Design of negative-refractive-index materials on the basis of rods with a gradient of the dielectric constant

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The authors propose an approach to the design of negative-refractive-index materials based on the use of dielectric rods with a gradient of the dielectric constant. A triangular-lattice photonic crystal assembled from multilayer dielectric rods with a refractive index approximating a fish-eye profile is shown to exhibit a negative refractive index in the wavelength range defined by the inequality $0.67 < a/\lambda < 0.83$, where a is the lattice constant of the photonic crystal. A lens consisting of a plane-parallel slab of such a photonic crystal slab is shown to be able to form an image of a point source in this wavelength range. According to the calculations, particularly high-quality images can be obtained at the wavelength $\lambda = (3/2)a$, where the fish-eye dielectric rods scatter the light like a medium with the refractive index equal to −0.85.
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The concept of left-handed electromagnetic media, which are also known as negative-index materials (NIMs), was introduced by Veselago[1] as a theoretical curiosity. Interest in these metamaterials was rejuvenated by Pendry[2] and Smith *et al.*,[3] who noted that the growth of evanescent fields within a NIM provides the opportunity for building a "perfect lens" that can focus electromagnetic waves to a spot size much smaller than a wavelength. Although various aspects of Pendry's treatment of NIMs have been questioned,[4,5] negative refraction has nonetheless been confirmed in recent experiments,[6–8] and its theoretical background has been further explored.[9–11] Negative-index materials have recently been designed on the basis of composite wire and split ring resonator structures,[3,7,12] backward-wave transmission lines,[13] and photonic-band-gap crystals.[10,14,15] In the work of Leonhardt and Philbin, the use of inhomogeneous spheres is proposed for NIM at wavelengths much smaller than the sphere radius.[16]

Usually, NIMs based on dielectrics are designed from periodically arranged homogenous materials. In such a case, for instance, thick slabs consisting of a large number of rods are required for realizing good focusing. In the present work, we propose the design of a NIM lens from dielectric rods with a specific dielectric constant profile. This design leads to comparable or even improved focusing from much thinner slabs thus containing a much smaller number of rods.

The proposed approach is based on using dielectric rods which themselves possess a negative refractive index at definite wavelengths. The approach consists of the following steps: (i) the design of elementary units (rods) exhibiting properties of NIM; and (ii) different periodic or quasiperiodic structures assembled from these elementary units are considered, and their properties are calculated numerically with the goal of producing negative refraction and optimizing the focusing effect. A highly efficient and accurate multiple-scattering approach[17] is used to calculate propagation of electromagnetic waves through these structures.

The elementary building blocks of our design are dielectric rods with a changeable refractive index. Its gradient resembles a "fish-eye" profile[18] given by

$$n(r) = \frac{n_0}{1 + (r/r_0)^2}, \tag{1}$$

where r is the distance from the center of the rod and n_0, r_0 are constants. In such a material light propagates in circular (or spiral) trajectories with a radius comparable to the quantity r_0, i.e., a medium with the fish-eye dielectric constant profile behaves like a NIM from the point of view of light scattering. Consider the design of dielectric rods from the point of view of light scattering. We use an approach based on the effective medium concept[19] to choose appropriate parameters for the dielectric profile of the rod. This method relies on using a hypothetic background medium with variable index of refraction in which the dielectric rod is immersed. The scattering cross section of the rod is calculated as a function of the refractive index of the background medium. It is obvious that the scattering cross section should exhibit a minimum when the refractive index of the background medium approaches that of the rod under investigation. For practical purposes, we approximate the fish-eye medium by use of several discrete layers of different refractive indices. We analyzed the scattering cross section for a rod which consists of three layers with the radii $r_1 = 0.5a$, $r_2 = 0.25a$, and $r_3 = 0.1a$, and refractive indices $n_1 = 1.5$, $n_2 = 3$, and $n_3 = 4$.

Analogous calculations were performed for a specific wavelength interval. The effective refractive index of the rod as a function of the radiation wavelength is illustrated in Fig.

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