Nanostructured non-magnetic left-handed composites

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Introduction

The materials with simultaneously negative values of effective dielectric permittivity and magnetic permeability, first introduced in [1], were shown to have negative value of the phase velocity (and the refractive index). Numerous counterintuitive physical effects have been predicted to take place in negative-n systems, also known as left handed media (LHM) [1, 2, 3, 4]. However, the absence of materials with naturally-occurring high-frequency magnetism has lead to abandonment of the LHM-related research till early 2000, when first negative-μ material has been synthesized[5]. The majority of modern LHM systems are based either on resonant structures[5, 6, 7], or on photonic band gap materials[8, 9]. The materials based on the former designs are extremely lossy, and thus are useful only in near-field applications[10]. The latter (PBG) systems typically have anisotropic refractive index and are intolerant to fabrication defects; with the present state of technology these structures can be realized only at GHz (radio) frequencies.

In the present work we propose a new approach to construct a system with negative refractive index. In contrast to all previous designs, our system is implicitly non-magnetic and homogeneous. The proposed material is based on the EM wave propagation inside strongly anisotropic dielectric material in waveguide geometry. This design is highly scalable from GHz to optical frequencies. We present the theoretical description of the EM properties of the proposed system and several realizations for different spectral ranges.

Theoretical foundations of non-magnetic LHMs

The geometry of the proposed system is shown in Fig. 1. The material is composed by a planar waveguide with its core extending in the directions (y, z). The core material has anisotropic uniaxial dielectric constant with anisotropy axis parallel to x. It can be shown that any propagating in such a system wave can be represented as a series of different waveguide modes, characterized by their polarization and structure in x direction[13]. Namely, one can distinguish two fundamentally different kinds of modes (see Fig. 1). The modes of the first kind (known as TE or *ordinary*) waves have their E vector in (y, z) plane. The modes of the second kind (TM, or *extraordinary* waves) have their H field in the waveguide plane. These waves whose propagation is affected by *both* $\epsilon_{||}$ and $\epsilon_{\perp}$, are the primary focus of this work.

The propagation of a given mode through the system is characterized by a free-space-like dispersion relation

$$k_y^2 + k_z^2 = \epsilon\nu\frac{\omega^2}{c^2}, \tag{1}$$

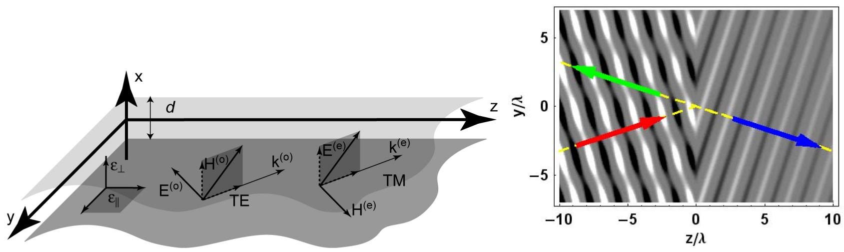

Figure 1: (a)Schematic configuration of the non-magnetic planar LHM system. Also in[12]; (b) Refraction of the mode on the boundary between conventional (right) and negative-n (left) systems. Parameters of $n > 0$: $\epsilon_{||} = \epsilon_\perp = \nu = 1/2 + 0.002i$; parameters of $n < 0$: $\epsilon_\perp = \nu = -1/2 + 0.003i$. Also in[12].

where k_y, and k_z are the components of the propagating wavevector, ω is the frequency of the electromagnetic oscillations, ϵ is $\epsilon_\perp$ for TM modes and $\epsilon_{||}$ for TE ones, and $\nu = 1 - \kappa^2/(\epsilon_{||} k^2)$, with parameter κ defined solely by the x structure of the mode[12, 13].

As it is seen from Eq. (1), the propagation of the mode inside the structure is possible only when ϵ and ν are of the same sign. The case of $\epsilon > 0$, $\nu > 0$ corresponds to conventional transparent waveguides, the case $\epsilon < 0$, $\nu < 0$ is described here. This system not only provides an easy way to concentrate the propagating wave in deeply subwavelength spatial areas, the phase velocity of any propagating in such a system mode would be negative, with refractive index $n_{\text{eff}} = -\sqrt{\epsilon\nu}$ (see Fig. 1) [12].

The strong anisotropy required to achieve the regime of left-handed propagation can be obtained using (i) materials with strongly anisotropic effective carrier mass, (ii) layered systems or (iii) anisotropic nanoplasmonic systems, as described in the following chapters. Also, the planar transmission line-LHM [11] can be considered as another realization of the proposed system.

THz realization: Bi

The effective dielectric constant of a material at high frequencies is dominated by a dynamics of its electrons. The dielectric properties of the materials having free electrons strongly resemble the behavior of the electron-gas plasma and are well-described by Drude formula:

$$\epsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\tau)}, \tag{2}$$

where ω_p is so-called plasma frequency, defined by $\omega_p^2 = \frac{Ne^2}{m_{eff}}$

As it is seen from the Eq. (2), in metallic (or semi-metallic) materials, $\epsilon < 0$ for $\omega < \omega_p$, and $\epsilon > 0$ when $\omega > \omega_p$. Therefore, since the plasma frequency is directly related to the effective electron mass in the material, the anisotropy of the effective mass may lead to anisotropy of effective dielectric constant.

To provide just one example, we show that a thin Bi film can be used as a natural left-handed material in THz frequency range. Apart from having extremely low loss, Bi has strongly anisotropic $m_{\rm eff}$ with $\omega_{p,||} = 187\ cm^{-1}$ for the electric field parallel to its C_3 crystalline axis, and $\omega_{p,\perp} = 158\ cm^{-1}$ when $E \perp C_3$[14]. Using these (experimental) values of ω_p in Bi film with C_3 axis co-aligned with x, we obtain: $\epsilon_\perp \approx -10 + 0.001i$; $\epsilon_{||} \approx 20 + 0.001i$ for $\lambda = 57\mu m$.

IR/optical realization: anisotropic random nanocomposites

Since only a limited number of materials have strong effective mass anisotropy required for described here non-magnetic LHMs, we propose an approach to build the composite with strongly anisotropic dielectric constant. In such a composite we embed the randomly distributed nanoparticles with negative dielectric constant into transparent ($\epsilon > 0$) dielectric host. The negative ϵ is easily accessible both in optical and infrared frequency ranges via plasmonic (Ag,Au,. . .) or polar (SiC,. . .) materials correspondingly.

If the typical size of inclusions is much smaller than the wavelength, the inclusions have elliptical shape, and the average inclusion concentration is small, the effective dielectric constant of the composite can be calculated using:

$$\epsilon_{\rm eff} = \frac{p\epsilon_m E_{\rm in} + (1-p)\epsilon_d(E_0 + < E_d >)}{pE_{\rm in} + (1-p)(E_0 + < E_d >)} \tag{3}$$

where ϵ_m and ϵ_d are the dielectric constants of the inclusion and host materials, $E_{\rm in}$ is the field inside the inclusion, E_0 and E_d are the homogeneous and "dipole" parts of the field inside the dielectric host, and p is the average inclusion concentration.

It can be shown that $< E_d >= 0$ for the case of evenly distributed spherical particles, yielding the well-known Maxwell-Garnett result [15, 16]. If the inclusions have anisotropic (ellipsoidal) shape or if the average separation between the inclusions is anisotropic [this can be achieved, for example, by stressing (deforming) the composite] E_d does not vanish and can be estimated using

$$< E_d >= \frac{p}{4}\frac{\epsilon_d(\epsilon_m - 1)\left(I(\alpha_d) - \frac{I(\alpha_i)}{\pi}\right)}{(1-n)\epsilon_d + n\epsilon_m}E_0, \tag{4}$$

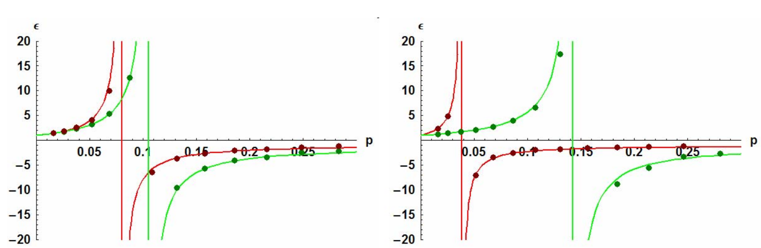

Figure 2: Effective dielectric constant in the material composed by a homogeneously distributed in a dielectric host metallic elliptic cylinders (left), and anisotropically distributed circular metallic cylinders (right); spatial anisotropy is 1.2, $\epsilon_d = 1$, $\epsilon_m = -1.2$, symbols correspond to numerical simulations, lines represent Eq. (4).

where n is so-called depolarization factor[13], α_d and α_i describe the anisotropy of the inclusion shape and distribution correspondingly, and the function I is obtained from a direct integration of a dipole field over the elliptical cell[17] (see Fig. reffigM-Gan). In particular, if the system is represented by stacked in x-direction metallic-dielectric layers, using $n_x = 1, n_y = n_z = 0$ we obtain: $\epsilon_{||} = p\,\epsilon_m + (1-p)\epsilon_d$; $\epsilon_\perp = \frac{\epsilon_d\,\epsilon_m}{p\,\epsilon_d + (1-p)\epsilon_m}$. We note that the existence of the left-handed behavior in this particular configuration has been also proposed in[18].

In conclusion, we have proposed a new approach to LHMs and suggested the realizations for THz, IR, and optical spectral ranges. The work was supported by OSU, NSF grants DMR-0134736, ECS-0400615, and PRISM.

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