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Perfect absorber metamaterials: Peak, multi-peak and broadband absorption

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ABSTRACT

We investigated the absorption in a sandwich model of absorber metamaterial (MM) which consists of periodic metallic dishes at the front and metallic plane at the back, separated by dielectric substrate. First, single perfect-absorption (PA) peaks were achieved by studying the influence of parameters in the unit cell of the MM. The electromagnetic properties were presented to understand the mechanism of the PA at resonance frequency. In order to yield a multi-peak absorption, the dishes were designed in different sizes and appropriately arranged on the front side of MM. For the furthermost purpose of our work, customizing broadband absorption was performed by adjusting the dishes sizes. Utilizing the symmetrical geometry of dishes, polarization-insensitivity of the broadband absorption was gained. Finally, the influence of the angle of incidence wave on the broadband absorption was examined.

1. Introduction

In last decade, artificial sub-wavelength materials, the so-called metamaterials (MMs), whose unit cell is structured to show unnatural electromagnetic (EM) properties potentially applicable to advanced devices, have attained great interests in optics and photonics researches [1–3]. The manipulation of effective parameters in effective media develops the diversification in applications of MMs. Among them, the perfect absorption (PA), which is potentially used in plasmonic sensing [4,5], solar-energy capturing [6], and camouflage, has become one of the significant issues for MMs. The first perfect absorber has been demonstrated under the concept of MMs at GHz regime by Landy et al. [7]. By modulating the refraction and the impedance $z\ (\omega)$ of MM, a near unity absorption peak can be realized at the resonant frequency. Up to date, PA has been demonstrated in every technologically relevant spectral ranges, from microwave [7,8], THz [4,5], NIR [9], to the near optical [6]. For different applications, the MM absorbers (MAs) have been achieved in narrow peak [4–7], multi-band peaks [10], and broadband [6,8–11]. Basically, PA is gained when the MMs simultaneously satisfy conditions: environment impedance-matching leads to EM wave propagating into the medium and high-loss factors dissipate EM energy to heat. Based on the effective material parameters, the mechanism of PA peak can be explained. The parameters are variables of frequency of exciting EM wave: effective relative permittivity, $\varepsilon(\omega)=\varepsilon'(\omega)+\varepsilon''(\omega)$, and effective relative permeability, $\mu(\omega)=\mu'(\omega)+\mu''(\omega)$. By adjusting the components of unit cells, the real and the imaginary parts of the effective parameters could be controlled separately to satisfy the conditions of PA. The multi-peak [12] and broadband [13] MAs have been observed by two configurations, arranging appropriately unit cells of PA peak [14,15] and using the multi-layer model of absorption [11]. It notices that there are many interactions between plasmons in the configurations. Hence, it is a problem to combine broadband MAs with high efficiency, since the sensitive PA conditions are easy to be broken by these interactions. Therefore, the achievement of narrow peak, multi-peak, and broadband absorption which deal with different applications are still the significant issue in the MM researches.

In our paper, a conventional MA was designed to operate in GHz range of EM radiation. First, we examined the influence of parameters on the absorption to understand the characteristics of effective medium. A PA peak was achieved at the plasmonic resonance frequency. Second, the EM properties of the PA peak were investigated to clarify the light trap at the magnetic resonance. Finally, a broadband absorption with high efficiency was gained by arranging appropriately unit cells of the PA peak. The broadband MA exhibited polarization-insensitive properties from utilizing the symmetrical geometry of disks [16]. The influence of the incident angle on broadband absorption was also examined to assess the efficiency.

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2. Results and discussion

The simulation was carried out by using a finite-integration-technique package of CST Microwave Studio [17]. For a single peak of absorption, the conventional absorber design, sandwich model: layer1–layer2–layer1′, was employed to investigate the absorptions. The front layer that is arranged periodically by metallic dishes and the back one that is metallic plane are separated by a dielectric layer. The conductor is copper with an electric conductivity of 5.96×10^7 Sm^{-1}. The dielectric is FR-4 with a relative dielectric constant of 4.0 and a loss-tangent of 0.025 that is proper with the fabrication on PCB substrate [15]. A unit cell of the MM was shown in Fig. 1(a). The geometrical parameters were set to be $a=12$, $R=3$, $t=0.4$ mm. The thickness of copper layer is 0.036 mm [18]. The MM was designed to work in the range of 12–18 GHz. The EM wave is polarized in such a way that the electric and the magnetic fields are parallel with the MM slab, while the wave vector k propagates normally to the front side of the MM (Fig. 1(a)). The boundary conditions are set so that the unit cells are periodic in the E–H plane. The environment in the simulations is defined as free space which corresponds with the previous experimental method [19]. In the conventional absorber model, the back layer is the EM-wave-prevented plane. Therefore, the absorption is only calculated from the reflectance and expressed through the $S_{11}(\omega)$ parameter as $A(\omega)=1-|S_{11}(\omega)|^2$.

First, in order to characterize the absorption properties of the designed MM, we examined the influence of parameters on the absorption at the resonance. In Fig. 1(b), the radius R of dishes is changed from 1.5 to 6.0 mm to observe the alterations of absorption. It presents that a PA (near 100%) is achieved at 13.80 GHz when radius R is 3.0 mm. In addition, the absorption is also strongly dependent on the dielectric thickness t of substrate layer and the lattice constant a, as shown in Fig. 1(c) and (e). The PA peaks are yielded by adjusting these parameters. From Fig. 1(d), we can see that conservation of the absorption with regard to the dielectric constant of the substrate layer. This shows that PA is impossible to be maintained by controlling the dielectric constant. Noticeably, the failure of absorption conservation is not applied to quality of substrate layer. The dielectric loss PA MM as presented one that will be demonstrated in later discussion is strongly influenced by loss-tangent of insulator layer [18–20]. Moreover, we showed that the dimensional parameters effect on the impedance-matching condition, and hence strongly impact on the absorption of the MM.

Next, we observed the dependences of the above parameters on the resonance frequency. As we can see in Fig. 1(b)–(d), the

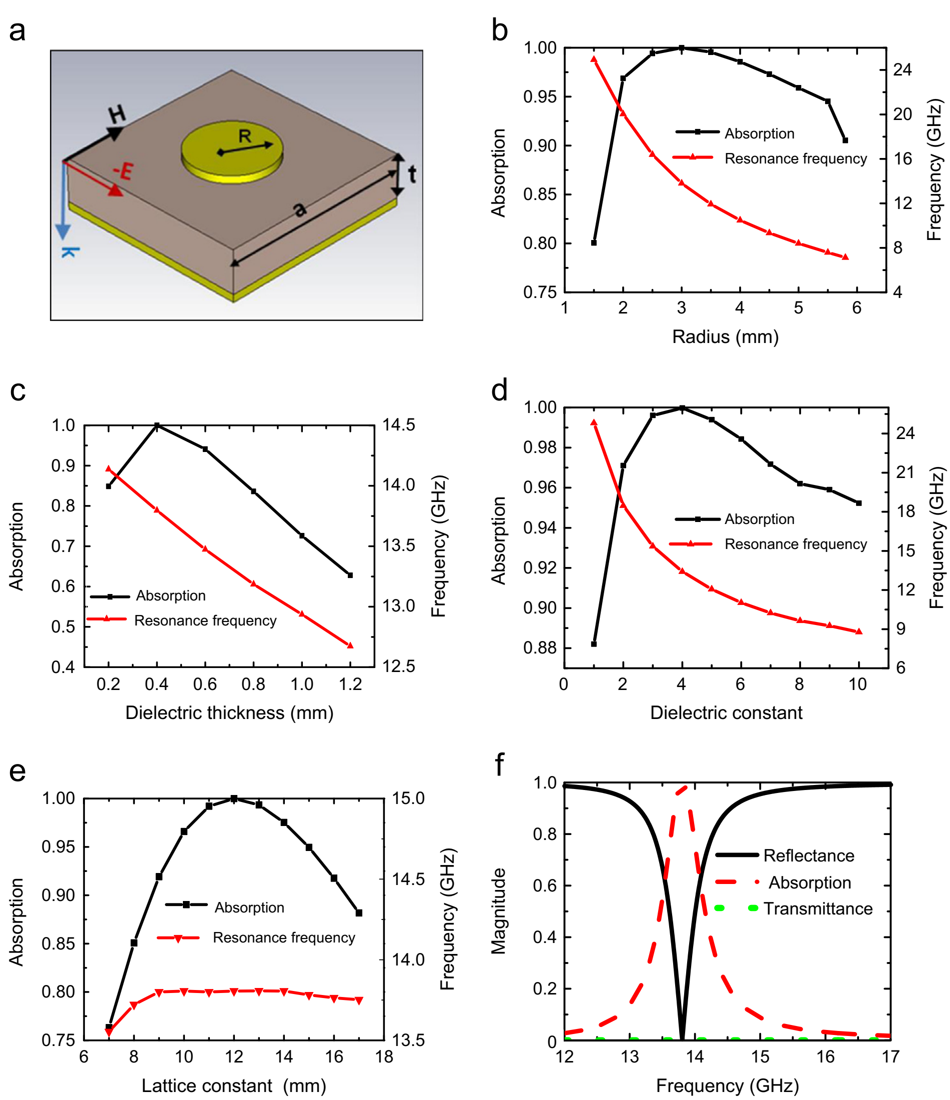

Fig. 1. (a) Unit cell of MA. Dependence of absorption spectra and resonance frequency on the MM parameters: (b) radius of dishes, (c) thickness of dielectric substrate, (d) dielectric constant of substrate, and (e) lattice constant. (f) Results of PA achievement.