Terahertz Attenuator Based on the Sub-wavelength Metal Structures

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Abstract — **In this paper, we present a THz attenuator based on the sub-wavelength metal s tructures. The T Hz attenuator is designed and fabricated on a copper foil. We measured TH z transmission of the at tenuator by means of terahertz time domain spectroscopy. The experimental results s how th at the attenuator ca n h ave a good frequency selectivity which depends on the polarization of THz radiati on. T Hz power can be atten uated continuously into any level at a certain THz frequency without changing the polariz ation and c oherence of T Hz beam. Its attenuated frequency is designable by ch anging the size and shape of metal s tructures. The frequency selective transmission of th e attenuator is determined experimentally. We belie ve that our r esults suggest a valuable T Hz component fo r THz a pplication, in particular, for THz space instruments.**

Keywords: Terahertz, Attenuator, Metal, Structure

Introduction

In recent years, terahertz (THz) optical components have been paid more and more attention. This is due to two reasons. One is from the technological needs of THz applications. Another is from the physics of THz devices. The surface plasma polaritons of metal have attracted much attention of scientists and engineers over the world. THz photonic components based on the sub-wavelength metal structures have been regarded as a potential candidate of THz devices.

Ever since 1998 Ebbesen *et al* [1] discovered the extraordinary optical transmission through sub-wavelength periodic of thin metal film, the physical origin of enhanced transmission has been investigated by huge experimental and theoretical work. The enhanced transmission exceed the limit of conventional electromagnetic wave theory [2], the numeric value exceed several magnitude relative to conventional aperture theory [3]. Such extraordinary enhanced transmission is often explained by two representative views: one regarded that it is induced by the resonant interaction between incident light and Surface Plasmon Polarizations (SPPs) on the metal surface [4-7], but it can not explained the wavelength of enhanced transmission occurs red shift with the increase of the thickness of metal film [1]. The other hold that it is caused by like F-P cavity effect [8, 9]. Such high enhanced transmission is very attractive for several potentials applications in nanometre scale and high efficiency electrical-optical device and large density numeral store, such as electrical-optical modulator, near-field microscope, photolithography technology and new type of optical integrated component. Therefore, the research of physical origin of the enhanced transmission has got more and more attentions.

As for optical device, manipulating and controlling light by photonic crystals is very attractive. In certain cases, metals tend to play an important role in photonic crystals. Particularly, a two-dimensional metallic photonic crystal (2D-MPC), which is perforated periodically with circular holes, has been known as a band-pass filter in the millimetre and far-infrared regions [10, 11]. At 2003, Fumiaki Miyamaru *et al*. [12] studied the interesting polarization characteristics of two-dimensional metallic photonic crystal (2D-MPC) through THz time-domain spectroscopic system, their studies indicates that in sub-terahertz region, 2D-MPC not only as band-pass filter, but also as a wave plate, the linear polarization of the THz wave transmitted through 2D-MPC becomes elliptical with a slight tilting of the incident angle from the normal incidence. At 2004, Fumiaki Miyamaru *et al.* [13] also found that the frequency range at which the polarization rotation occurs is related to the lattice constant of a photonic crystal, indicating the importance of photonic band modes of the 2-D MPC in the mechanism of the phenomenon. At 2004, R.Gordon *et al.* [14] investigated the strong polarization dependence of optical transmission through elliptical nanometre ring. Their results show that the degree of polarization is determined by the ellipticity and orientation of the holes, the polarization axis lies perpendicular to the broad edge of the ellipse. At 2006, Jean-Baptiste Masson *et al.* [15] investigated two overlapping arrays of orthogonally oriented sub-wavelength elliptical holes over 0.1-1THz range. Their experimental result shows that the enhanced transmission exhibits polarization sensitive frequency shift. At 2004, Cao Hua and Ajay Nahata [16] also refer to the polarization property of rectangular holes with different aspect ratio, but they mainly describe the effect of hole's shape to the transmission and do not consider the polarization property profoundly. In this paper, we investigate the polarization dependence of enhanced transmission through the period array of rectangular holes with different aspect ratio of length to width. The polarization dependence of sub-wavelength metal structures has the potential for many applications, such as band-pass filter and wave plate in the THz frequency region.

I. Experiment Setup and Sample Preparation

Our experiment setup used in this research is a type of THz Time-Domain Spectroscopy (THz-TDS) system. The schematic diagram of THz-TDS setup is shown in Figure 1. A repetition rate of 82 MHz, diode-pump mode-locked Ti:Sapphire laser (Mai Tai, Spectra-Physics) provided the femtosecond pulses with a pulse duration of 100 fs and the centre wavelength of 810 nm. The femtosecond beam is divided into two beams: one is used as a pump beam, another as a probe beam. A p-type InAs wafer with <100> orientation is used as the THz emitter. A 1mm-thick of <110> ZnTe crystal is employed as the sensor. The pump beam is used to generate THz radiation and the probe beam acted as a gated detector to monitor the temporal waveform of THz field. A silicon lens and four parabolic mirrors are used to collimate and focus the THz beam through the free space onto the detector. A balanced photodiode detector detected the probe beam. The measured signal is amplified by a lock-in amplifier and sent to the computer for the data processing and analysis. The THz beam path as the dashed line frame in Fig. 1 is purged with the dry nitrogen to minimize the absorption of water vapour and enhance the SNR. The spectral resolution is better than 50 GHz. The effective range of frequency is 0.2-2.5THz. The temperature is keep around 21.2^{o}C. The relative humidity is keep at 3.6% in this experiment.

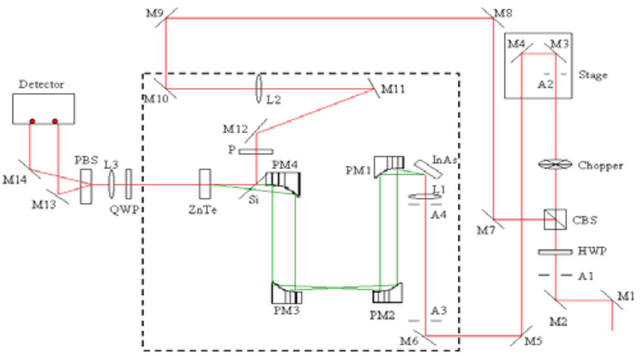


Fig.1 Schematic Diagram of THz-TDS System
M1~M14: mirrors; CBS: cubic beam splitter; L: convex lens; PM1~PM4: parabolic mirrors; PBS: polarized beam splitter; HWP: 1/2 wave plate; QWP: 1/4 wave plate.

We design a set of periodic array of rectangular holes with different aspect ratio of length-to-width. Our design principle is to change the aspect ratio of rectangular holes while keeping their area (~22500 μm^2) and the period of their lattice as a constant. We design totally five periodic arrays of rectangular holes. The aspect ratio of length-to-width for single rectangular hole are 1:1, 1.5:1, 2:1, 2.5:1, 3:1, respectively. The array patterns of rectangular holes are fabricated by the cut of YAG laser on a 100um thickness of copper film. The specification of the five rectangular holes array with different aspect ratio is designed as in table 1.

TABLE 1
Sample Parameter of Structures

Sample	Parameters of Structure (μm)		
	a:b	**a (μm) b**	**(μm)**
1	1:1	150	150
2	1.5:1	184	122
3	2:1	212	106
4	2.5:1	236	95
5	3:1	260	86

In Table 1, *a* represents the length of a single rectangular hole, and *b* as the width of a single rectangular hole. The *a:b* is the aspect ratio of a single rectangular hole. We designs the period of rectangular holes array *T* as 425 μm, which is the spacing between the centres of two adjacent rectangular holes. The thickness of copper foil used is 100 μm.

II. Data Extracting of THz Transmission Spectrum

Terahertz time-domain spectroscopy (THz-TDS) can provide the information of THz electric field of incident and transmitted THz wave including amplitude and phase. By means of Fast Fourier Transform (FFT), we can obtain the frequency-domain transmission spectra $E_{reference}$ (f) and $E_{transmitted}$ (f) as, respectively, the incident and transmitted THz field. Therefore, the transmission coefficient of sample can be extracted as follows

$$T(f) = \frac{E_{transmitted}(f)}{E_{reference}(f)}, \tag{1}$$

Here *T(f)* is the transmission spectrum. The transmission coefficient as a function of frequency indicates the amplitude and phase of transmission ability of THz radiation through the periodic array of rectangular holes on the copper foil. So we obtain THz transmission spectrum by means of FFT and from the THz-TDS measurement.

III. Experiment Results and Discussions

Using a THz time domain spectroscopic system (THz-TDS), we can measure directly the temporal waveform of reference signal and sample signal. After Fast Fourier Transformation (FFT), we can obtain the corresponding frequency spectrum. After that we can extract out the transmission spectrum of samples by keeping the incidence angle as a constant ϕ =0^{o}, that is the case of normal incidence, and varying the azimuth angle θ, where θ is the angle between THz polarization and the long side of rectangular holes. Through measuring the signal of the sample every 15^{o} of azimuth angle, we can get transmission spectrum at different azimuth angle. Figure 2 presents the transmission spectrum of rectangular holes array with the aspect ratio of 2:1, that is the sample 3 at different azimuth angle θ=0°, 15°, 30°, 45°, 60°, 75°, and 90°. Other samples show the similar properties of THz transmission except for the sample 1 with the structure of square hole shown as figure 3.

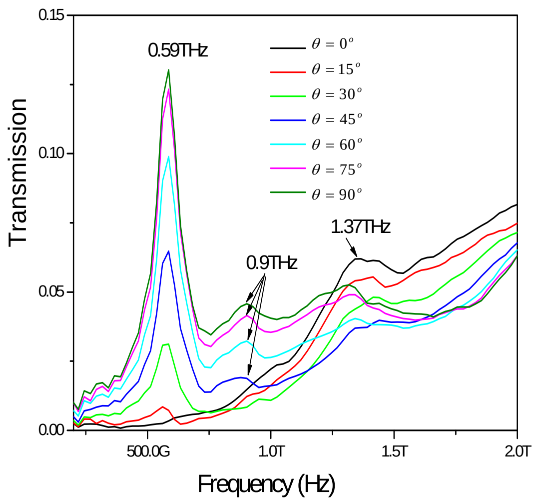


Fig. 2 THz transmission of rectangular hole array with the 2:1 of length-to-width ratio at different polarization

Fig. 3 shows that the THz transmission through the array of square holes is less obviously than those through the rectangular holes, and its polarization dependence of THz transmission is not so distinguished. It is clear that the polarization dependence of THz transmission results mainly from the unsymmetrical metal structures.

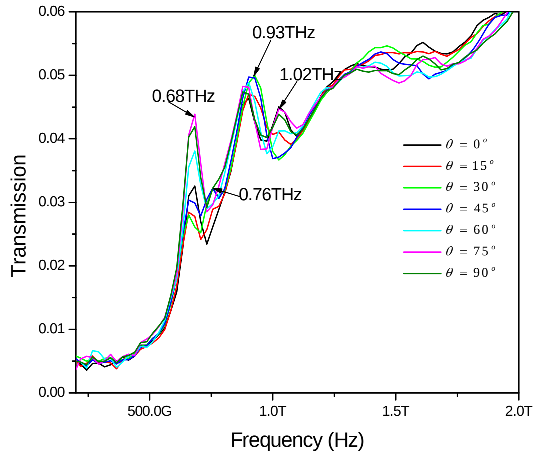
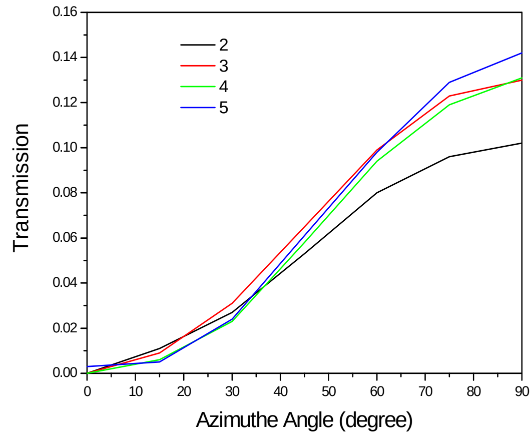


Fig. 3 THz transmission of square hole array with the 1:1 of length-to-width ratio at different polarization

By comparing THz transmission spectrum of the five samples at different azimuth angle, we found that the five period arrays of rectangular holes with different aspect ratio have obvious resonant transmission peak at 0.68THz, 0.63THz, 0.59THz, 0.54THz, 0.49THz, respectively. This indicates that the transmission of sub-wavelength periodic array of rectangular holes has obvious frequency selectivity in THz frequency region. This is significant for the band-pass filter of THz wave.

More importantly, due to the strong polarization dependence of THz transmission through the metal structures, it is possible to develop the sub-wavelength THz attenuator. From Fig. 2 and Fig. 3, we can see that the frequency position of resonant transmission peak do not change with the increase of azimuth angle, that is, the angle between the THz polarization and the long side of rectangular hole. However, THz transmission of four samples 2-5 with the rectangular holes at their resonant frequencies increases with increasing of azimuth angle. Figure 4 shows that the THz transmission peak of four samples 2-5 of rectangular holes as a function of azimute angle between the THz polarization and



the long side of rectangular holes.

Fig. 4 THz transmission peak of four arrays of rectangular holes for the sample structures 2-5 as a function of azimuth angle.

From Fig. 4, it is clear that THz transmission peak of the periodic array of rectangular holes depends nonlinearly on the polarization of incident THz wave. By rotating the metal structures on the copper foil, one can change the THz transmission at the resonant frequency. Based on this kind of THz transmission, it is helpful to serve as an attenuator of THz wave. It is significant to attenuate THz wave for the application of high power of THz radiation. We believe that the sub-wavelength metal structures will play an important role on the application of the THz photonic devices in the future.

IV. CONCLUSIONS

THz Transmissions of sub-wavelength metal structures show the obvious frequency selectivity and polarization dependence. The frequency position of transmission peak does not change with changing of the direction of THz polarization, but its transmission peak depends strongly on the THz polarization. Therefore, it is easy to utilize the metal structures as an attenuator of THz wave. By rotating the metal structure, one can change the THz transmission intensity through the metal plate. The THz attenuator can be fabricated based on the metal structures.

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