Magnetically tunable left handed metamaterials by liquid crystal orientation

Fuli Zhang,[1,2] Lei Kang,[3] Qian Zhao,[4] Ji Zhou,[3] Xiaopeng Zhao[2] and Didier Lippens[1,*]

[1]*Institut d'Electronique de Microélectronique et de Nanotechnologie, Université des Sciences et technologies de Lille,59652 Villeneuve d'Ascq Cedex, France*
[2]*Department of Applied Physics, Northwestern Polytechnical University, Xi'an 710072, People's Republic of China*
[3]*State Key Lab of New Ceramics and Fine Processing, Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, People's Republic of China*
[4]*State Key Lab of Tribology, Department of Precision Instruments and Mechanology, Tsinghua University, Beijing 100084, People's Republic of China*
[*]*Corresponding author: didier.lippens@iemn.univ-lille1.fr*

Abstract: The tunability of an omega–type left handed metamaterial was demonstrated at microwave frequencies via the magnetic control of liquid crystal (LC) orientation. From the experimental and simulation results, it is shown that the left handed pass-band can be tuned by 220 MHz by changing the orientation of LC molecules by 90°. A maximum index variation of 0.25 was obtained in the negative index regime with a measured LC birefringence of 0.05 in the 10 - 12GHz frequency band.

OCIS codes: (160.3918) Metamaterials; (160.1190) Anisotropic optical materials; (050.5080) Phase shift; (160.3710) Liquid crystals.

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1. Introduction

Over the past few years, electromagnetic metamaterials with unique properties have attracted much attention [1-4] with a rapid development from microwave frequencies [5] to optical regime [6]. As resonant restructures, metamaterials exhibit strong frequency dispersion and hence narrow bandwidth operation with the center frequency determined by geometry and dimensions of constitutive materials. In fact, all the interesting effects achieved by metamaterials, such as negative refraction [1], perfect lensing [2] and cloaking [3, 4], are limited to a fixed narrow spectral bandwidth. For many potential applications, the fabrication of frequency tunable metamaterials whose operating frequency can be adjusted, is of great interest to alleviate these limitations. There have been some efforts to realize tunable metamaterial by the judicious incorporation of active devices or materials, such as varactor diode [7-9], semiconductors [10-12], ferroelectics [13] and more generally anisotropic materials [14-18], as a part of the metamaterial elements to change the resonance condition. Among these works, liquid crystals (LCs), possessing a large birefringence which can be controlled by an external field, have shown promise as tunable metamaterial substrates, over a relatively large spectrum of the electromagnetic waves [15-17]. However, up to now, the experimental demonstrations of LC-based metamaterial are mainly focused on single negative metamaterials fabricated via Split Ring Resonator (SRR) technology [17, 18]. In this context, the tuning of left handed metamaterials (LHMs) properties, which can be realized by controlling the LC molecular orientation, deserves attention with the prospect of tunable negative index. Although several numerical works have shown that tunable LHMs can be achieved by the infiltration of LC [14-16], the experimental verification has yet to be reported.

In this paper, we report on the experimental results of a frequency-tunable LHM operating at microwave frequencies, which incorporated LC into sub-millimeter voids as multilayered substrate. By using an external magnetic field excitation on the alignment of LC, a frequency shift of the left handed pass-band was observed. In addition, the index variation of metamaterial was also assessed by both numerical retrieval effective parameters on the basic cell and a measurement of phase offset of a nine-cell prototype. Generally, the LC compounds exhibit dipole relaxation in the low frequency part of the microwave spectrum notably at radio frequency. As a consequence, their dielectric constants and hence refractive indexes considered here are quite comparable to those measured in the optical range. On the other

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hand, it was shown by several groups in the literature notably in [6] that the operating frequency of the SRR array can be extended at optical wavelengths. Under this condition, it is believed that the conclusions drawn in the present work on the basis of a microwave demonstration still hold at least at terahertz frequencies, in which the metal loss can be maintained at a reasonable level.

2. Tunable Metamaterial infiltrated by LC

Figure 1(a) shows the schematic of the basic unit of the tunable metamaterial, which is composed of two omega patterns stacked in a reversed orientation in order to cancel the magneto-electric effects [19]. Under an illumination with E-polarized along the x and H-polarized along the y axis, the basic unit operates as a combination of broadside-coupled C-shaped-split right resonators (BC-SRRs), providing negative permeability and wire arrays, yielding negative permittivity below the plasma frequency. As a consequence, the device exhibits negative index due to simultaneous negative permittivity and permeability in a frequency band between the resonant frequency and the magnetic plasma frequency of BC-SRR arrays. In the present work, the omega patterns are supported by Teflon fiberglass with infiltration of LC in between. Let us suppose that the LC director lies in the x-y plane (Fig. 1(a)). For the LC slab with the director of the molecules aligned along x, the director axis $\mathbf{n}$ can take all values $\{\cos\theta, \sin\theta, 0\}$ by applying a magneto-static field based on the Fréedericksz effect, where θ denotes the rotation angle of the molecular director with respect to the x axis. With the reorientation of the LC molecular director, we can control the effective permittivity of LC layer which influences the magnetic resonance of BC-SRR [18], and consequently modifies the condition of the negative index regime.

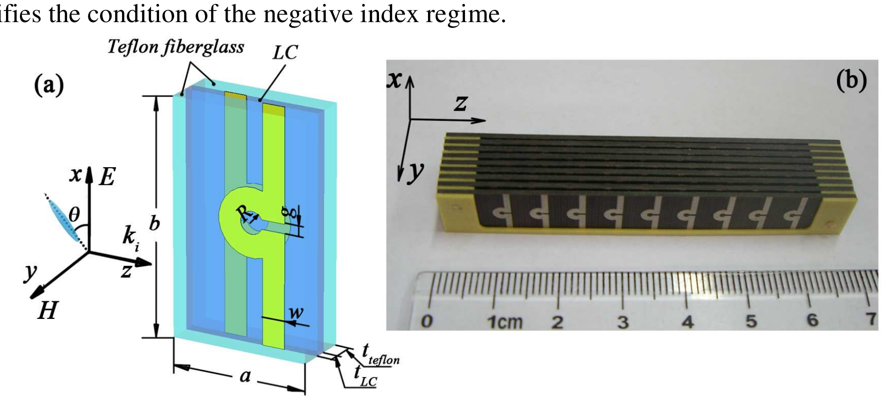

Fig. 1. (a) Schematic of the basic unit cell of the tunable negative index metamaterial as well as the reorientation of the LC molecule in the x-y plane. The geometry dimensions are as follows: R = 0.5, g = 0.4, w =1.0, t_{teflon} = 1.0, t_{LC} = 0.5 (unit: mm). The unit cell is stacked along the x and z directions with periodicities of 10.0 and 6.0 mm, respectively. (b) Close-up view of the mid-plane of the sample with the other part was removed to clarify the configuration of the voids.

Figure 1(b) shows a close-up view of the metamaterial sample. By using the standard print circuit board technology, two omega motifs with the same orientation were firstly patterned on both sides of a 1.0-mm-thick Teflon fiberglass board. In this way, there is no possibility for magnetic coupling occurring between omega patterns on both sides of one Teflon fiberglass board. By means of a numerically controlled machine, a U-shaped thin slice of epoxy fiberglass with a thickness of 0.5 mm was fabricated and then used as a spacer between Teflon fiberglass boards with voids for LC infiltration. The width of the spacer edge was set to 1.0 mm, thus leaving enough room for the LC infiltration. Finally, Teflon fiberglass boards and spacers were alternatively stacked and aligned by means of via holes and plastic rods. It is worth mentioning that omega patterns on adjacent Teflon fiberglass boards were stacked in a back-to-back configuration to form BC-SRRs as shown in Fig. 1(a).

In the experiment, a mixture of nematic LC compounds was synthesized with an overall

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positive magnetic anisotropy and a large birefringence of 0.22 at optical regime. As the birefringence of LC decreases at microwave or millimeter waves [20-22], it was necessary to measure the dielectric properties of LC at microwave frequencies. By employing the method based on a phase shift in LC cells of different lengths as proposed in Ref. [20], the LC indexes were measured between 10 and 12 GHz. Figure 2(a) shows the frequency dependence of the extraordinary n_e and ordinary n_o in this band. The LC compound exhibits a positive birefringence ($n_e > n_o$) in the frequency band of interest, in which n_e varies between 1.33 and 1.48 whereas n_o changes from 1.28 to 1.41. The birefringence Δn versus frequency is plotted in Fig. 2 (b). Δn fluctuates around 0.05, which is comparable to the birefringence of some commercial nematic compound such as 5CB in the same frequency range.

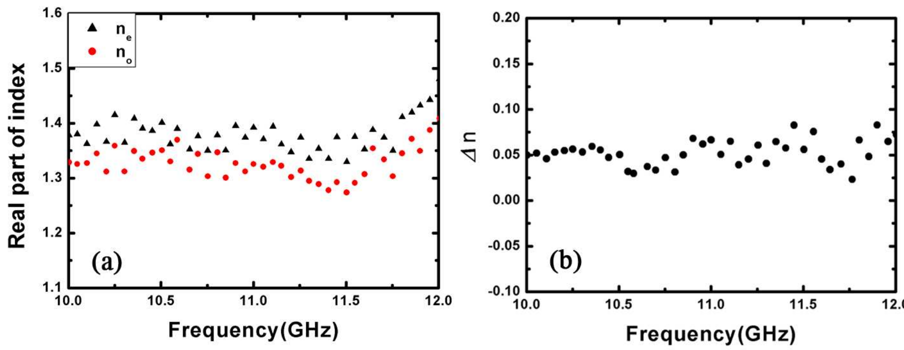

Fig. 2. (a) Extraordinary (black triangular) and ordinary (red circle) refractive indexes measured at room temperature as a function of frequency. (b) Birefringence of the nematic compound was deduced in the 10-12 GHz frequency band.

By using a needle tube, the LC compound was infiltrated into the board interspacing via capillary forces. In order to orientate the LC molecules, a pair of permanent magnets with centimeter size was mounted externally to apply a uniform magnetic field in the *x*-*y* plane. The external magnetic field of 500 G measured by a digital magnetometer enables a good alignment of the LC molecules as the threshold field is less than 100 G for thin cells [23]. The metamaterial sample was then inserted in an X-band hollow waveguide and the scattering parameters were measured by using a HP8720 ES Vectorial Network Analyzer.

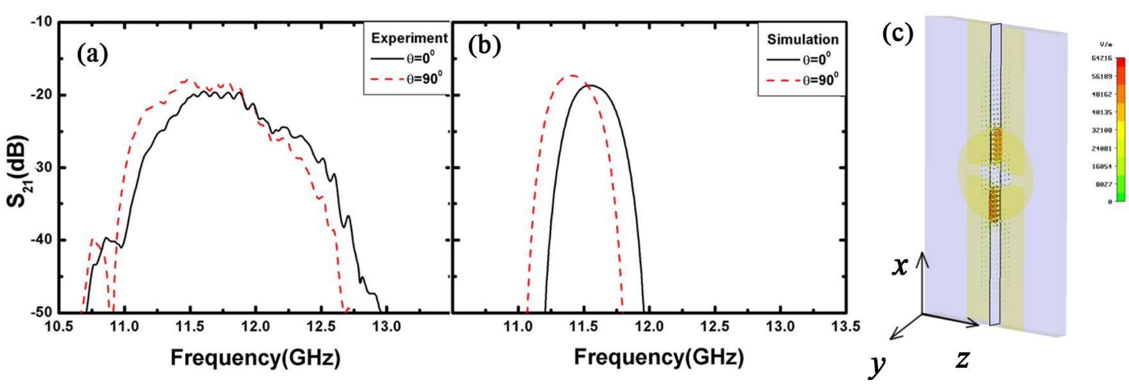

Fig. 3. The experimental (a) and simulation (b) transmission responses of the metamaterial with infiltrated by LC under different molecules orientations: $\theta = 0°$ (solid black line) and 90° (dashed red line), respectively. (c) The local electric field distribution is plotted in the *x*-*y* plane at the magnetic resonance of omega pattern. Teflon fiberglass boards were invisible for clarity.

The measurements of the transmission spectra were carried out (i) with the magnetic field applied along the *x* axis ($\theta = 0°$) and (ii) along the *y* axis ($\theta = 90°$). The results are reported in

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Fig. 3(a). When the magnetic field is applied along the x axis (θ = 0°), the omega arrays exhibit a well-defined transmission pass-band, as expected with negative index material. The transmission maximum is at 11.72 GHz. For θ = 90° and hence for an orthogonal magnetic field excitation, a red-shift of the pass-band was observed with a maximum of transmission at 11.50 GHz. Although the pass-band shift of 220 MHz is not large compared to the relatively broad bandwidth, it can be measured nonetheless without any ambiguity due to the fact that the overall form of the transmission band is relatively unchanged between the two LC reorientation states. In addition, it is also noted that the redshift occurs with an increasing transmittance.

For a better understanding of the tuning of the omega-type metamaterial based on LC orientation, simulations were performed by using the full wave software CST Microwave Studio. A permittivity tensor was used for a rigorous description of LC molecules, where $\varepsilon_e = n_e^{\ 2}$ and $\varepsilon_o = n_o^{\ 2}$ are the permittivities parallel and perpendicular to the molecule director, respectively. For these calculations, we employed the experimental data n_o = 1.38, n_e = 1.43 and thus a birefringence of 0.05 (See Fig. 2). The loss tangents of LC were set as $\tan\delta_o$ = 0.020 for n_o and $\tan\delta_e$ = 0.016 for n_e in order to fit the experimental transmittance level. A slightly larger $\tan\delta_o$ compared to that of $\tan\delta_e$ was chosen according to the previous report on the dielectric properties of some LC compounds at microwave frequencies [22]. Therefore in simulation, a LC layer is treated as $\{2.0449, 1.9044, 1.9044\}$ and $\{1.9044, 2.0449, 1.9044\}$ for the respective two reorientations: θ = 0° and 90°.

Figure 3(b) shows the simulation results for the transmission response versus frequency For the LC reorientation corresponding to θ = 0°, the omega arrays exhibit a well-defined pass-band with a centre frequency at 11.55 GHz, which is in a fairly good agreement with the experimental results. However, the experimental result (Fig. 3(a)) shows a broader operating bandwidth. This is mainly due to the slightly variations of the voids interspacing as the Teflon fiberglass is not perfectly rigid. Further simulation results confirmed that the pass-band position is very sensitive to the void thickness variation. For instances, a 360 MHz frequency shift occurs when the thickness of voids changes 50 µm. The unwanted spacing differences result in different magnetic resonances between layers, causing multiple adjacent pass-bands and consequently a broader transmission window. Under the orthogonal excitation of external magnetic field (θ = 90°), the pass-band shifts down to 11.40 GHz, showing the same dependence on LC reorientation as the experimental results.

To provide an insight on the relation between the LHM pass-band shift and the reorientation of LC molecules, the electric field map was monitored. It is shown in Fig. 3(c). It can be noticed that local electric field is polarized along the y axis rather than along the x axis which corresponds to the incident electric field polarization. This is a result of the broadside coupling between the omega patterns facing together as explained in Ref. [18]. In fact, the capacitance of the omega pattern is mainly determined by the permittivity component ε_y along the y direction which thus dominates the magnetic response as shown in Fig. 3(c). When an external magnetic field is applied to orientate the LC molecules from randomly distributed to parallel to x, ε_y is mainly experienced as ε_o. As the LC director is reorientated from θ = 0° to 90°, ε_y is increased from ε_o to ε_e, giving rise to an increase of the capacitance and therefore a redshift of the resonant frequency. Additionally, as the loss tangent of the molecule along the y axis is decreased from $\tan\delta_o$ to $\tan\delta_e$, the pass-band transmittance is increased to a higher level.

3. Modeling of the index variation

The frequency dependences of the index real parts were subsequently calculated from the scattering parameters of a basic unit cell by employing a well-established algorithm [24, 25] (Fig .4). In Fig. 4, negative values of index are observed from 11.0 to 13.0 GHz, verifying that the pass-bands correspond to a left handed dispersion branch. With the change of LC orientation by the magnetic field, a shift of the index curve is only noted between 11 and 12.0 GHz. In the lower frequency band identified by shadowed region, the metamaterial

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transmission is very weak and dominated by the evanescent waves, so that the derivation of a refractive index value becomes questionable.

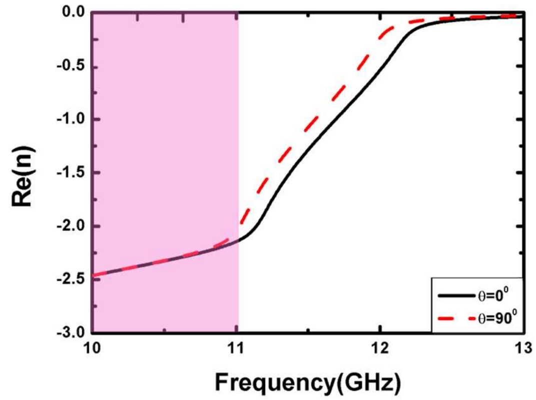

Fig. 4. The real parts of retrieval indexes for metamaterial infiltrated by LC under different LC molecular reorientations: $\theta = 0°$ (solid black line) and 90° (dashed red line).

4. Experimental phase shift of a nine-cell prototype

The measured phase-shift of a nine-cell-long sample (Fig. 1(b)), as a consequence of the index variation between the two orthogonal magnetic field excitations, is shown in Fig. 5. As the director of LC is reorientated from 0° to 90°, the phase shift increases around 10.6 GHz and reaches a maximum value of 174.5° at 10.93 GHz. This phase offset corresponds to an approximate index variation peak of 0.25 for the 5.4-cm-long sample considered here. This enhanced index variation arising from a LC birefringence of 0.05 is mainly due to the intrinsic strong magnetic resonant character around 11.0 GHz.

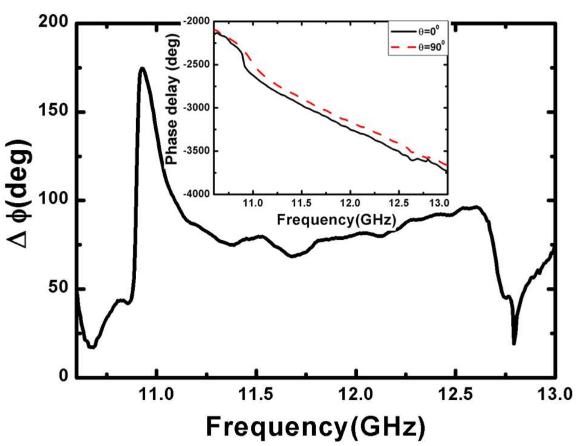

Fig. 5. The measured phase shift for a nine-cell prototype when the LC molecules are reorientated from $\theta = 0°$ to 90°. The inset shows the phase delays for the two orientations of LC.

5. Conclusion

The left handed pass-band of an omega-type uniaxial metamaterial was successfully controlled magnetically at microwave frequencies via the infiltration of nematic LC into millimeter-sized voids. Simulation and experimental results demonstrate unambiguously that the left handed pass-band can be tuned by an external dc magnetic field via the orientation of LC director. A maximum shift of 220 MHz was observed experimentally for a LC birefringence $\Delta n = 0.05$ measured at X band. These finding were further confirmed by phase

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shift measurements on a nine-cell prototype, supported by the modeled index variation retrieved from a one-cell device. As the birefringence of LC increases dramatically with frequency (For instance, 5CB LC exhibits a birefringence as large as 0.21 at 1 THz [26]), it is believed that the efficiency of the tunability via a LC approach could be enhanced by operating in the infrared spectral region. On the other hand, the omega-type motif used in the present experimental demonstration is a generic pattern of metamaterial technology with several related inclusions whose operation relies on the same principles. This is notably the case of S-type arrays, whose fabrication under self sustaining condition by means of a frame, were recently demonstrated and frequency assessed around 2 THz [27]. This free standing technology with natural voids between the staked arrays appears very promising for the extent of LC controlled metamaterials in the Terahertz spectral range. At last, there is no principle obstacle to envisage further extents in the optical range. However two important things seem to be imperatively addressed. The first one is the dramatic increase of metal loss. The other issue concerns the verification of a correct orientation of liquid crystal, despite the increase of boundary surface effects which result from the scale shrinking.

Acknowledgments

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