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Fast roll-off and sensitivity of a transparency window with dual magnetic resonant modes from a split double-ring metamaterial

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ABSTRACT

Dual magnetic resonant modes at neighboring frequencies are induced in a split double-ring metamaterial, which contribute to a transparency window within a broad stopband. This resonance-based window exhibits a favorable filtering performance due to its fast roll-off characteristic, and a considerable sensitivity to refractive index changes of the surrounding medium.

1. Introduction

Various intriguing characteristics in electromagnetic metamaterials have been explored from the last decade, such as the negative refraction [1], super-resolution imaging [2], invisibility [3], optical activity [4], surface plasmon amplification by stimulated emission of radiation (SPASER) [5–7], and the metamaterial analogue of electromagnetically induced transparency (EIT) [8,9]. These interesting electromagnetic behaviors are more or less resulted from different resonant eigenmodes in particularly designed subwavelength structures or from different hybridization states due to the plasmon coupling between adjacent elements when they are assembled into metamaterials. For instance, a metallic split ring resonator (SRR) [10,11], or a rod-pairing structure [12,13], can induce the magnetic dipole response beyond the terahertz regime, for which frequency range the magnetism cannot be found in any naturally occurring materials.

In contrast to the symmetric resonant dip with a Lorentzian-type lineshape in the transmission spectrum for the SRR, a bilayered fishnet [1], symmetry-broken SRR [14], or a closed double-ring structure [15], can offer an asymmetric transmission spectrum in Fano-type lineshape, where a resonant dip is closely accompanied with a resonant peak in the transmission spectrum [16]. Usually, such an asymmetric resonant spectrum is related to either left-handed or EIT-like metamaterials, as well as contributes to potential applications for sensing [17], filtering [18], and spasing [19]. In the previous work of ours, a closed double-ring metamaterial was designed to investigate its antiparallel resonant magnetic-dipole moments that results in a Fano-type transmission spectrum and negative refraction phenomenon [15]. This interesting resonant structure is isotropic within the ring plane, and the same resonant mode can be excited both laterally and normally as long as the incident electromagnetic wave is polarized with the electric field component parallel to the ring plane [20,21]. Subsequently, a variation and a complementary structure of the double-ring metamaterial were reported in Refs. [21] and [22], respectively. The closed double-ring structure was also adopted to mimic the EIT-like response by virtue of the identical resonant mode with antiparallel magnetic dipole directions [23]. More recently, J. Kim et al. proposed a concentric closed multi-ring metamaterial (also called bull's eye), as an extension of the double-ring structure, to investigate the multi-peak EIT-like characteristic [24].

In this work, by splitting the double rings symmetrically with respect to the polarized electric-field direction, an additional resonant mode with co-directional magnetic dipole moments can be induced in a neighboring frequency regime regarding to the previously introduced resonant mode with antiparallel magnetic dipoles [15]. It is found that these two neighboring magnetic resonant modes in the split double-ring structure can modify the resonant transmission spectrum in a very favorable manner, resulting in a steep as well as a sensitive transparency window within a broad stopband. Consequently, such a structured metamaterial composed

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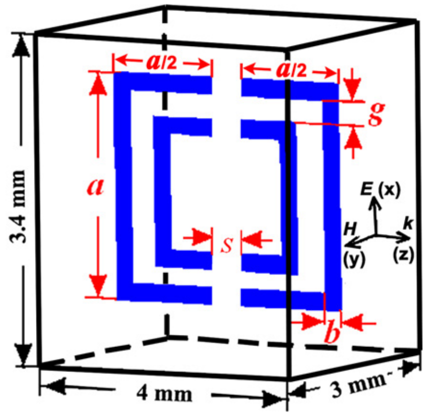

Fig. 1. (Color online.) The schematic illustration for a unit cell of the split double-ring metamaterial.

of split double rings can be considered for filtering, slowing down light, and sensing applications in the microwave regime.

2. Numerical model

Fig. 1 shows schematically the split double-ring metamaterial, which is geometrically different from a closed double-ring structure in those four splits introduced symmetrically along the x direction. The squared-ring structure is composed by copper with the edge length $a = 3.0$ mm, width $b = 0.2$ mm, and thickness $c = 0.02$ mm. The split in the ring is $s = 0.2$ mm, and the gap between the outer and inner ring is $g = 0.1$ mm. In addition, stacking periodicities are $P_x = 3.4$ mm, $P_y = 3.0$ mm, and $P_z = 4.0$ mm. Our numerical simulations were carried out by solving Maxwell's equations based on the finite element method [25,26]. The structural model is excited by a normally incident plane wave (i.e., the incident wave vector propagates along the z direction). The polarized electric field is parallel to no-split ring edges (along the x axis), while the magnetic field perpendicular to the ring plane (along the y axis). Due to the structural symmetry, this incident configuration can be numerically approximated by using perfect electric and magnetic boundary conditions [20,25,26]. Note that the structural scale selected in this simulation work leads to concerned resonant modes in the microwave regime, in which frequencies all resonant modes can exhibit themselves clearly due to the neglectable metal loss.

3. Numerical results

Fig. 2(a) presents the transmission spectrum of the split double-ring metamaterial. It is interesting to find that, within a broad stopband ranging from about 20 GHz to 45 GHz, a narrow passband with very steep cut-off profiles on both lower and upper frequency regimes is obtained around 30 GHz. The fast lower-frequency as well as upper-frequency roll-off performance for this narrow transparency window indicates a great efficiency in rejecting electromagnetic waves with frequencies neighboring to the passband. It should be noticed that the transmission spectrum from the split double-ring metamaterial is different from those of a closed double-ring structure [Fig. 2(b)] and a common SRR [Fig. 2(c)]. Specifically speaking, only a Fano-type resonance can be induced for the closed double-ring structure at around 30 GHz (i.e., a resonant dip accompanied by an adjacent resonance peak). In this case, only the lower-frequency roll-off behavior for the Fano-type transmission peak is fast enough as compared with the transparency window in Fig. 2(a). It should be emphasized that this resonant mode has antiparallel magnetic dipoles in one unit cell [15]. For the SRR, except that a same Fano-type resonance can be induced at about 32 GHz, an additional resonant transmission dip is formed at 10 GHz, which is a fundamental magnetic-dipole resonant mode with circulating current induced on the SRR surface [10,11]. In contrast, the transmission spectrum around 30 GHz is modified significantly for a split double-ring structure so that a passband can be formed with a narrow bandwidth (tunable, shown in the next) and a very fast roll-off performance in rejecting both lower and upper frequencies, as specified earlier.

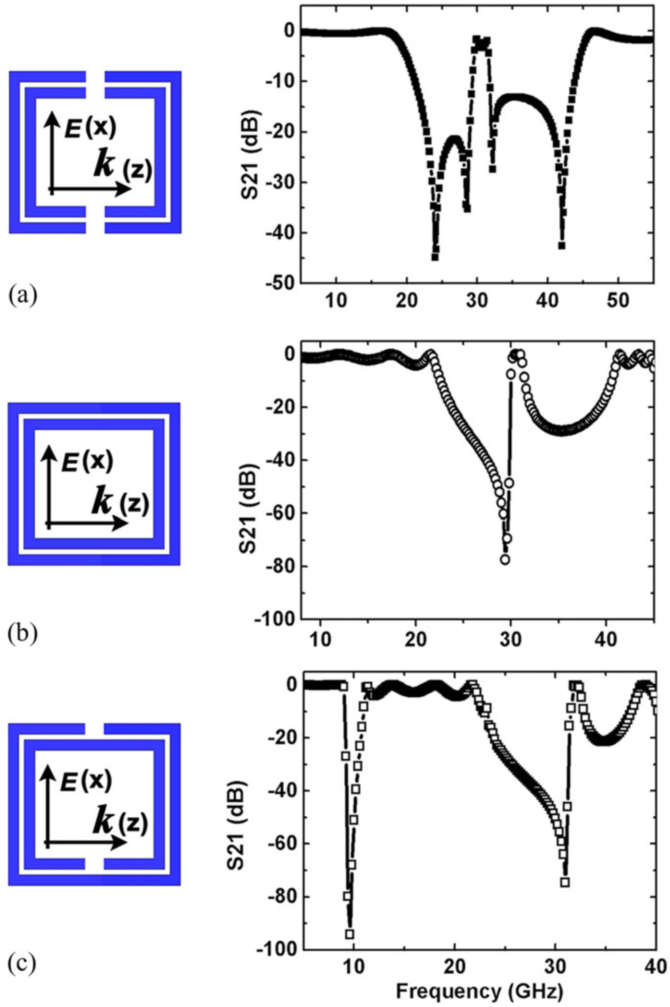

Fig. 2. (Color online.) Transmission comparison between the split double ring (a), closed double ring (b), and a common SRR (c). The transparency window for the split double-ring metamaterial at about 30 GHz shows a fast roll-off performance for both lower-frequency and upper-frequency band edges.

In order to investigate the underlying resonant mode for the steep bandpass characteristic of the split double-ring structure, Fig. 3 shows the induced resonant modes around 30 GHz in terms of the surface current distribution and the magnetic field map. It is interesting to find that dual magnetic resonant modes are excited around the bandpass regime. The first one is the anti-bonding magnetic resonance with antiparallel magnetic dipole moments between the left and the right gaps [Figs. 3(a) and (b)]. This is the same mode induced in the closed double-ring structure and the SRR. However, another magnetic resonant mode with co-directional magnetic dipole moments for left and right gaps [Figs. 3(c) and (d)] is particular for the split double-ring structure, which was not found in either the closed double-ring or the SRR. This particular magnetic resonance exhibits circulating surface current distribution for both the outer and inner ring, but with reversed circulating directions between each other. Thus, it is different from the fundamental magnetic resonant mode in the SRR [10].

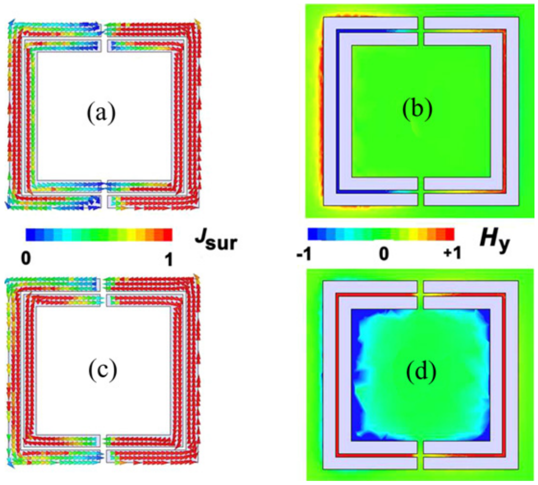

Fig. 3. (Color online.) Dual magnetic resonant modes for the narrow bandpass regime of the split double-ring structure, presented by excited surface current distributions and amplitude maps of y-component magnetic field. (a) and (b) Antiparallel magnetic dipoles are induced in left and right gaps (shown at 28.2 GHz). Note the reversed amplitudes between left and right gaps. (c) and (d) Co-directional magnetic dipoles are induced in left and right gaps (shown at 30.8 GHz). Note that this magnetic resonant mode confines an intensive magnetic field in the gaps, which distinguishes itself from that of a common SRR.

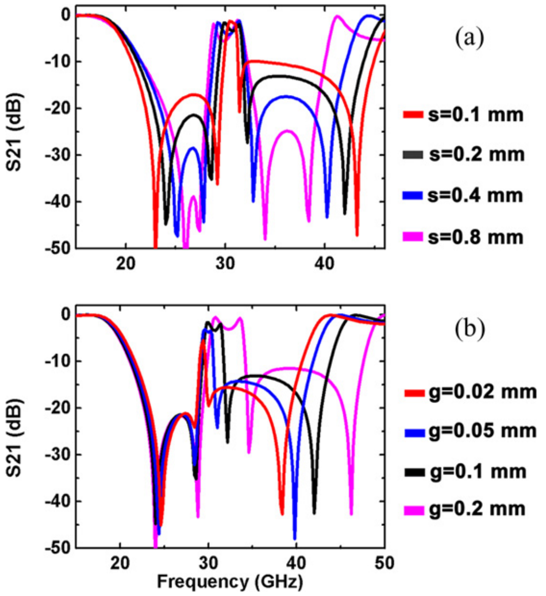

Fig. 4. (Color online.) The geometric dependence of the transparency window. (a) Dependence on the split s. (b) Dependence on the gap g.

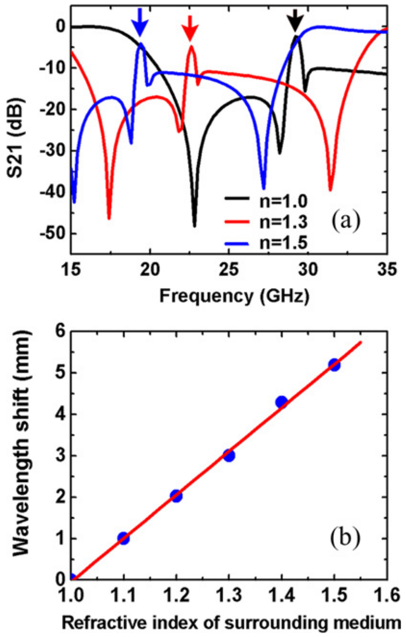

Fig. 5. (Color online.) Sensitivity of the narrow transparency window to refractive index changes of the surrounding medium, with arrows indicating peak locations of the shifted transparency window. (a) Transmission spectra at different refractive indices of the surroundings. (b) Wavelength shift in dependence on the refractive index of the surroundings.

We also confirm by numerical simulations that the antibonding magnetic resonance (i.e., antiparallel magnetic dipole moments in one unit cell) is located at lower frequencies of the transparency window, while the bonding magnetic resonance (i.e., parallel magnetic dipole moments in one resonant unit, particular to the split double-ring structure) happens at upper frequencies. Accordingly, it is obvious that dual magnetic resonances are responsible for the fast roll-off performance at both low-frequency and upper-frequency band edges of the transparency window, similar to the filtering behavior realized by the excitation of a trapped mode [27]. It is worth of mentioning that the transparency window presented in Fig. 2(a) is only for the laterally incident configuration, it cannot be found for a normally incident case because the particular magnetic resonance with parallel magnetic dipole moments, according to our simulation results, can only be excited by the polarized magnetic field of the incident electromagnetic wave.

Figs. 4(a) and (b) present the modification of the transparency window by tuning structural parameters s and g. It is found that the bandwidth for this transparency window can be extended with the increase of both split and gap values, meanwhile the steep cut-off profile is kept as well for both lower and upper bandpass edges. Notice that the transmission intensity for the passband will be suppressed gradually with the decreasing of the transparency bandwidth. Nevertheless, a large signal to noise ratio can always be expected for different bandwidths, no matter it is wide or narrow, attributed to these two resonant dips at lower and upper passband edges, respectively.

In addition to the favorable bandpass-filtering characteristic with a very steep roll-off performance, for which the bandwidth can be considerably modulated from a narrow to a broad one by modifying structural parameters, the transparency window is also promising for the sensing purpose in detecting refractive index changes of the surrounding medium, since it is inherently resulted from plasmon resonances that confine strong electromagnetic field in the gap of metal elements [17,28,29]. Figs. 5(a) and (b) present the wavelength shift of a narrow transparency window in dependence of refractive index changes of the surrounding medium. It is found that the calculated sensitivity, defined as the resonance wavelength shift per refractive index unit (RIU), can reach a value as much as 10.5 mm/RIU. The well-kept transparency windows under different refractive index of the surroundings, as shown in Fig. 5(a), manifest a reliable sensing performance for this split double-ring structure.

Last but not least, transparency window in EIT-based metamaterials has a major application potential in slowing down the electromagnetic propagation due to the Fano resonance [8,9,30–33]. It is expected that a large group index can be obtained from the split double-ring metamaterial, since its transparency window caused by the dual magnetic resonances exhibits the characteristic of Fano-type lineshape [see Fig. 2]. According the calculation results shown in Fig. 6, the group index can reach a maximum value about 40 for a narrow transparency peak at $s = 0.2$ mm and

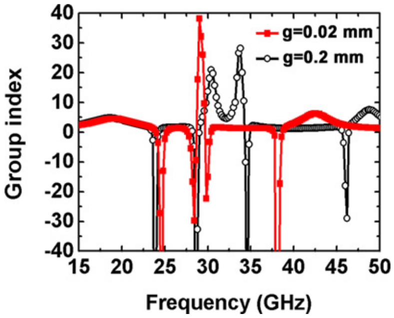

Fig. 6. (Color online.) Group index of the EIT-like transparency window for the split double-ring metamaterial.

$g = 0.02$ mm. In contrast, two group index peaks can be found corresponding to the slightly separated dual magnetic resonances at a larger gap $g = 0.2$ mm. It should be noted that negative group indices are found in the pure electric resonance regimes. This is attributed to so-called superluminal wave propagation [34], experimentally also observed in atomic EIT systems [35,36].

4. Summary and conclusion

By introducing symmetric splits in the otherwise closed double-ring structure, a transparency window can be obtained within a broad stopband due to dual magnetic resonant modes excited in the neighboring frequency regime. The significant roll-off performance for the transparency window indicates a great potential in filtering applications. By modifying geometric scales such as the split s and the gap g, a narrow bandwidth for the transparency window, instead of a wide one, can be obtained with a great capability in sensing refractive index changes of the surrounding medium. Additionally, the resonant group index for the transparency window is also presented for the major application potential on slowing down light, which is a commonly concerned EIT-based phenomenon in Fano-resonance metamaterials. It should be mentioned that the occurrence of a fast roll-off transparency window not only depends on the double-ring scales, but also it depends on the array intervals. This implies the importance of the ordered arrangement or fabrication perfections on getting the significant roll-off characteristic.

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