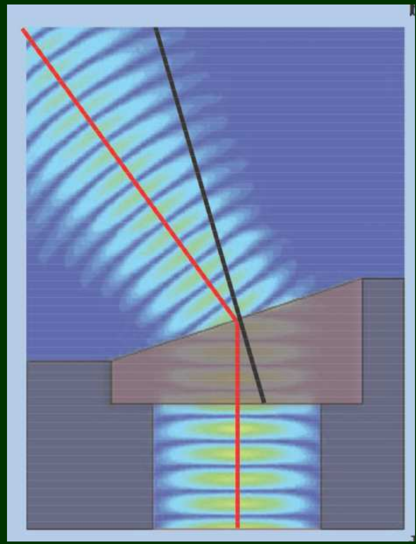
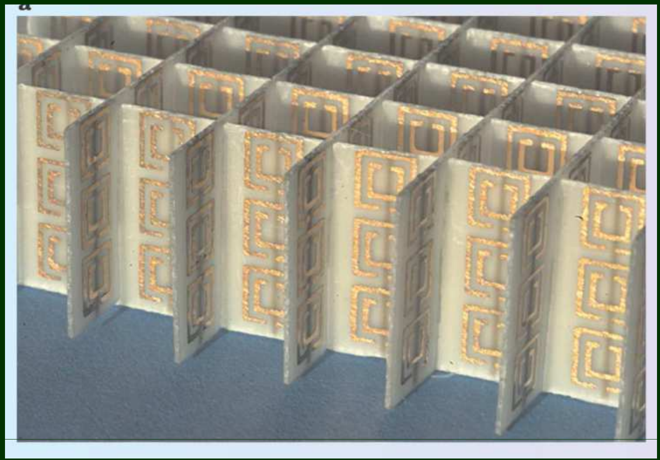
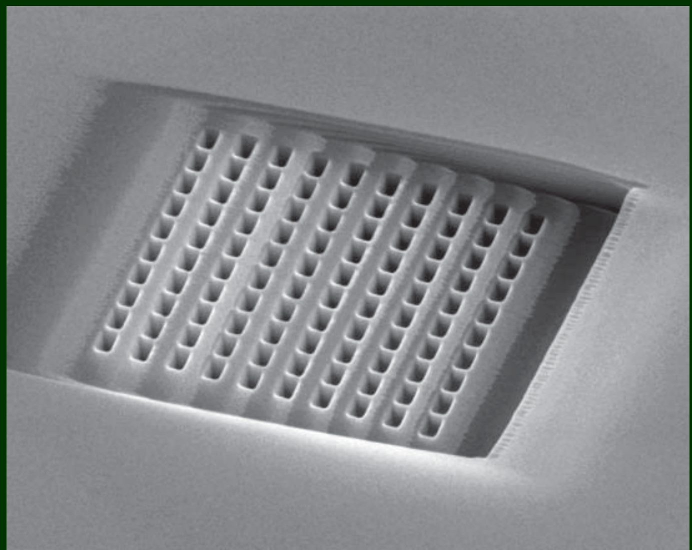
Metamaterials







Metamaterials

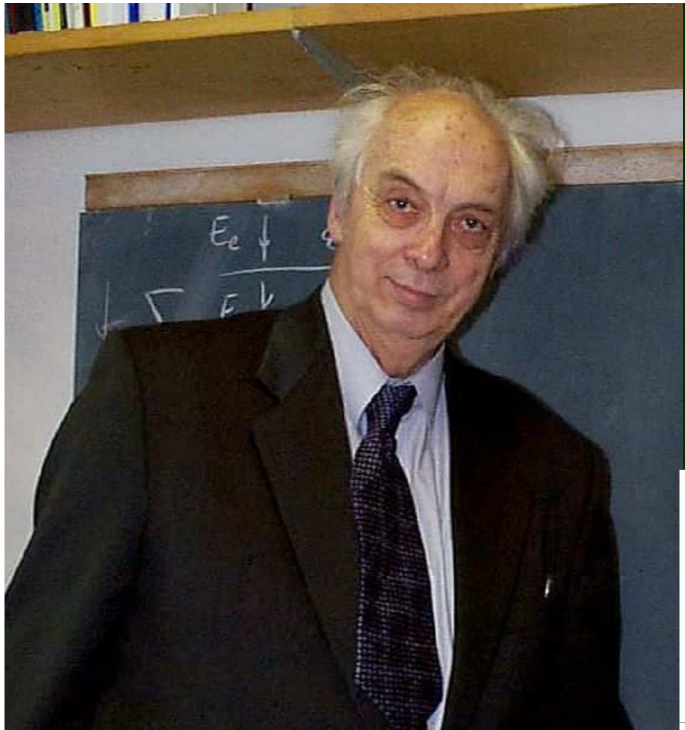
From Greek “μετά-” - "beyond”

Materials with the characteristics beyond that of common materials.

The term is applied to materials with very unusual properties. For example, to materials with negative refraction index.

They are called also “negative materials” or “left-handed materials” (LHM).

Metamaterials



V.G.Veselago

1967 г. Июль Том 92, вып. 3

УСПЕХИ ФИЗИЧЕСКИХ НАУК

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ЭЛЕКТРОДИНАМИКА ВЕЩЕСТВ С ОДНОВРЕМЕННО ОТРИЦАТЕЛЬНЫМИ ЗНАЧЕНИЯМИ ε И μ

В. Г. Веселаго

I. ВВЕДЕНИЕ

Диэлектрическая проницаемость ε и магнитная проницаемость μ являются основными характеристиками, которые определяют распространение электромагнитных волн в веществе. Это связано с тем, что они являются единственными параметрами вещества, входящими в дисперсионное уравнение

$$\left|\frac{\omega^2}{c^2}\varepsilon_{il}\mu_{lj}-k^2\delta_{ij}+k_ik_j\right|=0, \qquad (1)$$

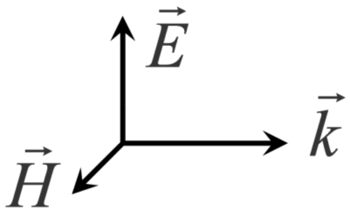
Refractive index $n = \sqrt{\varepsilon\mu}$

But what if $\varepsilon < 0$ and $\mu < 0$?

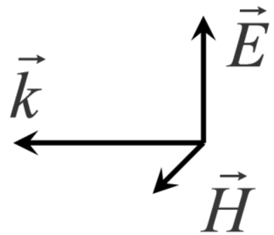
$$[\mathbf{kE}] = \frac{\omega}{c}\mu\mathbf{H},$$

$$[\mathbf{kH}] = -\frac{\omega}{c}\varepsilon\mathbf{E}.$$

- If $\varepsilon > 0, \mu > 0$ then $\left(\vec{E}, \vec{H}, \vec{k}\right)$ is a ***right*** set of vectors:



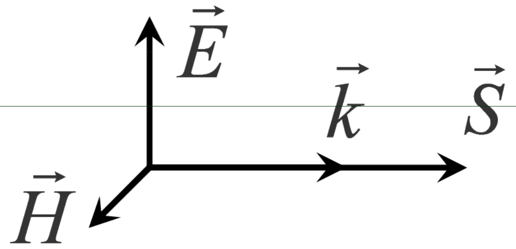
- If $\varepsilon < 0, \mu < 0$ then $\left(\vec{E}, \vec{H}, \vec{k}\right)$ is a ***left*** set of vectors:



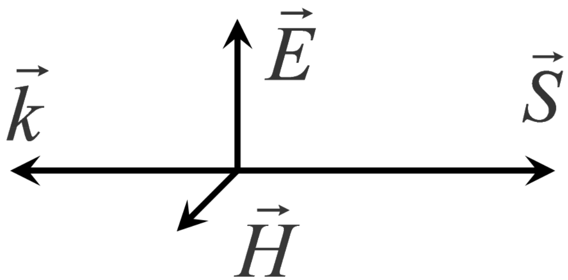
Energy flux

$$\mathbf{S} = \frac{c}{4\pi}[\mathbf{E}\mathbf{H}]$$

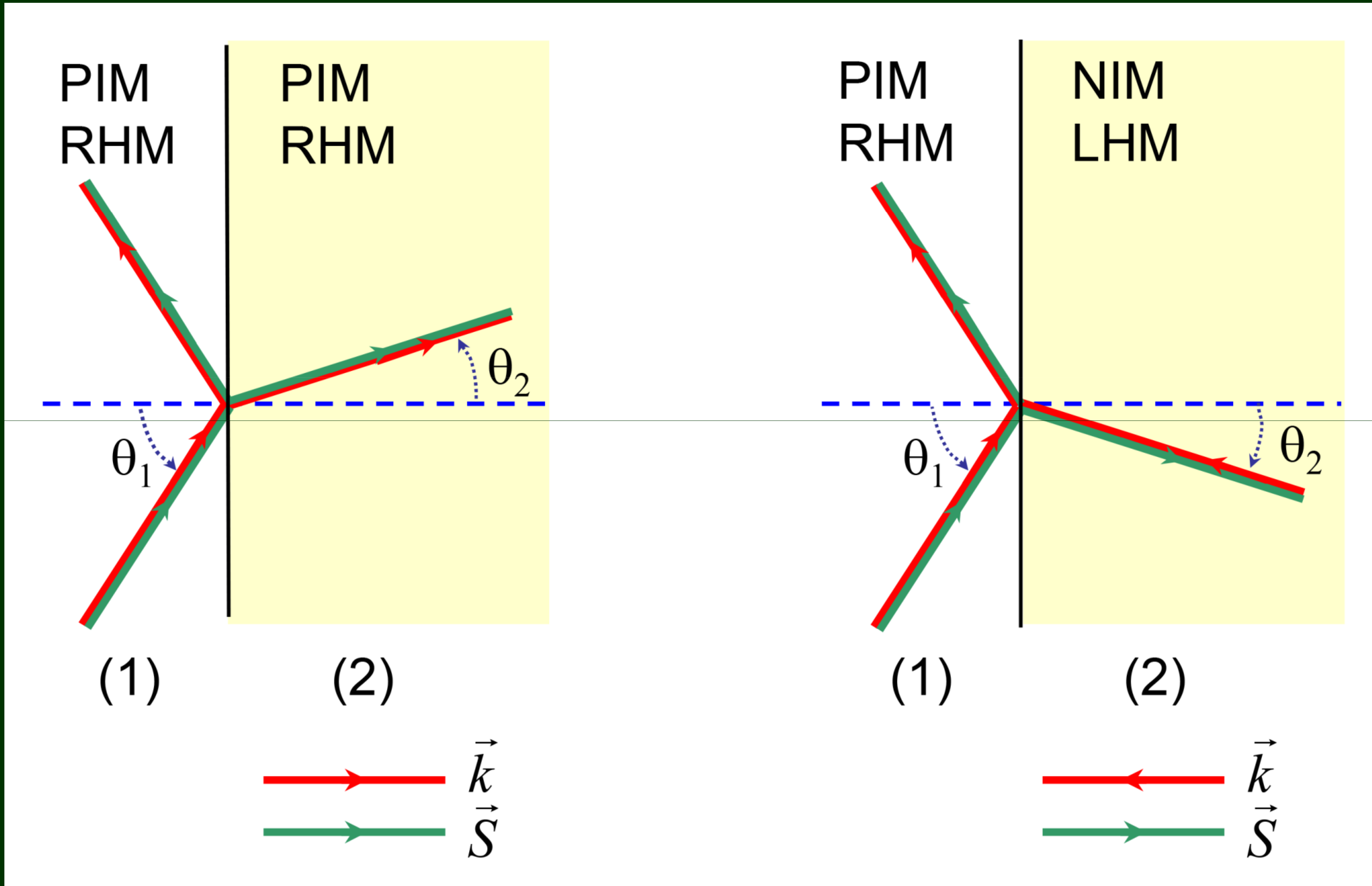
– Conventional (right-handed) medium



– Left-handed medium



Refraction and Snell's law



Lenses

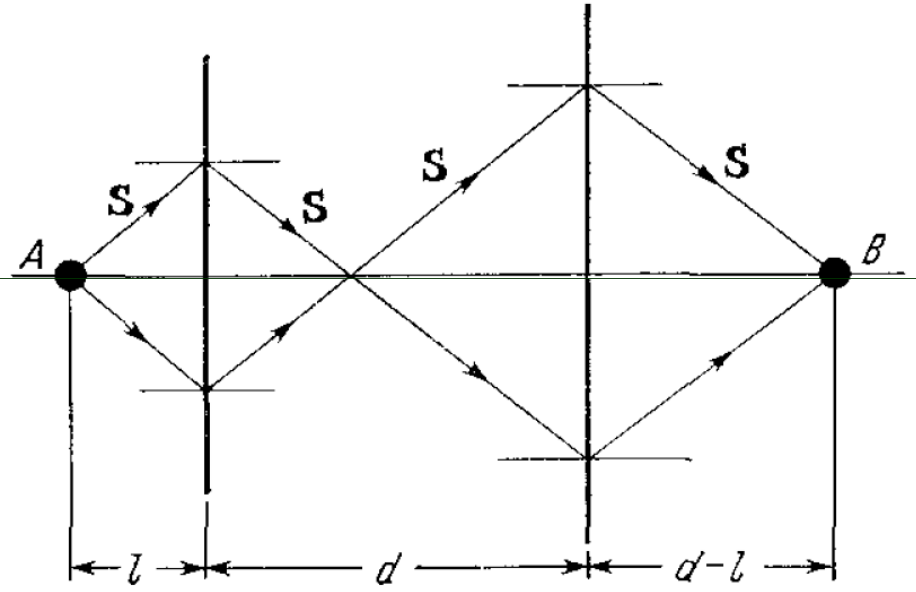
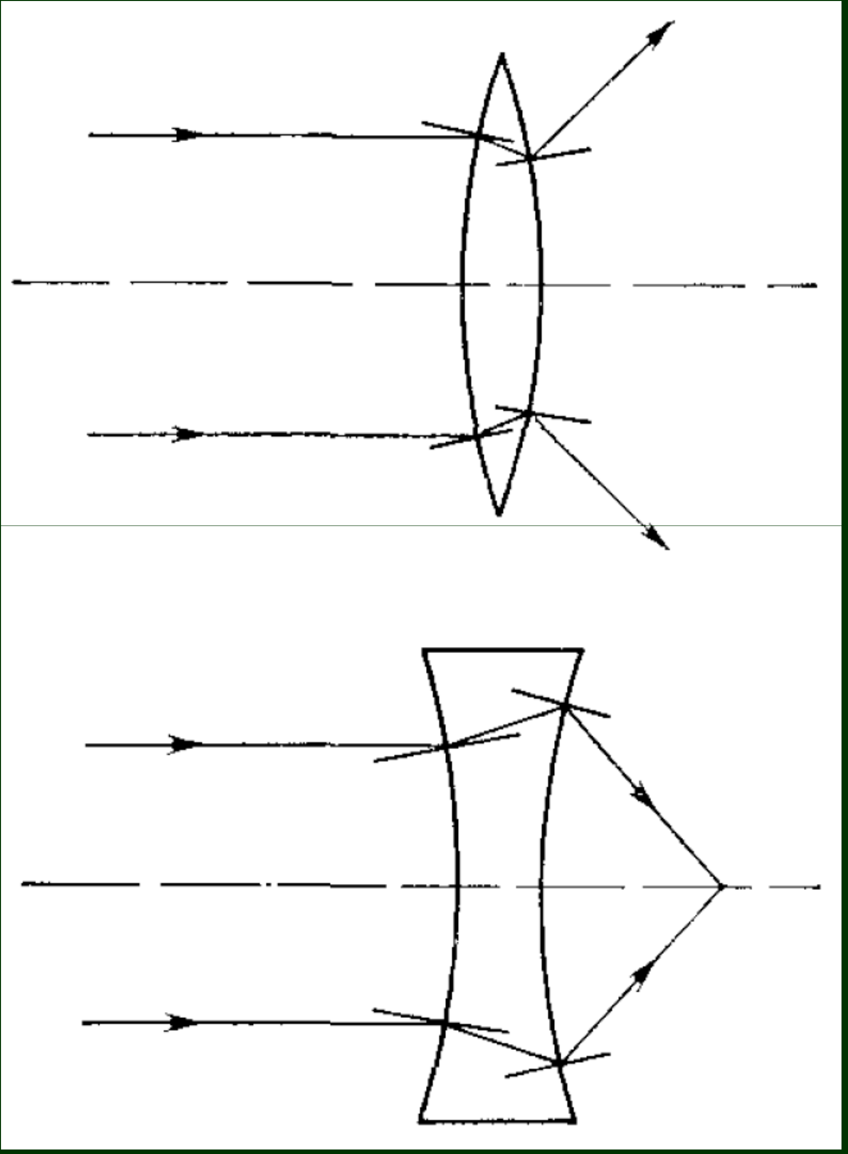
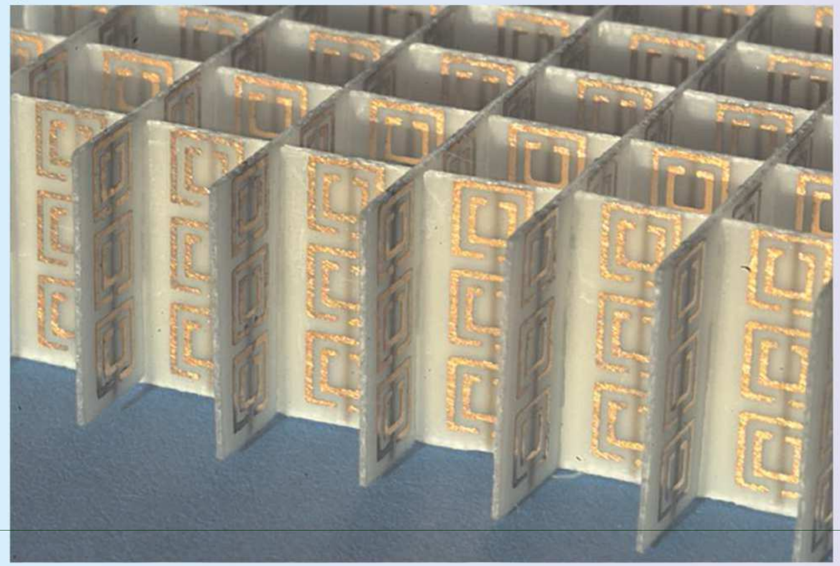


Рис. 4. Прохождение луча света через пластину из левого вещества толщиной d.



Practical realization in microwave frequency range



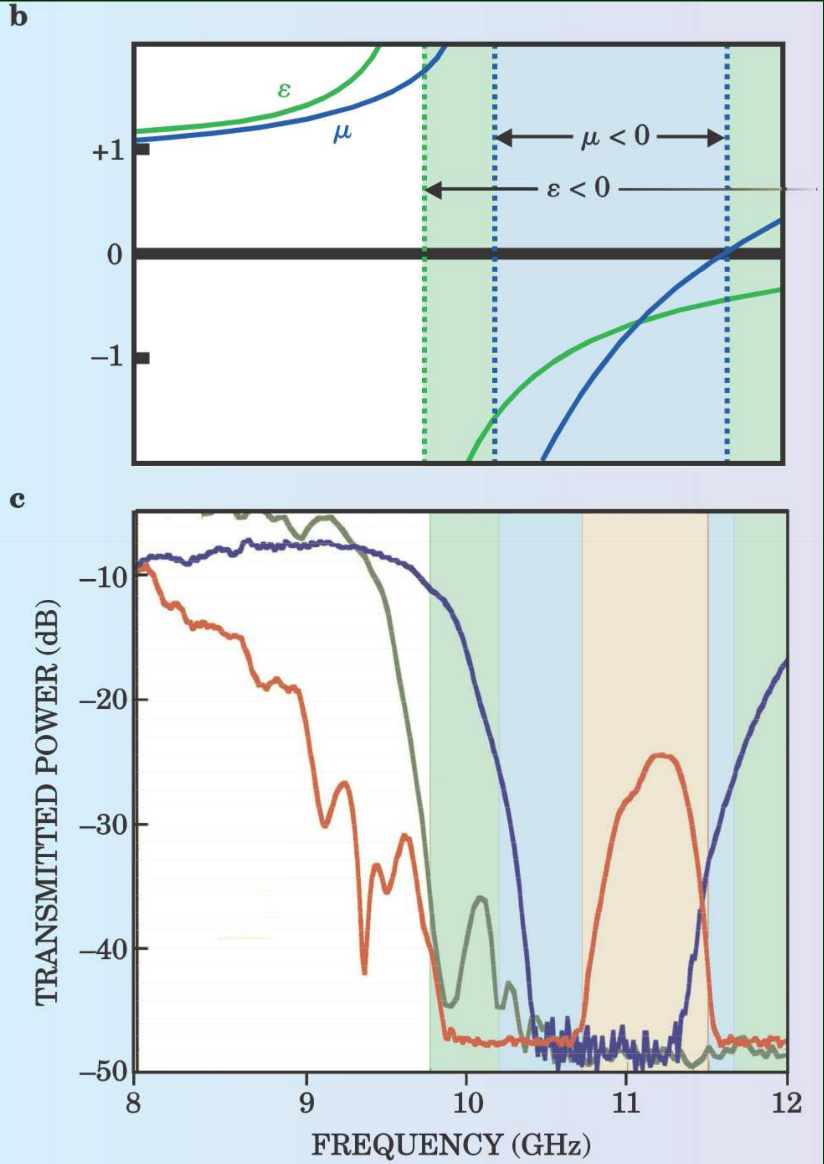


Figure 1. Metamaterials can be designed to create negative refraction. **(a)** In this example of a metamaterial used in microwave experiments, unit cells consist of a split-ring resonator and a wire spanning the cell, just visible on the reverse of the supporting sheets. **(b)** Schematic variation of ε (green) and μ (blue) with frequency. The shaded green and blue bands denote negative regions for ε and μ, respectively. **(c)** The transmitted power spectra[16] for a metamaterial of cut wires (green), a metamaterial of split ring resonators (blue), and a metamaterial combining wires and split-ring resonators (red). The yellow band, corresponding to the red curve's transmission window, indicates the region of negative refractive index.

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Theory of operation

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2 - \omega_0^2}{\omega^2 - \omega_0^2 + i\omega\Gamma}$$

For $\omega_0 < \omega < \omega_p$ ε(ω)<0

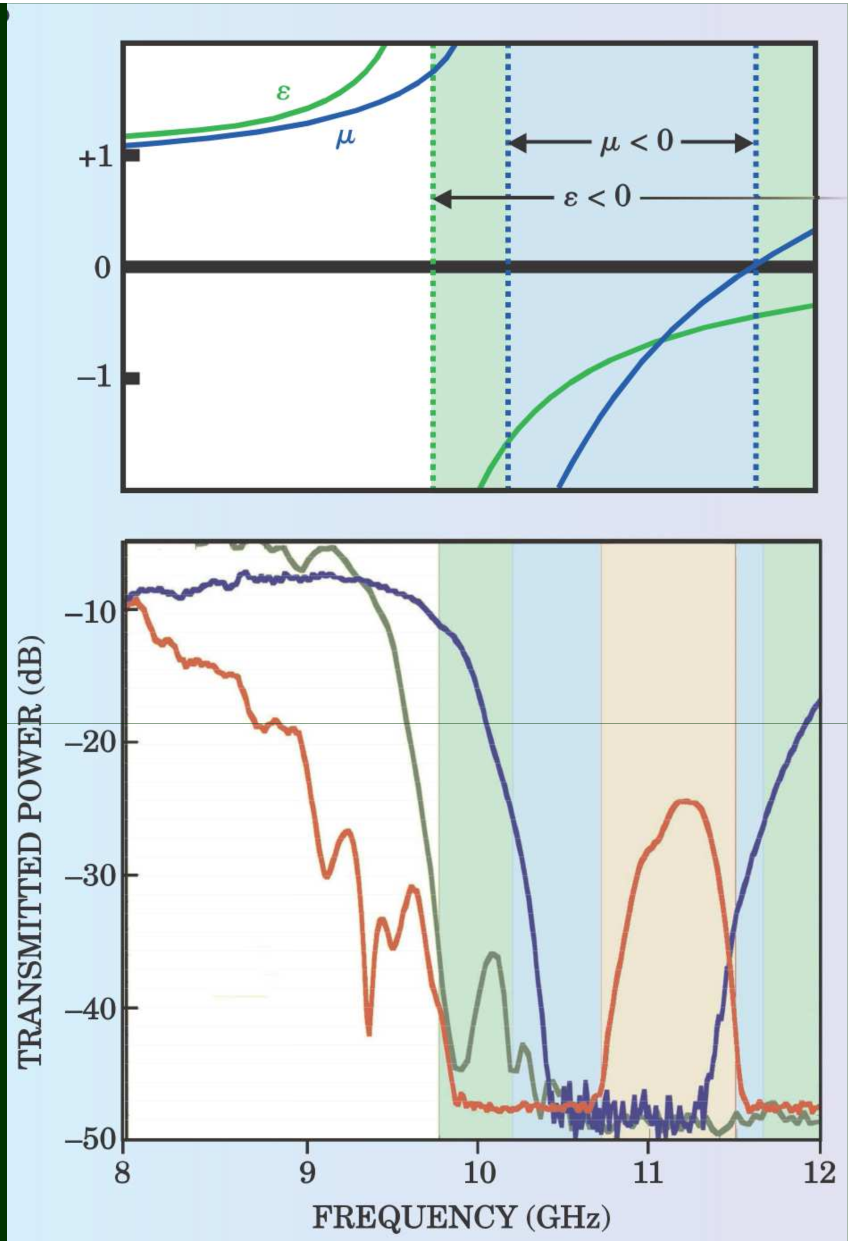
$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\Gamma}$$

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

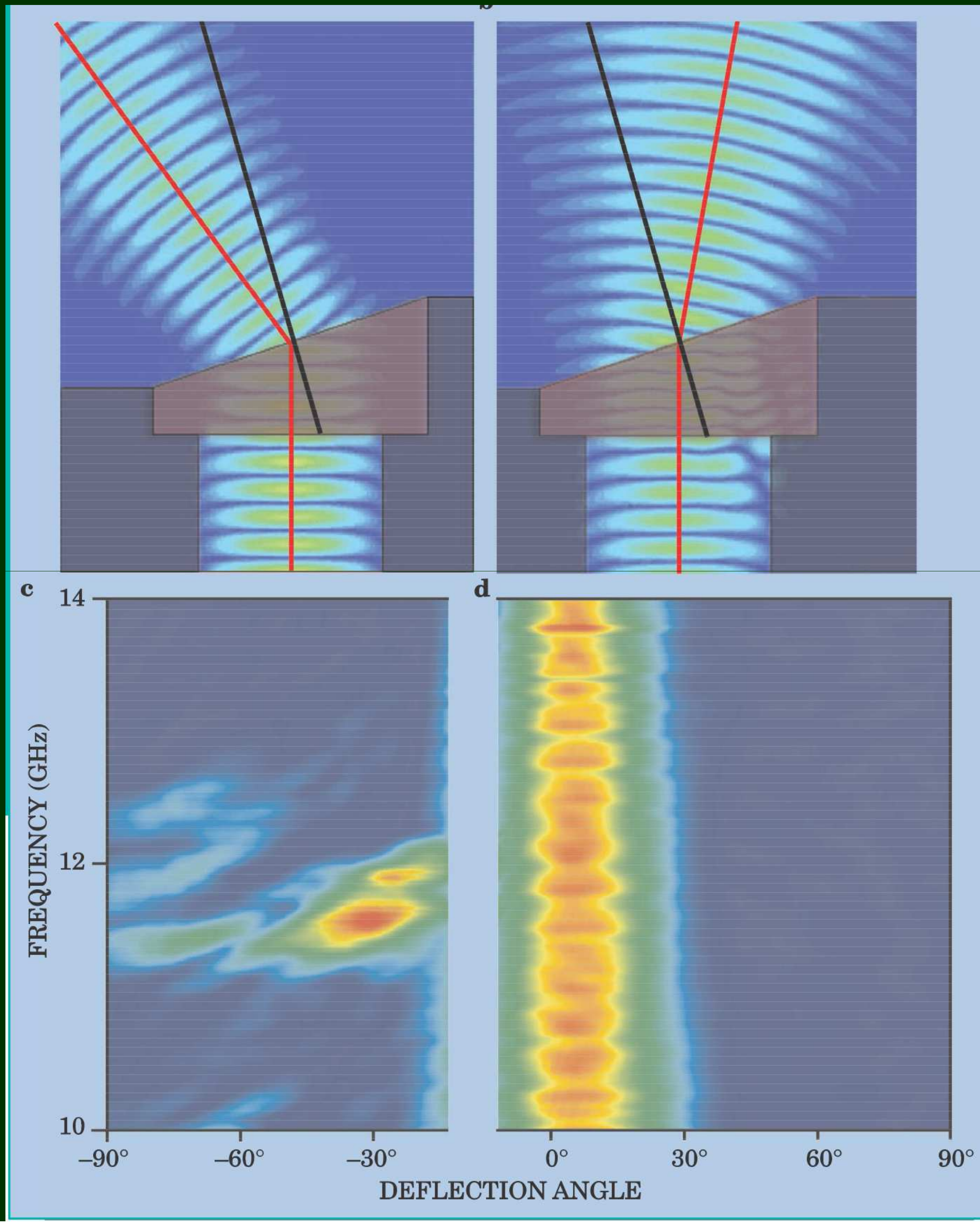
But instead of ε = -1 and μ = -1 we can write ε=exp(iπ) and μ =exp(iπ)

Then

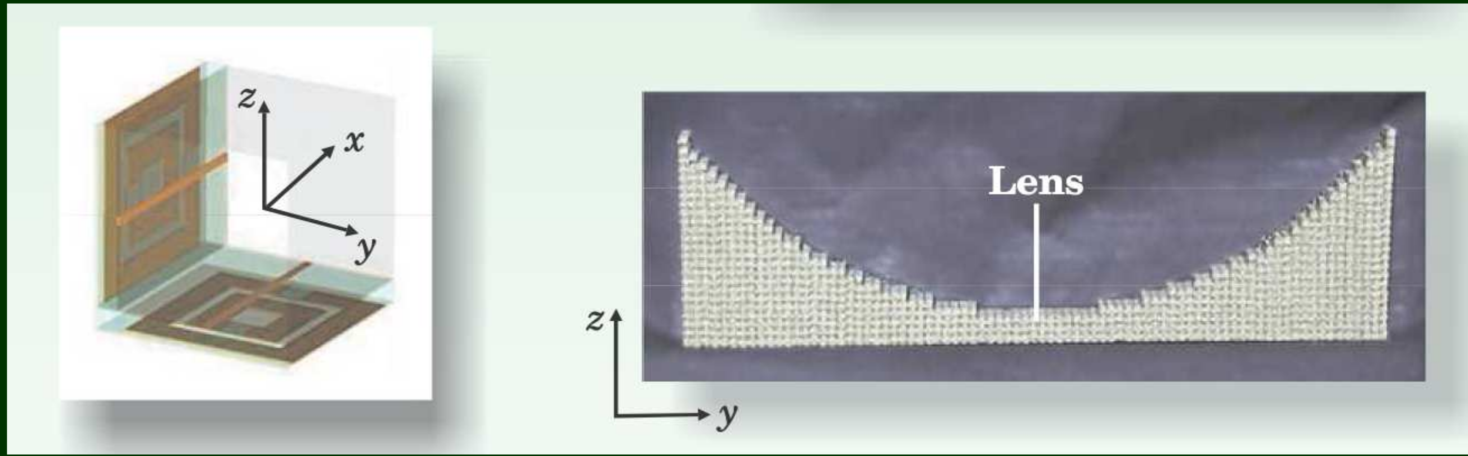
$$n = \sqrt{\varepsilon\mu} = \exp(i\pi/2)\exp(i\pi/2) = \exp(i\pi) = -1$$

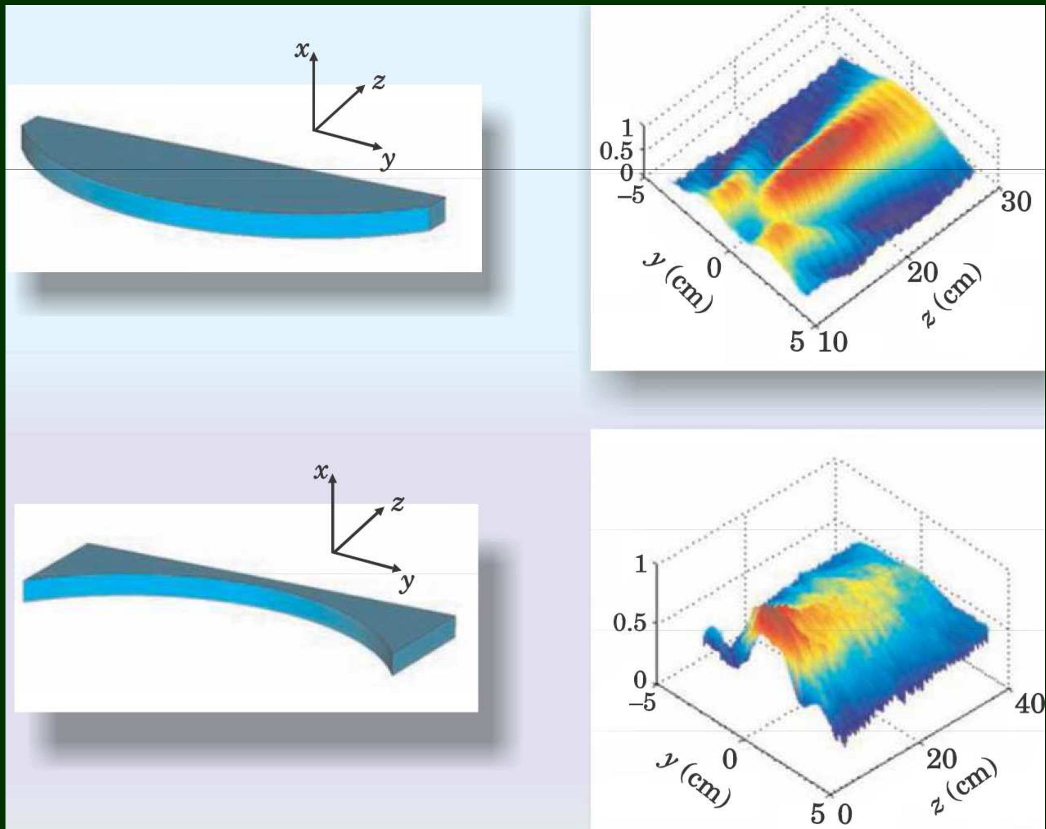


Experimental confirmation of negative refraction

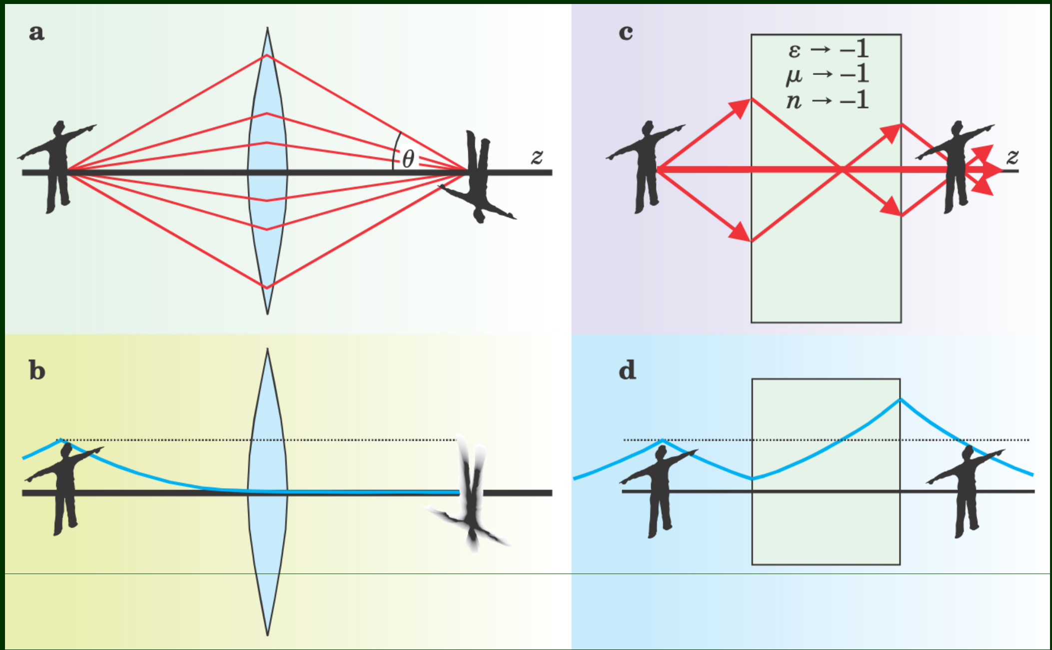


Lenses


z
x
y
Lens
z
y


x
z
y
1
0.5
0
−5
0
5
10
20
30
y (cm)
z (cm)
x
z
y
1
0.5
0
−5
0
5
0
20
40
y (cm)
z (cm)

Lenses


a
θ
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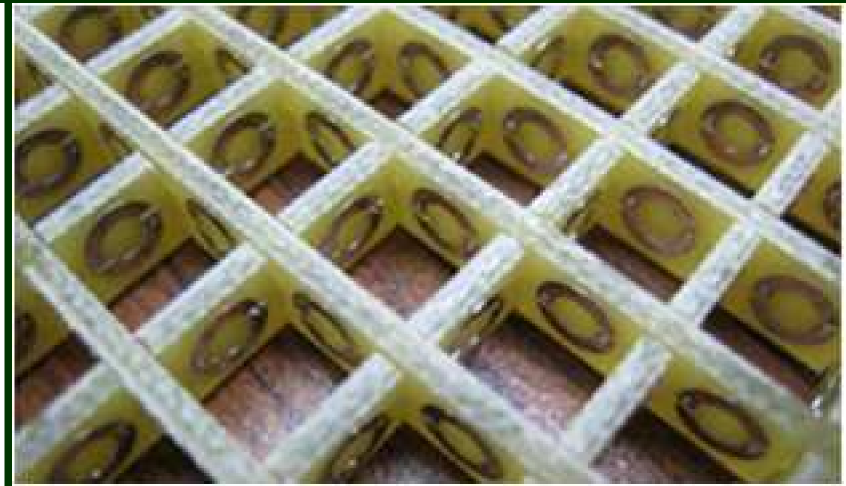
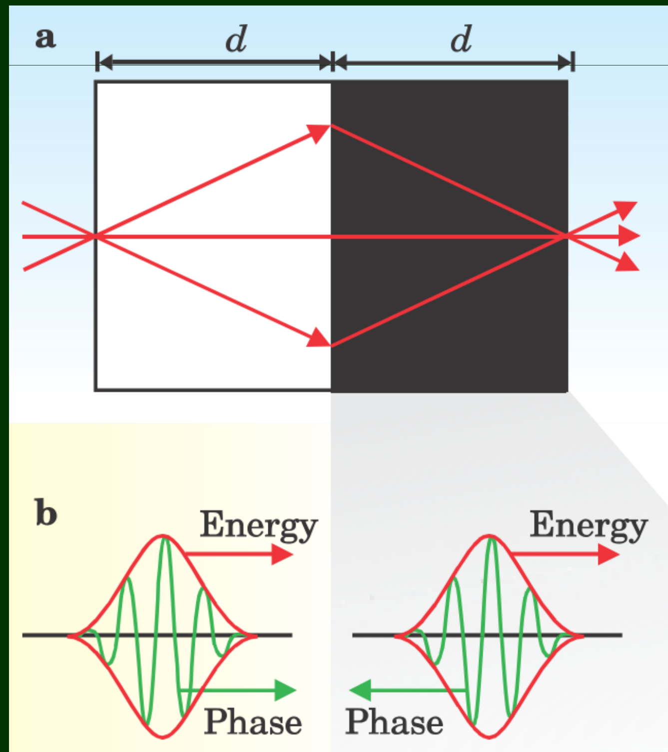
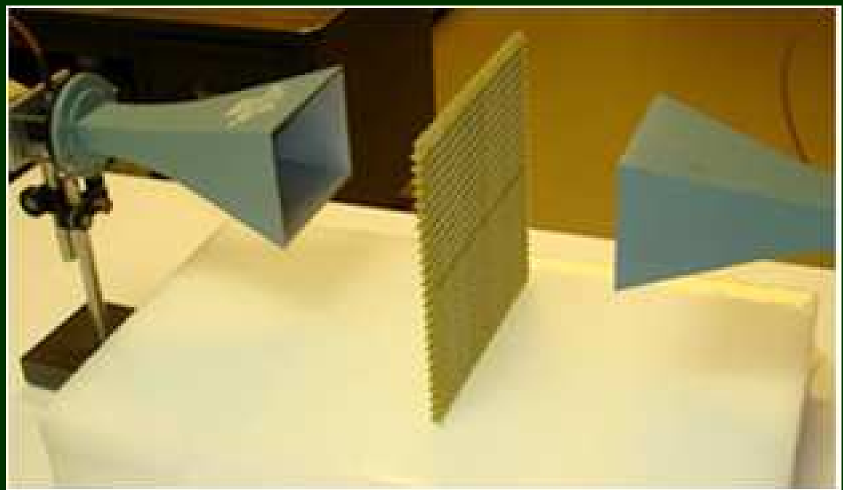
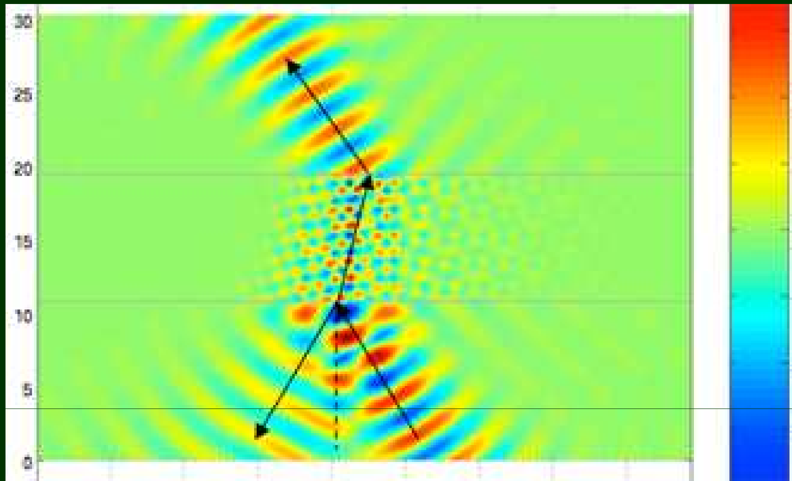
$\varepsilon \to -1$
$\mu \to -1$
$n \to -1$
z
b
d




a
d
d
b
Energy
Phase
Energy
Phase



Simulation



Simulation of negative refraction in a photonic crystal: The incident beam is refracted to the "wrong" side inside the slab.

(a) (b) (c)

Three-dimensional optical metamaterial with a negative refractive index

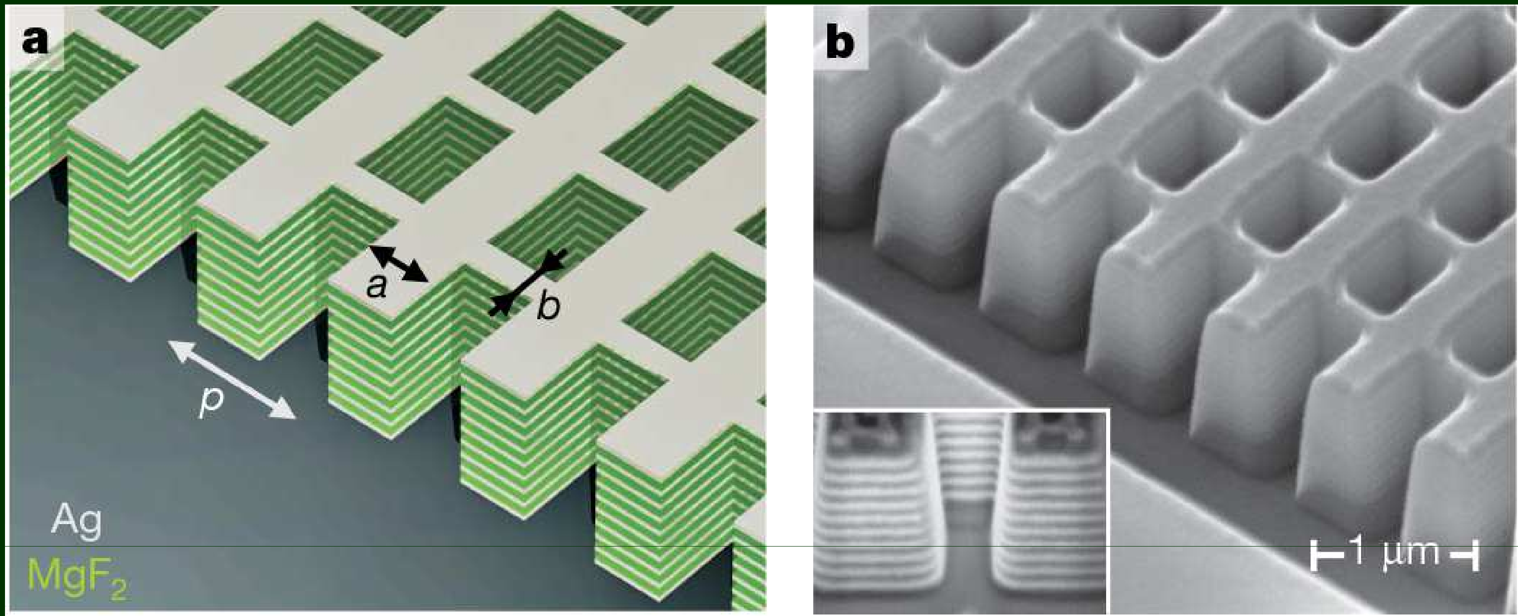


Figure 1 | Diagram and SEM image of fabricated fishnet structure. **a**, Diagram of the 21-layer fishnet structure with a unit cell of $p = 860$ nm, $a = 565$ nm and $b = 265$ nm. **b**, SEM image of the 21-layer fishnet structure with the side etched, showing the cross-section. The structure consists of alternating layers of 30 nm silver (Ag) and 50 nm magnesium fluoride (MgF_2), and the dimensions of the structure correspond to the diagram in **a**. The inset shows a cross-section of the pattern taken at a 45° angle. The sidewall angle is 4.3° and was found to have a minor effect on the transmittance curve according to simulation.

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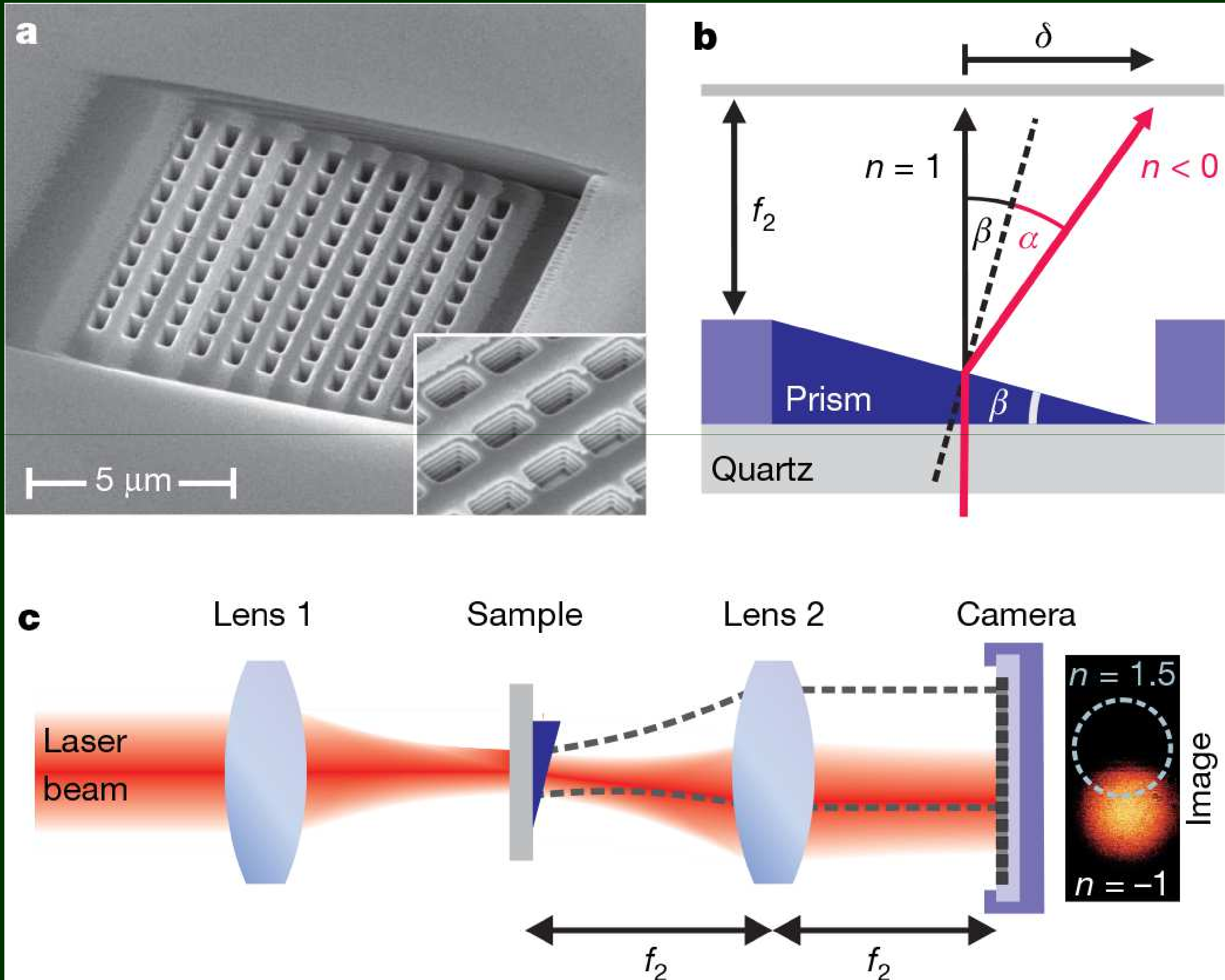
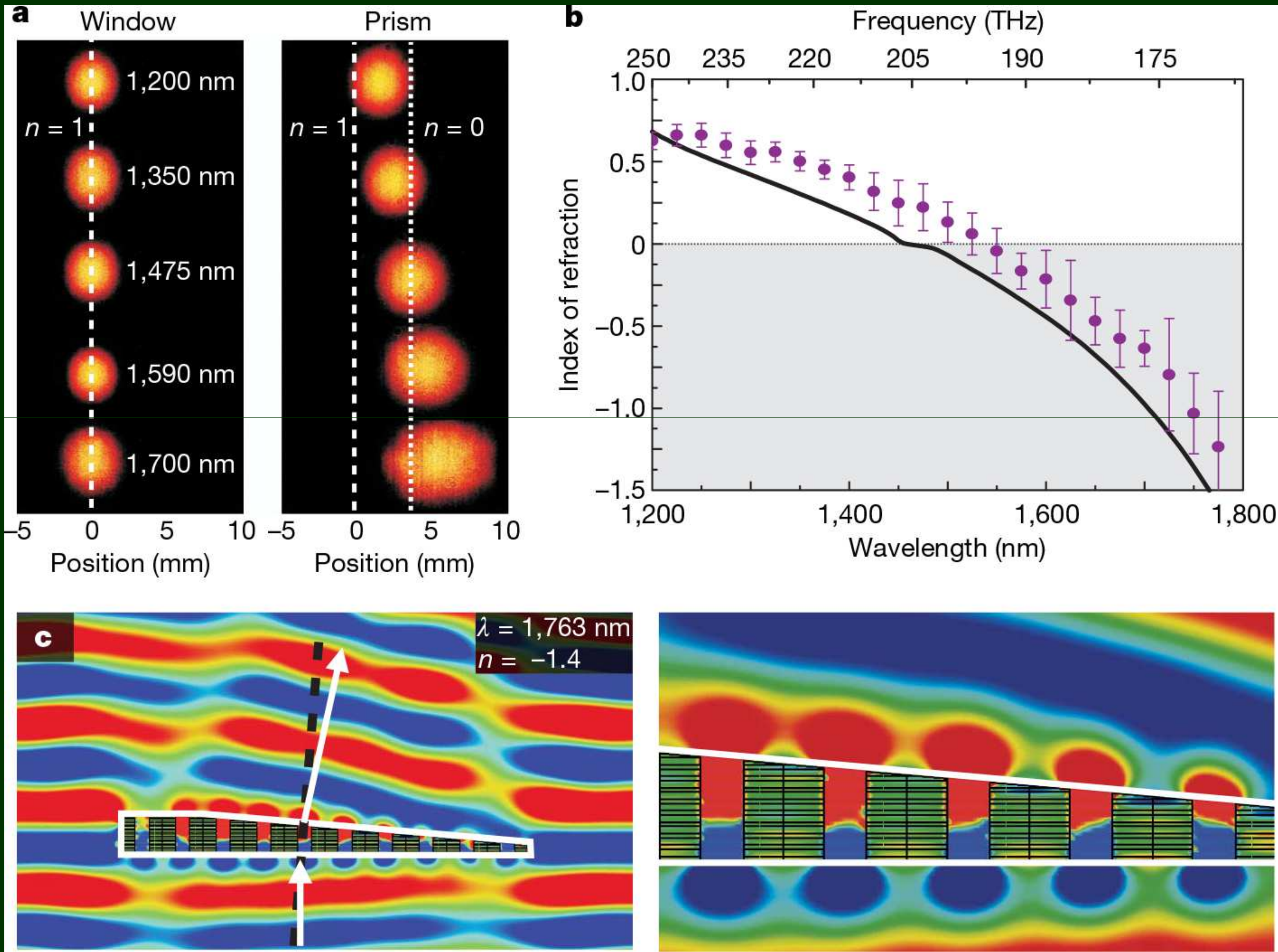
Microscopic image and schematic of measurement



Results of measurements



Optical Negative Refraction in Bulk Metamaterials of Nanowires

15 AUGUST 2008 VOL 321 SCIENCE

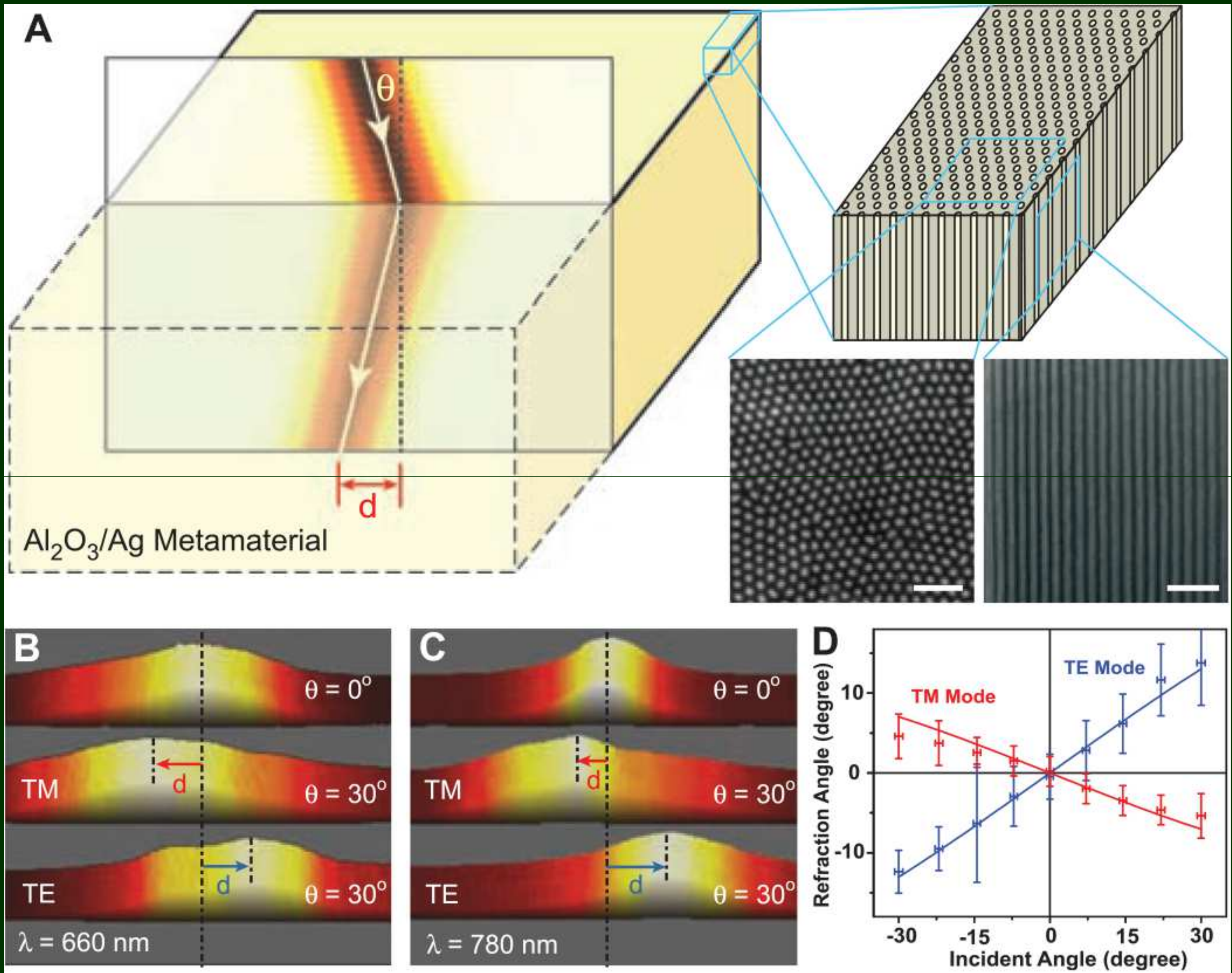


Fig. 1. Negative refraction in bulk metamaterial at visible frequencies. (**A**) (Left) Schematic of negative refraction from air into the silver nanowire metamaterials.