Illusion Optics and Photonics: a brief introduction

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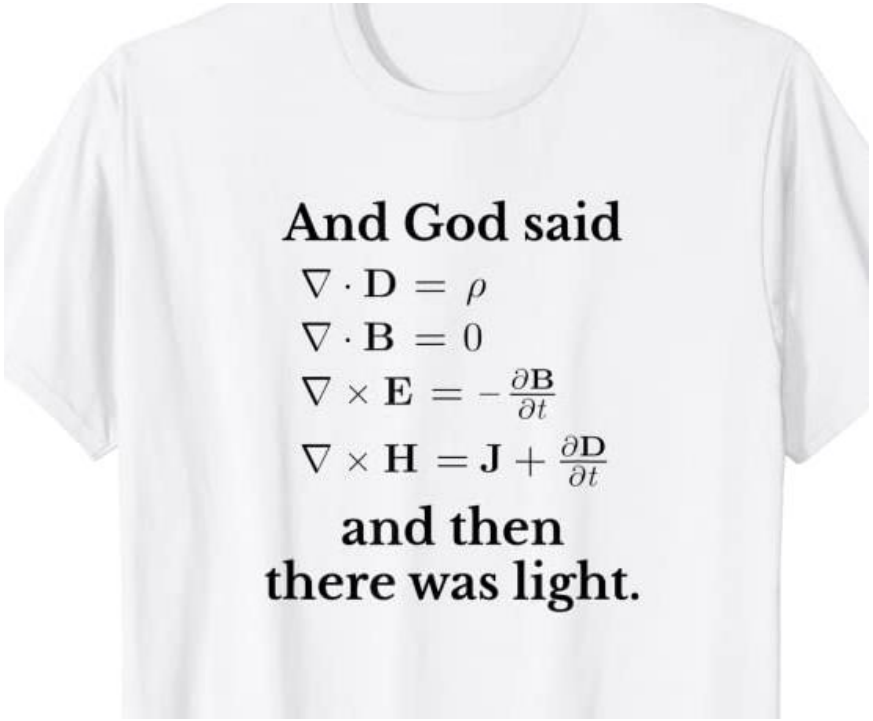
Light Sciences meet optical illusions – Firenze, 24/05/2022

Maxwell equations and e.m. waves

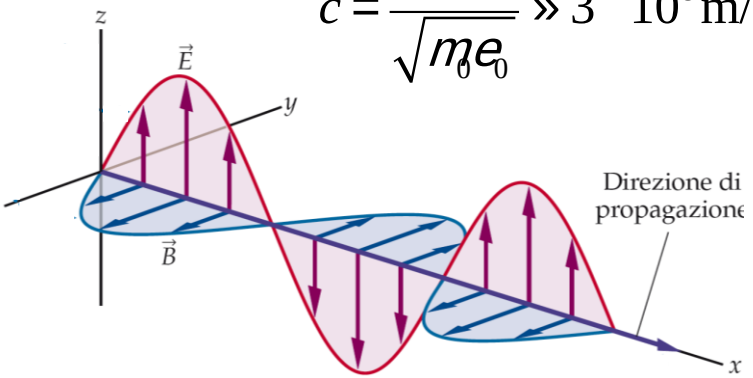


with $\mathbf{D}(\mathbf{r},t) = \varepsilon_0 \varepsilon(\mathbf{r}) \mathbf{E}(\mathbf{r},t)$

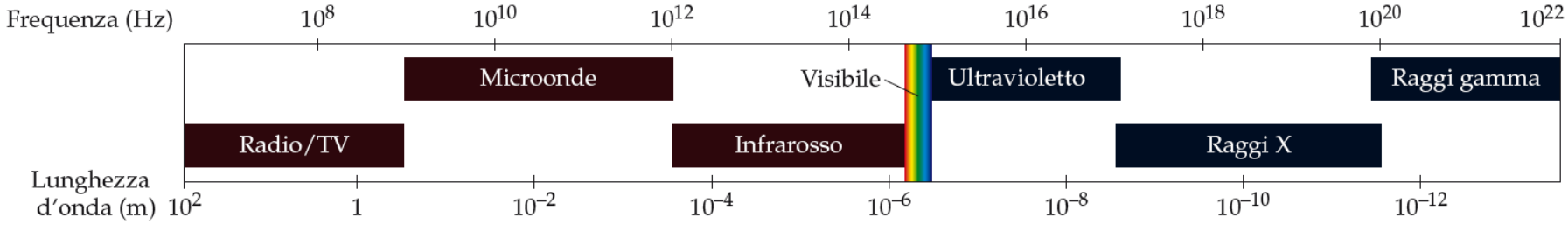
$\mathbf{H}(\mathbf{r},t) = \mu_0 \mu(\mathbf{r}) \mathbf{B}(\mathbf{r},t)$

A solution: e.m. waves in vacuum
all propagating at the same speed

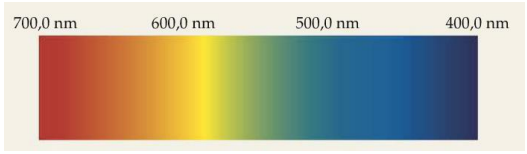
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3 \times 10^8 \text{ m/s}$$



$$\lambda = \frac{c}{f}$$

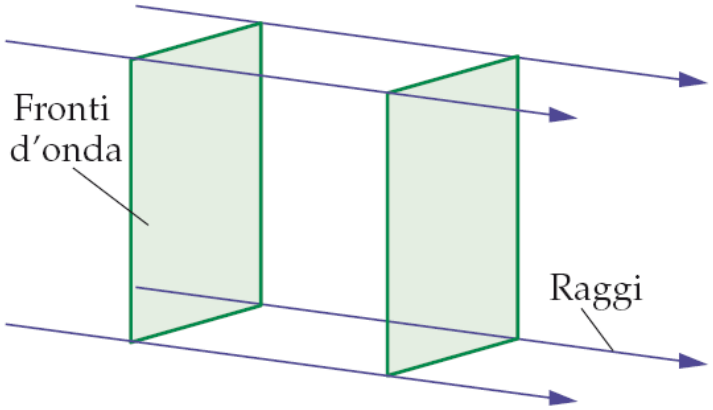


visible spectrum → LIGHT!



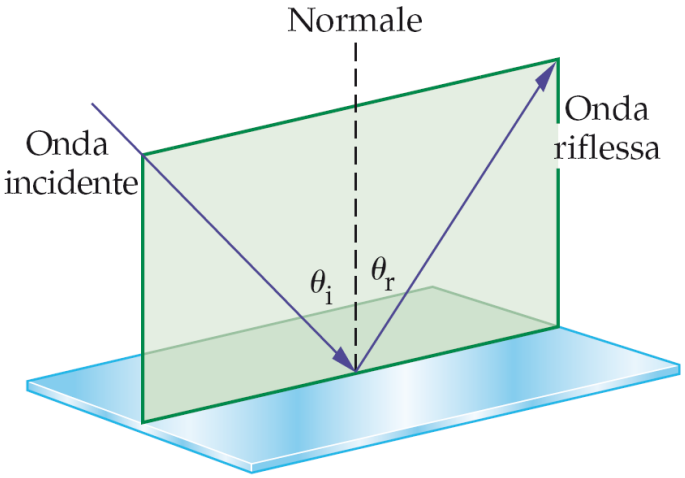
Geometrical optics: Reflection law

- Far from sources → **plane wave approximation**



- For visible light → **ray optics theory (geometrical optics)**

- **Reflection** at interfaces → $q_i = q_r$



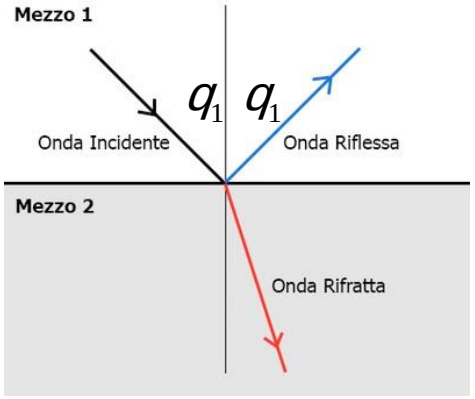
Geometrical optics: Refraction law

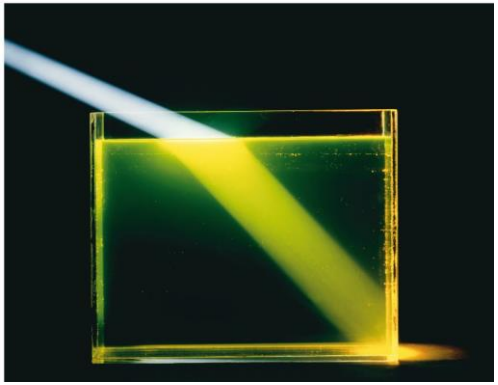
- Speed of light in a homogeneous medium → $$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \mu_r \varepsilon_r}} = c\frac{1}{\sqrt{\mu_r \varepsilon_r}}$$

- Refractive index in transparent, non magnetic media $$\mu_r = 1 \Rightarrow v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{c}{n}$$

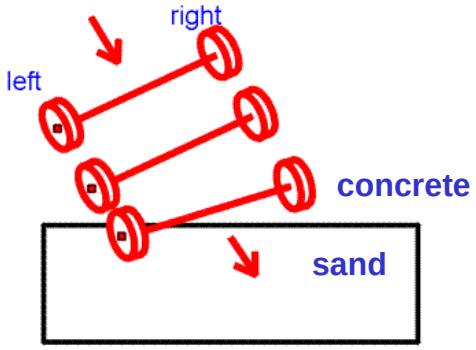
- **Refraction** law (Snellius, ~1620)

$$\frac{v_1}{\operatorname{sen}\theta_1} = \frac{v_2}{\operatorname{sen}\theta_2} \Rightarrow \boxed{n_1 \operatorname{sen}\theta_1 = n_2 \operatorname{sen}\theta_2}$$



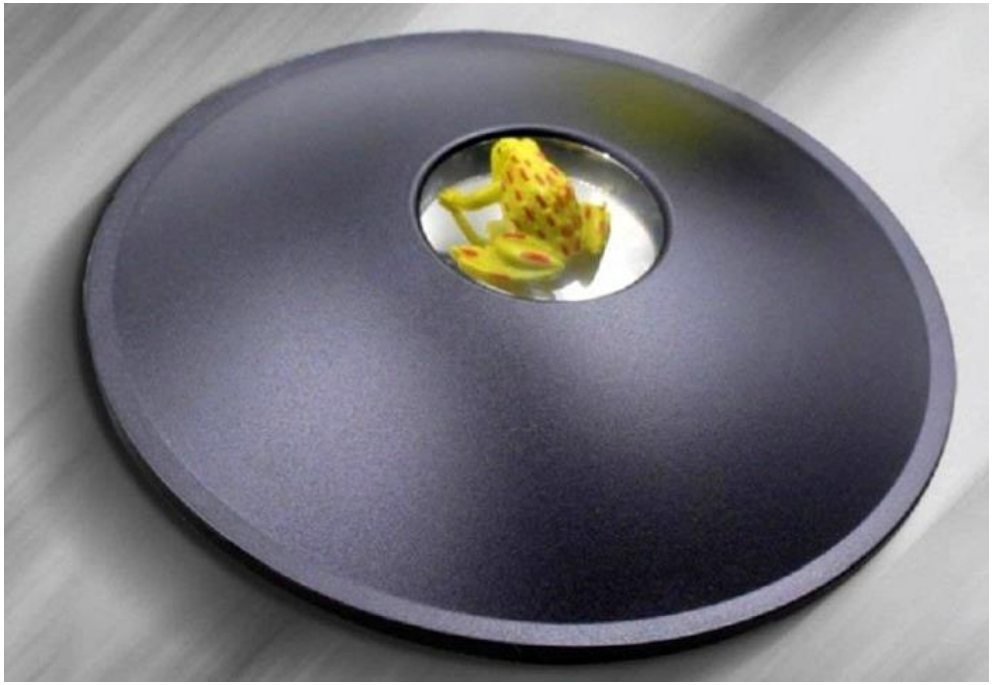


mechanical analogy

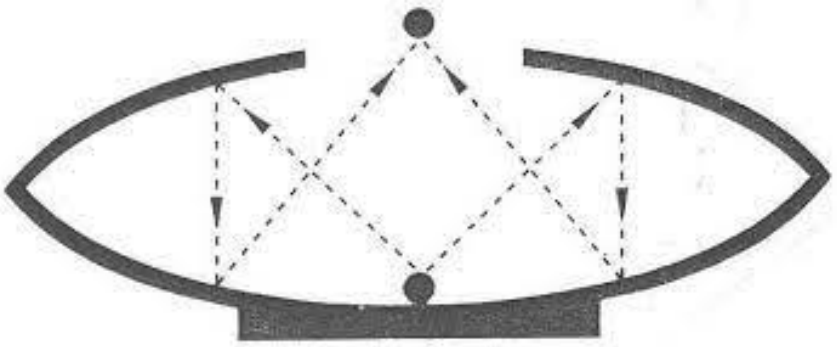


Simple illusions from reflections

3D image: a virtual object appears in a defined position



...due to double reflection
at facing concave mirrors
when object is in the focus

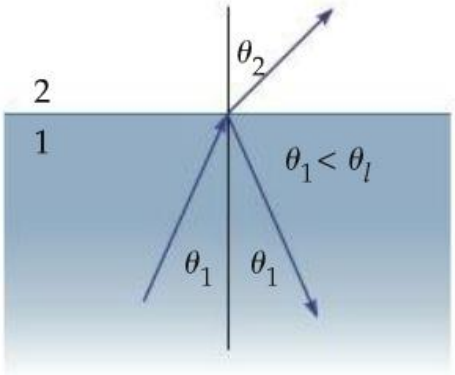


don’t believe what you see

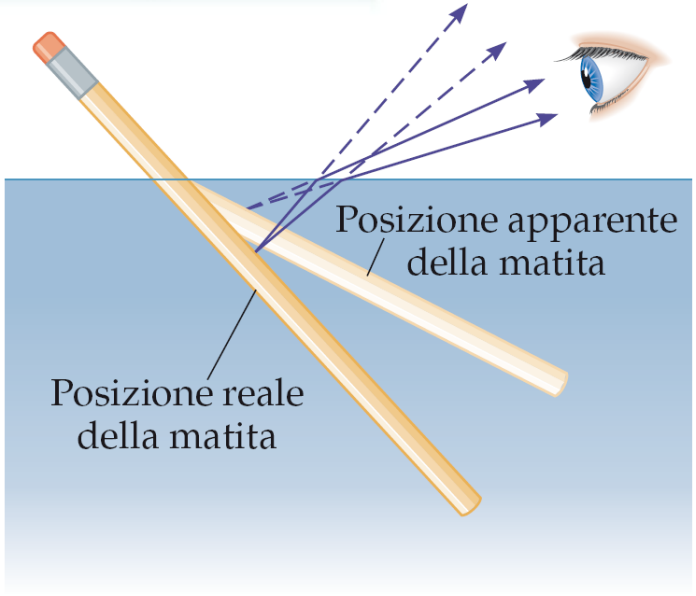
Simple illusions due to refraction

Broken objects...

...due to passage from high refractive index medium to low refractive index one



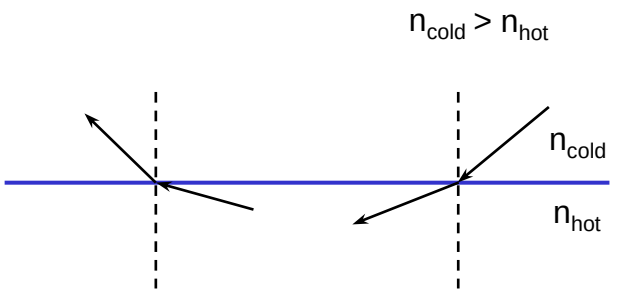
from Snell's law

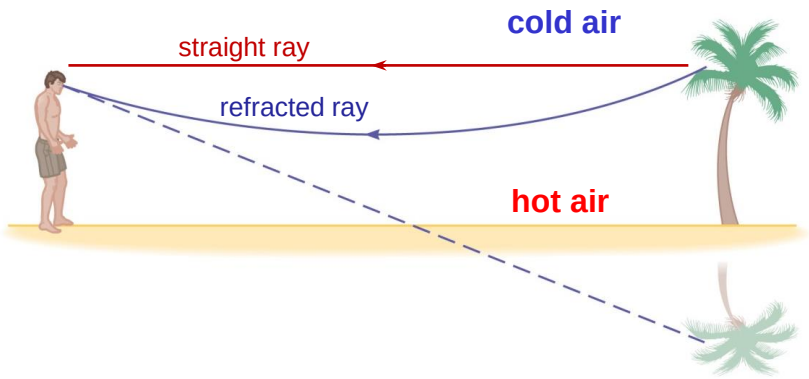


Mirages

Appearence of virtual islands and water in desert

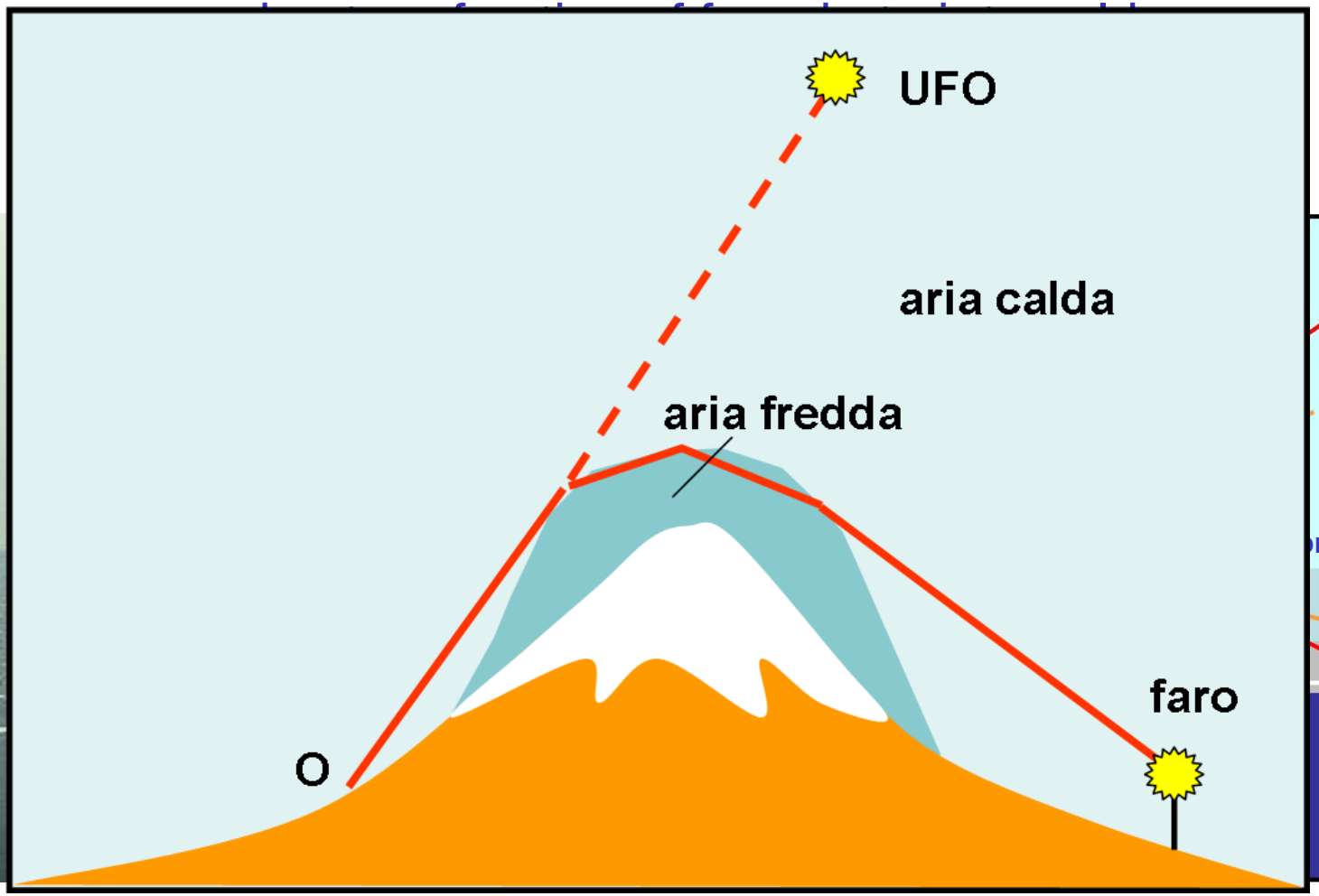
...due to refraction of from cold air to hotter (next to the ground) and back...water-like appearence due to blue components of light

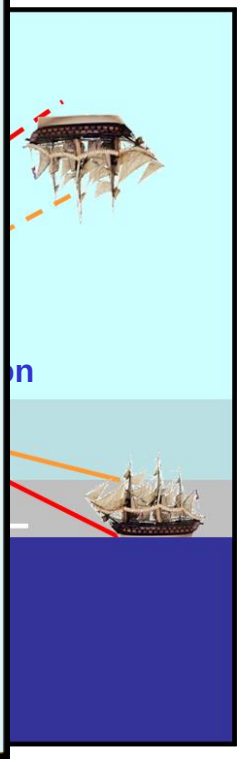




Fata Morgana mirage effect

Floating objects appearing...

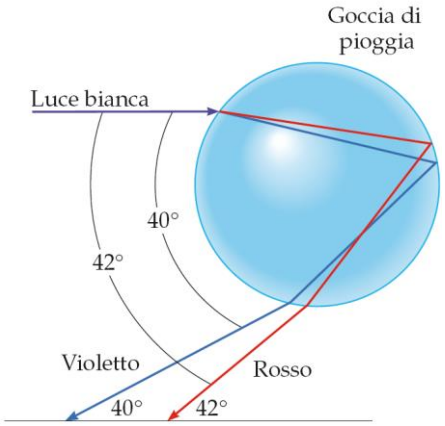




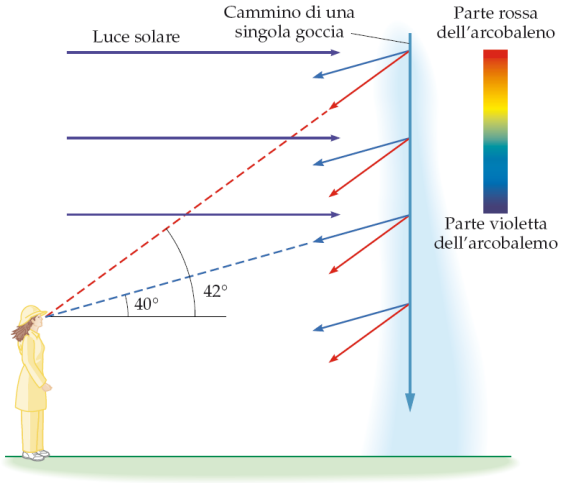
...and even more complex phenomenology

Rainbows

...due to **dispersion**, **reflection**, and **refraction** from water droplets

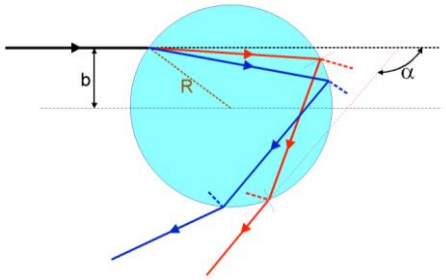


light dispersion: different colors propagate at different speeds



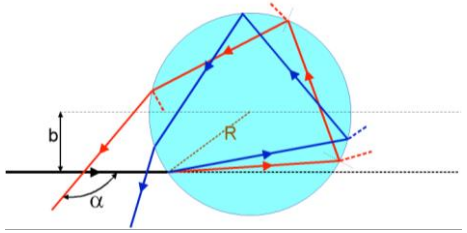
primary rainbow

$a \approx 40^{o}$



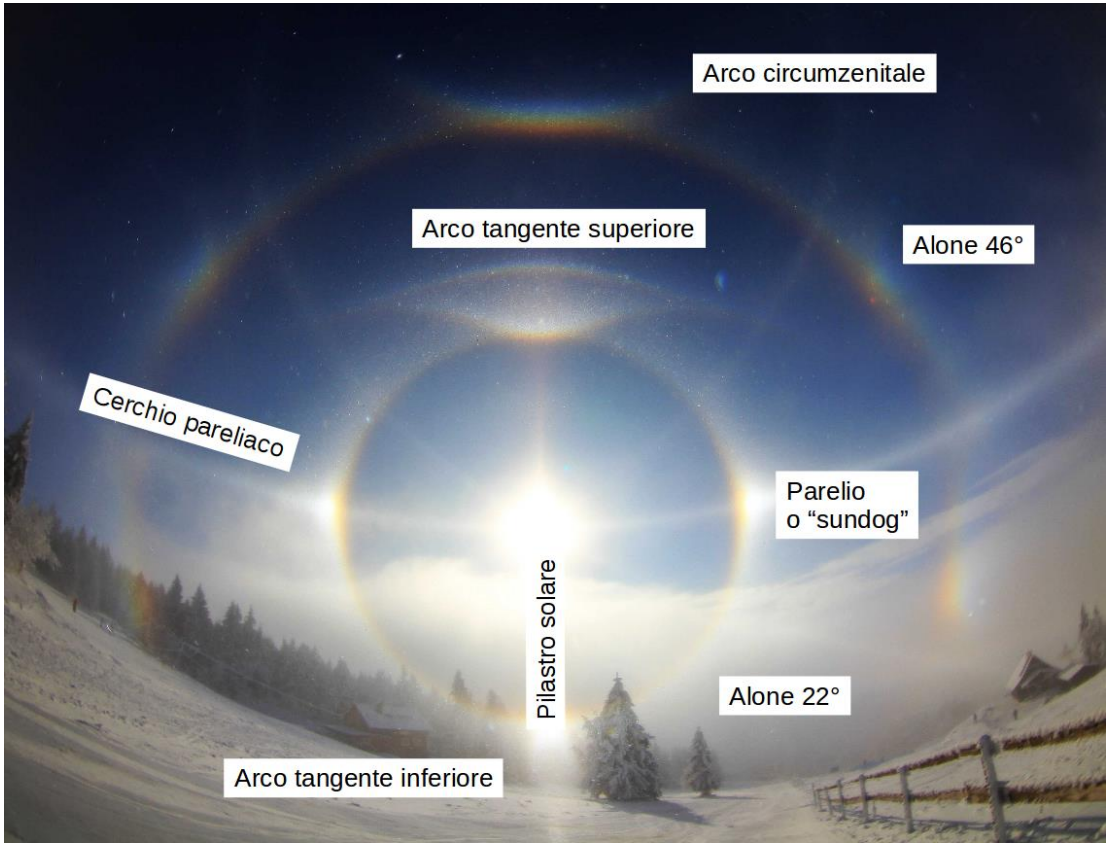
secondary rainbow

$a \approx 50^{o}$

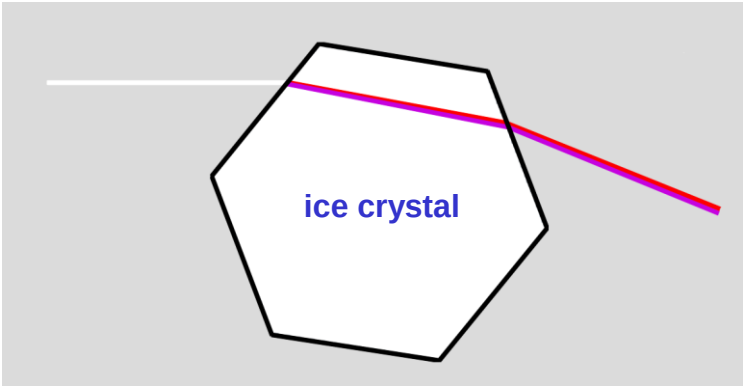


22º halo

Circular rainbow-like halo with around sun (or moon)

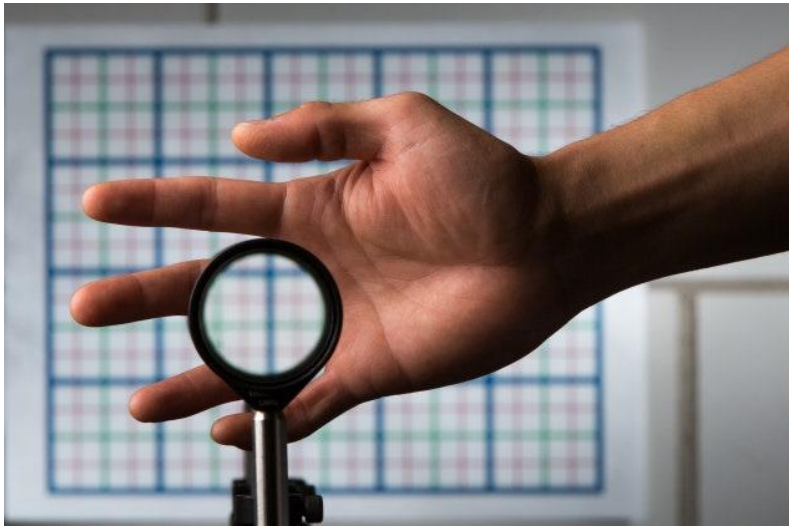


...due to double refraction through randomly oriented, hexagonal ice crystals



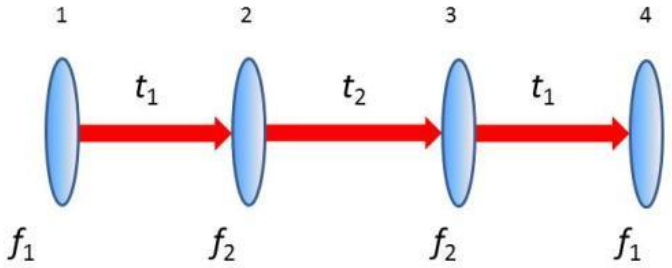
...and more complex phenomenology

Invisibility



$t_1 = f_1 + f_2$

$t_2 = 2f_1(f_1+f_2)/(f_1-f_2)$

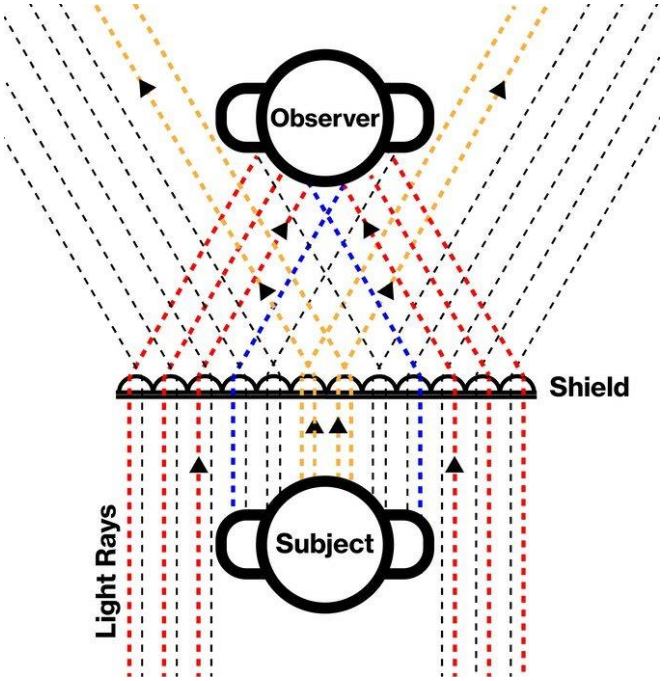


Commercial cloaking?

DIEGO BARBERA GADGET 16.03.2022

Hanno inventato (davvero) il mantello dell'invisibilità

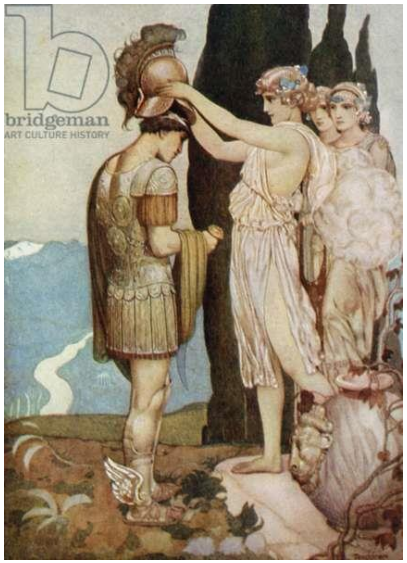
Costa 350 euro ed è un curioso progetto apparso su Kickstarter, che si rivolge a “chi vuole stupire gli amici e nascondersi dai nemici”



Invisibility cloak...is it possible?

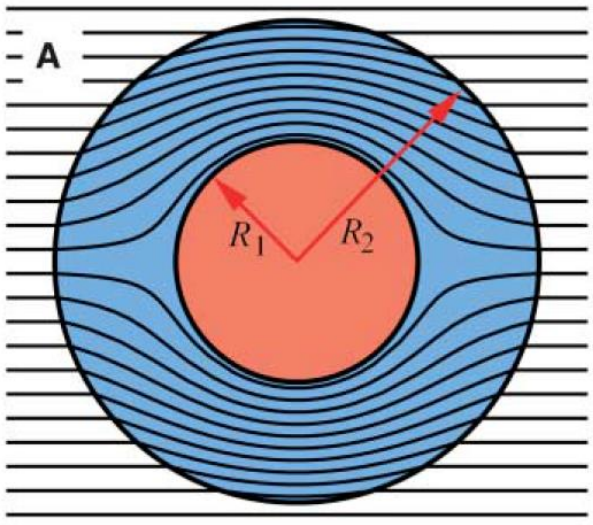
- Invisibility in Greek mythology

Perseus wearing the cap of invisibility →



- Invisibility in modern Optics

Sir John Pendry



J. B. Pendry, D. Schurig and D. R. Smith, Science **312**, 1780 (2006)

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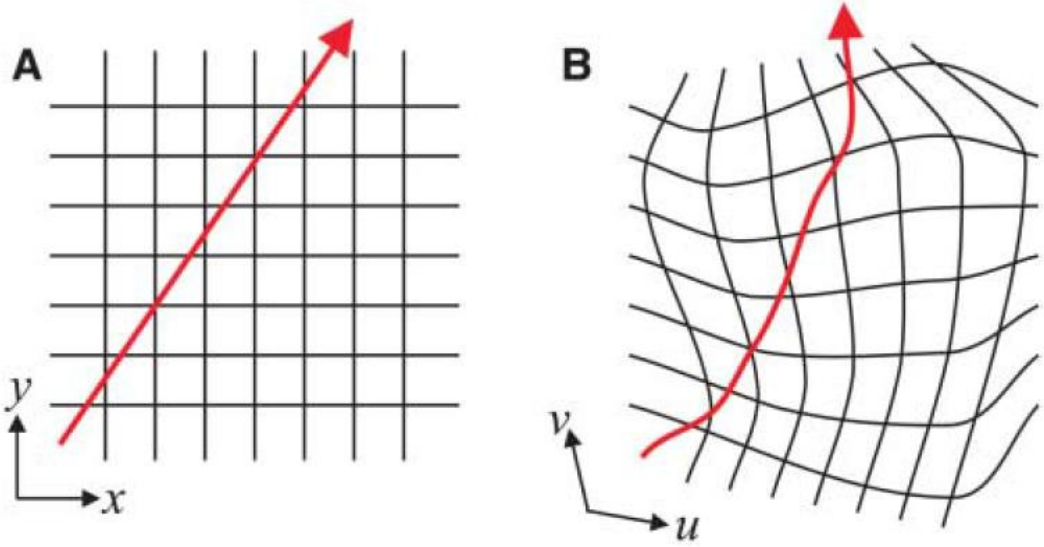
A new paradigm: transformation optics

ray optics in cartesian space



ray optics in distorted space

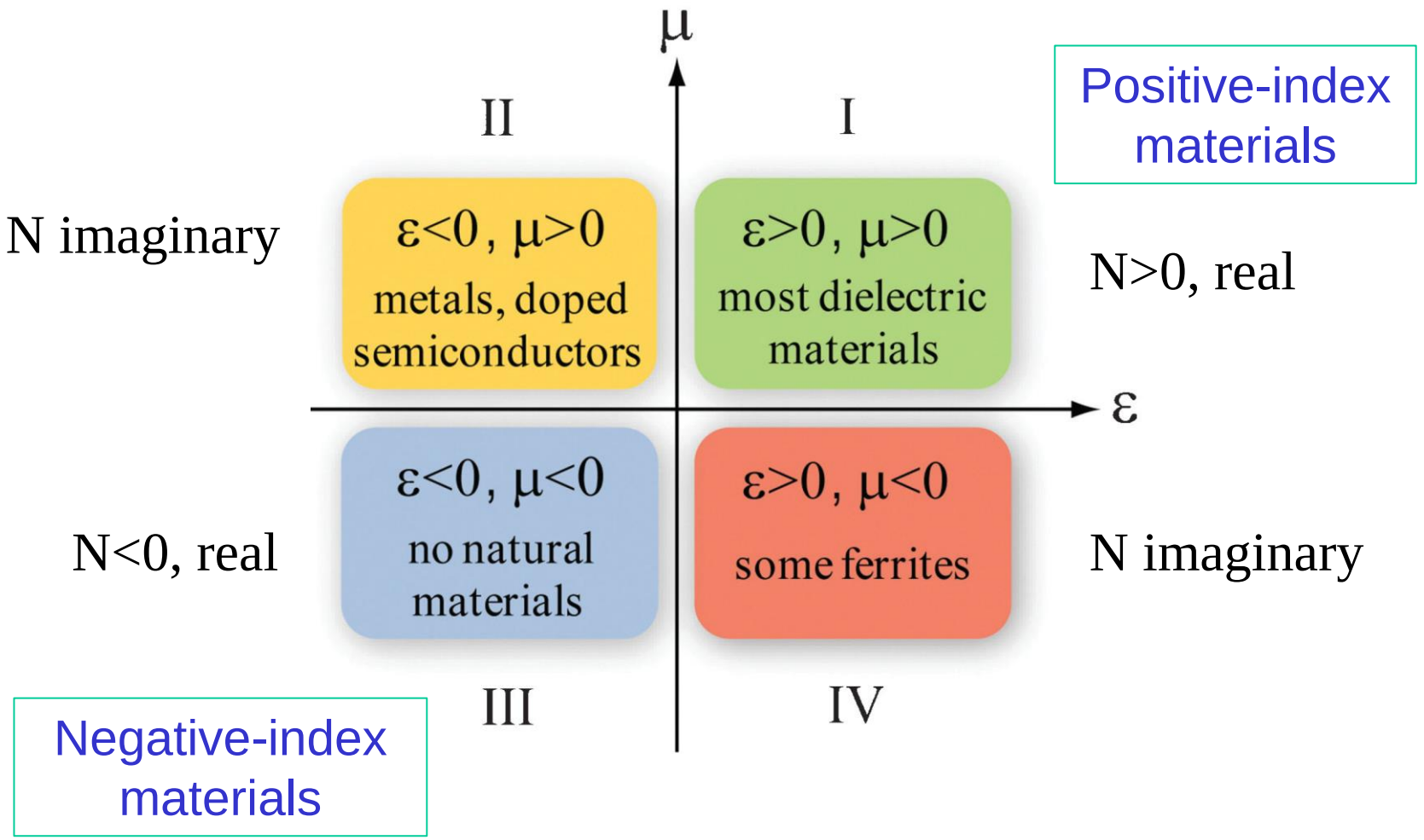
Fermat's principle can be modified by suitably engineered inhomogeneous electromagnetic media through $\varepsilon(\mathbf{r})$ and $\mu(\mathbf{r})$

PRINCIPLES BORROWED FROM GENERAL RELATIVITY

J. B. Pendry, D. Schurig and D. R. Smith, Science **312**, 1780 (2006)

The parameters space of e.m. response in dense media

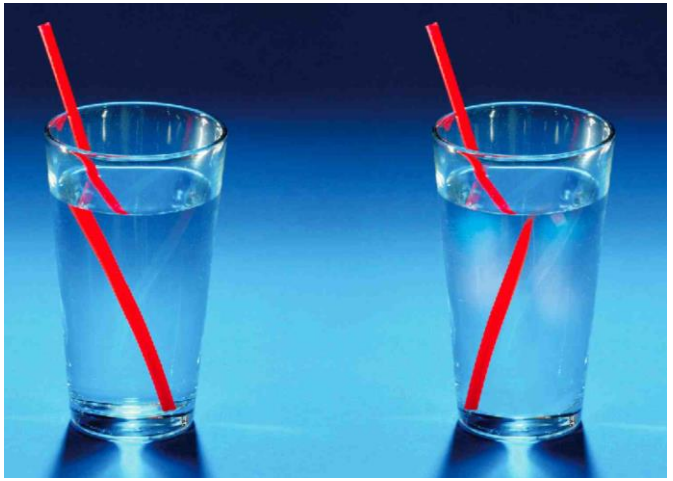
Generalized refractive index $N = \pm\sqrt{\varepsilon_r \mu_r}$



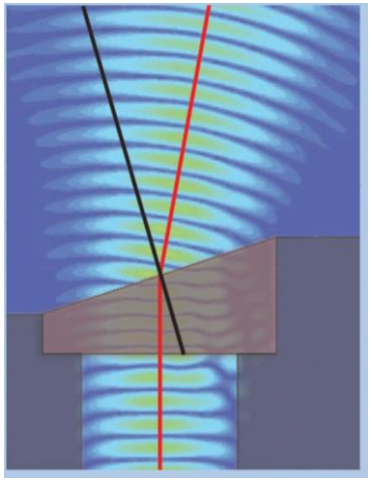
Negative refraction

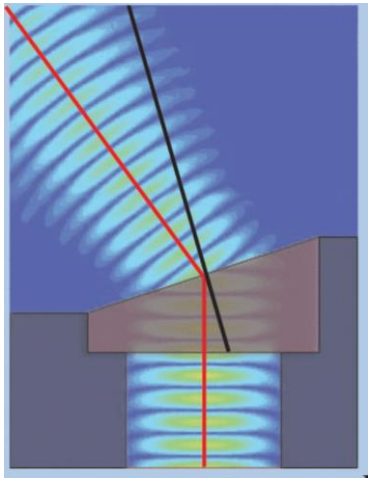
V. G. Veselago (1929-2018)

what would happen?



Numerical simulation from Maxwell equations

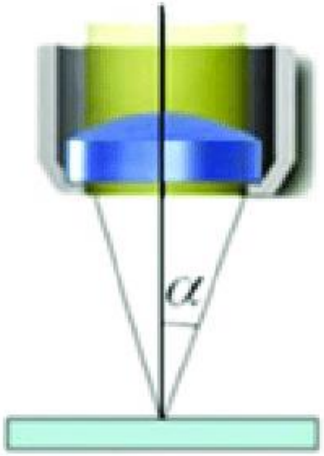




J. B. Pendry, Physics Today **57**, 6, 37 (2004)

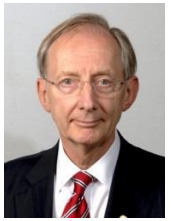
Superlensing

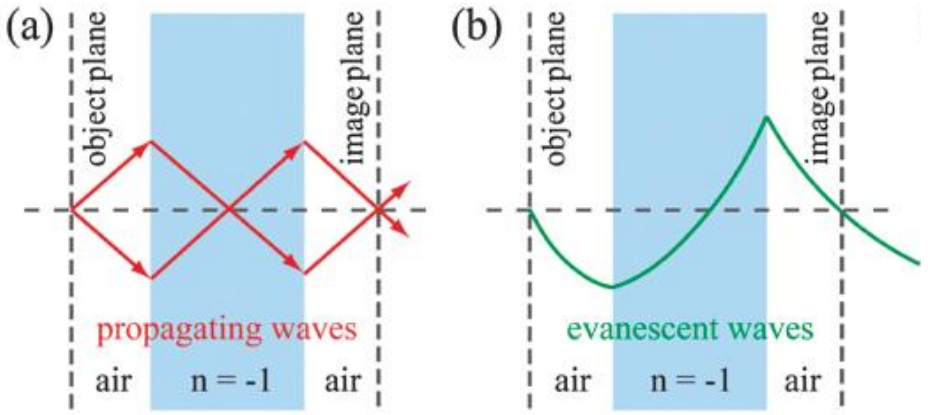
Normal lens: diffraction limit
(E.K. Abbe, 1873):



The resolution is limited to λ
by evanescent waves, which
cannot be refocused

a negative index layer is able to amplify evanescent components, thus allowing (in principle) full refocusing not wavelength dependent!





Perfect lens = image formation and focusing beyond diffraction limit.
Both propagating and evanescent waves contribute to resolution

J.B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000) [>14000 citations!]

Photonics: light as an e.m. wave

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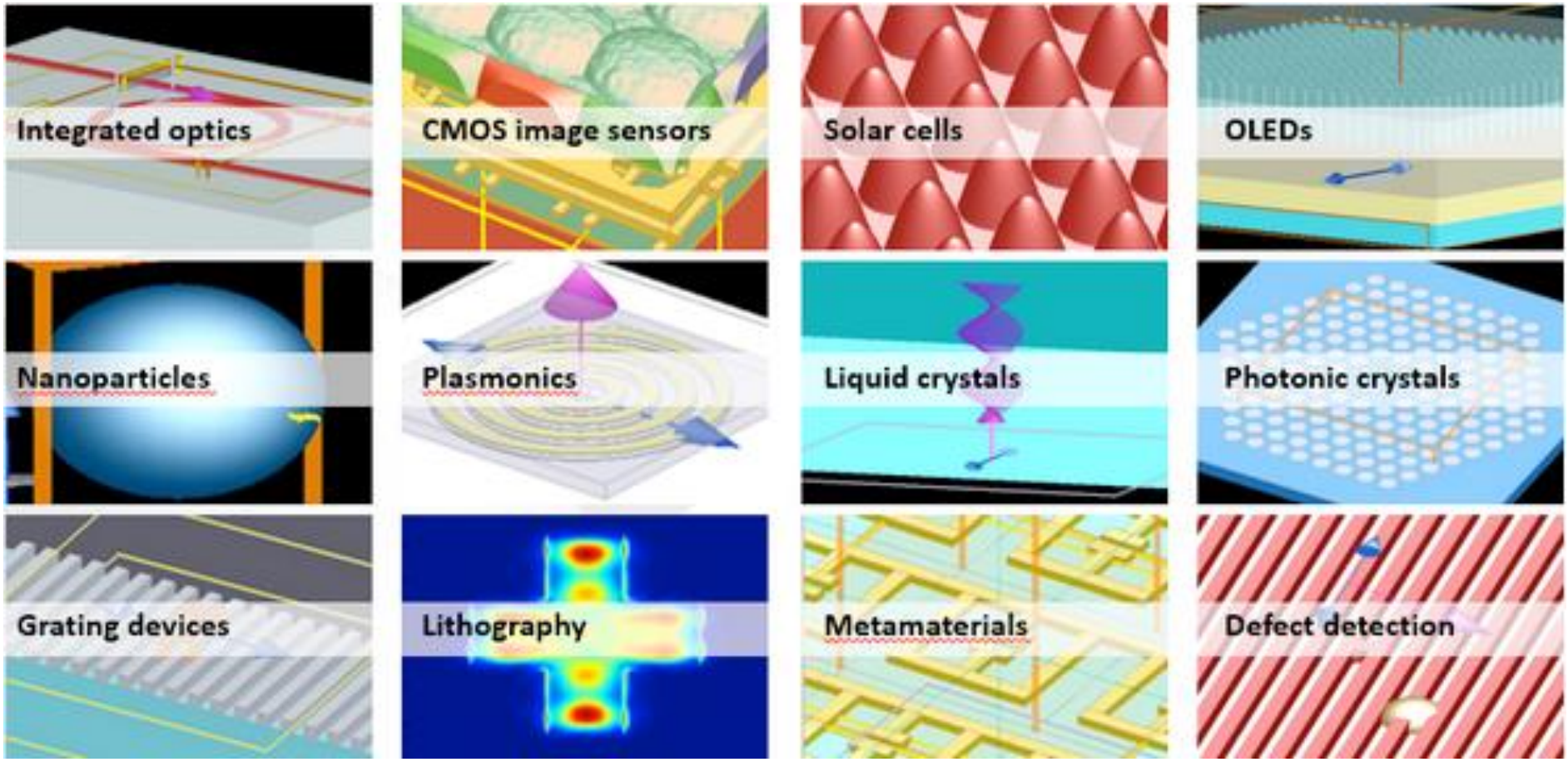
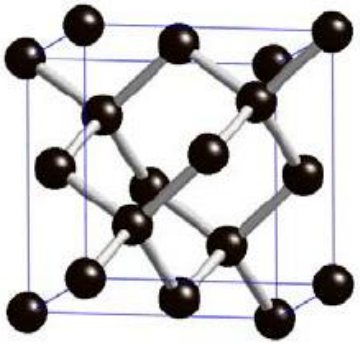
Solving Maxwell equations in complex media, scattering features on the order of light w.length



https://www.lumerical.com/

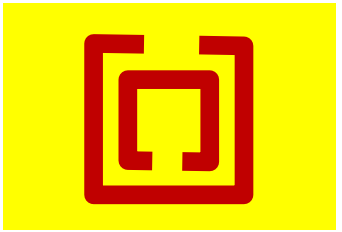
Metamaterials

Normal material:
from the atoms in the lattice…

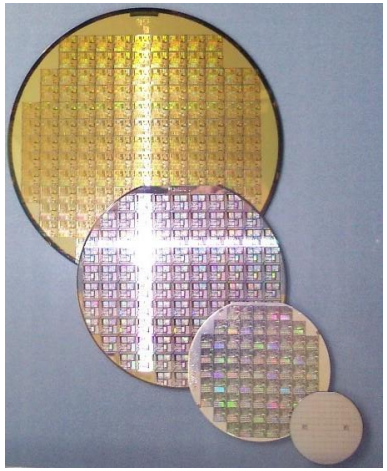


Metamaterial:
from the meta-atoms…

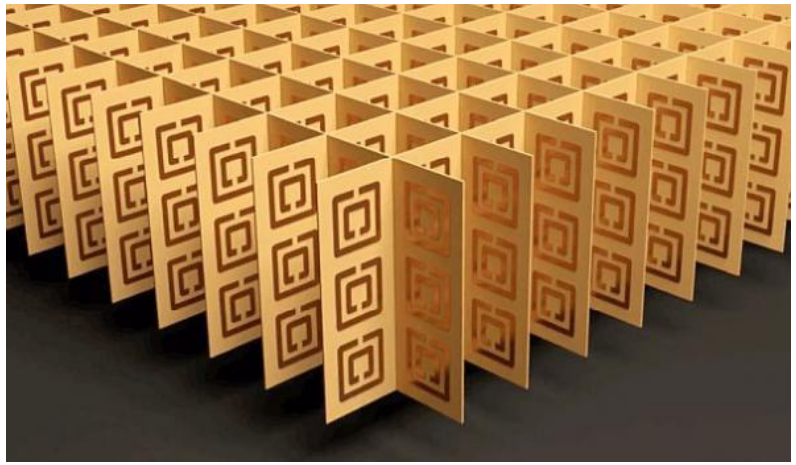
example:
split-ring resonator



… to the solid (with useful properties)

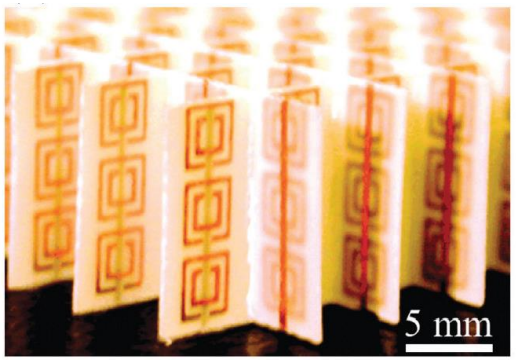


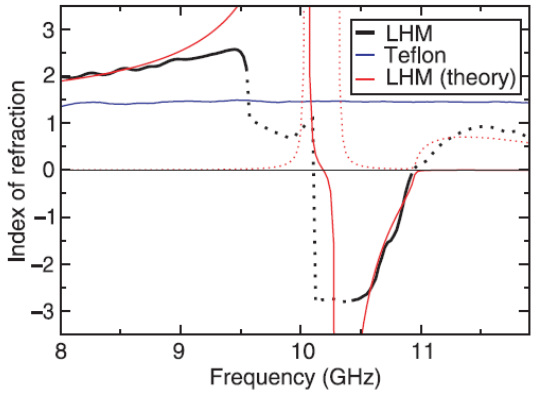
… to an artificial (effective) material with tailored optical properties



Negative effective index

- **microwave metamaterial**

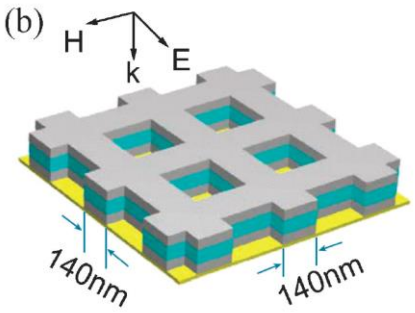


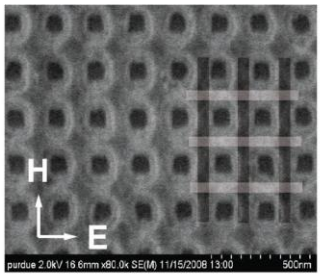


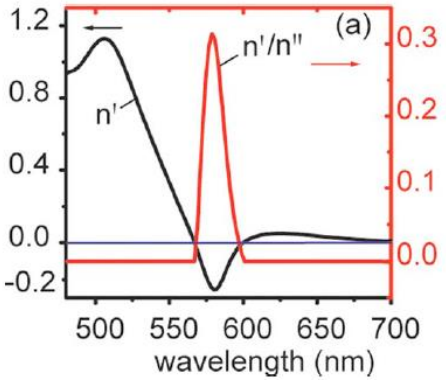
ν~10 GHz, λ~ 3 cm

R. A. Shelby, D. R. Smith and S. Schultz, Science **292**, 77 (2001)

- **optical metamaterial**

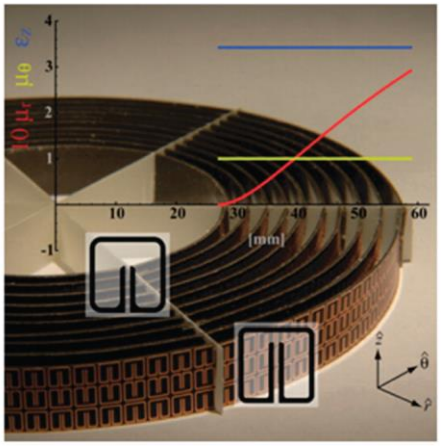


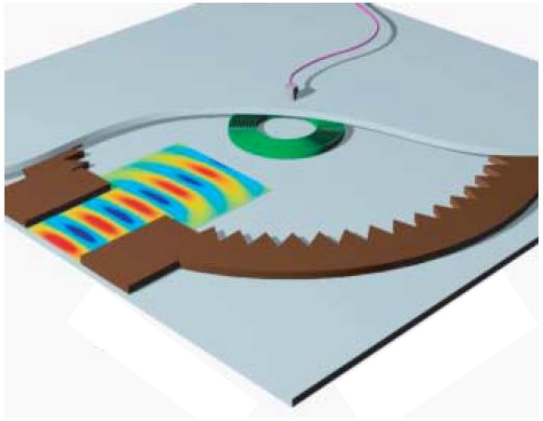




S. M. Xiao, …, V. M. Shalaev, Opt. Lett. **34**, 3478 (2009): Yellow-light NIM

Invisibility cloak...at microwaves

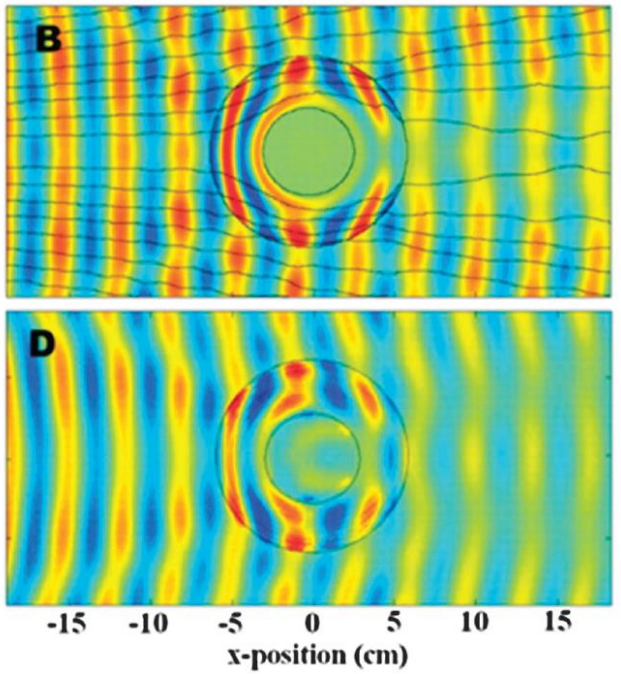




In-plane transmission
field profiles, $\nu = 8.5$ GHz

simulation

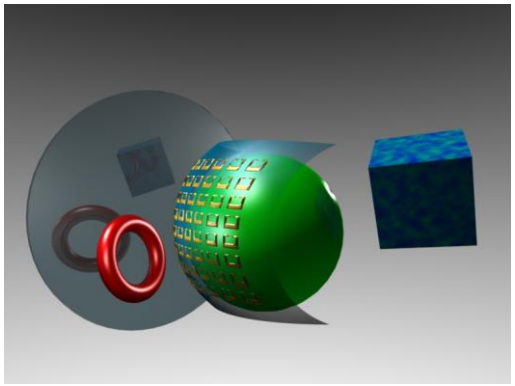
experiment

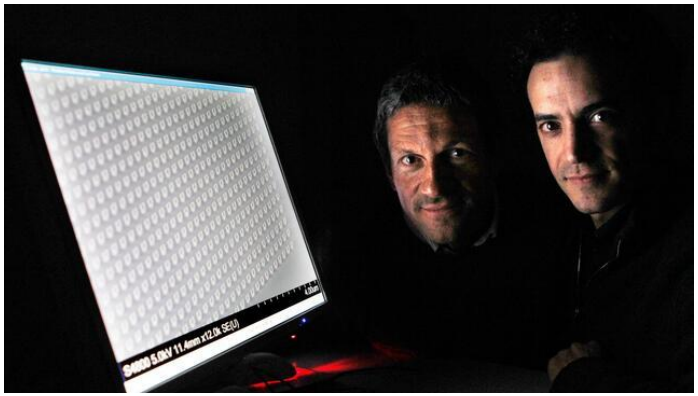


D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr and D. R. Smith, Science **314**, 977 (2006)

Metamaterials applications

- flexible cloaking



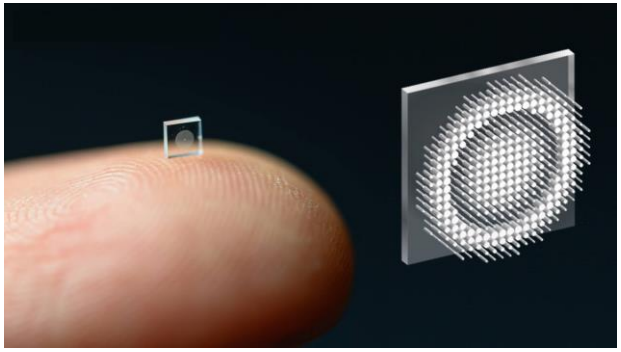


T. F. Krauss & A. Di Falco

http://www.2physics.com/2010/12/flexible-metamaterials-at-visible.html

New J.Phys. **12**, 113006 (2010)

- miniaturized cameras

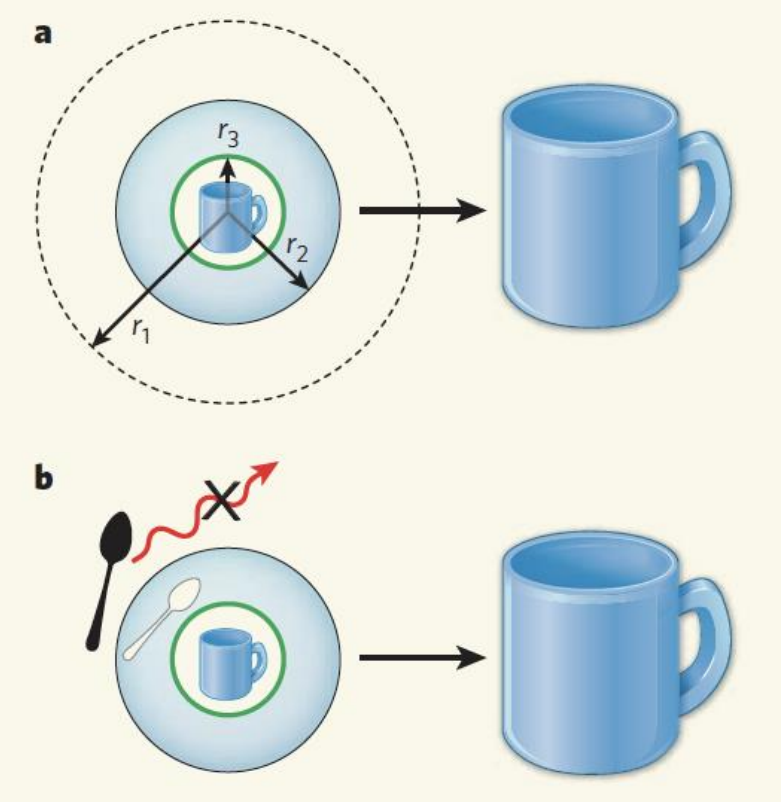


A. Majumdar & F. Heide

Nat. Comm. **12**, 6493 (2021)

https://www.princeton.edu/news/2021/12/02/researchers-shrink-camera-size-salt-grain

In the future: Illusion photonics



a negative refractive index shield is able to remove scattering from an object (e.g., a spoon), making it appear as a different one (e.g., a cup)

original idea → Y. Lai, …, C. T. Chan, Phys. Rev. Lett. **102**, 253902 (2009)

see also → J. B. Pendry, Science **312**, 1780 (2006)

Take home...

- Most simple illusions can be simply obtained and explained by neglecting the wave nature of electromagnetic fields at optical w.lengths

- Engineering artificial materials on the w.length scale allows to obtain optical effects and illusions not common to ordinary media

Illusion Photonics:
interface of electromagnetic theory, nanoscale engineering and manufacturing to create illusion devices

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