Multiple-band terahertz metamaterial filter using coupling effect of U-type resonator and two same sizes of metallic split rings

Chao Tang, Qingshan Niu, Yuanhao He, Xiangyang Zhang and Ben-Xin Wang
School of Science, Jiangnan University, Wuxi, 214122, People’s Republic of China
E-mail: wangbenxin@jiangnan.edu.cn
Keywords: metamaterials, multiple-band filtering, terahertz, coupling effect

Abstract
This paper presents the multiple-band terahertz metamaterial filter consisting of an U-type resonator surrounded by two same sizes of metallic split rings. Four resonance dips with near zero transmission rates are obtained, of which three dips have narrow line-widths, about one-quarter of the other dip. The physical mechanism of the four resonance dips can be attributed to near field coupling between the three sub-resonators. Influence of structure parameters on the performance of the device is discussed. It is revealed that the frequencies of the four resonance dips can be effectively controlled by adjusting the dimensions of the two surrounded rings, while the number of resonance dips show the significant dependence on the parameters of the U-type resonator. These results indicate that the proposed structure can provide more ideas for multiple-band or broadband metamaterial resonance effects in absorption, filtering, imaging and other related applications.

1. Introduction

Metamaterials, usually referred to artificial composites, have attracted extensive interest from researchers because their peculiar electromagnetic properties that natural materials cannot directly obtain. Many types of structures have been proposed to verify the concept of metamaterials, such as nanorods [1, 2], cut-wire pairs [3, 4], fishnets [5], split ring resonators [6–8] and other stereo-structures [9, 10]. These metamaterial structures are typically composed of metallic frequency selective surfaces arranged in periodic patterns placed on a very thin dielectric substrate. These structures have the ability to control their effective electromagnetic parameters and are often capable of scattering light, microwaves, and radio waves in a specific manner. In recent years, many applications based on the resonance effect of metamaterials have attracted a lot of interest, such as antennas [11, 12], superlens [13], cloaking [14–16], absorbers [17–19], imaging [20, 21], filters [22, 23] and so on.

So far, many metamaterial structures have been proposed for exhibiting different properties. For example, Hu et al achieved the single channel resonance device with an absorption rate of 70% using composite structure of electric split ring and cut-wire [24]. Zhao et al proposed a dual-channel resonator using the structure of two split rings and nanorod, which can manipulate group delay and spectral configuration using modes of dark-bright-bright and bright-dark-dark [25]. A dual-band resonator based on electromagnetically induced transparency effect was proposed by Pan et al [26], which is composed of a circular split ring and a square split ring, and can realize sensing with a refractive index sensitivity of 96.2 GHz/RIU. Unfortunately, these efforts have common shortcomings that it is difficult to further increase the number of frequency bands, which greatly hampers their practical applications.

Compared with single-band resonance devices, multiple-band resonators offer more selectivity for absorbers, filters and other related devices due to their ability to achieve multiple-band transmission at a fixed frequency. An effective way to expand the amounts of channels is to increase the number of resonators in the unit structure. For example, unit structure composed of four square metallic rings was designed to obtain quad-band resonance response, and the number of channels can be further increased by using more metallic rings [19]. Metamaterial structure consisted of three different sizes of metallic resonators provides the ability to achieve triple-band resonance effect [27]. Multiple-band resonance device constructed by a double-channel Mie
resonator in a unique configuration was demonstrated [28]. Although these metamaterial designs have been proven to produce multiple-band resonances, these efforts have the common characteristics that each metallic resonator or sub-unit corresponds to only one resonant mode and the coupling effect of the sub-units is neglected (almost independent of each other). In particular, there are very few papers on increasing the number of resonant bands using the coupling effects of sub-units or metallic resonators.

Herein, we demonstrate a four-band terahertz meta-device that utilizes the coupling effect of three sub-units of metamaterial formed by two same sizes of split rings embedded by an U-type resonator. Four resonance dips are obtained, of which one resonance dip has broad line-widths, about 4 times of the other three narrow-band dips. The formation of these bands can be attributed to the electric field coupling effect between different parts of the metamaterial. The number of the resonance bands are tunable by the coupling distances and the gap sizes. Meanwhile, the bandwidth of the four resonance dips and the transparent windows can also be tunable by varying the geometrical dimensions of the three sub-units. These results show that we can use a coupling effect between sub-units to achieve multiple-band resonance effect, thus providing more ideas for absorption, filtering, imaging, and other related applications for multiple-band resonance.

2. Materials and method

Figures 1(a) and (b) respectively show the cross section and top view of the four-band resonator, which is consisted of an U-type resonator surrounded by two same sizes of metallic split rings placed on an appropriate thickness of dielectric layer. The lengths of the two same sizes of split rings and the U-type resonator are respectively \( a = 60 \ \mu m, b = 40 \ \mu m, \) and the wire width of them is fixed at \( l_1 = 5 \ \mu m. \) The width of their gaps are set to \( l_2 = 5 \ \mu m \) and \( c = 30 \ \mu m. \) The thickness of the dielectric layer (\( \text{SiO}_2 \)) is set to 200 \( \mu m \) with a refractive index of 1.5, and the thickness of the Au is 0.4 \( \mu m \) with a frequency independent conductivity of \( \sigma = 4.09 \times 10^7 \ \text{Sm}^{-1}. \) The repeat period is \( P = P_x = P_y = 100 \ \mu m. \) The calculation results are carried out using finite-difference time-domain method (FDTD Solutions, Canada), where the period structures are incident perpendicular by a normally incident plane wave with the electric field polarized along the x direction. The periodic boundary conditions are in both directions of X and Y directions and perfectly matched layers are applied along the Z direction. Due to the shortage of experimental instruments, we are very sorry that further experimental verification is hard to implement. However, metallic gold could be deposited on the selected substrate by thermal spin coating, and then the metallic structure of the top layer could be processed by photolithography, so that the structure designed in the text may be fabricated.

3. Results and discussion

Figure 2(a) shows the transmission spectra of the proposed structure, it can be seen that there are three obvious dips with narrow bandwidths (of less than 0.13 THz) and a wide dip of the 0.5 THz bandwidth, the resonance bandwidth was defined as the full width at half maximum (FWHM). The four resonance dips are labeled as resonance modes D1, D2, D3, and D4, and the resonance frequencies of them are 1.00, 1.20, 2.29 and 2.65 THz, respectively. The transmission amplitudes of these four resonance dips are very low (close to the zero).
reasons for these resonance dips are the interaction of different parts of metamaterial. The electric field distribution shown in figure 3 below reveals their physical mechanism. According to the definition of Q factor [29], the bandwidth of the full width at half maximum (FWHM) and the corresponding frequency point $f_0$ are taken, and the Q factor is calculated by the formula $Q = f_0/\sqrt{2} \text{FWHM}$ because the figure 2(a) is the transmission, not the transmittance, and the Q factor of the three narrowband resonance dips ($D_1$, $D_2$, $D_4$) are 25, 15 and 42, respectively. These results show that the proposed structure has strong frequency selectivity in some related applications due to three narrow bands and the broad dip.

To better analyze the spectral characteristics of the proposed resonator, the transmission spectra of the reduced structure consisted of two same sizes of split rings, and the U-type resonator are respectively given, as the red and blue curves of figure 2(b) shown. What can be observed in the red curve are two narrow-band dips and one broad resonance peak, the bandwidth of the two narrow bands (amplitude of the resonance close to zero) is approximately 0.19 and 0.08 THz, while the bandwidth of the broad resonance peak with the transmission intensity of more than 90% even reaches 1.5 THz or more. The transmission spectrum (blue curve) of the reduced structure formed by U-type resonator is represented by a resonance dip with a bandwidth of 0.5 THz. By comparing these transmission curves, we found that the resonance dips of two split rings and the U-type ring correspond to the $D_2$, $D_4$ and $D_3$ of the proposed structure, respectively, so it can be inferred that two split rings and the U-type ring are not simply superimposed.
electric field distribution of D4, as shown in Figure 4(a). It can be seen from Figure 2(a) that the resonance dips D1 and D2 are very similar, but can be observed from Figures 3(b) and 4(b) that the D2 is mainly due to the coupling between the left and right arms of the U-type ring and two split rings. Some incident terahertz radiation is trapped at the lower gap of two split rings. The electric field diagram of D3 is shown in Figures 3(c) and 4(c), a little electric field is localized at the left and right arms of two split rings, however, the coupling between the two gaps plays a major role in the formation of D3, as we see that the electric field is mainly concentrated at the gaps of the split rings. By analyzing the electric field distribution of D4, at $f = 2.65 \text{THz}$ the electromagnetic radiation is localized at the four corners of two split rings and the U-type ring, while a strong coupling effect is also observed at the two gaps. Coupling is also observed between the bottom of the U-type ring and the split rings. The formation of D4 is due to the interaction of electric fields at these sections of the proposed structure, as shown in Figures 3(d) and 4(d).

Through the analysis of Figures 3 and 4, we found that these resonance dips are mainly formed by the coupling effect between the different parts of two split rings and the U-type ring. Firstly, the influence of the size of two split rings on the performance of the proposed structure is discussed. Figure 5(a) shows the transmission when the length $a$ of two split rings has been changed from 50 to 70 $\mu m$ (keeping the U-type ring constant). With the increase of the length $a$, the coupling intensity between the split rings and the U-type ring gradually decreases, it can be seen that each resonance dip has a significant shift in the corresponding frequency, and there are more obvious changes in the resonance dips (D1 and D2). As the length of $a$ increases, the transmission intensity of the two dips gradually increases, and the bandwidth of them decreases, by calculating, the Q factor of the D1 increase to 65, while the Q factor of D4 even increased to more than three times of the proposed structure, and its value is 147. When the length of $a$ is reduced to 55 $\mu m$, the frequency shift phenomenon can also be observed, as shown by the blue curve in Figure 5(a). Specifically, the resonant dips D3 and D4 are gradually merged into a wide band with the bandwidth of 0.4 THz.

Different from the figure 5(a), when we reduce the width $b$ of the U-type ring from 40 $\mu m$ to 25 $\mu m$, as shown in the figure 5(b), as the width $b$ decreases, the transmission spectrum shows a significant blue shift. When the width $b$ is reduced to 35 $\mu m$, the bandwidths of D1 and D4 are narrowed and the transmission intensities are increased, while the bandwidths of the D2 and D3 are obviously increased. The resonance dips (D1 and D4) become very weak, when the width $b$ of the U-type ring is 30 $\mu m$, see the pink curve in the figure 5(b). Four-band resonance can be converted to dual-band resonance by using a U-type ring with a width of 25 $\mu m$. These results

In order to elucidate the physical mechanisms of these resonance dips and the origin of this difference, the calculated electric field ($|E|$ and $E_z$) distributions corresponding to the four lowest transmission minimum (D1, D2, D3, and D4) are given, as shown in Figures 3 and 4. At 1.00 THz, the incident electromagnetic radiation is mainly localized in the upper and lower arms of two split rings, especially at the two gaps, and the coupling of electric field at the upper gap is stronger than that at the lower gap, thereby explaining the cause of D1, see Figures 3(a) and 4(a). When the length of $\mu m$ increases, while the bandwidths of the D2 and D3 are obviously increased. The resonance dips (D1 and D4) become very weak, when the width $b$ of the U-type ring is 30 $\mu m$, see the pink curve in the figure 5(b). Four-band resonance can be converted to dual-band resonance by using a U-type ring with a width of 25 $\mu m$. These results

![Figure 4](image-url)
indicate that adjusting the size of the proposed can change the number of multiple bands and the bandwidth of the broadband, which is more potentials in related fields such as multiple-channel resonance devices.

As can be seen from figure 3, the coupling effect of the two gaps in the two split ring plays an indispensable role in the process of the formation of the four band resonator. In order to figure out the impact of the gaps on the performance of the transmission spectrum, two cases of just adjusting the number and the size of the gaps are discussed, as shown in the figure 6. First, when we close the upper gap, there is a significant red shift in the spectrum, and it can be observed that the bandwidth of the resonance dip D3 is increased to 0.6 THz, which can be seen the pink curve in the figure 6(a). However, when we close the lower gap, the resulting transmission spectrum is very different from the proposed structure. It can be seen that there are five bands in one and half terahertz, seeing the red curve in the figure 6(a). When the closed-ring (no gaps) and the U-type ring are combined, the obtained transmission spectrum is shown in the black curve of figure 6(a), resonance dips D2 and D3 merge into a new broadband with a bandwidth of 1 THz.

The odd properties of metamaterials stem from their precise geometry and size, therefore changing the geometry of the proposed structure will inevitably lead to changes in the transmission spectrum, however, this change is hard to predict in advance. Therefore, it is easy to adjust the performance of the transmission spectrum by changing the size of the gaps, as shown in figure 6(b), the coupling effect between the gaps becomes weak due to the increase of the width of the gaps, when we enlarge the width of the gaps from 5 μm to 10 μm, by comparing the spectrum of the proposed structure, the whole spectrum appear an obvious blue phenomenon and it is worth noting that the bandwidth of D1 increases and the bandwidths of D2 and D3 decreases, while the bandwidth of D4 does not change significantly, seeing the pink curve in the figure 6(b).

A similar phenomenon can also be observed in the black and red curves of figure 6(b), but the differences are that when we increase the width of the gaps to 20 μm, the resonance dip D4 disappears, which indicate that the transition of the four-band to three-band can be regulated by adjusting the length of the gaps. In figure 6(b), an interesting phenomenon can be found that the bandwidth of the peak between the D2 and D3 gradually becomes large with the increase of the width of two gaps, when the width of the gaps is increased from 5 μm to 10 μm, by comparing the spectrum of the proposed structure, the whole spectrum appear an obvious blue phenomenon and it is worth noting that the bandwidth of D1 increases and the bandwidths of D2 and D3 decreases, while the bandwidth of D4 does not change significantly, seeing the pink curve in the figure 6(b).

Figure 5. Dependence of the resonance performance of the designed structure on the changes of the length a of two split rings and the width b of U-type ring, (a) 70 μm to 55 μm, (b) 40 μm to 25 μm.
coupling to analyze the observed resonance phenomenon. Although this method can explain most of the observed phenomena, it is not perfect and clear. The authors hope to use the near-field magnetic field coupling or the combining ways of the near-field electric field coupling and near-field magnetic field coupling to explain the observed resonance performance more systematically and clearly. Because we don’t fully grasp the method of the near-field magnetic field coupling, we also look forward to the following readers or more professional researchers to give the better analysis.

4. Conclusion

A four-band tunable terahertz metamaterial resonator is proposed herein, which is placed on a dielectric substrate of SiO$_2$ and consists of two metallic split rings and an U-shaped resonator. These four resonant dips are three narrow bands and one broadband with the transmission intensities are very close to zero, respectively, and their formation mechanism can be attributed to the electric field coupling effect between different parts of the sub-resonators. In particular, by adjusting the size of the two split rings and the U-shaped resonator, the resonant frequencies of the dips and the transition from the four-band to the dual-band resonance can be effectively tunable, while the three-band and ultra-bandwidth transparency peak can be obtained by changing the number and size of the gaps. These results indicate that the proposed structure can provide more ideas for multiple-band or broadband metamaterial resonance devices in absorption, filtering, imaging, and other related applications.

Funding

This research was funded by National Natural Science Foundation of China (11647143), Natural Science Foundation of Jiangsu (BK20160189), China Postdoctoral Science Foundation (2019M651692), Jiangsu Postdoctoral Science Foundation (2018K113C), Fundamental Research Funds for Central Universities (JUSRP51721B).

ORCID iDs

Ben-Xin Wang @ https://orcid.org/0000-0003-0489-9861
References

[1] Wang P, Krassavin A V, Nasir M E, Dickson W and Zayats A V 2017 Reactive tunnel junctions in electrically driven plasmonic nanorod metamaterials Nat. Nanotechnol. 13 159–64
[2] Wang J, Jia Z, Fan G, Ma K, Liang E and Pei D 2017 Electromagnetic field manipulation in planar nanorod antennas metamaterial for slow light application Opt. Commun. 383 36–41
[3] Burukov S N, Sellier A, Kante B and Lustrac A De 2009 Symmetry breaking in metallic cut wire pairs metamaterials for negative refractive index Appl. Phys. Lett. 94 201111
[4] Yudistira H T, Liu S, Cui T J and Zhang H 2018 Tailoring polarization and magnetization of absorbing terahertz metamaterials using a cut-wire sandwich structure Beilstein J. Nanotechnol. 9 1437–47
[5] Chen F, Yuan L and Johnston R L 2012 Low-loss optical magnetic metamaterials on ag–au bimetallic fishnets J. Magn. Magn. Mater. 324 2625–30
[6] Lin Y J, Chang Y H, Chien W C and Kuo W 2017 Transmission line metamaterials based on strongly coupled split ring/complementary split ring resonators Opt. Express 25 30395
[7] Wang B X, Wang G Z and Wang L L 2016 Design of a novel dual-band terahertz metamaterial absorber Plasmonics 11 523–30
[8] Wang B X 2017 Quad-band terahertz metamaterial absorber based on the combining of the dipole and quadrupole resonances of two SRAs IEEE J. Sel. Top. Quantum Electron. 23 4700107
[9] Totero Gongora J S, Favra G and Fratalocchi A 2017 Fundamental and high-order anapoles in all-dielectric metamaterials via fano-feshbach modes competition Nanotechnology 28 104001
[10] Wang B X and Wang G Z 2017 New type design of the triple-band and five-band metamaterial absorbers at terahertz frequency Plasmonics 13 123–30
[11] Ziolkowski R W 2018 Metamaterial-inspired efficient electrically small antenna IEEE Transactions on Antennas & Propagation 54 2113–30
[12] Wang B X, Wang G Z and Sang T 2016 Simple design of novel triple-band terahertz metamaterial absorber for sensing application Journal of Physics D 49 165307
[13] Wong Z I, Wang Y, O’Brien K, Rho I, Yin X and Zhang S 2017 Optical and acoustic metamaterials: superlens, negative refractive index and invisibility cloak J. Opt. 19 084007
[14] Wei B and Jian S 2017 Realization of super-reflection and cloaking based on graphene–silica metamaterial Opt. Eng. 56 066713
[15] Islam S S, Faruque M R I and Islam M T 2016 An object-independent enz metamaterial-based wideband electromagnetic cloak Sci. Rep. 6 53624
[16] Xia B, Dai H and Yu D 2016 Symmetry-broken metamaterial for blocking, cloaking, and supertunneling of sound in a subwavelength scale Appl. Phys. Lett. 108 064306
[17] Wang L, Ge S, Hu W, Nakajima M and Lu Y 2017 Graphene-assisted high-efficiency liquid crystal tunable terahertz metamaterial absorber Opt. Express 25 23873–9
[18] Wang B X, Wang G Z, Wang L L and Zhai X 2016 Design of a five-band terahertz absorber based on three nested split-ring resonators IEEE Photonics Technol. Lett. 28 307–10
[19] Wang B X, Zhai X, Wang G Z, Huang W Q and Wang L L 2015 Design of a four-band and polarization-insensitive terahertz metamaterial absorber IEEE Photonics Journal 7 1–8
[20] Li T, Nagal V, Gracias D H and Khurgin J B 2017 Limits of imaging with multilayer hyperbolic metamaterials Opt. Express 25 13588
[21] Montoya J A, Tian Z B, Krishna S and Padilla W J 2017 Ultra-thin infrared metamaterial detector for multicolor imaging applications Opt. Express 25 23343
[22] Hu F, Fan Y, Zhang X, Jiang W, Chen Y and Li P 2018 Intensity modulation of a terahertz bandpass filter: utilizing image currents induced on mems reconfigurable metamaterials Opt. Lett. 43 17
[23] Czyrnyý J, Gonzalo J W, Kwiecien P, Richter I, Litvik J and Schmid J H 2018 Design of narrowband bragg spectral filters in subwavelengt grating metamaterial waveguides Opt. Express 26 179
[24] Hu T, Lardy N, Bingham C, Zhang X and Padilla W 2008 A metamaterial absorber for the terahertz regime: design, fabrication, and characterization Opt. Express 16 7181–8
[25] Zhao Z Y, Zheng X B, Peng W, Zhang J B, Zhao H W, Luo Z J and Shi W Z 2017 Localized terahertz electromagnetically-induced transparency-like phenomenon in a conductively coupled trimr metamolecule Opt. Express 25 24410
[26] Pan W, Yan Y J, Ma Y and Shen D J 2019 A terahertz metamaterial based on electromagnetically induced transparency effect and its sensing performance Opt. Commun. 431 115–9
[27] Gao E D, Liu Z M, Li H J, Xu H, Zhang Z B, Luo X, Xiong C X, Liu C, Zhang B H and Zhou F Q 2019 Dynamically tunable dual plasmon-induced transparency and absorption based on a single-layer patterned graphene metamaterial Opt. Express 27 13884
[28] Long H Y, Gao S X, Cheng Y and Liu X J 2018 Multiband quasi-perfect low-frequency sound absorber based on double-channel Mie resonator Appl. Phys. Lett. 112 033507
[29] Cong L, Manjappa M, Xu N, Al-Naib I, Zhang W and Singh R 2016 Fano resonances in terahertz metasurfaces: a figure of merit optimization Adv. Opt. Mater. 3 1537–43