Left-Handed Materials

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About 35 years ago, the Russian physicist Veselago considered theoretically the propagation of an electromagnetic waves (EMW) in a hypothetical medium where both electric permittivity ε and magnetic permeability μ are negative in some frequency range and both of them have small imaginary parts. He deduced that such a medium would have very unusual optical properties within this frequency range. Since the light velocity $c^2 = 1/\varepsilon\mu$, the wave equation has a propagating solutions at $\varepsilon < 0$, $\mu < 0$. Veselago has shown, however, that the EMW at $\varepsilon < 0$, $\mu < 0$ are not the same as in a regular medium (RM), where $\varepsilon > 0$, $\mu > 0$. It follows from the first order Maxwell's equations that in the RM case, the vectors **k**, **E**, and **H** form a right-handed set, whereas in the former case they form a left-handed set. Therefore, the medium with $\varepsilon < 0$, $\mu < 0$ is called the left-handed medium (LHM).

All unusual properties of the LHM originate from the fact that in the isotropic LHM the energy flux given by Poynting vector **S = E**x**H** is anti-parallel to the wavevector **k**. The negative refraction of EMW at the interface of LHM and RM, as well as the negative Doppler effect, are among the most drastic theoretically predicted manifestations of the LHM.

The phenomenon of the negative refraction can be easily understood from Fig. 1, where reflection of the light is shown at the RM-LHM interfaces. It follows from the continuity of tangential components of **k** and normal component of **S** that the sign in the Snell's law is negative. Negative refraction at the interface of photonic crystal and vacuum has been observed recently experimentally by the San Diego group.

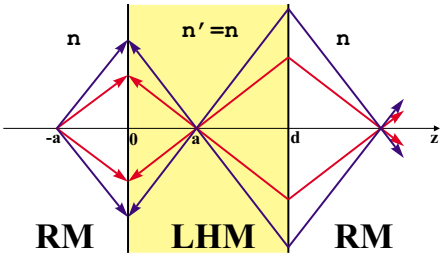

FIG. 1: Veselago lens. A point source is at the point –a. Arrows show the directions of **k**-vectors. In the LHM, Poynting's vectors are opposite to the directions of **k**.

The interest to the negative refraction is connected with the possibility of creation of a unique lens, first proposed by Veselago, which is just a slab of LHM with $\varepsilon' = -\varepsilon$, $\mu' = -\mu$ embedded into a normal medium with $\varepsilon > 0$, $\mu > 0$ (see Fig. 1). Such a lens may be used for the 3D-imaging.

During few recent years there was an intense theoretical discussion covering many aspects of the theory of the LHM, including very fundamental questions, such as whether the Veselago lens has a wavelength limitation typical for all other optical devices, whether the LHM has a negative index of refraction, whether the San Diego group had indeed observed the LHM and so on. A review of the recent experimental and theoretical results in this field will be presented.