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Broadband absorption in mid-infrared metamaterial absorbers with multiple dielectric layers

Nan Zhang [a,b,c,*], Peiheng Zhou [a,b,c], Shuya Wang [b,c], Xiaolong Weng [a,b,c], Jianliang Xie [a,b,c], Longjiang Deng [a,b,c]

[a] National Engineering Research Center of Electromagnetic Radiation Control Materials, China
[b] State Key Laboratory of Electronic Thin Film and Integrated Devices, China
[c] University of Electronic Science and Technology of China, China

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ABSTRACT

We have designed and fabricated broadband metamaterial absorbers working in the mid-infrared regime by employing the multilayered metal-dielectric-metal resonant stacks. Magnetic resonance is excited in each resonant stack, and the absorption peak wavelength is tuned by the dielectric constant of the dielectric layer. By stacking several resonant stacks with different dielectric layers, the absorption bandwidth can be effectively broadened through the hybridization of magnetic resonances in all resonant stacks. The presented design approach is an effective complement for constructing broadband metamaterial absorbers, and also meaningful in the design of other photonic devices.

1. Introduction

Metamaterial absorbers (MAs) are artificially constructed “atoms” that composed of sandwiched multilayers, in which the top layer is the metallic resonators separated from the bottom metallic ground plane by a dielectric interlayer. After first demonstration of the microwave MA [1], research interest in this topic has grown rapidly [2–4]. Presently, MAs could achieve high absorption over a large portion of the electromagnetic spectrum, from microwave [5], terahertz [6], infrared [7], to optical regimes [8]. The definable and tunable electromagnetic absorption effects afford MAs with incomparable advantages to the naturally existing materials, and make MAs as ideal candidates for applications including sensors [9], solar cells [10], thermal emitters [11], and imaging devices [12]. However, the inherent resonant nature of metamaterials determines that the absorption bandwidth of MAs is usually narrow, which has thus restricted MAs from more extensive applications such as the energy harvesting. Efforts have been made to extend the absorption bandwidth through the concept of multiresonances [13–18]. Multiresonant broadband absorbers are generally realized by the elaborate blending of dimensionally dispersed metallic resonators either vertically [13–15] or horizontally [16–18]. Each resonator of the absorber resonates at a frequency slightly different from the others, and the superposition of all these resonances results in the broadband absorption. However, the designs in Refs. [13–15] need to precisely align several resonators between the layers, making the fabrication process very complicated; while the designs in Refs. [16–18] cannot broaden the absorption bandwidth significantly because it is quite difficult to arrange many different sizes resonators in one unit-cell. Although there are some other designs that have been proposed to obtain broadband MAs, such as the structure proposed by Wang et al. using the multiple plasmon resonances [19]. Nevertheless, up to now, almost all of the presented researches associated with the bandwidth extending have been focused on engineering the metallic resonators, while the important role of the constituent materials, especially the potential values of the dielectric layers has not been sufficiently illuminated.

In this paper, we present an alternative design for broadening the absorption bandwidth of MAs. The multiresonances composing the broadband absorption peaks are tuned by the magnetic responses originating from different dielectric layers. The resonant wavelength of each absorption peak is determined by the dielectric constant (ε_d) of the dielectric layer in the corresponding metal-dielectric-metal resonant stack, and the broadened absorption bandwidth is the synthetic effect by the excitation of all resonances in the multiple resonant stacks. In addition, the absorption magnitude of the proposed MAs are still very high even at large incident angles for both transverse magnetic (TM) and

* Corresponding author at: University of Electronic Science and Technology of China, China.
E-mail address: n.zhang.uestc@gmail.com (N. Zhang).

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transverse electric (TE) waves, which provide more efficient absorption for the nonpolarized and wide angle incident light.

2. Design method

In order to get an insight view into the resonant behavior of the MAs, we first explore the resonant wavelength as a function of ε_d by utilizing the equivalent circuit model. It is known that when light incident upon the MA, antiparallel current will be excited in the metallic resonator and bottom metal ground plane [9]. As a result, an electric current loop emerges. In this sense, one unit cell of the MA corresponds to a "closed" wire loop, which is often called a magnetic resonance because the magnetic moment resulted from the current loop can strongly interact with the magnetic field of incident light. The electric current loop can be mimicked by an LC equivalent circuit model [20]. The resonance absorption is realized when the frequency of the external light equals the eigenfrequency of these resonators. The eigenfrequency of the resonator can be quantitatively described by circuit elements of the LC equivalent circuit model, which depends on the geometrical parameters and dielectric properties of the MA. Here, we only consider the effect of varying ε_d on the resonant behavior. The singleband MA structure discussed in our LC equivalent circuit model is composed of square resonators as described in Fig. 1 (a) with ε_d varies from 1.5 to 3.3. The interaction between the upper Al resonators and the bottom continuous Al film can be represented by a parallel plate capacitor of $C_m=\varepsilon_0\varepsilon_d\sigma_{eff}/t_2$ and a parallel plate inductor of $L_m=\mu_0 d_{eff}t_2/(2d)$ where ε_0 is the permittivity of vacuum, $\sigma_{eff}=c_1d^2$ is the effective area of the square resonator where charges spread ($c_1=0.3$ was gotten by inspection as a numerical factor that accounts for the ends of the resonator covered with charges), t_2 is the thickness of the dielectric layer, μ_0 is the permeability of vacuum, $d_{eff}=d$ is the effective length of the resonator under which most of the magnetic field was trapped. The interaction between the neighboring resonators can be modeled as a gap capacitor with $C_g=\pi\varepsilon_0 d/\ln(g/t_3)$, where $g=p-d$ is the separate distance of the resonators, and t_3 is the thickness of the resonators. Therefore, total impedance can be expressed as

$$Z_{tot}=\frac{i\omega L_m}{1-\omega^2L_mC_g}+\frac{2}{i\omega C_m}+i\omega L_m, \tag{1}$$

where ω is the angular frequency [20]. Then eigenfrequency ω_r can be deduced from $Z_{tot}=0$, so

$$\omega_r=\sqrt{\frac{C_m+C_g-(C_m^2+C_g^2)^{(1/2)}}{L_mC_mC_g}} \tag{2}$$

We then calculated the dependence of resonant peak wavelength against the dielectric constant of the dielectric layer. In Fig. 1(b), it can be seen that the approximately linear increase of the resonant peak wavelength with the increasing of ε_d, showing the effective tuning of the resonant absorption. Considering the geometry and material parameters used here, Eq. (1) can be simplified as $\omega_r=1/\sqrt{L_mC_m}$, since $C_g\approx 0.1C_m$. Consequently, the resonant peak frequency is given by

$$f_r=\frac{c}{2\pi d\sqrt{c_1\varepsilon_d/2}}, \tag{3}$$

which shows that the resonant peak frequency of the absorption caused by the magnetic polaritions is determined by ε_d and d. As mentioned above, there are many works have been carried out to obtain the multiresonant broadband absorption by engineering the geometry parameters of the metallic resonators. From Fig. 1 (b) and Eq. (3), we can see that dielectric layer of the MA also provide an effective way to tune the absorption peak wavelength and have the potential to achieve the multiresonant broadband absorption.

Numerical simulations were also carried out with the CST microwave studio to verify the calculated results [21]. In the simulations, the complex permittivity of Al is described by the Drude model with the plasma frequency $\omega_p=2\pi\times 2895$ THz and the collision frequency $\omega_\gamma=2\pi\times 15.5$ THz [22]. Periodic boundary conditions were employed for the x–y plane, and a plane wave of TM polarization (with magnetic field H perpendicular to the x–z plane) was normally incident upon the structure as the excitation source. The frequency-dependent absorption was obtained from the S-parameters by $A(\omega)=1\text{-}T(\omega)\text{-}R(\omega)=1\text{-}|S_{21}|^2\text{-}|S_{11}|^2$, where $T(\omega)$ and $R(\omega)$ are the frequency-dependent transmission and reflection, respectively. Since the bottom metallic ground plane with a thickness of 200 nm is thick enough to suppress all the transmission light ($T(\omega)=0$), the absorption could be calculated by $A(\omega)=1\text{-}R(\omega)$. The simulated results were also plotted in Fig. 1(b). It is seen that the predicted absorption peak wavelengths are in good agreement with the results indicated by the LC equivalent circuit model.

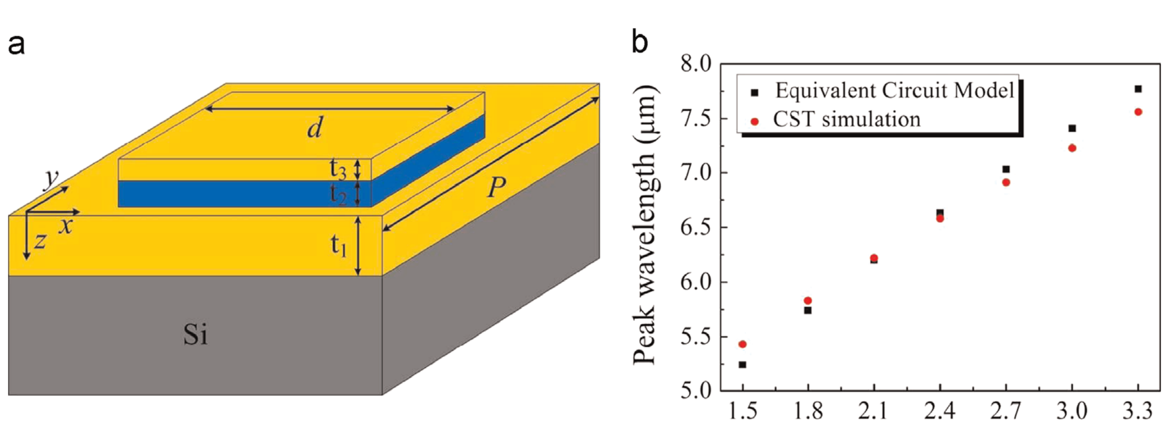

Fig. 1. (a) Schematic of the discussed singeband MA. The geometry parameters are as: period of the unit cell $p=2.4$ μm, diameter of the square resonator $d=1.7$ μm, thickness of the metallic and dielectric layers $t_1=200$ nm, $t_2=60$ nm, $t_3=40$ nm. (b) Comparison between the predicted absorption peak wavelengths by LC equivalent circuit model and results obtained from the CST simulations for ε_d varies from 1.5 to 3.3.