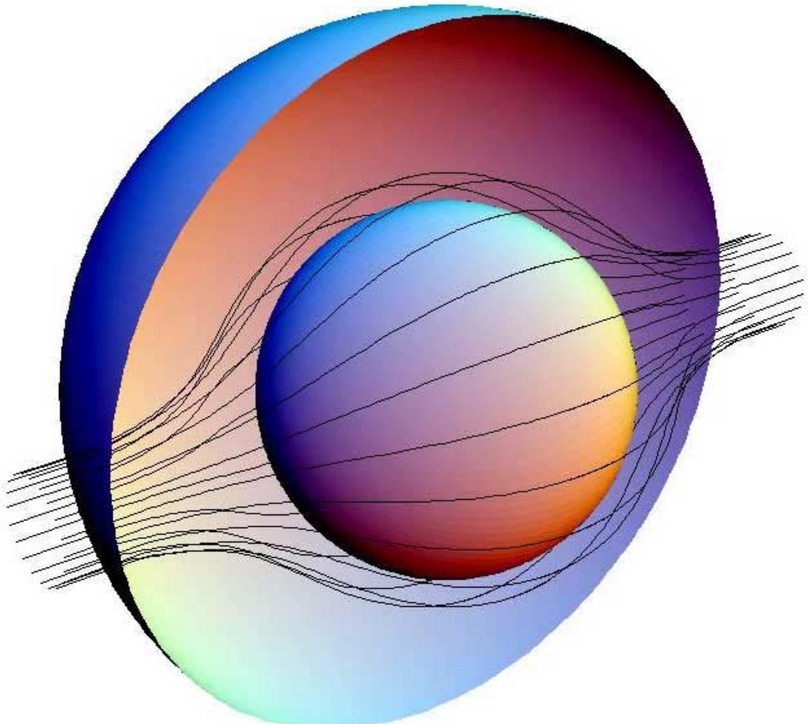


Cloaking Static Magnetic Fields

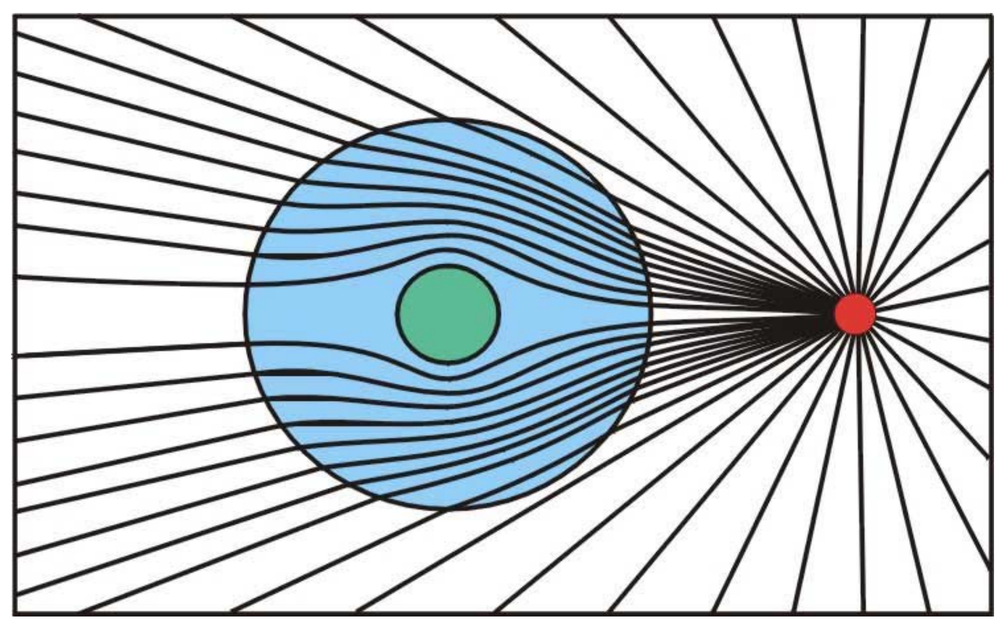
see: J. Phys.: Condens. Matter **19** (2007) 076208 (*B. Wood and JB Pendry*)

Cloaking works for fields as well as waves!

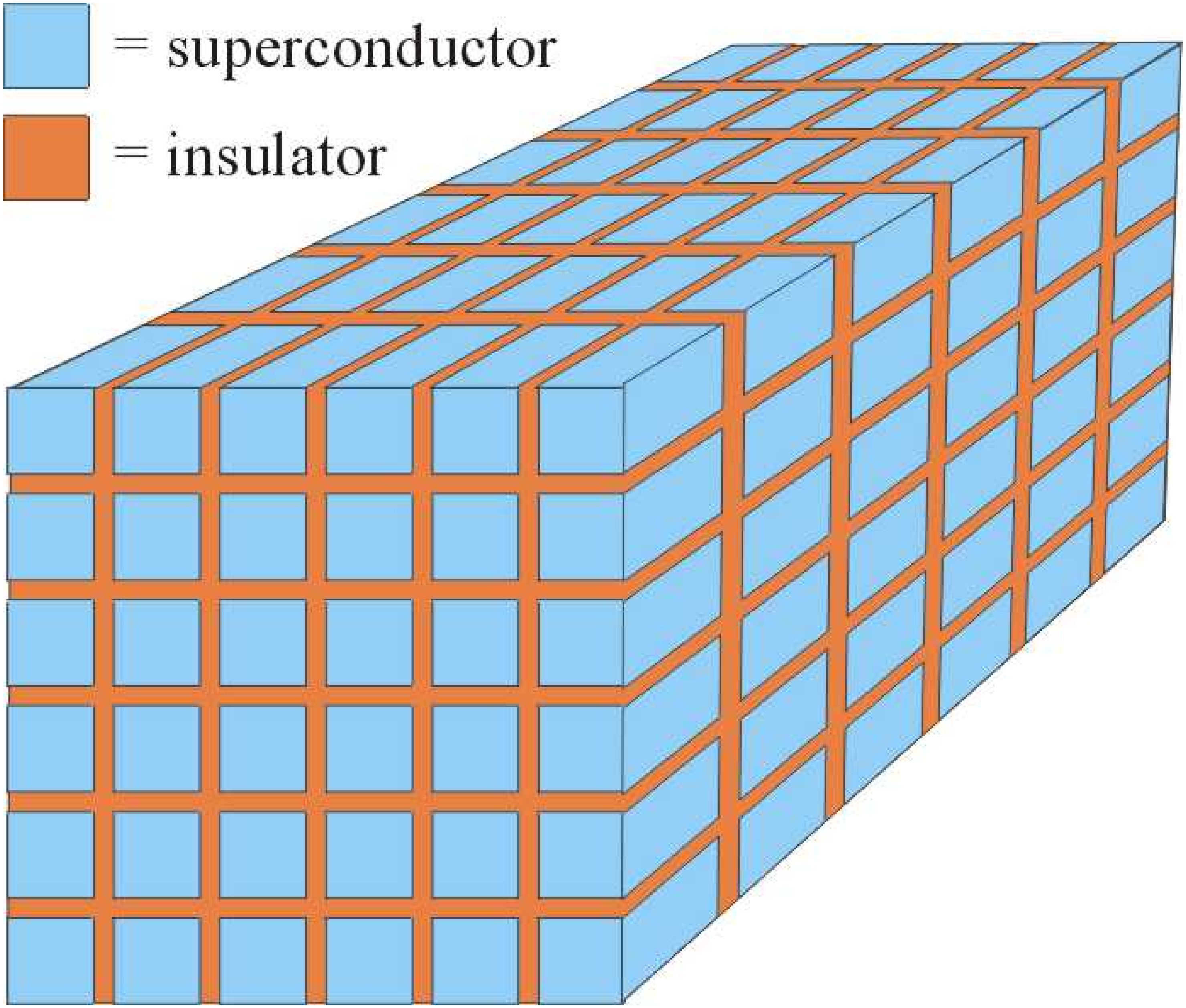
deflection of rays
(far field)



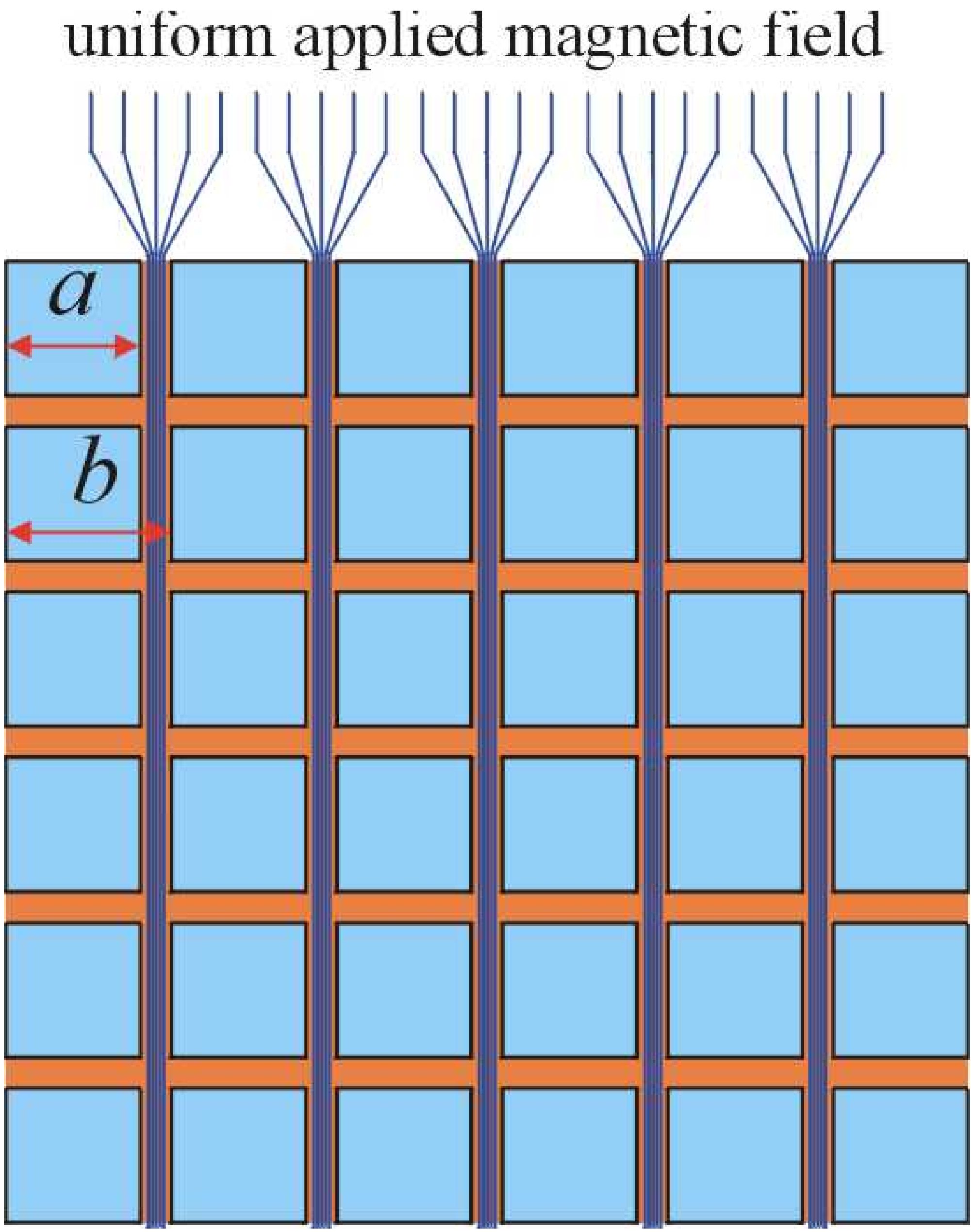
deflection of field lines
(near field)



A metamaterial with $0 < \mu < 1$ *and* no dispersion



Calculating μ_{eff}



The effective permeability is given by:

$$\mu_{eff} = \frac{B_{ave}}{\mu_0 H_{ave}}$$

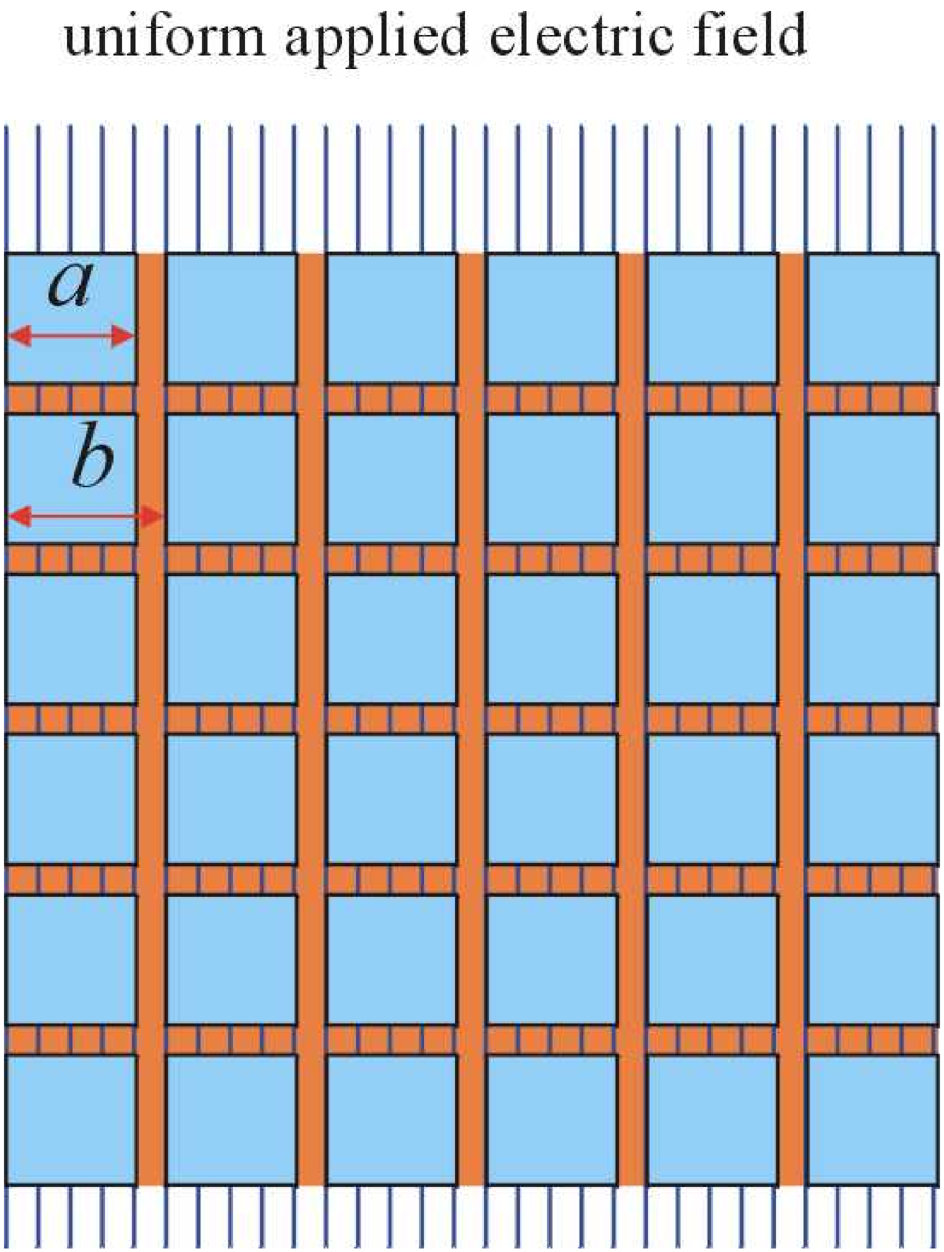
where we define B_{ave} as an average over the cross sectional area of the sample, and H_{ave} as an average along a line through the interstices of the sample. Since all flux is excluded from the superconductor the flux lines are squeezed into a smaller area, hence,

$$\mu_{eff} = \frac{b^2 - a^2}{b^2}$$

Note that this result is independent of the frequency. Does this imply

$$c = c_0 / \sqrt{\mu_{eff}} > c_0 ?$$

Calculating ε_{eff}



The effective permittivity is given by:

$$\varepsilon_{eff} = \frac{D_{ave}}{\varepsilon_0 E_{ave}}$$

where we define D_{ave} as an average over the cross sectional area of the sample, and E_{ave} as an average along a line through the sample. Since all the E field is concentrated in the gap between superconductors,

$$\varepsilon_{eff} = b/b - a$$

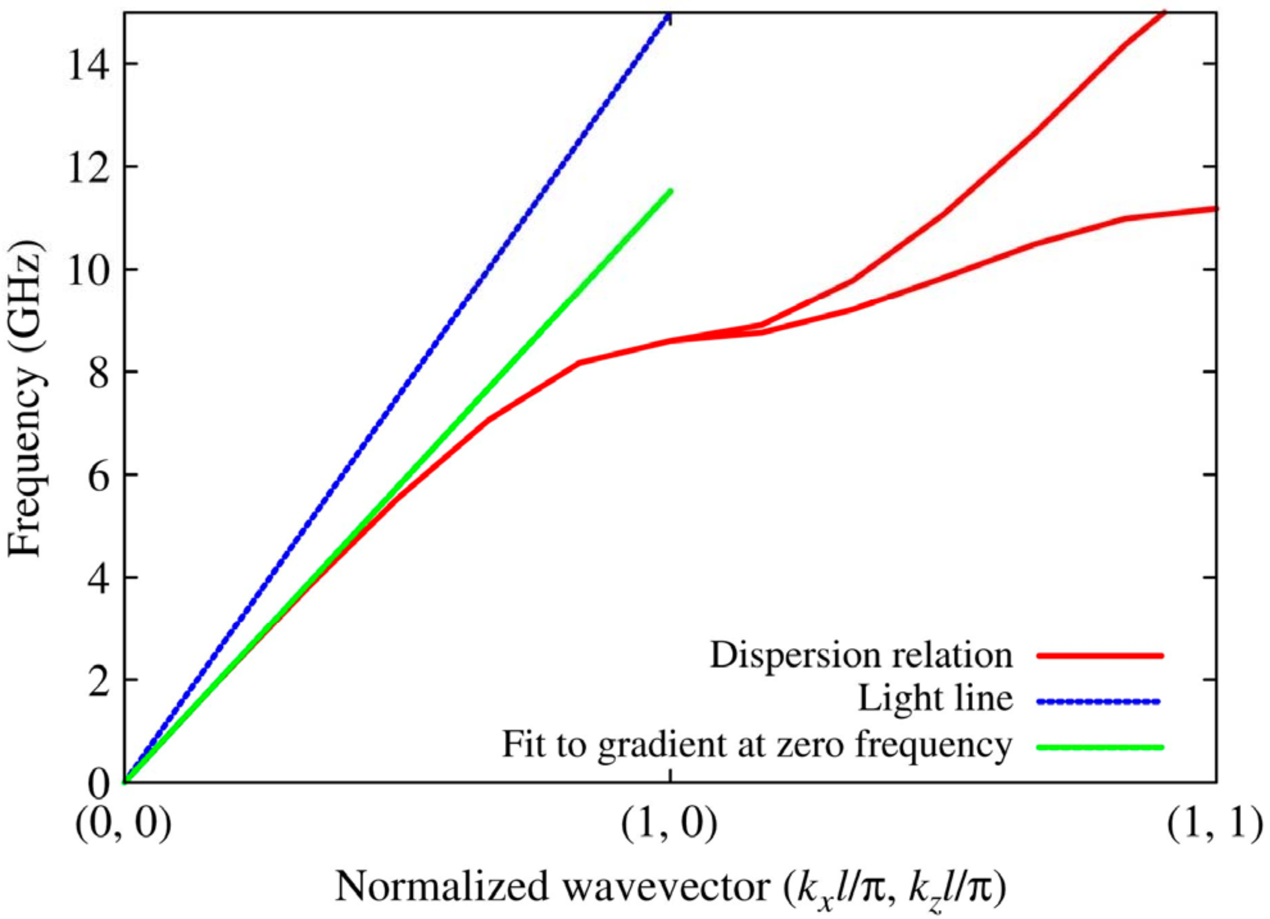
Hence,

$$\varepsilon_{eff}\mu_{eff} = \frac{b}{b-a}\frac{b^2-a^2}{b^2} = \frac{b+a}{b} > 1$$

$$\lim_{a\to b} c = \lim_{a\to b} c_0 \Big/ \sqrt{\varepsilon_{eff}\mu_{eff}} = c_0/\sqrt{2}$$

Superconducting Cubes:

lattice constant $a = 10\text{mm}$ and a range of cube lengths b.

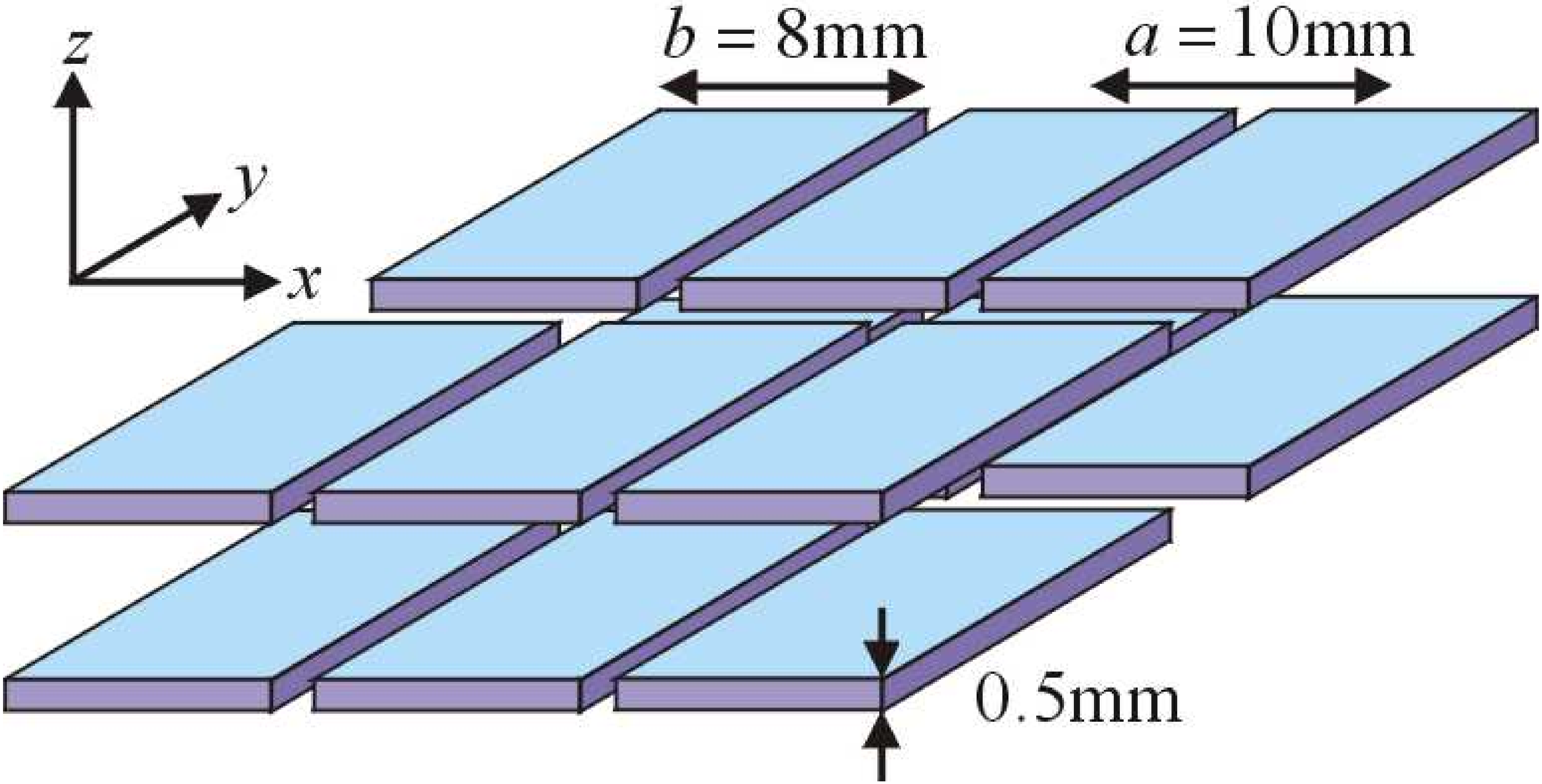


Dispersion relation for superconducting cubes with $a = 10\text{mm}$ and $b = 8\text{mm}$. (Microwave Studio)

Phase velocities calculated from the dispersion relations: various values of b.

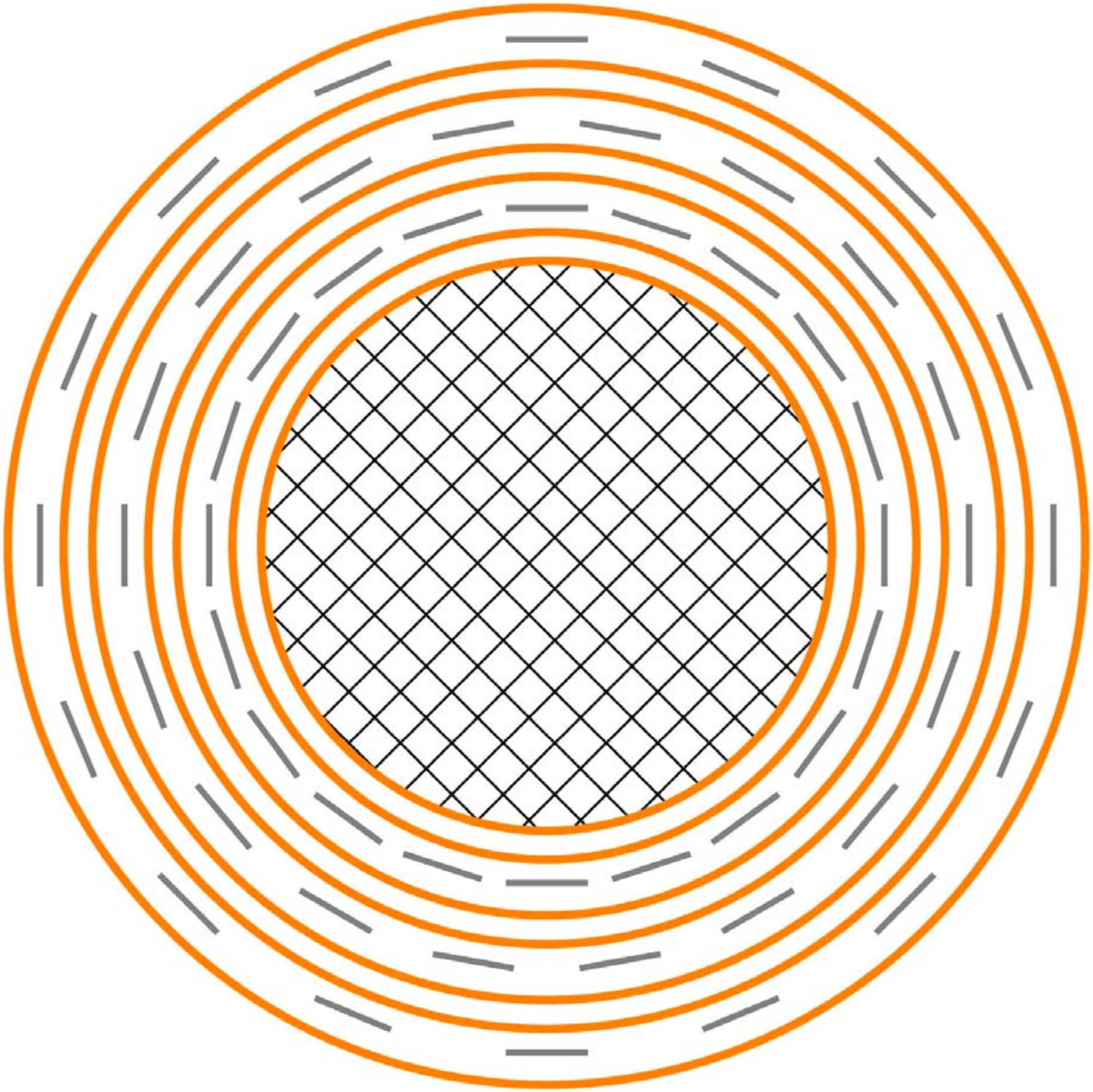
b (mm)	$\omega/(kc_0)$
8	0.768
9	0.734
9.5	0.719
9.8	0.711
$a \to b$	0.707

Lattice of superconducting plates



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

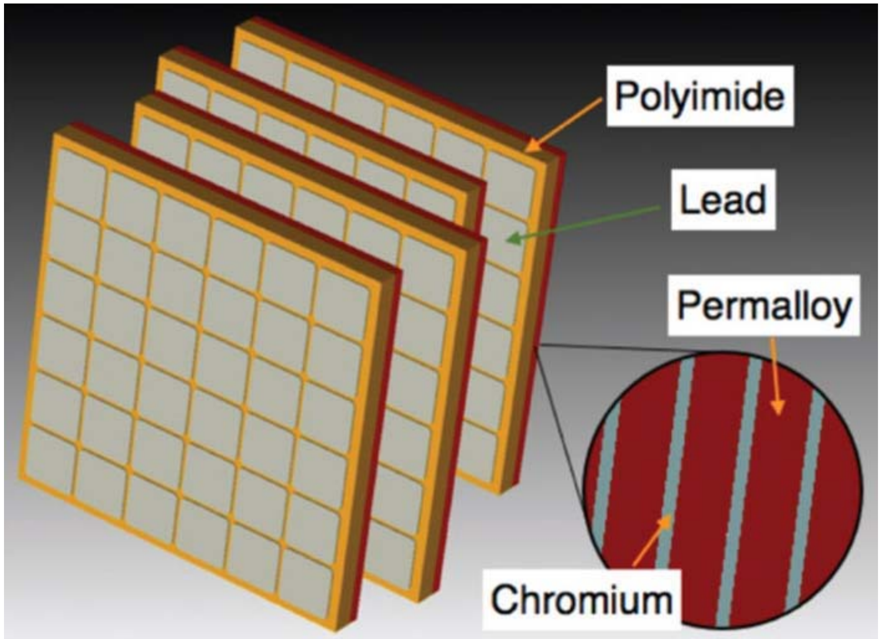
The proposed magnetic cloak



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

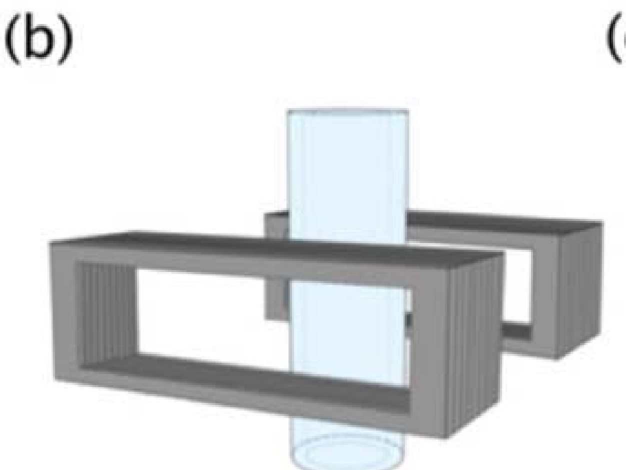
Supradeep Narayana and Yuki Sato, *Advanced Materials*, **24**, 71-74 (2012)

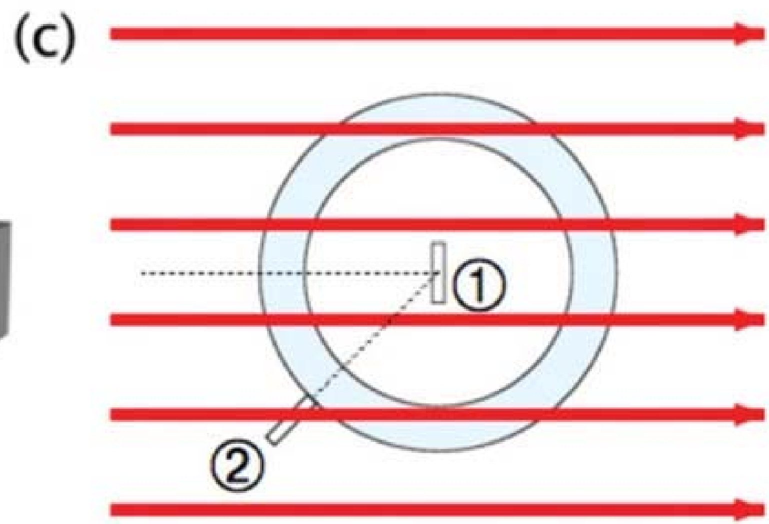


Schematic of the cloaking material consisting of an array of superconducting and soft ferromagnetic elements.

(b) Apparatus geometry.

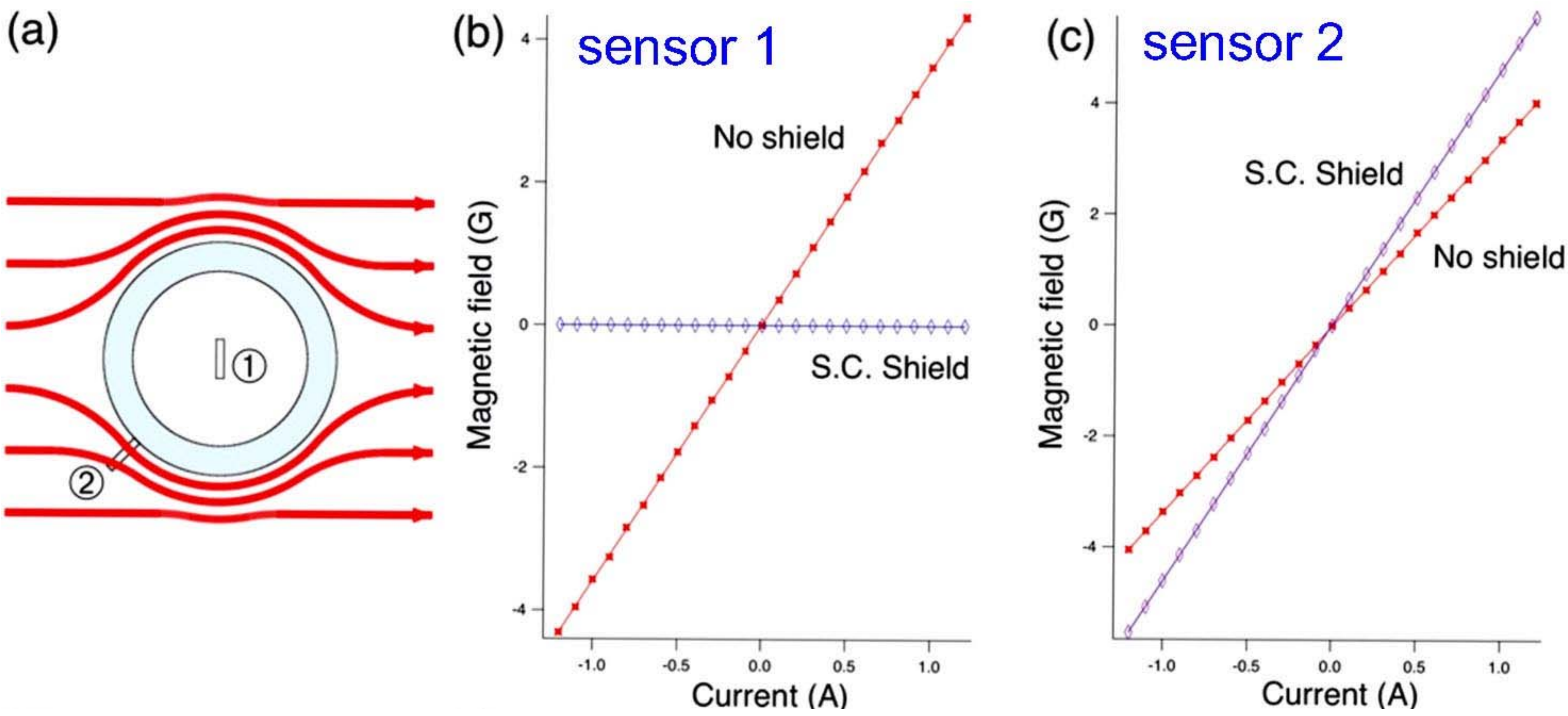
(c) Top-view schematic showing the locations of two Hall sensors and magnetic field lines in empty space. Sensor 1 detects the field that penetrates through the cloak, and sensor 2 is positioned to capture external field perturbations due to the presence of the cloak.





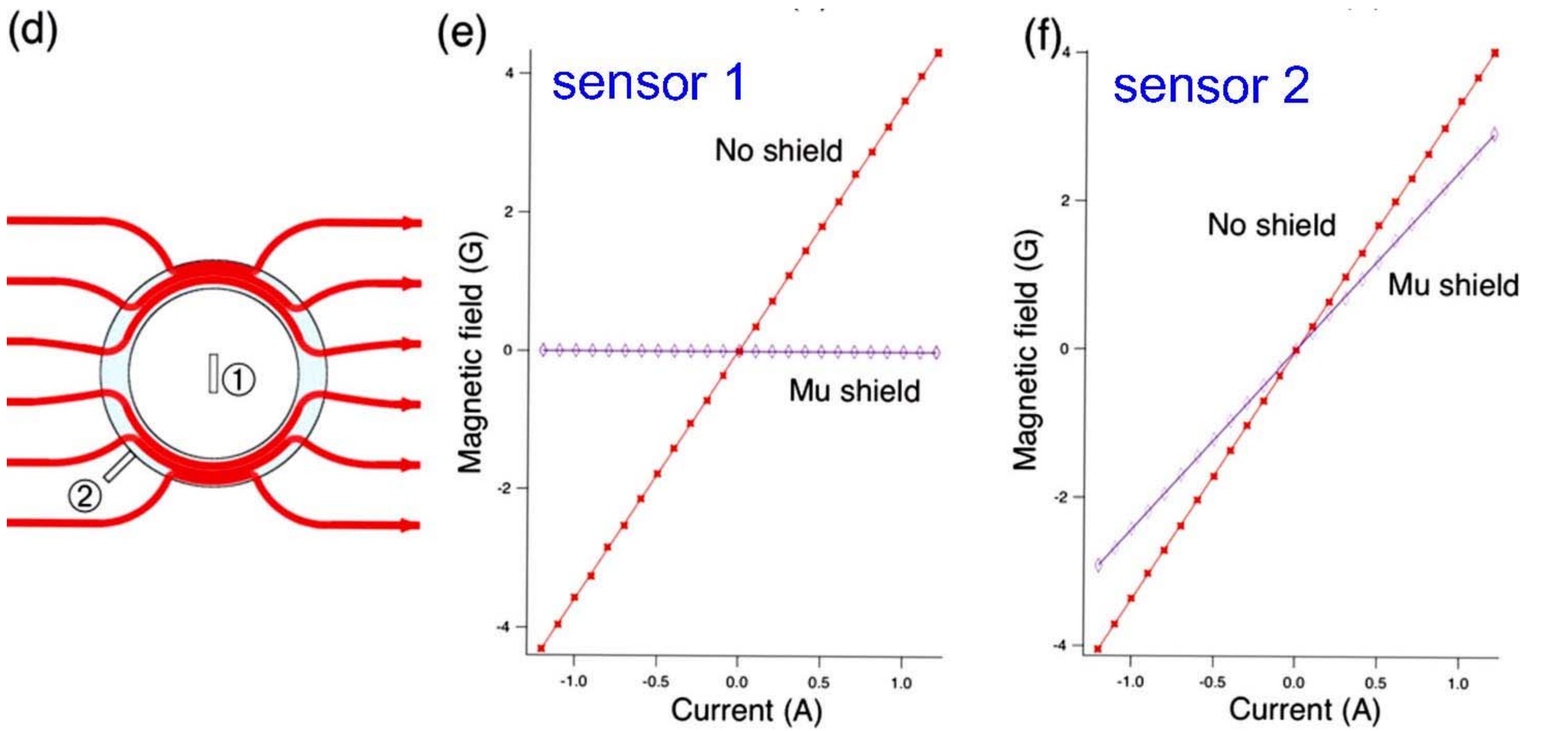
A DC magnetic cloak - 2

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



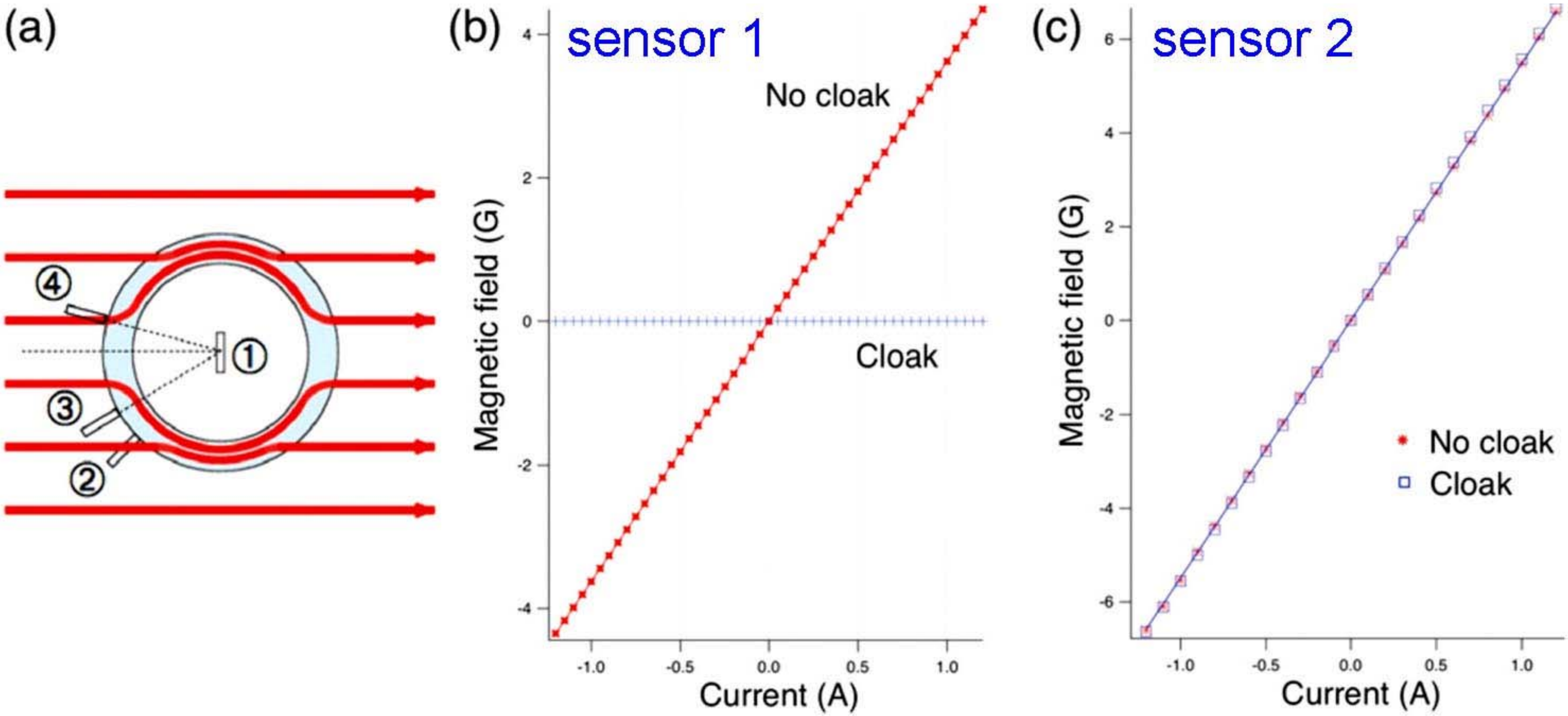
A DC magnetic cloak - 3

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



A DC magnetic cloak - 4

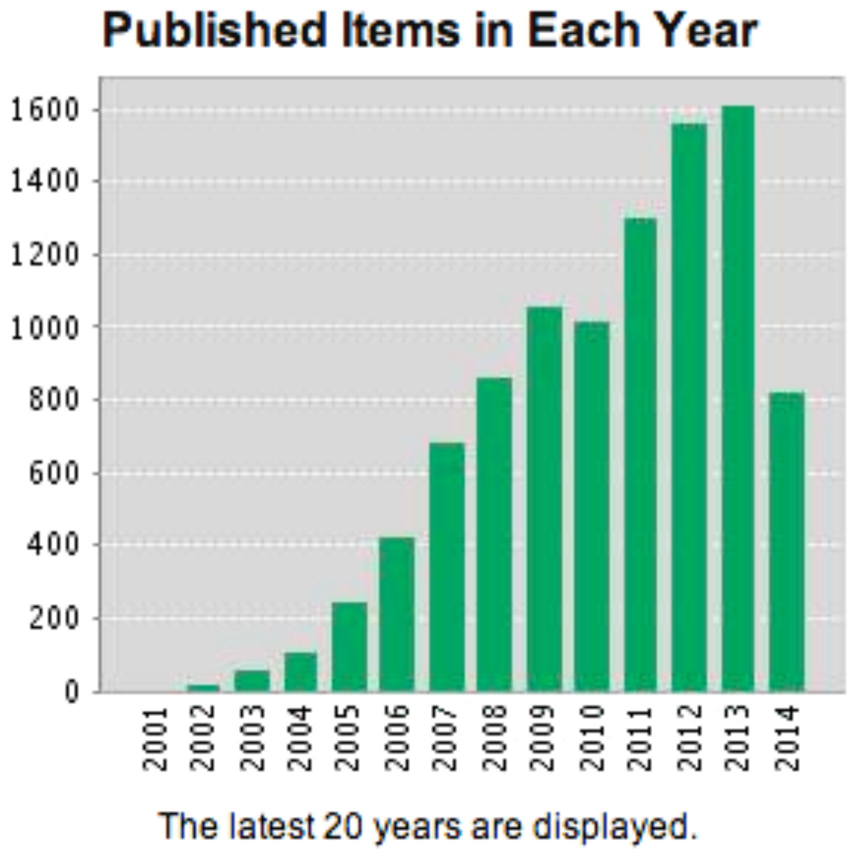
Cloaking magnetic fields using *metamaterials* excludes fields from inside the cloak, and leaves the external field undisturbed.

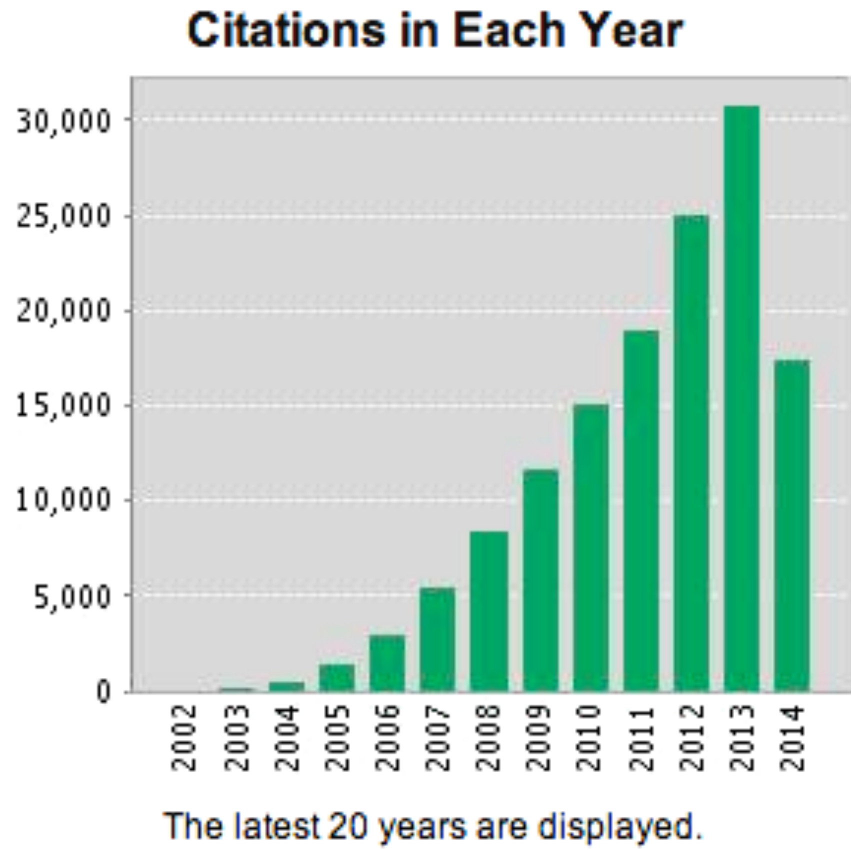


The rise of metamaterials

Citation report topic = metamaterials

Web of Science





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

papers published in 2013: **1600**

citations in 2013: **30,779**

INTELLECTUAL VENTURES®

Metamaterial Surface Antenna Technology (MSA-T)

MSA-T: Enabling affordable, all-electronic beam steering satcom user terminals

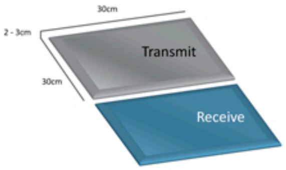
Intellectual Ventures' (IV) Metamaterial Surface Antenna Technology (MSA-T) is a new class of antenna technology that can electronically steer an RF beam rapidly and precisely over wide angles, without the need for moving parts or expensive phase-shifting components.
A first application of MSA-T will be the development of user terminals for the new generation of Ka-band High Throughput Satellites (HTS), serving communications-on-the-move customers in aeronautical, maritime and land transport markets. It may also be used for fixed applications where ease of installation is important.

Unlike today's large, heavy and hand-built mechanical and phased array user terminals, MSA-T's antenna structure is similar to printed circuit boards and can be fabricated using established lithography and mass-production techniques. MSA-T allows for lower-cost user terminals as thin as 2-3 cm and that weigh only a few kilograms. MSA-T transmit and receive modules can be tiled as needed to meet customer bandwidth requirements. Variants of MSA-T offer the potential for curved antenna products that conform to a mounting surface, such as the fuselage of an aircraft.

About Metamaterials at IV

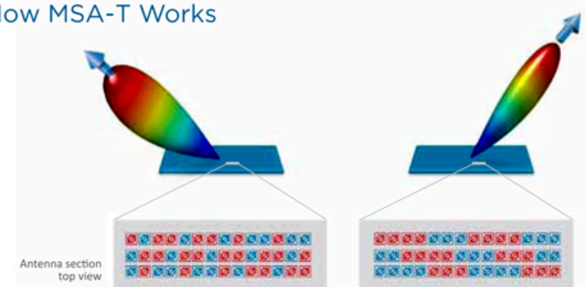
Metamaterials are broadly defined as synthetic materials engineered to have electromagnetic and other characteristics not found in nature. MSA-T is just one valuable application of tunable metamaterials and is expected to lead to a completely new class of dynamic antenna products. IV's extensive metamaterials invention portfolio was developed internally and in close cooperation with some of the pioneers in the field at Duke University and Imperial College, London.

MSA-T Ka-band user terminals will allow satellite service providers to address existing customers and will open the door to new customers who can benefit from its compact form factor, ease of use and installation and expected affordable price points.



Antenna Panels

How MSA-T Works



1. A radio frequency (RF) signal is fed into a guided mode which propagates along the surface of a thin circuitboard-like structure covered with tunable metamaterial elements.
2. When activated, the tunable elements scatter RF energy out of the guided mode. Software is used to activate a specific pattern of tunable elements to generate a beam of scattered RF energy in a desired direction.
3. The pattern of activated elements determines the direction of the radiated wave through the formation of a reconfigurable holographic grating. All of this is achieved without the need for phase shifters.

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MSA-T satcom terminal applications

User terminals incorporating MSA-T offer an affordable and efficient way to connect a wide variety of mobile customers with broadband satellites. Possible applications include:

Aeronautical
Ideally suited for all airborne broadband communications where low aerodynamic drag, weight, power and cost are critical. Designed to be easily installed on commercial transport, business jets, military aircraft and remotely piloted vehicles.

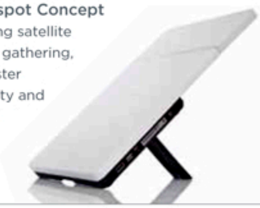
Maritime & Recreation
Configurable for any communications over the water, including shipping vessels, cruise liners and even leisure recreational craft.

Rail
Delivers broadband Internet services on any rail system, including commuter, high-speed rail and freight trains. Affordable, low-profile terminals are easy to install, ensuring rail passengers have access to the same type of high-speed Internet services they would have at home or in the office.

Technical Specifications

Parameter	Preliminary specifications
Single panel dimensions	Transmit: 30 x 30 x 2-3 cm Receive: 30-50 x 30-50 x 2-3 cm Panels can be tiled for required performance
Mass	1-3 kg Excludes modem, power handling, interfaces etc.
Packaging efficiency	90% Aperture area divided by the package footprint.
Total bandwidth	1 GHz @ Ka-band
Instantaneous bandwidth	100 MHz
Radiation efficiency	50% (3dB)
Polarization	Circular, left-handed or right-handed User selectable.
EIRP	37.5 dBW for 1 W RF 43.5 dBW for 4 W RF
G/T	8.3 dB/K for a 30 cm receive panel 12.7 dB/K for a 50 cm receive panel
Scan range	+/-65 deg from broadside, all azimuth
Beam steering rate	30 deg/sec, elevation and azimuth Expected to meet FCC pointing requirements.
Operating temp range	-54 to 85 deg C

Portable Satellite Hotspot Concept



Laptop-sized, self-pointing satellite hotspot for remote news gathering, mining, exploration, disaster response, defense, security and other applications where high-speed Internet access is essential.

Status and Availability

IV's dedicated project team has designed and fabricated prototype MSA-T antennas to demonstrate wide angle beam steering at Ka-band. MSA-T is now transitioning to commercialization and full-scale product development, with initial availability planned for late 2014.
If MSA-T can meet your needs, please contact:
Russell Hannigan - Director, Business Development
email: rhannigan@intven.com
http://www.intellectualventures.com/msat

About Intellectual Ventures

Founded in 2000, Intellectual Ventures (IV) is the global leader in the business of invention. IV collaborates with leading inventors, partners with pioneering companies, and invests both expertise and capital in the process of invention. IV's mission is to energize and streamline an invention economy that will drive innovation around the world.

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Intellectual Ventures & Kymeta

About Metamaterials

Intellectual Ventures has granted Kymeta an exclusive, fully-paid, perpetual global license for all satellite and related applications of its Metamaterials Surface Antenna Technology (MSA-T), providing Kymeta with commercial protection for this cutting-edge technology. Our current focus is on more practical applications of the technology:

- Satellite user terminals to connect boats, planes, cars and other vehicles to broadband service
- Dynamic cellular base station antennas to expand cell phone service
- Dynamic antennas for home and office wireless routers
- Collision avoidance radar systems for vehicles
- Advanced medical devices for focused surgical procedures
- Imaging systems for non-destructive testing of composite materials

KYMETA - transportable broadband

Easy-to-use, transportable device with high speed internet connectivity through Ka-band satellites. Customers for such products are expected to include:

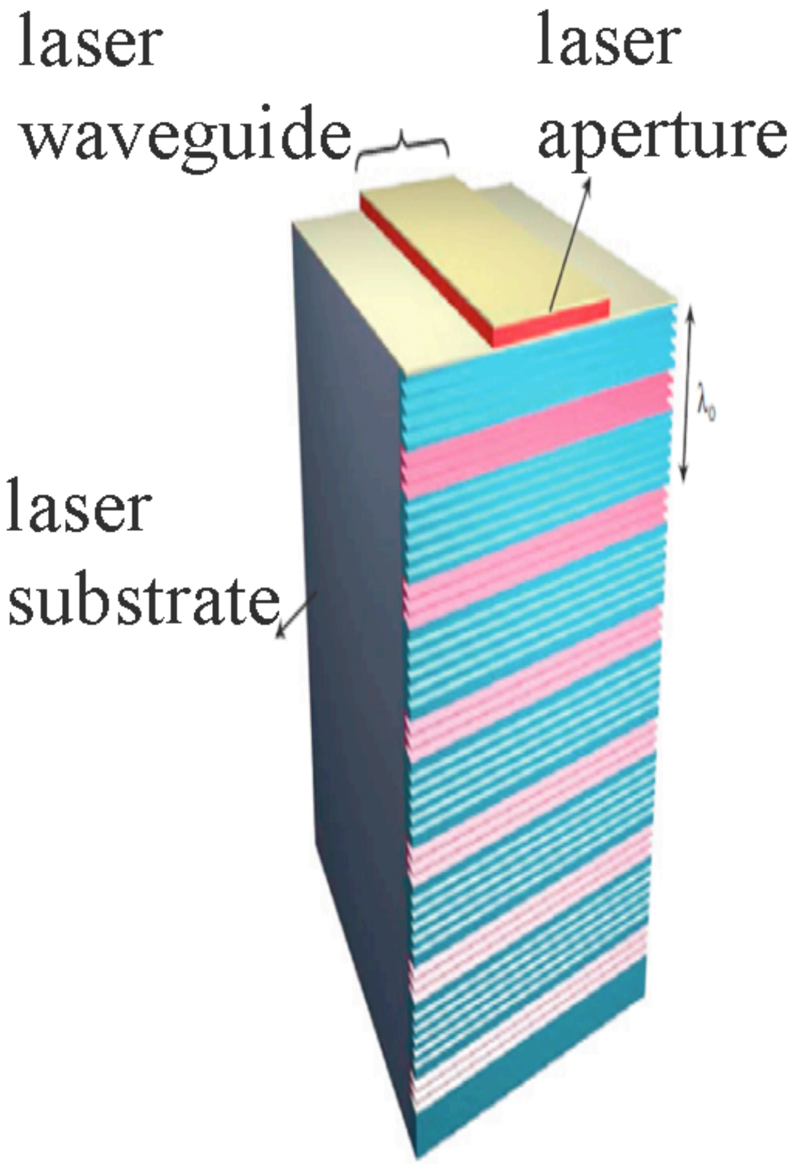
- Journalists (Satellite News Gathering)
- Energy and mining
- Aid agencies
- Disaster recovery
- Remote temporary office

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.

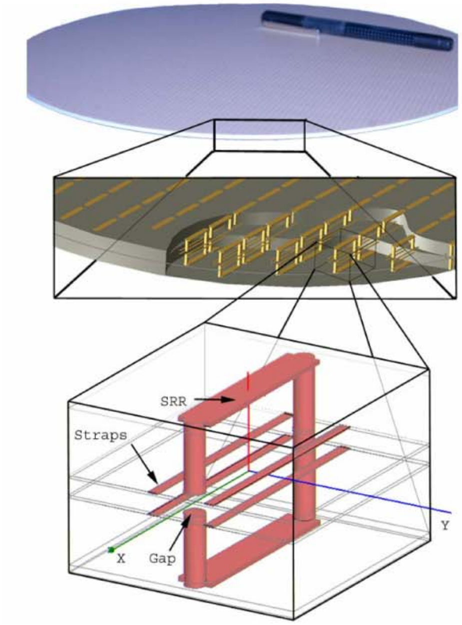
Intellectual Ventures spinout Evolv gets $11.8M from Bill Gates and others, aims to transform security scanning. The second company to commercialize an invention from IV’s portfolio of metamaterials patents.

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



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.

Prototype Application: Metamaterial Gradient Index Lens



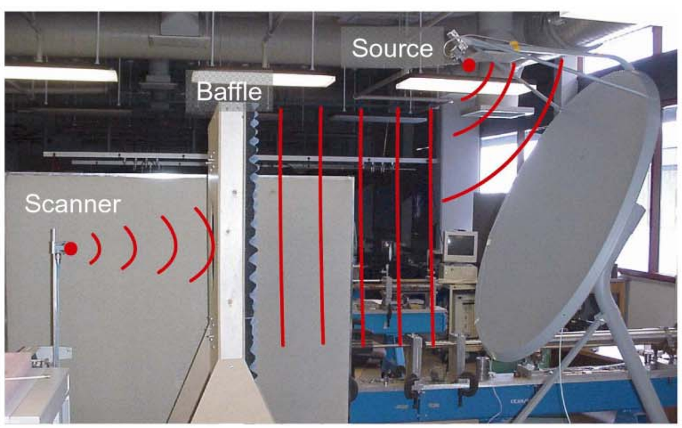
Single X-Band GRIN Lens Disk

- *10 Ghz center frequency*
- *30 cm diameter*
- *~2 mm (λ/14) thick*
- *7872 unit cells*
- *952 unique cell designs*
- *Index range -0.9 to -2.9*
- *Impedance matched to ± 7%*
- *Internal structure dimensional control to ~microns*
- *100 μ outside overlayers*
- *Structurally Strong!*

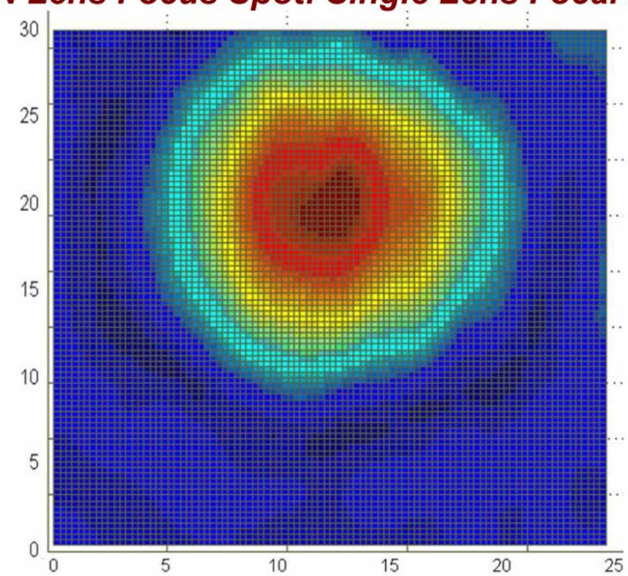
SensorMetrix

Measurement of Metamaterial Gradient Index Lens

CEAM Compact X-Band Range



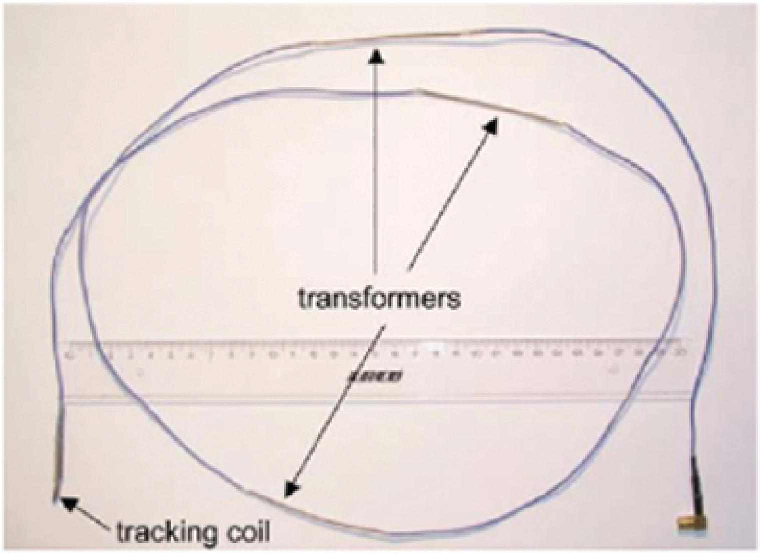
GRIN Lens Focus Spot: Single Lens Focal Length = 90 cm

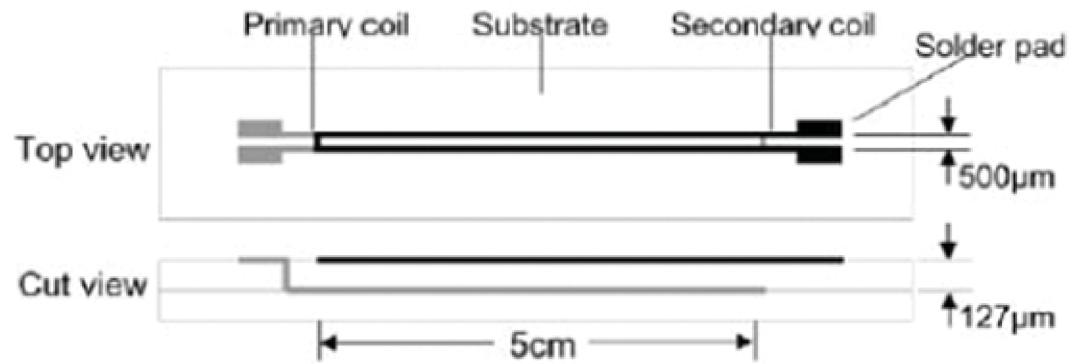


Endoscopically Compatible MR-Safe Magneto-inductive Imaging Catheter

R.R.A. Syms[1], I.R.Young[1], M.M.Ahmad[1],
S.Taylor-Robinson[2], M.Rea[2]
[1]EEE Dept., Imperial College London,
[2]St. Mary's Hospital, Imperial College NHS Trust, London, UK
TEL +44 207 594 6203; email r.syms@imperial.ac.uk

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

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

NEXT INSTANT EXPERT
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

NewScientist

INSTANT EXPERT

7

THE LECTURE SERIES OF THE

36TH PROFESSOR HARRY MESSEL INTERNATIONAL SCIENCE SCHOOL

LIGHT AND MATTER

3–16 JULY 2011

Light and Matter
ISBN: 978-1-74210-236-8

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