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MULTI-PLASMON RESONANCES SUPPORTING THE NEGATIVE REFRACTIVE INDEX IN "SINGLE-ATOM" METAMATERIALS

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The search for a simple meta-system with negative refractive index has attracted a lot of attention recently. In this paper, we study a negative refractive transmission operating at 300 GHz by using "single-atom" metamaterials which were initially designed for achieving negative permeability. The nature of the negativity is discussed extensively by the effective medium analysis and confirmed by the dispersion diagram.

Keywords: Metamaterials; negative refractive index; cut-wire pair.

1. Introduction

More than three decades after they were predicted theoretically by Veselago,[1] the first implementation of metamaterials was realized experimentally[2] in a microwave metamaterial composed of periodic split-ring resonators (SRRs)[3] and continuous wires.[4] It confirmed the fact that the electromagnetic wave could propagate inside a negative-refractive medium which was created by having negative permittivity and permeability simultaneously which might offer the opportunity to explore a large variety of optical phenomena associated with negative-refractive index, as well as applications in the fields of scaling down the photonics and superlens imaging. Nevertheless, a direct transfer of the original design[2] from microwave to optical regimes was not successful due to the complexities in fabrication and measurement. In order to bridge this gap, a simple magnetic resonator, the cut-wire-pair (CWP), has been introduced and this propagated widely as a potential candidate for negative permeability at both GHz and THz frequencies.[5] The optical negative refraction, hence, was achievable in a combined structure which is composed of continuous wires and CWPs.[6–8] The great potential of combined structure and its analog–fishnet structure has been shown to be true in recent research where negative refraction of a three-dimensional optical metamaterial was demonstrated for the first time.[9] However, the large fraction of metal contained in such structures is an important drawback since it can lead to high level losses, especially in the optical domain. Recently, among efforts to overcome this point, an extraordinary negative-refractive transmission in a microwave CWP structure which is used to provide the magnetic resonance as a "single-atom" metamaterial without additional continuous wires, has been proposed.[10] In this study, characterizations of a negative-refractive CWP metamaterial working at 300 GHz are described in detail.

2. Effective Medium Analysis for CWP Structure

Figure 1 defines the computational configuration of a CWP unit cell, which is composed of two symmetric metallic CWs spaced by a thickness t_s of dielectric layer. The width and the length of CWs are denoted by w and l, which are kept at 0.14 mm and 0.78 mm in our simulations respectively. The periodicities of unit cell are $a_x = 0.5$ mm, $a_y = 1.0$ mm and $a_z = 0.28$ mm. The thickness of the metallic pattern and dielectric layer are 0.005 and 0.057 mm respectively. The dielectric layer is assumed to be FR4 with permittivity of 3.9. Our simulations are carried out by using finite integration technique via CST Microwave Studio.[11]

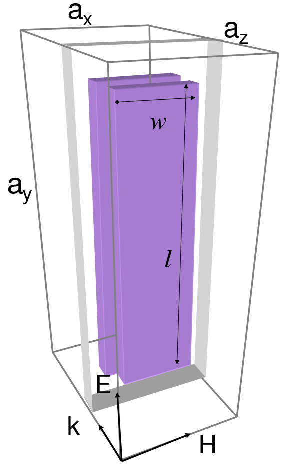

Fig. 1. (Color online) Computational configuration of a CWP unit cell.

It is noted that the CWP structure can also exhibit, in principle, both electric and magnetic resonances[12,13] regardless of being used widely as a meta-magnetic resonator in combined systems.[6–8] The magnetic resonance can be excited by antiparallel induced currents in pairs of CWs while at the electric resonance, CWP structure behaves as an electric dipole antenna. However, the most used design of negative refractive systems is combining magnetic resonance of CWP and plasma behavior of continuous wires, since many efforts to overlap the fundamental electric and magnetic resonances of CWP have not been successful. Recently, Kante *et al.*[14] reported a plasmon hybridization scheme that allows the observation of negative refraction in asymmetric CWP structure by rigorously adjusting the geometric parameters.

In this report, we will show that the negative-refractive index is achievable in a simple symmetric CWP structure, especially three times higher than the conventional one. The electric and the magnetic responses of such structure are discussed in order to interpret the physical mechanism of this negativity.

3. Negativity of Refractive Index in CWP Structure

Differing from results of Ref. 14 which control the fundamental modes of electric and magnetic resonances to be overlapped by breaking the symmetry of structure, we obtained a negative refractive index in symmetric CWP with use of the fundamental electric resonance and the third-order magnetic resonance. In fact, it is known that besides the fundamental modes, the higher order resonances are also excited in such resonators under incident waves.[15] Therefore, by independently tuning the electric-resonance frequency,[16] it is possible to conduct a doubly negative transmission in simple symmetric CWP structure.

Since the magnetic resonances are generated by induced circular currents, we apply the effective medium analysis[17] to investigate which resonance is consistent with the magnetic or the electric one. The most well-known method is shortening the ends of CWPs to find out what happens to the transmission of CWP structure. The shorted CWP structure is expected to behave like an electric-dipole CW metamaterial with the capacitance at the ends of shorted CWPs eliminated. Therefore, the driven force in the circular current is removed and the magnetically originated resonance disappears without significantly affecting the electric resonance. For this purpose, we present the transmission spectra of CWP and its shorted version in Fig. 2. Obviously, there are three resonances at 100 GHz, 225 GHz and 300 GHz in transmission spectrum of CWP structure while only the second resonance at 225 GHz remains in shorted version. The reasonable interpretation is that the first and the third resonances are of magnetic origin while the second one responds to the applied electric field. More importantly, a passband in the transmission of CWP structure at the third resonance instead of the stopband as in the case of the first one, is observed which is demonstrated hereafter to be a negative

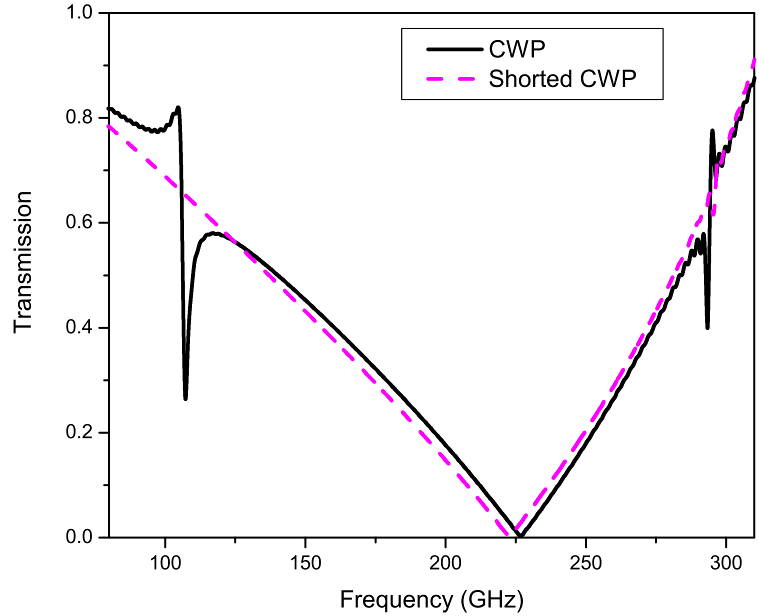

Fig. 2. (Color online) Transmission spectra of CWP and its shorted version.

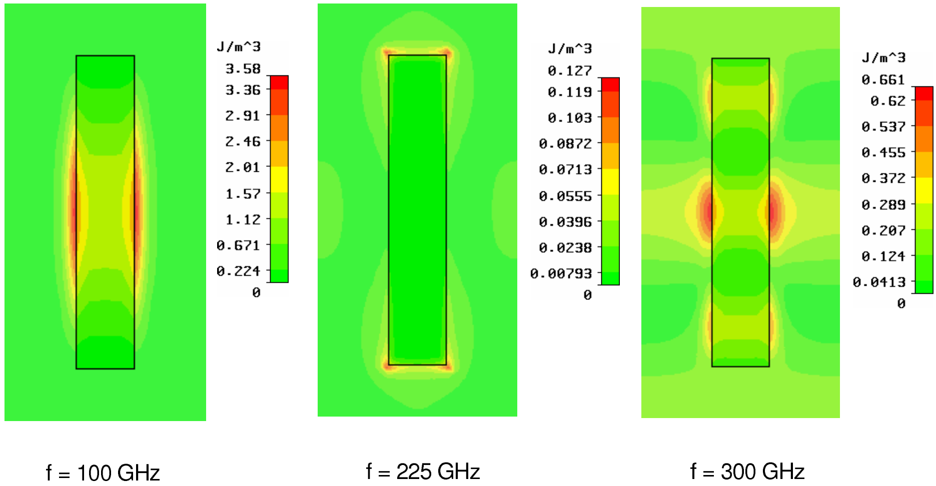

Fig. 3. (Color online) Magnetic energy distribution according to the first ($f = 100$ GHz) and the third ($f = 300$ GHz) resonances and the electric energy distribution for the case of second resonance ($f = 225$ GHz).

refractive transmission peak associated with overlapping of the fundamental electric and third-order magnetic resonances.

Here, we further clarify the nature of this passband and explain why it exhibits left-handed behavior. Figure 3 shows the distribution of induced energy densities in CWP structure at 100 GHz, 225 GHz and 300 GHz. It is clear that the first and the third resonances respond to the applied magnetic field while the second is excited by electric field. However, from the distribution of induced magnetic energy at $f = 300$ Ghz, one can see that the magnetic response of the third resonance behaves like three induced dipole moments generated by fundamental magnetic resonance. These magnetic moments are induced by three circular currents but in different directions since the central one is opposite to the others. Moreover, the strength of magnetic moment is proportional to the area subtended by the circular current loop. Thus, the third-order magnetic resonance is expected to be weaker than the fundamental one. Further simulations (not shown here) also confirm the existence of other odd modes. The even magnetic modes might not exist since the antiparallel induced magnetic fields cancel each other.

On the other hand, for the fundamental electric resonance at 225 GHz, the CWP structure behaves like an electric dipole antenna as discussed above. Note that during the electric resonance, the negative permittivity band appears only on the right side of the center frequency. Therefore, the passband at 300 GHz results from the doubly negative behavior, or the so-called negative-refractive behavior and is composed of the fundamental electric and third-order magnetic resonances.

The simulation is carried out to calculate the dispersion diagram of CWP structure with electric field along the y axis and magnetic field along the x axis. The resulting dispersion curves are given in Fig. 4. It is clearly seen that there are three

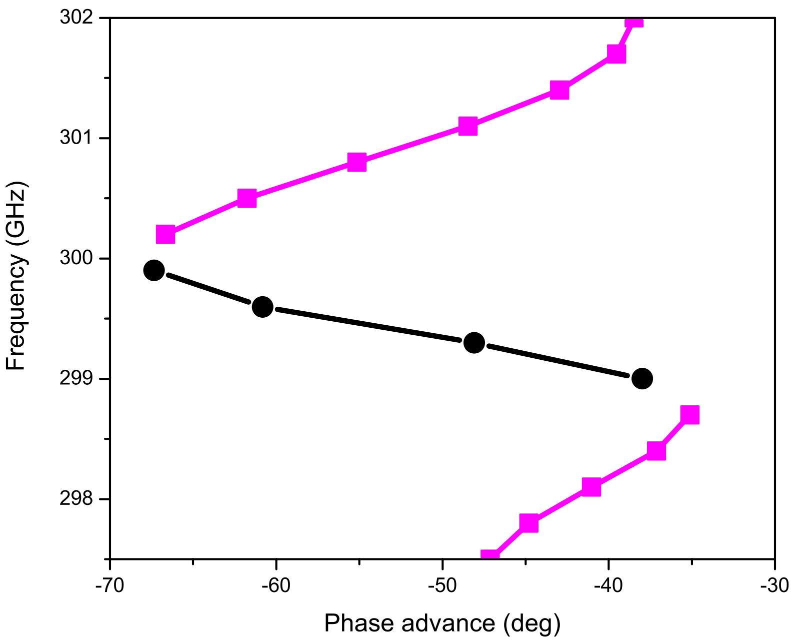

Fig. 4. (Color online) Dispersion curve for CWP structure at the polarization indicated in Fig. 1. The second branch (black curve with circles) corresponds to the negative phase velocity range.

branches of wave propagation in the frequency domain. The first and third branches (magenta line with square) are associated with a positive phase advance. Meanwhile, the second propagating branch appearing around 300 GHz (black line with circles) clearly presents a negative slope which suggests that the phase and group velocities have opposite signs. All above, it is indicated that the CWP medium supports negative-refractive propagation.

4. Conclusion

We have investigated a negative-refractive transmission in the simple symmetric CWP structure. The mechanism of this negative refraction has shown to be different from common understanding. It is revealed that the negativity of refraction in CWP is achievable by the combination of the fundamental electric resonance and the third-order magnetic resonance of CWP. The negative-refractive behavior was further verified by a dispersion diagram. The use of CWP without additional continuous wires provides a significant reduction in fabrication as well as suggests a simple but promising design for left-handed systems, possibly at optical regimes.

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