Perfect imaging with positive refraction

Ulf Leonhardt
University of St Andrews, UK
Transformation optics

To invisibility and beyond

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

Negative Refraction Makes a Perfect Lens

J. B. Pendry

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(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
Photolithography
Microscopy
Standard diffraction limit of imaging

Evanescent waves

\[
(\nabla^2 + k^2) \psi = 0 \\
(\nabla^2 + k_x^2 - k_y^2 + k^2) \tilde{\psi} = 0 \\
\tilde{\psi}(z) = \tilde{\psi}(z_0) \exp(i \sqrt{k^2 - k_x^2 - k_y^2} (z - z_0))
\]
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New Journal of Physics

General relativity in electrical engineering

Ulf Leonhardt and Thomas G Philbin
Negative refraction and perfect lens

\[ \epsilon = \mu = \mp \frac{\sqrt{-g}}{g_{00}} \, g^{ij} \]

\[ \epsilon = \mu = 1 \quad \epsilon = \mu = 1 \]

Xiang Zhang et al.  
@ Berkeley

Controversy on perfect imaging with negative refraction
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 optoelectronic 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).
Section “Perfect imaging”
THE SCIENTIFIC PAPERS OF
JAMES CLERK MAXWELL

MATHEMATICAL
THEORY OF OPTICS

by
R. K. LUNEBURG

Figure 114
Conformal maps

Cosmographia, sive Descriptio

Adedit 40 foliorum. Gemma Fassin, nummerum Automanicius argumenti Tadatesae Libellis variis, quarum multis veris paginae demonstratur.
Maxwell’s fish eye makes a perfect lens
Maxwell 1854
Luneburg 1944: Stereographic projection
Refractive index

\[ n = \text{virtual length/ real length} \]

\[ n = \frac{2n_0}{1 + \frac{r^2}{r_0^2}} \]
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)]

\[ n = \frac{2n_0}{1 + \frac{r^2}{r_0^2}} \]  

Index contrast: factor of 2
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 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

No drain, no gain

Xiang Zhang

I take issue with Leonhardt and colleagues' claim that Maxwell's fish eye is a perfect lens. Maxwell's fish eye, proposed 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

\[(\nabla^2 + k^2) u = 0\]
\[
\left( \nabla_z^2 - k_x^2 - k_y^2 + k^2 \right) \tilde{u} = 0
\]
\[
\tilde{u}(z) = \tilde{u}(z_0) \exp \left( i \sqrt{k^2 - k_x^2 - k_y^2} (z - z_0) \right)
\]

Evanescent waves
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
Near field is not evanescent
No outlet, no running wave, no perfect image

[Ref: NJP 13, 033016 (2011)]
Light waves on virtual sphere
Lessons from acoustics
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

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!