Sensors and Actuators A 231 (2015) 74–80

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Optically tunable metamaterial perfect absorber on highly flexible substrate☆

Xiaoguang Zhao[a], Kebin Fan[a], Jingdi Zhang[b], Huseyin R. Seren[a], Grace D. Metcalfe[c], Michael Wraback[c], Richard D. Averitt[b,d], Xin Zhang[a,*]

[a] Department of Mechanical Engineering, Boston University, Boston, MA 02215, USA
[b] Department of Physics, Boston University, Boston, MA 02215, USA
[c] U.S. Army Research Laboratory, Adelphi, MD 20783, USA
[d] Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA

ARTICLE INFO

Article history:
Received 16 April 2014
Accepted 10 February 2015
Available online 20 March 2015

Keywords:
Metamaterials perfect absorber
Optically tuning
Flexible
Terahertz

ABSTRACT

We present our recent progress on a highly flexible tunable perfect absorber at terahertz frequencies. Metamaterial unit cells were patterned on thin GaAs patches, which were fashioned in an array on a 10 μm thick polyimide substrate via semiconductor transfer technique, and the backside of the substrate was coated with gold film as a ground plane. Optical-pump THz-probe reflection measurements show that the absorptivity can be tuned up to 25% at 0.78 THz and 40% at 1.75 THz through photo-excitation of free carriers in GaAs layers in presence of 800 nm pump beam. Our flexible tunable metamaterial perfect absorber has potential applications in energy harvesting, THz modulation and even camouflages coating.

1. Introduction

During the past decade, electromagnetic (EM) metamaterials (MMs) have attracted considerable interest due to their unusual EM response and promising applications [2]. MM perfect absorbers (MPAs) have been considered as one particular and important branch of MMs enabling near-unity absorption in a thin slab with thickness much smaller than $\lambda/4$ [2,3]. Since 2008, a great number of examples of MPAs have been demonstrated in different frequency regimes, including microwave [4], terahertz (THz) [5], infrared [6], mid-infrared [7], near-infrared [8] and visible frequency [9].

Tunable metamaterials have shown the ability to manipulate EM waves to build modulators, sensors, detectors, and many other devices [10]. Routes to realize tunable MM include photo-excitation [11], electrical [12,13], phase change [14], and mechanical reconfiguration [15]. In our previous work [16], we demonstrated the fabrication and characterization of optically tunable metamaterials on a thin and flexible substrate. The gold MM unit-cells on GaAs patches were successfully transferred to 4 μm thick polyimide and we achieved 60% modulation depth at 0.98 THz with the pump beam power of 8 mW.

In the same vein, introducing dynamics into MPAs provides a new path toward exotic devices thus extending applications of MPAs for imaging, sensing, energy harvesting [17], spatial light modulators [18], and even camouflage of IR emission from detection [19]. Furthermore, the integration of tunable MPAs on ultrathin and flexible substrates enables high adaptability to wrap and fit on arbitrary surfaces for a range of practical applications.

Here, we report our progress on a novel flexible tunable perfect absorber in the THz regime. We used the semiconductor transfer process to pattern the MMs and GaAs patches on polyimide and coated the backside with gold thin film to construct the flexible tunable perfect absorber. Subsequently, the device was characterized by optical pump THz-probe spectroscopy. The modulation depth in absorptivity was measured as 25% at 0.78 THz and 40% at 1.75 THz when the pump beam power was 25.6 mW with original absorptivity of 84% and 99%, respectively. Our flexible perfect absorber may find applications in a variety of areas including camouflage coating, THz modulation and switching, energy harvesting, and chemical/biological sensors.

☆ This paper was presented at the 27th IEEE MEMS conference, held in San Francisco, CA, USA, January 26–30, 2014 [1], and is an expansion of paper in the Technical Digest of this meeting.

* Corresponding author at: Department of Mechanical Engineering, Boston University, 110 Cummington Mall, Boston, MA 02215, USA. Tel.: +1 617 353 2702; fax: +1 617 353 5866.
E-mail address: xinz@bu.edu (X. Zhang).

http://dx.doi.org/10.1016/j.sna.2015.02.040
0924-4247/

2. Design and fabrication

Our absorber makes use of photo-excitation of carriers in GaAs to dynamically control the response of electric split-ring resonators (eSRRs) overlying the GaAs patches. Fig. 1(a) schematically shows the tunable flexible perfect absorber photo-excited by an 800 nm optical pump beam. The unit cell of the absorber as shown in Fig. 1(b) is composed of a GaAs patch, a gold eSRR, polyimide spacer and gold ground plane. The array of GaAs patches and eSRRs composes the tunable MM, sandwiching the polyimide spacer along with the ground plane. The windows in each unit are intentionally fabricated to etch the sacrificial layer during the releasing of the flexible absorber.

The metallic eSRRs and ground plane together determine the effective electromagnetic properties (i.e. permittivity-ε_{eff} and permeability-μ_{eff}) of the perfect absorber. When the electric field of the incident THz wave is perpendicular to the capacitive gap in the eSRR structure, it will couple to the eSRR and excite the LC resonance that arise an effective permittivity. At the same time, the magnetic field generates circulating currents between the two metallic layers as shown in Fig. 2(a) and (b), resulting in an effective permeability. According to Fresnel's law, the reflectivity of a transverse magnetic (TM) polarized wave from the interface of air/MPA is

$$R_{TM} = |r_{TM}|^2 = \left| \frac{Z_0\varepsilon_{eff}\cos\theta - \sqrt{Z_M^2\varepsilon_{eff}^2 - Z_0^2\sin^2\theta}}{Z_0\varepsilon_{eff}\cos\theta + \sqrt{Z_M^2\varepsilon_{eff}^2 - Z_0^2\sin^2\theta}} \right|^2 \quad (1)$$

where $Z_M = \sqrt{[(\mu_0\cdot\mu_{eff})/(\varepsilon_0\cdot\varepsilon_{eff})]}$ is the effective impedance of the metamaterial perfect absorber, $Z_0 = \sqrt{(\mu_0/\varepsilon_0)}$ is the impedance of free space, and θ is the incident angle. For the normal incident condition, the reflectivity can be simplified as

$$R_{TM} = |r_{TM}|^2 = |(Z_M - Z_0)/(Z_M + Z_0)|^2 \quad (2)$$

With an appropriate geometric design, the impedance of the MPA can be matched with free-space around the resonant frequencies to eliminate the reflection; meanwhile, the ground plane ensures that the transmission (T) is negligibly small. The absorptivity can be calculated by

$$A = 1 - R_{TM} - T \approx 1 - R_{TM} \quad (3)$$

Fig. 2(c) shows the near-unity absorption is achieved at the LC resonance of a device optimized for normal incidence without transmission and reflection. Although the absorption degrades for oblique angles, it is possible to optimize the device for a particular angle by simply increasing the dielectric spacer thickness.

MPAs provide a new approach to construct absorbers, in which the permittivity and permeability can be engineered independently. That is, the absorption response can be easily tailored by modifying either the permittivity or permeability. Simply changing the capacitance in the eSRRs' gap can modify the resonant frequency, amplitude and phase of the reflection, thus altering the effective permittivity, ε_{eff}. If an optical pump beam is incident on our MM perfect absorber (as shown in Fig. 1), the free carriers will be generated in the GaAs patches due to photo-excitation, which can in turn lead to an increase in their conductivity. This will alter the ε_{eff} and cause a mismatch of impedance and higher reflection. Consequently, the absorption can be modulated in this fashion.

Fig. 3 shows the fabrication process of the flexible perfect absorber. Initially, a 300 nm sacrificial $Al_{0.95}Ga_{0.05}As$ layer and a 300 nm semi-insulating (SI) GaAs layer were epitaxially grown on a 2″ SI-GaAs wafer consecutively. Then, a 15 mm × 15 mm array

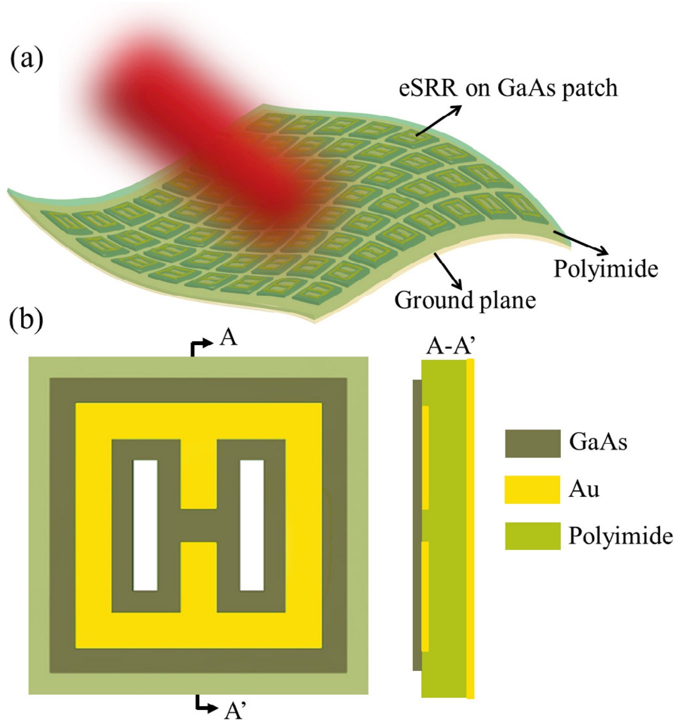

Fig. 1. (a) The illustration of flexible tunable MM perfect absorber illuminated by an 800 nm beam and (b) unit cell of the MM perfect absorber (top view and cross section view).

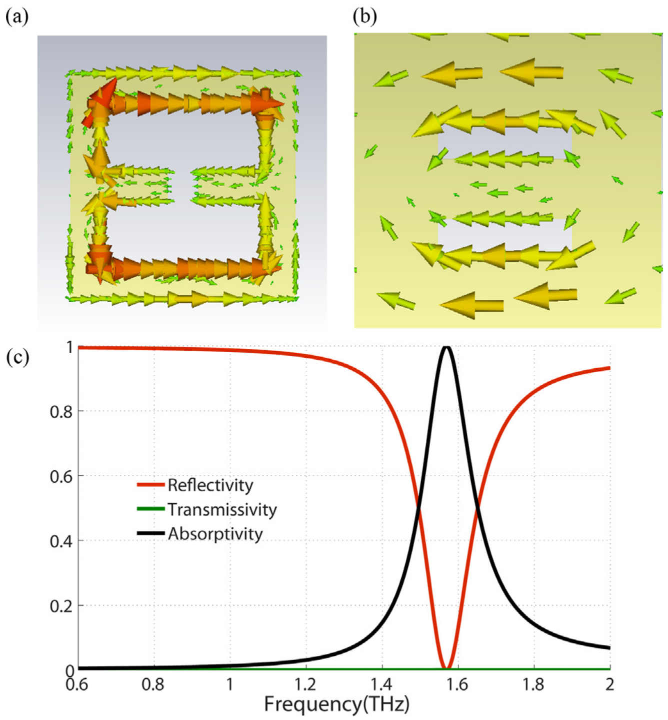

Fig. 2. (a) Simulated current distribution on the eSRR structure; (b) simulated current distribution on the ground plane; (c) simulated reflectivity (R: red curve), transmissivity (T: green curve) and absorptivity (A: black curve) of the tunable MM perfect absorber. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)