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Polarization Dependence of the Metamagnetic Resonance of Cut-wire-pair Structure by Using Plasmon Hybridization

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The influence of lattice constants on the electromagnetic behavior of a cut-wire-pair (CWP) structure has been elucidated. In this report, we performed both simulations and experiments to determine the influence of polarization on the metamagnetic resonance of the CWP structure. The key finding is the result of an investigation on the plasmon hybridization between the two CWs, which showed that the polarization of the incident wave was affected. Good agreement between numerical simulation and measurement is achieved.

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I. INTRODUCTION

Sub-wavelength materials, so-called metamaterials (MMs), are artificial structural materials composed of metals and dielectrics arranged periodically. The electromagnetic (EM) parameters of MM, e.g., permittivity and permeability, are defined by the effective medium theory (EMT). A MM can be tailored through the design its unit cell. Owing to this controllable property, MMs with permittivity or permeability less than that of vacuum or with the negative value have been successfully achieved over a broad region of the EM spectrum ranging from radio to visible, which is not available with natural materials. The primary research on MMs is to investigate materials with negative refractive index, which exhibit reversed physical characteristics firstly described theoretically by Veselago in 1968 [1]. In 2000, Smith *et al.* reported the experimental demonstration of functioning EM MMs by stacking, horizontally and periodically, split-ring resonators (SRRs) and thin wires [2]. To date, beyond the early-invented SRR structure, several different structures such as Ω-shaped, S-shaped, π-shaped and cut-wire-pair (CWP) structures have been developed to achieve negative magnetic permeability [3-5]. Among them, the CWP structure has received considerable interest.

To understand the essence of the interaction between the EM wave and the CWP structure, we can use the plasmon hybridization scheme recently introduced in Refs. 6 and 7, which gives "an intuitive picture" to simplify the EM response of the original CWP structure. The response of complex micro- and nano-structures can be described by a collection of the hybridized plasmons of the interacting system arising from a simpler structure. Recently, by breaking the symmetry of paired CWs [8], researchers were able to explain the effects of horizontal and vertical alignment on the transmission of CWP by using the plasmon interaction. Generally, the strength of the plasmon hybridization greatly depends on the symmetric alignment of paired CWs. In this paper, by both simulation and experiment, we investigate the plasmon hybridization, resulting in an effect on the polarization of incident wave. It is shown that the strength of the plasmon hybridization depends on not only the structural change but also the polarization of incident wave.

II. SIMULATION AND EXPERIMENT

The geometrical structure of the CWP is depicted in Fig. 1. The CWP structure was fabricated on both sides of a printed-circuit board (PCB) with a copper thickness

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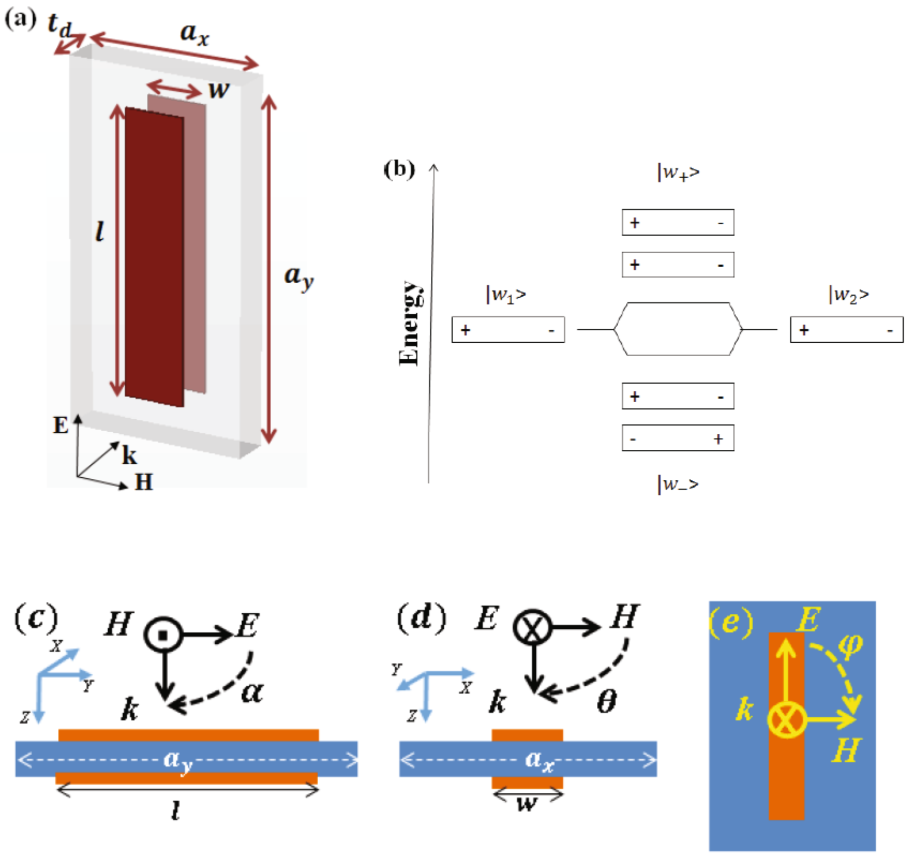

Fig. 1. (Color online) (a) Schematic representation of the CWP structure with geometric parameters. (b) Hybridization scheme for two coupled metallic CWs. (c) and (d) CWP structure working with incident angle of α and θ, respectively. (e) CWP structure working with polarization angle of φ.

of 36 μm. The thickness of the dielectric PCB was 0.4 mm with a dielectric constant of 4.8. The period of the CWP in the $x-y$ plane was kept constant at $a_x = 3.6$ and $a_y = 7.2$ mm. The length l and the width w of the CWP were 5.5 mm and 1.0 mm, respectively. For all simulations, the incident wave propagated along the z direction while the **H** and the **E** fields were assumed to be polarized along the x and the y axes, respectively. The evolution of the transmission spectra was calculated by utilizing the finite integration method [9]. In this paper, the incident angles (α and θ) were changed from 0 to 30° [Figs. 1(c) and (d)]. We also changed the polarization angel (φ) from 0 to 40° [Fig. 1(e)].

III. MAGNETIC RESONANCE HYBRIDIZATION IN A CWP STRUCTURE

In this Section, we examine the EM properties of the original CWP structure by changing the incident wave. This can be more easily understood when it is considered that the plasmon is an EM response which induces a surface current, in case of the CWP structure [6], and that the main EM response is in each CW. The CWP structure consists of two CWs, which are arranged symmetrically and separated by a dielectric layer, and the total plasmonic response is simply considered as an interaction or a “hybridization” between the plasmon responses of the individual CWs in a pair. Due to the plasmon hybridization scheme [6], two separated modes could be excited with symmetric and asymmetric current distributions. While the symmetric mode operates as two electric dipoles contributing to the negative permittivity, the asymmetric mode with anti-parallel currents behaves as an effective magnetic resonance, providing a negative permeability through oppositely-induced magnetic moments in response to the external field. In fact, it can be considered that the coupling between paired CWs originates from the degenerate state of two isolated CWs. The asymmetric mode, which is induced by an attractive force, corresponding to out-of-phase charge oscillations has a lower energy level ($|w_- >$) ; while the symmetric mode due to in-phase oscillations should be located at a higher energy level ($|w_+ >$) [Fig. 1(b)]. In this paper, only the lower mode $|w_- >$, relevant to the magnetic resonance, is considered, owing to its importance in constructing the left-handed behavior by combining it with

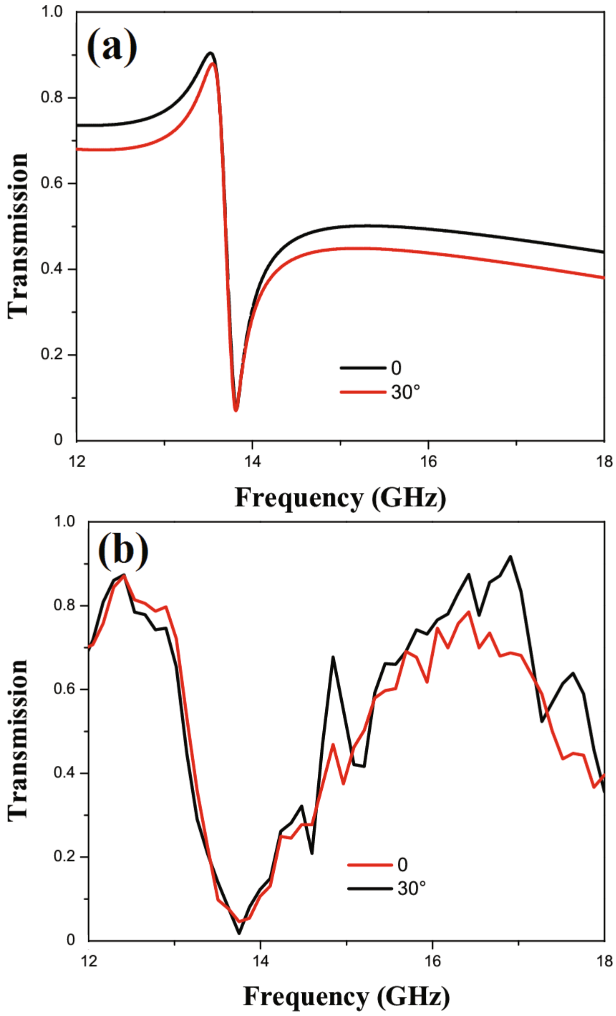

Fig. 2. (Color online) (a) Simulated and (b) experimental transmission spectra of CWP structure by changing α.

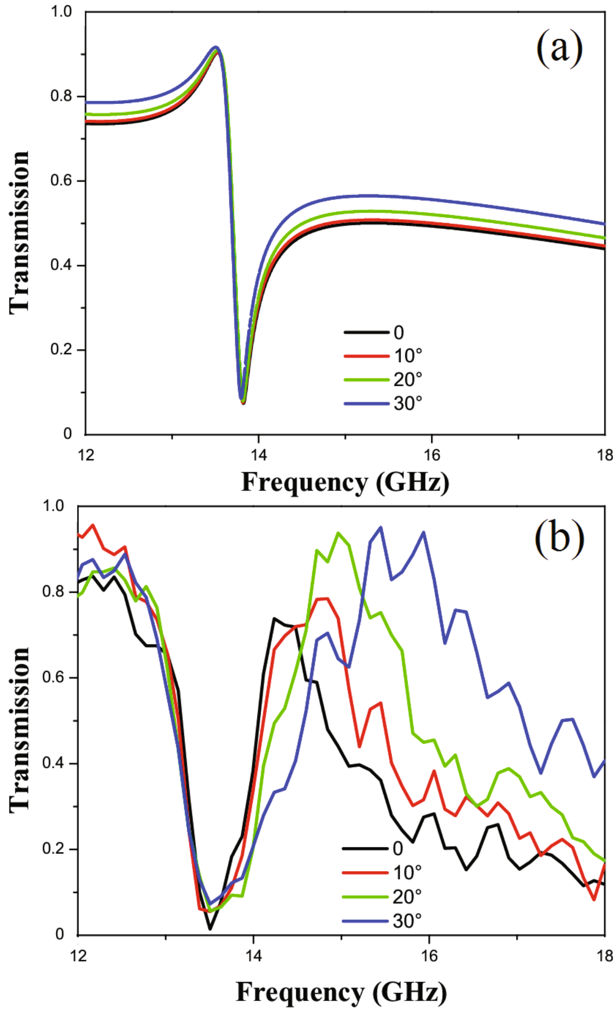

Fig. 3. (Color online) (a) Simulated and (b) experimental transmission spectra of CWP structure by changing θ.

an electric resonance in the same frequency range [10].

Figures 2 and 3 present the transmission spectra [both simulation (a) and experiment (b)] of the original CWP structure, according to the incident angles (α and θ, respectively) from 0 to 30°. In Fig. 2, the bandgap around 13.8 GHz in both simulation and experiment results corresponds to the magnetic resonance, in other words, the lower mode $|w_- >$ in Fig. 1(b) [11]. It is shown that the magnetic resonance does not depend on α.

In addition, by changing θ of the incident wave from 0 to 30°, the CWP structure exhibits a slight reduction of the transmission spectra, which are plotted in Fig. 3. This is easy to understand because of the reduction of magnetic field strength at the magnetic resonance:

$$H = H_0 * \cos\theta, \quad (1)$$

where H_0 is the magnetic field strength of the incident wave when the incident angle is equal to 0 and θ is the incident angle. A good agreement between simulation and experiment was achieved.

The next task was carried out to analyze the influence of the polarization angle on the magnetic resonance. For this purpose, we examined the transmission spectra of the CWP structure by tuning the polarization angle φ from 0 to 40°. The results are in Fig. 4. Interestingly, the asymmetric mode $|w_- >$ shows a red-shift with increasing ϕ. This observation can be understood by means of the plasmon hybridization.

In order to deepen the understanding, we investigated the transmission spectra of the CW structure, which are depicted in Fig. 5. In contrast to the CWP structure, the CW structure has only one metallic CW on the dielectric substrate, and then only electric resonance occurs at 24.5 GHz corresponding to the $|w_1 >$ (or $|w_2 >$) mode. In Fig. 5, the resonance shows a blue-shift upon increasing polarization angle; in other words, the interaction increases. According to the hybridization model, it is natural that, when the interaction increases, the lower level (bonding mode: $|w_- >$) red-shifts. Therefore, the magnetic resonance shifts towards lower-frequency

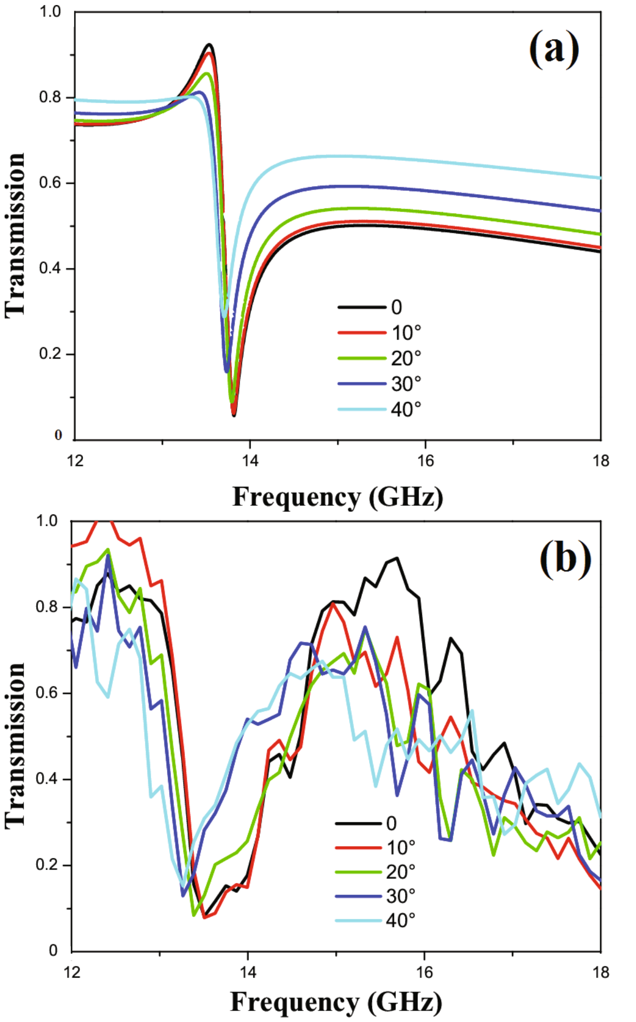

Fig. 4. (Color online) (a) Simulated and (b) experimental transmission spectra of the CWP structure by changing φ.

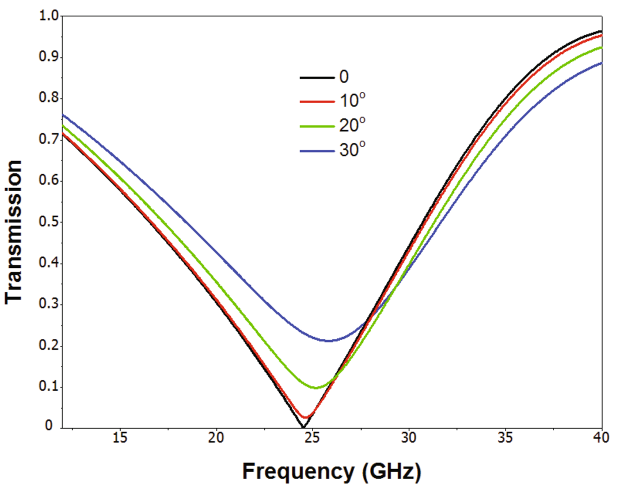

Fig. 5. (Color online) Simulated transmission spectra of the CW structure by changing φ.

region upon increasing polarization angle. For a large φ, the interaction become larger, then the lower mode $|w_- >$ moves downward on the energy-level diagram. The larger ϕ, the further reduction of the magnetic resonance frequency.

IV. CONCLUSIONS

We have presented a simple extended picture of plasmon hybridization for a metamagnetic CWP structure by changing the incident wave. We have shown that the plasmon interaction does not only depend on the incident angle of the EM wave, but depends weakly on the polarization angle of the incident wave.

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REFERENCES

[1] V. G. Veselago, Sov. Phys. Usp. **10**, 509 (1968).
[2] D. R. Smith, Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser and S. Schultz, Phys. Rev. Lett. **84**, 4184 (2000).
[3] K. Aydin, Z. Li, M Hudlika, S. A. Tretyakov and E. Ozbay, New J. Phys. **9** 326 (2007).
[4] H. Chen, L. Ran, J. Huangfu, X. Zhang, K. Chen, T. M. Grzegorczyk and J. A. Kong, Phys. Rev. E **70**, 057605 (2004).
[5] Z. G. Dong, S. Y. Lei, Q. Li, M. X. Xu, H. Liu, T. Li, F. M. Wang and S. N. Zhu, Phys. Rev. B **75**, 075117 (2007).
[6] B. Kant, S. N. Burokur, A. Sellier, A. de Lustrac and J.-M. Lourtioz, Phys. Rev. B **79**, 075121 (2009).
[7] E. Prodan, C. Radloff, N. J. Halas and P. Nordlander, Science **302**, 5644 (2003).
[8] N. T. Tung, D. T. Viet, B. S. Tung, N. V. Hieu, P. Lievens and V. D. Lam, Appl. Phys. Express **5**, 112001 (2012).
[9] http://wwww.cst.com.
[10] V. M. Shalaev, Nature Photonics **1**, 41 (2007).
[11] N. T. Tung, J. Y. Rhee, J. W. Park and Y. P. Lee, J. Korean Phys. Soc. **57**, 1733 (2010).