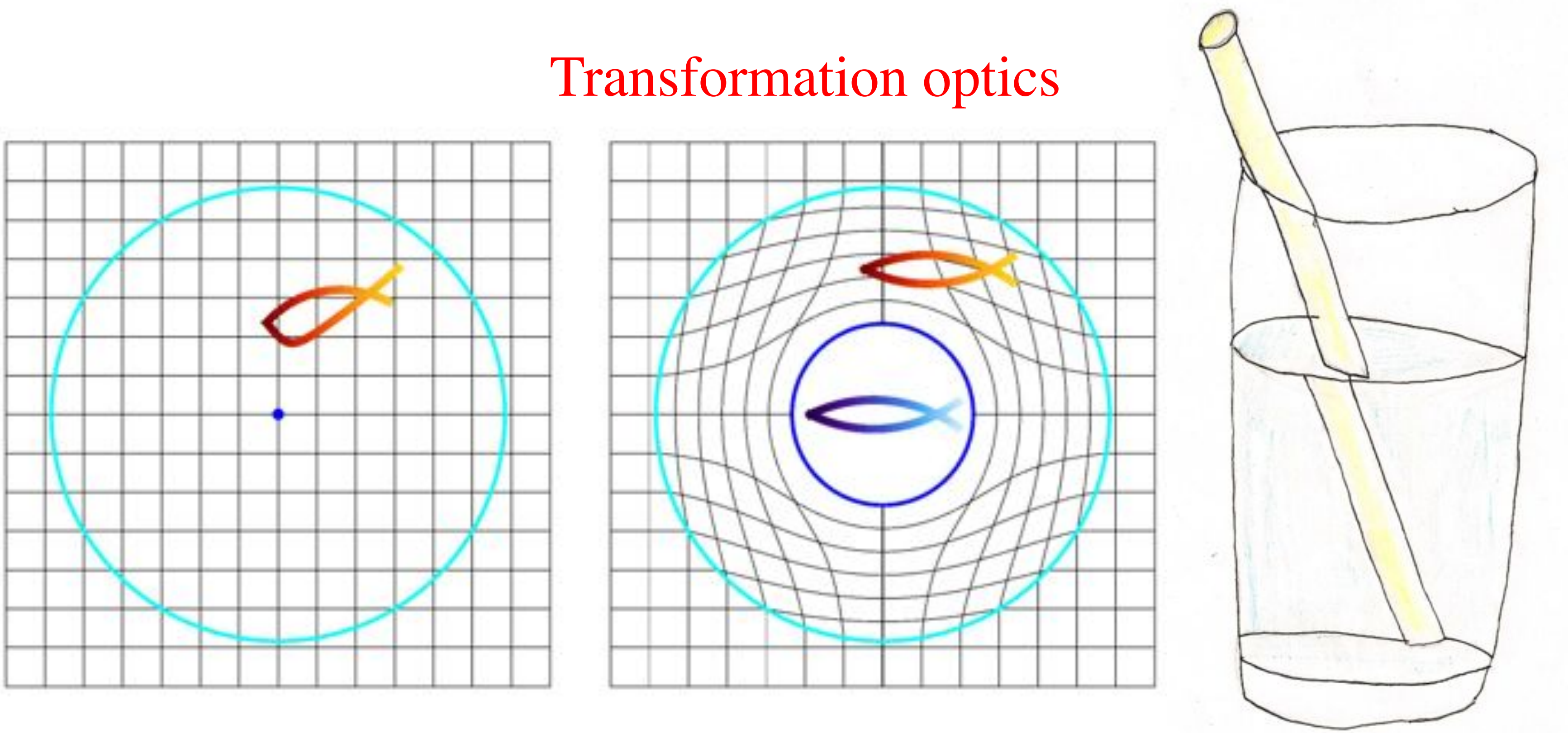
Perfect imaging with positive refraction

Ulf Leonhardt

University of St Andrews, UK

THE ROYAL SOCIETY

Transformation optics



[Greenleaf, Lassas and Uhlmann, Math. Res. Lett. **10**, 685 (2003) electrostatics;
Leonhardt, Science **312**, 1777 (2006) conformal transformations;
Pendry, Schurig and Smith, Science **312**, 1780 (2006) spatial transformations;
Leonhardt and Philbin, NJP **8**, 247 (2006) space-time & negative refraction]

A new fish-eye lens based on an idea of James Clark Maxwell.

To invisibility and beyond

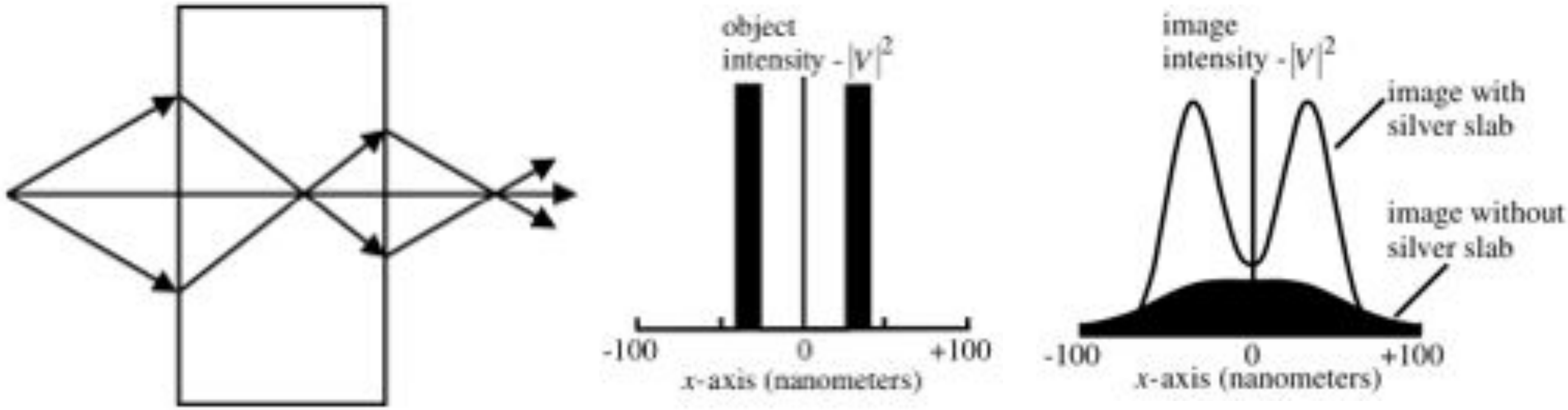
Combining Maxwell's equations with Einstein's general relativity promises perfect images and cloaking devices, explains **Ulf Leonhardt**.

[Leonhardt, Nature **471,** 292 (2011)]

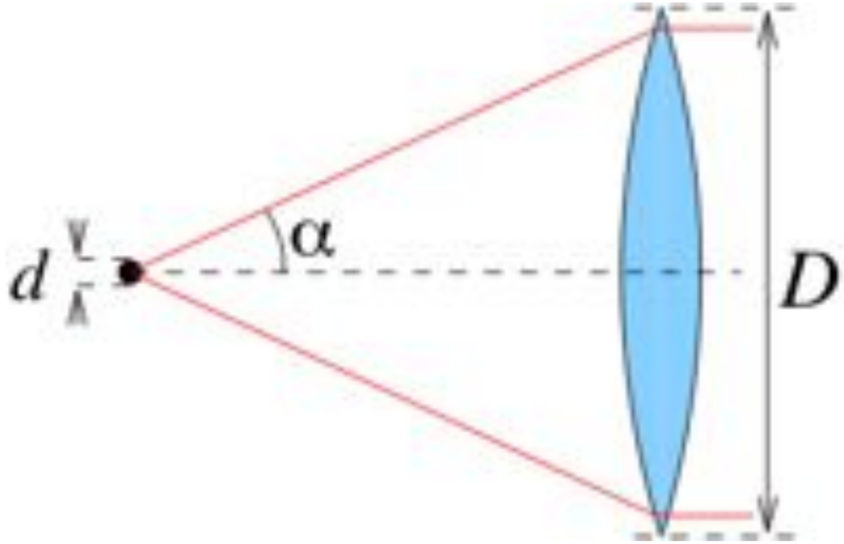
Negative Refraction Makes a Perfect Lens

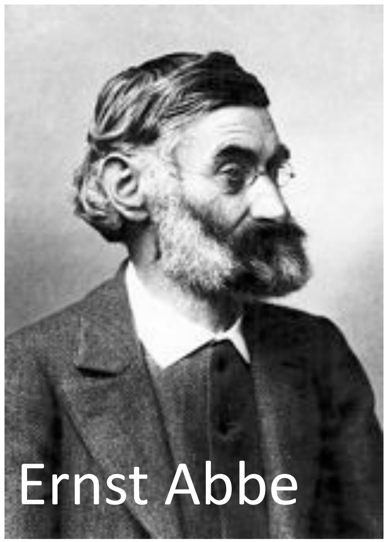
J. B. Pendry
Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
(Received 25 April 2000)

With a conventional lens sharpness of the image is always limited by the wavelength of light. An unconventional alternative to a lens, a slab of negative refractive index material, has the power to focus all Fourier components of a 2D image, even those that do not propagate in a radiative manner. Such "superlenses" can be realized in the microwave band with current technology. Our simulations show that a version of the lens operating at the frequency of visible light can be realized in the form of a thin slab of silver. This optical version resolves objects only a few nanometers across.



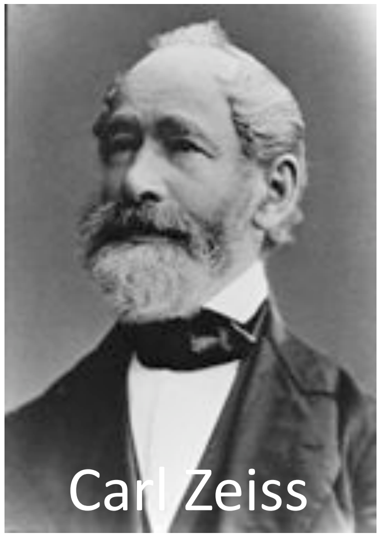
The resolution limit of imaging, established around 1870

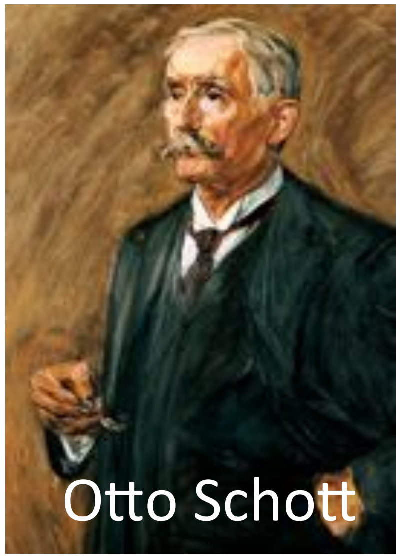




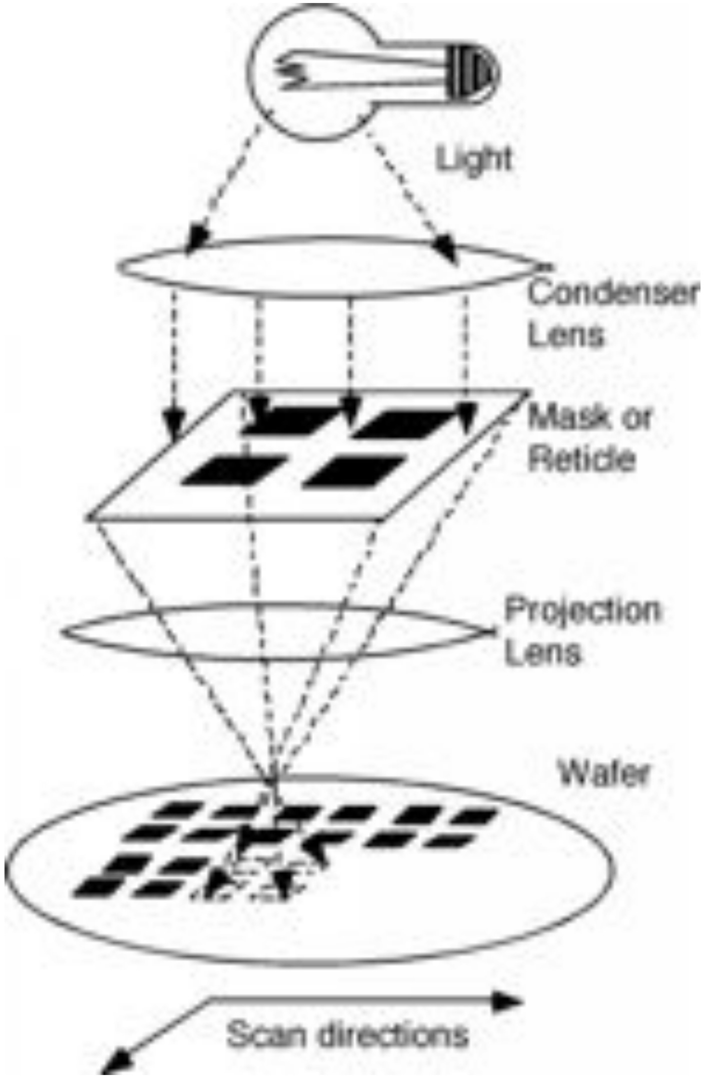
ZEISS

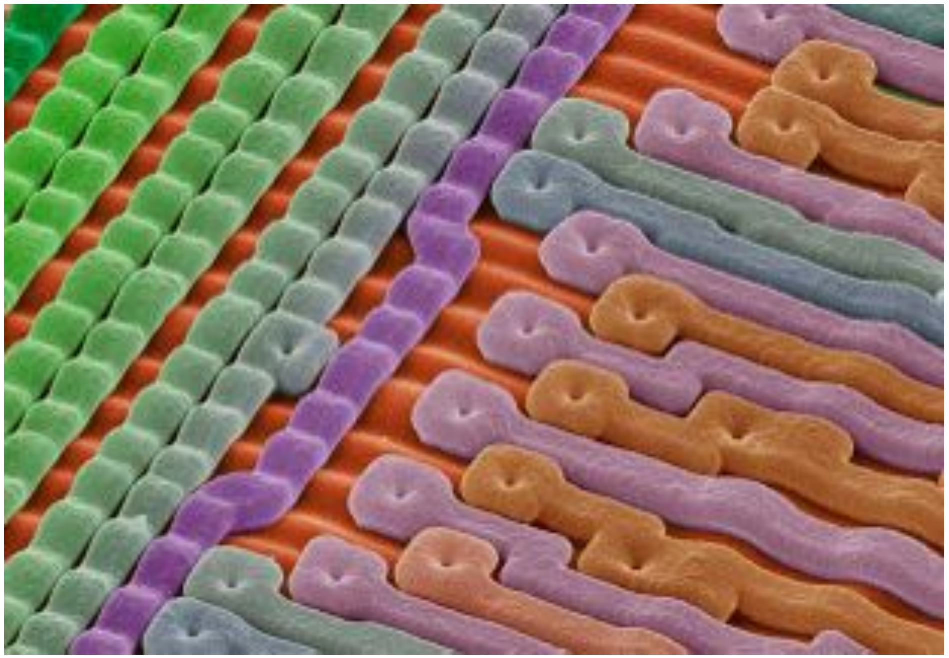
SCHOTT
125 YEARS



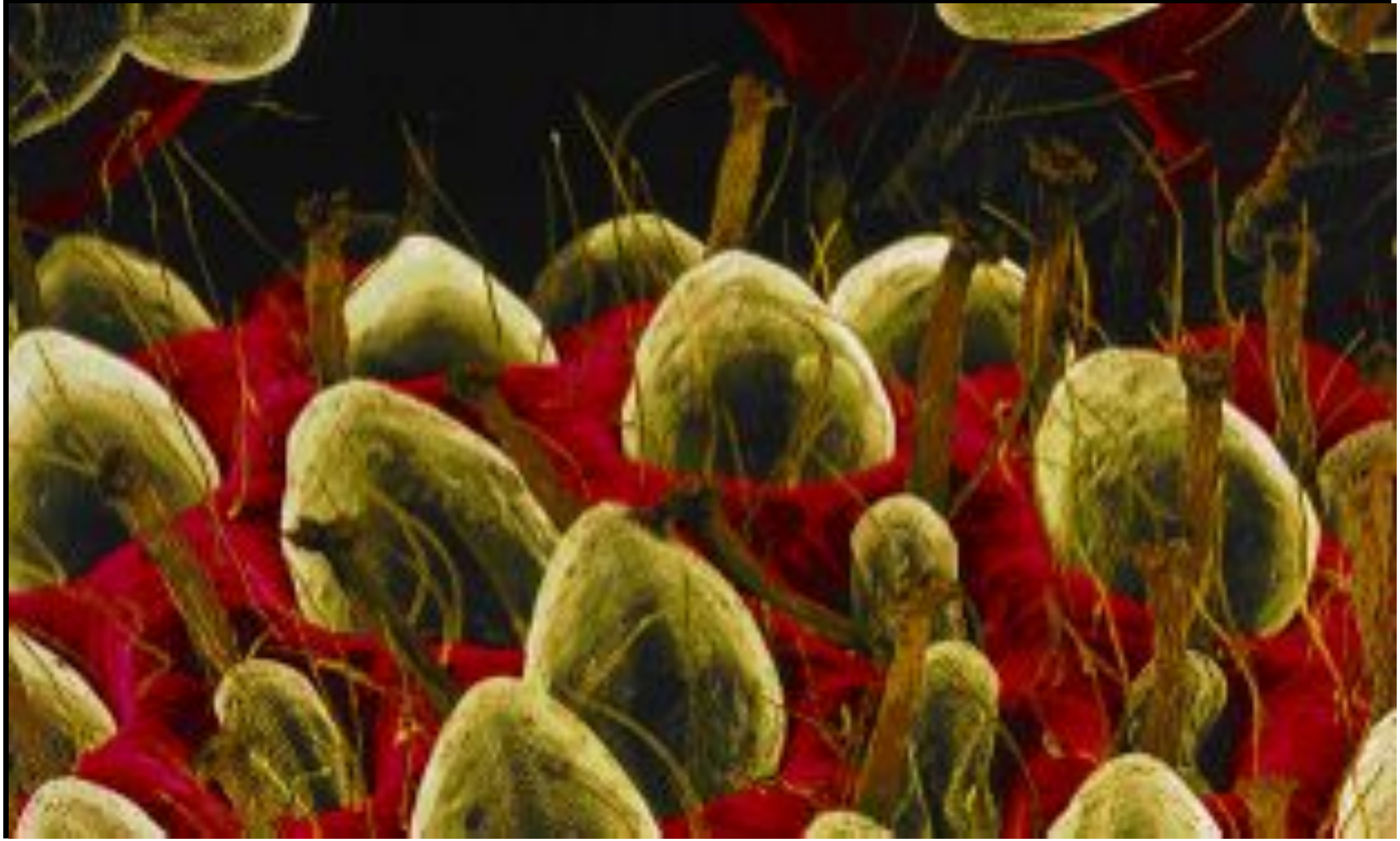


Photolithography

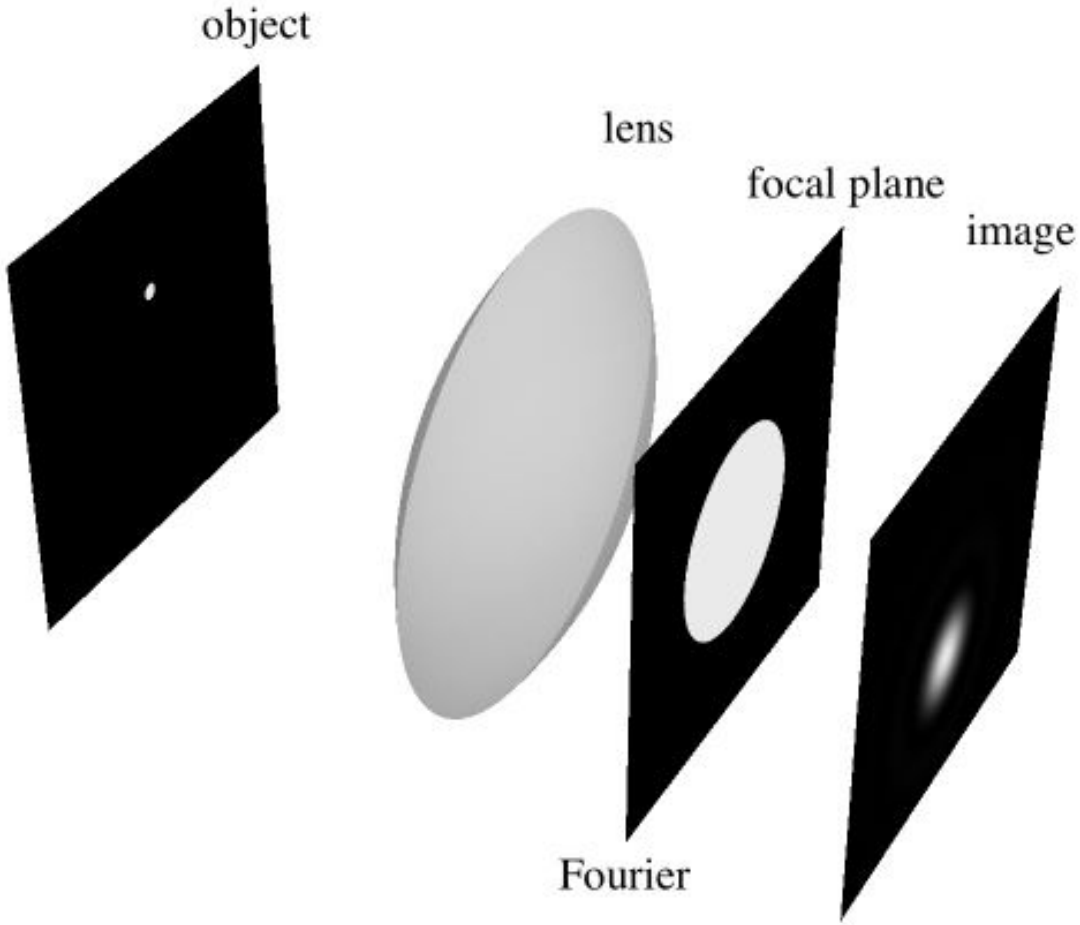




Microscopy



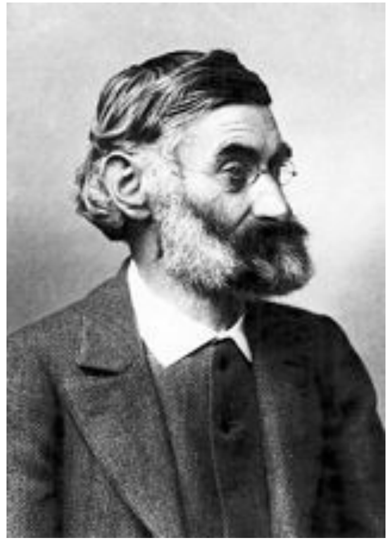
Standard diffraction limit of imaging

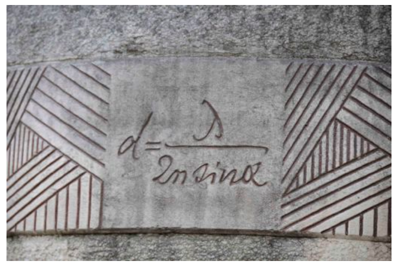


$$(\nabla^2 + k^2)\, u = 0$$

$$(\partial_z^2 - k_x^2 - k_y^2 + k^2)\, \tilde{u} = 0$$

$$\tilde{u}(z) = \tilde{u}(z_0)\, \exp\left(i\sqrt{k^2 - k_x^2 - k_y^2}\,(z - z_0)\right)$$





Evanescent waves

Negative Refraction Makes a Perfect Lens

J. B. Pendry
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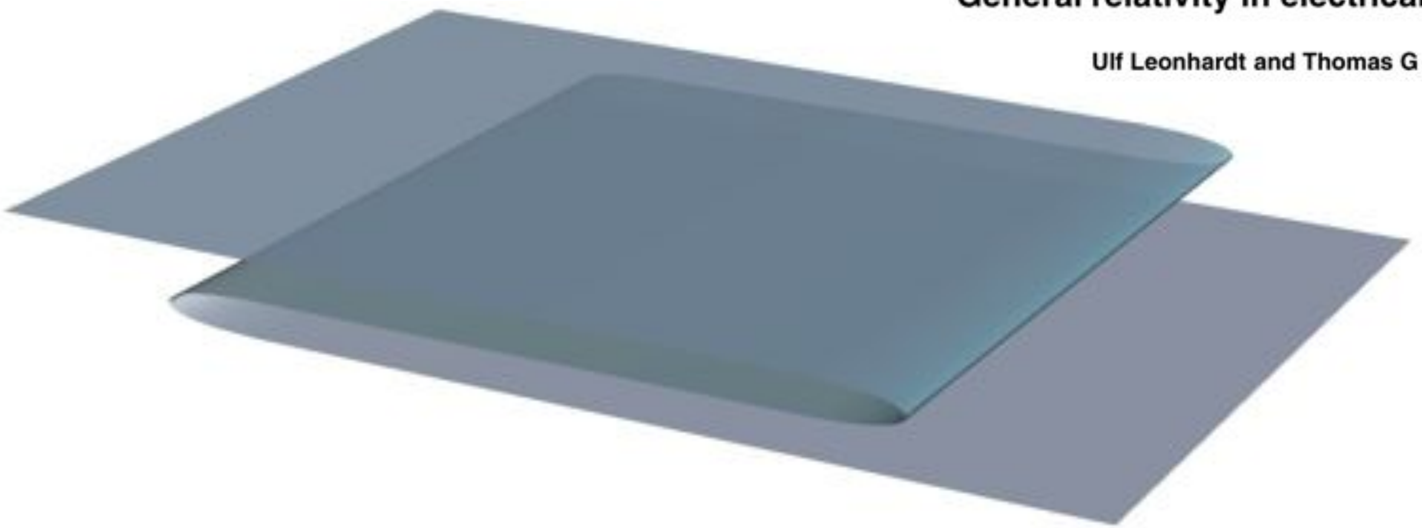
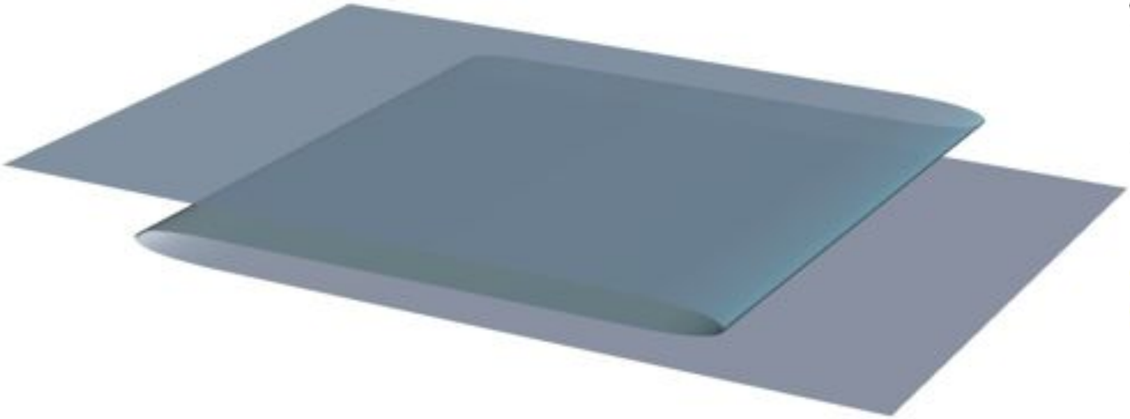
New Journal of Physics
The open-access journal for physics

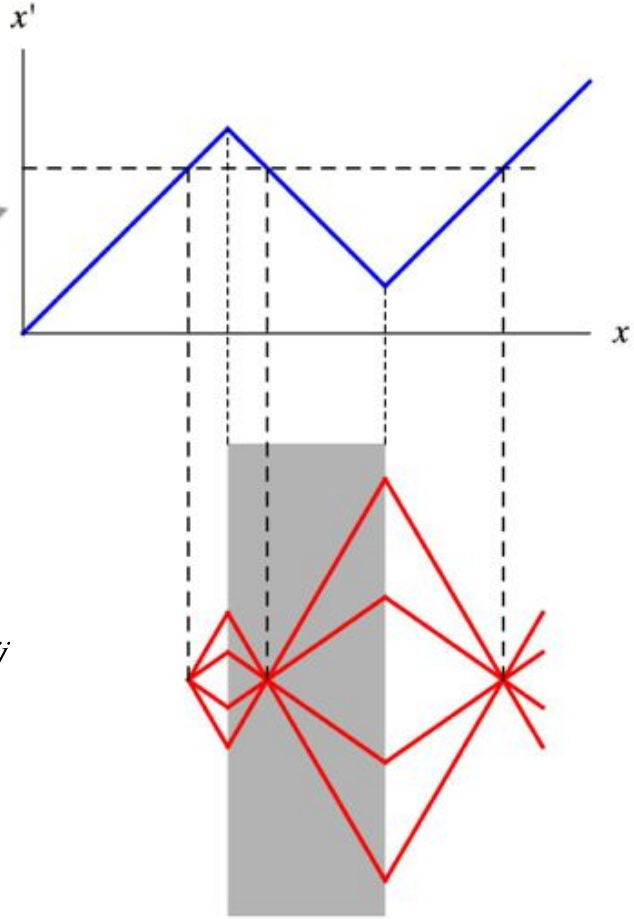
General relativity in electrical engineering

Ulf Leonhardt and Thomas G Philbin



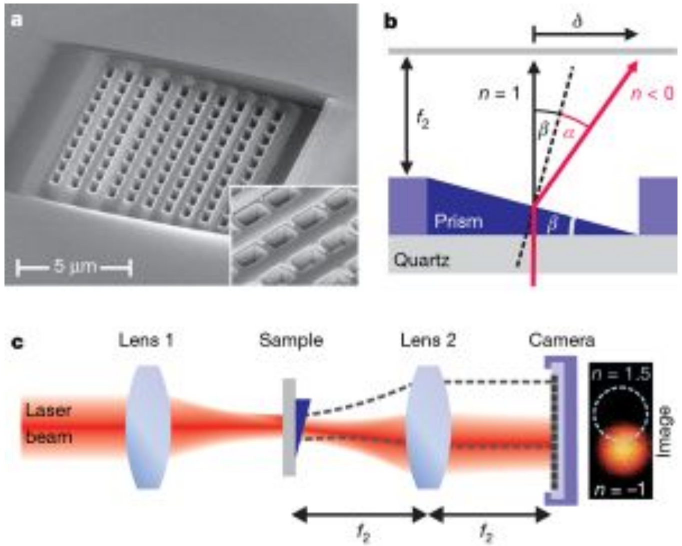
Negative refraction and perfect lens





$$\varepsilon = \mu = \mp \frac{\sqrt{-g}}{g_{00}} g^{ij}$$

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



Xiang Zhang et al.
@ Berkeley

[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)]

Controversy on perfect imaging with negative refraction

Phys. Rev. Lett. **88**, 187401
(issue of 8 May 2002)
Phys. Rev. Lett. **88**, 207403
(issue of 20 May 2002)
Titles and Authors

3 May 2002

Left-Handed Materials Debate Heats Up

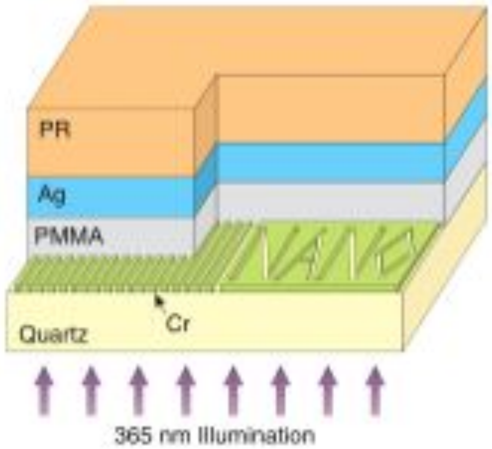
“Poor man’s perfect lens” [Science. **308**, 534 (2005)]

REPORTS

Sub–Diffraction-Limited Optical Imaging with a Silver Superlens

Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang*

Recent theory has predicted a superlens that is capable of producing sub–diffraction-limited images. This superlens would allow the recovery of evanescent waves in an image via the excitation of surface plasmons. Using silver as a natural optical superlens, we demonstrated sub–diffraction-limited imaging with 60-nanometer half-pitch resolution, or one-sixth of the illumination wavelength. By proper design of the working wavelength and the thickness of silver that allows access to a broad spectrum of subwavelength features, we also showed that arbitrary nanostructures can be imaged with good fidelity. The optical superlens promises exciting avenues to nanoscale optical imaging and ultrasmall opto-electronic devices.



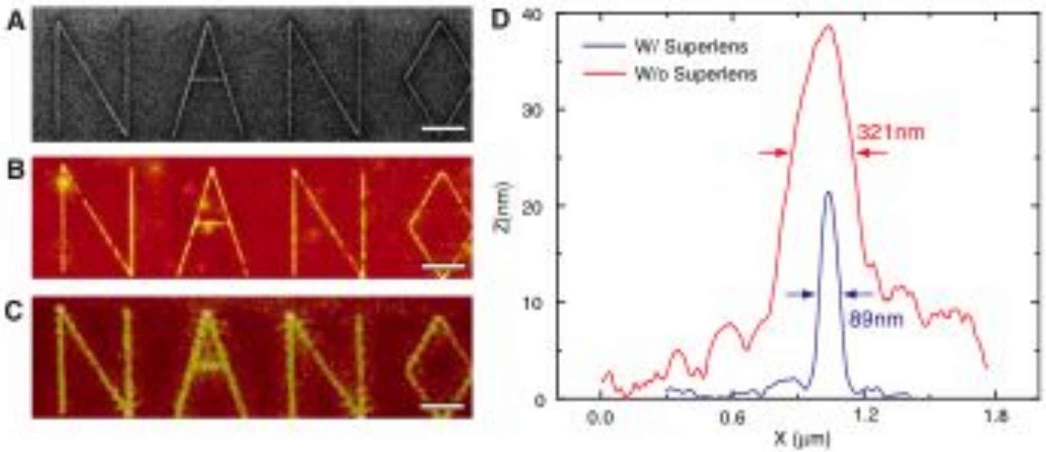
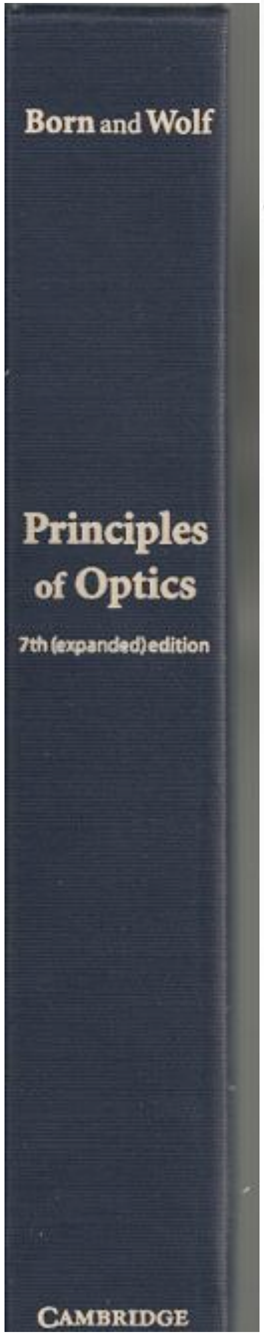


Fig. 4. An arbitrary object "NANO" was imaged by silver superlens. (**A**) FIB image of the object. The linewidth of the "NANO" object was 40 nm. Scale bar in (A) to (C), 2 μm. (**B**) AFM of the developed image on photoresist with a silver superlens. (**C**) AFM of the developed image on photoresist when the 35-nm-thick layer of silver was replaced by PMMA spacer as a control experiment. (**D**) The averaged cross section of letter "A" shows an exposed line width of 89 nm (blue line), whereas in the control experiment, we measured a diffraction-limited full width at half-maximum line width of 321 ± 10 nm (red line).



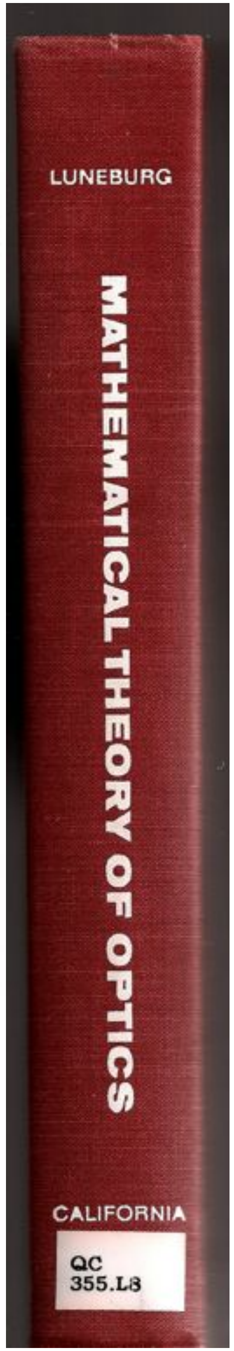
Principles of optics

Electromagnetic theory of propagation, interference and diffraction of light

MAX BORN
MA, Dr Phil, FRS
Nobel Laureate
Formerly Professor at the Universities of Göttingen and Edinburgh

and

EMIL WOLF
PhD, DSc
Wilson Professor of Optical Physics, University of Rochester, NY



Section "Perfect imaging"

THE SCIENTIFIC PAPERS OF

JAMES CLERK MAXWELL

MATHEMATICAL THEORY OF OPTICS

by

R. K. LUNEBURG

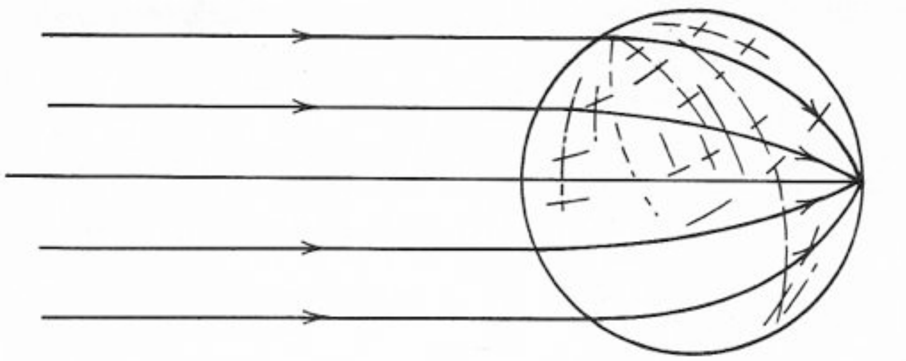
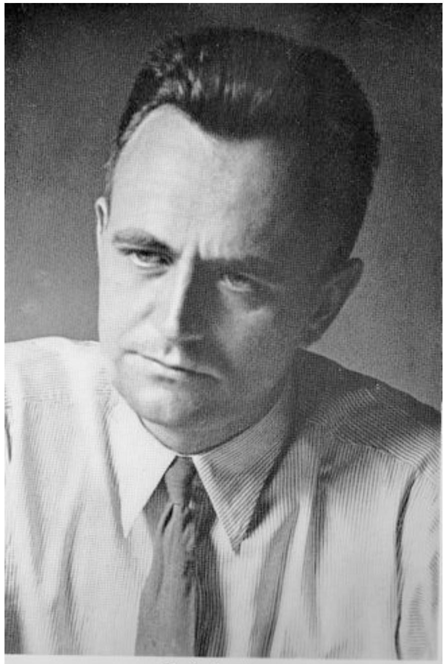
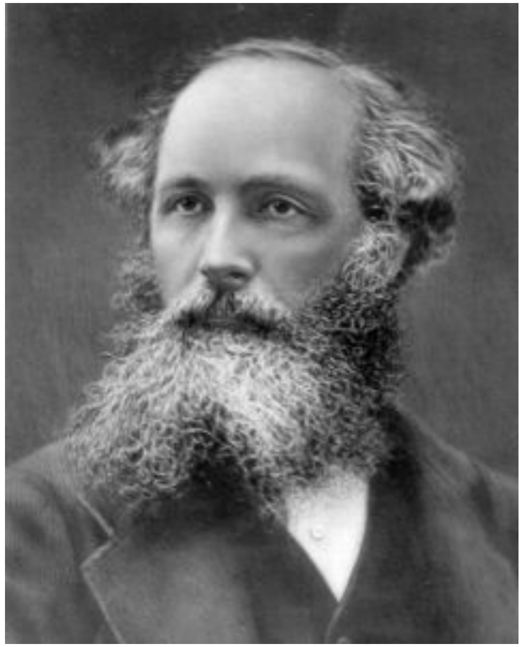


Figure 114



R. K. Luneburg



Conformal maps

Coſmographia, ſiue Deſcriptio vniuerſi Orbis, Petri Apiani & Gemmæ Friſij, Mathematicorum inſignium, iam demùm integritati ſuæ reſtituta.

Adiecti ſunt alij, tum Gemmæ Friſij, tum aliorum Auctorum eius argumenti Tractatus ac Libelli varij, quorum ſeriem verſa pagina demonſtrat.

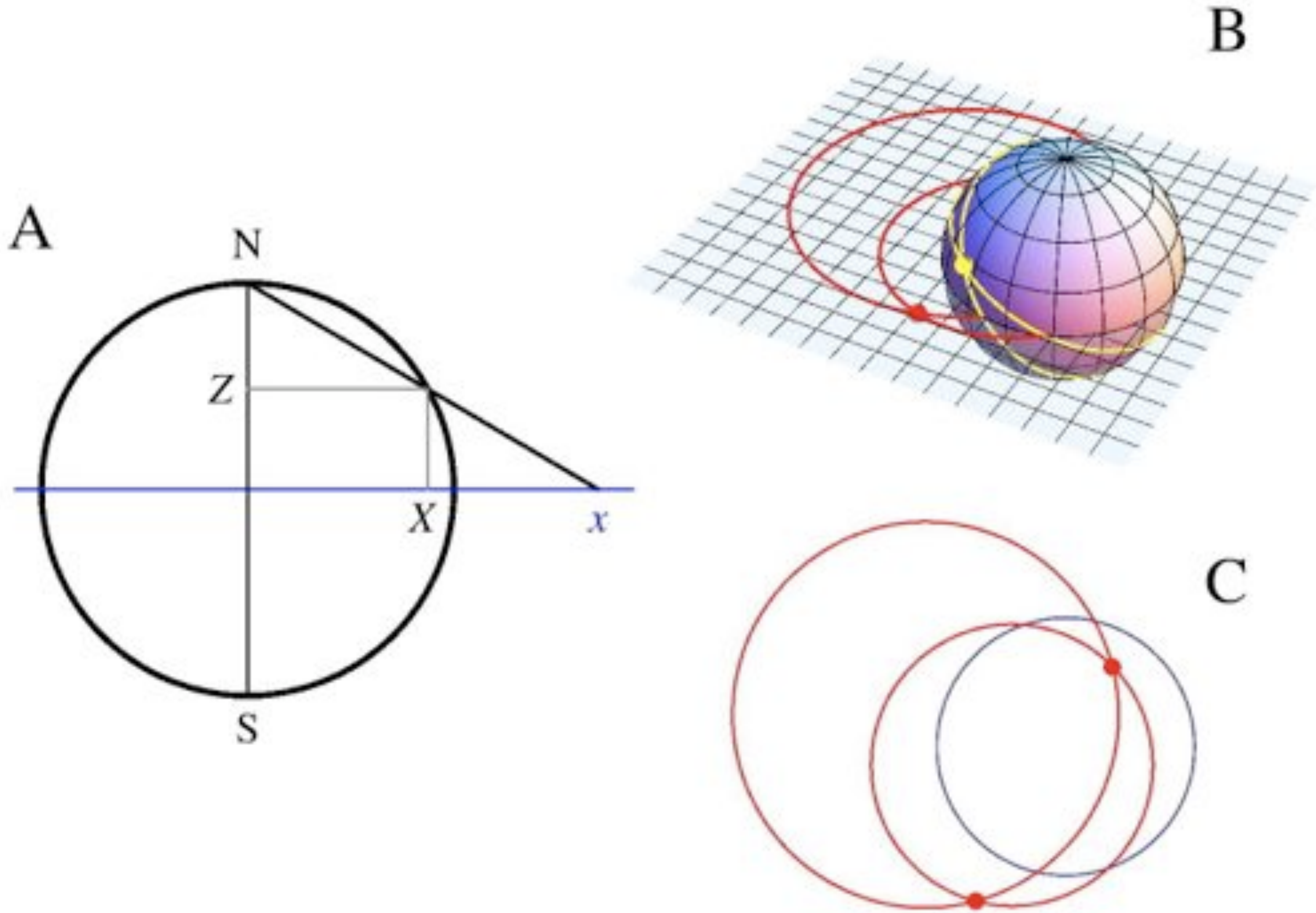
Anno 1584.

Antuerpiæ, ex Officina Ioannis VVithagij.

Maxwell's fish eye makes a perfect lens

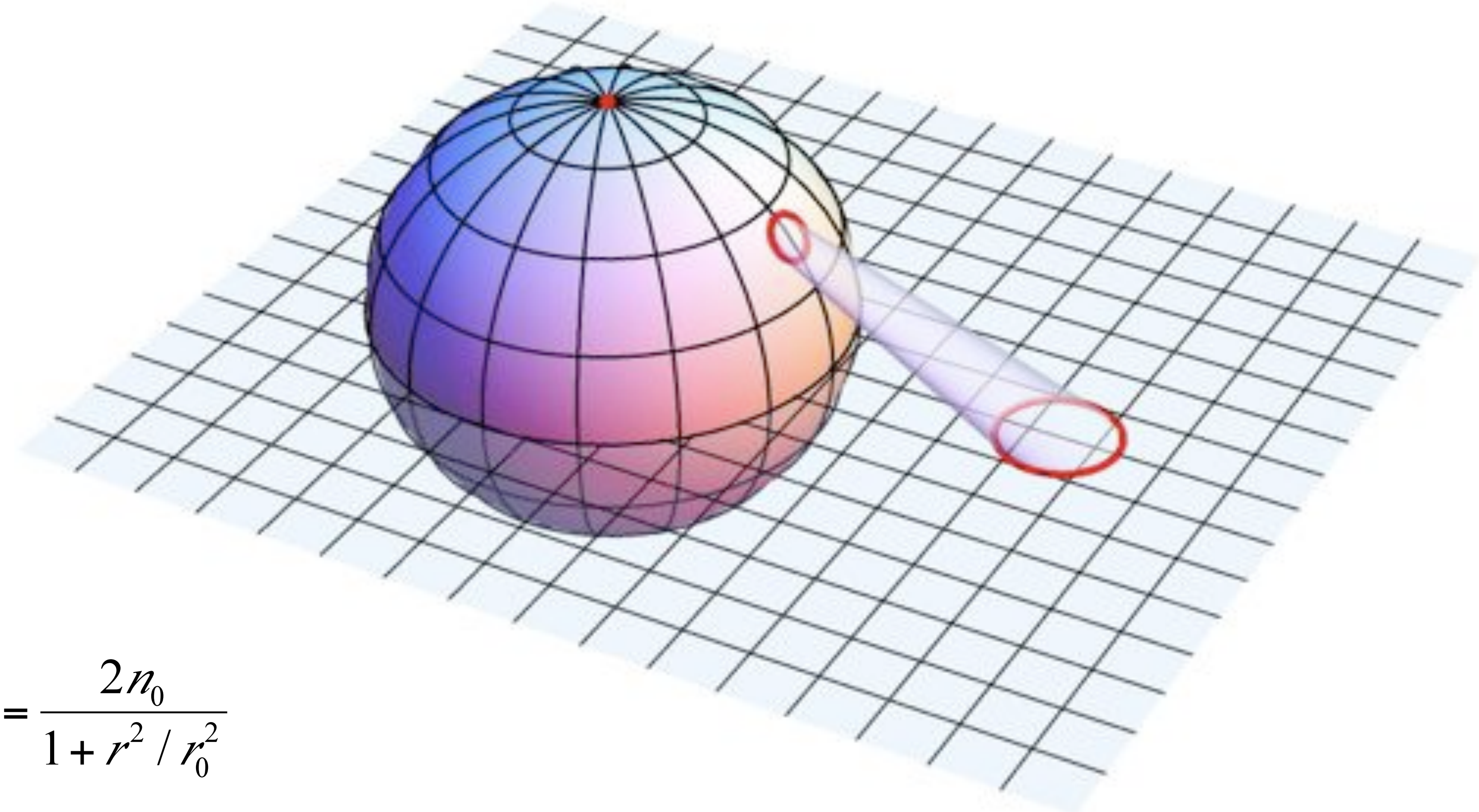
Maxwell 1854

Luneburg 1944: Stereographic projection



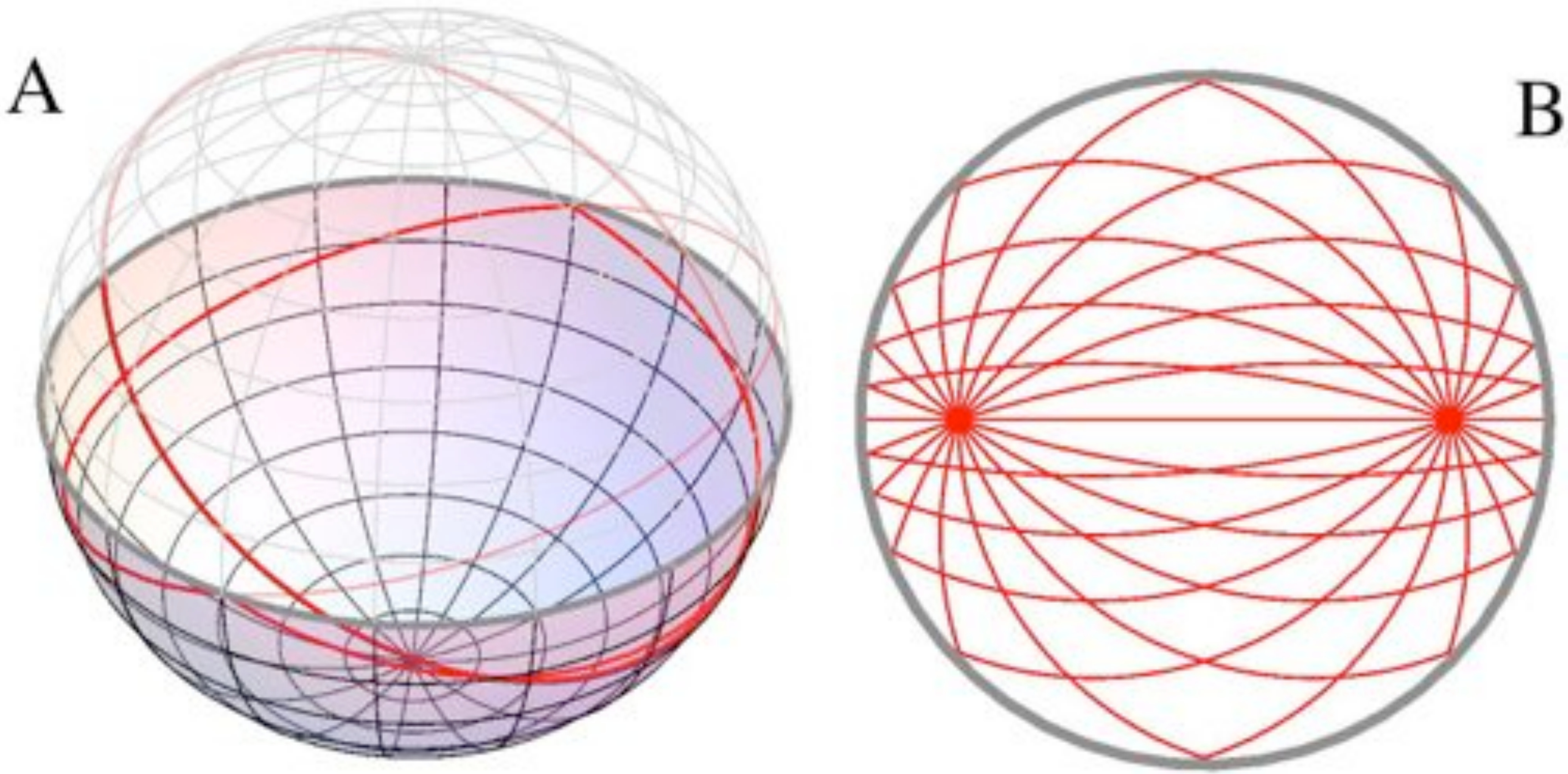
Refractive index

n = virtual length/ real length



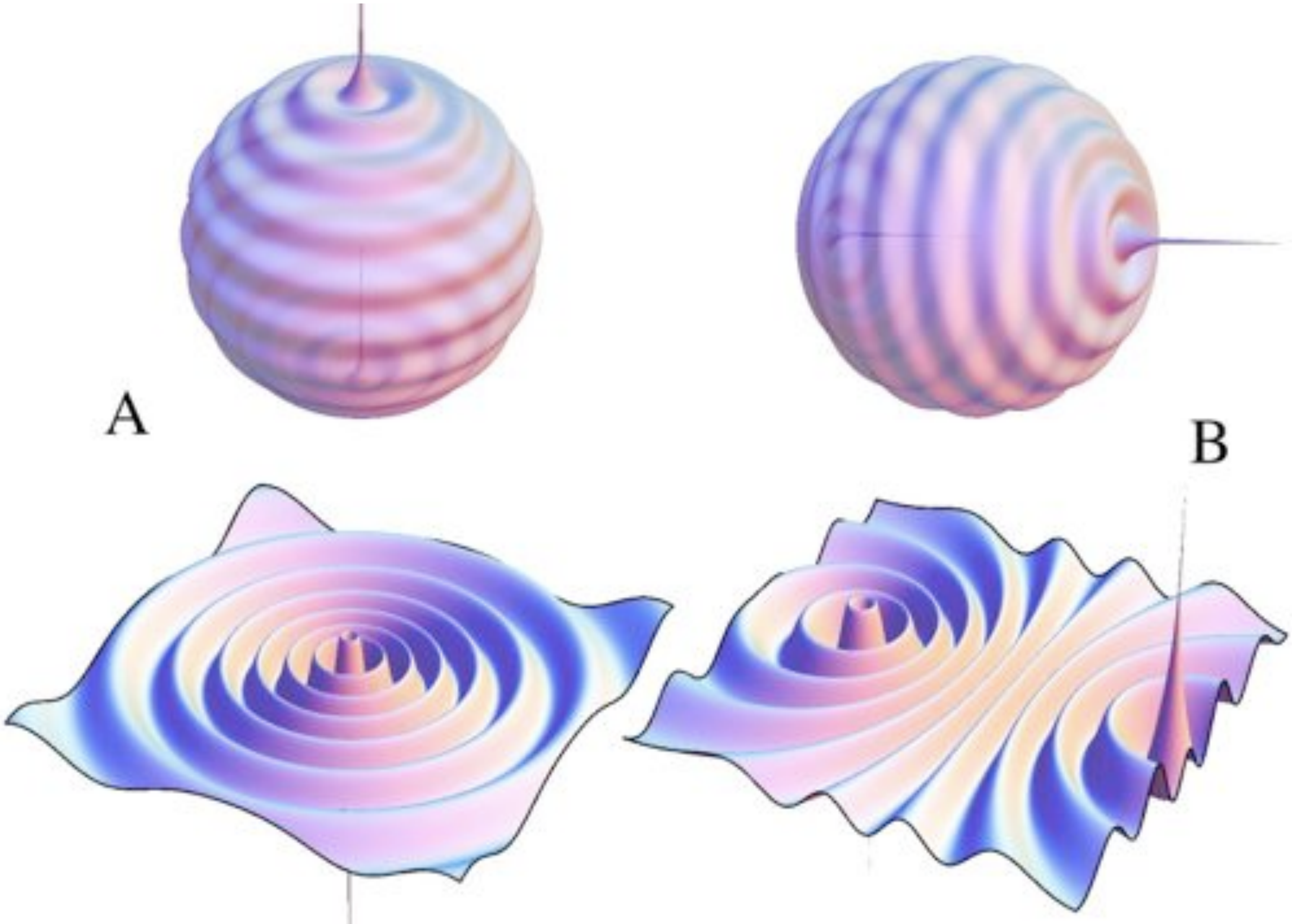
$$n = \frac{2n_0}{1 + r^2 / r_0^2}$$

Fish-eye mirror



[Leonhardt, New J. Phys. **11**, 093040 (2009)]

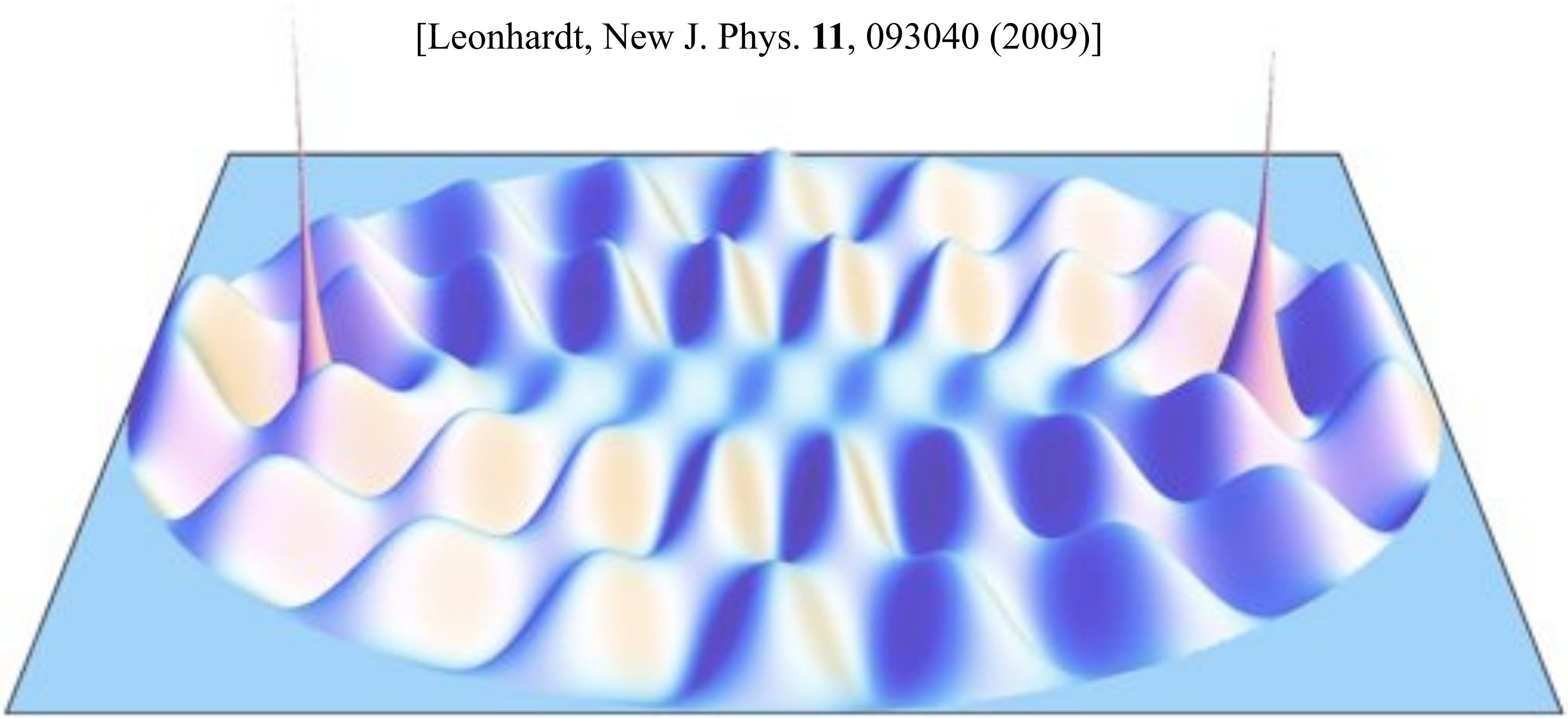
What about waves?



[Leonhardt, New J. Phys. **11**, 093040 (2009)]

Perfect imaging without negative refraction

[Leonhardt, New J. Phys. **11**, 093040 (2009)]



$$n = \frac{2n_0}{1 + r^2 / r_0^2}$$

Index contrast: factor of 2

Controversy

NEWS & VIEWS Nature **480**, 42-43 (1 December 2011)

FORUM OPTICS

Perfect lenses in focus

Materials that refract light backwards are thought to be required for making super-resolution lenses. An alternative proposal — that conventional, positively refracting media can do the job — has met with controversy. Two experts from either side of the debate lay out their views on the matter.

Positive thinking

TOMÁŠ TYC

In 2000, Pendry showed[1] that a slab of material that bends light at a negative angle can work as a lens with the ability to resolve details much smaller than the wavelength of light. This is due to the fact that, unlike conventional lenses, which refract light at a positive angle (Fig. 1), this device transfers not only the propagating (long-range) waves of light from an object to its image, but also the object's evanescent waves — short-range light that carries smallest-scale information about the object. However, such

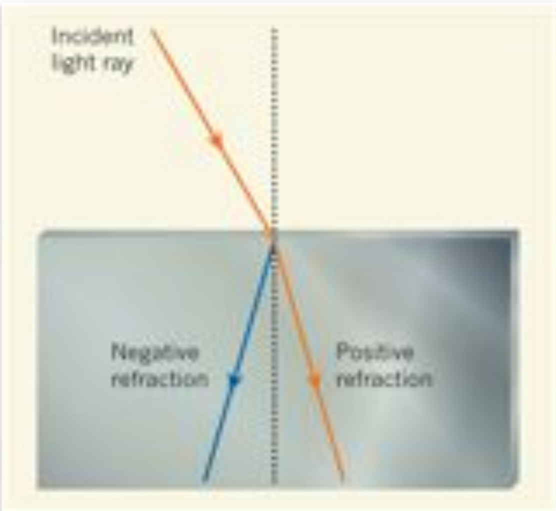


Figure 1 | Positive versus negative refraction.

No drain, no gain

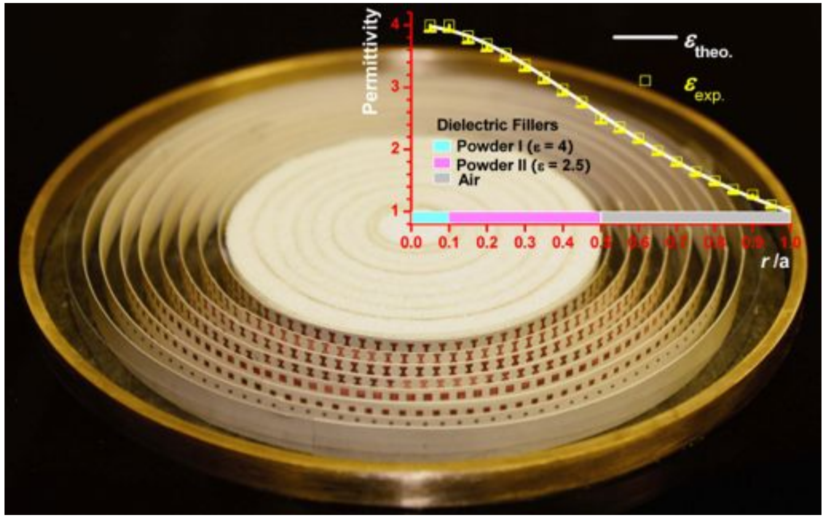
XIANG ZHANG

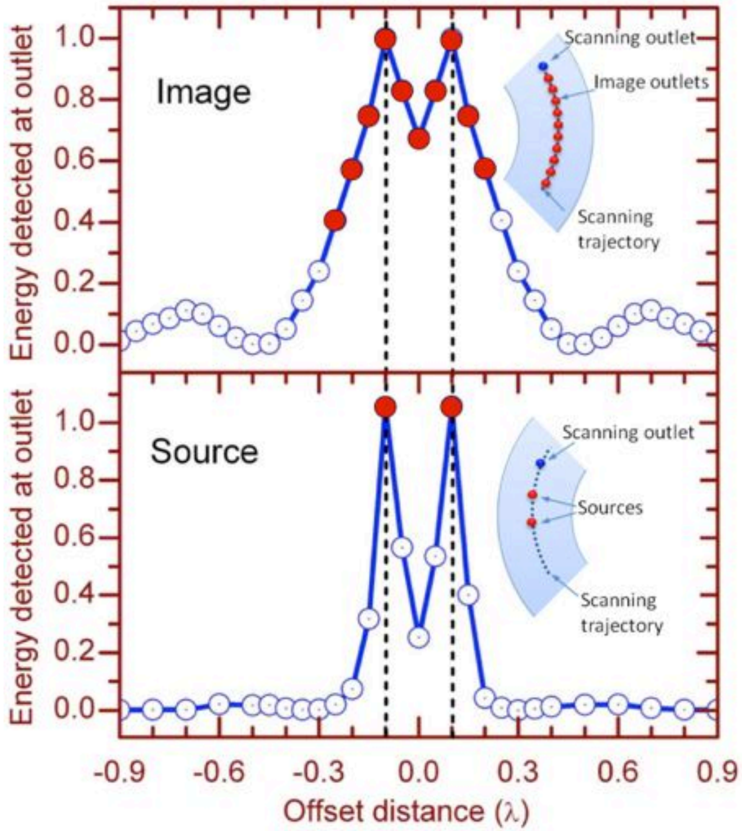
I take issue with Leonhardt and colleagues' claim[2,3] that Maxwell's fish eye is a perfect lens. Maxwell's fish eye, proposed[4] more than 150 years ago, is subject to a diffraction limit: it cannot resolve any feature smaller than a fraction of the wavelength of the light being used.

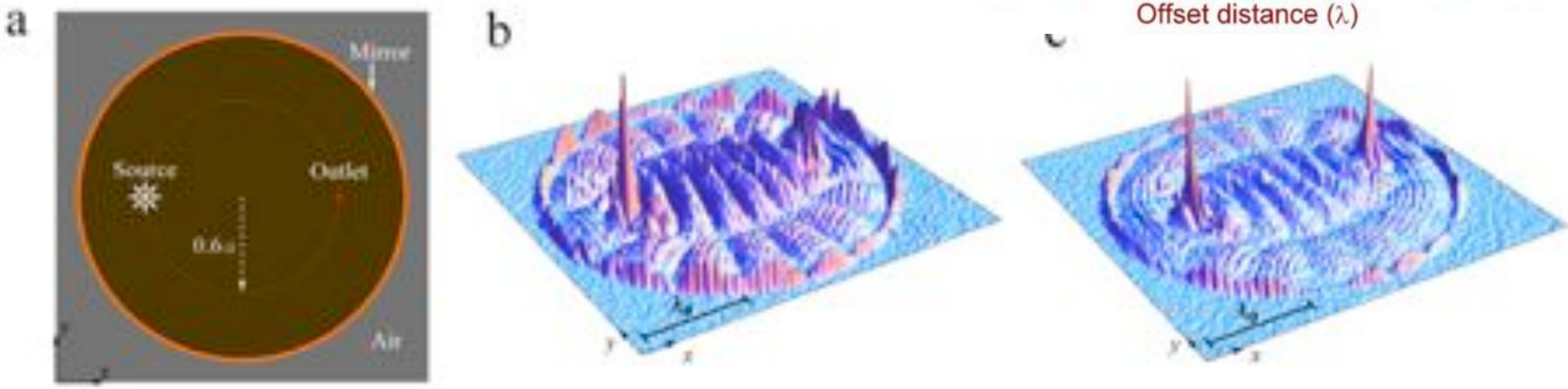
Over the past decade, negative-index metamaterials, which are made of artificially structured composites, have been used as a means to overcome the diffraction limit and

Perfect imaging with positive refraction for microwaves

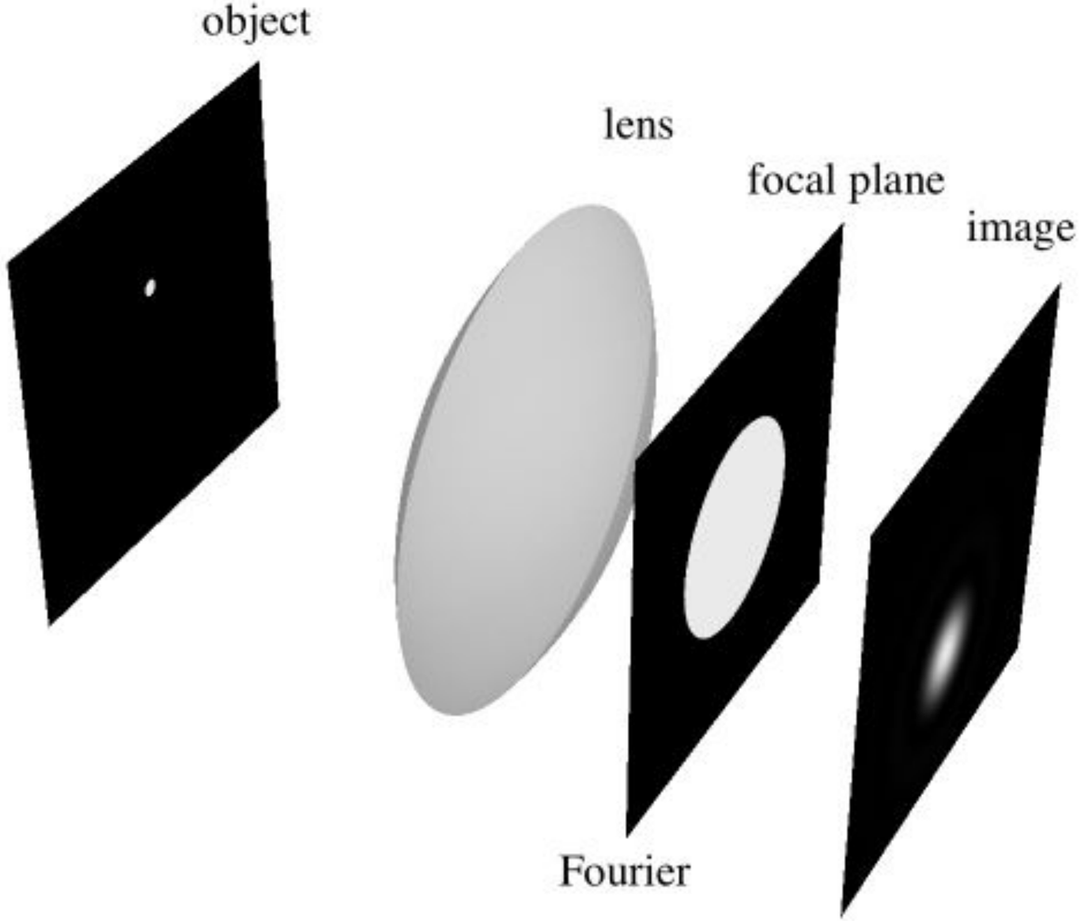
[Ma, Sahebdivan, Ong, Tyc, Leonhardt,
NJP **13**, 033016 (2011)]







Standard diffraction limit of imaging



$$(\nabla^2 + k^2)\, u = 0$$

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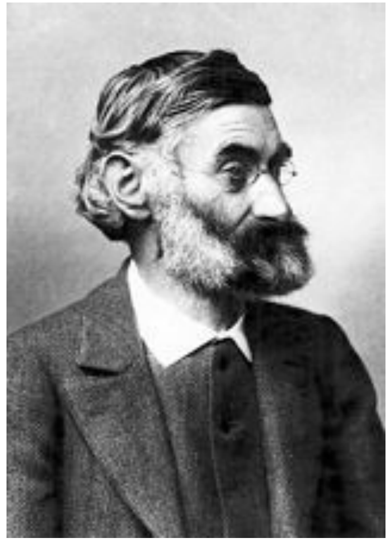
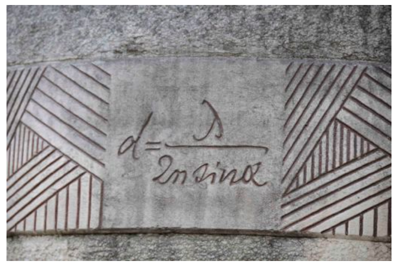
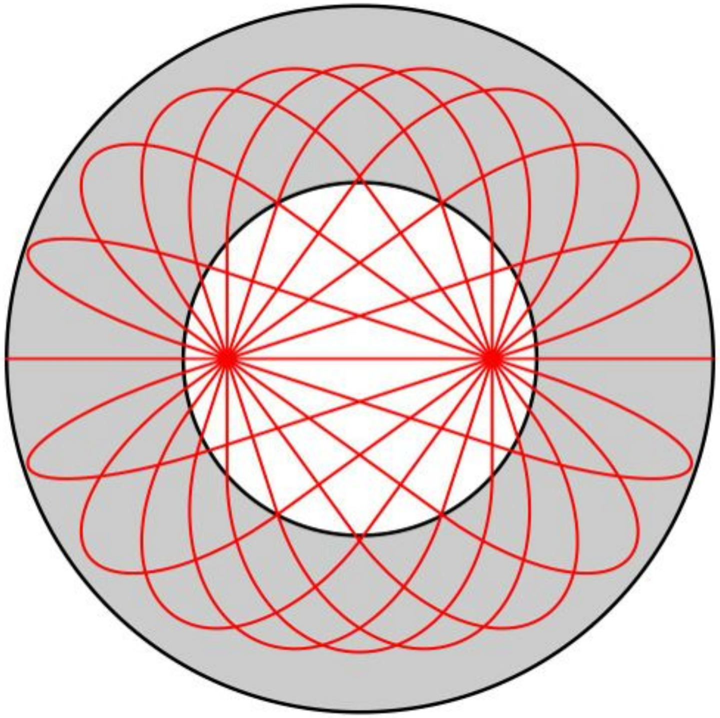




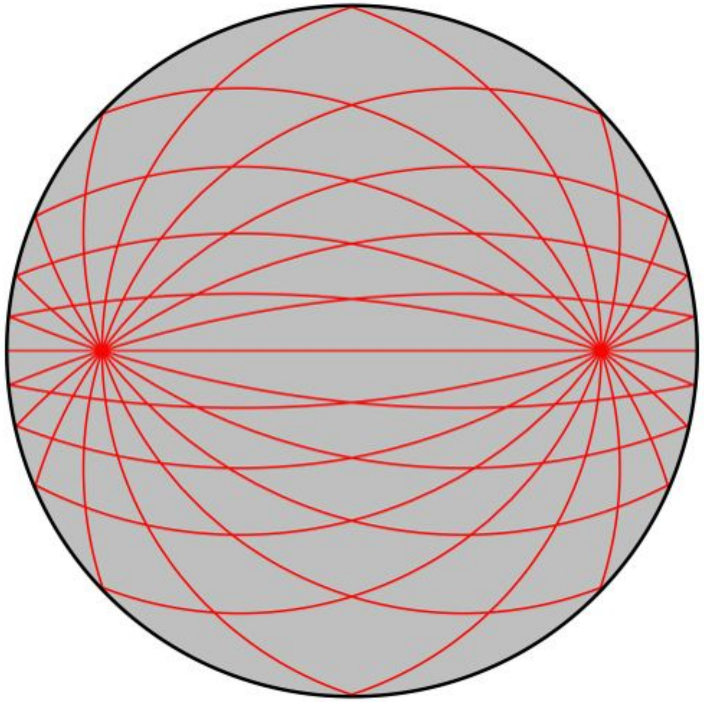
Evanescent waves

Perfect imaging with positive refraction



Inside-out Eaton lens

[Miñano, Opt. Express 14, 9627 (2006)]



Maxwell's fish eye
with mirror

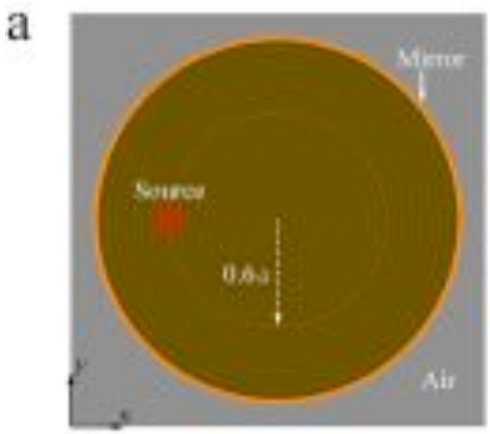
Perfect focus: near field

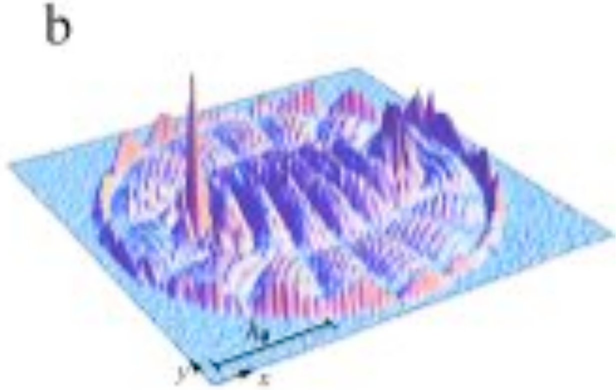
$n \sim \ln r$

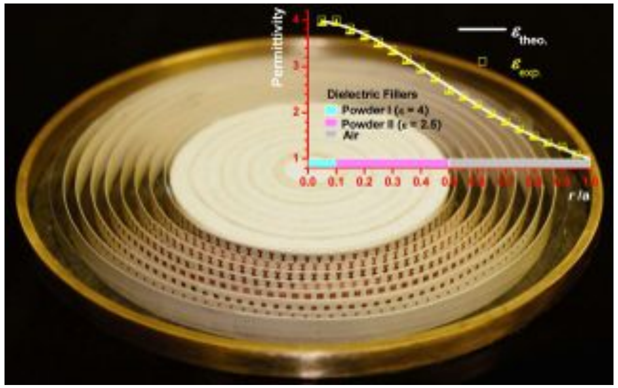
Near field is not evanescent

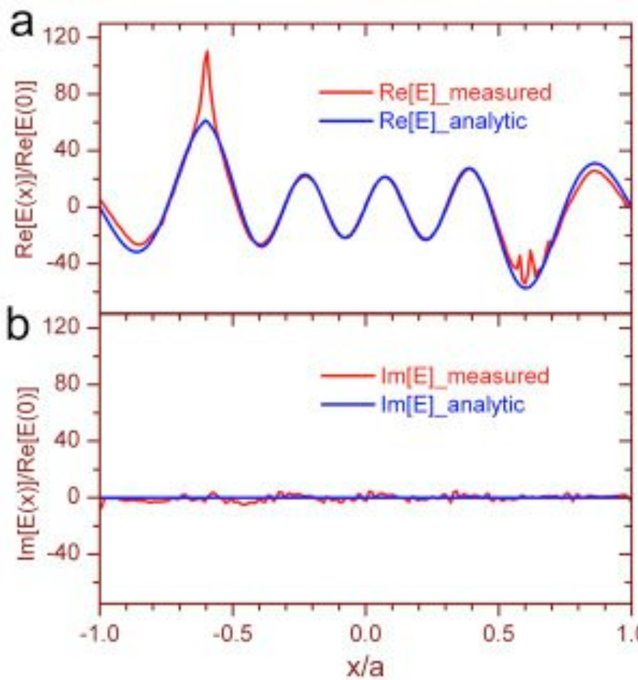
No outlet, no running wave, no perfect image

[NJP **13**, 033016 (2011)]

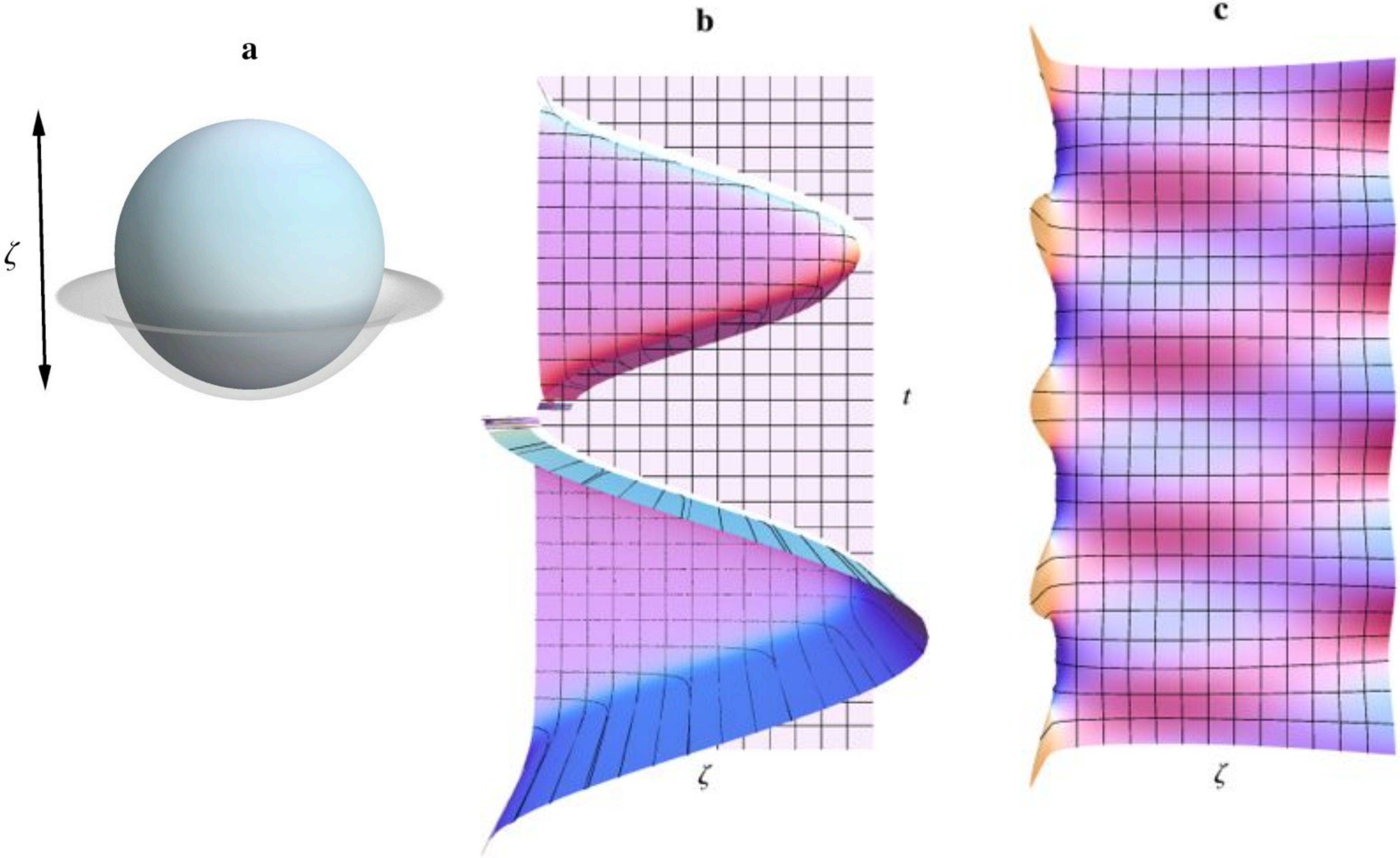








Light waves on virtual sphere



VOLUME 89, NUMBER 12 PHYSICAL REVIEW LETTERS 16 SEPTEMBER 2002

Overcoming the Diffraction Limit in Wave Physics Using a Time-Reversal Mirror and a Novel Acoustic Sink

J. de Rosny* and M. Fink
Laboratoire Ondes et Acoustique, ESPCI, Université Paris VII, U.M.R. 7587 C.N.R.S., 10 rue Vauquelin, 75005 Paris, France
(Received 26 October 2001; published 30 August 2002; publisher error corrected 31 October 2002)

Lessons from acoustics

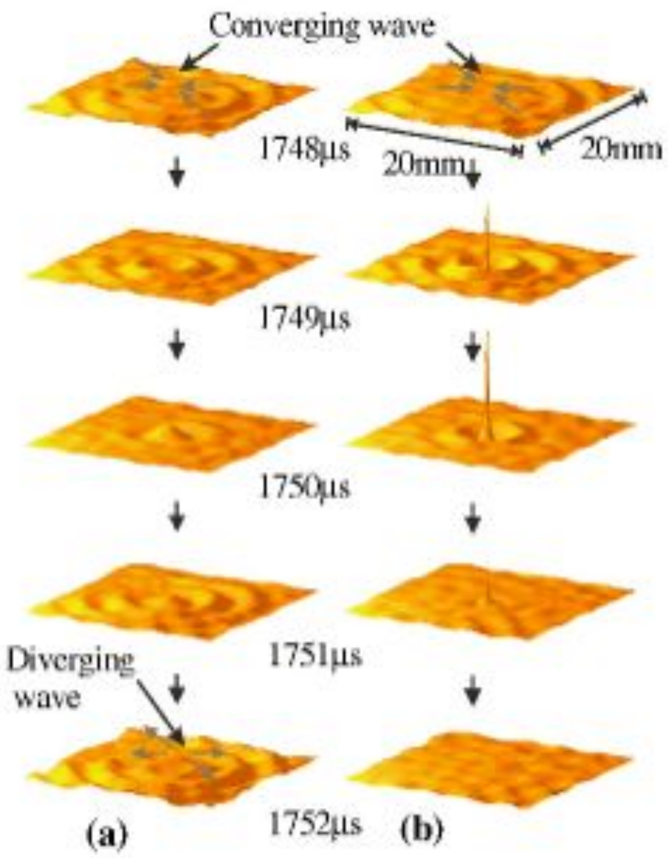


FIG. 3 (color). Time evolution recorded by the interferometer over a 20 mm by 20 mm square around the initial source during time-reversal propagation (1 ms separates each snapshot): (a) without the TR source, (b) with the TR source. On sequence (b), an acoustic sink is obtained.

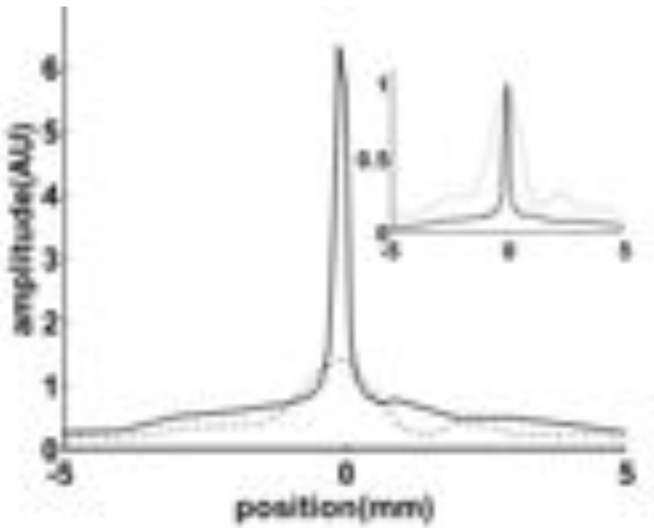
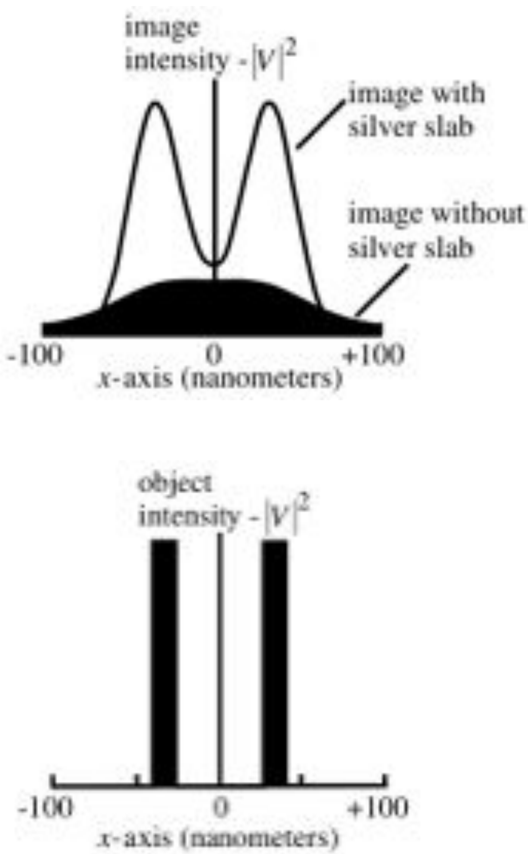
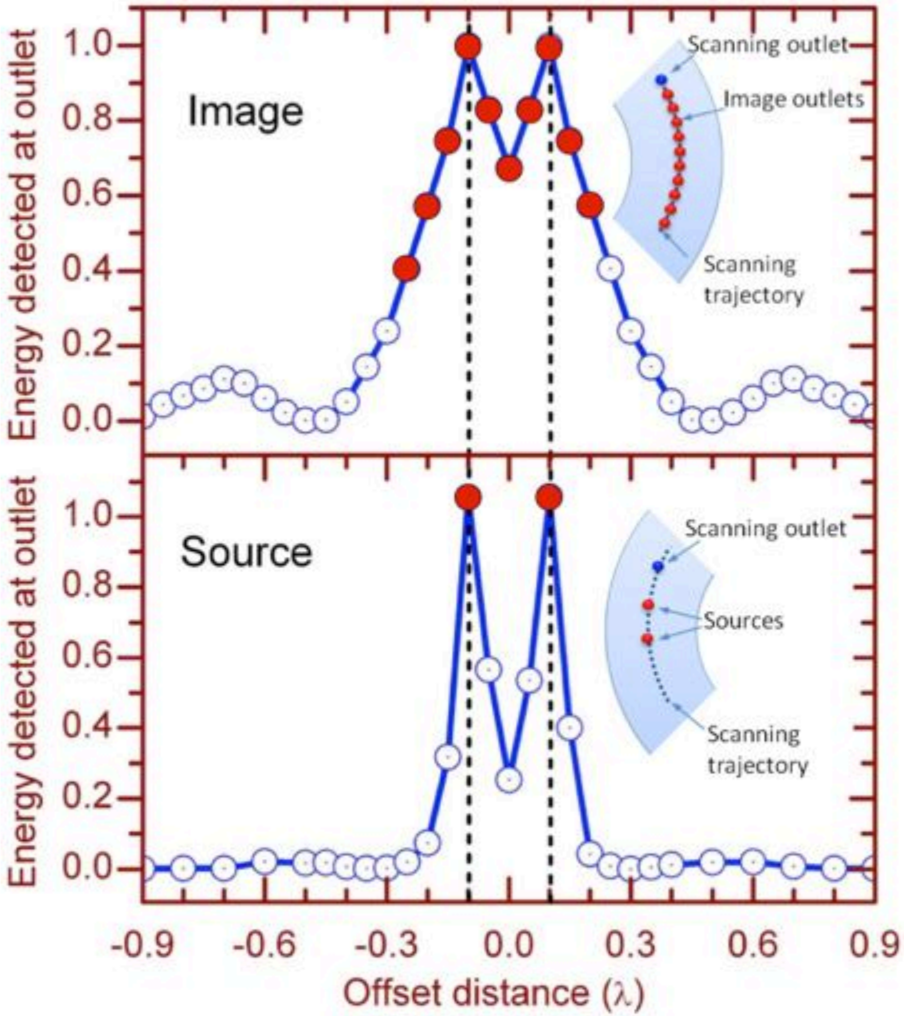


FIG. 4. Focal spot sections without the TR source (dashed line), with TR source (continuous line). Inside the graphic box, the focal spots normalized with respect to their maximums are plotted.

Evidence for subwavelength imaging with positive refraction

[Ma, Sahebdivan, Ong, Tyc, Leonhardt, NJP **13**, 033016 (2011)]

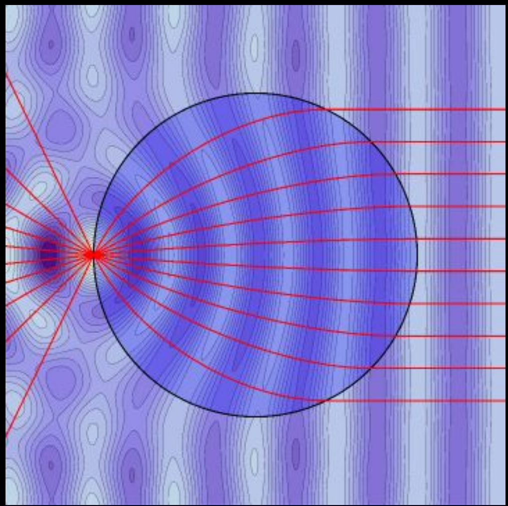


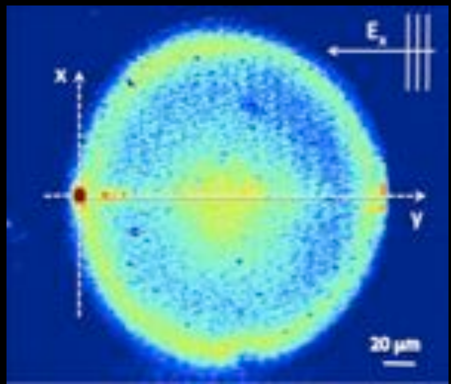


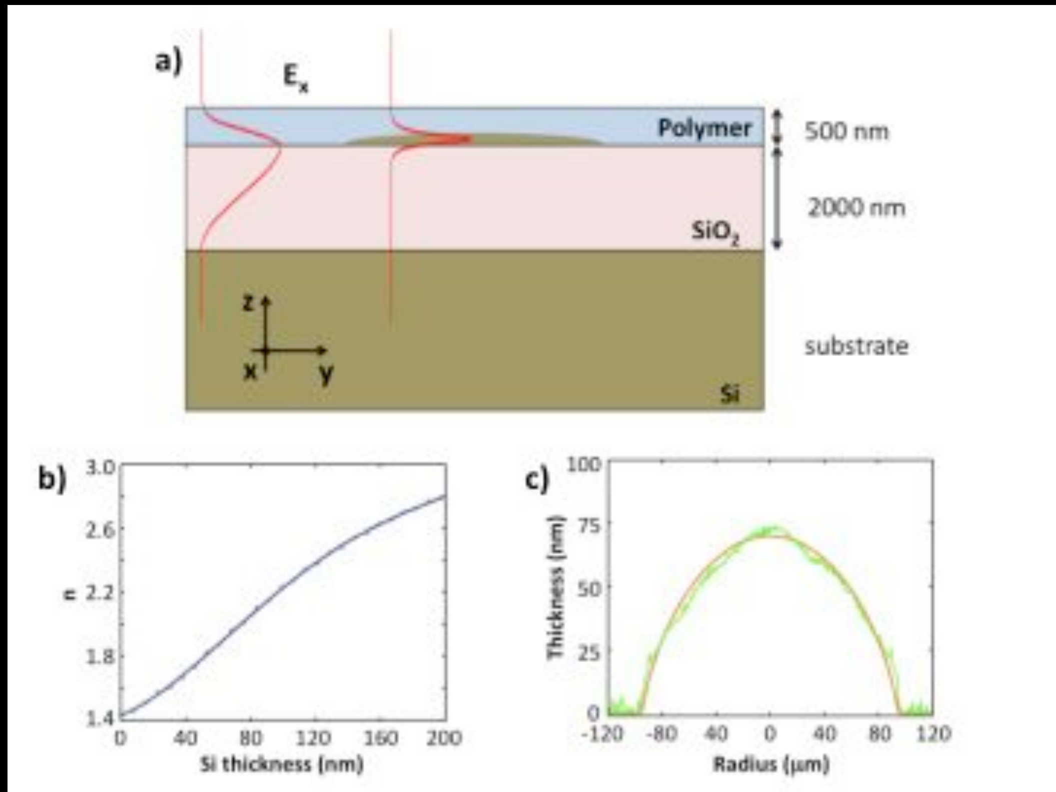
[Pendry, PRL **85**, 3966 (2000)]

Luneburg lens in silicon photonics

Greyscale lithography for making tapered waveguides

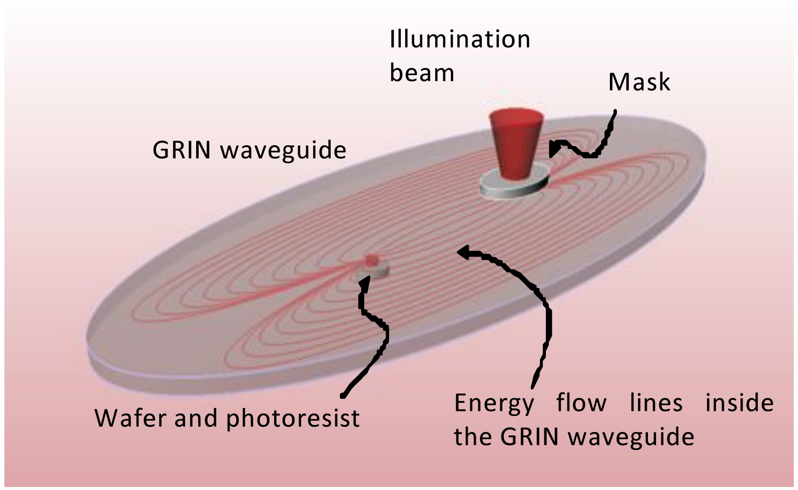


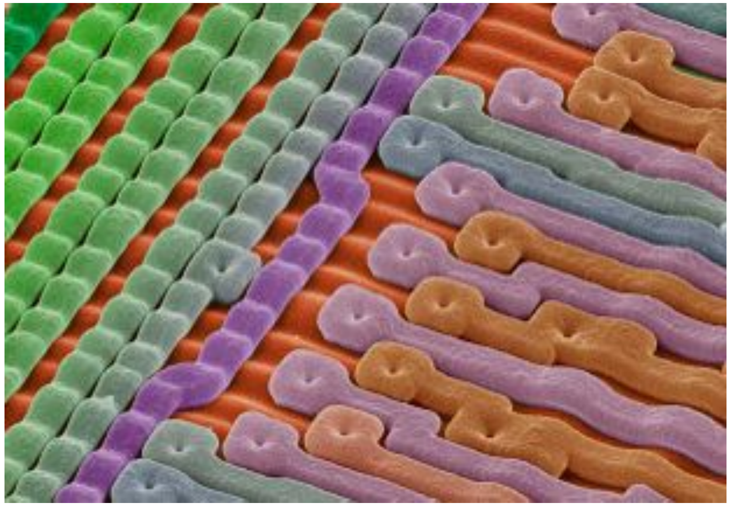




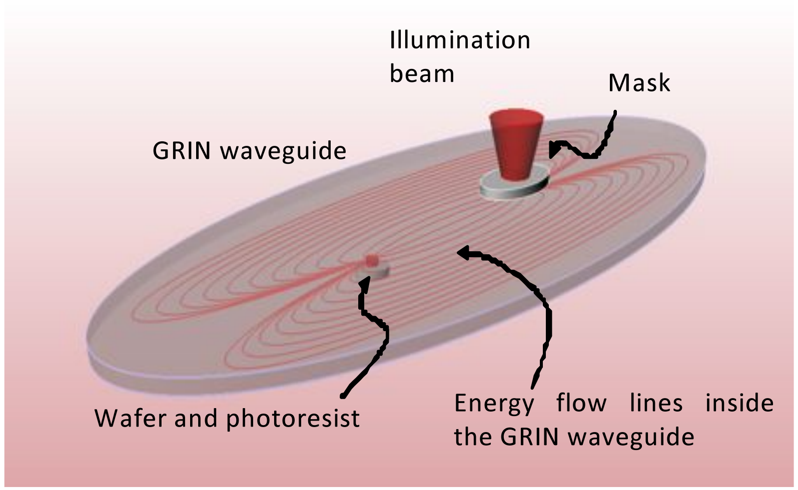
[Di Falco, Kehr, Leonhardt, Optics Express 19, 5156 (2011)]

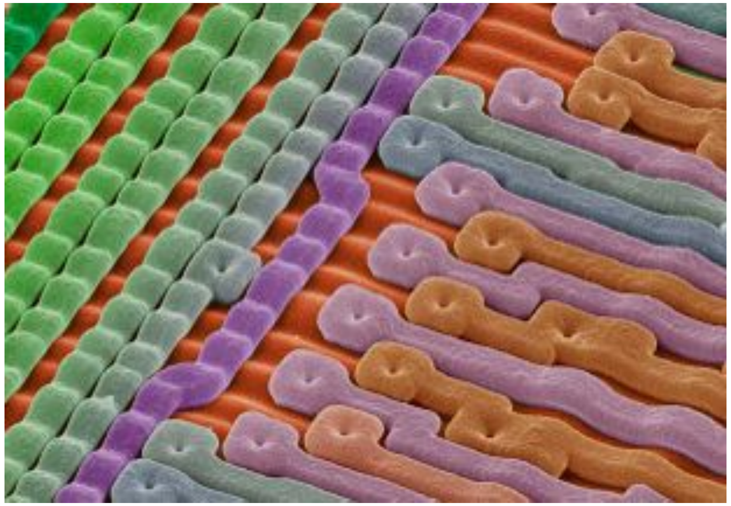
Applications





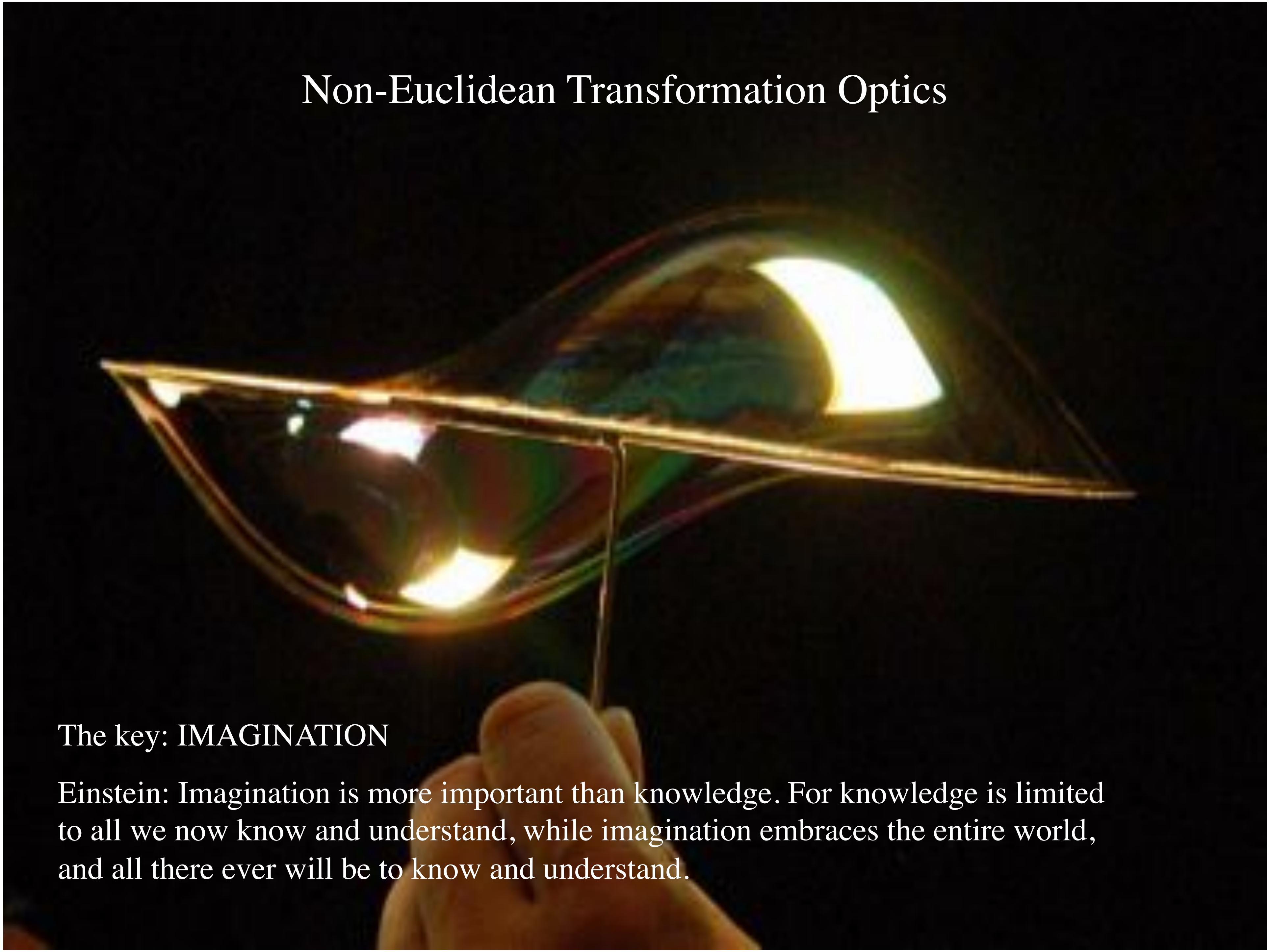
Applications





Mythbuster

* Amplification of evanescent waves needed
* Near field = evanescent field
* Near-field information is lost in propagation
* Detectors do not change images
* Field concentrations are artefacts


Non-Euclidean Transformation Optics
The key: IMAGINATION
Einstein: Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand.


Happy birthday!