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Terahertz spatial-shift modulation by photo-excitation of polymer/silicon hybrid structures

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ABSTRACT

A spatial shift of the terahertz wave reflected from a polymer/silicon hybrid structures was efficiently modulated by an external continuous wave laser. The intensity and mode of the terahertz reflected wave field change with period depending on the incidence angle of the terahertz wave. This dependence arises from the Fabry–Perot effect and matches the theoretical result. Compared with pure Si, larger spatial shifts can be obtained for the reflected terahertz wave from the MEH-PPV/Si sample in the single mode and multi-mode settings with 510 μm and 1190 μm attained, respectively, using the external laser. The results demonstrate what differentiates traditional intensity modulator is an active functioning terahertz spatial-shift modulator by photo-excitation of polymer/silicon hybrid structures.

1. Introduction

Terahertz (THz) technology has attracted much attention for applications, such as high-speed communications, spectroscopy, terahertz radar, and biological imaging [1–8]. The realization of active THz devices such as terahertz modulators is necessary to develop applications [9–14]. Many researchers have demonstrated the possibility of active control of the transmission, reflection, polarization, and phase of terahertz waves and spatial position [15–19]. To realize an optical intensity modulator of terahertz waves, the carrier density of the modulation material must be adjusted. Recently, active terahertz modulators with high modulation efficiency have be realized. They include those exploiting optically induced changes in the carrier concentration of heterojunctions made from metamaterials to generate the modulation, matching terahertz and energy levels by adjusting the energy separation of the electron bands, injecting electrons into semiconductor hetero-interfaces using external electrodes, artificial metamaterial resonance, and using the phase transformation of VO_2 to accomplish broadband terahertz modulation and the terahertz-wave absorption by plasma [20–31]. The investigation of spatial shift of terahertz waves usually focuses on the Goos–Hänchen shift by electrical and heat tuning. Recently, Liu et al. showed such shifts with graphene and exploited it to manipulate the lateral shift of terahertz wave [18]. Using an interference method, the temperature variation of the GH shift of terahertz waves from an aluminum surface has been obtained for temperatures between 26 °C and 101 °C in our previous work [19]. However, optical spatial shifts of terahertz waves have had scarce reporting but are of sufficient interest to warrant investigation.

In this work, the spatial shift of a terahertz wave reflected from the poly[2′-methoxy-5-(2′-ethylhexyloxy)-1, 4-phenylenevinylene] (MEH-PPV)/silicon interface was efficiently modulated by an external continuous wave (CW) laser. The intensity and mode of the terahertz reflected wave field varied periodically depending on the angular variation of the incidence terahertz wave. This dependence contrasts that with pure Si when illuminated by an external CW laser. What differentiates traditional intensity modulator is an active functioning terahertz spatial-shift modulator by photo-excitation of polymer/silicon hybrid structures.

2. Experimental details

For the structure of the device, the MEH-PPV film was spin coated onto a 2-mm-thick silicon wafer, with a high sheet resistance of

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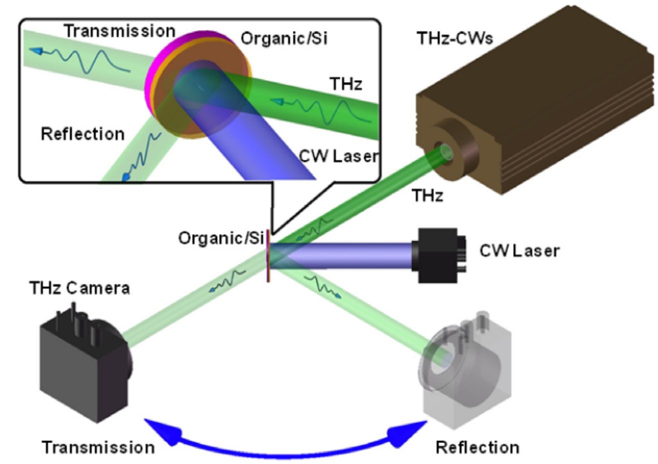

Fig. 1. Experimental setup that measure terahertz transmission and reflection from a polymer/organic interface illuminated by an external laser.

10,000 Ω/sq. The spin-coated polymer films about 100 nm thick were dried in a vacuum at 80 °C for 1 h. The energy band of the MEH-PPV matches that of silicon in carrier transitions. The spatial shift of the terahertz wave reflected on MEH-PPV/Si sample was measured using a terahertz continuous wave (CW) source produced by a CO_2-pumped THz laser (SIFIR-50 FPL Far-Infrared Laser System) with an output frequency of 3.1 THz. The experimental setup for measuring terahertz transmission and reflection enables measurements of the angle of the wave beam on the modulator, shown in Fig. 1. The terahertz wave was focused on an area of 0.25 mm^2 on the sample. The numerical aperture is approximately 0.052. The reflected or transmitted wave field was recorded using a pyroelectric-array camera (Pyrocam III Series) on or through the sample. The distance between camera and sample is about 50 mm. The variation in intensity and mode of the reflected wave field under changes in incident angle of the wave were also measured. The measurements of the spatial shifts of the reflected wave with external CW laser (450 nm) excitation from both the pure Si and the MEH-PPV/Si samples were taken.

3. Results and discussions

Fig. 2 shows that the variation in intensity and mode of the reflected terahertz wave field on incidence angle were measured. We remark that the reflected wave appears as a single spot (termed single mode) when the intensity is strongest and as multiple spots (termed multi-mode) when the total intensity of the reflection is weakest [see Fig. 2(a) and (b)]. Based on the isoclinic interference theory, the condition in constructive and destructive interference can be expressed by the equation:

$$2nd(1-\sin^2\theta/n^2)^{1/2} = k\lambda/2, k = 2, 4, 6, 8...... \quad (1)$$

$$2nd(1-\sin^2\theta/n^2)^{1/2} = k\lambda/2, k = 1, 3, 5, 7...... \quad (2)$$

where n is the refractive index of simple in terahertz, θ is the incidence angle of terahertz wave and λ is wavelength of 3.1 THz. The constructive interference occurred when k is even number. The destructive interference occurred when k is odd number. As the incidence angle varies, the intensity of the reflected wave field varies periodically [Fig. 2(c) and (d)] and the mode follow its changes [Fig. 2(e)]. The period of change corresponds to the 2-mm thickness of the Si-substrate. The interference pattern originated the first reflected wave and the second reflected wave which are on the upper surface and bottom surface of MEH-PPV/Si sample. When the two reflected waves satisfy the condition of constructive interference, the single-mode appears. When the two reflected waves satisfy the condition of destructive interference,

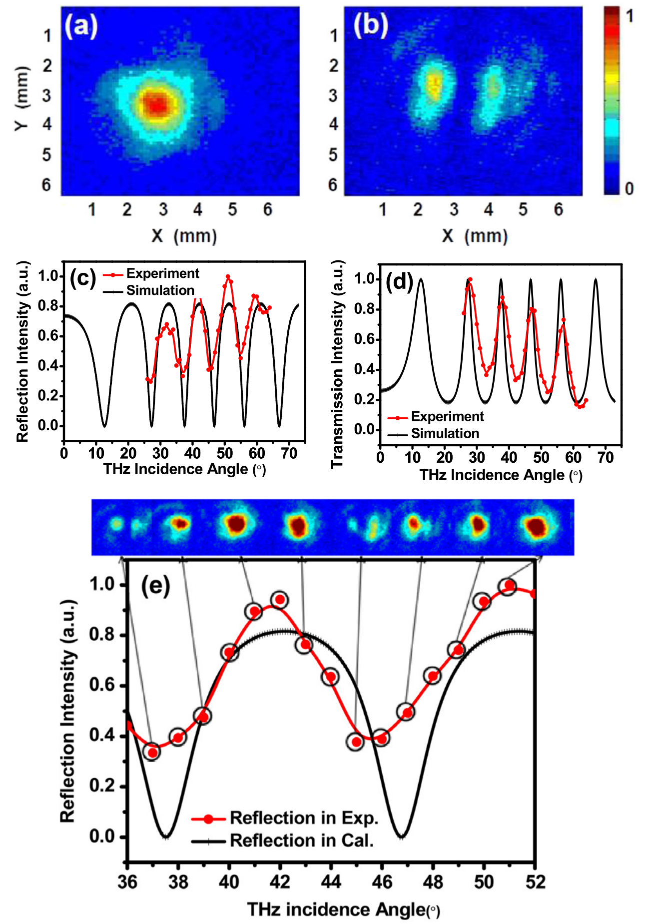

Fig. 2. Reflected terahertz wave field in (a) single-mode and (b) multi-mode; angular dependence of (c) reflection and (d) transmission power obtained from experiments and calculations; (e) Reflected terahertz wave intensity and the corresponding THz field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

no interference pattern is supposed to appear. However, the multi-mode appears due to the two reflected waves are divergent light which does not satisfy destructive interference in some areas of the receiving region rather than the ideal parallel light which satisfy destructive interference everywhere. Based on the Fabry–Perot effect, we calculated the intensities of reflection and transmission for a 2-mm-thick substrate [Fig. 2(c) and (d); black lines]. Compared calculated periods to the experimental measurements (red lines), both results are well matched.

Fig. 3 shows that the single mode of the terahertz wave was observed from reflection measurements at an incidence angle of 51°. As the optical excitation intensity was increased, a shift of the reflected spot was observed [Fig. 3(e)]. The spatial-shift distance is defined that is the THz field peak X-direction shift distance whether in single-mode or multi-mode. Fig. 3(a) shows reflected wave field from the MEH-PPV/Si structure without any optical excitation. Under a laser intensity of 0.7 W/cm^2, the center of field shifts 255 μm [Fig. 3(c)]. For the pure Si, Fig. 3(b) and (d) show in contrast no significant shift in applying a 4-W/cm^2 optical excitation. Moreover, the reflected field from the pure Si substrate did not move significantly with different laser irradiances [Fig. 3(e); black line]. In contrast, for MEH-PPV/Si structure, the reflected wave field shifted nonlinearly, moving laterally by 510 μm under a laser irradiance of 2 W/cm^2 at 3.1 THz [Fig. 3(e); red line].

Next, the multi-mode of the wave field was observed at the incidence angle of 45°. Fig. 4(a) shows the reflected wave field from the MEH-PPV/Si structure without any optical excitation. However, under a laser