Optical-control terahertz modulator based on subwavelength metallic hole arrays

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Abstract: Terahertz modulator plays an important role in the development of terahertz technology. Optical transmission efficiency of subwavelength metallic hole arrays can be much higher because of the excitation of surface plasmon polaritons, and a higher modulation depth could be obtained by using this structure. A terahertz modulator based on subwavelength metallic hole arrays controlled by optical pump was demonstrated. Firstly, the principles of our sample were researched. Secondly, two-dimensional subwavelength metallic hole arrays were fabricated on semi-insulating GaAs substrate. Lastly, utilizing the terahertz time domain spectroscopy system, the transmission of terahertz radiation through subwavelength hole arrays was measured. Experimental results show that extraordinary optical transmission is excited by subwavelength hole arrays, and optically pumping reduces the terahertz transmission. A higher modulation depth is obtained at special frequency. This research can be the reference to the design and fabrication of terahertz modulator with high modulation depth.

Key words: terahertz modulator; subwavelength metallic hole array; surface plasmonpolaritons

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基于亚波长金属孔阵列的光控太赫兹强度调制器

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摘 要: 太赫兹波强度调制器对太赫兹技术的发展至关重要。亚波长金属孔阵列可以激发表面等离子激元,增加入射电磁波的透射效率,极大地提高调制器的调制深度。提出了一种基于表面等离子激元的光控太赫兹波强度调制器。首先给出了器件所依赖的基本原理;其次利用传统的微纳加工技术在半绝缘砷化镓衬底上制作出二维亚波长金属孔阵列;最后搭建了太赫兹时域光谱系统,测试了器件样品对太赫兹波的透过率。结果表明:亚波长金属孔阵列可以引起透射率的异常增强,且透射率随着泵浦光强的增大而减小,在特定频率点实现了较高的调制深度。此研究为实现高调制深度的太赫兹波强度调制器提供了参考。

关键词: 太赫兹波强度调制器; 亚波长金属孔阵列; 表面等离子激元

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0 Introduction

Terahertz wave has an extensive perspective in both short-range wireless communications and data transmission of high-speed and high-bandwidth. However, the terahertz wave has not been fully exploited in electromagnetic spectrum[1]. As one of the key components to realize active control of terahertz radiation, terahertz modulator is essential not only for terahertz communication, but also for other fields such as terahertz imaging, terahertz sensing, the development of terahertz modulator is of great value for the practical process.

Since T. W. Ebbesen et al.[2] reported the phenomenon that subwavelength hole arrays can excite surface plasmon polaritons(SPPs), causing extraordinary optical transmission, applying this structure to terahertz modulator has attracted great attention. Switching of the SPPs has been demonstrated using external controls including magnetic[3], electric[4], and thermal[5] techniques, but these methods either can't obtain a high modulation depth, or just support modulation in a low speed. E. Hendry et al.[6] have applied an optical technique on silicon-based periodic metallic holes. A. K. Azad et al.[7] achieved optical control of terahertz radiation at room temperature by fabricating subwavelength hole arrays on GaAs substrate.

In this work, we present a terahertz modulator based on subwavelength metallic hole arrays controlled by optical pump, and measure its performance. This kind of device has a small planar and simple structure with the advantages of low cost and simple fabrication.

1 Principle

SPPs are surface electromagnetic oscillations, excited at the interface between metal and dielectric (air) when the incident electromagnetic wave illuminates the surface of metal. And the electric field perpendicular to the surface decays exponentially with distance from the surface[8]. Thus, SPPs is a kind of surface wave, and its electromagnetic field is restricted near the metal-dielectric interface.

The wave vector of SPPs on a planar metal-dielectric interface is given by:

$$k_{spp}=\frac{\omega}{c}\left(\frac{\varepsilon_d\varepsilon_m}{\varepsilon_d+\varepsilon_m}\right)^{1/2} \tag{1}$$

where c is the speed of the light in vacuum; ω is the angular frequency of incident light; and ε_m, ε_d are the relative dielectric constants of the metal and dielectric, respectively.

It is obvious that the wave vector or momentum of SPPs is larger than that of freely propagating light of the same frequency. Momentum matching could be achieved using subwavelength metallic hole arrays that are considered as a form of two-dimensional grating that provides appropriate tuning of the in-plane momentum to excite SPPs. Then the component of the wave vector along the interface is given by:

$$k_x=\frac{\omega}{c}\sqrt{\varepsilon_d}\sin\theta\pm m\mathbf{G}_x\pm n\mathbf{G}_y \tag{2}$$

where θ is the incident angle relative to normal; m and n are integer numbers; $\mathbf{G}_x$, $\mathbf{G}_y$ represent the grating wave vectors and $\mathbf{G}_x=\mathbf{G}_y=2\pi/L$ for a square lattice where L is the period of the hole arrays. In the case of normal incidence, the resonant wavelength excited by subwavelength metallic hole arrays can be written as[9]:

$$\lambda_{spp}=\frac{L}{\sqrt{m^2+n^2}}\sqrt{\frac{\varepsilon_d\varepsilon_m}{\varepsilon_d+\varepsilon_m}} \tag{3}$$

As shown in Fig.1, a photoconductive layer is formed on the top of the substrate under the pump beam[7], and therefore the substrate shows stronger metallic properties, reducing the transmission of the

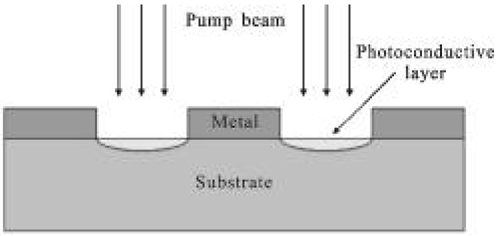

Fig.1 Schematic diagram of optical control

incident light. With this method, the optical-control of optical transmission could be realized.

2 Structure and process of sample

The schematic diagram of the structure of the terahertz modulator we demonstrated is depicted in Fig.2.

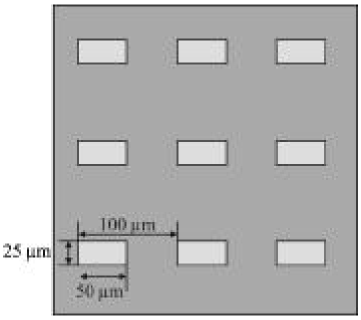

Fig.2 Schematic diagram of sample structure

The orange portion represents the metal(Al) film, when the gray areas represent the location of the metallic hole arrays.

Our sample was fabricated using conventional process. And the flowchart for process is shown in Fig.3.

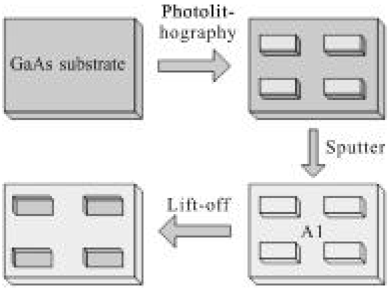

Fig.3 Flowchart for process

Firstly, we got the period rectangular holes of dimension 50 μm ×25 μm patterned in a square array with a lattice constant of 100 μm by standard photolithography. Then we sputtered the Al (200 nm) film on the substrate. And the subwavelength metallic hole arrays were fabricated on the substrate through the lift-off process lastly.

The image of our sample was shown in Fig.4, where the light portion represents the Al film, and the dark portion stands for the exposed GaAs substrate.

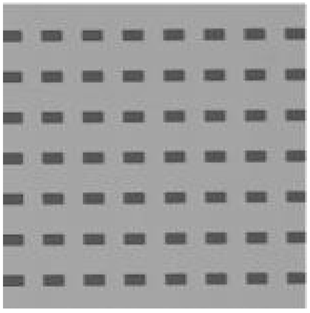

Fig.4 Microscopic image of sample

3 Experiment and analysis of results

The transmission of terahertz radiation through our sample was measured using terahertz time-domain spectroscopy (TDS). The experimental setup is illustrated in Fig.5.

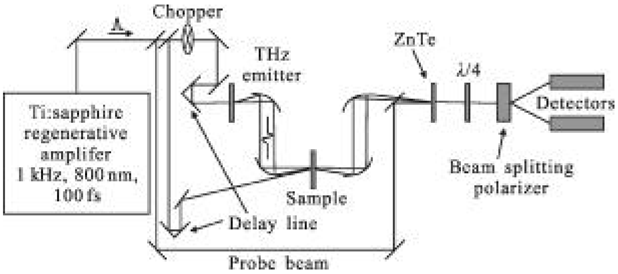

Fig.5 Schematic diagram of terahertz time domain spectroscopy

The terahertz TDS used in this experiment utilizes a 1 kHz regeneratively amplified Ti:sapphire laser capable of generating 1 W, 100 fs pulses at 800 nm. Part of the output laser power is used for terahertz generation by exciting air plasma; and part of the output is used for terahertz detection using ZnTe crystals. The remainder of the femtosecond laser power passes through a variable attenuator to form a ~5 mm diameter illumination spot on the sample to excite carriers in the substrate. The transmission of terahertz radiation could be changed via adjusting the attenuation ratio.

We measured the terahertz time-domain signal through air $\mathbf{R}(t)$ as reference at first. Then we detected the terahertz time-domain signal through our sample $\mathbf{S}(t)$ with different pump powers. And we can get their transmission spectrum $\mathbf{R}(\omega)$, $\mathbf{S}(\omega)$ by Fourier transform, respectively. Figure 6 shows the terahertz transmission

$\mathbf{T}(\omega)=|\mathbf{S}(\omega)/\mathbf{R}(\omega)|$ through the metal hole arrays.

In Fig.6, measurements show pronounced surface plasmon resonances of the [1,0] and [1,1] modes at 0.76 THz and 1.04 THz, respectively. Without optical excitation, the peak amplitude transmission of [1,0] SPPs resonance is 8.84% relative to the air. The transmission drops under photo excitation because of the creation of a photoconductive layer on the surface of the GaAs substrate. The amplitude transmission at the resonance frequency drops to 7.44% with an optical pump power of 100 mW. The intensity modulation depth can be defined as $(\mathbf{T}_0^2-\mathbf{T}_{pump}^2)/\mathbf{T}_0^2$, where $\mathbf{T}_0$ and $\mathbf{T}_{pump}$ are the amplitude transmission without and with pump. We obtained 29.1% modulation depth with an optical pump of 100 mW.

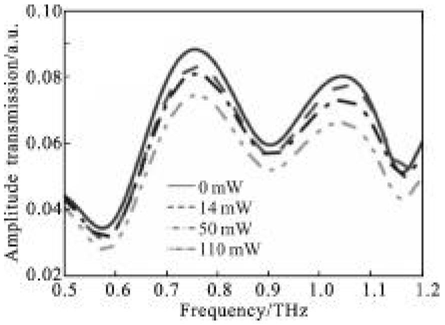

Fig.6 Terahertz amplitude transmission through sub wave length metallichole arrays with different pump powers

The measured peak transmission positions are basically consistent with the theoretical expectations. However, the modulation depth we have obtained was on a low level. The reason may be that the GaAs substrate is not pure enough. Thus the substrate contains a certain amount of carriers, which drops the peak transmission of SPPs resonancewithout optical fluence.

4 Conclusions

We demonstrated a terahertz modulator based on subwavelength metallic hole arrays controlled by optical pump. The transmission of terahertz radiation through 2D periodic holes was measured. We observed the SPPs resonance at 0.76 THz, and obtained an intensity modulation depth of ~29.1% with an optical pump of 100 mW, achieving the modulation of terahertz radiation in a low pump power. Our results supports the feasibility that applying SPPs to terahertz modulator. We will optimize the structure parameters and improve the process technology to improve the performance of our devices in future. Our research can provide reference for the design and fabrication of the optical control terahertz modulator.

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