Polarization-controlling dual-band absorption metamaterial

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Received 3 May 2013
Accepted for publication 3 June 2013
Published 25 June 2013
Online at stacks.iop.org/ANSN/4/035009

Abstract

We investigated sandwich structure of the conventional absorber metamaterials to expand the study on dual-band absorption in our previous work (2013 Appl. Phys. Lett. 102 081122). The advantages of the artificial structuring of plasmonic resonators or ‘meta-atoms’ were exploited to gradually enhance/degrade the absorption peaks by polarization angle of electromagnetic wave. By reshaping the rings at the font of slab, dual- or single-peak absorption is controlled. The absorber is demonstrated in the GHz region.

Keywords: metamaterials, perfect absorption

Classification number: 5.17

1. Introduction

Artificial sub-wavelength materials, so-called metamaterials (MMs) which show unnatural electromagnetic (EM) phenomena, such as negative refraction [1], EM-wave cloaking [2], super-lensing [3] and perfect absorption [4–7], have attained great interest in photonics and optics researches. Since the first negative-refraction medium was realized by Smith and co-workers [1], together with the development of nanotechnology, MMs have been presented in most of the EM-wave range from radio to visible [4, 6, 8, 9], and have produced many optical effects with high potential applications in plasmonic materials. Thanks to their artificial advantages, they have provided the turning points to develop useful extraordinary materials, leading to real devices sooner or later. Among them, ‘black bodies’, bodies with high-absorption properties were firstly realized by Landy et al [6] with the concept of sub-wavelength materials, that is, perfect absorber MM, and have come to be greatly important at present in many fields of science and technology. The perfect absorption (PA) of EM wave, no radiation passing through and none reflected, is gradually realized in plasmonic sensors [10] by exploiting their sensitive, efficient and controllable properties. Recently, the effects of EM polarization on absorptions in MMs have attracted attention because of possible use for tunable filters, detectors [10, 11] and optical switches [12] in the near future. By manipulating the polarization in MM, the embedded diode leads to switchable absorption in the GHz region [13]. Control of the distance between coupling components allows us to obtain the tunable dual-band perfect absorbers based on extraordinary optical transmission and Fabry–Perot cavity resonance [14]. The reshaping of MM elements, using micromachined actuators to devise the switchable dual-band absorption (DBA) at THz frequency, has been successfully realized in other work [15]. Polarization-insensitive and polarization-controlled dual-band absorption was demonstrated in both GHz and mid-IR regimes of EM wave by modifying the pattern on the surface of MM [7]. Progressively, polarization-controllable absorber MMs are being developed for relevant devices in the near future.

In current work we extensively examined polarization-controllable DBA which was presented partly in our previous work [7]. The sandwich structure of conventional absorber, metal–dielectric–metal layers, in which periodic couple rings at the front and metallic plane at the back were separated by FR-4 dielectric, was
designed to operate in the GHz regime of EM wave. Firstly, the outer rings are connected along the x direction to observe the polarization-controlling absorption at 12.8 GHz without any effect on the second peak. This showed a 90° polarization switching of the first resonance peak. Secondly, the polarization-controlling absorption is achieved at both resonances by horizontally designing the line through centers of rings in the x direction. According to polarization angle not only does the DBA disappear gradually but also a new peak is generated for the modified structure and comes to be perfect at a polarization of 90° of incident EM wave.

2. Results and discussion

The design of the sandwich-structure absorbers is illustrated in figure 1. The original structure includes a couple of metallic rings, and dielectric and metallic layers, which are arranged through the wave vector k (figure 1(a)). The couple rings are concentric circles with different radii and widths [7], placed on the x–y plane. The geometrical parameters were set to be $a = 7.0$, $w_1 = 0.2$, $w_2 = 0.8$, $d_1 = 4.6$ and $d_2 = 4.0$ mm. The metallic layer is that of copper with a thickness of 36 µm. The substrate was FR-4 with a thickness of 0.4 mm. The dimensions were chosen to exactly observe a resonance in a range of 12–20 GHz. More detail of the parameters can be found in reference [7]. The longest lattice constant is smaller than the center wavelength of the operating range of EM wave. The unit cells of modified MMs are demonstrated in figures 1(b) and 1(c). For the control of the first peak, the connection of outer rings in x direction was made with narrow bridges whose width is 0.15 mm (figure 1(b)). For the control of both peaks, centers are connected in the x direction with narrow wires whose width is 0.2 mm. The modified MM is expected to switch the absorption by polarization (figure 1(c)).

The simulations were performed by using a finite-integration-technique [16] package, CST Microwave Studio 2010. The unit cells and the polarization of incident EM wave are illustrated in figure 1. The simulation was done with the periodic boundary condition on the x–y plane. Planar EM radiation was polarized, as shown in figure 1(a) where the wave vector is perpendicular and goes to the front of the structure and the E and H fields are parallel to x and y directions, respectively. Polarization angle phi was rotated as in figures 1(b) and (c) from 0 to 90°. The simulation was performed in free space. According to the designed structure, EM wave is only reflected and absorbed when it is incident on the MM. The transmission is vanished by the metallic plane at the back with a thickness much larger than the skin depth (about 0.46–0.60 µm while the thickness is 36 µm) in operating frequency range. Therefore, the absorption can be calculated by using the scattering parameter of reflection: $A(\omega) = 1 - R(\omega) = 1 - |S_{11}(\omega)|^2$ [17]. The electric conductivity of metal was set to be $\sigma = 5.96 \times 10^{7}$ S m$^{-1}$ (real copper). The dielectric constant of nonmagnetic FR-4 was defined to be $\varepsilon = 4.2 + 0.018 i$, which corresponds to the experiments on the printed circuit board [6, 7, 15].

The original dual-band perfect absorption has been demonstrated in previous work [7] with polarization-insensitive properties, for which the structure in figure 1(a) was responsible. In this work, firstly we examined the absorption of modified MM according to phi, as illustrated in figure 1(b). In figure 2(a), the dual-band perfect absorption is obtained at a polarization angle of phi = 0. The high absorptions emerge at 12.8 and 17.1 GHz by exploiting the coupling of outer and inner rings with the copper plane, respectively. The first peak is weakened by rotating the angle to be larger without effect on the second one. This is eventually switched off at phi = 90°.

Figure 2(b) plots the absorption spectra according to polarization angle phi, of the MM structure for polarization control of both absorption peaks, and the configuration is shown in figure 1(c). The dual peaks of perfect absorption are also demonstrated at 12.8 and 17.1 GHz when phi is zero because of the same mechanism employed. As expected, the dual absorptions are gradually reduced up to 90° polarization of EM incidence. Interestingly, it is found that a new resonance, the third absorption, appears at 18.3 GHz and is concomitantly enhanced with weakening original DBA. The new one comes to be perfect at a polarization angle of 90°. This could be explained by a new resonance mode which is responsed by the coupling of connected rings (by connection wire) with metallic plane at the back.

We now clarify the resonances in order to further interpret the mechanism of DBA, and manipulation by the incident polarization. Figure 3 presents the behavior of EM wave to explain how they are absorbed perfectly in the MM slab at two resonances. The induced fields, as shown in figure 3(a), demonstrate that the perfect absorption peaks correspond, respectively, to the outer and the inner rings. By understanding
Figure 2. Spectra of (a) the polarization-controlling absorption at the first resonance (figure 1(b)) and (b) the polarization-controlling absorption at both resonances (figure 1(c)).

Figure 3. EM properties at each resonance (a) Distribution of induced field $E_z$, (b) power flow given by Poynting vector and (c) the distribution of loss energy.

the distribution of loss energy (figure 3(a)), which shows the dominance of dielectric loss, it is confirmed that the external magnetic field affects both resonances, which is typical for the perfect absorption effect in MMs at GHz frequency [18]. The power flow by Poynting vector (figure 3(b)) is a description of trapped EM wave, and shows that the energy is nearly dissipated inside the MM, which is the role of dielectric layer. It can be seen that the connection between rings through $E$ field releases the free electrons which are confined in the metallic patterns, or confine them in the other case. This is the reason for the polarization-switching absorption, and the tuning to another frequency. In other words, the polarization released or confined in ‘new’ MM in order to control the absorption effect.

3. Conclusions
We investigated the polarization-controlling absorption by artificially modifying the MM structure to manipulate the resonances for different purposes. The polarization-insensitive DBA MM was reshaped to be converted to the polarization-controllable absorber. Firstly, the peak at lower frequency is switched gradually with no influence on the other by outer-ring connection. Then, with another kind of modified MM, not only are two absorption peaks controlled, but also the third one emerges, and can be enhanced to be perfect by optimizing polarization. Finally, the EM properties were also studied to interpret the nature of the effects.
Acknowledgments

This work was supported by the Information and Communications Technology (ICT) Standardization program of Korea Communication Commission (KCC), by the Korean Ministry of Science, ICT and Future Planning (MSIP) though the Korea Communication Association, MSIP and Pohang Accelerator Laboratory, Korea, and the National Research Foundation funded by the MSIP (numbers 2010–0029418, 000712 (FY 2012) and 2012K1A2B2A07033424).

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