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Voltage tunable short wire-pair type of metamaterial infiltrated by nematic liquid crystal

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In this letter, we report an experimental demonstration on voltage tunable short wire-pair metamaterial with negative permeability at microwave frequencies. After infiltrated by nematic liquid crystal, magnetic resonance of short wire-pair can be effectively tuned via relatively low static electric field. The results show, by increasing bias voltage from 0 to 100 V, magnetic resonance is continuously and reversibly shifted from 9.91 down to 9.55 GHz. Moreover, the effective permeability of metamaterial, for operation frequency around magnetic resonance, varies from negative to positive values. Numerical analysis has a good agreement with experimental results.

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Electromagnetic metamaterial¹ has undergone rapid development from microwave frequencies² to terahertz³ even optical regime⁴ over past few years on account of its unique properties. As a kind of resonant restructure, metamaterial inevitably suffers from narrow bandwidth. The creation of tunable metamaterials, whose operational frequency could be adjusted to other desired frequency range, is of great interest to overcome this limitation.

Basically, typical metamaterial such as split ring resonator (SRR) behaves as a negative permeability medium yielding a narrow band, whereas wire arrays display negative permittivity in a broad band. Therefore, it is worth more attention on the tunability of SRR whose magnetic resonance can be predicted using capacitance-inductance circuit analysis. Inductance variation involves surrounding permeability alteration, which is not readily available.⁵ On the contrary, there have been various efforts to realize tunable metamaterial via capacitance variation by the incorporation of active devices, such as varactor diode,^{6–8} semiconductors,^{9–11} ferroelectric,¹² and anisotropic materials.^{13–19} Among these works, liquid crystal (LC) has been demonstrated as a promising substrate for tunable metamaterial.^{14–20} Khoo *et al.*¹⁴ proposed a tunable metamaterial based on core-shell nanospheres dispersed in LC. Werner *et al.*¹⁵ presented a reconfigurable metamaterial by sandwiching LC into negative index metamaterial. Very recently, Minovich *et al.*¹⁷ numerically investigated the effective index variation in fishnet structure infiltrated by LC. Xiao *et al.*¹⁸ realized a thermal control of magnetic response of metamaterial at visible frequency. We have experimentally investigated the tunability of SRR via magnetic¹⁹ and electrical control.²⁰ For the latter, SRR with a periodicity of several millimeters requires bias

voltage as high as several thousand volts, which cannot be afforded in actual application. Therefore it is of interest to develop a low voltage control approach. On the other hand, SRR suffers from indirectly producing negative permeability at optical frequencies due to the technological challenge of bulk sample preparation. Instead, short wire-pair motif was demonstrated as a well-developed structure for the realization of negative permeability.²¹ However, the active control of short wire-pair is yet reported.

In this paper, we experimentally realized a tunable short wire-pair metamaterial operating at microwave frequencies, which incorporated LC into submillimeter void. By utilizing a relatively low static electrical excitation on the alignment of LC, a significant frequency shift in resonance dip was observed. In addition, the variation in effective permeability was also assessed.

Figures 1(a) and 1(b) depict schematic views of tunable metamaterial elementary cell, which consists of a pair of short wires placed on the surface of Teflon fiberglass slabs with void in between which was infiltrated with a nematic LC. An extra pair of narrower bars was added to connect adjacent unit cells. A thin layer of polyimide (PI) was spanned on the surface of Teflon substrate and metallic elements to force nematic LC alignment parallel to short wire surface [Fig. 1(b)]. An incident beam with the electric field polarized along the x direction and the magnetic field polarized along the y direction was assumed to illuminate the structure along the z direction.

In this work, a commercial LC, TEB30A, with a birefringence $\Delta n=0.1703$ at optical range was employed. However, due to the dielectric characteristics dispersion of LC,^{22–24} we obtained a smaller birefringence of TEB30A; $n_0=1.65$ and $n_e=1.73$ (@10GHz), along with $\Delta n=0.08$.

For the sample preparation, short wire-pair array were printed on one side of 1-mm-thick Teflon fiberglass board. A

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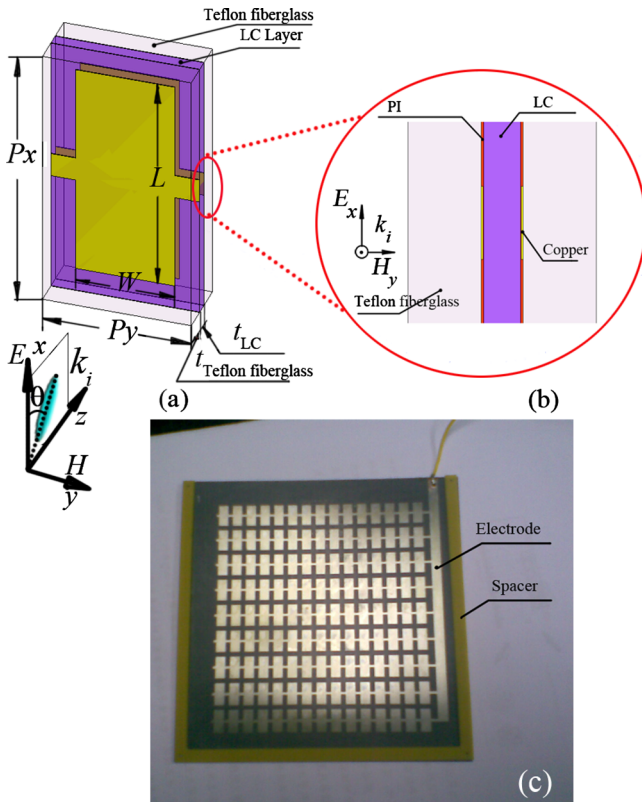


FIG. 1. (Color online) Tunable short wire-pair type of negative permeability metamaterial based on nematic LC. (a) Three-dimensional and (b) side views of elementary cell. (c) Photograph of metamaterial sample (the top layer of short wire-pair array was removed for clarity). The geometrical parameters of unit cell are as follows: $W=4.00$, $L=9.00$, $P_x=11.00$, $P_y=6.00$, $t_{LC}=0.60$, and $t_{\text{Teflon fiberglass}}=1.00$ (unit: mm). The copper bar used for connection is 1.00 mm wide. Teflon fiberglass ($\epsilon_r=2.65$, $\tan \delta=0.001$) was chosen as host material.

long wire used for bias bus was placed to provide a uniform bias voltage [Fig. 1(c)]. A rubbed PI film was coated on the surfaces of Teflon board and metallic elements. A 0.5-mm-thick U-shaped epoxy glass board was fabricated as a spacer to realize a void for LC infiltration. Finally, two layers of the

resulting Teflon boards and spacer were stacked to form one layer of negative permeability metamaterial. To make sure LC leakage-proof, cyanoacrylate glue was used to bond Teflon boards and spacer, resulting in a slight increase in void interspacing to 0.60 mm. Nematic LC was infiltrated into the void using a needle tube. Due to the presence of PI, the infiltrated LC will be initially aligned parallel to the surface of short wire-pair. Using a pair of standard horns, scattering parameters were measured via an HP8720 ES vectorial network analyzer.

Figure 2(a) displays the measured transmission spectra of short wire-pair array under various bias voltages. For zero-bias voltage, a pronounced dip occurs at 9.91 GHz, around which the effective permeability is expected to be negative. As bias voltage gradually increases from 0 to 100 V, the resonant frequency shifts down to 9.55 GHz, followed by tuning saturation even the bias voltage is further enhanced. Thus, a frequency shift of 360 MHz is achieved experimentally. Figure 2(c) shows the transmission phase variation as a function of bias voltage. Without bias voltage, a deep dip appears around 9.8 GHz, indicating a sign change in effective permeability of short wire-pair. As bias voltage increases, transmission phase exhibits a visible redshift, which is in accordance with transmission spectra response. Furthermore, around magnetic resonance, it is noticed that the transmission phase can be modulated. When the bias voltage is increased by 100 V, for some given frequency point such as $f=9.75$ GHz, the transmission phase of metamaterial experiences -180.9° to -97.6° , accounting for nearly 90° variation, indicating the potential application as effective phase modulator. Further experimental results show that this voltage tuning process is reversible and repeatable. The electrical response time is around 300 ms. It is believed that this process can be reduced by decreasing the thickness of LC void or employing another LC with low viscosity.²⁵

For a deeper insight into the underlying physics of tuning, a full wave numerical analysis was carried out using a commercial finite element code High Frequency Structure Simulator (HFSS). At the beginning, let us assume the nem-

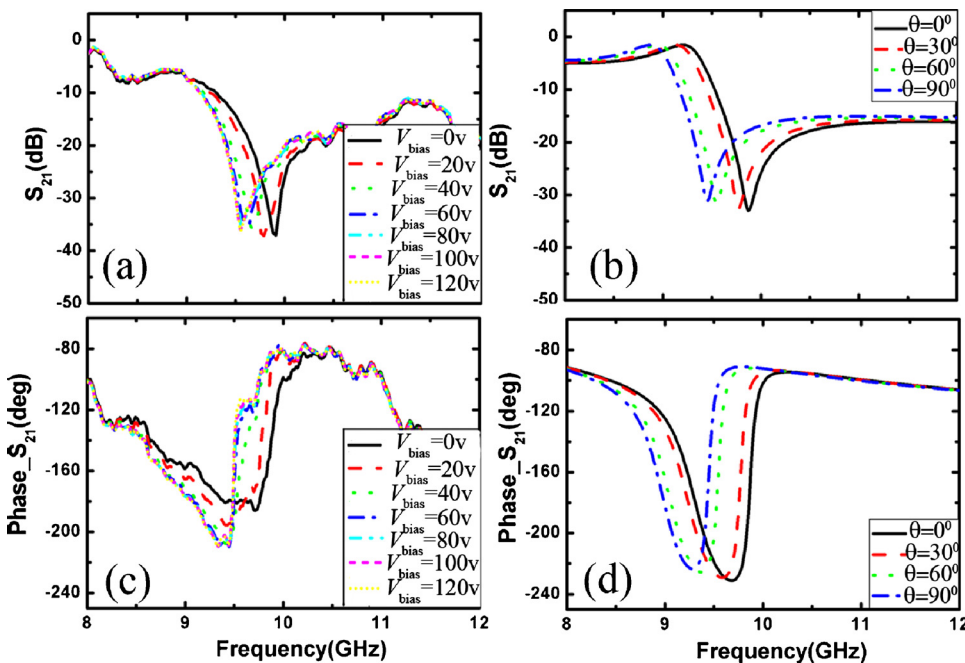


FIG. 2. (Color online) Experimental transmission magnitude (a) and phase (c) for short wire pair metamaterial as a function of external dc bias voltage. Simulated transmission magnitude [(b) and (d)] phase of the basic unit cell as a function of the reorientation angle of the LC molecules.

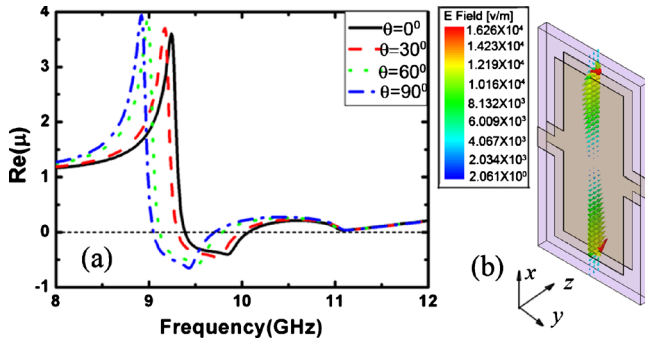


FIG. 3. (Color online) (a) The retrieved real part of effective permeability of tunable short wire pair as a function of LC director angle. (b) Local electric field distribution of short wire-pair in the x - z plane around magnetic resonance frequency.

atic LC director lies in the x - z plane with an initial director along x . Under external static electrical field, the director axis \mathbf{n} can take all values $\{\cos \theta, 0, \sin \theta\}$, where θ denotes the molecular director angle with respect to the x axis [Fig. 1(a)]. In the following analysis, $\varepsilon_{\parallel} = n_x^2 = 2.9929$ and $\varepsilon_{\perp} = n_z^2 = 2.7225$ were taken to describe the dielectric property of TEB30A, where ε_{\parallel} and ε_{\perp} represent the respective permittivity for the incident beams polarized parallel and perpendicular to the director axis \mathbf{n} . It is worth mentioning the influence of LC reorientation on magnetic response of short wire-pair was investigated rigorously by utilizing a permittivity tensor $\{\varepsilon_x, \varepsilon_y, \varepsilon_z\}$ for the description of LC dielectric property.²⁰ In the experiment, since an increasing bias voltage was used to reorientate LC director from initial state to perpendicular to the surface of short wire, we will check the influence of LC reorientation on magnetic response of metamaterial when LC director changes by 90° .

Figure 2(b) shows the simulated frequency dependence of metamaterial on the LC reorientation. For the initial case of $\theta = 0^\circ$, short wire-pair exhibits a well-resolved transmission extinction around 9.87 GHz. When LC alignment is reorientated from 0° to 90° , magnetic resonance frequency of short wire-pair decreases gradually toward 9.45 GHz. From the comparison between experimental and simulated results, both magnitude and phase agree well with numerical results. A slightly narrow frequency variation is presumably due to the presence of pretilted angle of LC via PI surface. This means LC reorientation will be less than 90° , leading to smaller permittivity variation and resonance frequency changes. Employing a well-established algorithm,²⁶ we retrieved the effective permeability of short wire-pair from calculated scattering parameters and plotted the corresponding spectra in Fig. 3(a). For initial case, short wire-pair exhibits negative permeability around 9.8 GHz. As LC director is reorientated from $\theta = 0^\circ$ to 90° , the negative permeability frequency range was shifted from 9.39–10.08 GHz down to 9.05–9.72 GHz. Importantly, such a frequency shift gives the possibility to tune effective permeability values around magnetic resonance. For a magnetic resonance frequency of 9.30 GHz, short wire-pair experiences effective permeability values of 1.48, 0, and -0.50 when LC director points to 0° , 30° , and 90° , respectively. Figure 3(b) illustrates localized electric field in the x - z plane at 9.87 GHz. Clearly, the localized electric field is mainly polarized parallel to z , hence, the permittivity along z , ε_z , dominates the capacitance of wire-pair. When an external electrical field is applied to reorien-

tate LC director from parallel to x to parallel to z , ε_z will be increased from ε_{\perp} to ε_{\parallel} , resulting in an increase in the capacitance and a decrease in the resonant frequency.

In summary, we experimentally demonstrated a dc voltage control short wire-pair metamaterial at microwave frequencies. Employing PI surface and static electrical field, LC molecular alignment experiences nearly 90° reorientation, resulting in 360 MHz frequency shift in magnetic resonance of metamaterial. A good agreement between simulation and experimental results is observed. As large birefringence of LC is recovered at THz and optical ranges, a more pronounced dynamic modulation of metamaterial based on LC can be expected at higher frequencies.

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