Liquid crystal clad near-infrared metamaterials with tunable negative-zero-positive refractive indices

Douglas H. Werner, Do-Hoon Kwon, and Iam-Choon Khoo

Department of Electrical Engineering, The Pennsylvania State University
University Park, PA 16802, USA

dhw@psu.edu

Alexander V. Kildishev and Vladimir M. Shalaev

Birck Nanotechnology Center, School of Electrical and Computer Engineering
Purdue University, West Lafayette, IN 47907, USA

Abstract: Near-infrared metamaterials that possess a reconfigurable index of refraction from negative through zero to positive values are presented. Reconfigurability is achieved by cladding thin layers of liquid crystal both as a superstrate and a substrate on an established negative-index metamaterial, and adjusting the permittivity of the liquid crystal. Numerical results show that the index of refraction for the proposed structure can be changed over the range from -1 to $+1.8$ by tuning the liquid crystal permittivity from 2 to 6 at a wavelength of 1.4 μm.

OCIS codes: (160.3710) Liquid crystals (160.4760) Optical properties

References and links

1. V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," Sov. Phys. Usp. **10**, 509–514 (1968).
2. R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," Science **292**, 77–79 (2001).
3. I. C. Khoo, Y. Williams, A. Diaz, K. Chen, J. A. Bossard, L. Li, D. H. Werner, E. Graugnard, J. S. King, S. Jain, and C. J. Summers, "Liquid-crystals for tunable photonic crystals, frequency selective surfaces and negative index material development," Mol. Cryst. Liq. Cryst. **453**, 309–319 (2006).
4. V. M. Shalaev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, and A. V. Kildishev, "Negative index of refraction in optical metamaterials," Opt. Lett. **30**, 3356–3358 (2005).
5. S. Zhang, W. Fan, N. C. Panoiu, K. J. Malloy, R. M. Osgood, and S. R. J. Brueck, "Experimental demonstration of near-infrared negative-index metamaterials," Phys. Rev. Lett. **95**, 137404 (2005).
6. S. Zhang, W. Fan, K. J. Malloy, S. R. J. Brueck, N. C. Panoiu, and R. M. Osgood, "Near-infrared double negative metamaterials," Opt. Express **13**, 4922–4930 (2005).
7. V. A. Podolskiy, A. K. Sarychev, and V. M. Shalaev, "Plasmon modes in metal nanowires and left-handed materials," J. Nonlinear Opt. Phys. **11**, 65–74 (2002).
8. I. C. Khoo, D. H. Werner, X. Liang, and A. Diaz, "Nanosphere dispersed liquid crystals for tunable negative-zero-positive index of refraction in the optical and terahertz regimes," Opt. Lett. **31**, 2592–2594 (2006).
9. U. K. Chettiar, A. V. Kildishev, T. A. Klar, and V. M. Shalaev, "Negative index metamaterial combining magnetic resonators with metal films," Opt. Express **14**, 7872–7877 (2006).
10. I. C. Khoo, *Liquid Crystals: Physical Properties and Nonlinear Optical Phenomena* (Wiley, New York, NY, 1995).
11. J. L. Volakis, A. Chatterjee, and L. C. Kempel, *Finite Element Method for Electromagnetics* (IEEE Press, Piscataway, NJ, 1998).
12. D. R. Smith, S. Schultz, P. Markoš, and C. M. Soukoulis, "Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients," Phys. Rev. B **65**, 195104 (2002).

#78819 - $15.00 USD
Received 9 January 2007; accepted 26 February 2007

13. A. V. Kildishev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, and V. M. Shalaev, "Negative refractive index in optics of metal-dielectric composites," J. Opt. Soc. Am. B **23**, 423–433 (2006).
14. P. B. Johnson and R. W. Christy, "Optical constants of the noble metals," Phys. Rev. B **6**, 4370–4379 (1972).
15. L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon Press, Oxford, UK, 1960).
16. A. D. Rakić, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, "Optical properties of metallic films for vertical-cavity optoelectronic devices," Appl. Opt. **37**, 5271–5283 (1998).

1. Introduction

A flurry of recent theoretical and experimental activity has confirmed the idea first proposed nearly four decades ago that the refractive index of a medium could be negative as well as positive [1]. The first demonstration of negative index behavior was at microwave frequencies [2]. More recently, material systems closer to visible wavelengths that exhibit negative index properties have been reported, which include periodic structures such as photonic crystals [3], nano-patterned noble metal particles [4] or their complements [5, 6], as well as bulk metamaterials containing a random distribution of nano-particulates [7, 8]. All of these designs targeted a fixed wavelength for achieving negative index behavior with the exception of [8], where reconfigurability of the metamaterial properties was realized using liquid crystal as the host medium containing randomly dispersed coated dielectric spheres as guests.

In this paper, we introduce a new and novel reconfigurable metamaterial that incorporates a superstrate and a substrate of nematic liquid crystal onto a conventional negative-index metamaterial (NIM) which utilizes a combination of magnetic resonators and metal films [9]. We demonstrate that the effective refractive index of the structure can be tuned from negative — through zero — to positive values, as the dielectric constant of the liquid crystal is varied. We also demonstrate that the bandwidth over which the metamaterial exhibits a negative index behavior can be changed (i.e., increased or decreased) by properly tuning the liquid crystal layers.

2. Liquid crystal properties and analysis methodology

In an aligned nematic liquid crystal, linearly polarized light incident as an extraordinary wave will see a permittivity ε_{LC} given by [10]

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

where $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ are the respective permittivities for light polarized parallel and perpendicular to the director axis $\hat{n}$. It is important to note that ε_{LC} is independent of frequency and only depends on the director axis orientation angle θ with respect to the optical wave vector $\mathbf{k}^i$. To date, nematic liquid crystal with very large dielectric anisotropy (or birefringence) has been synthesized ($\varepsilon_{\parallel} \approx 4$, $\varepsilon_{\perp} \approx 2$, and the resulting tuning range for the refractive index $\Delta n \approx 0.6$) over the visible-infrared spectrum. In this spectral region, micron-thick nematic liquid crystal layers are nearly lossless. Studies over the last two decades have also conclusively demonstrated their unusually large electro- and all-optical (i.e., nonlinear-optical) response associated with the field induced director axis reorientation. These unique optical properties, in addition to their compatibility with almost all technologically important optoelectronic materials and their fluid nature, make them prime candidates for incorporation into nanostructured (electrically or all-optically) tunable materials/devices.

The optical properties of the metamaterials in this study are analyzed using a rigorous full-wave electromagnetic scattering analysis technique known as the finite-element boundary-integral method [11]. Electric field values in a single unit cell of an infinitely periodic structure are determined by imposing periodic boundary conditions in the computational domain. Once

Received 9 January 2007; accepted 26 February 2007

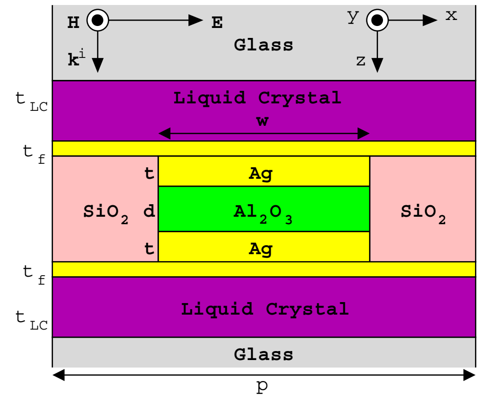

Fig. 1. A two-dimensional metamaterial with thick liquid crystal superstrate and substrate layers having a reconfigurable index of refraction.

the complex reflection and transmission coefficients are determined from the numerical analysis, the effective index of refraction $n = n' + in''$ of a homogenized layer can be unambiguously determined from well-established inversion procedures [12, 13]. In the following numerical analysis, the liquid crystal is treated approximately as a homogeneous isotropic dielectric layer with a relative permittivity of ε_{LC}.

3. Reconfigurable near-IR metamaterial

Figure 1 shows a single unit cell of a two-dimensional periodic metamaterial structure with reconfigurable negative-zero-positive index of refraction. The structure is infinite in the $\pm\hat{y}$ directions and periodic with period p in the $\pm\hat{x}$ directions. This is a slightly modified version of a near-infrared (near-IR) metamaterial geometry previously reported in [9]. A magnetic resonator comprises two strips of silver of width w and thickness t separated by a thin layer of alumina of thickness d. The negative permittivity needed for negative-index behavior is provided by thin silver films of thickness t_f bounding the periodic array of magnetic resonators from the $\pm\hat{z}$ directions. Finally, the space between neighboring magnetic resonators is filled with silica.

Unlike in [9] where thin protective layers of silica were placed over silver films, here a layer of liquid crystal with thickness t_{LC} is used both as the superstrate and the substrate. Finally, the entire metamaterial is sandwiched between thick glass substrate and superstrate layers which, for modeling purposes, are treated as two half-spaces. A monochromatic light wave with the electric field polarized in the $\hat{x}$ direction is assumed to illuminate the structure at normal incidence propagating in the $+\hat{z}$ direction.

The magnetic resonators can cause the effective permeability $\mu = \mu' + i\mu''$ to deviate from unity and possibly reach negative values. In contrast, control over the effective permittivity is achieved mainly through an averaging effect, i.e., by averaging over the permittivities of constituent components of the metamaterial. Varying ε_{LC} will have a primary influence on the effective permittivity $\varepsilon = \varepsilon' + i\varepsilon''$ of the metamaterial. Hence, it follows that positive, zero, or negative values of ε' properly combined with magnetic resonances can produce any desired positive, zero, or negative value of n'.

Figure 2 shows plots of the three effective parameters n, ε, and μ for a near-IR version of the metamaterial depicted in Fig. 1. The geometrical parameters of the base NIM design are the same as those used in [9], i.e., $p = 600$ nm, $w = 300$ nm, $t = 30$ nm, $d = 40$ nm, and $t_f = 20$ nm. The thickness of the liquid crystal layers is assumed to be $t_{LC} = 200$ nm. The silica, alumina, and glass are assumed to have refractive indices equal to 1.445, 1.62, and 1.50, respectively. For the silver, a dielectric function based on published experimental results [14] was employed.

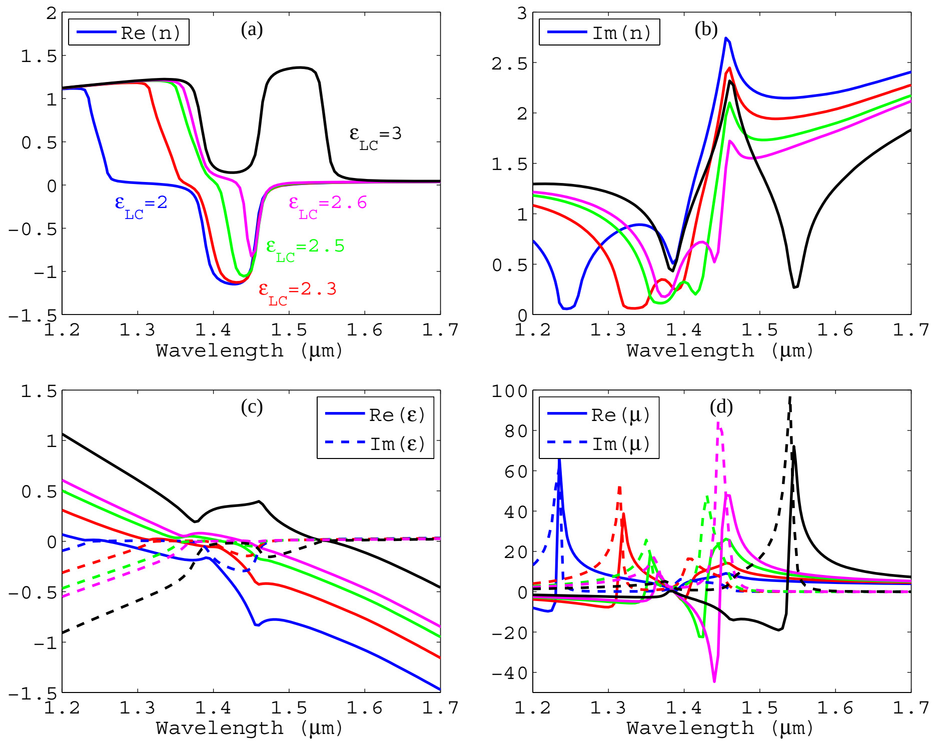

Fig. 2. Effective parameters of the reconfigurable near-IR metamaterial for different values of ε_{LC}: (a) n', (b) n'', (c) ε, and (d) μ with respect to wavelength.

Figure 2(a) shows n' plotted for five different values of ε_{LC} in the range $2 \leq \varepsilon_{LC} \leq 3$. With $\varepsilon_{LC} = 2$, the metamaterial exhibits a negative index band between 1.37 μm and 1.47 μm. As ε_{LC} is increased, it is seen that the negative index band decreases from shorter wavelengths toward the longer wavelength side, which remains fixed as long as the negative index band is present. Therefore, as ε_{LC} is increased, the negative index band diminishes from the shorter wavelength side until it completely vanishes. No negative index characteristic is observed for values of $\varepsilon_{LC} \geq 2.7$. Taking $\varepsilon_{LC} = 2$ as the minimum practical value for the permittivity of a liquid crystal, the proposed near-IR metamaterial possesses a reconfigurable index of refraction over a negative-zero-positive range from $\lambda = 1.37$ μm to $\lambda = 1.47$ μm, which represents a 7.1 % fractional bandwidth.

The dependence of the effective permittivity on the parameter ε_{LC} is shown in Fig. 2(c). The averaging effect on the bulk metamaterial permittivity is evident by observing that ε' monotonically increases as the value of ε_{LC} is increased. Moreover, the fact that the dielectric function of silver is a decreasing function of λ explains why the negative index band diminishes with increasing values of ε_{LC}. To this end, as ε_{LC} is increased, the starting wavelength for which $\varepsilon' < 0$ moves toward longer wavelengths, causing the negative index band to decrease. For all cases exhibiting a negative index band (i.e., for $\varepsilon_{LC} \leq 2.6$), magnetic resonances are observed in Fig. 2(d) to exist within the 1.39 μm to 1.46 μm range with varying strengths and bandwidths.

Comparing n' and n'' in Figs. 2(a) and 2(b), respectively, for different values of ε_{LC} over the region where $n' < 0$, one can observe a trade-off relationship between bandwidth and loss. As the negative index bandwidth becomes narrower with increasing ε_{LC}, n'' monotonically decreases over the same bandwidth. This consistent relationship between n' and n'' vanishes as soon as the negative index band disappears with $\varepsilon_{LC} = 3$. The trade-off between bandwidth and

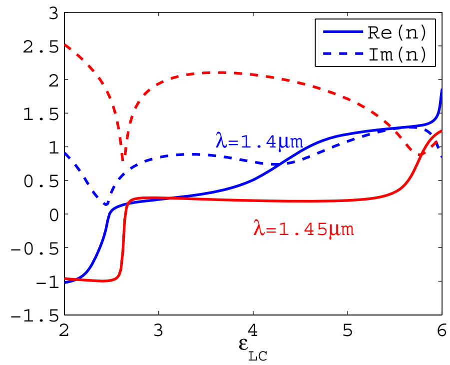

Fig. 3. The effective index of refraction n with respect to ε_{LC} at two different wavelengths $\lambda =$ 1.4 and 1.45 μm.

loss of the NIM can also be understood in terms of the Kramers-Kronig relations [15].

A different perspective is offered by Fig. 3, where the variations of n are shown plotted with respect to ε_{LC} for the metamaterial to demonstrate its ability to be reconfigured between a NIM, a zero-index metamaterial (ZIM), and a positive-index metamaterial (PIM) at a fixed wavelength. At this point two wavelengths ($\lambda = 1.40$ μm and 1.45 μm) within the negative index band corresponding to $\varepsilon_{LC} = 2$ are chosen for further consideration. The value of n' is seen to increase from -1 to $+1.8$ or $+1.2$ when ε_{LC} is varied from 2 to 6, respectively, demonstrating reconfigurability for NIM-ZIM-PIM behavior. It is noted that n' does not vary linearly with ε_{LC}. Instead, n' increases abruptly from -1 to about $+0.2$ over a relatively narrow range of ε_{LC} values for both of the targeted wavelengths. The rate of change of n' over this interval is higher for the longer wavelengths. Within the range of ε_{LC} values considered and for both wavelengths, it is observed that n'' has a sharp dip and reaches the minimum value where n' increases rapidly from negative values towards zero.

4. Scaling to mid-infrared wavelengths

Scaling the near-IR reconfigurable design to shorter wavelengths poses difficulty because thinner liquid crystal layers would be required. In contrast, scaling into longer mid-infrared (mid-IR) wavelengths is relatively straightforward. Considering the same base NIM structure, it is observed that the dielectric function of silver yields a larger negative permittivity together with higher losses at mid-IR wavelengths compared to near-IR wavelengths. To compensate for the larger negative permittivity of silver requires a correspondingly larger volume of positive permittivity material in order to achieve an average permittivity close to zero. This can be achieved by cladding thicker layers of liquid crystal on both sides of the base NIM. Then, as in the previous case, the permittivity of the liquid crystal can be appropriately adjusted to tune the metamaterial response throughout a desired negative-zero-positive index range.

Figure 4 shows the characteristics of a mid-IR reconfigurable metamaterial in the 4 to 6 μm range. The geometrical parameters used for this design example are given by $p = 2.4$ μm, $w = 1.2$ μm, $t = 120$ nm, $d = 160$ nm, and $t_f = 20$ nm. A liquid crystal superstrate and substrate are incorporated into the design, each having a thickness of $t_{LC} = 600$ nm. Finally, a Lorentz-Drude model [16] was used to represent the bulk silver properties in the mid-IR range.

Several performance aspects can be compared with those of the near-IR design. For the lowest value of ε_{LC} (i.e., $\varepsilon_{LC} = 2$), it is seen from Fig. 4(a) that the bandwidth over which a negative index of refraction exists is 4.32 μm $\leq \lambda \leq$ 5.08 μm. This range of wavelengths also corresponds to where the index of refraction is reconfigurable between negative, zero, and positive values. The corresponding fractional bandwidth for negative index behavior is equal to

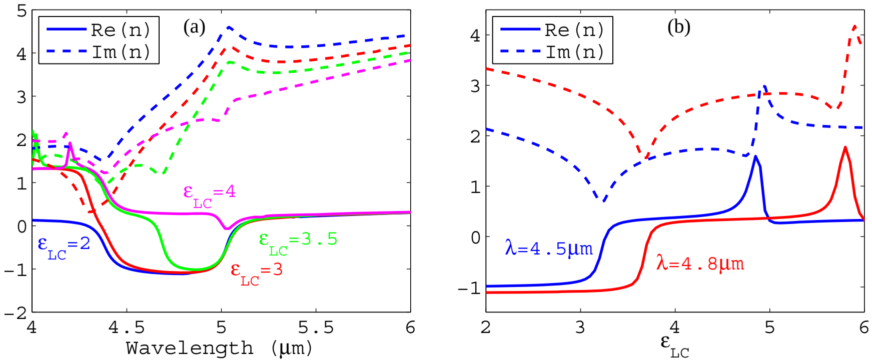

Fig. 4. The effective index of refraction n for a mid-infrared reconfigurable metamaterial design: (a) n with respect to wavelength for different values of ε_{LC}, (b) n with respect to ε_{LC} at two different wavelengths $\lambda = 4.5$ and 4.8 μm.

16.2 %, which is much wider than in the near-IR design. However, this bandwidth enhancement is accompanied by a higher loss. Figure 4(a) shows that over the bandwidth of negative n', the value of n'' ranges from 1.51 to 4.60 when $\varepsilon_{LC} = 2$, whereas n'' ranges from 0.51 to 2.74 (see Fig. 2(b)) even though the two designs have the same silver film thickness of $t_f = 20$ nm. This phenomenon is due to the higher loss present in silver at longer wavelengths. As ε_{LC} is increased, the negative index bandwidth exhibits the same trend of diminishing from the lower wavelength side toward longer wavelengths.

In Fig. 4(b), variations of n at two wavelengths, $\lambda = 4.5$ μm and 4.8 μm, are shown plotted with respect to ε_{LC}. The value of n' for both wavelengths changes from -1 to $+1.7$ over the tuning range $2 \leq \varepsilon_{LC} \leq 6$. Similar to the near-IR design shown in Fig. 3, n' for the mid-IR design changes abruptly over a relatively narrow range of ε_{LC}, with the rate of change greater at the longer wavelength $\lambda = 4.8$ μm. Furthermore, minimum loss is observed again over the same narrow bandwidth corresponding to the largest change in n'.

5. Conclusion

Near-IR metamaterials incorporating tunable liquid crystal layers as superstrates and substrates have been presented. Having the ability to vary the permittivity of the liquid crystal layers provides a means for controlling the overall effective permittivity of the metamaterial in an averaging fashion. Coupled with properly designed periodic magnetic resonators, the effective refractive index of the metamaterial structure can be readily reconfigured or tuned between negative, zero, and positive values at a given wavelength. Moreover, the bandwidth over which the metamaterial exhibits a negative index behavior can be controlled (i.e., increased or decreased) via the liquid crystal tuning. A 0.54 μm-thick near-IR metamaterial design was presented which exhibits tunability of n' from -1 to $+1.8$ around $\lambda = 1.4$ μm by varying ε_{LC} from 2 to 6. It was also observed that the negative index band diminishes from the short wavelength side upward as ε_{LC} is increased, until eventually it completely disappears. The near-IR design has been extended to a mid-IR design that provides reconfigurability of the negative index behavior over a wider bandwidth at the expense of higher losses.

Acknowledgments

This work was supported in part by the Penn State Materials Research Institute and the Penn State MRSEC under NSF grant DMR 0213623, and also in part by ARO grant W911NF-04-1-0350, NSF-PREM grant DMR-0611430, and by ARO-MURI award 50342-PH-MUR.

#78819 - $15.00 USD

Received 9 January 2007; accepted 26 February 2007