Liquid Crystal Clad Metamaterial with a Tunable Negative-Zero-Positive Index of Refraction

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Introduction

Over the last few years, the phenomenon of negative index of refraction has been predicted and demonstrated in various forms of metamaterials in several frequency spectrums. Many realizations employ periodic structures such as photonic crystals and nano-patterned noble metal particles or holes, but bulk metamaterials with random distributions of nano particles [1] have also been suggested. Recently, reconfigurability of the index of refraction was suggested using liquid crystal as the host medium containing a random distribution of coated dielectric nano-spheres [2]. This paper extends the reconfigurability to metamaterials by cladding liquid crystal as substrate and superstrate layers onto a conventional negative-index metamaterial (NIM). It is demonstrated that a metamaterial can be reconfigured between negative, zero, and positive refractive index states at a fixed wavelength.

To a linearly-polarized incident wave, an aligned nematic liquid crystal presents the permittivity ϵ_{LC} given by

$$\epsilon_{LC} = \frac{\epsilon_{\|}\epsilon_{\perp}}{\epsilon_{\|}\cos^2\theta + \epsilon_{\perp}\sin^2\theta}, \tag{1}$$

where $\epsilon_{\|}$ and $\epsilon_{\perp}$ are the permittivities for the fields polarized parallel and perpendicular to the director axis $\hat{n}$. The angle between $\hat{n}$ and the incident wave vector $\mathbf{k}^i$ is equal to θ. Changing θ tunes the value of ϵ_{LC} between $\epsilon_{\|}$ and $\epsilon_{\perp}$. Nematic liquid crystal with large dielectric anisotropy on the order of $\epsilon_{\|} \approx 4$, $\epsilon_{\perp} \approx 2$ has been fabricated over the infrared spectrum, where it is nearly lossless.

Tunable Metamaterial in the Near-IR Spectrum

Fig. 1 illustrates the unit cell of a two-dimensional metamaterial with a tunable index of refraction, which is a liquid crystal-clad version of the near-infrared (near-IR) metamaterial reported in [3]. Two silver strips separated by a thin layer of alumina form a magnetic resonator, which can provide a less-than-unity or negative permeability. The resonators form an infinite array in the $\pm\hat{x}$ direction with period p, while the space between neighboring resonators is filled with silica. A negative permittivity is provided by thin silver films of thickness t_f tightly binding the magnetic resonators from the $\pm\hat{z}$ directions. Liquid crystal layers of thickness t_{LC} are placed both as a substrate and a superstrate. The entire metamaterial structure is finally placed on a glass support structure.

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The metamaterial is illuminated by a time-harmonic light wave at normal incidence from air propagating in the $+\hat{z}$ direction, and the electric field is polarized in the $\hat{x}$ direction. This electromagnetic scattering problem by an infinitely periodic structure is analyzed using the finite element-boundary integral (FE-BI) method [4]. The reflection and the transmission coefficients referenced on the top and the bottom surfaces of the metamaterial slab having the total thickness of $2(t_{LC} + t_f + t) + d$ are converted to effective material parameters using a well-established homogenization procedure [5]. In the FE-BI simulation, the thick glass structure is treated as a half-space, and the liquid crystal is approximated by a homogeneous, isotropic dielectric material. The refractive indices used in the simulations for silica, alumina, and glass are given by 1.445, 1.62, and 1.50, respectively. Published experimental results [6] were used to represent the permittivity function for the silver.

Fig. 2 shows the effective index of refraction $n = n' + in''$ plotted with respect to ϵ_{LC} for a near-IR design at the free-space wavelengths of $\lambda = 1.40$ and 1.45 μm (see Fig. 3 for the values of the geometrical parameters). It is noted that the real part n' of the index of refraction does not vary linearly with ϵ_{LC}. For $\lambda = 1.40$ μm, n' instead increases steeply from -1.0 to 0 over the narrow range of ϵ_{LC} between 2.0 and 2.5, followed by a much slower transition to $n' = 1.34$ at $\epsilon_{LC} = 6.0$. It is also observed that the minimum loss is realized at $\lambda = 2.42$ μm, where n' increases most rapidly. Tuning the liquid crystal permittivity reconfigures the metamaterial in three ranges of significance — a NIM in the range $2 \leq \epsilon_{LC} < 2.46$, a zero-index material (ZIM) at $\epsilon_{LC} = 2.46$, and a positive-index material (PIM) in the range $\epsilon_{LC} > 2.46$ — at $\lambda = 1.40$ μm. Another reconfigurable NIM-ZIM-PIM characteristic is also seen to exist corresponding to $\lambda = 1.45$ μm.

The effective parameters $n = n' + in''$, $\epsilon = \epsilon' + i\epsilon''$, and $\mu = \mu' + i\mu''$ for the metamaterial design are plotted as a function of wavelength in Fig. 3 for different values of ϵ_{LC}. Fig. 3(a) shows that with $\epsilon_{LC} = 2$, the metamaterial exhibits a negative index behavior from 1.37 to 1.47 μm. As ϵ_{LC} is increased, it is observed that the negative index band diminishes from the shorter wavelength side before it completely disappears when $\epsilon_{LC} = 2.7$. The portions of the n' curves which transition from negative values to zero between 1.45 and 1.48 μm are nearly the same for the two cases $\epsilon_{LC} = 2$ and 2.5, although their loss characteristics (indicated by n'') are different as can be seen in Fig. 3(b). One can observe that a wider negative index bandwidth for the case with $\epsilon_{LC} = 2.0$ is accompanied by higher losses compared with the case corresponding to $\epsilon_{LC} = 2.5$. This may be interpreted as an example of the well-understood trade-off relationship between bandwidth and loss.

The fact that the negative index band decreases from the shorter wavelength side as ϵ_{LC} is increased can be understood by inspecting the behavior of ϵ in terms of ϵ_{LC} and λ. The tuning over the effective permittivity in negative, zero, and positive ranges is achieved mainly through an averaging effect over the permittivities of constituent components of the metamaterial. The averaging effect on ϵ is obvious from Fig. 3(c) by observing that ϵ' increases monotonically as the value of ϵ_{LC} is increased. In addition, the permittivity of bulk silver is a decreasing function of λ. Therefore, the range for which the condition $\epsilon' < 0$ is satisfied starts at a longer wavelength as ϵ_{LC} is increased, making the negative index band decrease from the shorter wavelength side. Magnetic resonances can be observed in Fig. 3(d) for all three values of ϵ_{LC}, so that the control over ϵ by tuning the liquid crystal permittivity will result in the desired reconfigurable index of refraction.

Conclusion

A near-IR metamaterial having a tunable index of refraction from negative, through zero, to positive values has been proposed. Liquid crystal layers are incorporated both as a superstrate and a substrate onto a conventional NIM. Tuning the permittivity of the liquid crystal layers controls the value of the effective permittivity in an averaging manner. Combined with proper magnetic resonances provided by a pair of silver strips separated by a thin layer of alumina, the effective index of refraction can be reconfigured between negative, zero, and positive values. The ability to vary the permittivity of the liquid crystal layers also provides a method to control the bandwidth of the negative index behavior.

Acknowledgments

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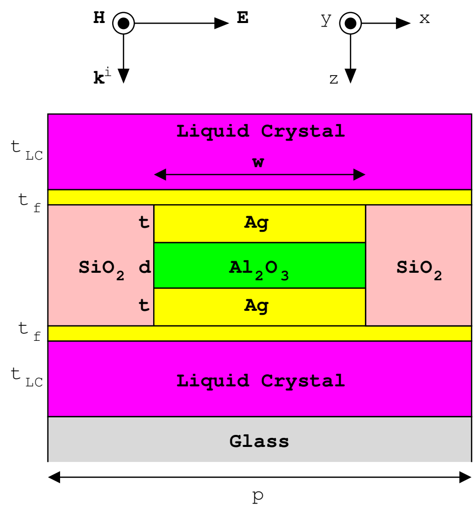


Figure 1: The geometry for a tunable refractive index metamaterial.

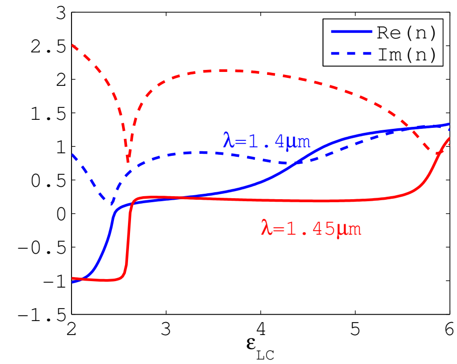
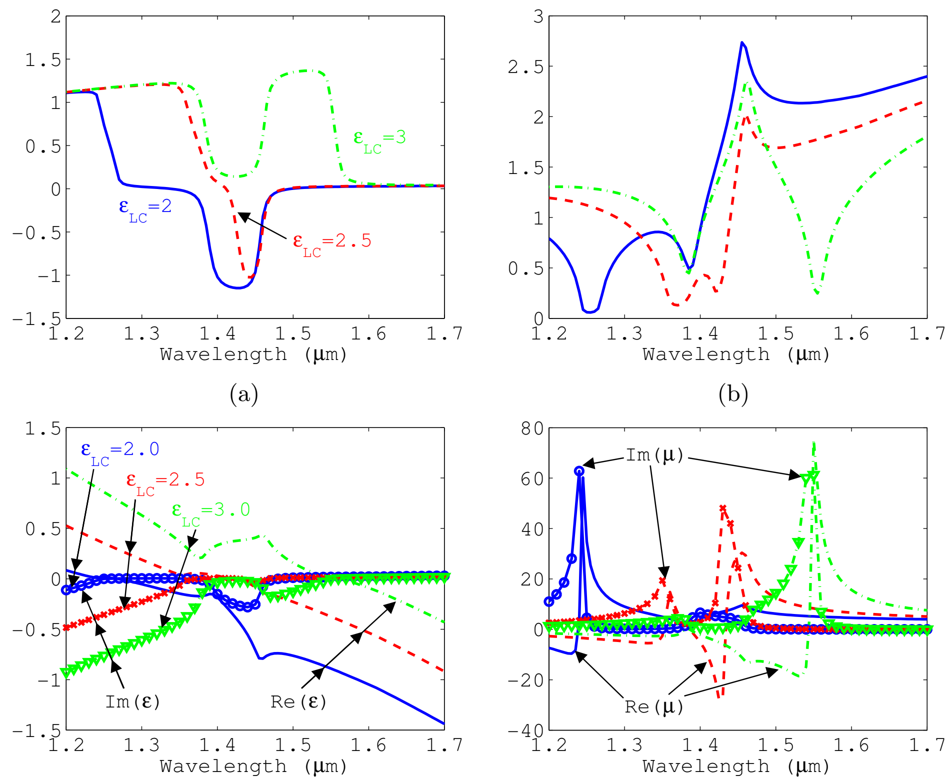


Figure 2: Variation of n with respect to ϵ_{LC} at $\lambda = 1.40$ and $1.45\ \mu$m. The parameters for this metamaterial design are listed in the caption of Fig. 3.



(a) (b) (c) (d)

Figure 3: Effective parameters of the tunable metamaterial for different values of ϵ_{LC}: (a) n', (b) n'', (c) ϵ, and (d) μ. The corresponding geometrical parameters are given by $p = 600$ nm, $w = 300$ nm, $t = 30$ nm, $d = 40$ nm, $t_f = 20$ nm, and $t_{LC} = 200$ nm.