第3卷 第1期
2010年2月
中国光学与应用光学
Chinese Journal of Optics and Applied Optics
Vol. 3 No. 1
Feb. 2010

文章编号 1674-2915(2010)01-0085-04

Negative permeability in planar metal-dielectric composites

HUANG Zhi-ming[1,2], ZHANG Dao-hua[1], HOU Yun[2], CHU Jun-hao[2]

(1. *School of Electrical and Electronic Engineering*, *Nanyang Technological University*, *Singapore*, 639798;
2. *National Laboratory for Infrared Physics*, *Shanghai Institute of Technical Physics*,
Chinese Academy of Sciences, *Shanghai* 200083, *China*)

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 eigenfrequency $\omega_{LC} = (LC)^{-1/2}$ [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 ~10^{10} 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-

Received date: 2009-10-11; Revised date: 2009-12-13.
Foundation items: supported by the National Research Foundation, Singapore; A * Star SERC grant (No. 0421010078); the National Natural Science Foundation of China (No. 60407014 and 60527005); the National Grant Foundation Project (No. G001CB3095).

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-$LaNiO_3$, $Pb(ZrTi)O_3$, and Pt on a Si substrate. The optical semitransparent $LaNiO_3$ layer is on top followed by the $Pb(ZrTi)O_3$ and Pt, as shown in Fig. 1. The thicknesses of the $LaNiO_3$ and Pt are the same for all three samples, namely 45 and 50 nm, respectively, while the thicknesses of the $Pb(ZrTi)O_3$ 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%.

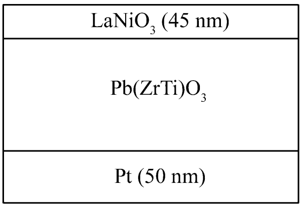

Fig. 1 Illustration of the three layer uniform metamaterials. The thicknesses of the top and bottom layers are fixed at 45 and 50 nm, respectively while the thickness of the $Pb(ZrTi)O_3$ is 645, 575 and 500 nm, respectively, for the three samples.

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.

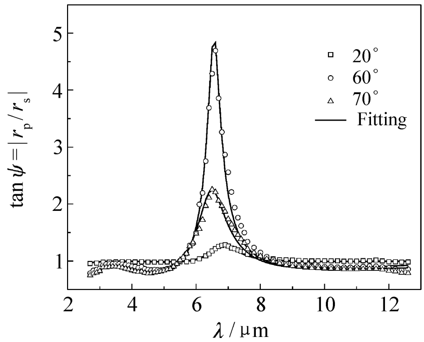

Fig. 2 Amplitude ratio $\tan\psi$ of $LaNiO_3/Pb(ZrTi)O_3/$Pt metamaterial (Sample Ⅰ) measured at three different incident angles 20° (square), 60° (circle), and 70° (triangle).

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

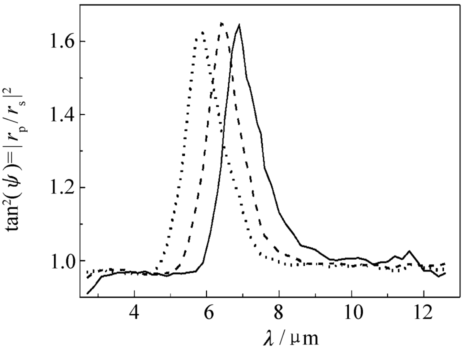

Fig. 3 Reflectance ratio of the p-polarization to s-polarization response as a function of wavelength of Sample Ⅰ (solid), Ⅱ (dash), and Ⅲ (dott) at an incident angle of 20°. The resonance wavelength shifts to higher energy as the thickness of the medium layer decreases.

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.

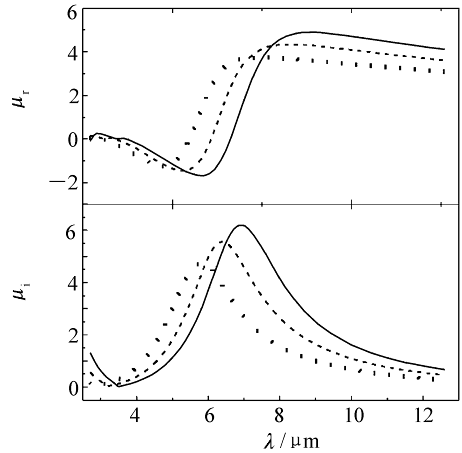

Fig. 4 Real (μ_r) and imaginary (μ_i) parts of the effective magnetic permeability estimated with the transfer matrix method for Samples Ⅰ, Ⅱ, and Ⅲ.

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-

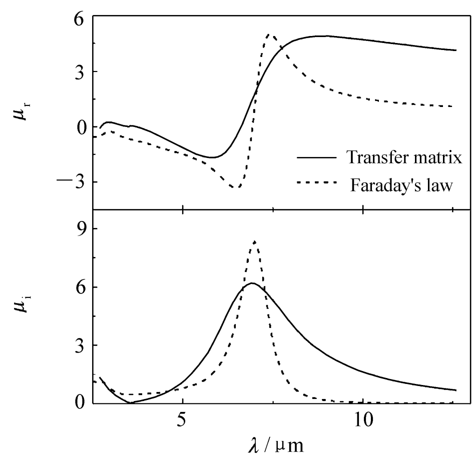

Fig. 5 Comparison of the real (top) and imaginary (bottom) part of the effective magnetic permeability function for Sample Ⅰ calculated by the transfer matrix method (solid) and Faraday's Law method (dash), respectively.

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 realized 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.

References:

[1] VESELAGO V G. The electrodynamics of substance with simultaneously negative value of ε and & μ[J]. *Sov. Phys. Usp.*, 1968, 10:509-514.

[2] PENDRY J B, HOLDEN A J, ROBBINS D J, *et al.*. Magnetism from conductors and enhanced nonlinear phenomena[J]. *IEEE Trans. Microwave Theory Tech.*, 1999, 47:2075-2084.

[3] PENDRY J B. Negative refraction makes a perfect lens[J]. *Phys. Rev. Lett.*, 2000, 85:3966-3969.

[4] SMITH D R. How to build a superlens[J]. *Science*, 2005, 308:502-503.

[5] YEN T J, PADILLA W J, FANG N, *et al.*. Terahertz magnetic response from artificial materials[J]. *Science*, 2004, 303:1494-1496.

[6] LINDEN S, ENKRICH C, WEGENER M, *et al.*. Magnetic response of metamaterials at 100 terahertz[J]. *Science*, 2004, 306:1351-1353.

[7] ZHANG S, FAN W, MINHAS B K, *et al.*. Midinfrared resonant magnetic nanostructures exhibiting a negative permeability [J]. *Phys. Rev. Lett.*, 2005, 94:037402.

[8] ENKRICH C, WEGENER M, LINDEN S, *et al.*. Magnetic metamaterials at telecommunication and visible frequencies[J]. *Phys. Rev. Lett.*, 2005, 95:203901.

[9] FONG D D, STEPHENSON G B, STREIFFER S K, *et al.*. Ferroelectricity in ultrathin perovskite films[J]. *Science*, 2004, 304:1650-1653.

[10] DEHLINGER G, DIEHL L, GENNSER U, *et al.*. Intersubband electroluminescence from silicon-based quantum cascade structures[J]. *Science*, 2000, 290:2277-2280.

[11] HUANG Z M, CHU J H. Optimizing precision of fixed-polarizer, rotating-polarizer, sample, and fixed-analyzer spectroscopic ellipsometry[J]. *Appl. Opt.*, 2000, 39:6390-6395.

[12] SMITH D R, SCHULTZ S, MARKOŠ P, *et al.*. Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients[J]. *Phys. Rev. B*, 2002, 65(3):195104.

[13] HUANG Z M, XUE J Q, HOU Y, *et al.*. Optical magnetic response from parallel plate metamaterials[J]. *Phys. Rev. B*, 2006, 74(19):193105.

[14] CHEN X, GRZEGORCZYK T M, WU B, *et al.*. Robust method to retrieve the constitutive effective parameters of metamaterials[J]. *Phys. Rev. E*, 2004, 70(1):016608.

Author biography: ZHANG Dao-hua(1956—), male, Ph. D, FInstP, Nanyang Technological University, Singapore, his research interests focus on semiconductor materials, devices and technology, nanostructure, metamaterials and their applications. E-mail: edhzhang@ntu.edu.sg