Metamaterials: a general definition

Artificial media with unusual electromagnetic properties

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Man-made,

Structures < wavelength,

Homogenization regime

??

Artificial media with unusual electromagnetic properties

Permittivty/permeability,

Refractive index,

Refraction/reflection

Propagation…

Metamaterials: a general definition

Man-made,
Structures < wavelength,
Homogenization regime

Artificial dielectrics can be viewed as metamaterials
(birefringence, dispersion)

Artificial media with unusual electromagnetic properties

Permittivty/permeability,
Refractive index,
Refraction/reflection
Propagation…

Metamaterials: a general definition

Man-made,
Structures < wavelength,
Homogenization regime

??
That cannot be found in nature
??

Artificial media with unusual electromagnetic properties

Permittivty/permeability,
Refractive index,
Refraction/reflection
Propagation…

Metamaterials: a research topic born in the early 2000s

Optical properties that cannot be found in nature

Negative index of refraction

Negative refraction

Left-handed materials

5 seminal papers (précurseurs, fondateurs)

1968: Viktor Veselago

"The electrodynamics of substances with simultaneously negative values of ε and μ"

What happens in a material when both the electric permittivity and the magnetic permeability are negative?

V.G. Veselago, Sov. Phys. Usp 10, 509 (1968). (first published in Russian in 1967)

1968: Viktor Veselago

Dispersion equation

$$\nabla^2 \mathbf{E} + \frac{\omega^2}{c^2}\varepsilon\mu\mathbf{E} = 0 \longrightarrow k^2 = \frac{\omega^2}{c^2}\varepsilon\mu$$

A simultaneous change of the signs of ε and μ has no effect

This situation can be interpreted in various ways. First, we may admit that the properties of a substance are actually not affected by a simultaneous change of the signs of ϵ and μ. Second, it might be that for ϵ and μ to be simultaneously negative contradicts some fundamental laws of nature, and therefore no substance with $\epsilon < 0$ and $\mu < 0$ can exist. Finally, it could be admitted that substances with negative ϵ and μ have some properties different from those of substances with positive ϵ and μ. As we shall see in what follows, the third case is the one that is realized. It

V.G. Veselago, Sov. Phys. Usp 10, 509 (1968). (first published in Russian in 1967)

1968: Viktor Veselago

Homogeneous material with $\varepsilon < 0$ and $\mu < 0$

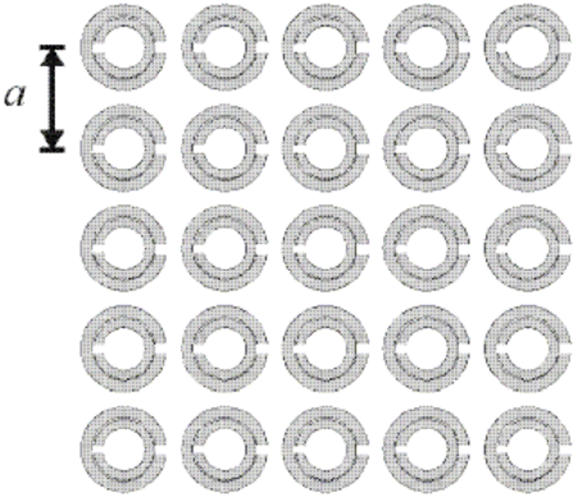
Left-handed material

Negative refraction

Negative index of refraction $n = -\sqrt{\varepsilon\mu}$

1999: John Pendry

"Magnetism from conductors and enhanced non-linear phenomena"



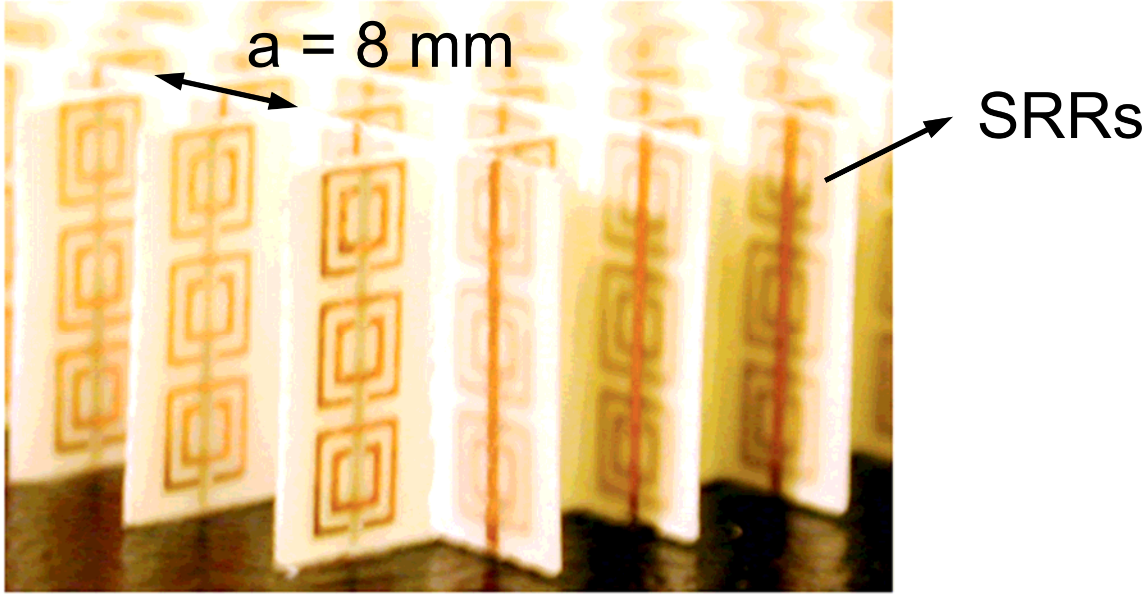
Split-ring resonators (SRR)

Subwavelength structures built from non-magnetic constituents exhibit an effective magnetic permeability μ_{eff}, which can be tuned to values not accessible in naturally occuring materials

J.B. Pendry *et al.*, IEEE Trans. Microwave Theory Tech. 47, 2075 (1999).

2000: David Smith

"Composite medium with simultaneously negative permeability and permittivity"



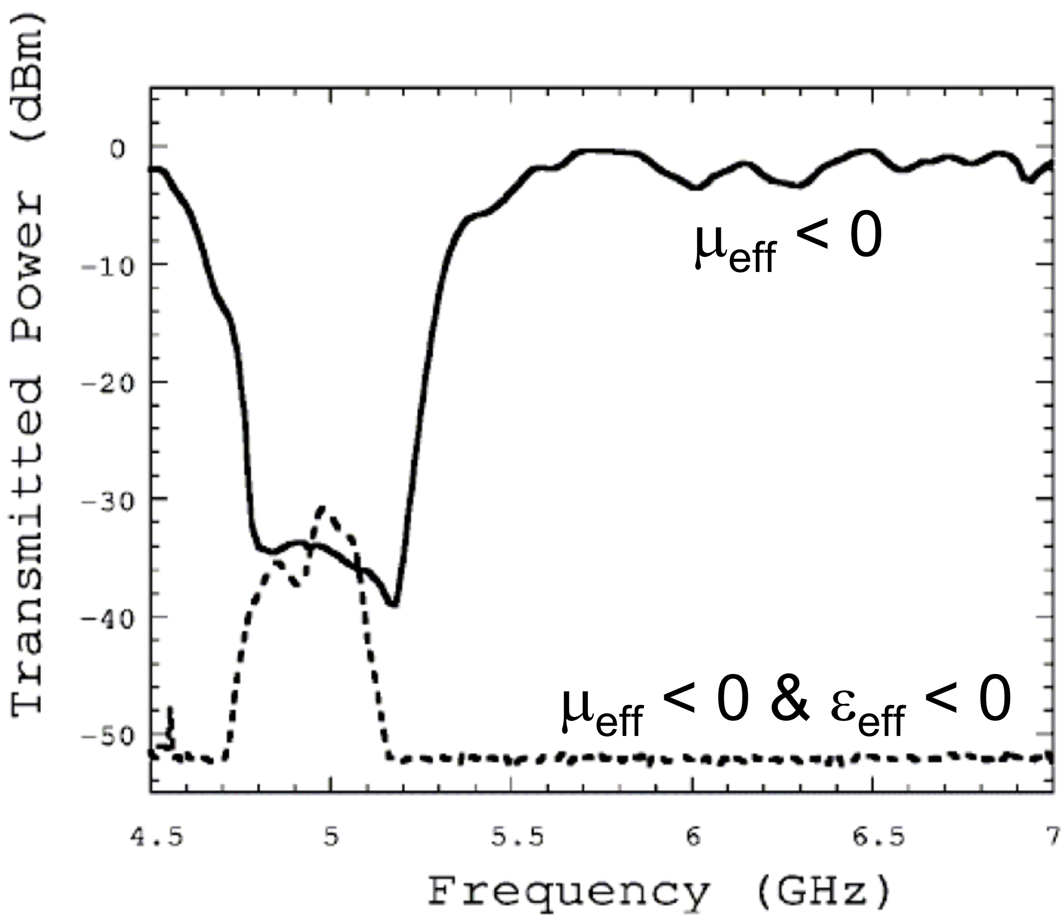
Experimental demonstration at λ = 60 mm (f = 5 GHz) of a metamaterial with $\varepsilon_{eff} < 0$ and $\mu_{eff} < 0$

Rediscovery of Veselago's paper

D.R. Smith *et al.*, Phys. Rev. Lett. 84, 4184 (2000).

2000: David Smith

How to demonstrate experimentally that $\mu_{eff} < 0$??

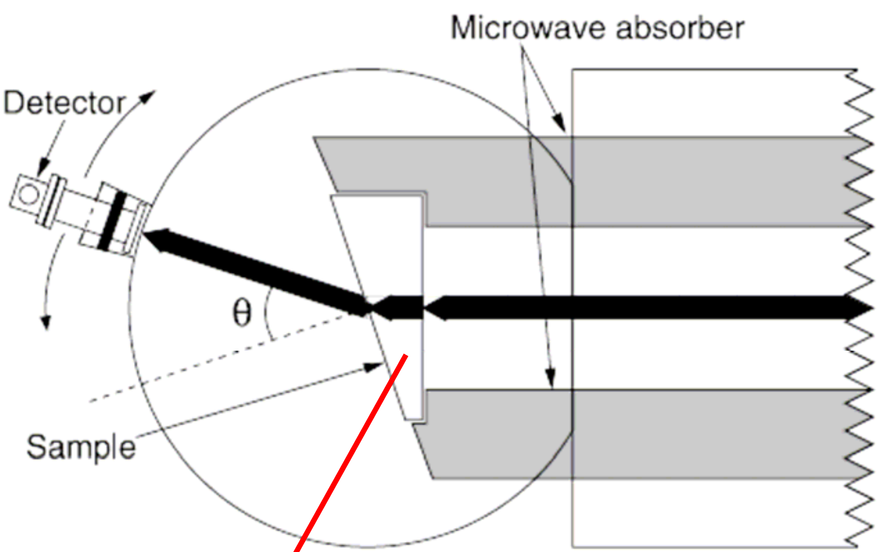


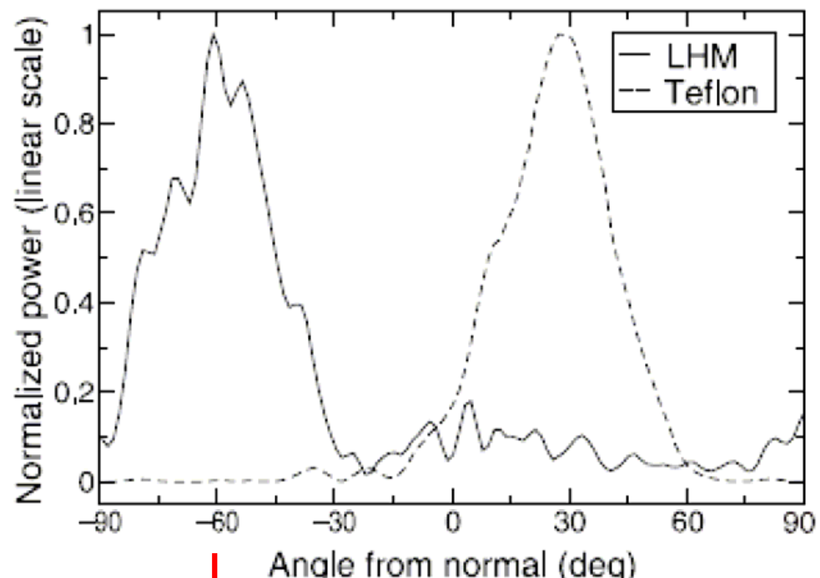
D.R. Smith *et al.*, Phys. Rev. Lett. 84, 4184 (2000).

2001: David Smith

"Experimental verification of a negative index of refraction"

Prism experiment to check Snell's law





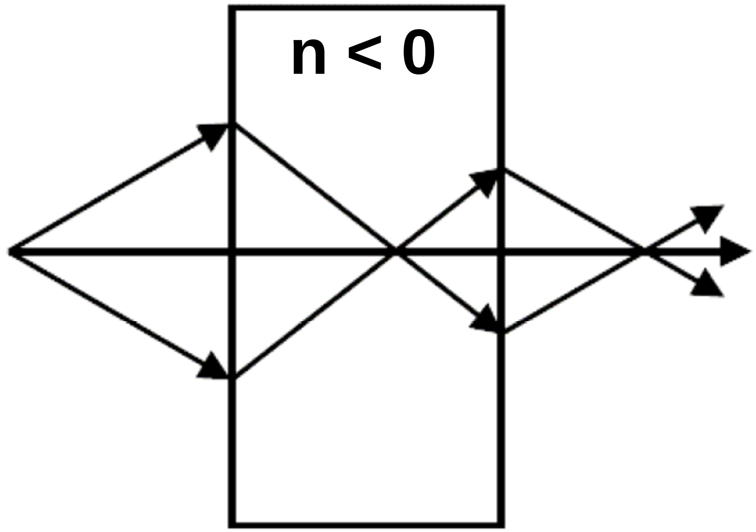
Metamaterial prism

Negative refraction

D.R. Smith *et al.*, Science 292, 77 (2001).

2000: John Pendry

"Negative refraction makes a perfect lens"



"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."

J.B. Pendry, Phys. Rev. Lett. 85, 3966 (2000).

Nobody is perfect… not even a lens

The image of a negative-index lens is not perfect in practice because of

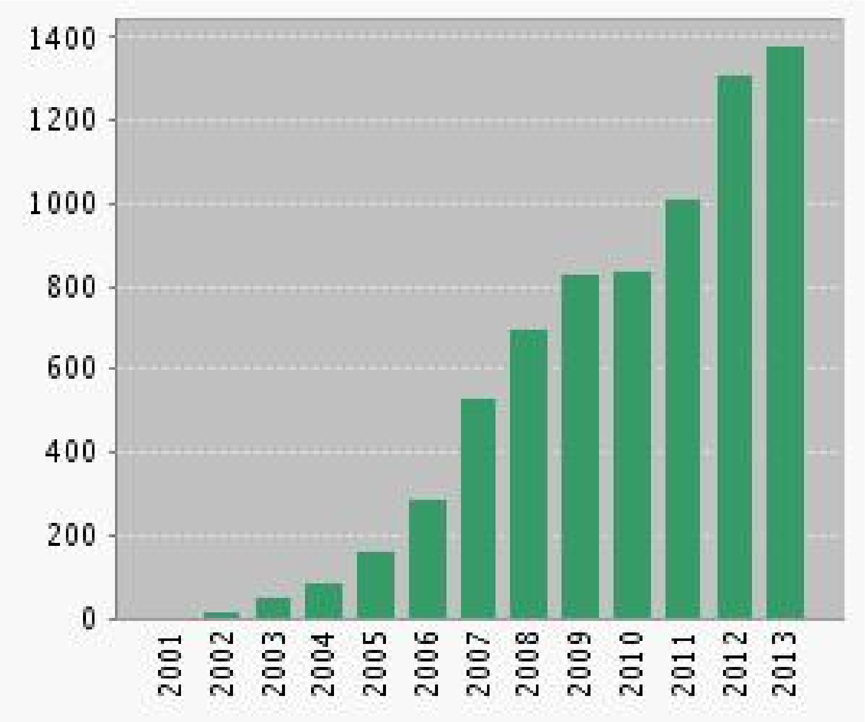
- Losses
- Imperfections
- Granular nature of the metamaterial
- …

However, most researchers agree that the concept of subwavelength imaging by a flat lens is both novel and useful

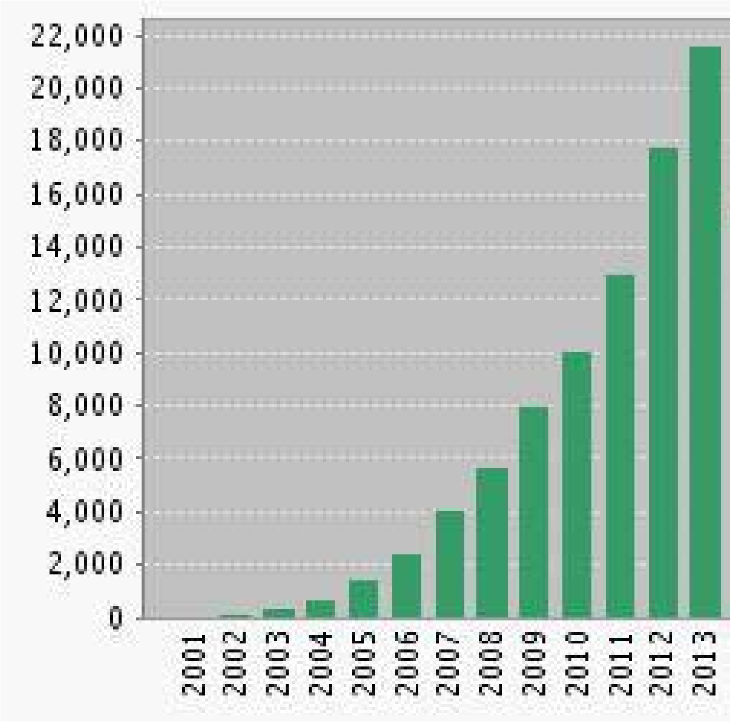
L. Solymar and E. Shamonina, *Waves in Metamaterials* (Oxford University Press, New York, 2009).

Metamaterials as a research topic

Published items in each year



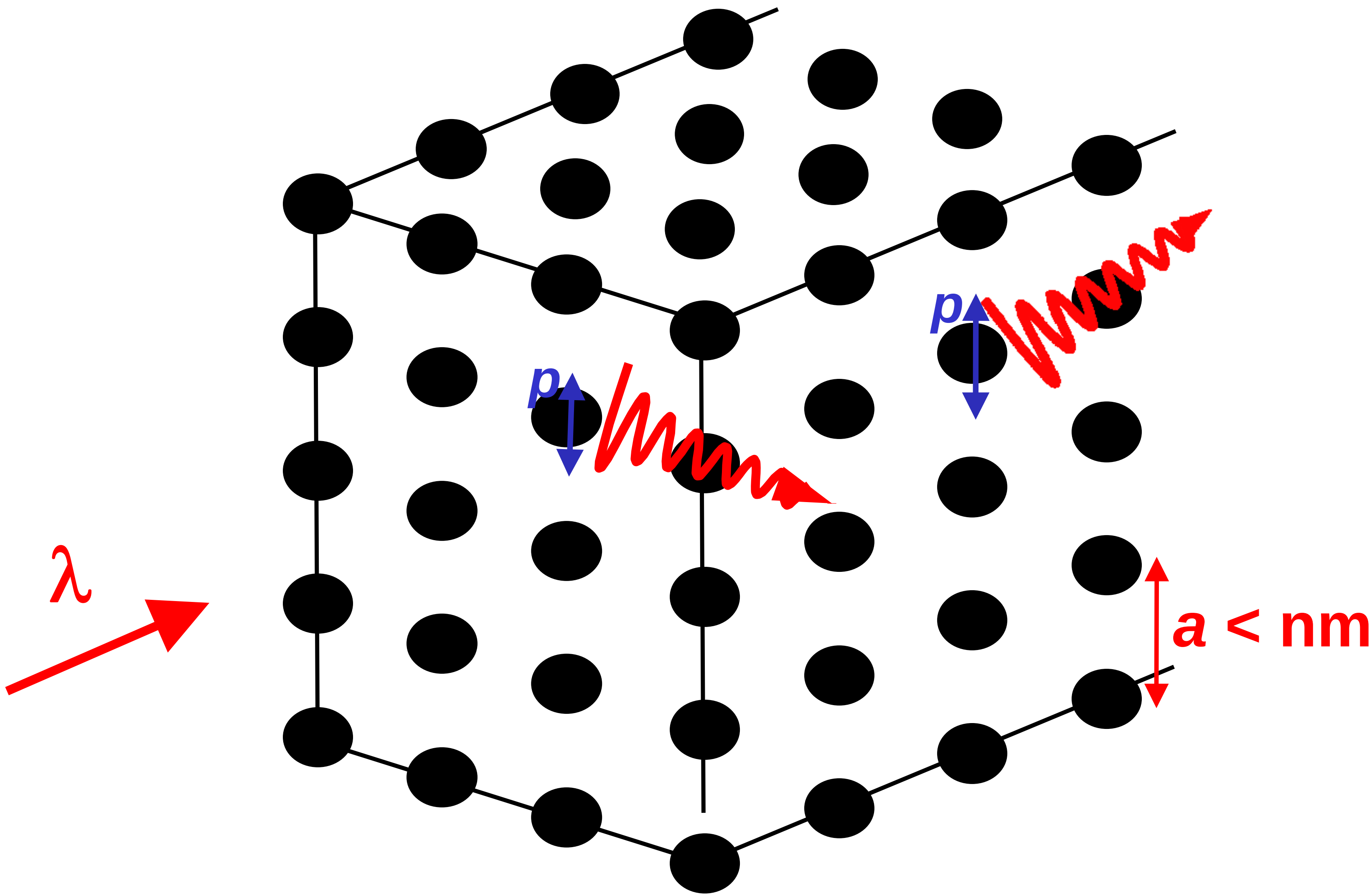
Citations in each year



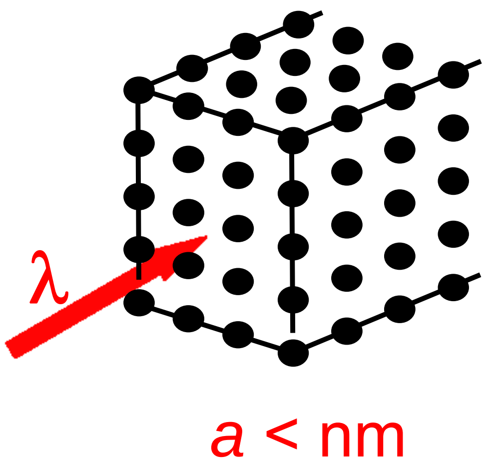
Source: Web of Science (keyword Metamaterial in the topic)

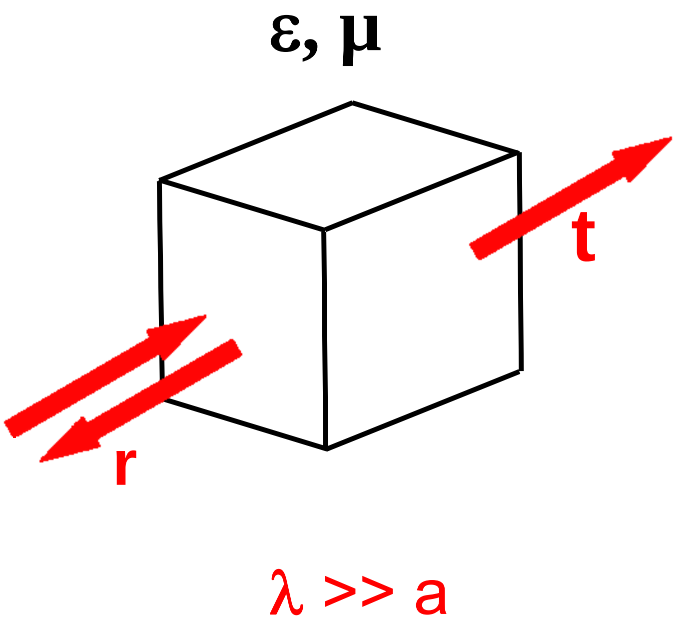
What is the microscopic origin of the relative permittivity and permeability of a material?

The incident field induces a displacement of the charges



Homogenization regime





Dielectric permittivity

$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P} = \varepsilon_0\varepsilon_r\mathbf{E}$$

P = Polarization induced by the electric field E

$$\mathbf{P} = \varepsilon_0\chi_e\mathbf{E}$$

$$\boxed{\varepsilon_r = 1 + \chi_e = 1 + P/(\varepsilon_0 E)}$$

N electric dipoles p induced by the electric field per unit volume

$$\mathbf{P} = N\mathbf{p}$$

$$\mathbf{p} = \alpha_e\mathbf{E}$$

$$\boxed{\epsilon_r = 1 + \frac{N\alpha_e}{\epsilon_0}}$$

Dielectric permittivity

$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P} = \varepsilon_0\varepsilon_r\mathbf{E}$$

P = Polarization induced by the electric field E

$$\mathbf{P} = \varepsilon_0\chi_e\mathbf{E}_{\mathbf{local}} \longleftarrow$$

N electric dipoles p induced by the electric field per unit volume

$$\mathbf{P} = N\mathbf{p}$$

$$\mathbf{p} = \alpha_e\mathbf{E}_{\mathbf{local}} \longleftarrow$$

$$\boxed{\epsilon_r = 1 + \frac{N\alpha_e}{\epsilon_0} \times \frac{1}{1 - \frac{N\alpha_e}{3\epsilon_0}}}$$

Local field effect

the induced dipole depends on the field created by all the other dipoles around

Clausius-Mossotti

Lorentz oscillator model

Drude model (free electrons in metals)

Magnetic permeability

$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P} = \varepsilon_0\varepsilon_r\mathbf{E}$

P = Polarization induced by the electric field E

$\mathbf{P} = \varepsilon_0\chi_e\mathbf{E}$

$$\boxed{\varepsilon_r = 1 + \chi_e = 1 + P/(\varepsilon_0 E)}$$

N electric dipoles p induced by the electric field per unit volume

$\mathbf{P} = N\mathbf{p}$

$\mathbf{p} = \alpha_e\mathbf{E}$

$$\boxed{\epsilon_r = 1 + \frac{N\alpha_e}{\epsilon_0}}$$

$\mathbf{B} = \mu_0\mathbf{H} + \mathbf{M} = \mu_0\mu_r\mathbf{H}$

M = Magnetization induced by the magnetic field H

$\mathbf{M} = \mu_0\chi_m\mathbf{H}$

$$\boxed{\mu_r = 1 + \chi_m = 1 + M/(\mu_0 H)}$$

N magnetic dipoles m induced by the magnetic field per unit volume

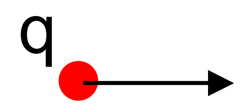
$\mathbf{M} = N\mathbf{m}$

$\mathbf{m} = \alpha_m\mathbf{H}$

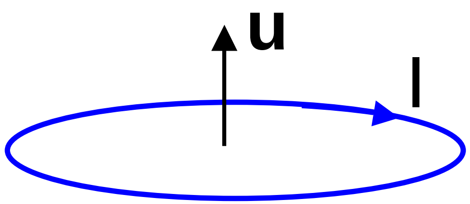
$$\boxed{\mu_r = 1 + \frac{N\alpha_m}{\mu_0}}$$

Elementary electric and magnetic dipoles

Charge q in motion $\mathbf{p} = q\mathbf{r}$



Loop with a current I $\mathbf{m} = \mu_0 S I \mathbf{u}$



A current I flows in a loop of section S

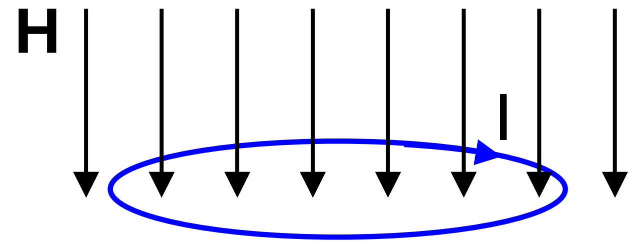
u: unitary vector perpendicular to the loop

Magnetism requires magnetic dipoles, i.e., current loops (much smaller than the wavelength)

Reminder: Faraday's law

A magnetic field H induces a current I and a voltage U in a loop of section S

$$U = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = i\omega\Phi$$



Φ = Magnetic flux through the loop

Reminder: Faraday's law

A magnetic field H induces a current I and a voltage U in a loop of section S

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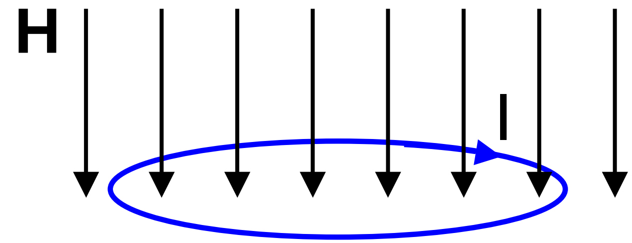
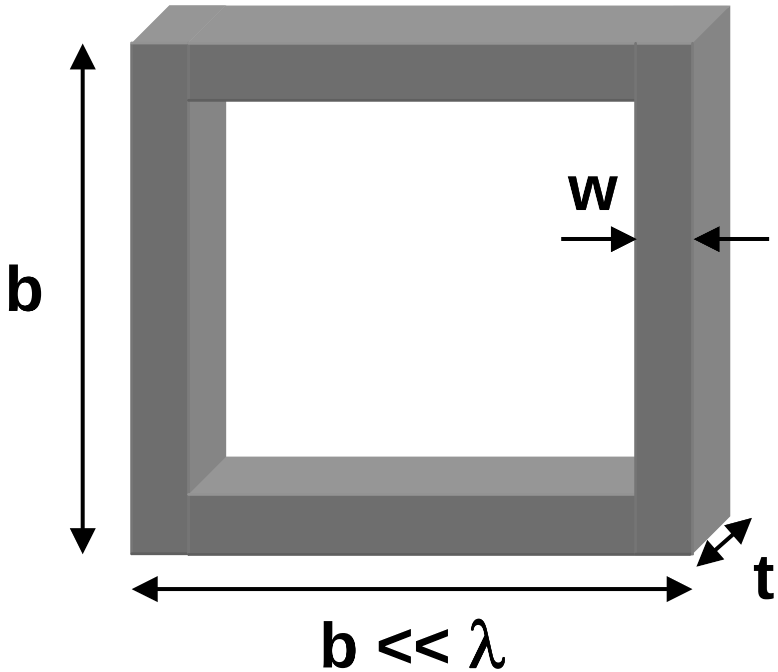


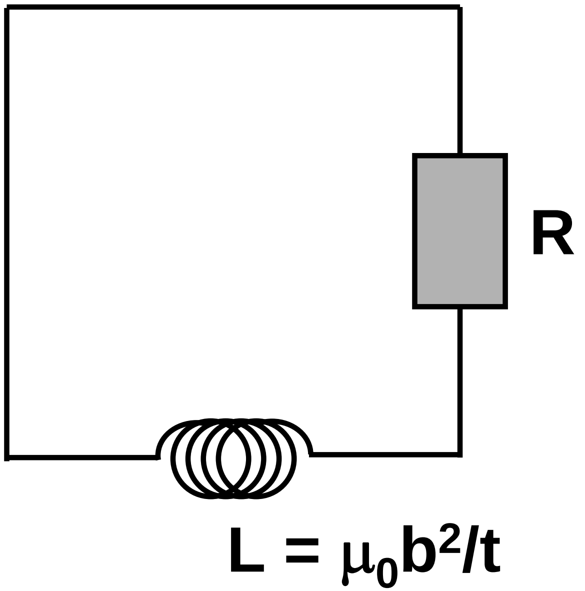
Φ = Magnetic flux through the loop = $\mu_0 H \times S$

Provided that the magnetic field is constant over the area of the loop

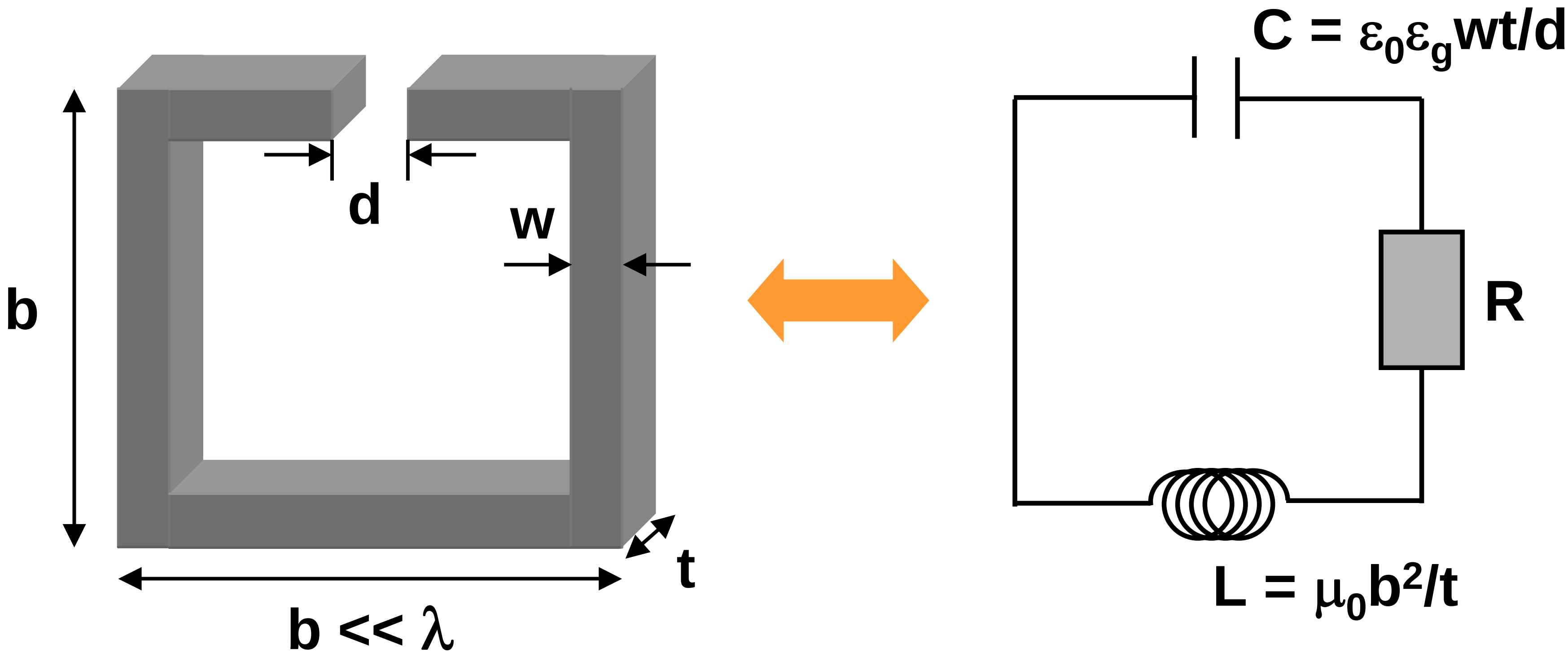
r << λ

Polarisability of a small metallic ring
Analogy with a RL circuit

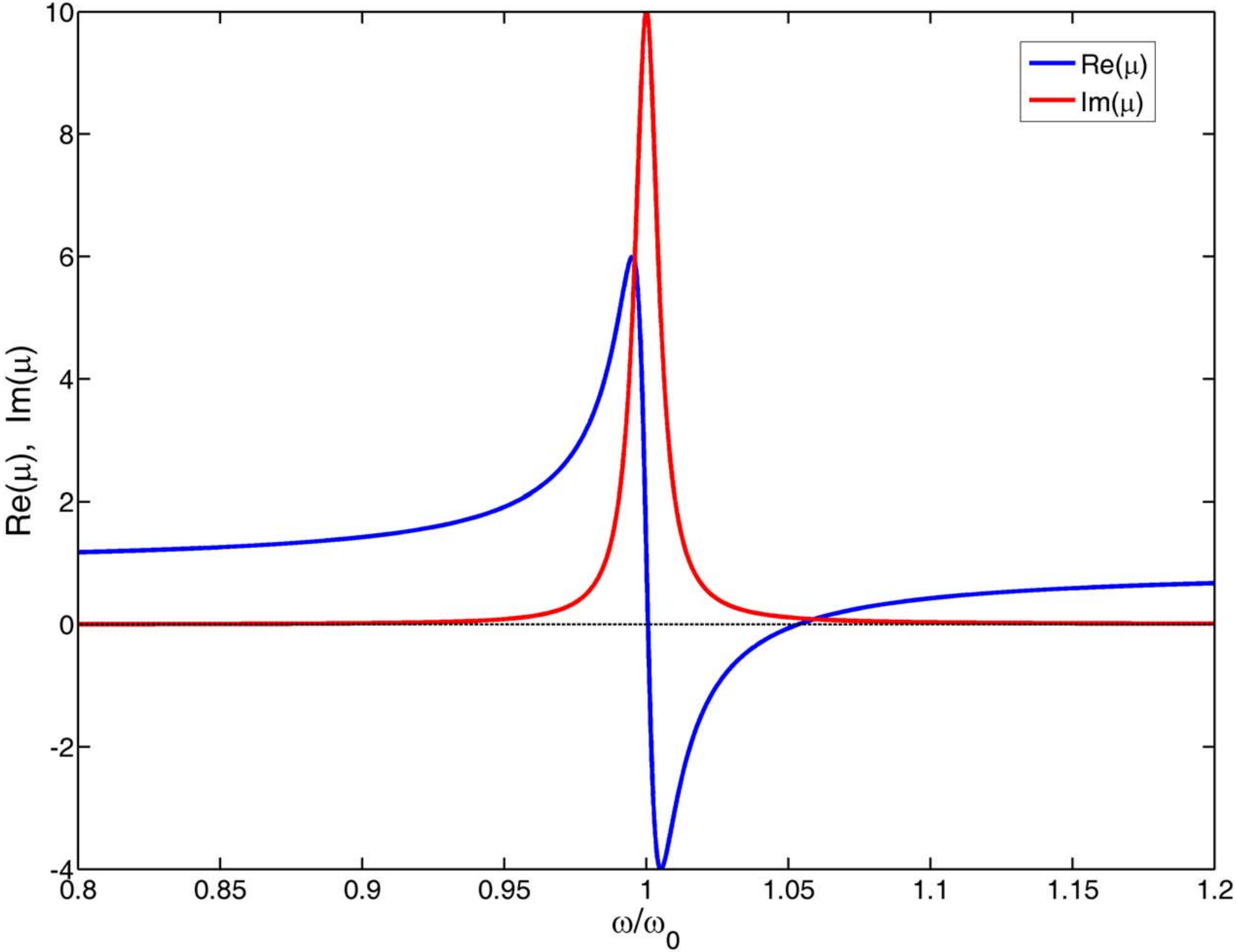




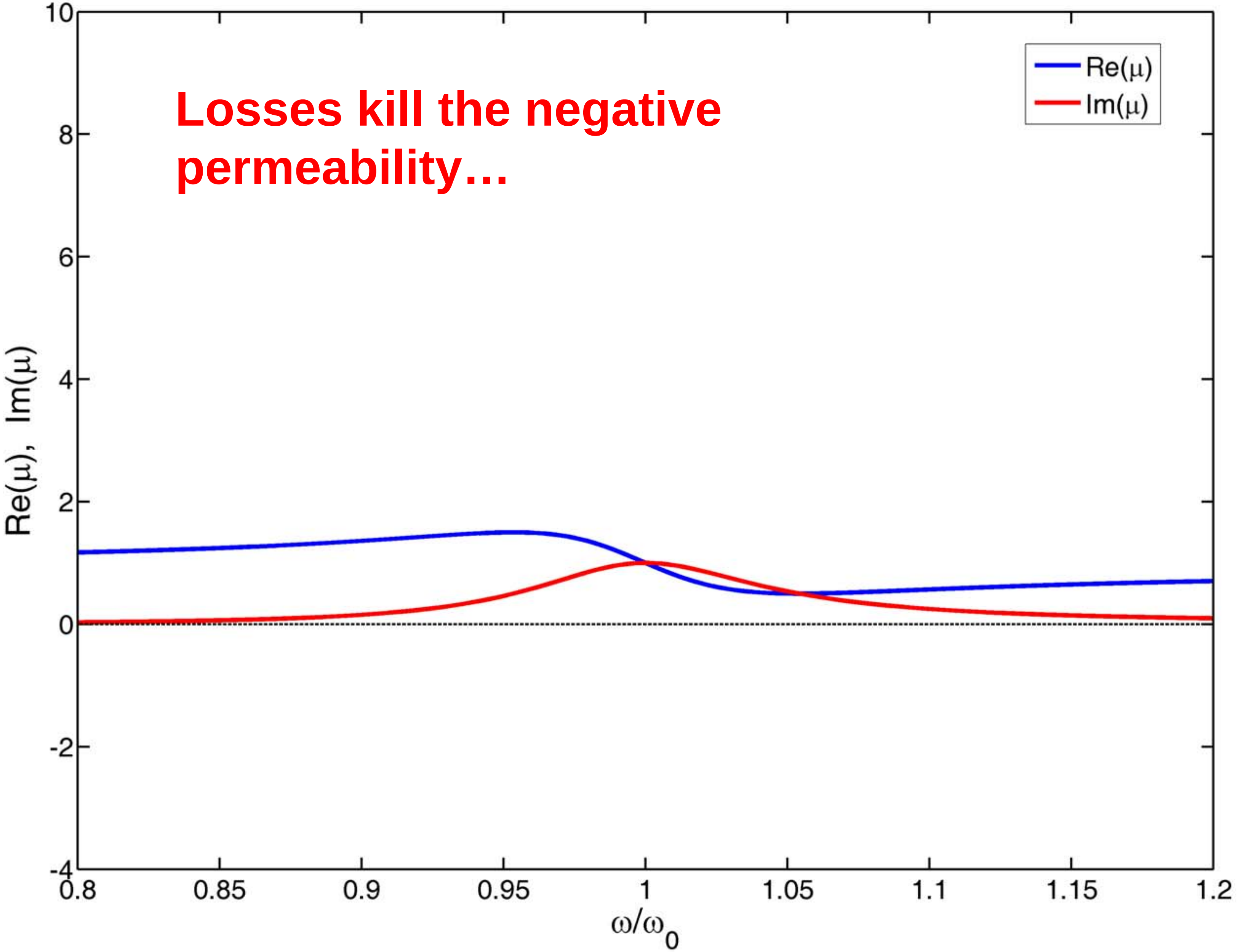
Polarisability of a split ring resonator (SRR)
Analogy with a RLC circuit



F = 0.1, Q = 100



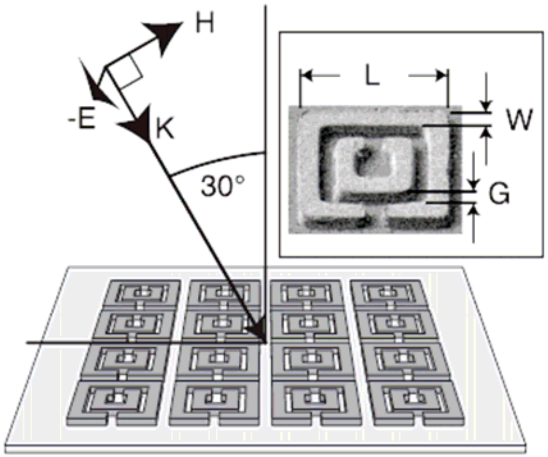
F = 0.1, Q = 10


Losses kill the negative permeability…
Re(μ)
Im(μ)
Re(μ), Im(μ)
ω/ω0
10
8
6
4
2
0
-2
-4
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2

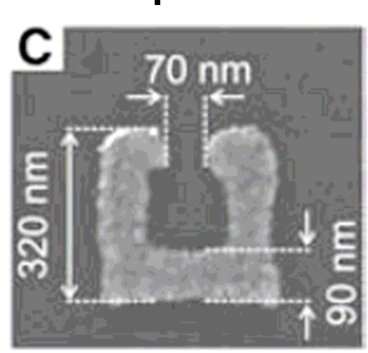
From microwaves to optics

Reducing the size of the split-ring resonators

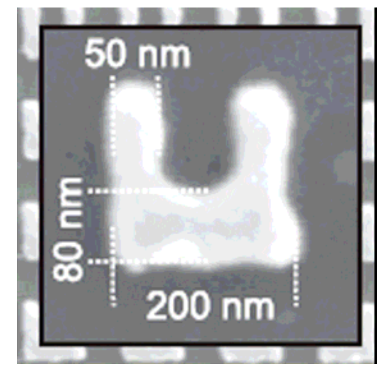
λ = 300 μm = 8a



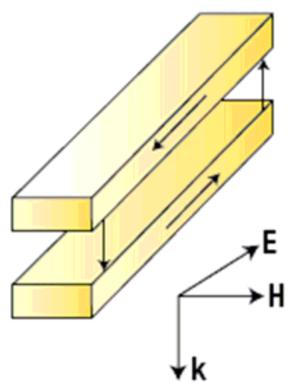
λ = 3 μm = 6a

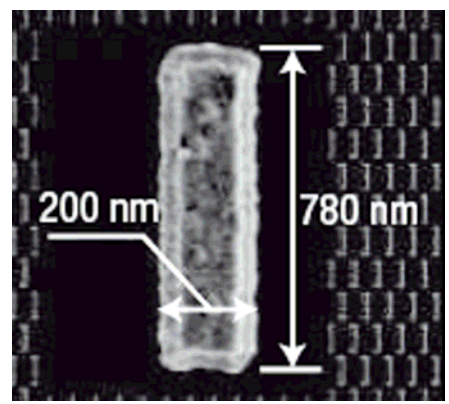


λ = 1.5 μm = 4a



In the visible and near-infrared (paired nanorods)



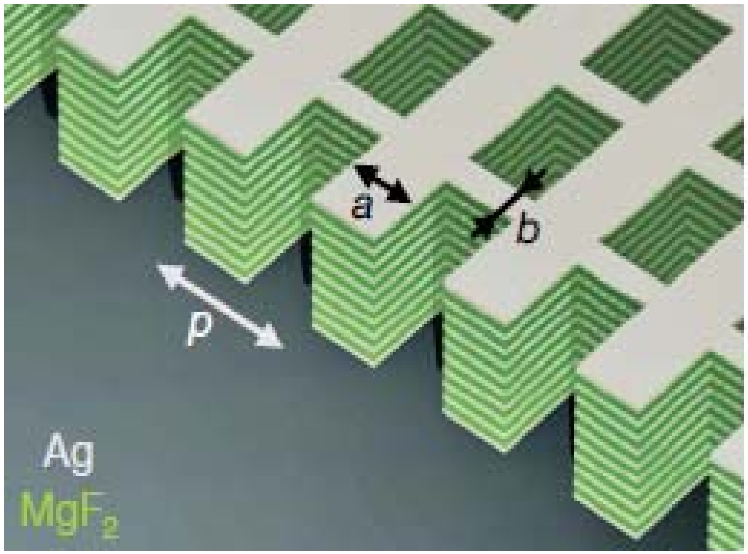


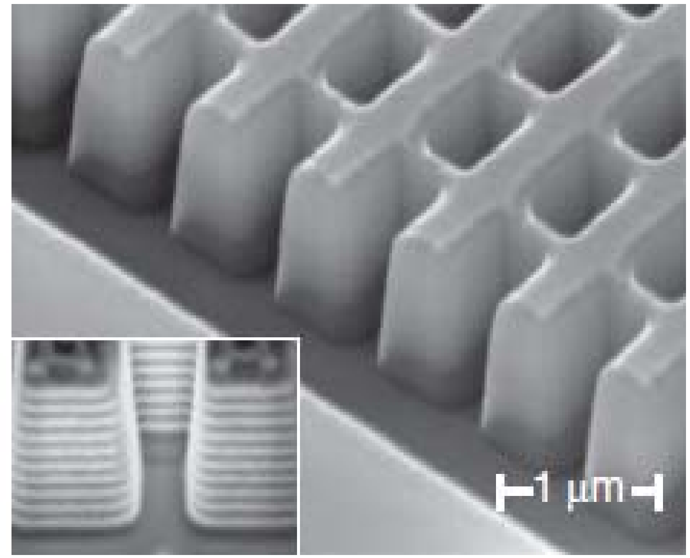
From microwaves to optics

Major issues

- No analytical model: only intuitive arguments
- Period ~ $\lambda/2$ (homogenization?)
- Losses (absorption in the metal)
- Fabrication

Structure with the smallest losses at optical frequencies: Fishnet metamaterial



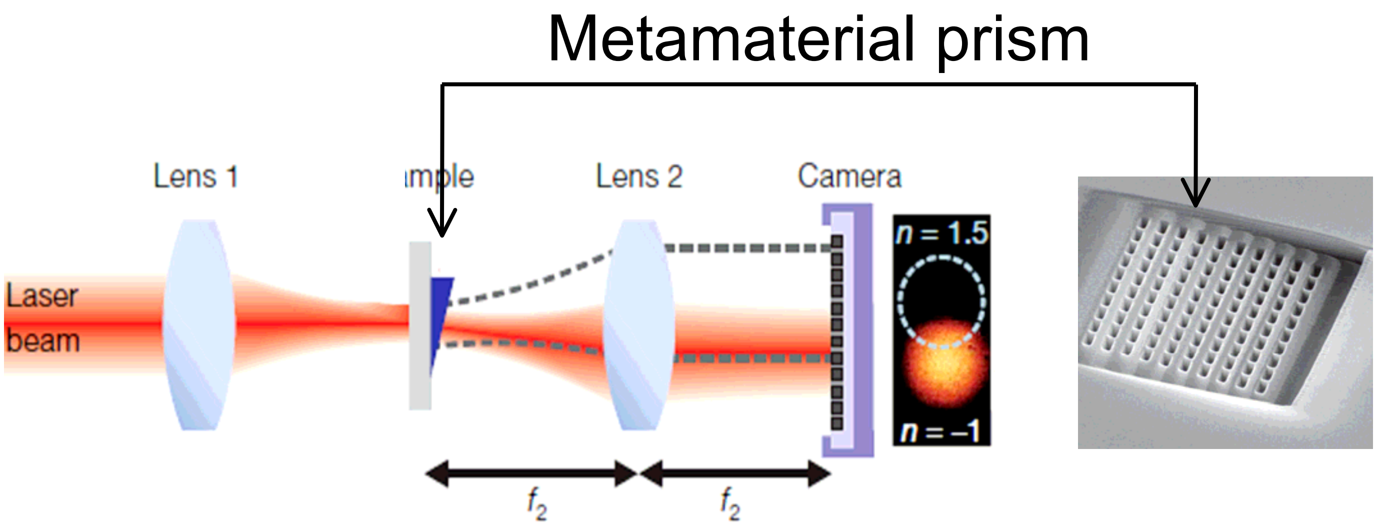


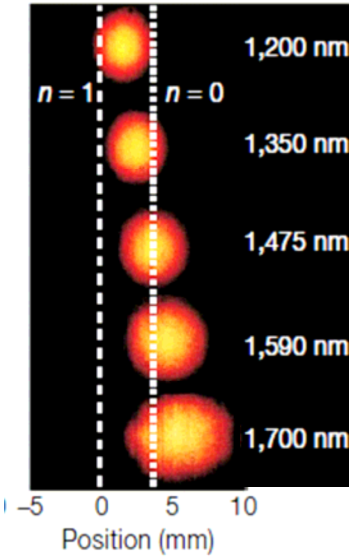
p = 860 nm ~ $\lambda/2$

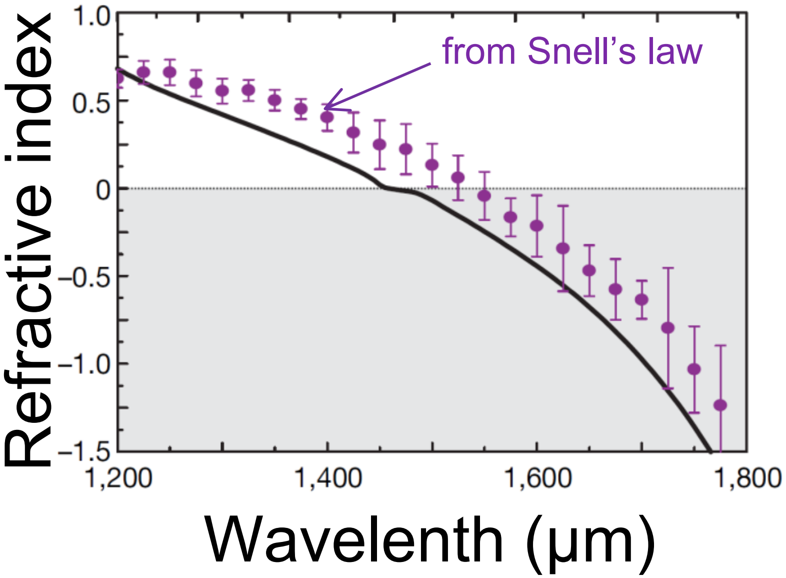
21-layer fishnet structure with a unit cell of p = 860 nm, a=565nm and b=265 nm. The structure consists of alternating layers of 30nm silver (Ag) and 50nm magnesium fluoride (MgF2).

J. Valentine *et al.*, Nature (London) 455, 376 (2008).

Fishnet metamaterial







J. Valentine *et al.*, Nature (London) 455, 376 (2008).

Major challenges for optical metamaterials

Metamaterials should become “More bulky and less lossy”

1. Fabrication of a real 3D material

2. Reducing absorption losses (gain media)

Major challenges for optical metamaterials

Metamaterials should become “More bulky and less lossy”

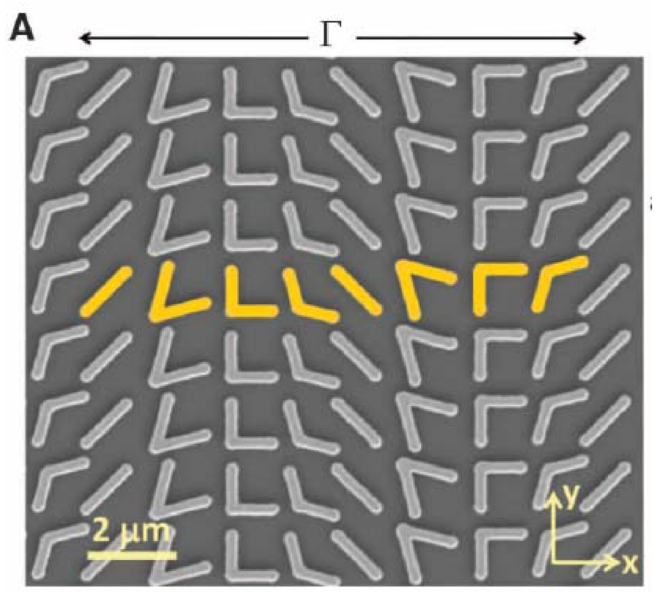
1. Fabrication of a real 3D material

   → Metasurfaces: a 2D alternative to metamaterials

2. Reducing absorption losses (gain media)

Metasurfaces

Metasurfaces (surfaces that are functionalized by arrays of miniature light scatterers) possess optical properties that go far beyond those of standard flat surfaces



“Flat optics”: thin optical components (blazed gratings, Fresnel lenses, beam shaping…)

N. Yu *et al.*, Science 334, 333 (2011).

Metasurfaces

Many open questions in this new field:

To what extent is it possible to control independently the reflected and the transmitted beams?

Is it possible to design optical components with completely new optical functionalities?

…