Angular Dependence in Optical Negative Index Materials

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The refractive index is the most important parameter describing the interaction of light with matter. Optical negative index materials (ONIM), i.e. the materials with the refractive index having a negative real part have generated a considerable amount of interest in recent years due to their unusual properties and a plethora of potential applications. The negative index can be obtained through the use of periodic elements which act as resonators resulting in effective permittivity and permeability. If the magnetic and electric resonances are suitably placed, the resultant structure can have a negative permeability and permittivity at the same wavelength resulting in negative refractive index. We have already discussed results that show experimental verification of a negative refractive index in a periodic structure of coupled nanorods (V.M. Shalaev *et al.*, Opt. Lett. **30**, 3356 (2005)).

Ideally, the individual resonant element should be much smaller than the wavelength of interest, but the unit cells of periodic structures can have dimensions that are comparable to the wavelength. It is very important to understand the angular dependence of equivalent optical characteristics in order to quantify the use of such structures in potential applications. The paper presents angular dependencies of sample geometries that show a negative index of refraction; the study also relates the anisotropic properties of ONIM prototypes to the geometry of elementary cells.

An example ONIM structure consists of coupled pairs of silver nanostrips separated by an alumina spacer. The unit cell for the sample geometry is shown in Figure 1-a. In simulations, the structure exhibits an effective refractive index of −2.57 + 2.46i for an incident wavelength of 596 nm at normal incidence.

Figure 1-b shows the angular dependence of the real and imaginary parts of the refractive index at an incident wavelength of 596 nm. The vertical dashed line shows the angle at which the first diffraction mode starts propagating, i.e. it is no longer evanescent. We note that the real part of the refractive index crosses over from the negative to positive values almost at the same angle. This angle is given by the relation $\sin\theta = (\lambda - d)/d$, where d is the periodicity of the structure.

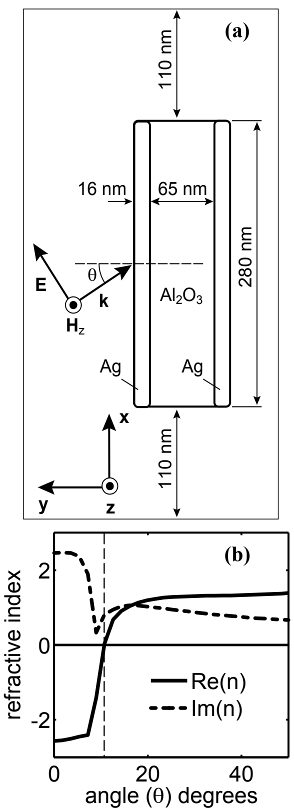

Figure 1. (a) An example of ONIM structure. (b) The angular dependence of the refractive index at 596 nm.

The transition of the first order diffraction mode forces the refractive index to come back to positive values. As soon as the first order diffraction mode starts propagating there is a flow of energy due to an additional propagating mode. The leakage of energy reduces the local fields inside the coupled nanostrip structure. The local fields play an important role in generating artificial permeability and permittivity. Hence, a reduction in the local field results in a lower resonance effect and pushes the refractive index to positive values. A possible way to avoid this problem is to design a structure that resonates at a wavelength, which is much larger than the periodicity d. This way the critical angle could be extended to higher values. For example, if the resonant wavelength is longer than two times the periodicity, the first order diffraction mode remains evanescent for all angles of incidence.