Tunable optical negative-index metamaterials employing anisotropic liquid crystals

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A full-wave analysis technique based on the finite element-boundary integral method is developed and used to rigorously treat the scattering from periodically structured metamaterials incorporating anisotropic liquid crystals (LCs) and dispersive materials. Reconfiguration of the negative-index metamaterials is achieved by controlling the magnetic resonance via tuning permittivity of the embedded anisotropic LCs. Numerical results show that the refractive index of the metamaterials can be reconfigured by tuning the director orientation of anisotropic LCs or by using temperature-dependent LCs. The design configurations and their characteristics in the near- and the mid-infrared ranges are presented.
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Current research and development in electro- and nonlinear-optical materials for photonic applications are largely centered on nanostructured metamaterials that exhibit unique physical and optical properties.[1–4] In particular, research in negative- and zero-index materials[3,4] (NIMs and ZIMs) has been very active over the past few years. In general, the actual fabrication of such materials and nanostructures involves very complex and tedious multistep nanometer scale processing. It is therefore highly desirable that some kind of tunability be built into the material/structures whereby the final product will exhibit the desired properties at the prescribed spectral range or resonances. The most commonly employed means are electro-optical tuning, where a constituent material possesses an electro-optics response such as the Pockel effect (where the refractive index change is proportional to the applied electric field) or the Kerr effect (where the refractive index change is proportional to the square modulus of the electric field). These effects require that some electrodes be built into the structure, which could introduce serious complications to the actual fabrication process for the NIM-ZIM materials. A preferable alternative is to have a nonlinear optical material as one of the constituents, in which the refractive index can be modified by the optical field intensity, i.e., the change in refractive index $\Delta n = n_2 I_{\mathrm{op}}$, where n_2 (in units of cm^2/W) is the so-called nonlinear coefficient and I_{op} is the optical intensity (in units of $\mathrm{W/cm}^2$).

In these respects, liquid crystals (LCs) are ideal candidate materials for such tunable applications. Ferroelectric liquid crystals possess the Pockel effect that allows index tuning of ~ 0.1 for an applied voltage on the order of a few $\mathrm{V}/\mu\mathrm{m}$, while nematic liquid crystals possess the Kerr effect that allows similar index tuning at a similar voltage requirement. Perhaps the most important property of nematic liquid crystal is that they possess a nonlinear coefficient n_2 that could be as large as $1000\ \mathrm{cm}^2/\mathrm{W}$,[5,6] thus allowing optical tuning with intensity on the order of $\mathrm{mW/cm}^2$ or $\mu\mathrm{mW/cm}^2$ and electrodeless material/structures.

An approximate isotropic treatment of nematic LCs has been employed to design and analyze metamaterials that have tunable negative-zero-positive refractive indices in the optical frequency range.[3,4] However, Pockel, Kerr, and other nonlinear optical properties of LCs arise from their anisotropy (birefringence) and the crystalline axis reorientation by the applied field. Therefore, a rigorous anisotropic treatment of LC elements is essential to ensure their incorporation into metamaterial structures.

In this letter, two design approaches are presented for tunable optical NIMs that incorporate anisotropic LCs. The first approach utilizes an external field to change the director orientation of the LC molecules to tune the refractive index of the metamaterial, while the second approach employs temperature dependence of the LCs. In addition, these designs differ from those reported in Ref. 4 in two important ways. First, the LC is used to tune the response of the magnetic resonator rather than changing the electric properties of the NIM. Second, the inherent anisotropic properties of the LCs are treated rigorously by a periodic finite element-boundary integral (FE-BI) technique,[7] which has been developed to compute the scattering from periodic structures composed of inhomogeneous, anisotropic, and dispersive materials of arbitrary shape.

Suppose the optical axis of the LC lies in the *x*-*z* plane (see Fig. 1). In an anisotropic LC slab with the initial homeotropic director of the molecules aligned along the *z* axis, an external static electric/magnetic field can align all the director axes to $\mathbf{n} = \{\sin\gamma, 0, \cos\gamma\}$, where γ denotes the angle between the $+z$ axis and the director of the LC. In this case, the permittivity tensor for the aligned anisotropic LC can be represented by[8]

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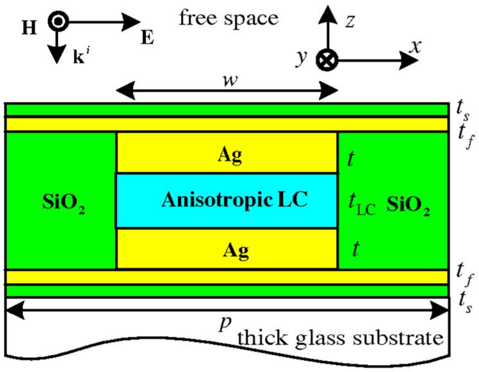

FIG. 1. (Color online) The unit cell geometry of a two-dimensional metamaterial incorporating anisotropic LCs with a reconfigurable index of refraction.

$$\bar{\bar{\varepsilon}}_{\mathrm{LC}} = \begin{pmatrix} \varepsilon_\perp + \Delta\varepsilon \sin^2\gamma & 0 & \Delta\varepsilon\cos\gamma\sin\gamma \\ 0 & \varepsilon_\perp & 0 \\ \Delta\varepsilon\cos\gamma\sin\gamma & 0 & \varepsilon_\perp + \Delta\varepsilon\cos^2\gamma \end{pmatrix}, \quad (1)$$

where $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$, and $\varepsilon_\parallel$ and $\varepsilon_\perp$ are related to the ordinary (n_o) and the extraordinary (n_e) refractive indices of the LC by $\varepsilon_\parallel = n_e^2$ and $\varepsilon_\perp = n_o^2$, respectively.

This choice of the anisotropic LC directors allows no cross-polarized components for the reflected and the transmitted fields for normal incidence. This is a direct consequence of the fact that the coupling between the $\hat{x}$- and $\hat{y}$-directed fields is zero in a LC having the permittivity tensor given in Eq. (1). Moreover, under these conditions, the effective refractive index can still be retrieved using the inversion techniques proposed in Ref. 9, which finds the effective parameters of a homogeneous slab that scatters the same transmitted and reflected fields as the metamaterial.

The two dimensional metamaterial configuration illustrated in Fig. 1 is considered in this study, which is infinite in the $\pm\hat{y}$ directions and periodic along the $\pm\hat{x}$ directions with period p. The unit cell is comprised of silver nanostrip pairs separated by anisotropic LCs and bounded by SiO_2 films from both sides. In addition, it is bounded by thin silver and SiO_2 films on the top and bottom. The metamaterial is then placed on top of a thick glass slab. An anisotropic LC slab is positioned between the silver strips forming a tunable magnetic resonator. The thin silver films provide negative permittivities and the nanostrip pairs provide negative permeabilities through magnetic resonances. The metamaterial design is assumed to be illuminated by a normally incident electric field polarized along the $\hat{x}$ direction and propagating in the $-\hat{z}$ direction.

The unique properties of anisotropic liquid crystals—very broadband transparency and large optical birefringence (Δn as large as 0.6)[10]—make them a good candidate for use in developing reconfigurable NIMs. In the analysis that follows, the LC parameter values are chosen as $n_o=1.5$ and $n_e=1.9$. A proper application of an external static electric or all-optical field rotates the director axis of the LCs[8] in the x-z plane, allowing $\bar{\bar{\varepsilon}}_{\mathrm{LC}}$ to be tuned in terms of γ according to Eq. (1).

The refractive indices of anisotropic LCs can also be tuned in the visible region utilizing their temperature dependence.[11] Therefore, the refractive indices of metamaterials incorporating anisotropic LCs can also be reconfigured

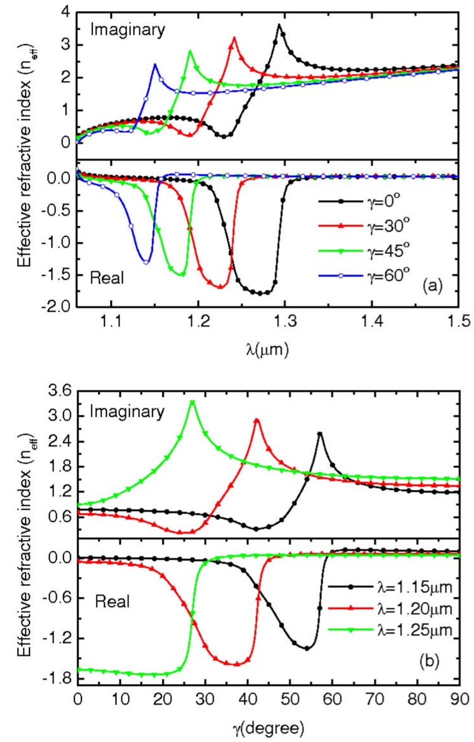

FIG. 2. (Color online) The n_{eff} at near-infrared ranges: (a) n_{eff} with respect to wavelength for several different angles γ and (b) n_{eff} with respect to the director angle at different wavelengths.

with respect to temperature. The permittivity tensor of the temperature-dependent LC is given by $\bar{\bar{\varepsilon}}_{\mathrm{LC}} = \mathrm{diag}\{n_o^2, n_o^2, n_e^2\}$, where the values of n_o and n_e at different temperatures can be taken from Ref. 11.

In the following analyses, SiO_2, Al_2O_3, and glass are represented by nondispersive dielectric materials with permittivity values equal to 2.088, 2.6244, and 2.25, respectively. The permittivity for the dispersive silver material is obtained by fitting experimental results.[12]

The following geometrical parameter values were used for the design configuration: $p=600$ nm, $w=300$ nm, $t=30$ nm, $t_{\mathrm{LC}}=200$ nm, $t_s=20$ nm, and $t_f=10$ nm. The retrieved effective refractive index $(n_{\mathrm{eff}}=n'+in'')$ for the metamaterial having a thickness of $2(t_s+t_f+t)+t_{\mathrm{LC}}$ are shown in Fig. 2(a) with respect to wavelength for different director angles $\gamma=0°$, 30°, 45°, and 60°. The effective permittivity $(\varepsilon_{\mathrm{eff}}=\varepsilon'+i\varepsilon'')$ and permeability $(\mu_{\mathrm{eff}}=\mu'+i\mu'')$ are not shown here due to limited space. We observed that ε' and μ' simultaneously reach negative values over limited ranges, allowing the structure to behave as a low-loss double negative-index metamaterial. Changing the angle γ has a larger effect on the location than on the bandwidth of the NIM behavior. Figure 2(b) shows the effective refractive index as a function of the director angle for three different wavelengths, i.e., $\lambda=1.15$, 1.20, and 1.25 μm. This clearly demonstrates that the refractive index can be tuned at the different wavelengths by varying the director angle γ of the LC.

Figure 3 shows the effective refractive index for a tunable metamaterial configuration designed for operation in the mid-IR range. The following parameters are used in the simulation: $p=2400$ nm, $w=1200$ nm, $t=120$ nm, $t_{\mathrm{LC}}=200$ nm, $t_s=20$ nm, and $t_f=20$ nm. One can observe that the NIM bandwidths for the mid-IR design are wider than

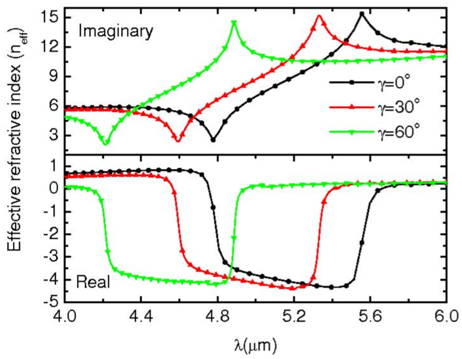

FIG. 3. (Color online) The n_{eff} at mid-infrared ranges with respect to wavelength for three different values of γ.

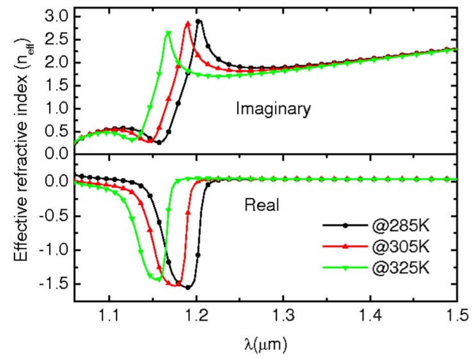

FIG. 4. (Color online) The effect on the refractive index of a change in the LC temperature.

those of the near-IR design shown in Fig. 2(a), but they are also accompanied by higher values of n'', which are mainly attributed to the higher losses in the silver at mid-IR wavelengths. It is also worth noting that the shifts in the NIM bands over the range $0° \leq \gamma \leq 60°$ are similar for the mid-IR ($\approx 15\%$) and the near-IR ($\approx 12\%$) designs. The behavior of n_{eff} as a function of the director angle γ (not shown here) reveals that n' stays negative over the range from $\gamma=0°$ to 68° at $\lambda=4.8$ μm, and from $\gamma=0°$ to 28° at $\lambda=5.4$ μm. At both wavelengths, the transition from a negative to a zero index of refraction occurs over a very narrow range of γ.

The effects of temperature on the effective refractive index are shown in Fig. 4 for a configuration having the same design parameters as those used in Fig. 2. The tuning range of the negative refractive index by changing temperature over 40 K is relatively limited due to the small change in the permittivity tensor for the temperature-dependent LCs.

In conclusion, two-dimensional reconfigurable NIMs incorporating anisotropic LCs have been presented that operate in the near-IR and the mid-IR ranges. The anisotropic behavior of the LCs was treated rigorously using the periodic FE-BI full-wave analysis technique. The entries in the permittivity tensor for the LCs can be tuned by changing the director orientation of the LC molecules or by their temperature dependence to control the magnetic resonance of NIMs. It provides an effectual method of tuning the location of the NIM band. There are several apparent design trade offs such as number of LC layers employed, biasing requirements, and ease of fabrication. Compared to other reconfigurable NIM designs (e.g., Ref. 3), the structures proposed here are more amenable to fabrication and characterization. In addition, the two thin silver films can serve a dual purpose by operating as the bias electrodes which control the orientation of the LC molecules.

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