Liquid Crystal Infiltrated Optical Magnetic Metamaterials

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Abstract

We study both experimentally and numerically the electric tunability of optical split-ring-resonator metamaterials infiltrated with liquid crystals. By examining the shift of the observed Fabry-Pèrot fringes and the metamaterial resonances, we show that the liquid crystal molecular anchoring to the nanoscale split-ring-resonator meta-atoms plays an important role in determining their tunability and optical properties.

1. Introduction

Tunability of the spectral response of metamaterials is considered as one of the most significant developments in the field, providing an effective route to practical application of metamaterial and plasmonic structures. While various tuning techniques have been considered in the literature, the possibility for electric "dial-up" of the metamaterial properties is probably the most advantageous of all. However, for such tunability electrically sensitive constituents need to be integrated into the metamaterial structures. While ferroelectrics are known to change their refractive index with an application of electric field, this change is usually small and the overall tunability is negligible. In contrast, liquid crystals (LC) having large optical anisotropy and electric field sensitivity have emerged as a promising alternative to realize tunable optical metamaterials [1]. Indeed the large change of refractive index of the nematic LC due to molecular re-orientation caused by external electric field has been already utilized to control the transmission through LC infiltrated plasmonic structures [2, 3]. Liquid-crystal tunability of magnetic [4] and negative index metamaterials [5] has also been suggested. Experimental verifications of these concepts have been demonstrated for thermal tunability of metamaterials [6], electric tunability of microwave metamaterials [7], as well as all-optical tunability of optical fishnet metamaterials [8].

However, for the case of optical metamaterials when the dimensions of the individual meta-atoms become comparable to the size of the LC molecules the effects of molecular anchoring to the nano-structured surfaces becomes an important problem with a significant impact on the tunability of the metamaterial's optical response. Here, for the first time to our knowledge, we study both experimentally and numerically the effect of liquid crystal alignment and anchoring on the tunability of optical magnetic metamaterials. For this purpose, we use magnetic optical metamaterials composed of split-ring-resonator (SRR) meta-atoms and show how the application of external biasing electric field causes controlled re-orientation of the liquid crystal molecules [see Fig. 1(a) and (b)].
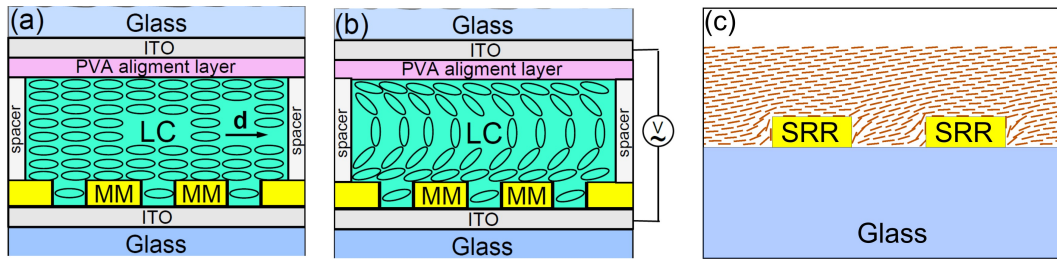
Fig. 1: (a) Schematics of the liquid crystal orientation (a) without and (b) with applied bias voltage. (c) Calculated orientation of the LC directors without applied voltage.
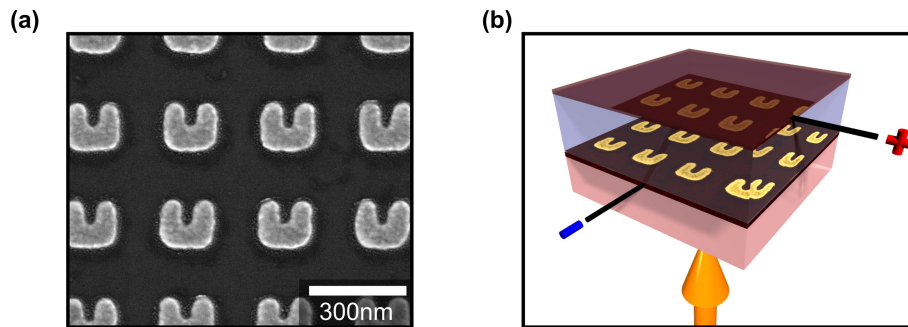

Fig. 2: (a) SEM image of the SRR metamaterial under investigation. Lattice constant of the SRR array is $a = 300\,nm$. (b) Illustration of the liquid crystal cell. The metamaterial is processed on top of the bottom (ITO-) electrode (dark red). The top electrode (dark red) is situated approximately $13\,\mu m$ above the sample surface. The liquid crystal liquid is indicated in light blue.

2. Fabrication

The SRR metamaterial under investigation is fabricated using standard electron-beam lithography, electron-beam evaporation, and lift-off techniques. The lattice constant of the SRR array is $a = 300\,nm$, the gold thickness is $20\,nm$ and the thickness of the underlying ITO-electrode is $5\,nm$. The lateral dimensions can be seen in Fig. 2(a). In order to build the liquid crystal cell [see Fig. 2(b), the metamaterial sample is sandwiched between the bottom (ITO-) electrode and an ITO-covered glass cover-slide with a polyvinyl alcohol (PVA) layer. Micro-trenches are formed in the PVA layer in order to facilitate uni-directional horizontal pre-alignment of the liquid crystal molecules. Hence, the use of a PVA layer on the top cover-glass slide forming the liquid crystal cell ensures that near this layer, the liquid crystal molecules are aligned parallel to the surface. Finally the liquid crystal solution is infiltrated with positive E7 LC from Merck.

3. Characterization

For optical characterization of the split-ring-resonator metamaterial, we perform broadband linear-optical transmittance spectroscopy using a $100\,W$ halogen lamp and a Glan-Thomson polarizer. We characterize the split-ring-resonator sample before infiltration and without the top electrode as a reference (see Fig. 3 black lines). Then after the assembly and infiltration of the LC cell we observe a significant red-shift of the split-ring-resonator's resonances as well as the occurrence of Fabry-Pèrot fringes due to the LC infiltrated cavity ($\Delta d \approx 13\,\mu m$) between the top and the bottom electrode (see Fig. 3 red lines). When applying a $1\,kHz$ square-wave voltage and increasing the amplitude U_i we observe a significant change of the Fabry-Pèrot fringes only when the incident field is polarized perpendicular to the SRR gap [see Fig. 3(a)] while only a negligible resonance shift is detectable. This indicates that both the re-alignment of the LC takes place in the plane perpendicular to the SRR gap (and parallel to the PVA alignment trenches) and that, due to strong surface anchoring, re-alignment is only present further away from the electrodes. Numerical simulations show that this LC anchoring results in the formation of $\sim 200\,nm$
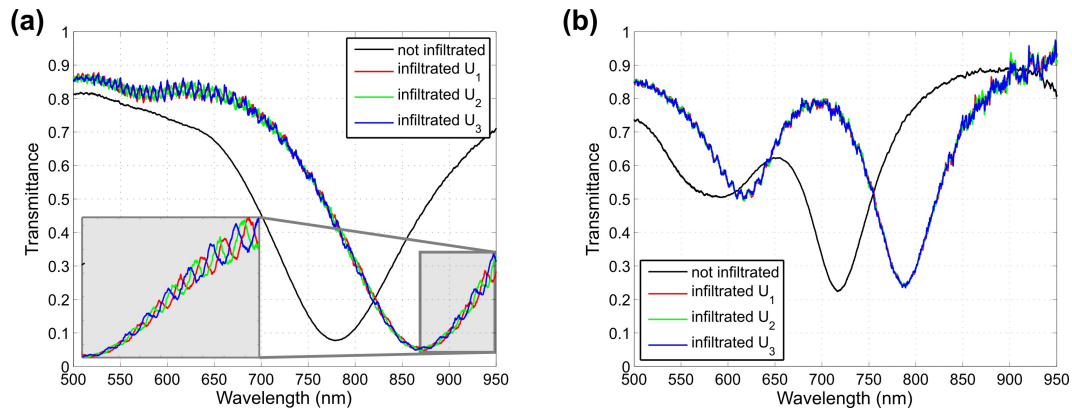
Fig. 3: (a) Experimental spectra of the SRR metamaterial before infiltration without the top electrode (black). The incident field is polarized perpendicular to the gap. After infiltration with the liquid crystal solution (red) a substantial red-shift and the occurrence of Fabry-Pèrot fringes is observed. With increasing applied voltage the fringes shift to shorter wavelengths indicating a realignment of the liquid crystals (green and blue lines, $U_1 = 0V < U_2 < U_3$). The inset shows a closeup. (b) Corresponding spectra of the SRR metamaterial with incident polarization parallel to the gap.

thin alignment layer where almost negligible change of the LC director occurs. Because this alignment layer covers the entire near field of the SRRs only the position of the Fabry-Pèrot fringes is affected, while negligible shift is observed in the metamaterials resonance. Importantly, for the perpendicular polarization neither shift of the Fabry-Pèrot fringes nor of the metamaterial resonances can be observed [see Fig. 3(b)], which is consistent with the in-plane reorientation of the LC molecule.

In conclusion, by independently measuring the shift of the Fabry-Pèrot fringes of the liquid crystal cell and the metamaterial's resonances, we are able to deduct the orientation and alignment properties of the liquid crystal molecules near the nanoscale SRRs. Our results are confirmed by numerical simulation of the Maxwell equations coupled to the equation of the LC director [see Fig. 1(c)] and show that anchoring of the LC to the nano-structured surfaces becomes an important problem with a significant impact on the tunability of the metamaterial's optical response. These results open new opportunities for application of LC tunable metamaterials, including for example tunable magnetic mirrors.

References

[1] I. C. Khoo, D. H. Werner, X. Liang, A. Diaz, and B. Weiner, "Nanosphere dispersed liquid crystals for tunable negative-zero-positive index of refraction in the optical and terahertz regimes," Opt. Lett. **31**, 2592 (2006).

[2] P. R. Evans, G. A. Wurtz, W. R. Hendren, R. Atkinson, W. Dickson, A. V. Zayats, and R. J. Pollard, Appl. Phys. Lett. **91**, 043101 (2007).

[3] W. Dickson, G. A. Wurtz, P. R. Evans, R. J. Pollard, and A. V. Zayats, "Electronically Controlled Surface Plasmon Dispersion and Optical Transmission through Metallic Hole Arrays Using Liquid Crystal," Nano Lett. **8**, 281 (2007).

[4] X. Wang, D.-H. Kwon, D. H. Werner, I.C. Khoo, A. V. Kildishev, and V.M. Shalaev, "Tunable optical negative-index metamaterials employing anisotropic liquid crystals," Appl. Phys. Lett. **91**, 143122 (2007).

[5] A. Minovich, D. N. Neshev, D. A. Powell, I. V. Shadrivov, and Yu. S. Kivshar, "Tunable fishnet metamaterials infiltrated by liquid crystals," Appl. Phys. Lett. **96**, 193103 (2010).

[6] S. Xiao, U. K. Chettiar, A. V. Kilkdishev, V. Drachev, I. C. Khoo, and A. V. Shalaev, "Tunable magnetic response of metamaterials," Appl. Phys. Lett. **95**, 033115 (2009).

[7] F. Zhang, W. Zhang, Q. Zhao, J. Sun, K. Qiu, J. Zhou, and D. Lippens, "Electrically controllable fishnet metamaterial based on nematic liquid crystal," Opt. Express **19**, 1563 (2011).

[8] A. Minovich, J. Farnell, D. N. Neshev, I. McKerracher, F. Karouta, J. Tian, D. A. Powell, I. V. Shadrivov, H. H. Tan, C. Jagadish, and Yu. S. Kivshar, "Liquid crystal based nonlinear fishnet metamaterials," Appl. Phys. Lett. 100, 121113 (2012).