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Optically-controlled metamaterial absorber based on hybrid structure

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ABSTRACT

An optically-controlled metamaterial absorber based on a hybrid structure was investigated. Our hybrid absorber structure is a rectangular bar array with a period of 180 μm, fabricated on a 25 μm thick polyimide flexible substrate adhered to the surface of a high resistance silicon/polymer wafer. We varied the metamaterial structure and found that the length of the rectangular unit can modulate the resonant frequency, which was verified by experiments. The experimental results also show that the terahertz amplitude transmission spectra through the rectangular bar array decreased with increased laser power. As laser intensity surpassed 1.6 W/cm^2, the frequency-selected absorber changed to become a broad band absorber. These results indicate that alternative terahertz absorbers can be created using an optically-controlled metamaterial hybrid structure.

1. Introduction

Metamaterials (MM) have attracted enormous research interest since Pendry et al. performed the initial theoretical and experimental demonstrations of their fascinating electromagnetic (EM) properties [1]. Several metamaterial structures, including split-ring resonators [2–4], fishnets [5], cut-wire pair [6], and other stereo structures [7–8], have been proposed for the development of metamaterial theory. Metamaterial-based devices could have a large impact in the terahertz (THz) regime if the resonance response characteristics could be actively controlled to produce novel devices with real time modulation.

Recently, organic optoelectronic materials have emerged as a new material in the field of terahertz modulation because of their high quantum efficiency, low cost, and compatibility with inorganic semiconductors. Yoo et al. reported on terahertz transmission modulation through copper phthalocyanine-coated silicon (Si) under various laser light irradiation conditions [9–11]. Also, transmission through a split-ring resonator array metamaterial, fabricated on phthalocyanine-coated Si, can be efficiently modulated by laser irradiation. Our recent investigation of a conjugated polymer-based broadband terahertz wave modulator with pathways for various types of metamaterials is suitable for easy device fabrication by spin-coating technologies [12]. An optical modulator offering ease of processing is highly desirable for modulating the resonant frequency of a terahertz wave.

We investigated an optically-controlled metamaterial absorber based on a hybrid structure, in this study. The hybrid absorber structure is a rectangular bar (RB) array with a period of 180 μm, fabricated on 25-μm-thick flexible polyimide substrate adhered to the surface of a high resistance Si/polymer wafer. Simulations showed that the length of the rectangular unit can modulate the resonant frequency, which was verified by experiments. The modulated transmission properties of the metamaterial structures were measured using a terahertz time-domain spectroscopy system (THz-TDS) under external continuous-wave (CW) laser irradiation.

2. Experimental details

The metamaterial samples were designed and fabricated with 400 nm thick copper structures on a 25 μm thick flexible polyimide substrate by conventional photolithography techniques. The microscope image of the sample is shown in Fig. 1(a). A schematic diagram of the THz wave modulation experiment is shown in Fig. 1(b). Here, the periods of the symmetric cell in both directions are 180 μm. The width of the rectangular bar is 30 μm and the lengths varied as 100 μm, 110 μm, 120 μm, 130 μm and 140 μm, respectively. A spin-coating process using poly [2-methoxy-5-(2′-ethylhexyloxy)-1,4-

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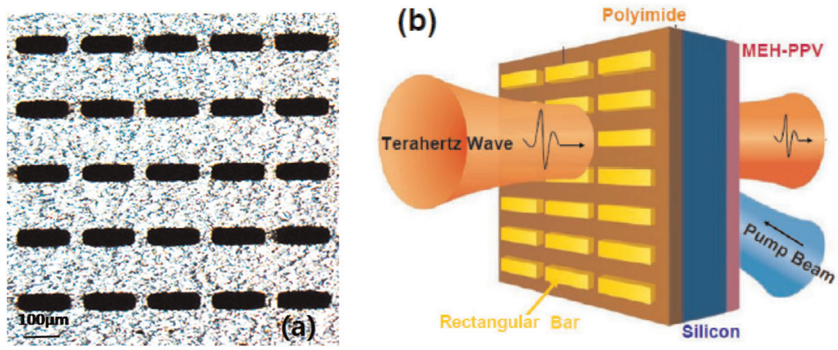

Fig. 1. (a) The microscopic photo of the metamaterial structure and (b) schematic diagram of the THz wave modulation experiment.

phenylenevinylene] (MEH-PPV) deposited the flexible metamaterial structure onto the surface of a high resistance Si (2 mm)/polymer (100 nm) wafer [13–14].

The flexible metamaterial structure itself can also be used to characterize the transmission properties in the experiment. A conventional THz-TDS system was used to measure the THz transmission characteristics through the MM/polyimide/Si/MEH-PPV hybrid structure under external CW laser irradiation, as shown in Fig. 1. The generated THz pulses had a normal angle of incidence to the hybrid structures, while the external CW diode laser had an oblique angle of incidence in the opposite direction.

3. Results and discussion

The simulated terahertz transmission characteristics were analyzed by the finite-difference time-domain (FDTD) method [15]. We adopted the RB array by surrounding it with a periodic boundary condition, and made the polarization of the incident wave perpendicular to the gap.

Fig. 2(a) shows that the simulated transmission characteristics of the RB array structure, in which the length of the rectangular bar L vary as 100 µm, 110 µm, 120 µm, 130 µm, and 140 µm, respectively. It can be seen from Fig. 2(a) that as L increased in length from 100 µm to 140 µm, the total attenuation frequency shift was lower by approximately 250 GHz. The modulation of the resonance frequency could be applied to produce band-stop filters in the terahertz region.

Once certain of our simulation results, we then hoped to verify them by experiments. The metamaterial samples were characterized by THz-TDS at room temperature at low humidity. The polarization of the linear polarized incident THz beam is perpendicular to the gap of the copper structures. The transmission characteristic of the RB array is obtained by $|T(\omega)| = |E_S(\omega)/E_R(\omega)|$, where $E_S(\omega)$ and $E_R(\omega)$ are Fourier-transformed frequency-dependent amplitudes of the terahertz electric fields with and without the structure, respectively.[15]

Fig. 2(b) shows that the measured transmission characteristics of the BR array structure, in which the length L of the rectangular bar varies as 100 µm, 110 µm, 120 µm, 130 µm, and 140 µm, respectively. Fig. 2(b) shows that the frequency at which the attenuation occurs shifts down from 1.04 T to 0.84 T and the value of the resonant frequency shift is 200 GHz. Compared with the simulation, the main effect on transmission characteristics is a small shift in the resonance peaks when substrate thickness changes.

Many theoretical and experimental results already shows that when a THz wave incidents upon the surface of a metamaterial, surface-plasmon polaritons (SPPs) can be resonantly excited. This is due to the metamaterial adjusted dielectric constant of metal, it actually realized function of artificial electromagnetic material. The resonance frequency is given by $f = \frac{c}{2L\sqrt{\varepsilon d}}$ [16], where c is the speed of light in vacuum, L is the lenghth of metal strip, and εd is dielectric constant of the sample substrate. Further analyzing this case, when THz wave incidents upon the surface of the metamaterial sample, the direction of the THz electric field is parallely to the metal strip of the metamaterial array. This is equivalent to exciting the metal strip by voltage, then creating countless electric dipoles, and the electric dipoles would launch another electromagnetic wave to generate electromagnetic resonance eventually. The above formula to calculate the resonant frequency still applies [17]. Using the dipole-electronic resonance mode, the resonant frequency for each rectangular bar length was calculated and is represented by blue triangles in Fig. 2(c). The similarity of the three results by simulation, experiment, and calculation, respectively, verifies that the dipole-electronic resonance mode is suitable to analysis the process of the interaction between THz wave and the metamaterial samples.

Next, we investigated the THz transmission characteristics of CW diode laser irradiation through a MM/polyimide/Si/MEH-PPV hybrid structure. Fig. 3 shows the THz amplitude transmission spectra through the RB array with a bar length of 130 µm with varying laser irradiation. The corresponding absorption approaches 0.9 THz as the laser irradiation of $I=0$ W/cm^2. With an increase in laser irradiation, the increased photo-excited charge carriers make the transmission weaker, resulting in an absorption increase. When the laser irradiation $I=3$ W/cm^2, the THz transmission decreased to zero and a broadband spectra absorber was created.

To evaluate the optical modulation performance of the absorber, the relative absorption factor (RAF) is introduced as

$$RAF(I_{laser}) = \frac{E_{THz-average}(I_{laser})}{E_{THz-valley}(I_{laser})}, \tag{1}$$

where $E_{THz-average}$ and $E_{THz-valley}$ are the average transmitted THz electric field within the frequencies in the experiment, and the transmitted THz electric field at the absorption frequency, respectively. Fig. 4 depicts the dependence of RAF of the 130 µm RB array on the modulation beam power. As shown in Fig. 4, the RAF decreases with an increase in laser intensity. These results indicate that a metamaterial absorber based on hybrid structure can react as a frequency-selected or a broadband absorber, and the relative intensity ratio for the frequency-selected absorber can be optically-controlled.

The terahertz transmission characteristics under various laser irradiations were analyzed using the FDTD method. Fig. 5 shows the simulated absorption spectra characteristics of the RB array with the bar length of 130 µm for different hybrid substrate (Si/MEH-PPV) conductivities, corresponding to different levels of pump laser power. The absorption frequency is 0.9 THz as the