Optical magnetic response from parallel plate metamaterials

Zhiming Huang,[1,2,*] Jianqiang Xue,[1] Yun Hou,[1] Junhao Chu,[1] and D. H. Zhang[2,†]
[1]*National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 500 Yu Tian Road, Shanghai, 200083, People's Republic of China*
[2]*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore*
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We propose a metamaterial with a three-layer structure based on Faraday's law. The metamaterial is simply formed by a pair of homogeneous parallel plates separated by a thin medium. We also propose a virtual current loop with length of $2a$ (a is the attenuation constant) in the plates, which can be formed upon excitation of an electromagnetic field. Strong magnetic response has been observed by spectroscopic ellipsometry and the resonant frequency can be widely tuned by varying the structure dimensions. The observations are also verified by optical transfer matrix. The easy fabrication and high interfacial quality of the structure will make the applications of the magnetic response and negative refractive index metamaterials a reality.

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In 1968, Veselago conceived of a material whose index of refraction could be negative with both a negative permittivity and a negative permeability, which would reverse nearly all known optical phenomena.[1] Such material has not been realized until recent years when the artificially structured materials, or metamaterials, were reported.[2] These metamaterials open the door to a variety of physical phenomena and potential applications.[3–5]

A negative permittivity is not unusual and occurs in any metal from zero frequency to the plasma frequency. However, a negative permeability, which means a negative magnetic response, at optical frequencies does not occur in natural materials.

At present, a popular magnetic metamaterial has been formed from a periodic array of nonmagnetic, conducting, split-ring resonators (SRRs), achieved in essence just by mimicking a small LC circuit structure of eigenfrequency ω_{LC} with $\omega_{\mathrm{LC}}=(\mathrm{LC})^{-1/2}$. Each SRR structure consists of a magnetic coil with inductance L and a capacitor with capacitance C.[6–9] Since the first demonstration at microwave frequencies,[10] the achieved magnetic resonance frequencies have been increased by more than four orders of magnitude over the last few years,[6–8] reaching a record of 370 THz (800 nm wavelength) in 2005.[9]

The structure of the metamaterials currently studied needs to be as fine as possible.[4] A variety of potential applications, including higher resolution optical imaging and nanolithography, will be limited by the complexity of the SRR structures. For example, a superlens, one of the most desirable applications in the negative refractive index, at optical wavelengths requires the structure being extremely smooth with a surface roughness less than 1 nm. Otherwise, the surface imperfections would scatter the incident light and wash out the finer details carried by the evanescent waves.[4,11] Another issue regarding the practicality of the present metamaterials is their complicated electromagnetic response, which makes their utilization as devices complicated and a full electromagnetic characterization difficult.[12] Furthermore, to improve the oscillator strength of the magnetic resonance, the number of SRR per unit area should be high enough.[9] This is limited by the capability of manufacture. Therefore, there is a strong demand to explore the structures of the negatively refracting metamaterials.[4,13]

In this paper, we propose a simple metamaterial formed by two thin parallel plates separated by a dielectric medium, where the top plate is semitransparent metal for light. Magnetic resonant response at optical frequencies from the metamaterial is experimentally observed by spectroscopic ellipsometry, and verified by Faraday's law and optical tranfer matrix methods. The structure is of significant importance to the applications, especially at optical and terahertz frequencies, because perfect interfaces and/or surfaces can be successfully realized in the layered structures using modern growth techniques.[14,15]

Let us consider the metamaterials consisting of a pair of parallel plates with nanometer size in the z direction and infinite in the xy plane as shown in Fig. 1. Assume that the thickness of the metamaterials is of subwavelength order ($\sim\lambda/9$ -$\lambda/10$ in our samples, where λ is the wavelength of the excited field at the resonance frequency), which allows the composite to behave as an effective medium to external THz radiation. Suppose that an external magnetic field $\mathbf{H}=\{H_0\exp(-i\omega t),0,0\}$ is applied parallel to the boundary of the plates. The external electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$ excite the electric current in the parallel plates along the y axis. A displacement current will also be excited by a time-varying electromagnetic field and it flows between the plates. When the wavelengths are much greater than the metamaterial physical dimensions, the current in the two parallel plates will have the same flow directions. By introducing nonbalanced structure, the current intensities are different in the two plates. Therefore the net current $I(y)$ is nonzero. Finally, a virtual current loop (VCL) will be formed along a contour $\{P_1,P_2,P_3,P_4\}$ in Fig. 1 thanks to the displacement currents.

From a classical perspective, we can consider the magnetic moment as being generated by the circular current flowing in the VCL. To find the current $I(y)$, we integrate the Faraday's law $\nabla\times\mathbf{E}=ik(\mathbf{H}+\mathbf{H}_{\mathrm{ind}})$ over the contour $\{P_1,P_2,P_3,P_4\}$, where $k=\omega/c$ is the wave vector, and $\mathbf{H}_{\mathrm{ind}}=\nabla\times\mathbf{A}$ is the magnetic field induced by the current. It is assumed that the length $2a$ (Ref. 16) between the points P_1

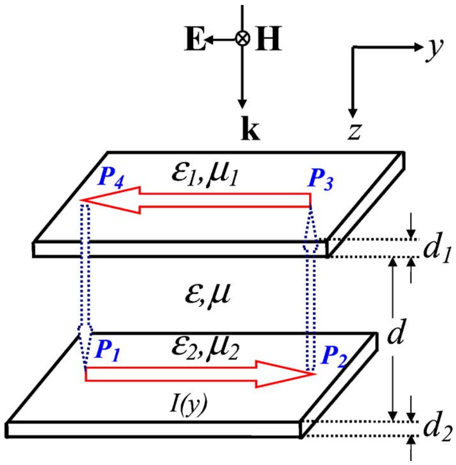

FIG. 1. (Color online) Illustration of uniform metamaterials consisting of a pair of parallel plates. Loop currents, closed by displacement currents (dashed lines), are excited by external electric and magnetic fields around the contour $\{P_1, P_2, P_3, P_4\}$. The length between P_1 and P_2 is $2a$; the distance between the plates is d; and the thickness is d_1 and d_2, respectively, for the plates 1 and 2. The permittivities are ε_1, ε_2, and ε for the plates 1 and 2 and the medium between them; and the permeabilities μ_1, μ_2, and μ are unity for all layers. **k** is the wave vector of incident light; **H** is the magnetic field; **E** is the electric field.

and P_2 is much greater than the plates thicknesses d_1 and d_2, and the distance between the plates $d \ll \lambda$. Then the vector potential **A** is directed primarily along the plates. For simplification we assume the two plates are of equal impedances. The integral of Faraday's law yields[17]

$$I = \frac{D}{\Theta^2}\left(\frac{\cos(\Theta y)}{\cos(\Theta a)} - 1\right), \tag{1}$$

when $-a < y < a$ and $I(-a) = I(a) = 0$. Where $\Theta^2 = k^2 \mathrm{LC} - \frac{2\varepsilon}{(\varepsilon_2 - 1)dd_2}$, and $D = \omega CkdH_0$.

The magnetic moment of the plates can be calculated by $\mathbf{M} = (2c)^{-1}\int \mathbf{r} \times \mathbf{J}(\mathbf{r})d\mathbf{r}$, where $\mathbf{J}(\mathbf{r})$ is the density of the current and the integration is over the VCL. We obtain

$$\mathbf{M} = \frac{Dad}{\Theta^2 c}\left(\frac{\tan(\Theta a)}{\Theta a} - 1\right). \tag{2}$$

Then the permeability $\mu_{\mathrm{eff}} = \mu_r + i\mu_i$ of the metamaterials is

$$\mu_{\mathrm{eff}} = 1 + \frac{k^2\varepsilon}{2\Theta^2}\left(\frac{\tan(\Theta a)}{\Theta a} - 1\right). \tag{3}$$

Thus, according to Eq. (3) magnetic resonance will occur in the uniform parallel plates when $\Theta a = N\pi/2$, where N is an odd integer. For metamaterials $N = 1$ is expected under the requirement of homogeneity.

To verify the above theory, we designed and fabricated three samples A, B, C using the structure of $LaNiO_3/Pb(ZrTi)O_3/Pt$ on Si substrate with the optical semitransparent $LaNiO_3$ metallic layer on the top and metal Pt layer at the bottom. The thicknesses of the $Pb(ZrTi)O_3$ for samples A, B, and C are 645, 575, and 500 nm, respectively. The thicknesses of $LaNiO_3$ and Pt are the same for the three

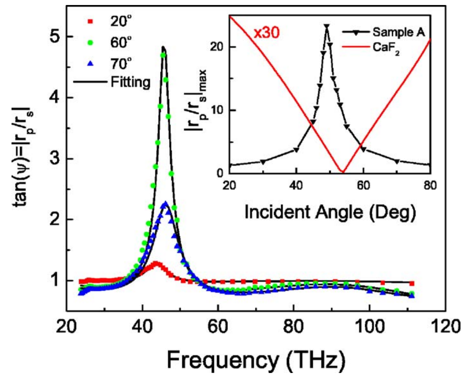

FIG. 2. (Color online) Amplitude ratio $\tan\psi$ of $LaNiO_3/Pb(ZrTi)O_3/Pt$ metamaterial (sample A) measured at three different incident angles (square, 20°; circle, 60°; and triangle, 70°). Inset, maximum response ratio of p polarization to s polarization for sample A as a function of incident angle. The ratio of p polarization to s polarization for normal dispersion material CaF_2 (refractive index, 1.36; thickness, 750 nm) with purely electric response is also depicted. The ratio of CaF_2 has been multiplied by a factor of 30 to improve visibility.

samples, and they are 45 and 50 nm, respectively. The samples were grown by radio frequency magnetron sputtering under a working pressure of 15 mTorr at a rf power of 80 W. Spectroscopic ellipsometric (SE) measurements were carried out by an improved variable-angle infrared spectroscopic ellipsometer (PhE-104) (Ref. 18) in the frequency range of 20–120 THz. The accuracy is better than 1% for $\tan\psi$ and $\cos\Delta$ in the measurements. It should be pointed out that the structure can operate easily at transmission mode by replacing the bottom Pt layer with a semitransparent metal.

Figure 2 shows the frequency-dependent ellipsometric measurements for sample A at three different incident angles of 20°, 60°, and 70°, respectively. The ellipsometric parameter $\tan\psi$ represents the absolute reflectance amplitude ratio of the p- and s-polarized lights. An obvious resonance peak is observed around 43.5 THz, which indicates that the amplitude of the p-polarization light is much stronger than the s-polarization light. The peak shifts slightly and its intensity varies with the angle of the incidence. Beyond this resonant peak, $\tan\psi$ is less than 1 for the three angles of incidence, which is not difficult to understand for the materials with electric response.

However, the resonant response can come from either electric response or magnetic response. To clarify it, first let us see the dispersion of $\tan\psi$ as a function of the angle of incidence with purely electric response. The inset in Fig. 2 shows the dispersion of a typical uniform CaF_2 thin film of 750 nm at 43.5 THz. The curve is smooth and has a minimum $\tan\psi$ at the principal angle ($\Delta = 90°$) of the material. The inset also shows the response peak values of sample A versus the angle of the incidence from 20° to 80°. A smooth evolution of the peak response in the broad angle range strongly suggests that the metamaterial can be viewed as homogeneous slab in the growth direction at the corresponding frequencies. Furthermore, the curve shape from sample A is opposite to that of the purely electric response, which sug-

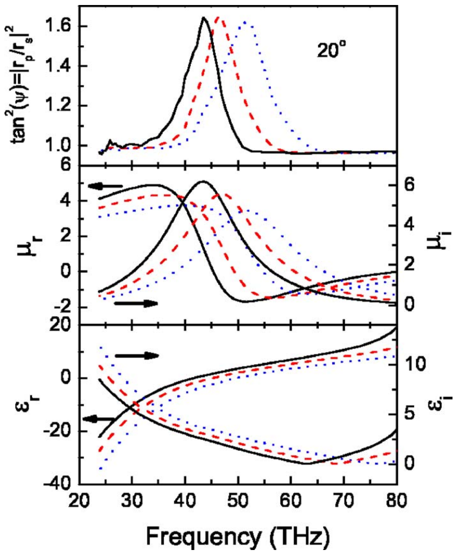

FIG. 3. (Color online) (Top) Reflectance ratio of the p-polarization to s-polarization response as a function of frequency for three different artificial magnetic structures, A (solid), B (dashed), and C (dotted) at an incident angle of 20°. The resonance frequency is a function of the nanostructure parameters. (Middle) The real (μ_r) and imaginary (μ_i) effective magnetic permeability functions as calculated by transfer matrix method for samples A, B, and C. (Bottom) The effective electric permittivity $\epsilon=\epsilon_r+i\epsilon_i$ as calculated by transfer matrix method for samples A, B, and C.

gests that a strong magnetic response occurs in the plate metamaterial structures. Second, our simulations using Fresnel equations also indicate that this is indeed the feature of magnetic resonance, where $\tan\psi \geqslant 1$. It is emphasized that ellipsometry is a powerful experimental tool to identify the magnetic resonance in the metamaterials.

Because the magnetic resonant response is independent of the incident angle of light, the plates are of omnidirectional magnetical response, which is very meaningful for the metamaterial applications.

If the magnetic response centered at 43.5 THz in the spectrum for sample A (Fig. 3, solid curve) results from the constituent parallel plates, then this resonant frenquency should scale with dimensions in terms of Maxwell equations. In order to justify our findings, two more metamaterials (samples B and C) with different dimensions d were characterized (Fig. 3, dashed and dotted curves). The two metamaterials both exhibit a similar magnetic mode to sample A, and their resonant frequencies occur at 46.5 and 51.8 THz, respectively. We find an expected monotonic blueshift of resonant frequencies as the dimensions of plates are scaled down, which elucidates that the magnetic response is from the constituent parallel plates.

We can use the transmission and reflectance information, which is extracted from SE fitting data,[19–22] to evaluate the metamaterial effective permeability μ_{eff} and effective permittivity ϵ_{eff} with transfer matrix method.[23,24] In Fig. 3, we display the simulated real (u_r) and imaginary (u_i) parts of the effective magnetic permeability that corresponds to the samples A, B, and C, respectively. The magnetic resonant responses are obtained for all three samples with the same center frequencies as that of ellipsometric data. Obvious negative permeabilities have been achieved when the frequencies are over the resonant ones for all three samples, because the induced dipole moments lag and are completely out of phase with the excitation fields. This is an important precondition for the realization of a homogeneous layered metamaterial with a negative index of refraction. Our three samples exhibit negative permeability with minima of about −1.68 at 51.7 THz, −1.47 at 56.6 THz and −1.25 at 63.8 THz, respectively. The value of −1.25 at 63.8 THz is better than the −0.43 at 63 THz reported by Ref. 8. All the values are also comparable to the −1.6 at 80 THz by Ref. 7 and −0.25 at 180 THz by Ref. 9. However, as shown in the figure, the corresponding effective permittivities have been changed from negative values to positive ones for the frequencies with negtive permeabilities. Because over scales much less than a wavelength, electric and magnetic effects decouple, and only one of the two parameters must be negative.[4]

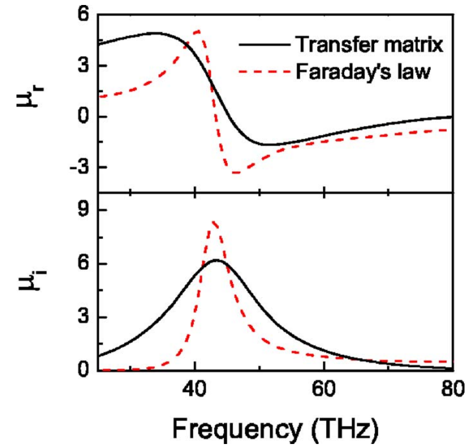

FIG. 4. (Color online) Comparison of the real (top) and imaginary (bottom) effective magnetic permeability functions for sample A calculated by transfer matrix method (solid curve) and Faraday's law method (dashed curve), respectively.

To further verify the magnetic response of the metamaterials, we performed a numerical simulation with Eq. (3) using the circulating current in the loop illustrated in Fig. 1. All the calculating parameters come from the experimental data. The length $2a$ is determined by the current attenuation in the plates.[17,25] The results are shown in Fig. 4 for sample A. Both the shape and peak position coincide well with those calculated from the transfer matrix method.

In conclusion, we have demonstrated that magnetic resonance can be realized in the homogeneous layered metamaterials consisting of a pair of parallel plates based on the VCL concept. The uniform planar structure we proposed is of the same functionality as the reported periodic arrays formed by SRRs. It first meets the virtues to recover evanescent waves carrying the finest details of the object and be completely compatible with modern mature thin film technology. It is of great significance to the device applications and extension of higher frequencies to deep UV range. The uniform metamaterials offers further opportunity to extend the negative refraction concept. We believe that it will open previously unknown avenues of investigation in this fast-growing subject.

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*Electronic address: zmhuang8@yahoo.com
†Electronic address: edhzhang@ntu.edu.sg

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