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Ultra-thin metamaterial absorber with extremely bandwidth for solar cell and sensing applications in visible region

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In this paper, we proposed a broadband and ultra-thin metamaterial absorber in the visible region. The absorber is composed of three layers, and the most remarkable difference is that the split ring resonators (SRR) made of metal stannum are encrusted in the indium antimonide (InSb) plane on the top layer. Numerical results reveal that a broadband absorption spectrum above 90% can be realized from 353.9 THz to 613.2 THz due to the coupling effect between the material of stannum and InSb. The metamaterial absorber is ultra-thin, having the total thickness of 56 nm, i.e. less than λ/10 with respect to the center frequency of the absorption band more than 90%. In addition, the impedance matching theory, surface current distributions, E-field and H-field are investigated to explain the physical mechanism of the absorption. The sensing applications are discussed and the simulated results show that the proposed absorber operates well with a good efficiency. Moreover, the visible absorber has potential applications in the aspects of solar energy harvest, integrated photodetectors and so on.

1. Introduction

Electromagnetic (EM) metamaterials (MMs) have been concerned during the past decade due to its ability to exhibit exceptional physical properties, such as negative refractive index [1], cloaking [2], cross polarization conversion [3,4]. Since the first MM absorber was proposed by landy et al. [5], metamaterial (MM) absorbers have stimulated the new research field, such as solar energy harvesting [6], sensor [7], pyroelectric detection [8], in term of their nearly perfect absorbance, polarization insensitive and wide-angle incidence. On the one hand, besides the widely incident angle and polarization insensitive, the absorption bandwidth of the MM absorber plays a crucial role in the design process. To increase the absorption bandwidth, researchers have tried their best and proposed several methods, such as using resistive film [9], stacking multilayer structure [10], applying magnetic medium [11] and loading with lumped elements [12]. However, all these methods are not still easy to implement. For example, it is very difficult to fit many different sizes of arrays in the same plane and complicated fabrication by using the multi-layer structure. The other way to realize broadband absorptivity is incorporating the lumped elements in the absorber. But incorporating lumped elements are not feasible in THz, IR or optical region. On the other hand, thickness of the MM absorber is another factor which should be carefully considered. Feng et al. demonstrated a broadband infrared absorber by engineering the frequency dispersion of metamaterial surface to minic an absorbing sheet [13]. However, the total thickness of the absorber is about 2.5 μm, i.e. about λ/4 with respect to the center frequency of high absorption above 90%. Moreover, Lee et al. presented an angle-insensitive, polarization-independent ultrathin (<150 nm) absorber in the visible regime exploiting strong interference behaviors in highly absorbing semiconductor materials this year [14]. However, it is desired and necessary to reduce the total thickness of the absorber.

MM absorbers are widely employed in research and development for energy harvesting and sensors. The most energy of solar radiation is located from 400 to 750 THz [15]. A MM absorber, with perfect absorption in this range, will be taken full advantage in the solar energy harvesting. For example, Patrick studied a perfect MM absorber with 99.99% and 99.90% at 543.75 THz and 663.75 THz [16]. However, the bandwidth with high absorption needs to be further broadened, in order to the better utilization of solar energy harvesting. Another interesting aspect is that accurate sensing of permittivity for different surrounding medium by using

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metamaterial absorber. In other words, a shift in the resonant peak position for a given absorber will determine the permittivity of the surrounding medium. In addition, Wide angle incidence, influence of temperature and the geometry parameter of the sensing medium must be considered carefully when it used as sensor.

In this paper, we proposed a broadband and ultra-thin MM absorber based on hybrid materials on the top layer. Numerical results show that a broadband absorption spectrum above 90% can be achieved from 353.9 THz to 613.2 THz due to the coupling effect between the material of stannum and InSb. The metamaterial absorber is ultra-thin, having the total thickness of 56 nm, i.e., less than λ/10 with respect to the center frequency of the absorption band above 90%. In addition, the MM absorber has the characteristic of high sensitivity, wide angle incidence when it is used as a sensor for permittivity measuring. Importantly, the idea of broadening absorption bandwidth also supplies a useful way for achieving broadband MM absorber in THz, infrared, even in the optical region.

2. Design and simulated

The absorber consists of three layers: a hybrid layer, a dielectric spacer and a metallic layer, as shown in Fig. 1. The top layer (hybrid layer) is a slot InSb plane and four split ring resonators (SRR) to be embedded in it. The gap between the slot InSb plane and the split ring resonator is 10 nm. SiO_2 is used as the dielectric layer to separate the metallic (stannum) layer and the hybrid layer. The dielectric constant and dielectric loss tangent of the dielectric are 3.9 and 0.025, respectively. The other parameters are given as follows: $t_1 = t_3 = 15$ nm, $t_2 = 26$ nm, $l_1 = 150$ nm, $l_2 = 130$ nm, $w = 50$ nm, $a = 520$ nm, $g = 5$ nm. The MM absorber is ultra-thin, having total thickness of 56 nm, less than λ/10 with respect to the center frequency of the absorption band more than 90%.

The simulation was performed with a commercial full-wall EM solver (CST Microwave Studio). The absorption ability can be calculated by $A = 1\text{-T-R} = 1\text{-}|S_{21}|^2\text{-}|S_{11}|^2$, where the A, T, R are absorption, transmittance and reflectance, respectively. Since the bottom layer is continuous metallic layer, absorption can be calculated as $A = 1\text{-}|S_{11}|^2$ and we can minimize the amplitude of the reflection for getting the maximize absorption rate. In addition, the effective impedance of the MA can be obtained from the effective medium theory [17,18]:

$$Z = \sqrt{\frac{\left(1+S_{11}^2\right)^2 - S_{21}^2}{\left(1-S_{11}^2\right)^2 - S_{21}^2}} = \frac{1+R}{1-R} \tag{1}$$

$$A = 1 - R = 1 - \frac{Z-1}{Z+1} = \frac{2}{Z+1} = \frac{2[\mathrm{Re}(z)+1]}{[\mathrm{Re}(z)+1]^2 + \mathrm{Im}(z)^2} - i\frac{2\mathrm{Im}(z)}{[\mathrm{Re}(z)+1]^2 + \mathrm{Im}(z)^2} \tag{2}$$

The MA can realize perfect absorption when the real part of the effective impedance matches the free-space value, $\mathrm{Re}(z) = 1$, and the imaginary part is close to zero, $\mathrm{Im}(z) = 0$ from the formula (2).

A simulated absorption and reflection spectra of the proposed absorber in Fig. 1(a) is described along with that of other two three-layer structures in Fig. 1(b) for comparison (i.e, metal-SiO_2-metal (MSM), InSb-SiO_2-metal (ISM)). As can be seen from Fig. 2(a), our proposed structure exhibits a much broadband absorption performance with the higher efficiency (>90%), which arose from three distinctive resonances appearing at 374.8 THz, 460.8 THz and 578.4 THz. The two absorption curves of the TE and TM modes are overlapped each other due to the symmetric structure, while the ISM structure shows only one resonance peak with a low absorption efficiency 81% at 547.6 THz. Moreover, a traditional dual band absorber can be easily achieved by using the MSM structure. However, in term of the MSM structure, the highest absorption efficiency is only 76% at 515.2 THz and the absorption band above 90% is very narrow as compared with that of our proposed structure.

The effective impedance is calculated and shown in Fig. 3. The real part of the impedance is near unity ($\mathrm{Re}(z) \approx 1$) and the imaginary part approach to zero, especially at the high absorption resonance points. Compared the cases of complete match ($\mathrm{Re}(z) = 1, \mathrm{Im}(z) = 0$), the value of reflectance at normal incidence are near zero. However, in our proposed absorber, the smallest reflectance is only 0.16 at the third resonance point (578.4 THz) shown in Fig. 2(a). Consequently, a small impedance mismatch of the imaginary part has a little influence on achieving complete absorption.

To further understand the physical mechanism of the broadband MM absorber, the analysis of the surface current on the top layer can be investigated at three distinct resonance points, which is shown in Fig. 4. The surface current present a symmetric distribution at the absorption peaks, which is similar to the electric LC resonator [19]. However, the strength of the current distribution in the three resonance points is distinct, especially in the 578.4 THz. In other words, the currents mainly concentrated in the every split resonance ring (SRR), rather than distributing in diagonal SRRs at the frequencies of 374.8 and 460.8 THz. Fig. 4(a_1)–(a_2) show that, for the TE mode at the low frequency resonance, the surface current on the metal SRR (top layer) mainly flows along the direction of the arrows, and that of the metal film (bottom layer) is unidirectional. Thus, parallel currents between two metal layers are formed and the electric resonance is excited. At the same time, the direction of

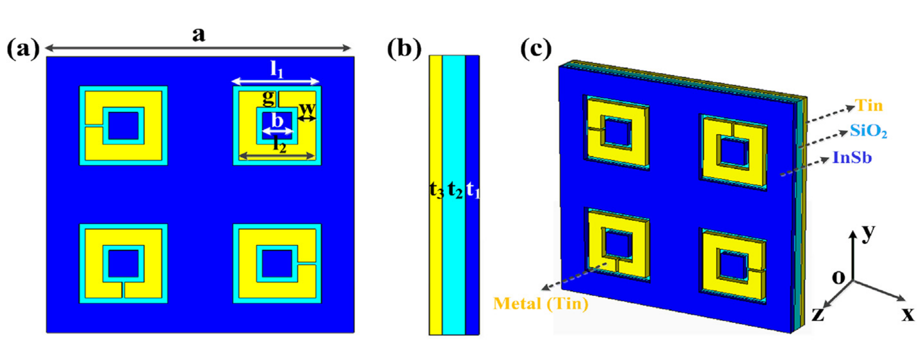

Fig. 1. Schematic representation of the unit cell of the three-layer metamaterial absorber (a) front view (b) left view (c) perspective view.