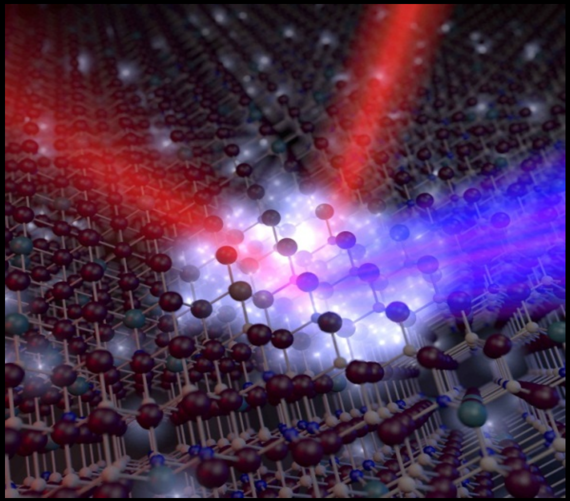
METAMATERIALS:
TECHNOLOGY OF THE FUTURE



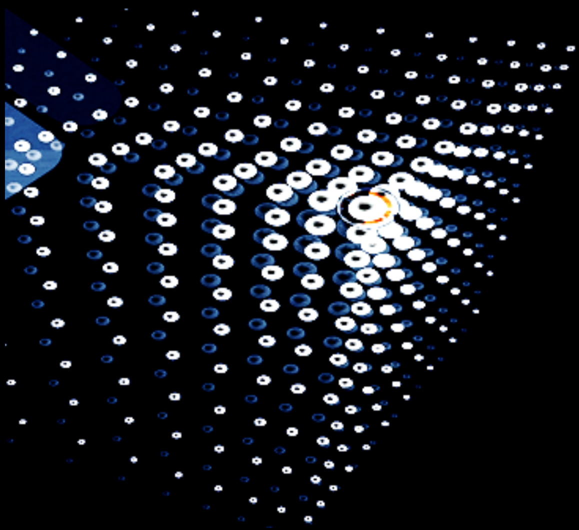
"To move, to breathe, to fly, to float,
To gain all while you give,
To roam the roads of lands remote,
To travel is to live."

— Hans Christian Andersen, The Fairy Tale of My Life: An Autobiography

OUTLINE

Brief intro to metamaterials

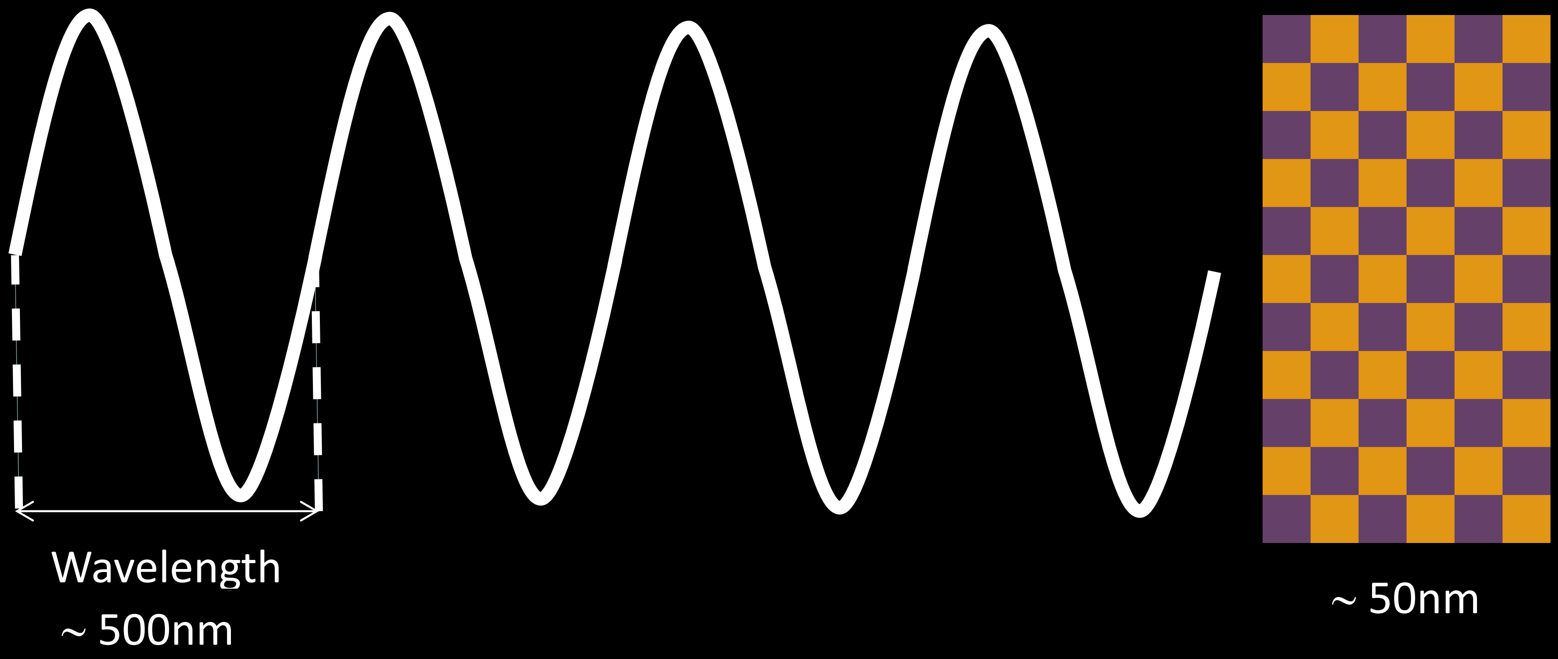
- Electrical metamaterials (plasmonics) for nanophotonics
- Magnetic metamaterials and negative refractive index
- Seeing a DNA in Optical Microscope?
- Cloaking: SciFi or reality?
- 2D metamaterials: Metasurfaces



METAMATERIALS

Is it possible to engineer materials with NEW OPTICAL PROPERTIES?

- **YES!**
- Wonderful things happen when structural dimensions are much less than λ light!
- Road to **NEW OPTICS and NEW TECHNOLOGIES**



ELECTROMAGNETIC PROPERTIES V.S. SIZES

0 1 ∞

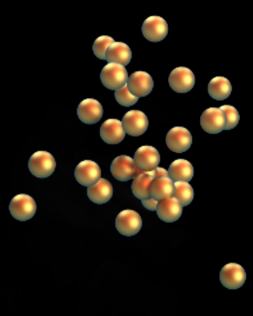
SIZE/WAVELENGTH

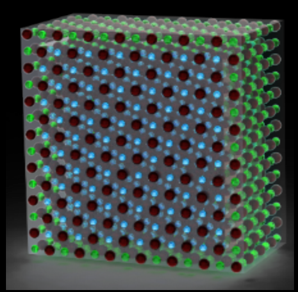
size << λ

Crystals

PLASMONICS

METAMATERIALS



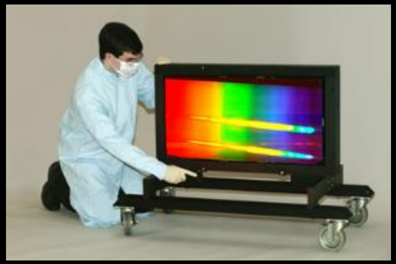


size ~ λ

Diffraction

Interference

Gratings

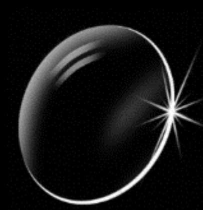


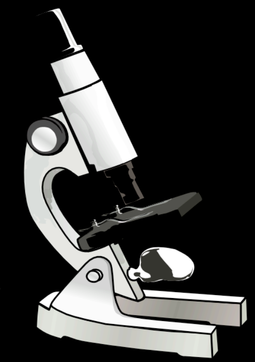
size >> λ

Geometrical Optics

Lenses

Shadows





Scientists have gone from BIG LENSES, to OPTICAL FIBERS, to ULTRA-SMALL/THIN DEVICES with unique functionalities using METAMATERIALS

WHY WE NEED METAMATERIALS?

$$n^2 = \varepsilon\mu$$

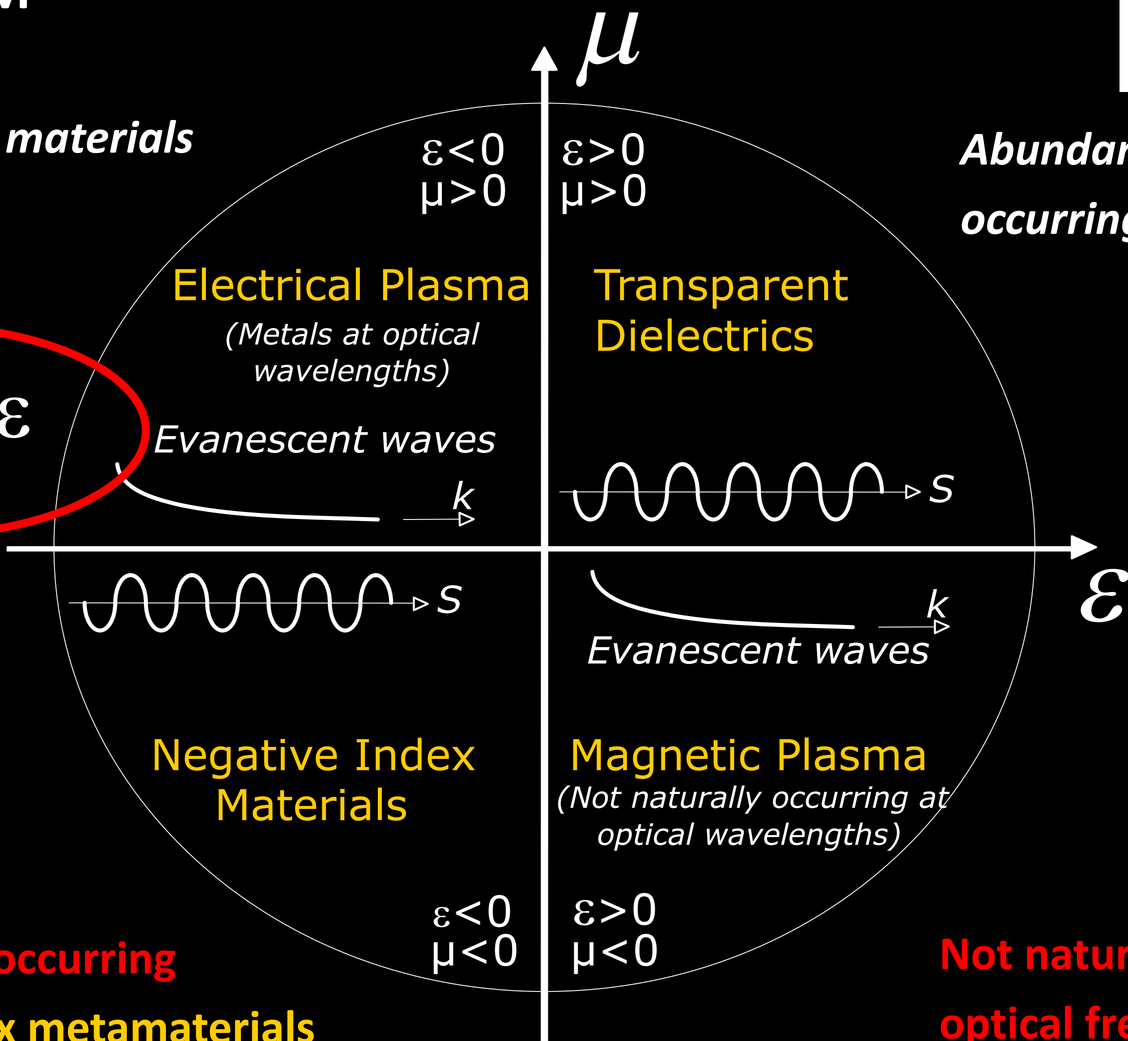
$$n = \pm\sqrt{\varepsilon\mu}$$

ε, μ DIAGRAM

Limited natural materials like METALS

Abundant naturally-occurring materials

Negative ε



$\varepsilon \leq 0$

$\mu \leq 0$

Not naturally occurring

Negative-index metamaterials

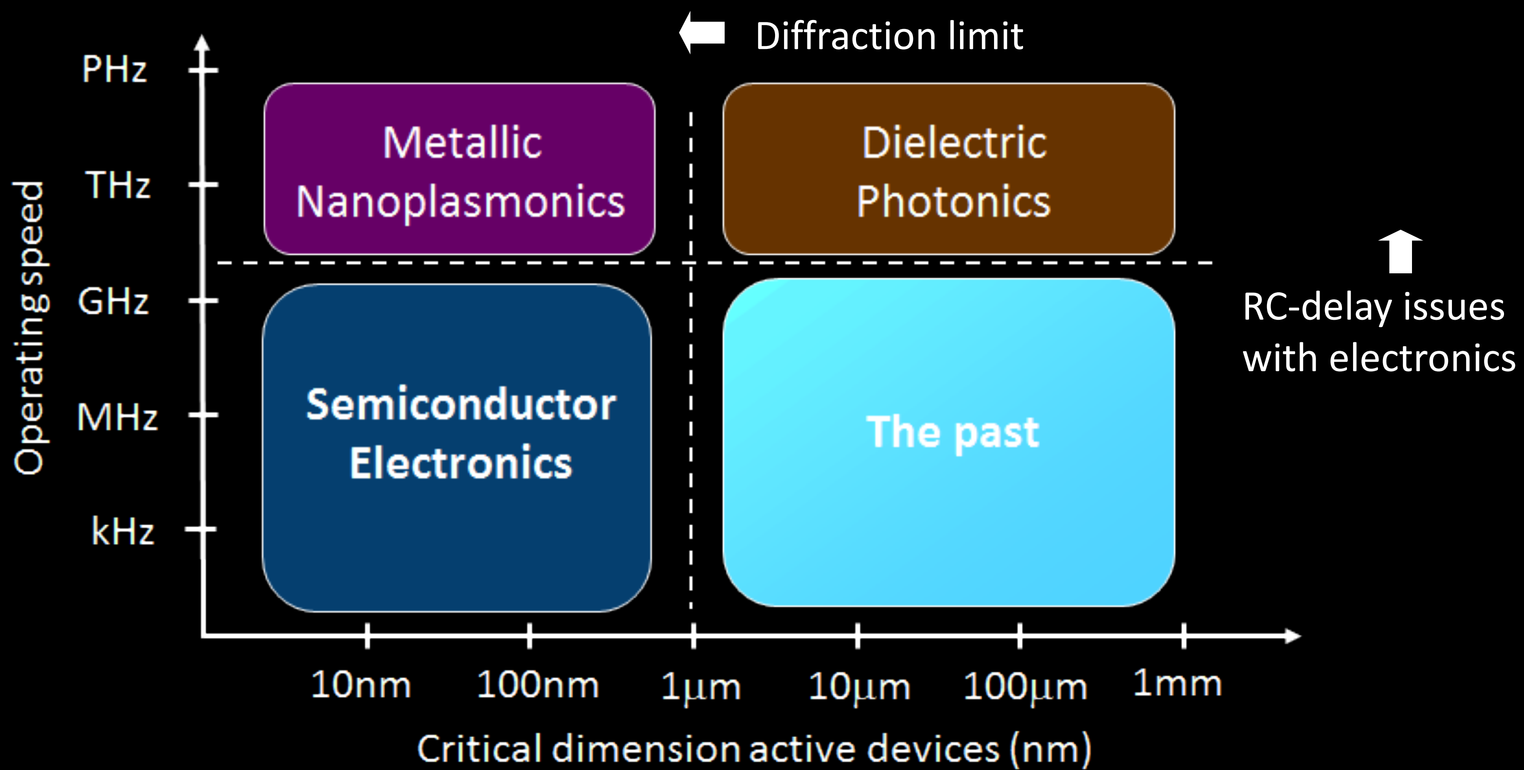
Not naturally occurring at optical frequencies

Magnetic metamaterials

Electrical Metamaterials (Plasmonics): a Route to Nanophotonics

WHY ELECTRICAL METAMATERIALS?

Operating regimes of different technologies

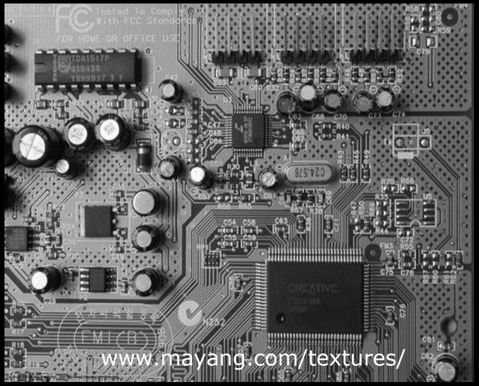


- Improved synergy between electronic and photonic devices
- Solution to the size-compatibility problem
  - Plasmonics naturally interfaces with *similar size electronic components*
  - Plasmonics naturally interfaces with *similar operating speed photonic networks*

M. Brongersma, V. Shalaev, Science (2010)

ELECTRONIC-PHOTONIC INTEGRATION

HOW TO INTEGRATE ELECTRONICS AND OPTICS?
SIZE MISMATCH…



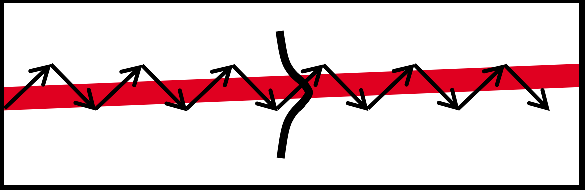
Electronic circuit

\+ Very compact (<~ 10nm)
\- Operational speed is limited (RC-delay)

Photonic circuit

\+ High speed
\+ High bandwidth
\- Component size is limited (>~ 1 μm)

Diffraction limit

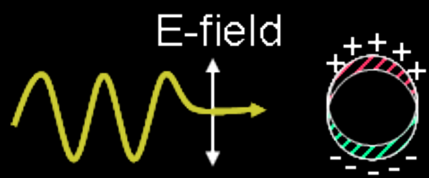


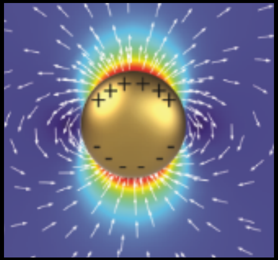
Optical mode in waveguide > $\lambda_0/2n_{CORE}$

SOLUTION: Optics on the Nanoscale
PLASMONICS/ELECTRICAL METAMATERIALS

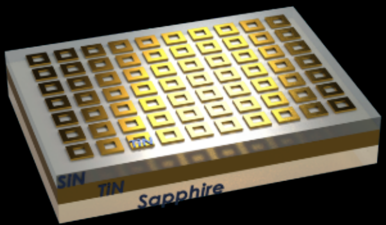
PLASMONICS/(ELECTRICAL)METAMATERIALS

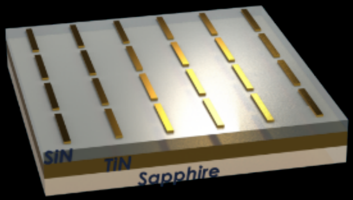
1 Localized SP = Optical Nano-Antenna (imaging, sensing, therapy, energy…)

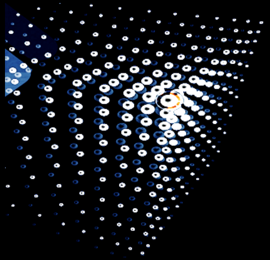




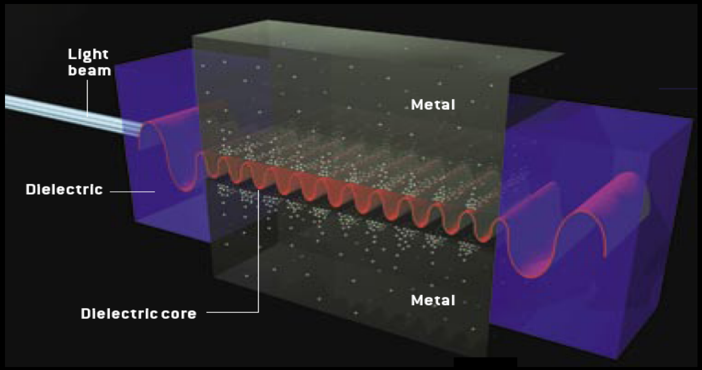
= Optical Metasurfaces (ultra-thin/flat optics, sensors…)



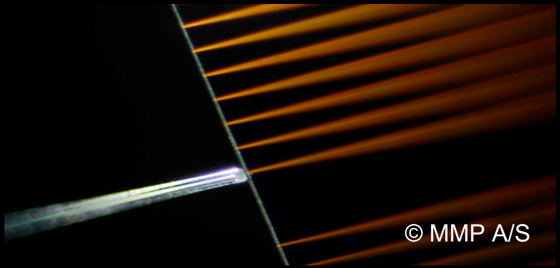


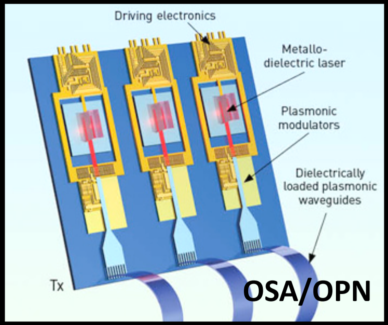


2 Propagating SP = Nano-Waveguide (integrated photonics, lab-on-a-chip…)



H. Atwater, Scientific American, April 2007





Optical
Negative-Index Metamaterials

WHY WE NEED METAMATERIALS?

ε, μ DIAGRAM

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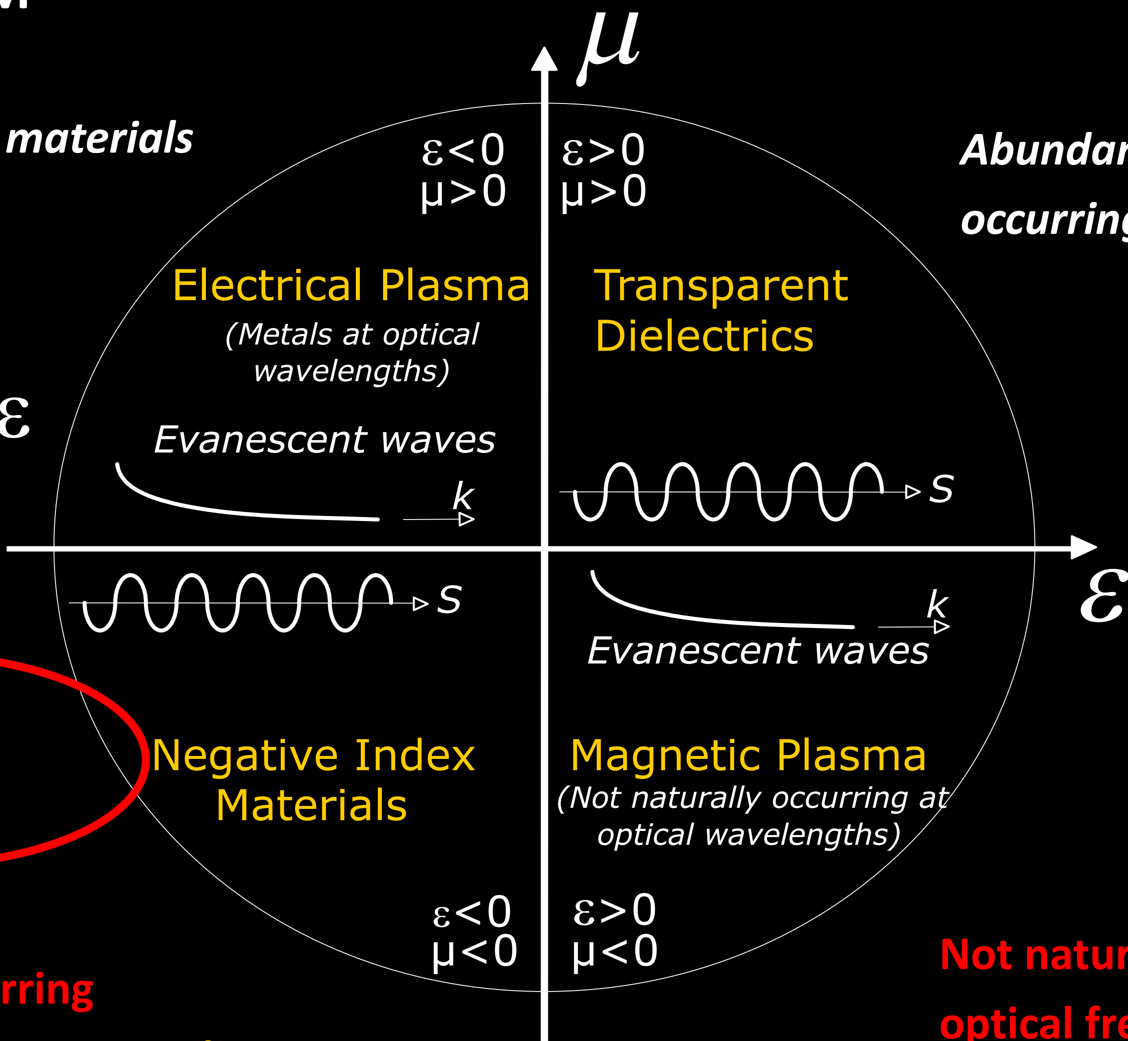
Negative ε



$\varepsilon \leq 0$

$\mu \leq 0$

Not naturally occurring

Negative-index metamaterials

Not naturally occurring at optical frequencies

Magnetic metamaterials

Negative refractive index: A historical review


Sir Arthur Schuster


Sir Horace Lamb

… energy can be carried forward at the group velocity but in a direction that is anti-parallel to the phase velocity…

Schuster, 1904

Negative refraction and backward propagation of waves

Mandel'stam, 1945


L. I. Mandel'stam


V. G. Veselago

Left-handed materials: the electrodynamics of substances with simultaneously negative values of ε and μ

Veselago, 1968

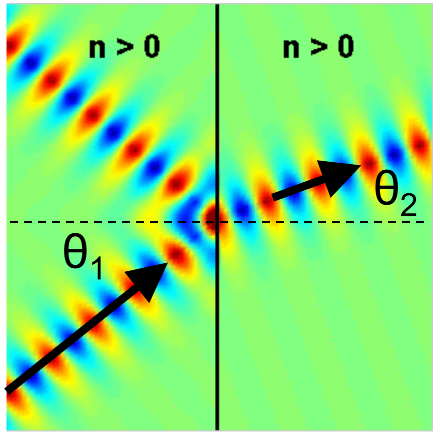
Pendry, the one who whipped up the recent boom of NIM researches

Perfect lens (2000)
EM cloaking (2006)


Sir John Pendry

Others: Sivukhin. Agranovich,…

Metamaterials with Negative Refraction



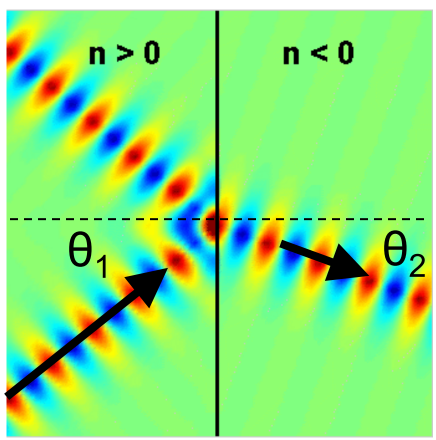
- **Refraction:**

$$n^2 = \varepsilon\mu$$

$$n = \pm\sqrt{\varepsilon\mu}$$

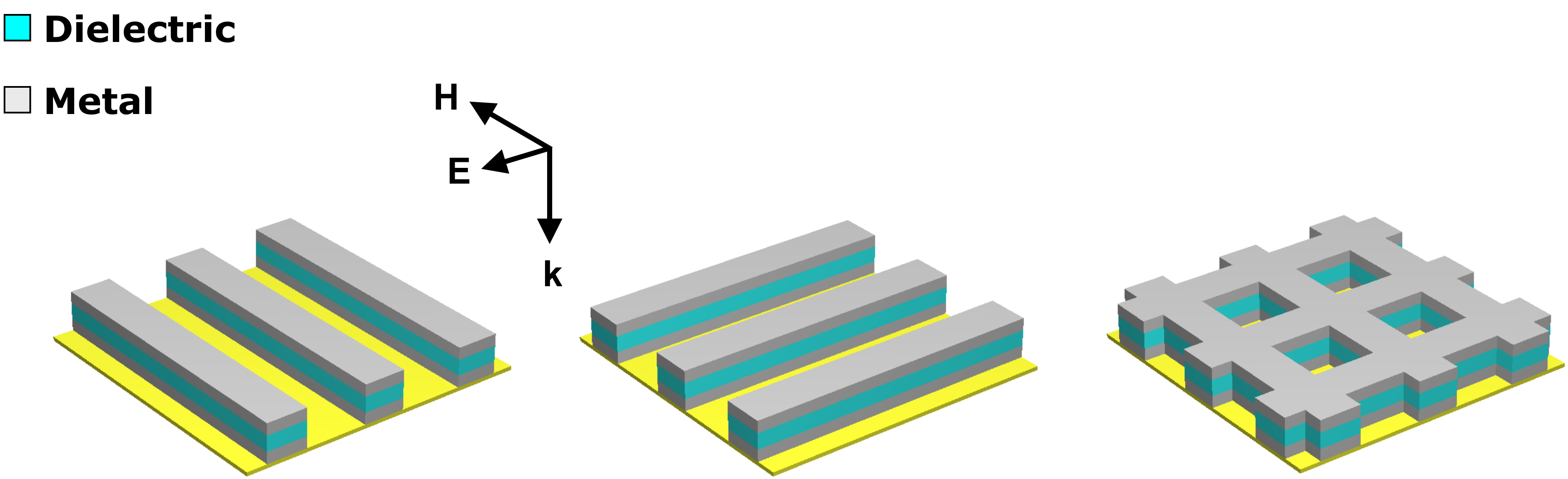
- **Figure of merit:** $F = |n'| / n''$

$$n < 0, \text{ if } \varepsilon'|\mu| + \mu'|\varepsilon| < 0$$



Negative Permeability and Negative Permittivity

S. Zhang, et al., PRL (2005)



Nanostrip pair (TM)

$\mu < 0$ **(resonant)**

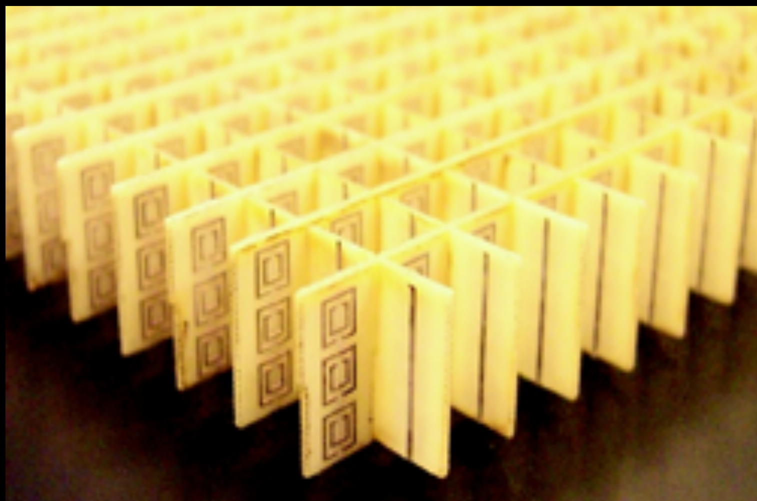
Nanostrip pair (TE)

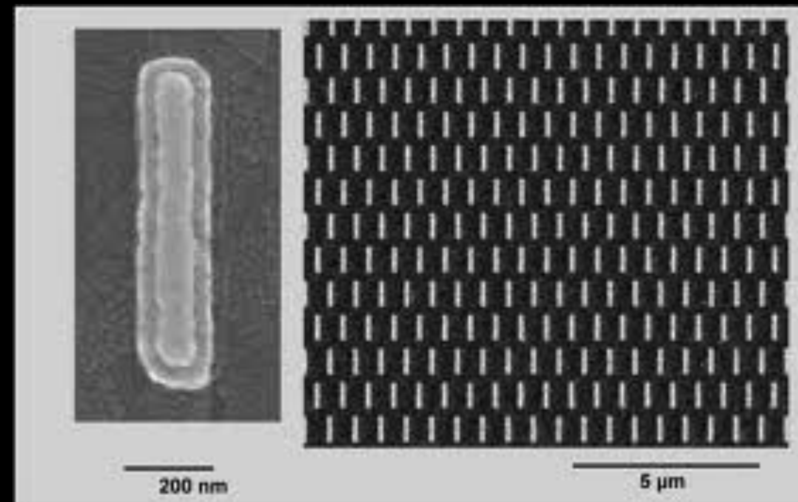
$\varepsilon < 0$ **(non-resonant)**

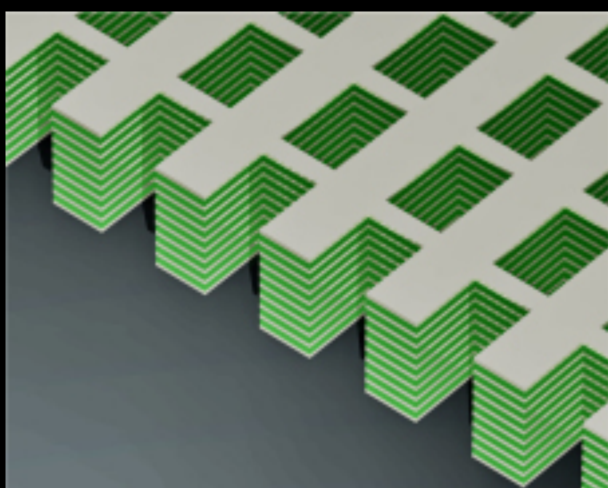
Fishnet

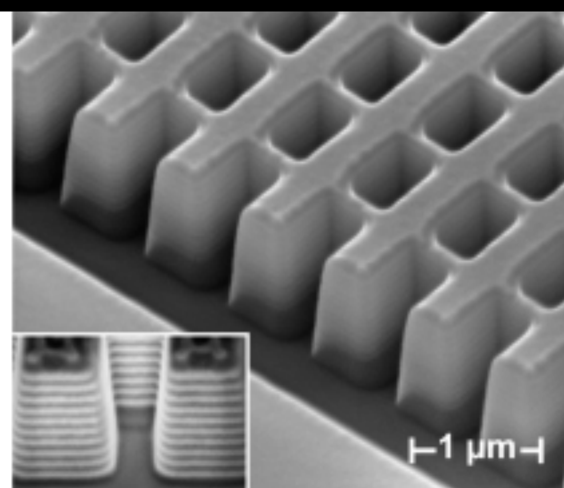
ε **and** $\mu < 0$

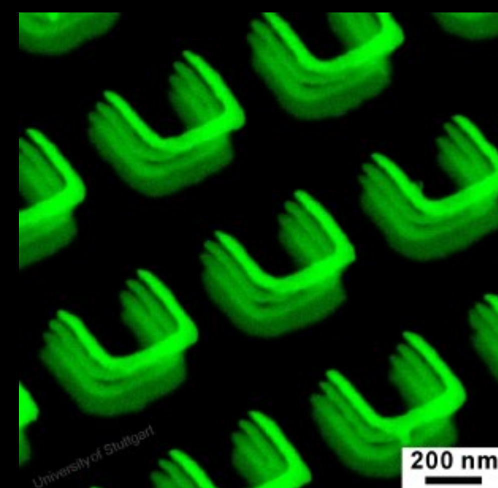
NEGATIVE INDEX MMs







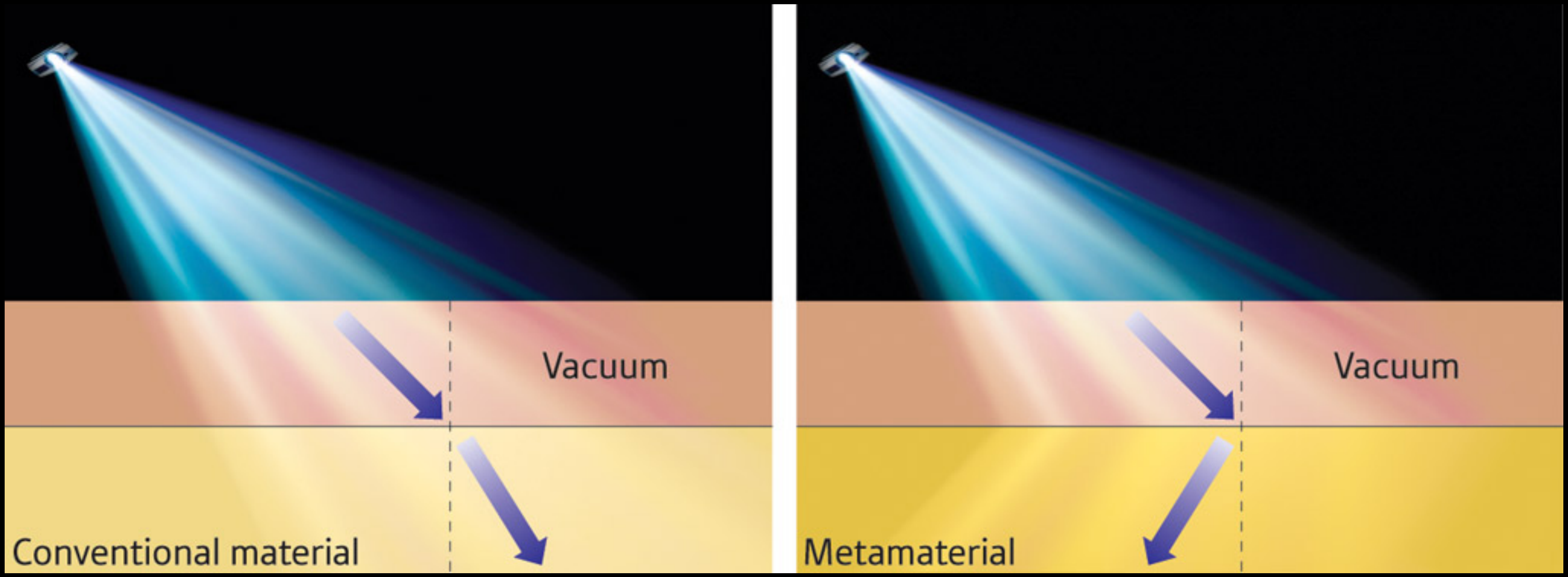




Groups of D. Smith, H. Giessen, X. Zhang, V. Shalaev

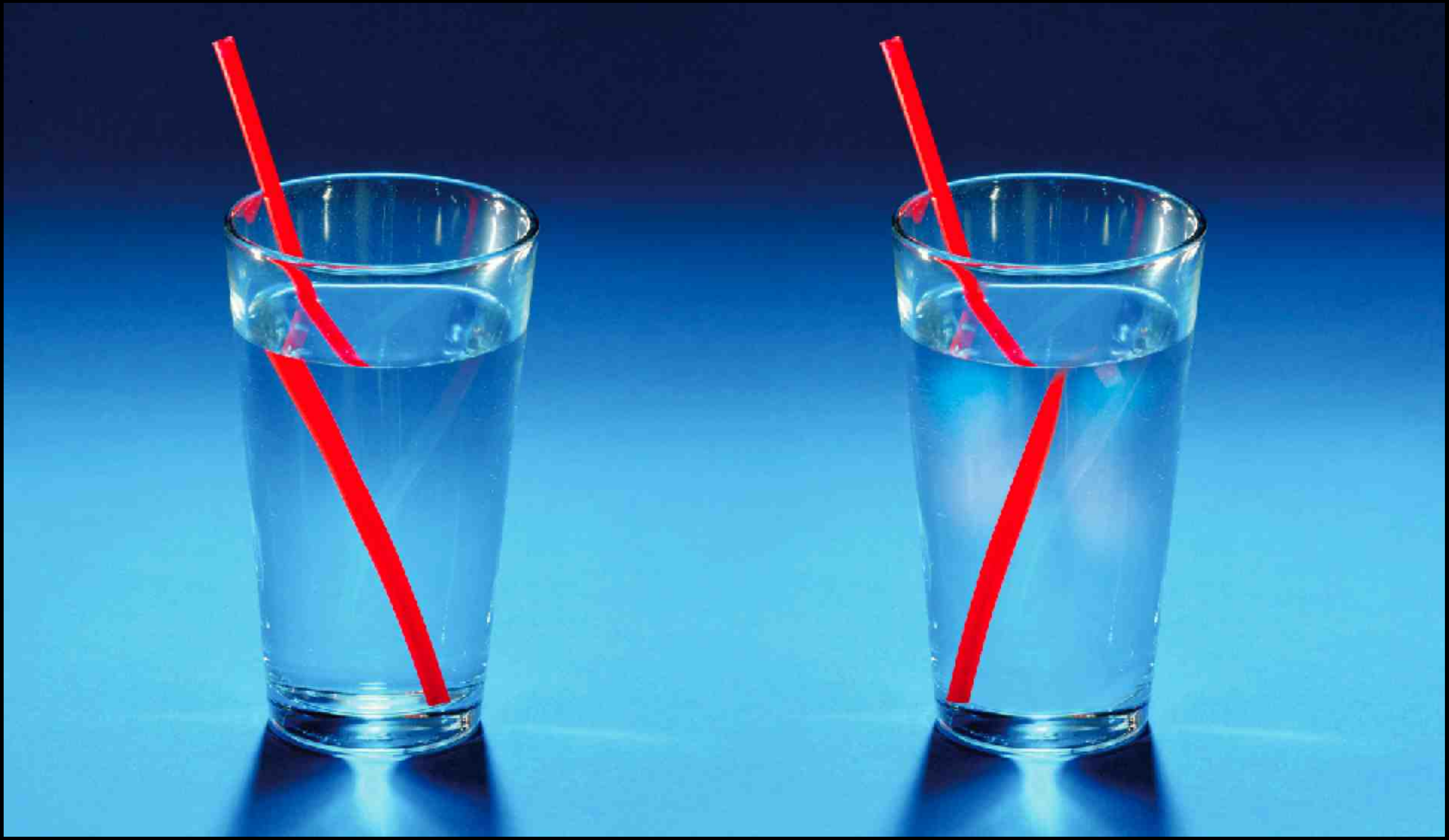
NEGATIVE REFRACTION EFFECTS

In normal materials, light cannot bend beyond the perpendicular to the interface but in Metamaterials it can.

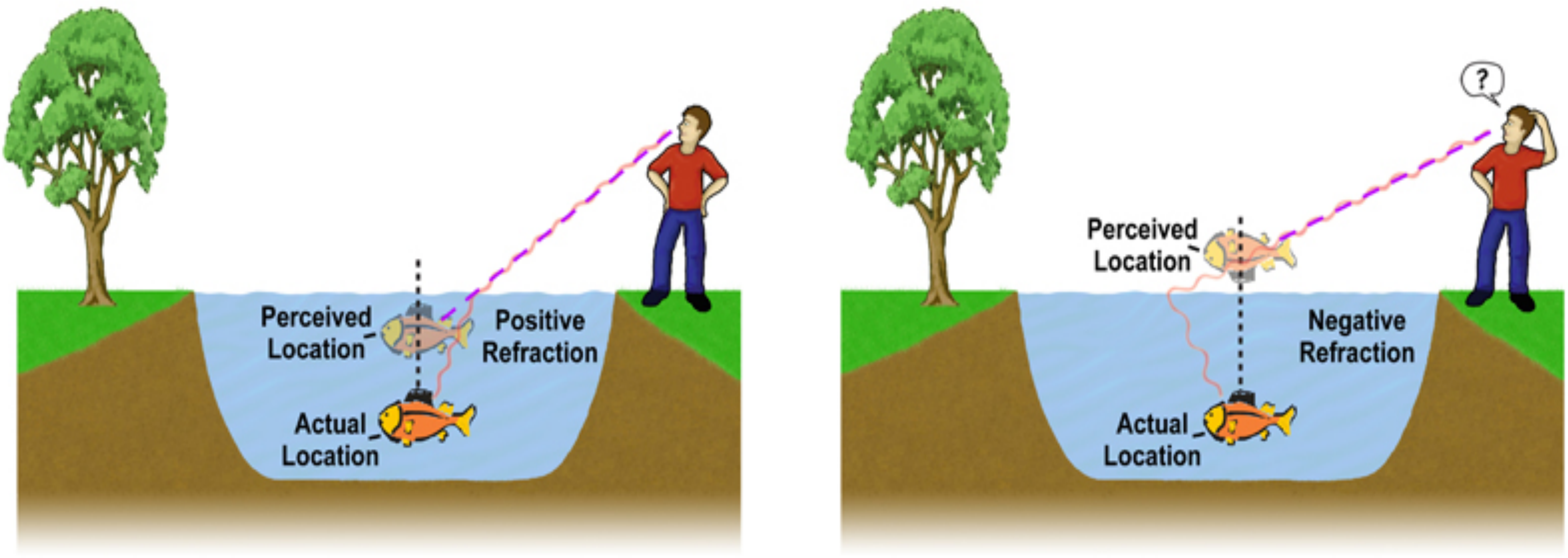


http://www.rikenresearch.riken.jp/images/figures/hi_4428.jpg/

NEGATIVE REFRACTION EFFECTS



O. Hess, Nature 455, 299 (2008)

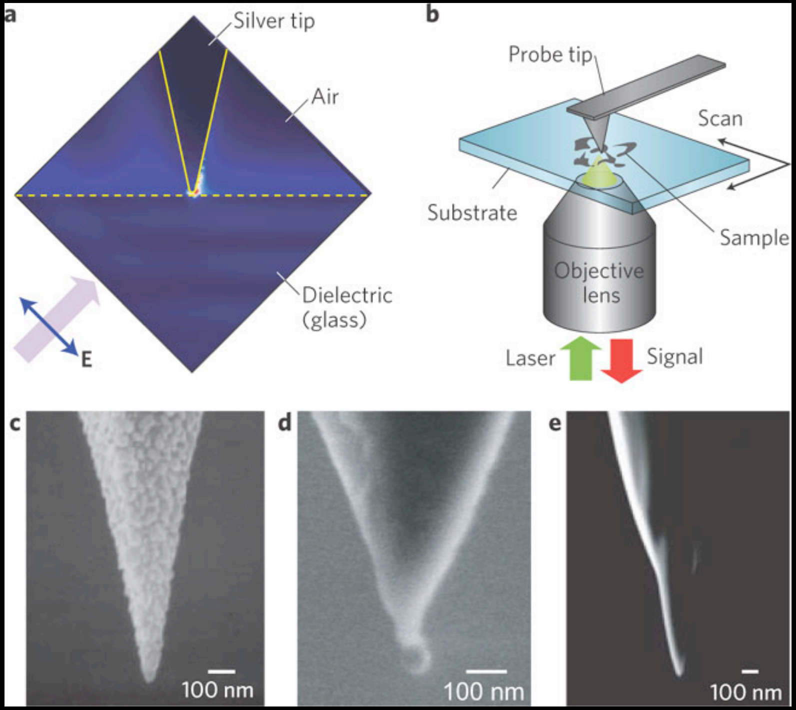


http://io9.com/5036183/secrets-of-the-metamaterials-that-will-make-you-invisible

WHAT WE HAVE SO FAR

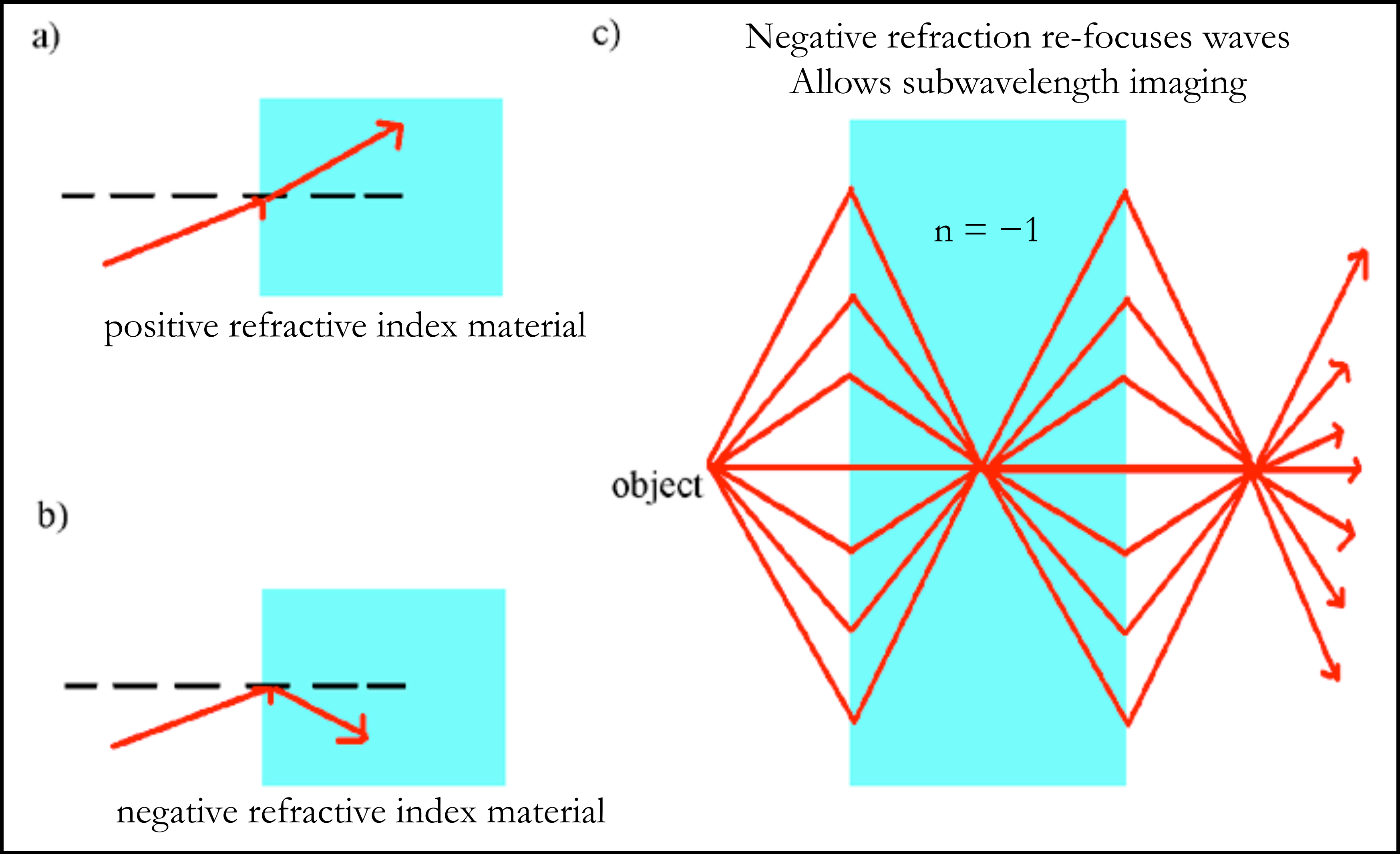
The diffraction limit is an inherent limitation in conventional optical devices or lenses: Optical microscope resolves features down to ~ 200nm

Nanoprobes are needed to go to the nanoscale…



Wiki

SUPERLENS: SEEING ON NANOSCALE



Wiki

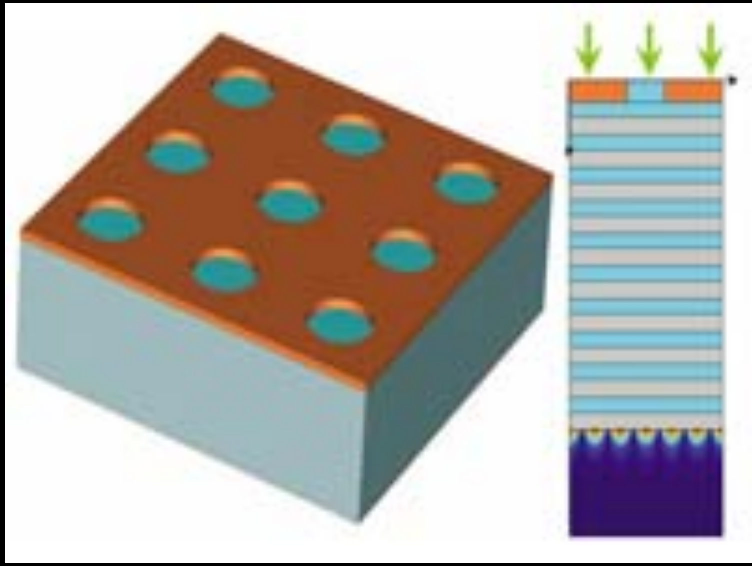
TECHNOLOGY/ECONOMY IMPACT

Superlens uses metamaterials to go beyond the diffraction limit

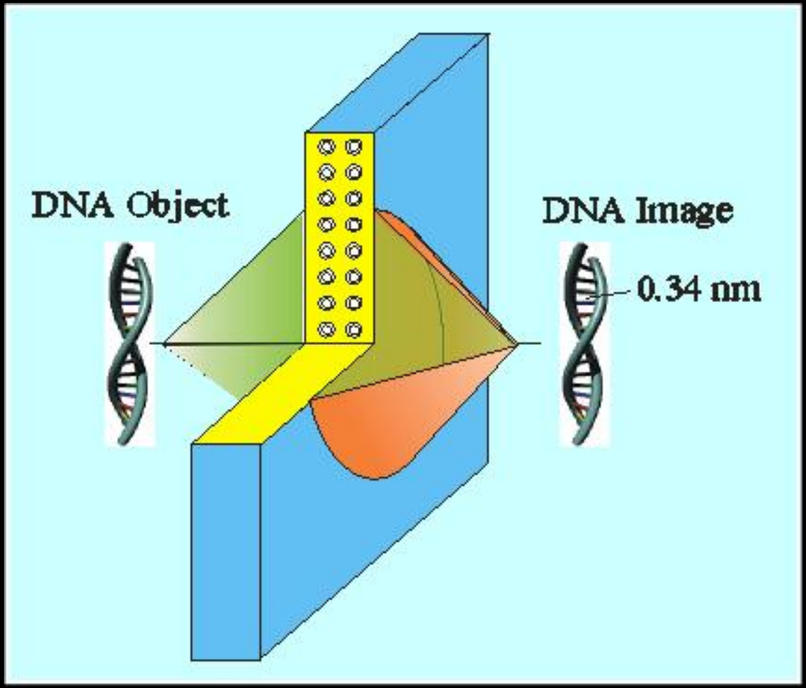
Seeing on the nanoscale

Next Generation of Imaging Systems

Next Generation of Nanolithography Tools



Group of Z. Liu

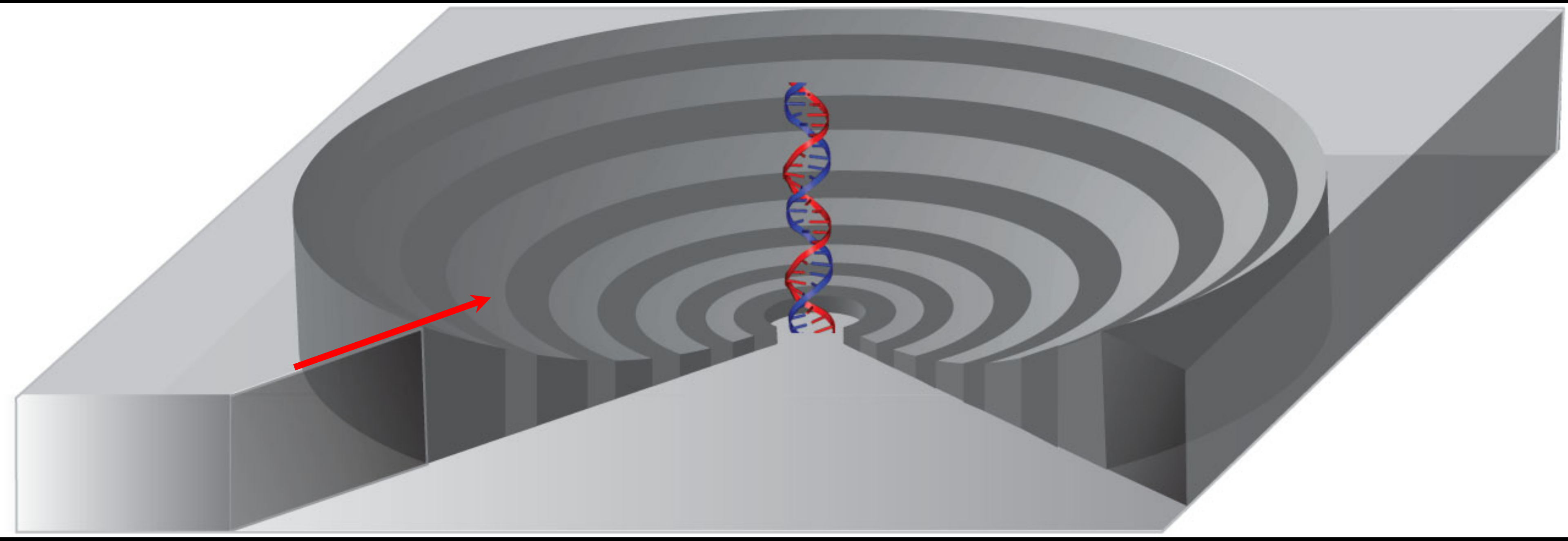


http://xlab.me.berkeley.edu

HYPERLENS

Magnifying Hyperlens:

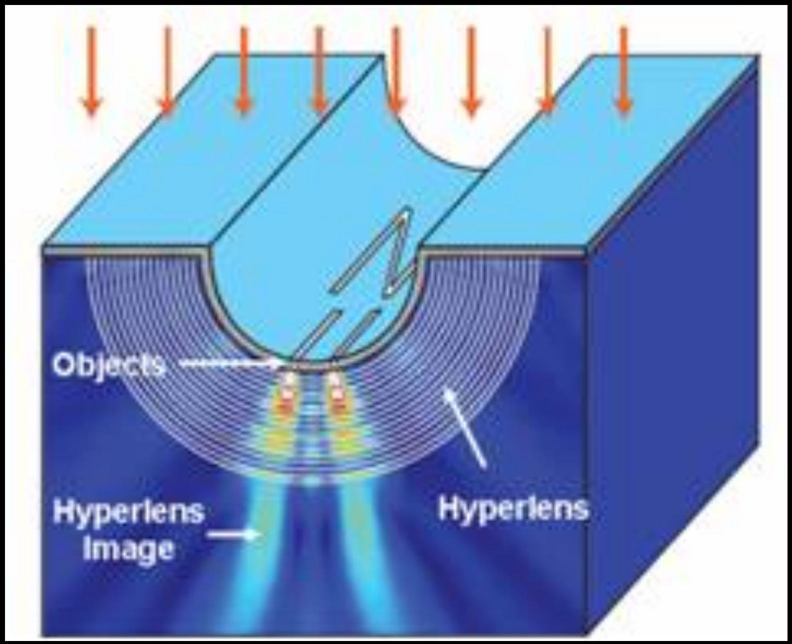
Resolving nanometer scale features

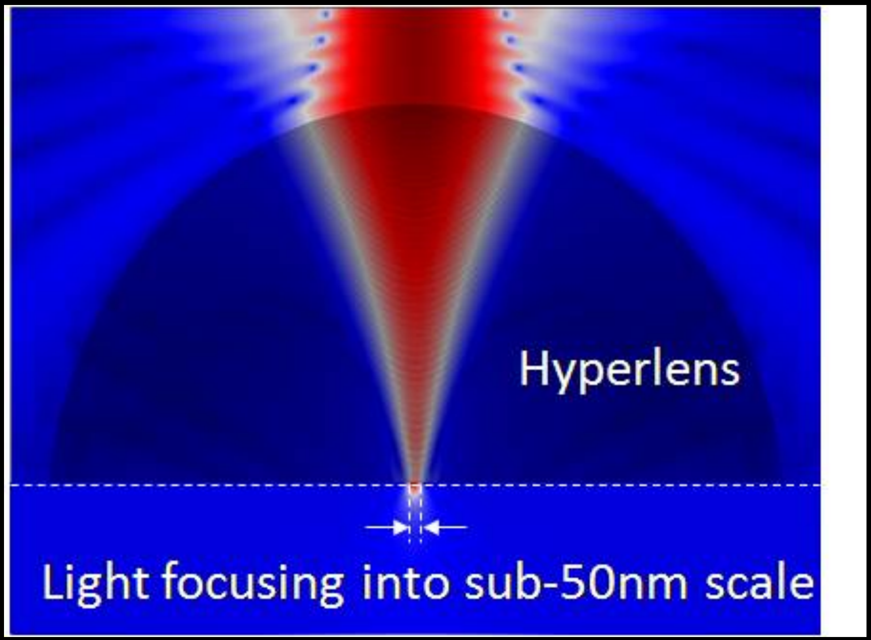


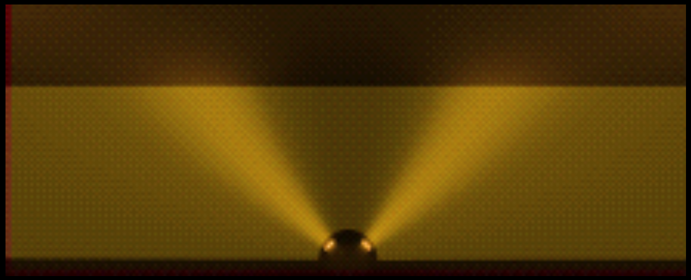
Far-field sub-λ imaging

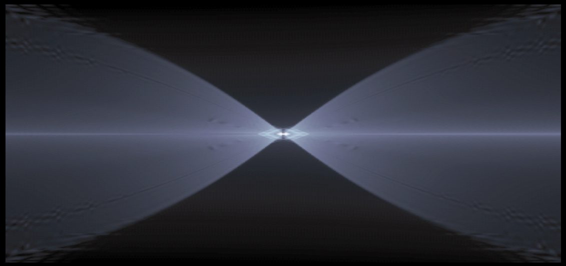
Narimanov et al; Engheta et al

HYPERLENS









Magnifying hyperlens **Light concentrator**

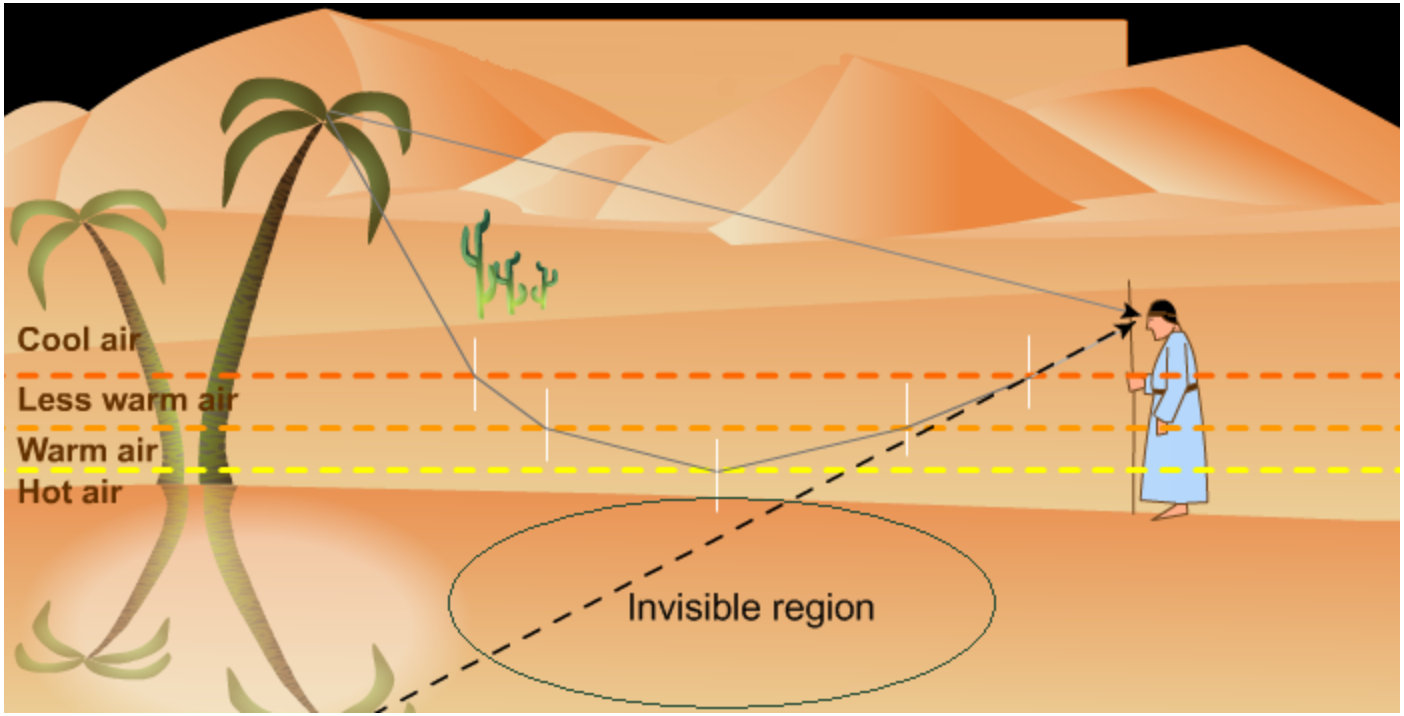
Work of Z. Liu, D. Schurig, X. Zhang, Engheta, Narimanov, Kildishev, Shalaev

Transformation Optics:

Optical Cloaking & Trapped Rainbow

A similarity in Mother Nature

The bending of light due to the gradient in refractive index in a desert mirage



Pendry et al., 2006

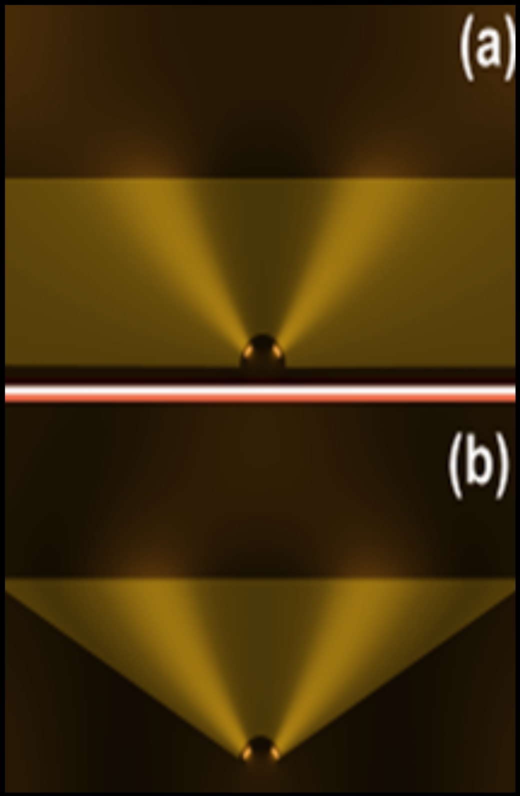
Engineering Meta-Space for Light via Transformation Optics

Kildishev, VMS *(OL, 2008)*; Shalaev, *Science 322, 384 (2008)*

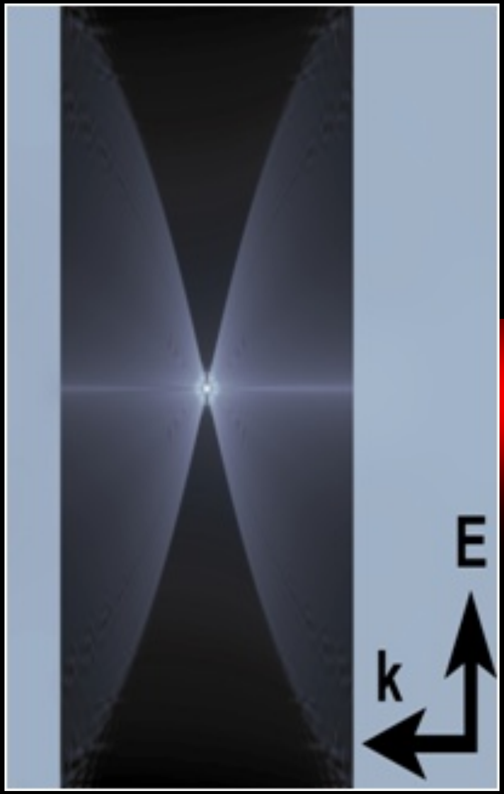
Fermat: $\delta\int n dl = 0$

$n = \sqrt{\varepsilon(r)\mu(r)}$

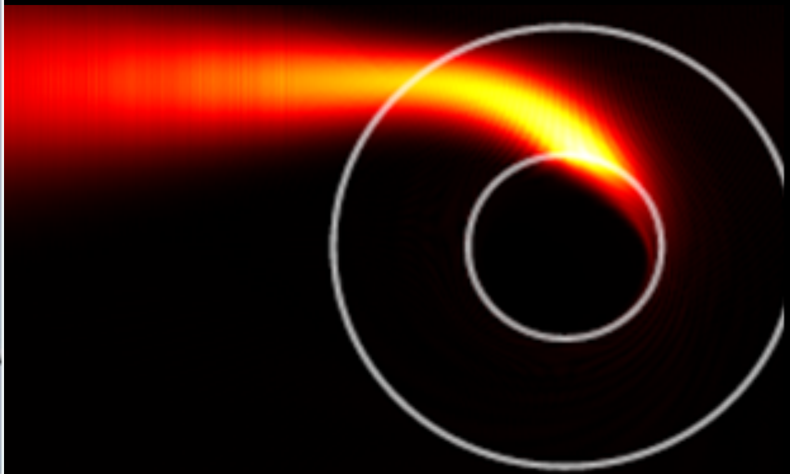
curving optical space



Planar hyperlens
(Kildishev and VMS)
(Schurig et al; Zhang group)



Light concentrator
(also, Schurig et al)



Optical Black Hole
(Zhang group;
Narimanov,Kildishev)

Form-invariance of Maxwell's equations

Coordinate transformation from **x** to coordinate **x′** is described using the Jacobian matrix **G**:

$$g_{ij} = \partial x'_i / \partial x_j$$

Maxwell's equation in x

$$\nabla \cdot (\varepsilon \vec{E}) = \rho$$
$$\nabla \cdot (\mu \vec{H}) = 0$$
$$\nabla \times \vec{E} = -\mu \partial \vec{H} / \partial t$$
$$\nabla \times \vec{H} = \varepsilon \partial \vec{E} / \partial t + \vec{J}$$

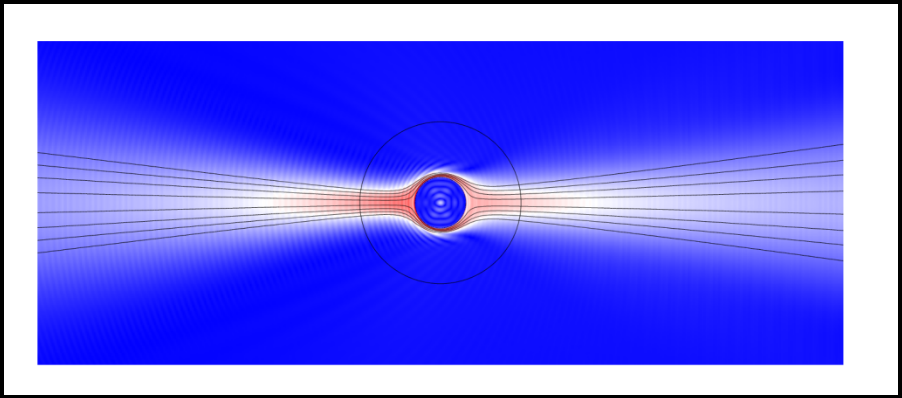
Transformation of variables

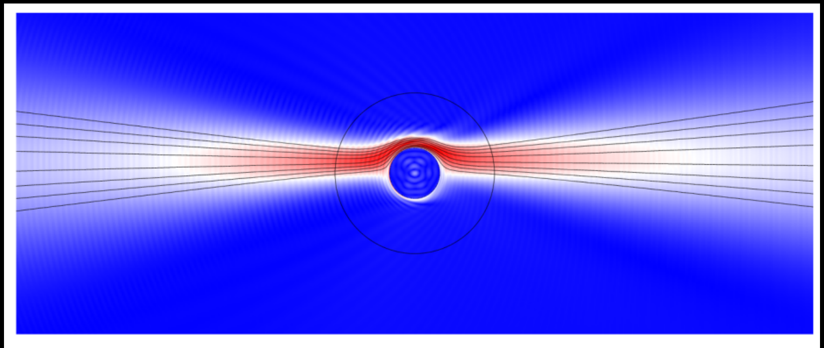
$$\varepsilon' = \frac{G\varepsilon G^T}{|G|};\ \mu' = \frac{G\mu G^T}{|G|}$$
$$\vec{E}' = (G^T)^{-1}\vec{E};\ \vec{H}' = (G^T)^{-1}\vec{H}$$
$$\vec{J}' = \frac{G\vec{J}}{|G|};\ \rho' = \frac{\rho}{|G|}$$
$$\nabla \to \nabla'$$

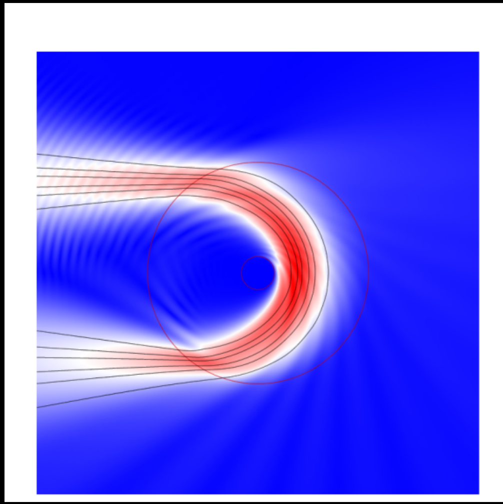
Ward and Pendry, J. Mod.Opt. 43, 777 (1996)

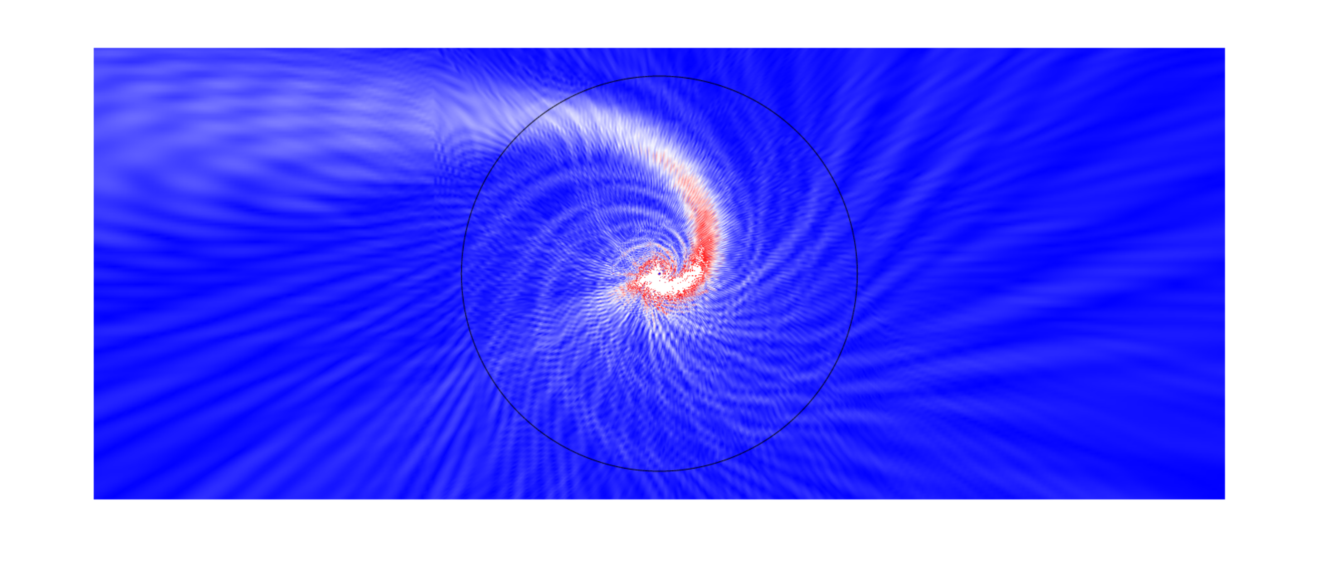
Trapping and Manipulating Light

Narimanov, Kildishev



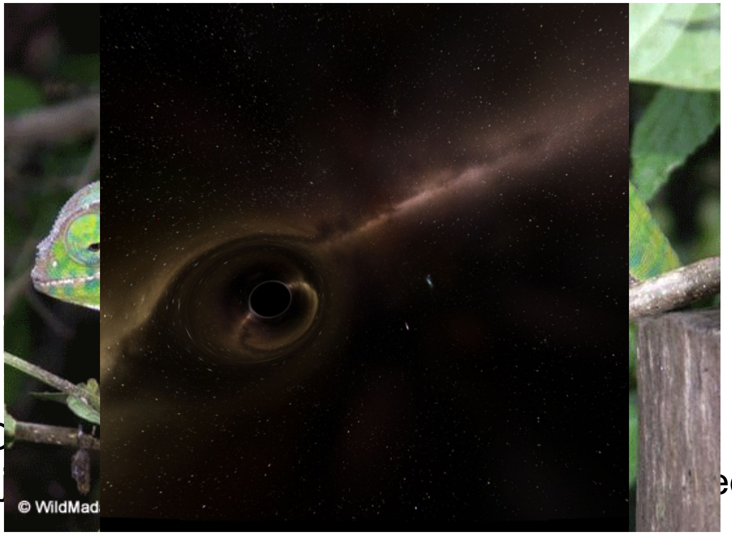






Invisibility in Nature, Physics and Technology

- Natural camouflage
- Black hole
- …



Current technologies to achieve invisib

➢ Stealth technique:
Radar cross-section reductions by absorbing paint / non-metallic frame / shape effect…

➢ C
Proj … ect.

F-117 "Nighthawk" Stealth Fighter

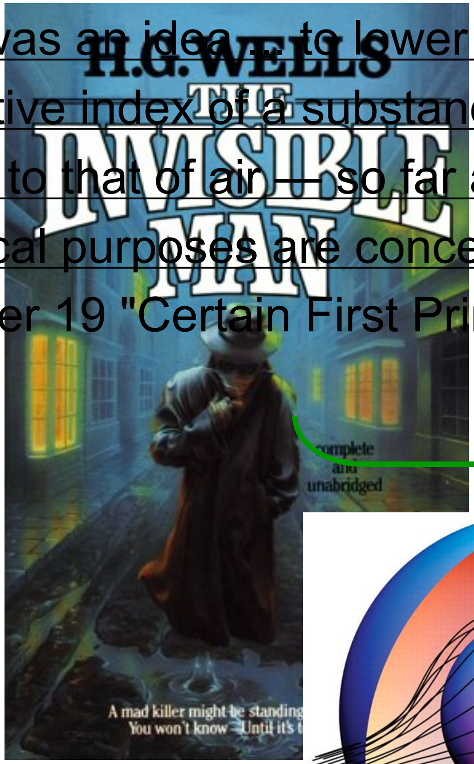
Optical Camouflage, Tachi Lab, U. of Tokyo, Japan

Invisibility: from fiction to fact?

Examples with scientific elements:

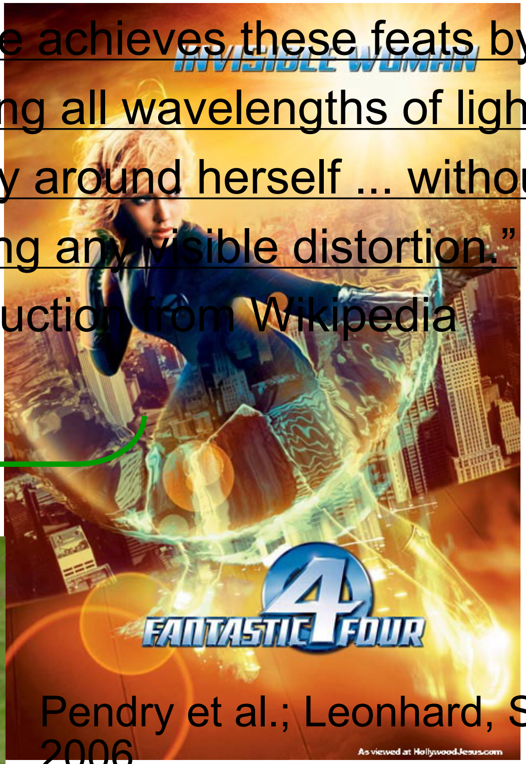
- The Invisible Man by H. G. Wells (1897)

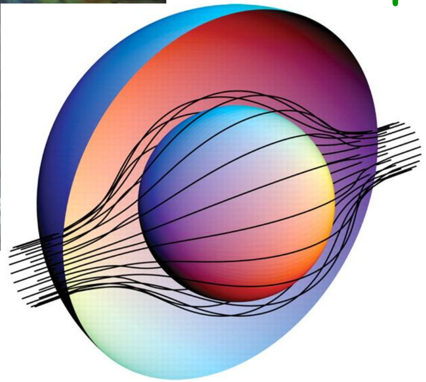
"... it was an idea ... to lower the refractive index of a substance, solid or liquid, to that of air — so far as all practical purposes are concerned." -- Chapter 19 "Certain First Principles"



- "The invisible woman" in The Fantastic 4 by Lee & Kirby (1961)

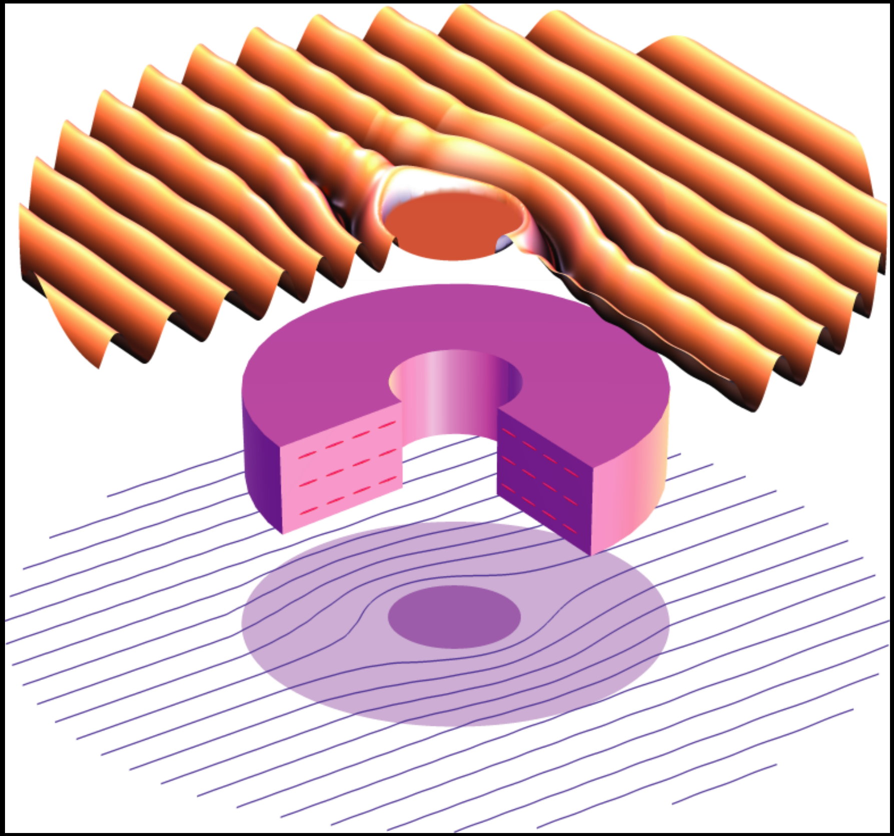
"... she achieves these feats by bending all wavelengths of light in the vicinity around herself ... without causing any visible distortion." -- Introduction from Wikipedia

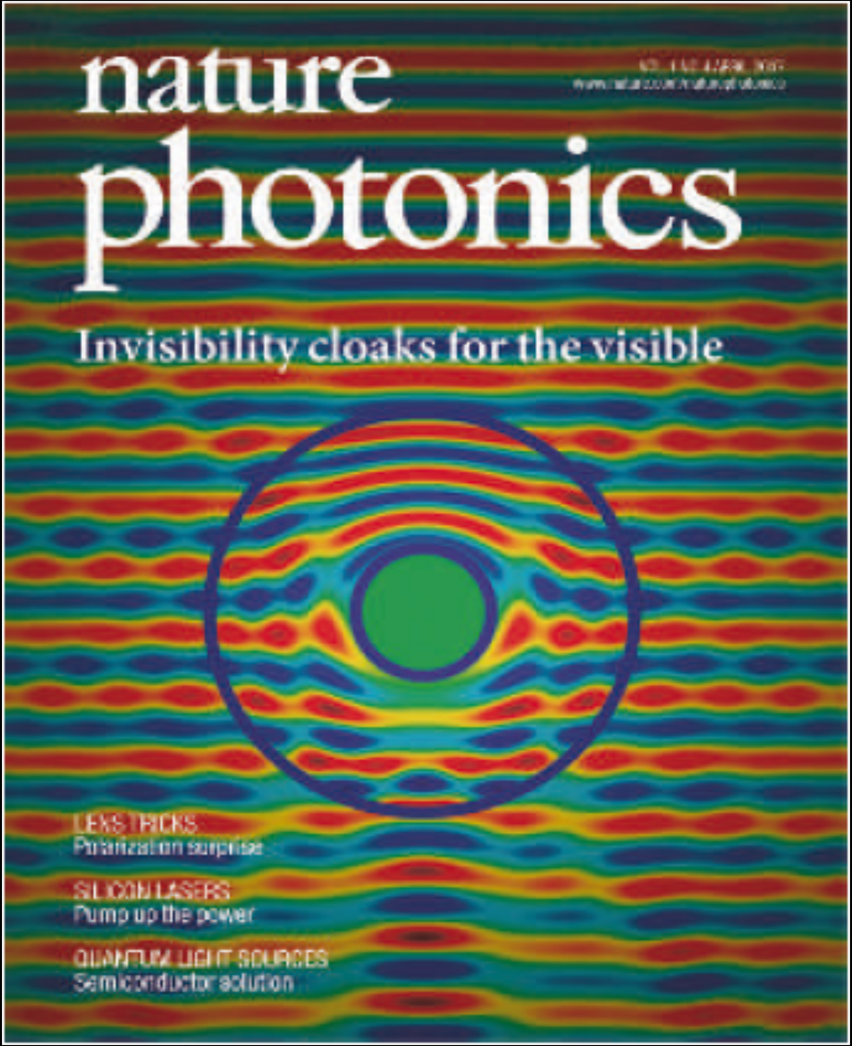




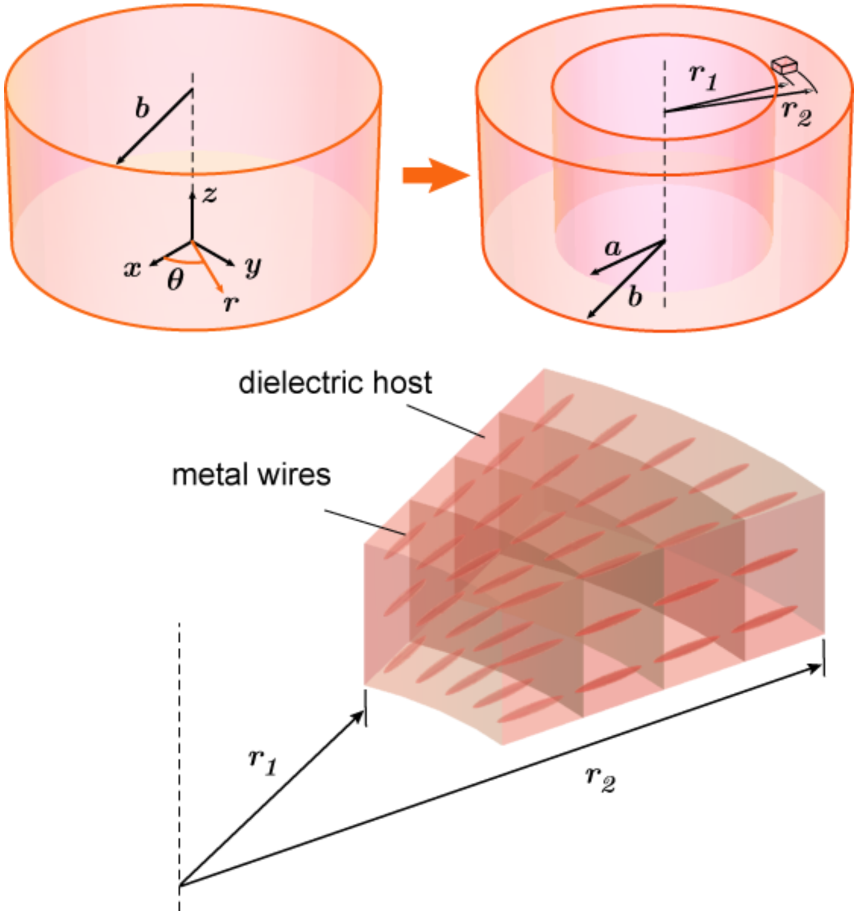
Pendry et al.; Leonhard, Science, 2006
(Earlier work: cloak of thermal conductivity by Greenleaf et al., 2003)

Optical Cloaking with Metamaterials: Can Objects be Invisible in the Visible?



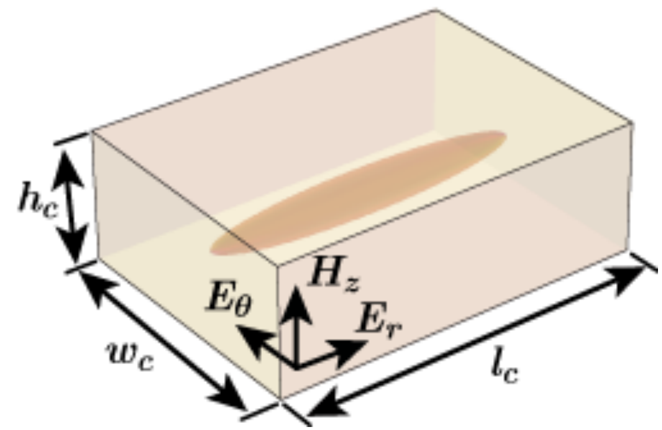


Structure of the cloak: “Round brush”



metal needles embedded in dielectric host

Unit cell:



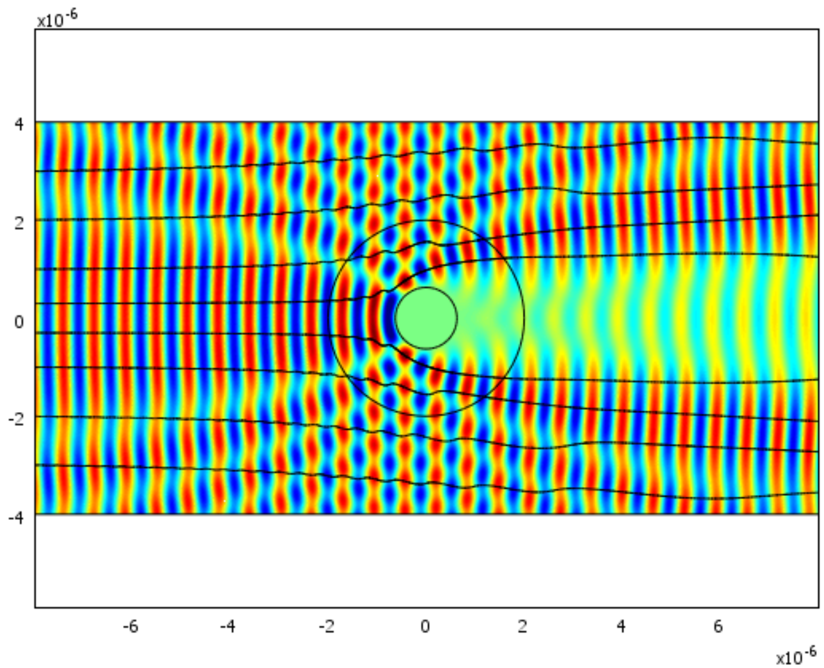
Flexible control of ε_r ;

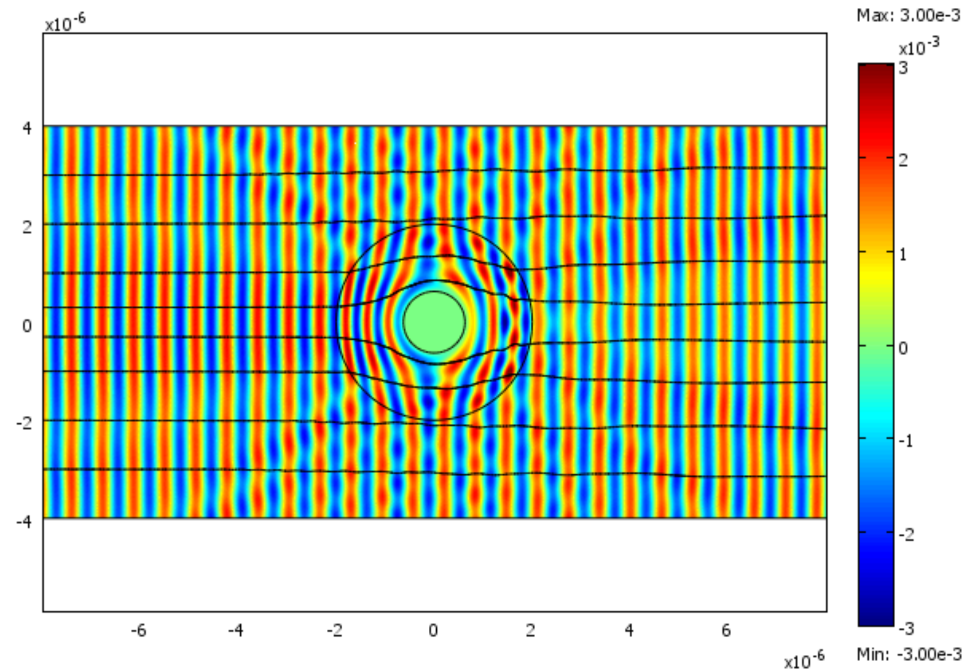
Negligible perturbation in ε_θ

Cai, et al., Nature Photonics, 1, 224 (2007)

Cloaking performance: Field mapping movies

Example: cloak @ 632.8nm with silver wires in silica

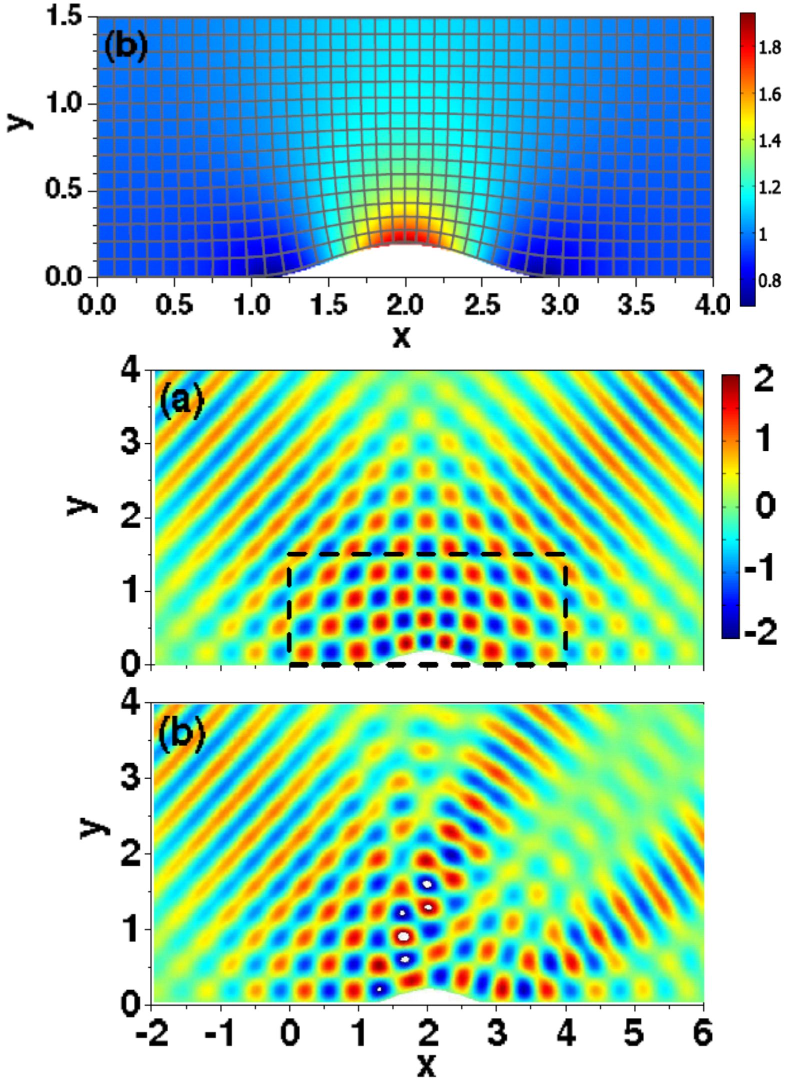




Cloak OFF

Cloak ON

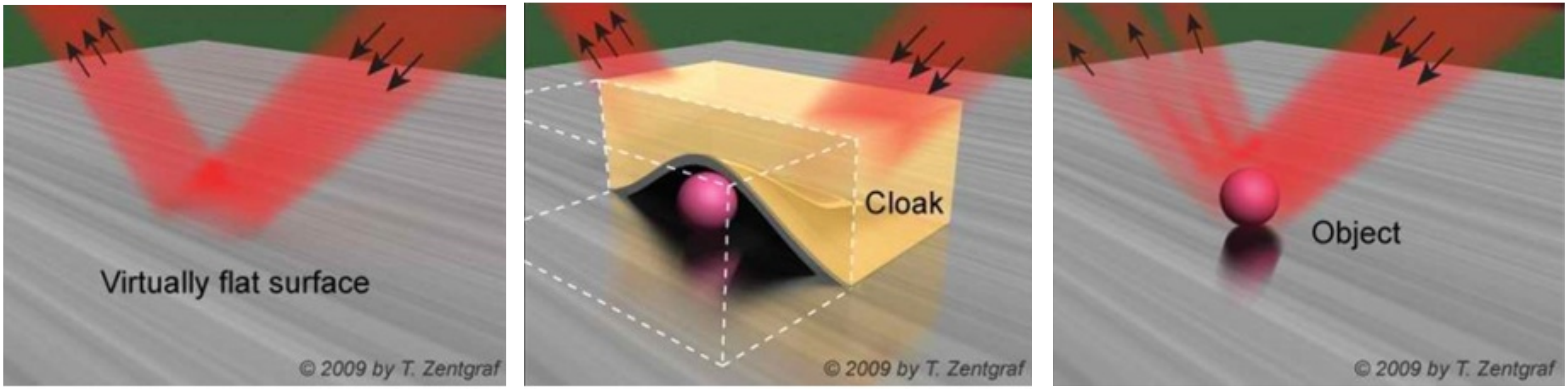
Invisible Carpet (ground-plane cloak)



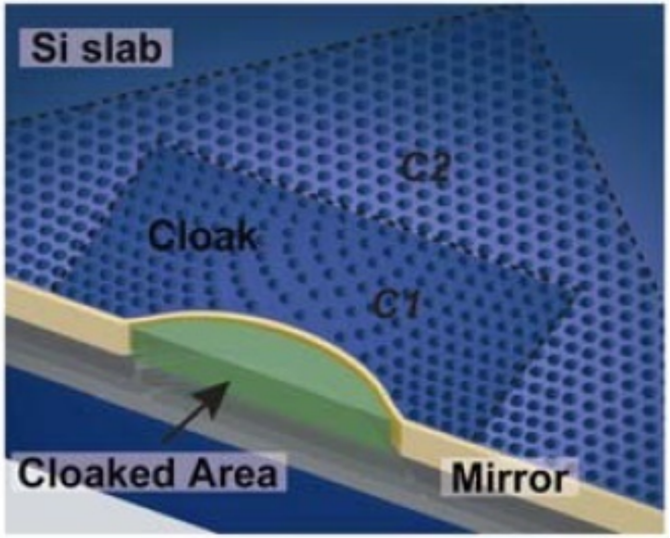
picture from discovery.com

J. Li and J. B. Pendry , Phys. Rev. Lett., 2008

Optical Mimicry

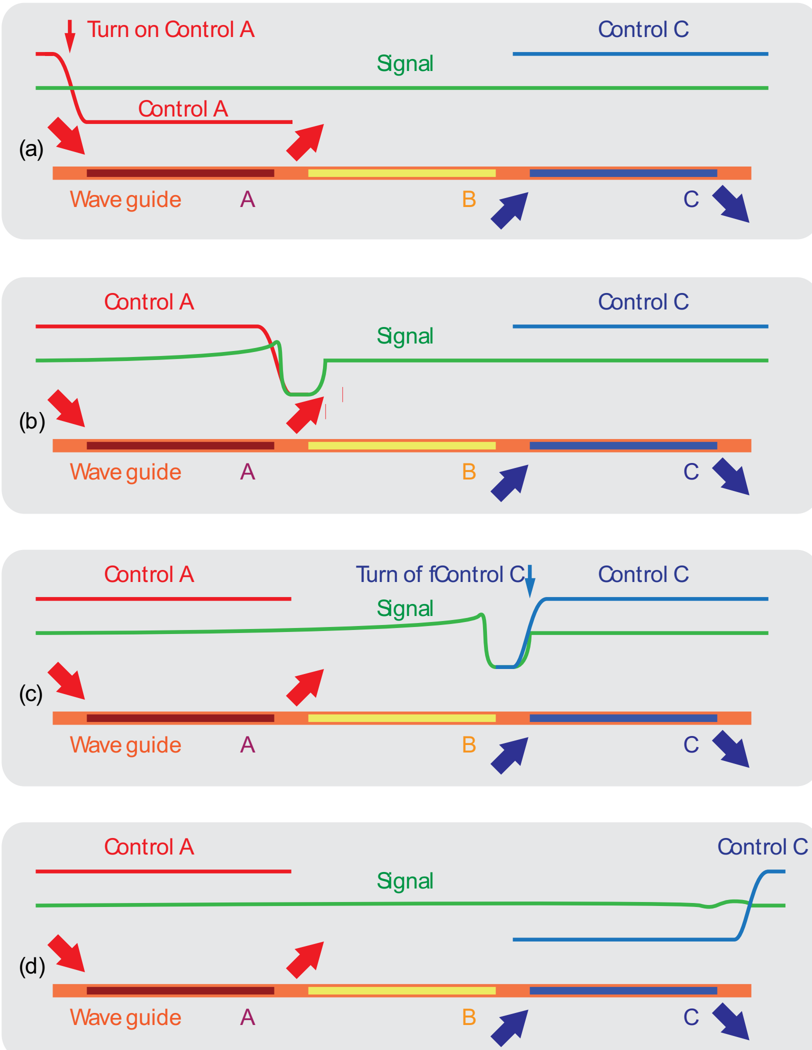


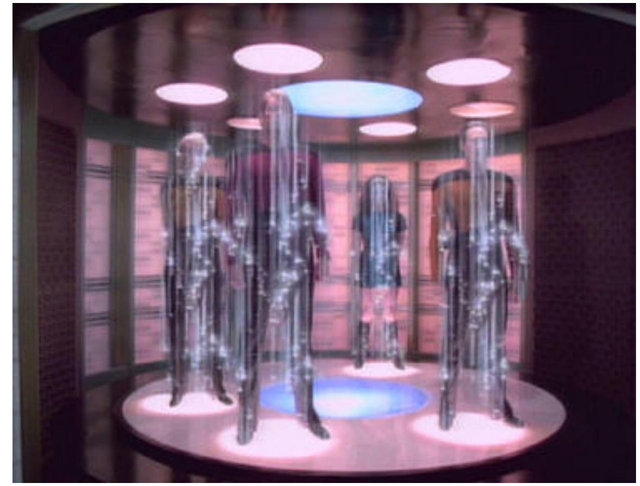
Progress Towards True Invisibility on May.17, 2009, under Science
www.codingfuture.com



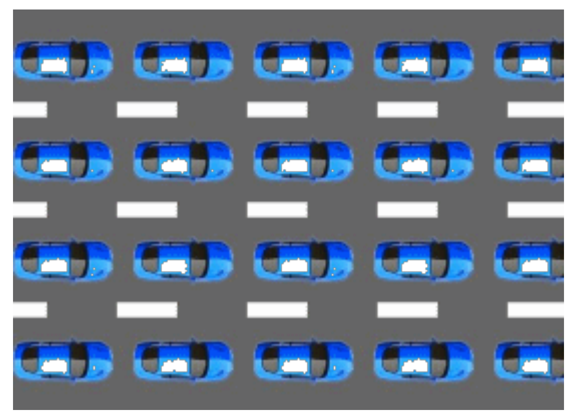
Theory: J. Li, J. Pendry
GHz: Smith et al (Duke)
Optical: Zhang et al (Berkeley)
Lipson et al (Cornel)

Space-time Cloak – History Editor





Star Trek transporter

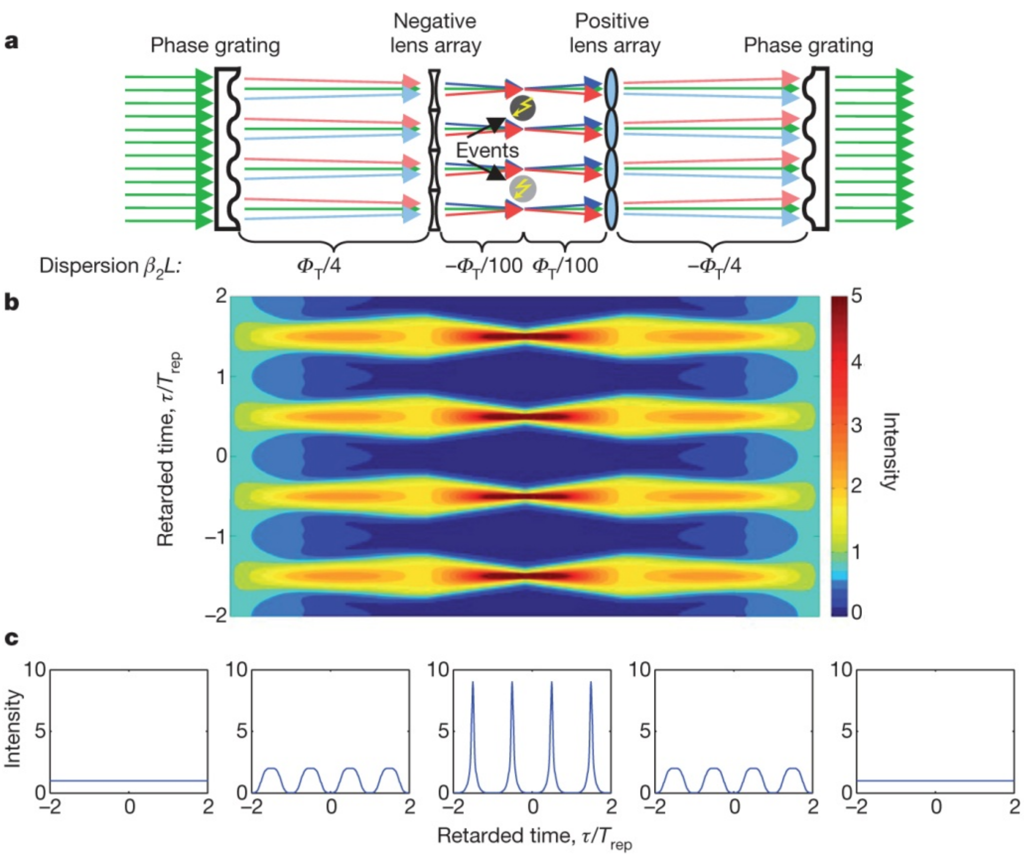


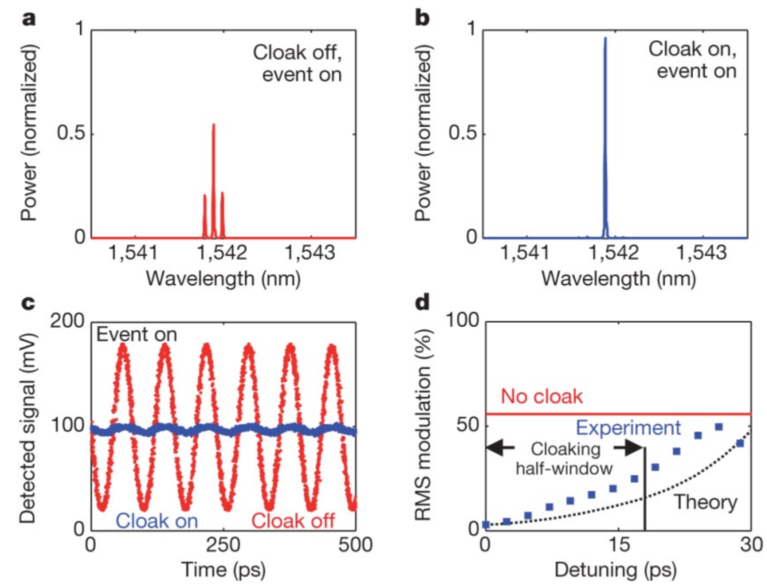
M. W. McCall and et al., *Journal of Optics*, 2011
Gaeta et al, experiment

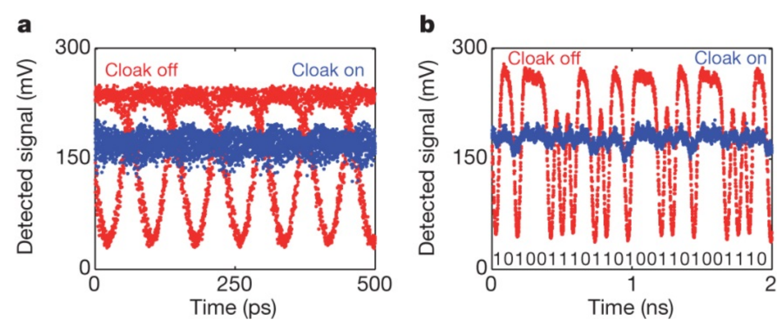
A temporal cloak at telecommunication data rate

Jun. 13 2013 • Vol 498, Issue 7453

Joseph M. Lukens, Daniel E. Leaird & Andrew M. Weiner





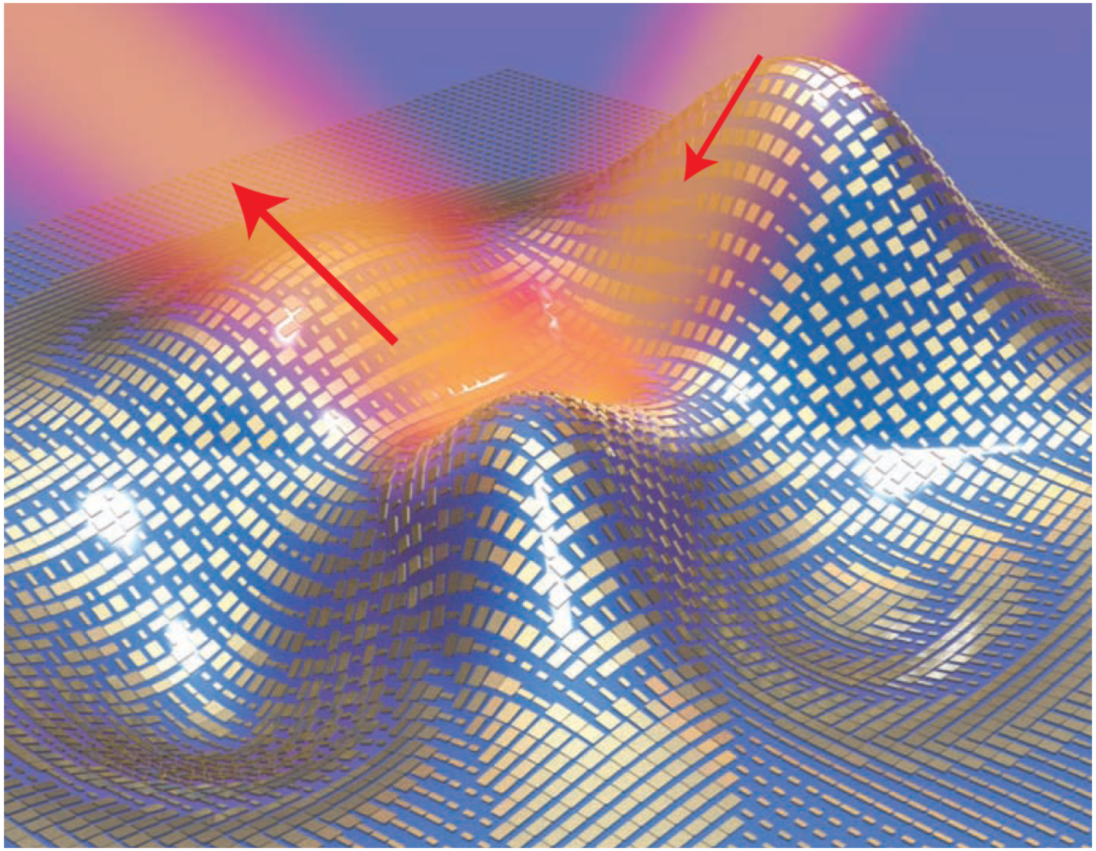


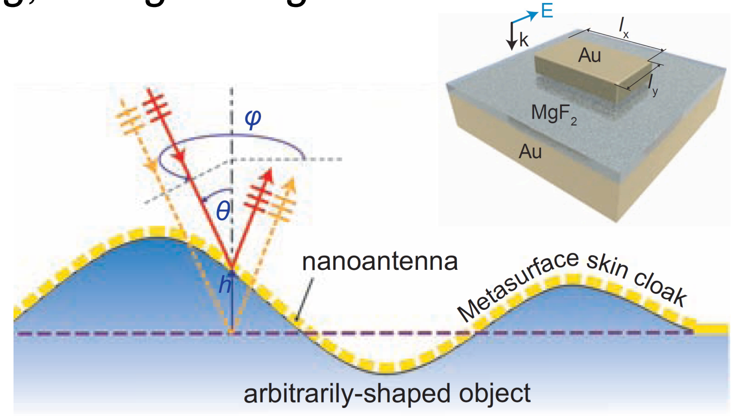
Similar work: "Fridman, M., Farsi, A., Okawachi, Y. & Gaeta, A. L. *Nature* 481, 62–65 (2012)"

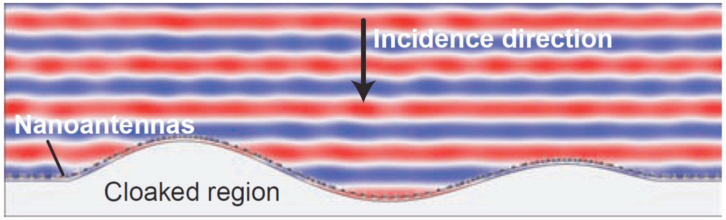
An ultrathin invisibility skin cloak for visible light

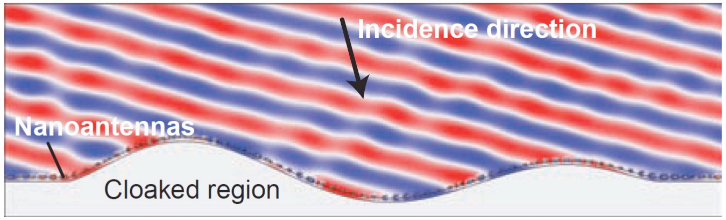
Sep. 18 2015 • Vol 349, Issue 6254

Xingjie Ni, Zi Jing Wong,* Michael Mrejen, Yuan Wang, Xiang Zhang*



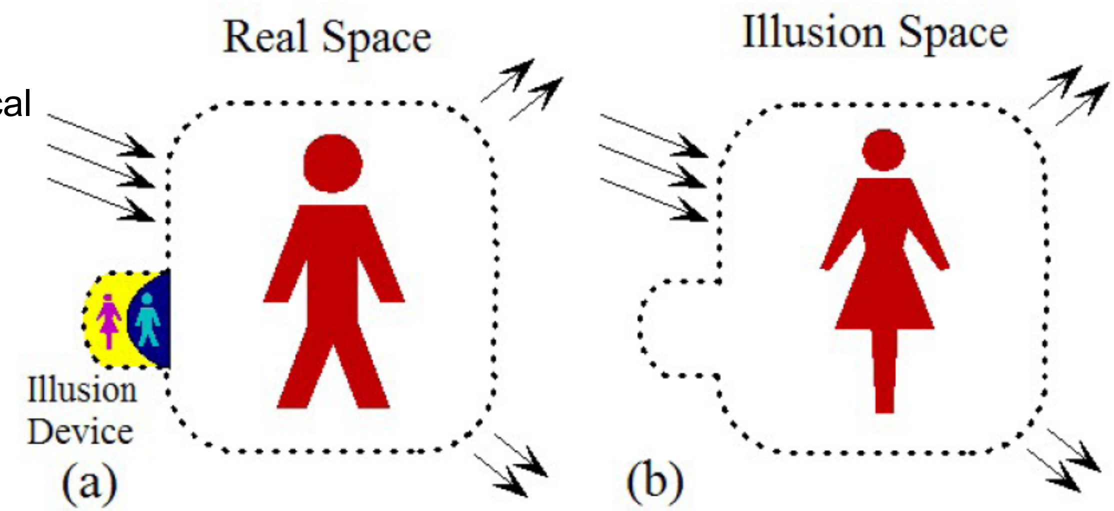






Optical transformation of one object into another: Optical Illusion

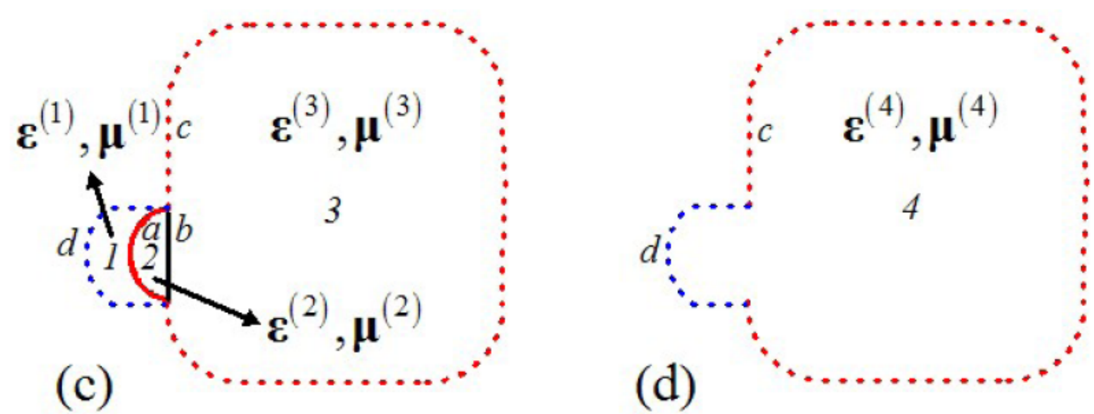
Illusion device can remotely change the optical response



a man (object)

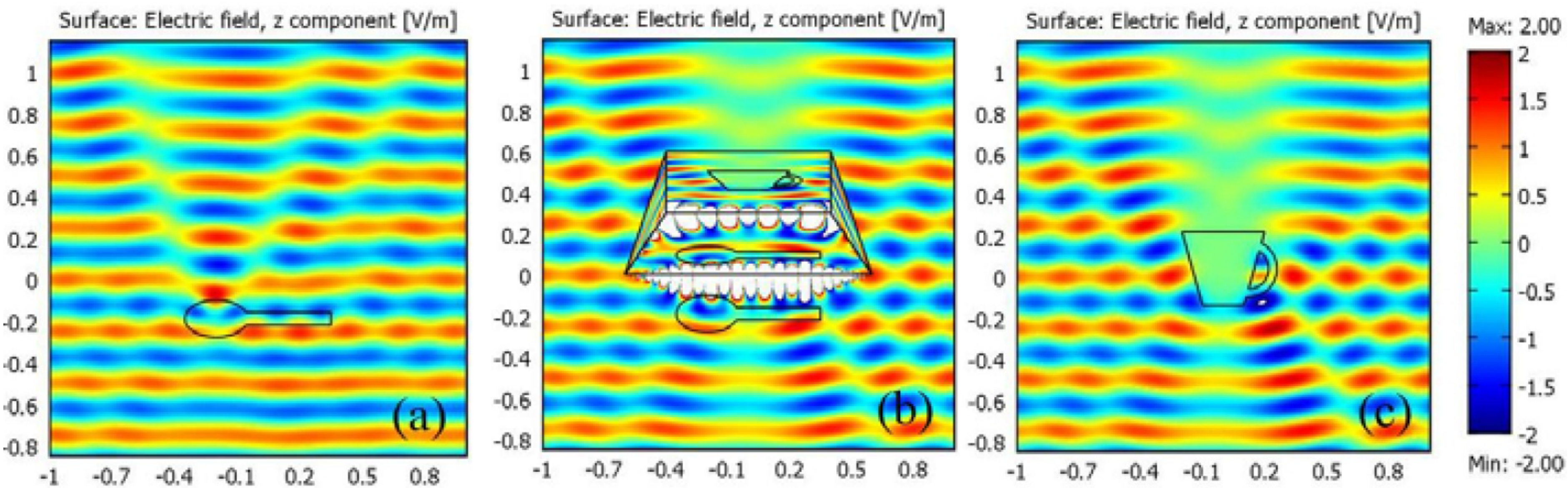
a woman (illusion)

region 1
restoring medium
region 2
complementary medium
region 3
folding region including the man
region 4
compressing region including the woman



Yun Lai et al., arxiv: 0905.1484

Numerical demonstration of the illusion optics



Object:
dielectric spoon of ε_o=2

scattering pattern

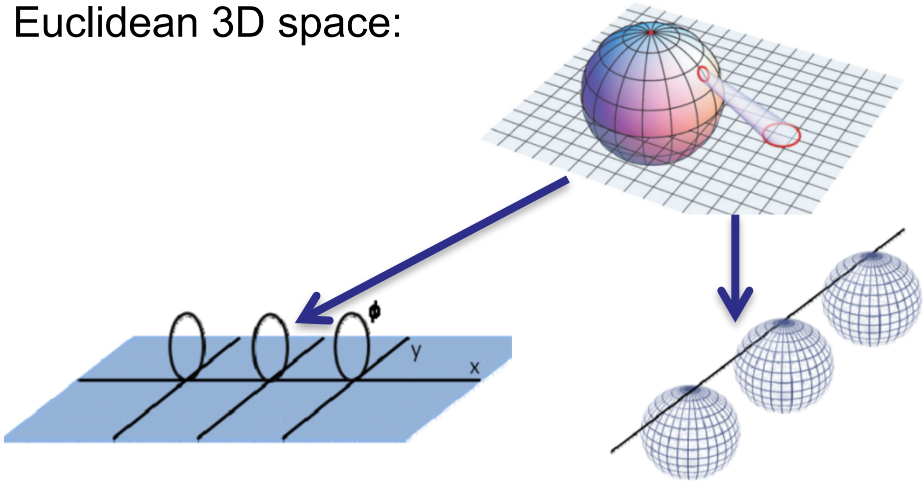
Illusion:
metallic cup of ε_i=-1

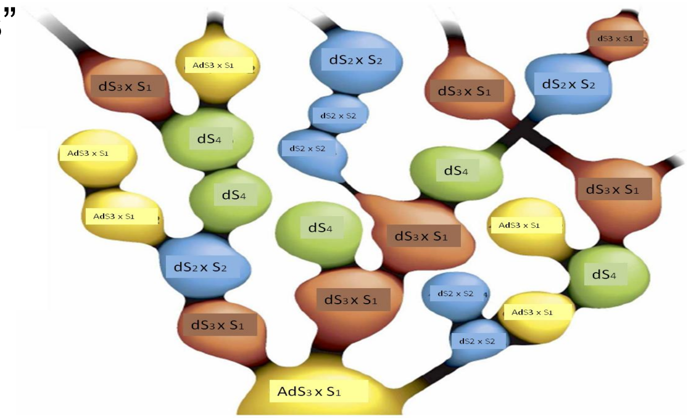
Scattering pattern of a dielectric spoon is changed by the illusion device.
Outside the virtual boundary, the scattering pattern becomes the same as that of a metallic cup

Yun Lai et al., arxiv: 0905.1484

Metamaterial "Multiverse" (Smolyaninov)

Using transformation optics we can create "optical spaces" having non-trivial topology, which cannot normally fit into Euclidean 3D space:





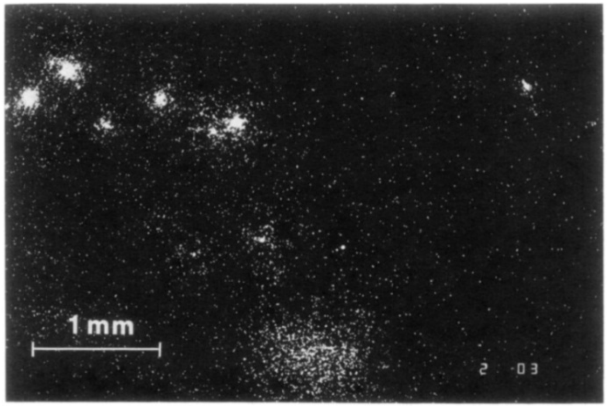
Modern cosmology describes Universe as collection of spaces connected by black holes and wormholes. These spaces may have different topology and different number of dimensions.

Even metric signature of the "optical space" may differ from the (+ - - -) signature of the Minkowski space. In hyperbolic materials (Smolyaninov, Narimanov – PRL, 2010):

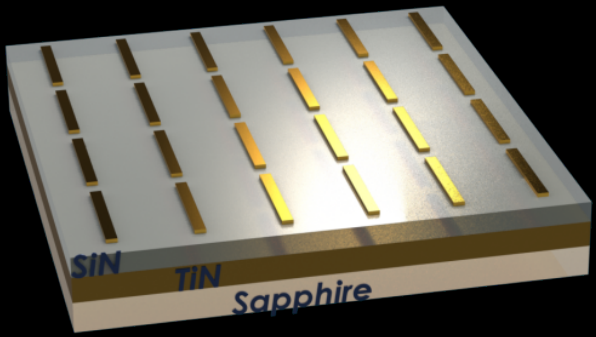
$$\frac{\partial^2\varphi}{c^2\partial t^2}=\frac{\partial^2\varphi}{\varepsilon_1\partial z^2}+\frac{1}{\varepsilon_2}\left(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}\right)\qquad \begin{matrix}\varepsilon_1<0\\ \varepsilon_2>0\end{matrix}$$

$$\left(\frac{\partial^2}{\partial x_1^2}+\frac{\partial^2}{\partial x_2^2}-\frac{\partial^2}{\partial x_3^2}-\frac{\partial^2}{\partial x_4^2}\right)\varphi=0$$

2T K-G



Flashes of light are observed during metric signature transitions : toy Big Bang physics



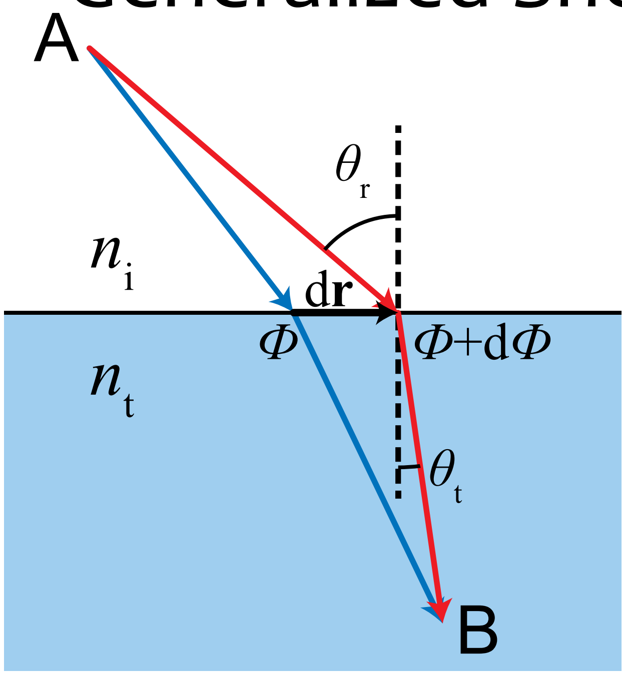
PURDUE UNIVERSITY

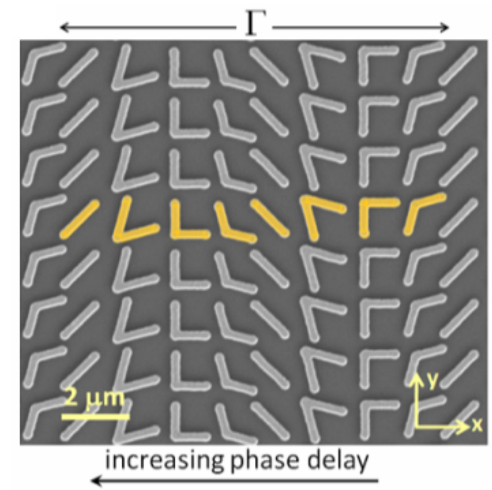
Metasurfaces

Review:
A.V. Kildishev, A. Boltasseva, V.M. Shalaev,
Planar Photonics with Metasurfaces, Science **339**, 6125 (2013)

Early and seminal work on metasurfaces:
E. Hasman, N. Zheludev, F. Capasso, S. Bozhevolnyi. …

Generalized Snell's Law (Capasso group)





N. Yu, et al. Science, 2011 (Capasso Group)

Principle of least action → The difference between blue and red path is zero

For reflection

$$sin\theta_r - sin\theta_i = n_i^{-1}k_0^{-1}\nabla\Phi$$

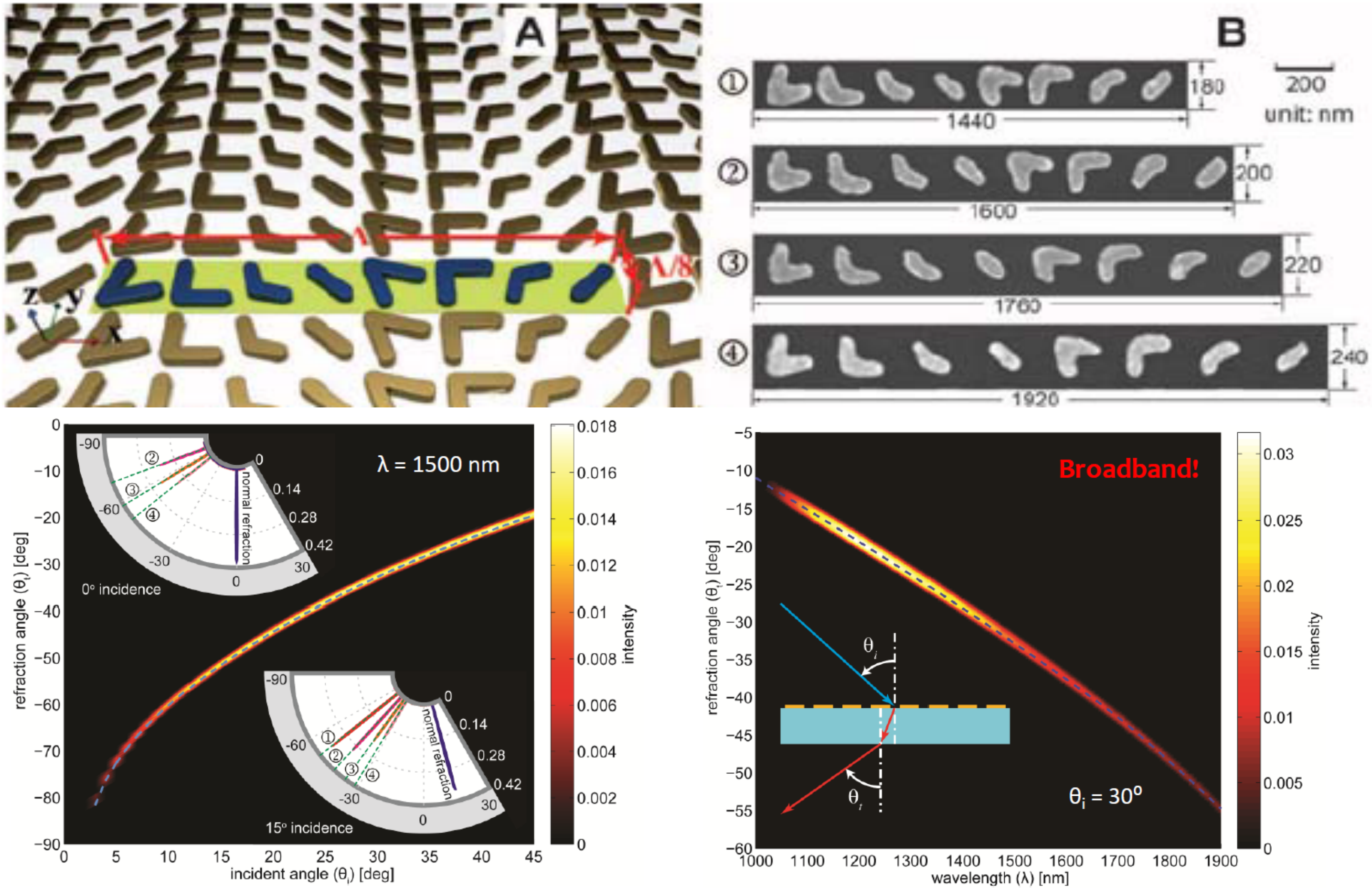
For refraction

$$n_t sin\theta_t - n_i sin\theta_i = k_0^{-1}\nabla\Phi$$

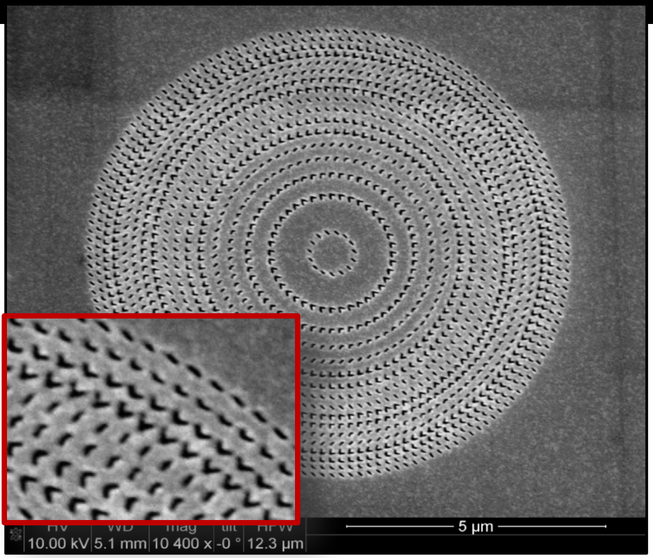
Broadband Light Bending

Operating at 1–1.9μm

Ni et al, *Science* *335* (2012)
(Shalaev group)



Meta-lens and Meta-holograms



Ni et al, *LSA 2, e72,* (2013)

Ni et al, *Nat Comm 4, 2807* (2013)

See also:

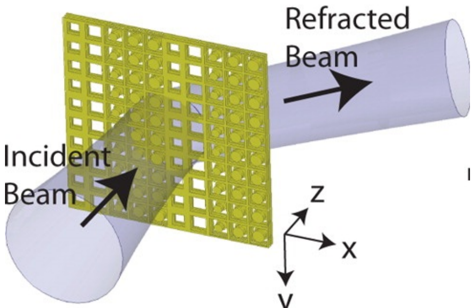
Meta-lens:
- Aieta et al., Nano Lett. 12, 4932 (2012) (Capasso group)
- Chen et al., Nat Comm 3, 1198 (2012) (S. Zhang & Zentgraf groups)

Meta-holograms:
- S. Larouche et al., Nat. Mat. 11, 450 (2012) (D Smith group)
- Lin et al, Nano Lett 13, 4269 (2013) (Capasso group)
- Huang et al, Nano Lett 15, 3122 (2015) (Tsai group)
- Zheng et al, Nat Nanotechnology 10, 308 (2015) (Guixin Li, Zentgraf, S Zhang groups)
- Kuznetsov et al, Sci Reports 5, 7738 (2015)

Bozhevolnyi group:
Gap plasmons for metasurfaces

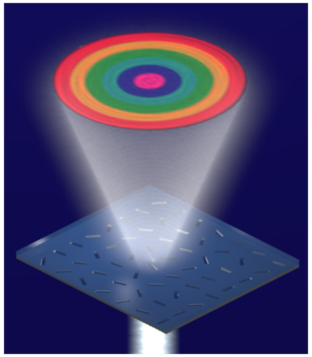
Metasurface optical devices

Huygens' surfaces

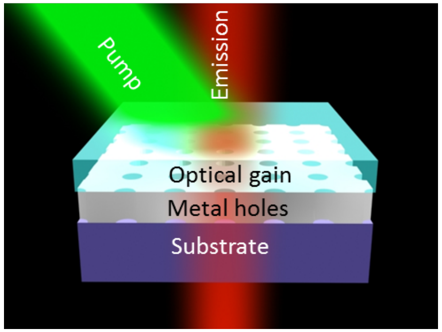


C Pfeiffer et. al., *Nano Lett.*, 14 (5), **2014**

Color Hologram

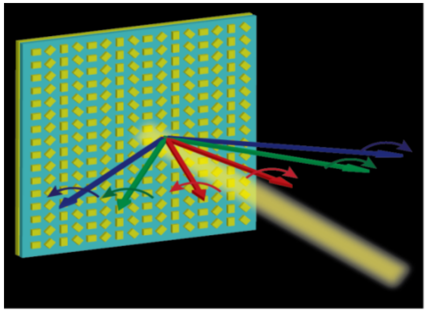


Active metasurface for lasing



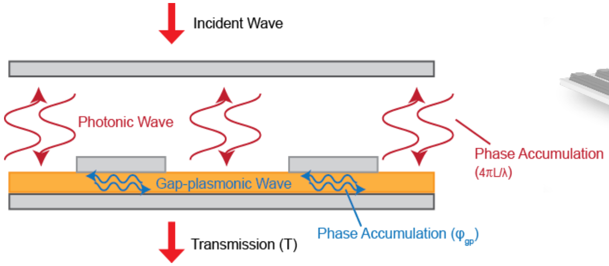
X. Meng et al, LPR (2014)

CD Spectrometer

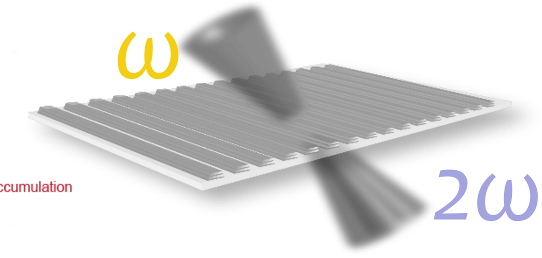


A. Shaltout et. al., *Optica* **2015**

Nanocavity

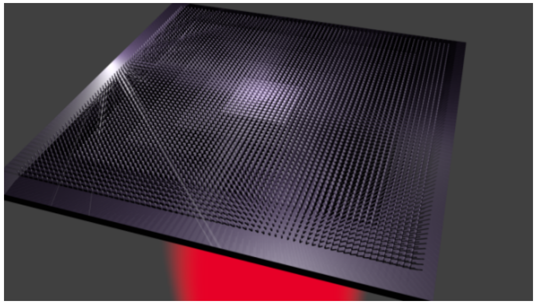


SHG with metasurfaces



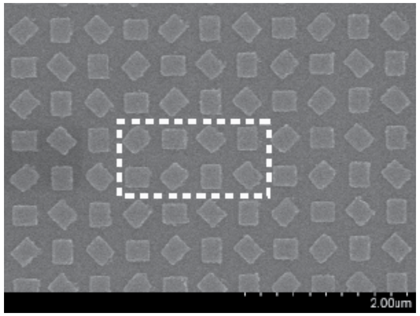
R. Chandrasekar et al, OMEX (2015)

Dielectric Metasurface Lens



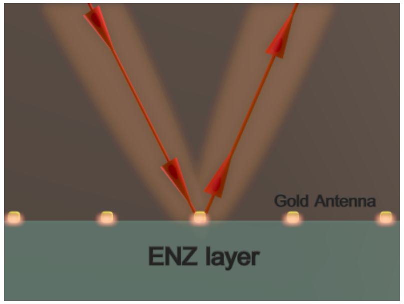
P. R. West, et al, *Opt. Express*, (2014)

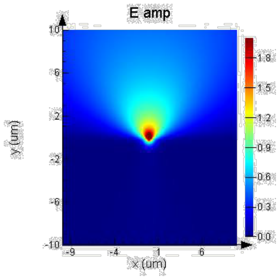
Broadband Optical Rotator



D. Fang et al, ACS Nano (2015)

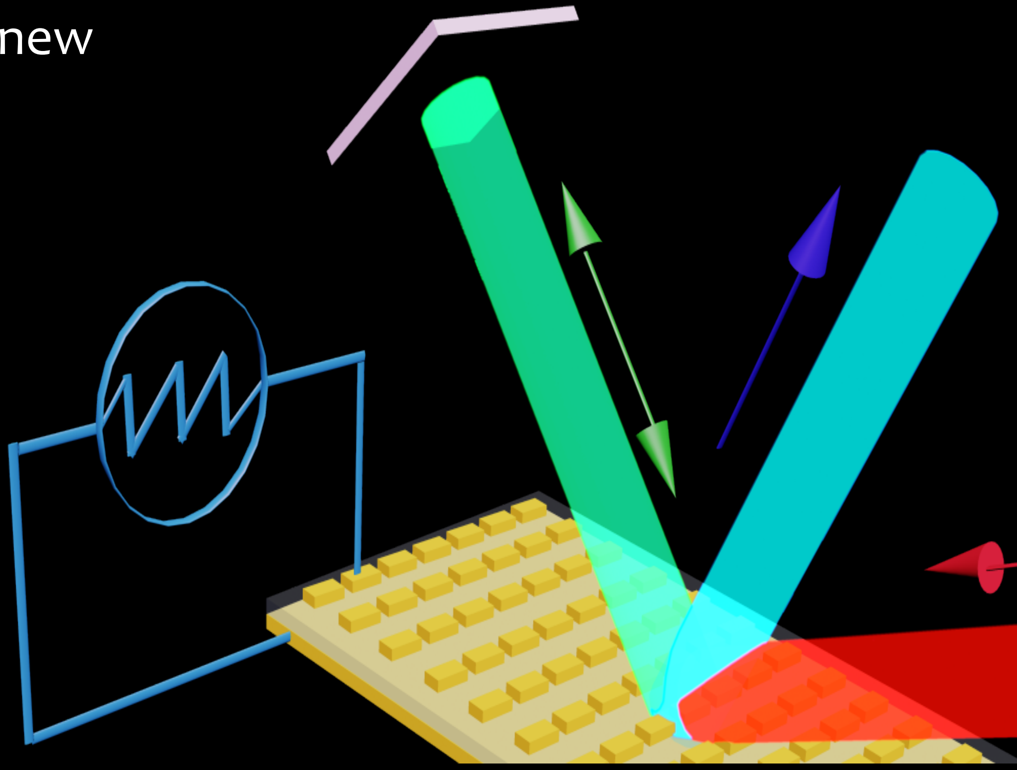
Antenna on ENZ





Time-Gradient Metasurfaces

Space-gradient metasurfaces relaxed Snell relation.
Time-gradient Metasurfaces enable new effects:
- Non-reciprocal Snell relation
- Doppler-like wavelength shift
- Energy exchange with light



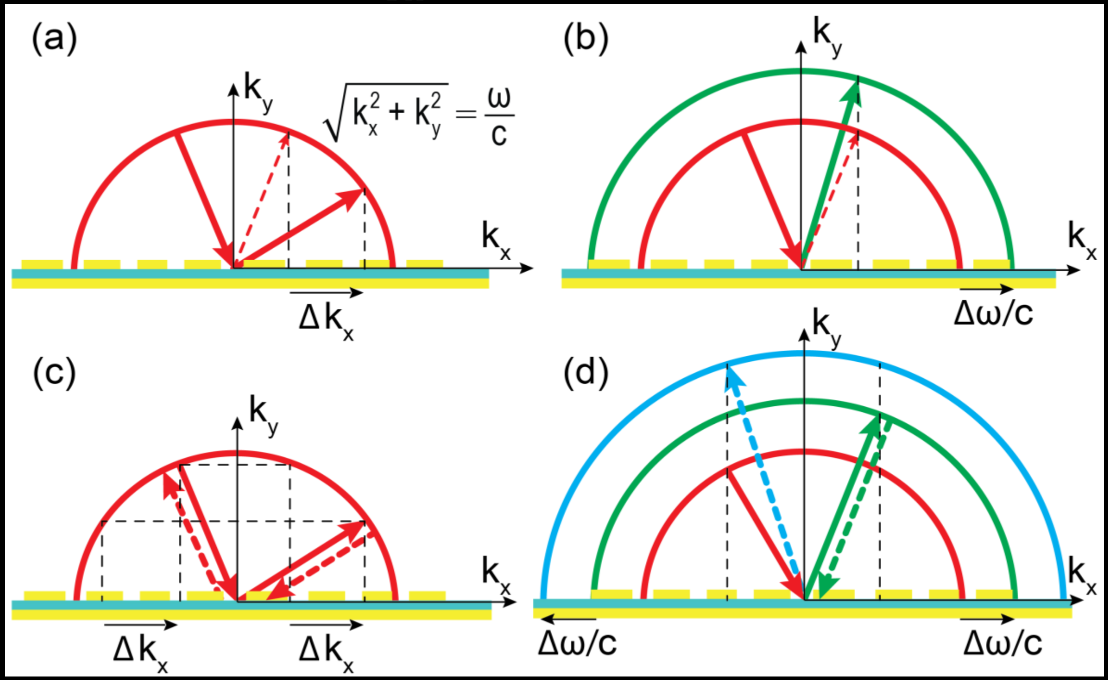
Shaltout et al. "Time-Varying Metasurface and Lorentz Non-reciprocity", arXiv 1507.04836 (2015)

See also non-reciprocal EIT effect: Hadad et al, "Space-time Gradient metasurfcaes", PRB 92(10), 2015.

Gradient metasurfaces: conservations laws & Lorentz non-reciprocity

- Conventional Snell's law conserves photon momentum and energy
- Space-gradient metasurface breaks momentum conservation (generalized Snell)
- Time-gradient metasurface breaks photon energy conservation (non-reciprocal universal Snell)

$$\Delta p_x = \hbar(\Delta k_x) = \hbar\frac{\partial \psi_{ms}}{\partial x} \qquad \Delta E = \hbar(\Delta\omega) = -\hbar\frac{\partial \psi_{ms}}{\partial t}$$



A. Shaltout et al. "Time-Varying Metasurface and Lorentz Non-reciprocity", arXiv 1507.04836 (2015)

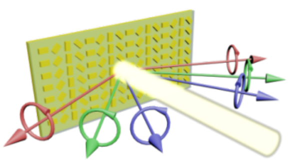
B. See alsom relevant work by M. Fink on time-reversial applications

Motivation: Metasurfaces for on-chip Photonics

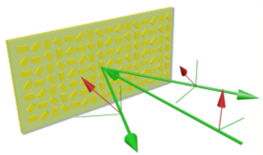
Objective: *unified on-chip metasurface platform* for photonic devices & systems

All-around Optical Control

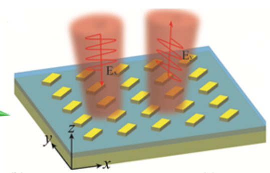
Polarization Control Devices



Circular Dichroism Spectrometer



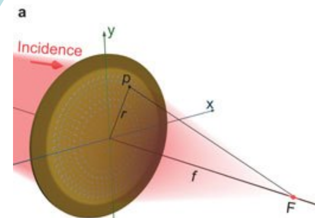
Optical Rotator



Half-wave plate

Optica, 2(10), 860 (2015)
ACS Nano, 9(4), 4111 (2015)

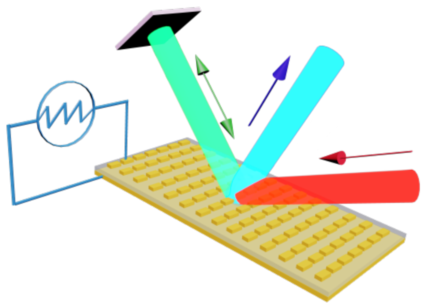
Phase Control devices



Meta-lens

Meta-hologram

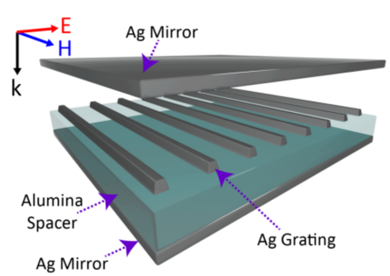
Non-Reciprocal Devices

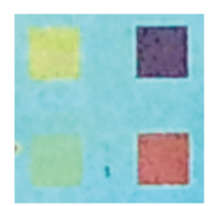


Time-Varying Metasurface

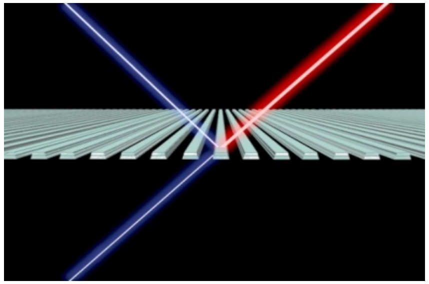
OMEX, 5(11), 2459 (2015)

Nano-Cavities & Color filters





Optical Non-linear Devices



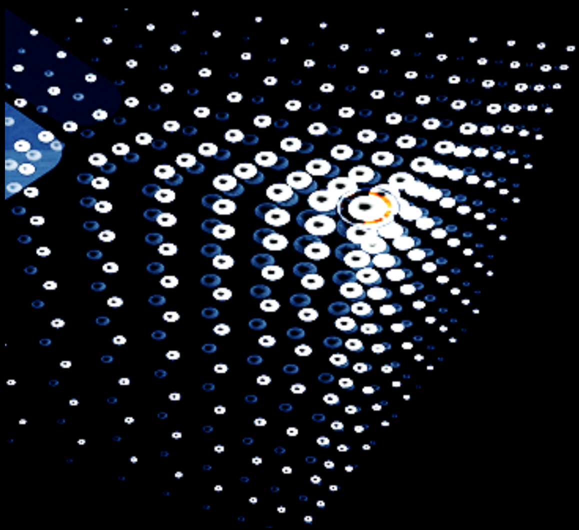
Second Harmonic Generation

OMEX, 5(11), 2682 (2015)

What we discussed today

Metamaterials:

- Electrical metamaterials (plasmonics) for nanophotonics
- Magnetic metamaterials and negative refractive index
- Metamaterials for super-resolution
- Optical cloaking
- Metasurfaces



METAMATERIALS

"Everything you look at can become a fairy tale and you can get a story from everything you touch."

— Hans Christian Andersen