THz-metamaterial absorbers*

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Abstract
An ultrabroad-band metamaterial absorber was investigated in mid-IR regime based on a similar model in previous work. The high absorption of metamaterial was obtained in a band of 8–11.7 THz with energy loss distributed in SiO2, which is appropriate potentially for solar-cell applications. A perfect absorption peak was provided by using a sandwich structure with periodical anti-dot pattern in the IR region, getting closed to visible-band metamaterials. The dimensional parameters were examined for the corresponding fabrication.

Keywords: metamaterials, perfect absorber

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1. Introduction

In the last decade, artificial sub-wavelength materials, the so-called metamaterials (MMs), whose unit cell is devised to show unnatural electromagnetic (EM) properties applicable to advanced devices, have attracted great interest for research [1–7]. The manipulation of effective parameters for the artificial medium diversifies the application of MMs. One of them, the perfect absorption (PA), which is potentially used for sensing [8, 9] and solar energy [10], has become one of the significant issues related to MMs. The initial PA MM was demonstrated for the GHz regime by Landy et al [11] in 2008. To date, PAs have been developed in every relevant spectral range, from microwave [11, 12], THz [8, 9], near-IR [13], to the near-optical [10]. By controlling the refraction and the impedance z(ω) of MM, a PA of near unity can be realized at the resonant frequency. For different applications, the MM absorbers have been devised as a narrow peak [8, 9, 11], multi-band peaks or a broad-band [10, 12, 14]. Basically, PA is gained when the MM satisfies the following conditions; impedance matching with the environment leading to propagation of EM wave into the medium and high factors to dissipate the wave as heat. Based on the effective material parameters, the mechanism of PA peak can be explained. The parameters are the function of frequency of the 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 constants of unit cell, the real and the imaginary parts of the effective parameters could be controlled separately to satisfy the conditions of PA. The multi-band and broad-band MM absorbers are realized by configuring appropriately the unit cell for PA peaks [15] or by using the multilayer model of absorption [14]. It is noticed that there are many interactions between plasma in a configuration. Hence, it is not easy to combine broad-band MM absorbers with high efficiency, since the sensitive PA conditions are easily broken by these interactions. Therefore, the development of EM PA is still the significant issue in MM research.

In our paper, firstly, by expanding the previous work of Ding et al [14], the broad-band absorption with an efficiency of nearly 100% was demonstrated in mid-IR range of EM wave. Secondly, PA peak was provided by using a sandwich structure with periodic anti-dot pattern in the IR region. The EM properties of both cases were examined to interpret the mechanism of THz MM absorber.

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2. Results and discussion

2.1. Broad-band metamaterial absorber in mid-IR range

The simulation was carried out by using a finite-integration-technique package of CST Microwave Studio. The unit cell of MM is designed as in figure 1(a) [14]. The conductor is copper with an electric conductivity of $5.96 \times 10^7 \text{S m}^{-1}$. The insulator is SiO$_2$ with a relative dielectric constant of 3.2. The geometrical parameters were $a = 11.5$, $l_{\text{max}} = 9.0$ and $l_{\text{min}} = 5.5 \mu\text{m}$. The thicknesses of SiO$_2$ and metallic layers are 0.2 $\mu\text{m}$ and 36 nm, respectively. The EM wave is polarized such that the electric and the magnetic fields are parallel to the MM slab, and the wave vector $k$ propagates to the front side of MM (figure 1(a)). The boundary conditions were set so that the unit cell is periodic in the $E\text{-}k$ plane. The simulation was performed for free space. In the conventional absorber model, the absorption is calculated from the reflection and expressed by the $S_{11}$ parameter as $A(\omega) = 1 - |S_{11}(\omega)|^2$. The operating range of EM wave was from 5 to 16 THz.

Figure 1(b) shows the absorption spectrum of MM with highly broad-band (3.7 THz from 8 to 11.9 THz) absorption. The highest and the lowest absorption are nearly 100% at 8.58 THz (‘perfect absorption’) and 92.24% at 11.5 THz, respectively. It is noted that the broad-band absorption results from the combination of absorption peaks which correspond to cut-wire pair (CWP) [15] separated by SiO$_2$ layer. The successive arrangement of this sandwich structure along the wave-vector direction significantly reduces the EM interaction and then leads to a series of independent operations for different frequencies. However, to yield the absorption peaks at desired frequencies the lengths of CWP should be gradually reduced. This affects the absorption conditions of the structure. The impedance matching [11, 16] is not properly achieved for all the peaks. Therefore, the decrease of absorption occurs according to the resonance frequency as shown in figure 1(b). This trouble could be overcome by changing the materials for the MM, but it is a
new challenge for future fabrication in the higher-frequency modes.

The EM properties are presented in figure 2 to numerically clarify the mechanism of absorption. It is known that there are conventionally two plasmonic resonances responsible for the sub-wavelength absorption: electric and magnetic [16]. In figure 2(a), the distribution of the induced current at 8.8 and 10.5 THz exhibits anti-parallel flows, indicating that the absorption is responded to by the magnetic resonances. The contour of the induced magnetic energy in figure 2(b) illustrates more clearly the magnetic plasmon. This also elucidates that the major EM energy is dissipated in the capacitor created by the magnetic dipole mode. In other words, the dielectric loss is dominant in achieving the high performance of the PA structure [16]. The distribution of the power flow of EM wave also supports the argument of magnetically induced broad-band absorption. The EM energy is focused in the substrate layer and dissipated by the dielectric loss as magnetic dipole excitations as in figure 2(c).

We now discuss further the magnetic excitation modes inducing the dielectric loss in the MM absorption with SiO$_2$ substrate. It is seen that the broad-band in THz of high absorption of the MM has great potential for applications in solar energy. In particular, in this MM, the dissipation is a semiconductor (SiO$_2$). This shows promise for high-efficiency MM solar panels in the future. However, the operating frequency in mid-IR is a disadvantage of this broad-band absorption. In higher frequency (for example, visible range), the broad-band MM by the magnetic excitation modes is not able to guarantee in induction of the dielectric loss when the Ohmic-loss of conductor is dominant. In addition, the multilayer structure is a significant impediment in nano-fabrication.

2.2. Perfect-absorption peak in IR range

To develop the MM absorber with semiconductor substrate, we investigated a conventional sub-wavelength absorber structure with anti-dot pattern for the IR range of EM wave [17]. The design for the unit cell of MM is depicted in figure 3(a). The geometrical parameters were set to be $a = 475$, $r = 150$, $t = 68$ and $t_s = 15$ nm. $t$ and $t_s$ are the thicknesses of substrate and metal layers, respectively. The conductor is silver with an electric conductivity of $6.301 \times 10^7$ S m$^{-1}$. The insulator is silicon with a relative dielectric constant of 11.9. The boundary conditions are as aforementioned. The operating frequency range of applied plane-EM wave is 350–450 THz. The calculation of absorption and reflection from $S$-parameters was as in the above discussion.

The reflection and absorption spectra are plotted in figure 3(b) in the near-IR frequency range (350–450 THz). This shows a perfect-absorption peak with nearly no reflection at 395 THz. Two conditions for PA are satisfied by employing the cavity resonance [17].

![Figure 3. (a) Unit cell of MM absorber. (b) Absorption and reflection spectra of the PA MM. (c) Energy loss is focused in the Si layer.](image-url)
We further studied the origin of loss in the MM. The distribution of the power loss (absorption) of the THz wave was calculated for the absorption, as indicated in figure 3(c). It is concluded that the absorber can concentrate the EM wave in some specified locations (for example, in the semiconductor area), where the energy is significantly reinforced and subsequently converted into thermal energy, leading to a strong absorption. This is significant for future application to solar energy.

3. Conclusion

We investigated the absorption of the MM whose dielectric layers consisting of semiconductors (\(\text{SiO}_2\) and Si) in the THz range of EM wave. Firstly, broad-band MA was obtained in the mid-IR frequency range with multi-coupled CWPs. The average efficiency of the MM absorber is 95\% with capturing in the band of 3.7 THz. Secondly, IR PA MM was achieved by using the conventional absorber structure with anti-dot pattern. The absorption reaches nearly 100\% at 395 THz. In particular, the energy loss of both cases is focused in the semiconductor layer which will be applicable to solar MMs in the near future.

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References

[1] Shalaev M 2007 Nature Photon. 1 41
[2] Krishnamoorthy H N S, Jacob Z, Narimanov E, Kretzschmar I and Menon V M 2012 Science 336 205
[3] Watts C M, Liu X and Padilla W J 2012 Adv. Mater. 24 OP181
[4] Lu Y, Jin X, Lee S, Rhee J Y, Jang W H and Lee Y P 2010 Adv. Nat. Sci. Nanosci. Nanotechnol. 1 045004
[5] Lam V D, Tuong P V, Viet D T, Tung N T, Thuy V T T, Hong L V and Lee Y P 2010 Adv. Nat. Sci.: Nanosci. Nanotechnol. 1 045016
[6] Thuy V T T, Tung N T, Rhee J Y, Lam V D and Lee Y P 2011 Adv. Nat. Sci.: Nanosci. Nanotechnol. 2 015003
[7] Tung N T, Lievens P, Lee Y P and Lam V D 2011 Adv. Nat. Sci.: Nanosci. Nanotechnol. 2 033001
[8] Liu N, Mesch M, Weiss T, Hentschel M and Giessen H 2010 Nano Lett. 10 2342
[9] Niesler F B P, Gansel J K, Fischbach S and Wegener M 2012 Appl. Phys. Lett. 100 203508
[10] Aydin K, Ferry V E, Briggs R M and Atwater H A 2011 Nature Commun. 2 517
[11] Landy N I, Sajuyigbe S, Mock J J, Smith D R and Padilla W J 2008 Phys. Rev. Lett. 100 207402
[12] Cheng Y Z, Wang Y, Nie Y, Gong R Z, Xiong X and Wang X 2012 J. Appl. Phys. 111 044902
[13] Dayal G and Ramakrishna S A 2012 Opt. Express 20 17503
[14] Ding F, Cui Y, Ge X, Jin Y and He S 2012 Appl. Phys. Lett. 100 103506
[15] Dolling G, Enkrich C, Wegener M, Zhou J F, Soukoulis C M and Linden S 2005 Opt. Lett. 30 23
[16] Tuong P V, Park J W, Lam V D, Kim K W, Cheong H, Jang W H and Lee Y P 2012 Comput. Mater. Sci. 61 243
[17] Chanda D, Shigeta K, Truong T, Lui E, Mhi A, Schulmerich M, Braun P V, Bhargava R and Rogers J A 2011 Nature Commun. 2 479