HORIZONTALLY PLASMON HYBRIDIZATION ON SYMMETRIC-BREAKING METAMATERIALS

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ABSTRACT

In this report, we present a study on the fundamental negative-permeability metamaterials, named as the cut-wire-pair structure. The physics of the cut-wire-pair metamaterial is interpreted using the electromagnetic analog of molecular-orbital theory. It is shown that a symmetric-breaking cut-wire-pair metamaterial is horizontally plasmon-hybridized, leading to an additional magnetic resonance beyond the conventional one. The transmission spectra and the induced energy distributions are performed to demonstrate our prediction.

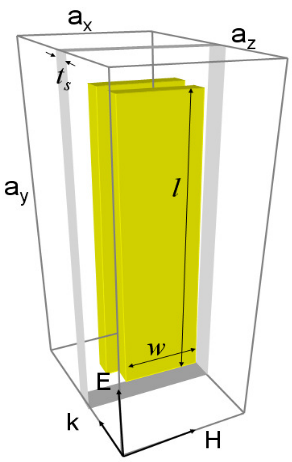
Keywords: metamaterials, cut-wire-pair, hybridization.

1. INTRODUCTION

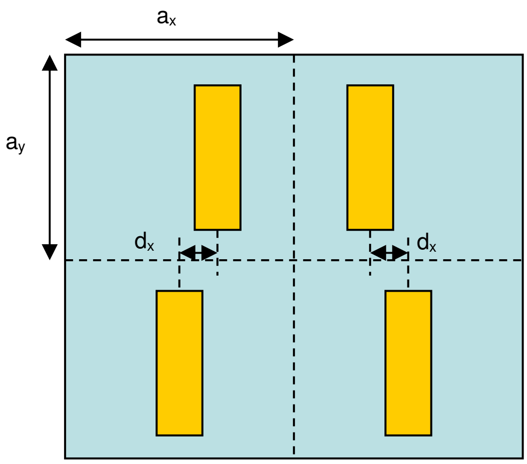
Recently, the classical concept of wave-matter interaction has been changed drastically by the marvelous debut of artificially electromagnetic materials, the so-called metamaterials [1]. Generally, metamaterials consist of periodically small, electric and magnetic “atoms” [2]. Interaction between the magnetic and the electric “atoms” plays the decisive role in enacting the intriguing macroscopic electromagnetic properties such as negative refraction. In this study, we consider a fundamental but effective meta-magnetic “atom”, named as cut-wire-pair (CWP) metamaterial, which is proposed to produce negative permeability [3]. While the major drawback of the conventional meta-magnetic structures is excited by the in-plane incident, leading to the complexities in fabricating and measuring, especially at THz and optical frequencies; the CWP design allows us to use the normal-to-plane incident, providing the strong response with only one functional layer [4]. Therefore, the CWP structure is commonly used to exhibit the magnetic resonance which combines with the electric plasma of the continuous wires to create the negative refractive index [5, 6, 7]. From the seminal report of Shalaev *et al.*, the electromagnetic properties of CWP metamaterials have been studied extensively, both experimentally and theoretically [8]. Lately, number of interest has been shown in exploring the short-range asymmetric behavior of CWP structure, which gives rise to a new versatile class of metamaterials [9, 10].

In this report, the dual magnetic resonance in a symmetric-breaking CWP metamaterial working at about 100 GHz is investigated. The transmission evolution of the symmetric-breaking metamaterial is presented using the finite integration simulation technique [11]. The finding result is explained by an electromagnetic analog of molecular-orbital theory: the horizontally plasmon hybridization scheme. This would reveal the potential in achieving the highly "flexible" negative refraction in both microwave and optical frequencies.

2. ELECTROMAGNETIC ANALOG OF THE MOLECULAR-ORBITAL THEORY



(a)



(b)

Figure 1. (a) A computational unit cell of CWP structure. (b) Schematic of a super cell CWP structure, including four original unit cells with the horizontal displacement d_x.

Figure 1(a) presents a computational CWP unit cell. The CWP structure consists of a periodic array of unit cells, and each unit cell contains a pair of CWs in the parallel direction. The lattice constants in the *x, y* and *z* directions are chosen to be $a_x = 1.0$, $a_y = 1.8$ and $a_z = 0.25$ mm, respectively. The incident wave propagates perpendicular to the sample plane (along the z direction) while the **H** and the **E** fields are polarized along the x and the y axes, respectively. The thickness of the dielectric spacer is chosen to be $t_s = 0.1$ mm, while the width and the length of CWs are $w = 0.3$ mm and $l = 0.8$ mm, respectively. For the dielectric spacer, the dielectric constant is kept at 3.8. CWs are assumed to be copper with the conductivity of 5.96 x 10^7 S/m. It is also assumed that the embedded reference medium is the vacuum.

To study the influence of the symmetric-breaking on the electromagnetic behavior, we introduce an extended CWP super cell, which is illustrated in Fig. 1(b). There, a super cell is considered by combining four original CWP unit cells in the **E-H** plane, where two top CWPs are shifted toward each other by d_x in the H direction while keeping two bottom ones unchanged. By tuning d_x, one might expect the symmetric breaking will result in decoupling between top and bottom CWPs and coupling between two top CWPs. Consequently, the induced charge distributions at the ends of CWs are therefore relocated, modifying the energy level of resonance modes.

The magnetic and the electric resonance of the individual CWP structure have been recently well described by the electromagnetic analog of molecular-orbital theory [12]. The key idea is to consider the CWP as a total plasmon hybridization of two individual plasmon responses of two CWs. The strength of the plasmon hybridization depends mainly on the symmetric alignment of the paired CWs. In the magnetic mode of the individual CWP, it is well known that the induced charges are anti-symmetrically divided at the ends of paired CWs. Consequently, the charge distributions result in the Coulomb forces, ruling the energy level of resonant modes. Herewith, we propose a short-range plasmon hybridization picture of the symmetric-breaking CWP super cell as shown in Fig. 2. For a super cell, when d_x is small enough, the symmetric breaking might bring an additional induction between two individual in-plane CWPs, modifying the charge distributions and therefore the energy level of resonant modes. While longitudinal hybridization has been investigated elsewhere [13], the mechanism of horizontal interaction has not been reported yet. In fact, increasing d_x leads to the coupling between two adjacent CWPs along **H** direction: the in-plane interaction is more repulsive, and the out-of-plane one is more attractive. These two additional interactions will change the energy level of the original mode, generating two additional magnetic modes correspondingly: the lower energy mode $|w_{--}\rangle$ where the attractive force is dominated and the higher one $|w_{-+}\rangle$ is due to the repulsive force.

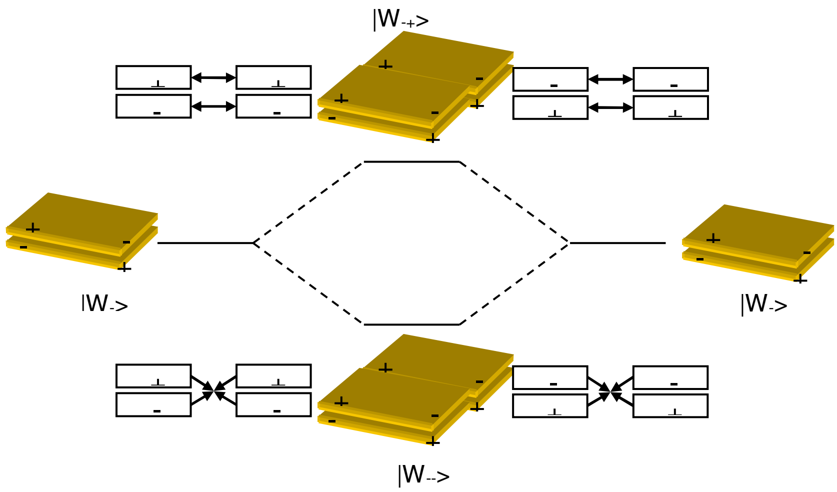


Figure 2. Hybridization scheme of super cell CWP structure with d_x displacement.

3. HORIZONTALLY PLASMON HYBRIDIZATION IN SYMMETRIC-BREAKING SUPER CELL CWP STRUCTURE

Figure 3 presents the transmission evolution of symmetric-breaking super cell CWP structure according to the horizontal displacement d_x. In the symmetric super cell (d_x = 0), only one bandgap is observed about 97.7 GHz corresponding to the original magnetic resonance of individual CWP structure. To study the influence of symmetric breaking on the resonance mode of super cell CWP structure, d_x is varied from 0 to 2.8 mm. It can be clearly seen that the resonance of super cell is sensitive to the displacement along the **H** direction. In detail, an additional lower resonance mode is interestingly stimulated as d_x increases. At d_x = 2.8 mm, the lower resonance mode is about 96.4 GHz. However, the horizontally plasmon hybridization scheme suggests that there should be two additional resonances instead of only the lower one observed in the symmetric breaking super cell. A possible reason is due to the weak in-plane repulsive interaction between two adjacent CWPs while the out-of-plane attractive force is favorable since the induced charges are mainly located at the ends of CWPs on the **E-H** plane.

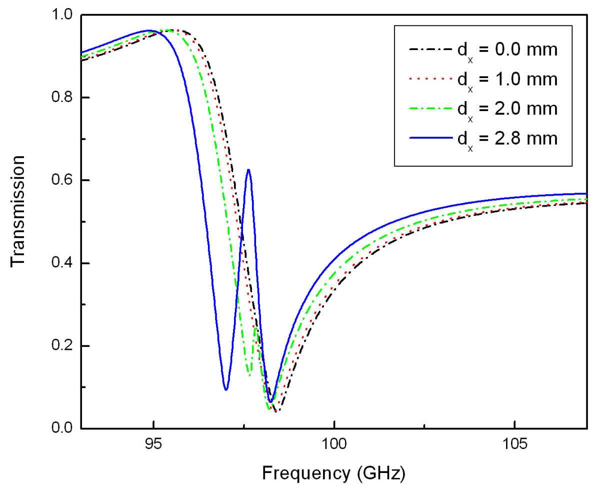


Figure 3. Transmission evolution of horizontally plasmon hybridized CWP super cell.

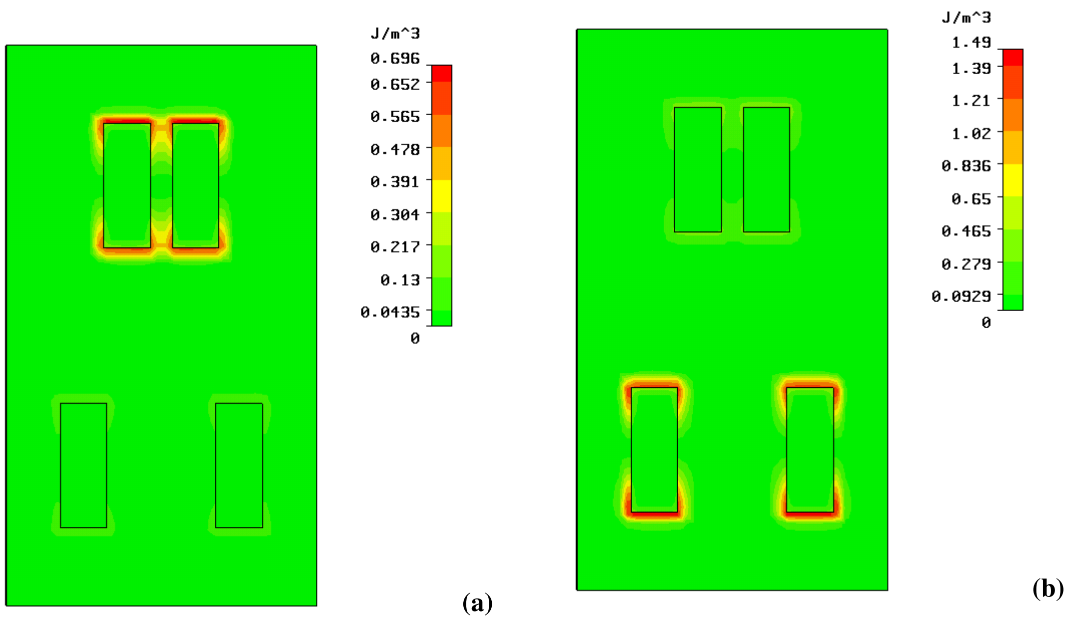
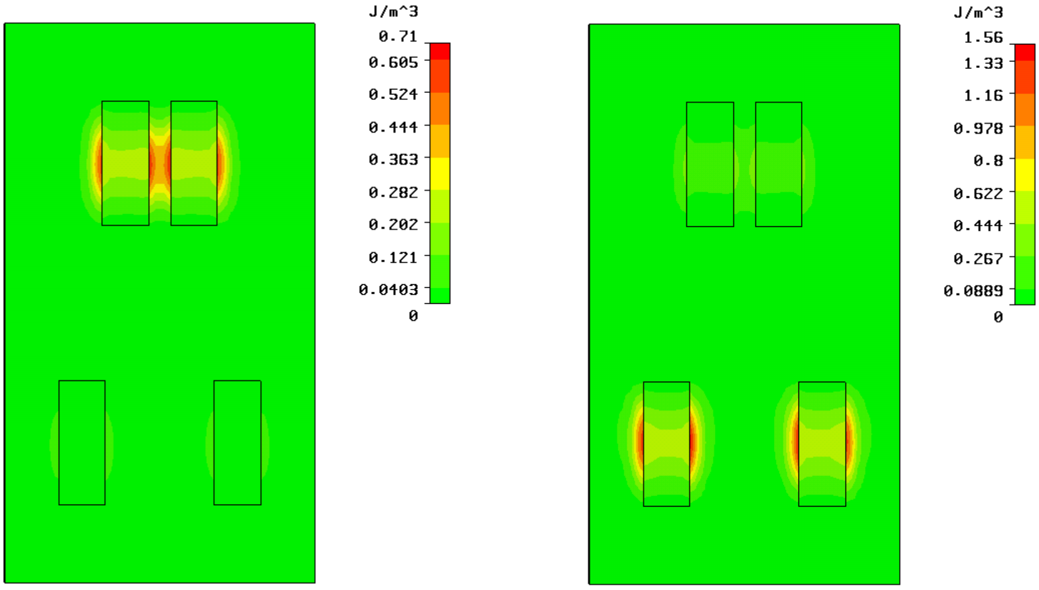


Figure 4. (Top) Electric energy field monitored at the resonant frequency (a) 96.4 and (b) 97.7 GHz.



(c) **(d)**

Figure 4. (Bottom) Magnetic energy field at (c) 96.4 and (d) 97.7 GHz.

For a better understanding of the physics of the additional mode, the magnetic and the electric energies of the symmetric-breaking CWP structure are performed. Figure 4 depicts the electric energies [(a) and (b)] and the magnetic energies [(c) and (d)] with d_x = 2.8 mm at 96.4 ($|w_{--}>$) and 97.7 ($|w_{-}>$) GHz, respectively. It is clearly shown that both original resonance at 97.7 GHz, and the additional hybridized resonance at 96.4 GHz indicate an identical physics: the electric energy is principally concentrated at the ends of CWPs while the magnetic energy is mainly located at two top (displaced) and bottom (original) CWPs. It means that at both two resonant frequencies, the anti-parallel charge currents are induced, indicating they are magnetically originated.

4. CONCLUSIONS

We propose a simple scheme to obtain dual magnetic resonance using a symmetry-breaking super cell CWP structure operating at about 100 GHz. The additional magnetic resonance is observed beyond the original one and is interpreted by the horizontally plasmon hybridization. The evolution of transmission spectra with regard to the horizontal displacement d_x is presented to demonstrate the physics of the resonances. The underlying physics of the resonances is demonstrated by the simulated energy distribution. Our results in combination to the previous work [13] have shown a comprehensive picture of the short-range plasmon hybridization of CWP metamaterials.

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TÓM TẮT

SỰ LAI HÓA PLASMON TRONG SIÊU VẬT LIỆU CÓ CẤU TRÚC BẤT ĐỐI XỨNG

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Trong bài báo này, chúng tôi trình bày kết quả nghiên cứu siêu vật liệu có độ từ thẩm âm dựa trên cấu trúc cặp dây bị cắt. Bản chất vật lí của siêu vật liệu có cấu trúc cặp dây bị cắt được giải thích bằng lí thuyết trường điện từ tương tự như lí thuyết obitan phân tử. Theo lí thuyết này, siêu vật liệu có cấu trúc cặp dây bị cắt bất đối xứng sẽ lai hóa plasmon theo chiều ngang, làm xuất hiện thêm một cộng hưởng khác ngoài cộng hưởng thông thường. Phổ truyền qua và phân bố năng lượng cảm ứng đã được đưa ra để kiểm chứng cho dự đoán này.

*Từ khóa***:** siêu vật liệu, cặp dây bị cắt, sự lai hóa.