

Negative permeability in planar metal-dielectric composites

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Abstract: We report a new type of planar metamaterial consisting of a pair of homogeneous parallel plates separated by a thin medium. Strong magnetic response and negative effective permeability are observed in the materials at wavelengths from 6.9 μm to 5.8 μm . The resonant wavelength and the value of the negative permeability can be tuned by varying the structure dimensions. Such planar metamaterials can be easily fabricated with mature thin film technology and are of great potential for device applications.

Key words: negative permeability; metamaterial; transfer matrix method

1 Introduction

Metamaterials open the door to a variety of new physical phenomena and potential applications^[1-4]. For example, negative refractive index, in which both the permittivity and permeability are negative, would reverse nearly all known optical phenomena. A negative permittivity is not unusual and occurs in any metal from zero frequency to the plasma frequency. However, a negative permeability at optical frequencies does not occur in natural materials.

Following the proposal of Pendry *et al.*, magnetic metamaterials have 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 eigenfre-

quency $\omega_{LC} = (LC)^{-1/2}$ ^[2]. Each SRR structure consists of a magnetic coil with inductance L and a capacitor with capacitance C . Since the first demonstration at microwave frequencies^[9], the achieved magnetic resonance frequencies have been increased by more than four orders of magnitude over the last few years^[5-8]. However, the extension to higher optical frequencies and larger areas faces a great challenge. This is because such metamaterials need the SRRs to have sizes down to about 100 nm and less with critical features at the level of ~ 10 nm, and a density of $\sim 10^{10} \text{ cm}^{-2}$. This is technologically difficult to achieve. Furthermore, the inherent losses associated with scaling down make the materials impractical for most applications.

In this article, we report a new metamaterial formed by two thin parallel plates separated by a die-

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lectric medium, where the top plate is semitransparent to light. The magnetic resonant response at optical frequencies from this metamaterial is experimentally observed by spectroscopic ellipsometry, and verified by Faraday's Law and optical transfer matrix methods. The new structure is of significant importance for 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^[9,10].

2 Experiments

We designed and fabricated three samples which consist of three layers-LaNiO₃, Pb(ZrTi)O₃, and Pt on a Si substrate. The optical semitransparent LaNiO₃ layer is on top followed by the Pb(ZrTi)O₃ and Pt, as shown in Fig. 1. The thicknesses of the LaNiO₃ and Pt are the same for all three samples, namely 45 and 50 nm, respectively, while the thicknesses of the Pb(ZrTi)O₃ for Samples I, II and III are 645, 575, and 500 nm, respectively. They were grown by radio frequency magnetron sputtering. Spectroscopic Ellipsometric (SE) measurements were carried out using the variable-angle infrared spectroscopic ellipsometer (PhE-104)^[11] in the wavelength range of 2.5 – 12.5 μm. The accuracy of the measured $\tan\psi$ and $\cos\Delta$ is better than 1%.

LaNiO ₃ (45 nm)
Pb(ZrTi)O ₃
Pt (50 nm)

Fig. 1 Illustration of the three layer uniform metamaterials. The thicknesses of the top and bottom layers are fixed at 45 and 50 nm, respectively while the thickness of the Pb(ZrTi)O₃ is 645, 575 and 500 nm, respectively, for the three samples.

3 Results and Discussion

Fig. 2 shows the value of $\tan\psi$ at different frequencies of Sample I at three different incident angles of 20°, 60° and 70°, respectively. An obvious resonant peak is observed around 6.9 μm, which indicates that the amplitude of the *p*-polarized light is much stronger than that of the *s*-polarized light. The peak shifts slightly and its intensity varies with the angle of the incidence. Beyond this resonant peak, $\tan\psi < 1$ for the three angles of incidence. These are obviously the features of a magnetic response rather than an electric response.

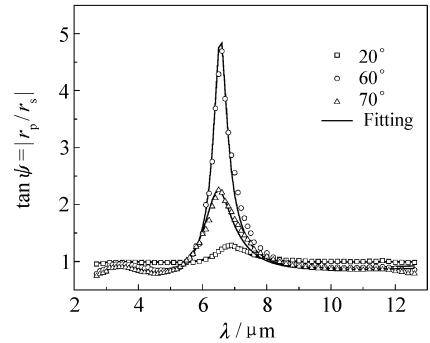


Fig. 2 Amplitude ratio $\tan\psi$ of LaNiO₃/Pb(ZrTi)O₃/Pt metamaterial (Sample I) measured at three different incident angles 20° (square), 60° (circle), and 70° (triangle).

If the magnetic response centred at 6.9 μm in the spectrum for Sample I results from the metamaterial, then the resonant frequency should scale with dimensions because of Maxwell equations. In order to verify this observation, two more metamaterials (Samples II and III) with different dimensions are also characterized and the results measured at normal incidence for the three samples are shown in Fig. 3. As can be seen from Fig. 3, two metamaterials exhibit a similar magnetic mode to Sample I, and their resonant frequencies occur at 6.5 and 5.8 μm, respectively. These observations clearly indicate that the magnetic response indeed results from the metamaterial structures. In addition, one

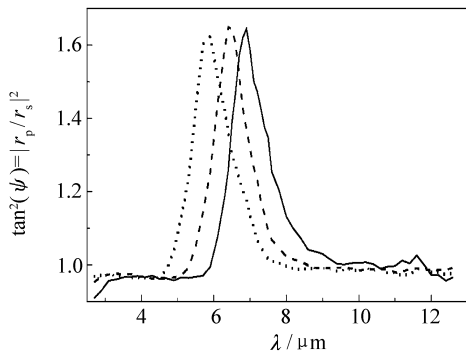


Fig. 3 Reflectance ratio of the p -polarization to s -polarization response as a function of wavelength of Sample I (solid), II (dash), and III (dott) at an incident angle of 20° . The resonance wavelength shifts to higher energy as the thickness of the medium layer decreases.

can also see that the ratios of the resonant frequency over the total thickness of the composite are about 9.30, 9.70 and 9.74 for Sample I, II and III, respectively. This indicates that the composites are of sub-wavelength order and each of them behaves as an effective medium.

From the SE data, the transmission and reflectance information can be extracted and then the metamaterial effective permeability μ_{eff} can be estimated using transfer matrix method^[12-14]. Fig. 4 shows the estimated real (μ_r) and imaginary (μ_i) parts of the effective magnetic permeabilities for the three samples. Three features can be seen in this figure: 1) the magnetic resonant responses are obtained for all three samples with the centre wavelengths the same as those of the corresponding ellipsometric data; 2) obvious negative permeabilities are achieved with minima in the negative permeability of about -1.68 at 51.7 THz, -1.47 at 56.6 THz and -125 at 63.8 THz, respectively; 3) the negative permeabilities occur at frequencies which are at 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 negative index of refraction in a homogeneous layered metamaterial.

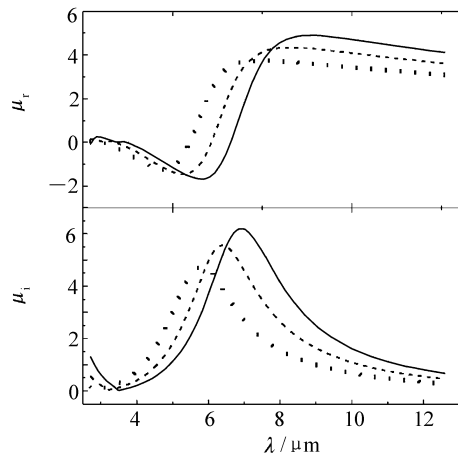


Fig. 4 Real (μ_r) and imaginary (μ_i) parts of the effective magnetic permeability estimated with the transfer matrix method for Samples I, II, and III.

To further verify the magnetic response of the metamaterials, we performed a numerical simulation using Faraday's Law. For simplification, we assumed identical impedance for the top and bottom layers. All the remaining parameter values come from the experimental data. The results are shown in Fig. 5 for Sample I. Both the shape and peak posi-

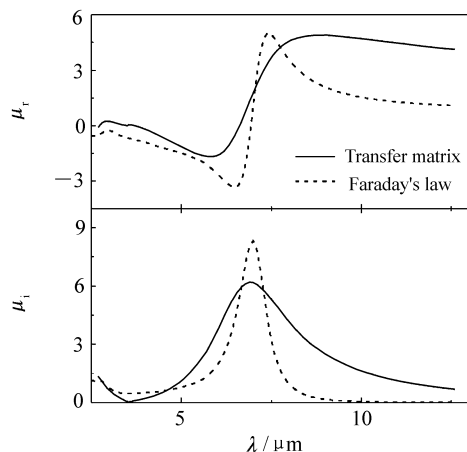


Fig. 5 Comparison of the real (top) and imaginary (bottom) part of the effective magnetic permeability function for Sample I calculated by the transfer matrix method (solid) and Faraday's Law method (dash), respectively.

tion coincide well with those estimated from the

transfer matrix method. The narrowed width and increased height are from Faraday's Law mainly due to the substitution of the symmetric top metal plate for the semitransparent conducting film.

4 Conclusions

In conclusion, magnetic resonance and negative permeability in the infrared region have been real-

ized in the homogeneous layered metamaterial consisting of a pair of parallel plates separated by a layer of the medium. The resonant frequency and the value of the negative permeability can be varied by changing the thickness of the composite. Such metamaterials can be easily fabricated with mature thin film technology and are of great significance to device applications.

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