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Surface plasmons based terahertz modulator consisting of silicon–air–metal–dielectric–metal layers

Wei Wang [a], Dongxiao Yang [a,b,*], Zhenhai Qian [a]

[a] College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China
[b] Research Center for RF and Photonic Information Processing, Zhejiang University, Hangzhou 310027, China

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ABSTRACT

An optically controlled modulator of the terahertz wave, which is composed of a metal–dielectric–metal structure etched with circular loop arrays on both the metal layers and a photoexcited silicon wafer separated by an air layer, is proposed. Simulation results based on experimentally measured complex permittivities predict that modification of complex permittivity of the silicon wafer through excitation laser leads to a significant tuning of transmission characteristics of the modulator, forming the modulation depths of 59.62% and 96.64% based on localized surface plasmon peak and propagating surface plasmon peak, respectively. The influences of the complex permittivity of the silicon wafer and the thicknesses of both the air layer and the silicon wafer are numerically studied for better understanding the modulation mechanism. This study proposes a feasible methodology to design an optically controlled terahertz modulator with large modulation depth, high speed and suitable insertion loss, which is useful for terahertz applications in the future.

1. Introduction

Active developments of generating and detecting terahertz (THz) wave have promoted great potential of THz technology in many applications such as imaging [1,2], communication [3,4] and biological detection [5,6]. However, the fundamental devices, such as THz modulator, are still backward in technique. As we known, modulator is a key device in communication system to control phase, amplitude or polarization state of the carrier. In the optical regime, active modulators are well established and considered standard devices, while there is still a great demand for highly efficient, reliable and versatile modulators in the THz regime [7]. Quite recently, major efforts have been devoted to developing THz modulators and a variety of schemes have been reported based on two dimensional electron gas [8,9], metamaterial [10,11] and graphene [12,13].

In previous work, X. Liu has theoretically and experimentally analyzed the transmission properties of the metal–dielectric–metal (MDM) structure etched with circular loop arrays on both the metal layers [14]. Due to the extraordinary optical transmission (EOT) caused by surface plasmon (SP) resonance, there are two transmission peaks in the frequency range from 0.27 to 0.34 THz. The transmission peak in the lower frequency range is dominated by localized surface plasmons (LSP), while that in the higher frequency range is dominated by propagating surface plasmons (PSP). The PSP peak is polarization-sensitive, which means its central frequency shifts with polarization state of the incident THz wave. However, the frequency shift is caused by structural asymmetry and cannot be tuned through external stimulus once the structure is fixed. Thus it is impossible to directly use the MDM structure to realize THz modulation.

In this paper, a THz modulator based on the MDM structure and a photoexcited silicon wafer separated by an air layer is proposed. According to the measured complex refractive index spectra of a high resistance silicon wafer, the simulated modulation depths of 59.62% and 96.64% based on LSP peak and PSP peak have been obtained, respectively.

2. Structural design and simulation

The THz modulator structure under consideration is shown in Fig. 1(a). It consists of a MDM structure and a silicon wafer separated by an air layer. Metal films deposited on edges of the silicon wafer are used to elevate the silicon wafer to form the air layer. The thicknesses of the air layer and the silicon wafer are $h_a = 1$ μm and $h_s = 20$ μm, respectively. A unit cell of the MDM structure is shown in Fig. 1(b). The dielectric substrate is quartz with relative permittivity of $\varepsilon_e = 3.61$ and

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[*] Corresponding author at: College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China.
E-mail address: dxyang@zju.edu.cn (D. Yang).

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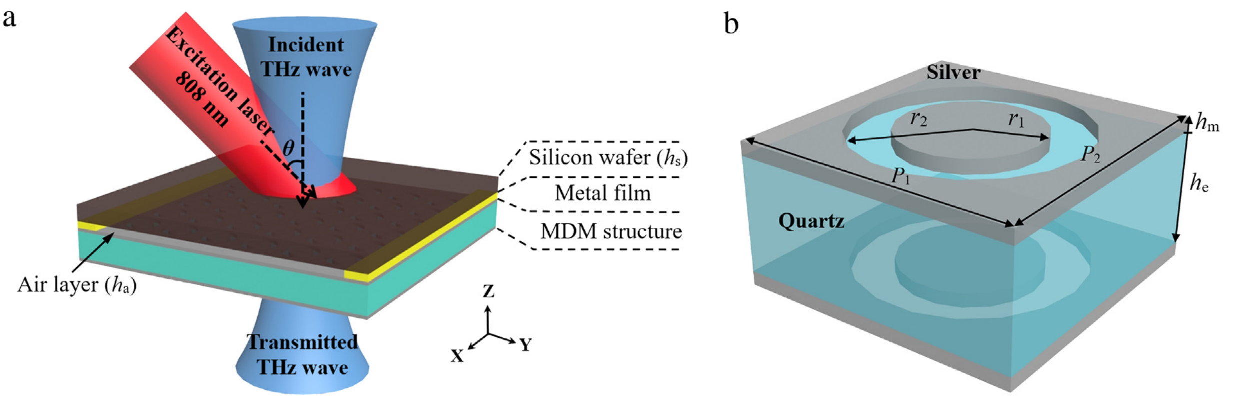

Fig. 1. (a) Schematic diagram of the THz modulator with structural parameters: $h_a = 1$ μm and $h_s = 20$ μm. (b) A unit cell of the MDM structure with structural parameters: $P_1 = P_2 = 480$ μm, $h_e = 290$ μm, $h_m = 1$ μm, $r_1 = 192$ μm and $r_2 = 216$ μm.

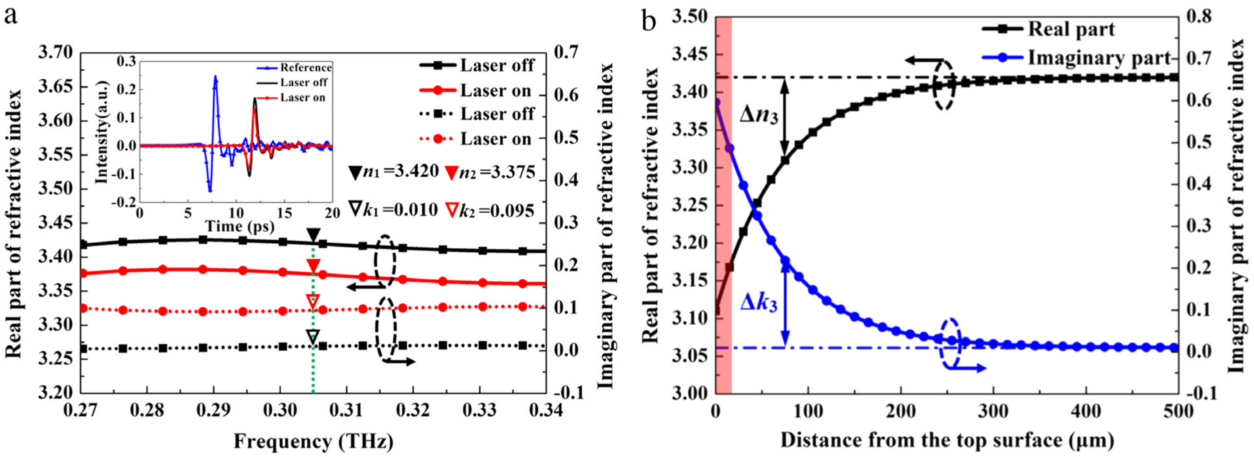

Fig. 2. (a) Complex refractive indexes of the high resistance silicon wafer obtained from THz-TDS measurements. Measured time-domain terahertz pulses are shown in illustration. The data at the frequency of 0.305 THz are obtained by fitting the adjacent data points and marked as inverted triangles. (b) Complex refractive index changes with the distance from the top surface of the silicon wafer when the laser power is 6 W. Complex refractive index with laser off is shown as dot dash line for reference. Region with thickness of 20 μm from the top surface is shaded in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

thickness of $h_e = 290$ μm. Both surfaces of the quartz are coated with silver films with thickness of $h_m = 1$ μm. The silver films are etched with the same periodic circular loop arrays with an inner radius of $r_1 = 192$ μm and an outer radius of $r_2 = 216$ μm. The periods along both x-axis and y-axis are set with the same value as $P_1 = P_2 = P = 480$ μm. The polarized THz wave with electric field component E_x is incident along negative direction of z-axis perpendicular to the modulator. A laser beam for photoexcitation is oblique incident with a small incident angle θ overlapping the THz wave in the silicon wafer. When the laser is turned on, complex permittivity of the silicon wafer changes immediately due to photo-induced carriers. As a result, transmission characteristics of the THz modulator in the interested frequency range change significantly, which can be used to realize modulation effectively.

Before simulation, it is necessary to obtain electromagnetic parameters of the silicon wafer. To the best of our knowledge, it is difficult to obtain a silicon wafer with thickness of 20 μm, even though similar thicknesses have been used by some other groups [15,16]. A high resistance silicon wafer with resistivity >10 000 Ω cm and thickness of 500 μm is used for measurements. The measurements are carried out using THz time-domain spectroscopy (THz-TDS) system and a continuous wave infrared laser at the wavelength of 808 nm with power of 6 W is used as excitation laser. Fig. 2(a) shows the measured complex refractive indexes of the silicon wafer. However, the measured complex refractive indexes are the average values of the whole silicon wafer. To extract photoexcited complex refractive index variations of the silicon wafer with thickness of 20 μm on the top surface (illuminated surface), analysis on propagation process of the laser is concerned. In the following, complex refractive indexes of the silicon wafer at 0.305 THz, as shown in Fig. 2(a), are used as the representative case to carry out the analysis considering that 0.305 THz is the center of the frequency range.

When the laser passes through the silicon wafer, it reflects at both interfaces (only first-order reflection is concerned due to the strong photoabsorption of silicon) and decays exponentially inside the silicon wafer. Thus:

$$I_{out} = I_{in}(1-R)^2 e^{-\alpha d} \qquad (1)$$

where I_{in} and I_{out} are the power of incident light and transmitted light, R is reflection coefficient of power, $d = 500$ μm is thickness of the silicon wafer, α is absorption coefficient at 808 nm. The reflection coefficient has been determined as 0.327 approximately according to Fresnel's equation at normal incidence, $((n_{silicon} - n_{air})/(n_{air} + n_{silicon}))^2$, where $n_{air} = 1$ and $n_{silicon} = 3.67$ at 808 nm [17]. The absorption coefficient has been determined as 13 775 m^{-1} according to the experimental data: $I_{in} = 6$ W and $I_{out} = 2.8$ mW.

Based on Eq. (1), laser power inside the silicon wafer as a function of the distance from the top surface is:

$$I_{Si}(\delta) = I_{in}(1-R)e^{-\alpha\delta} \qquad (2)$$

where I_{Si} is the power of laser inside the silicon wafer, δ is the distance from the top surface of the silicon wafer.

According to third-order nonlinear optical effect, variations of refractive index are proportional to the intensity of laser [18]. Thus complex