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Investigation of transmission resonances on the one-dimensional metallic cylindrical gratings in THz frequency range

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In the experiments of THz wave transmitting through the metallic cylindrical gratings fabricated by sub-wavelength brass wires, this paper reports that the discrepancy in the sharp resonances occurred as the grating perpendicular or parallel to the electric vector are observed. A simulation based on the finite difference time domain (FDTD) indicated that the enhanced transmission through the grating is attributed to the combined effects of surface plasmons and cavity modes in the perpendicular condition, while the cavity modes dominate the resonant transmission under the other conditions. Additional experimental data and calculated results show that ∼1 enhanced coupling efficiency can be realized in some THz frequency, which could be applied to the design and improvement of various optoelectronic devices, or detection of biological molecule and powder samples, etc.

Keywords: THz wave transmitting, gratings, surface plasmons, cavity modes
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1. Introduction

Several interesting and curious phenomena have been generated when the electromagnetic waves incident on a dielectric/metal gratings interface.[1−4] It has been investigated for many years and many electromagnetic modes in optical response have been identified and described. Examples of these modes include Wood-Rayleigh anomalies, surface plasmons, cavity modes, and diffracted modes, etc. Though there has been considerable disagreement in their relative roles and the physics behind this phenomenon remains in dispute,[5−8] the surface plasmons and cavity modes play a significant role in transmission and are the emphasis of the researchers' study all the time. It is well known that only an incident beam with an electric vector perpendicular to the metal wires can couple with and stimulate surface plasmons, which are surface charge oscillations and their associated electromagnetic fields at a metal/dielectric interface. In contrast, other phenomena could occur for both the electric vector perpendicular or parallel to the metal wires under proper condition. These phenomena have already been studied in detail at many frequencies including microwave, infrared, and more recently THz. In particular, the work of John F. O'Hara,[9] dealt with the metallic gratings made from brass rods mounted in contact with each other in the wasTHz region, reported the feature of transmission resonance induced by surface plasmons when the electric vector is perpendicular to the brass rods. However, in our work, THz-TDS is used to investigate the transmission dependence on the location of the grating. With theoretical calculation of the finite difference time domain (FDTD), we proved that as the grating is perpendicular to the electric vector, the combined effects of surface plasmons and cavity modes resonances induced the transmitted resonances, while the cavity modes resonances dominate the resonances transmission for the other condition. Moreover, ∼1 enhanced coupling efficiency is confirmed in some THz frequency, which will bring potential applications in the THz devices design and samples detection, etc.

2. Experimental setup

Figure 1 shows the geometry of the one-dimensional metal grating studied in this paper. The

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input THz pulses are incident on the metal surface with the electric vector along x axis, by rotating the sample stage we make the grating along y axis or x axis to realize the two radiation conditions mentioned above. An array of brass wires is mounted on a PE plate by adhesive tape (the refractive index of the tape is 1.45 in THz range). To ensure that there is no edge diffraction or other effects from the holder, a metallic hole with 4-mm diameter is put over the Teflon holder in the incident plane. We fabricated the gratings as: $R = 75$ μm, $D = 300$ μm, here, R is radius of brass wire and D is grating constant. The number of wires in gratings is 120.

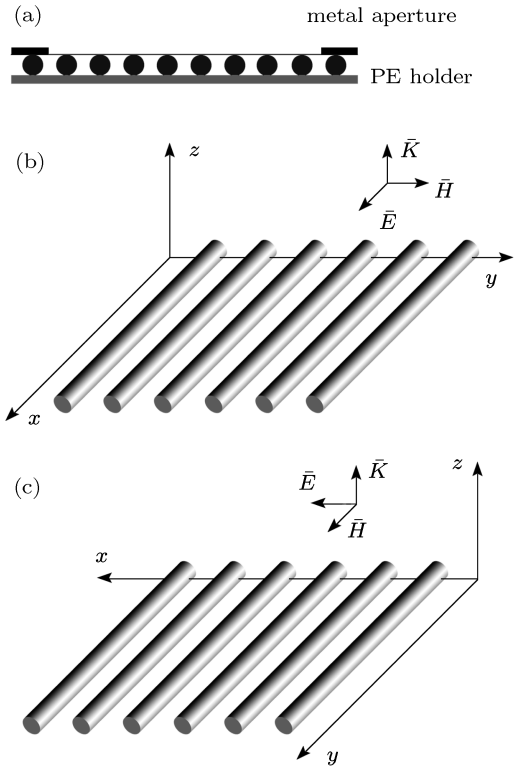


Fig.1. (a) The geometry of the one-dimensional metal grating on a PE plate. (b) Electric vector of incident THz radiation parallel to the metal wires. (c) Electric vector of incident THz radiation perpendicular to the metal wires.

A standard THz-TDS apparatus for transmission measures was used. The setup and corresponding experimental data analysis method have been discussed in detail in our previous reports.[10] In brief, the THz-ray is generated by the (1 0 0)-oriented, InAs wafer, which is stimulated by optical pulses from a mode-locked Ti-sapphire laser ($\lambda = 800$ nm, $\tau_{\mathrm{FWHM}} = 100$ fs). The repetition rate of the laser is 82 MHz. The THz beam is focused on the sample by means of the two off-axis parabolic mirrors. We generated and detected the THz signal in the vacuum ambience to get rid of the influence of water vapor on the spectra. THz-TDS allows the direct measurement of the THz electric field, yielding both amplitude and phase information. So the experimental parameters allow us to directly determine the absolute amplitude transmission coefficients. By transforming the time domain data to frequency domain, we are able to determine independently both the magnitude and phase of the amplitude transmission coefficient, $T(\omega)$, using the relation $E_{\mathrm{t}}(\omega)/E_{\mathrm{i}}(\omega) = T(\omega) = |T(\omega)| \exp[\phi(\omega)]$, where E_{i} and E_{t} are the incident and transmitted THz field, respectively, $T(\omega)$ and $\phi(\omega)$ are the magnitude and phase of the amplitude transmission coefficient, respectively, and ω is the THz frequency. Here in our experiment, E_{i} is the magnitude of THz pulses transmitting through the PE plate while E_{t} is the magnitude of THz pulses transmitting through gratings with PE plate.

3. Results

The temporal waveforms of the transmitted THz pulses through gratings dependent on the grating's location are shown in Fig.2(a), referenced to the Hz pulses transmitting through the PE plate. For clarity, a waveform vertical offset is introduced. It is clearly seen that when either the grating is perpendicular or parallel to the electric vector, the time-resolved signals are characterized by broad oscillations. In the corresponding frequency domain spectra Fig.2(b), we plot two regions within the detected range of 0.1 THz to 1.6 THz, as shown as regions I and II. In region I, the amplitude transmission coefficient is distinctively greater for the perpendicular condition than the parallel condition. Obviously, the greatest transmission coefficient for the perpendicular condition nearly reaches 1, as a result of surface plasmons and cavity modes which are overlapped and affect the transmission. Due to the different amounts by overlapping, there is no general rule to explain in detail about the maximum $\sim$1 transmission. As to the sudden dip, we will discuss it in the next section. In the higher frequency region II, the transmission coefficient of both grating locations expresses the same trend. Maybe the amounts of surface plasmons modes are further decreased for the perpendicular condition, and the transmittance is affected mainly by the cavity modes.

4. Analysis and discussion

Theoretical calculations using FDTD are shown in Fig.3. In our simulation, the calculation is strictly according to our experimental condition. During the calculation, we get both the transmission and reflection spectra. In Fig.3(a), it presents the theoretical calculations of the THz electric vector perpendicular to the grating, the transmission coefficient reaches 1 around 0.5 THz, and then suddenly decreases. Compared to the transmission coefficient shown in Figs.3(a) and 3(b), we also see the distinction induced by the grating location, which agrees with experimental data in Fig.2(b). Owing to the periodical structure of the grating, the minimum transmission coming forth in the transmission spectra correspond to the maximum transmission appearing in the reflection spectra. So we can explain that the sudden dip in Fig.2(b) is caused by the reflection of the grating.[11] More importantly, according to Fig.3, we can see that the grating acts as a perpendicular wave reflector (parallel wave transmitter) at ω = 0.89 THz, 1.52 THz, and 1.9 THz. However, due to the detected limitation of the THz-TDS system, we just demonstrated it at 0.89 THz, which is shown in Fig.2(b). And the application of interest is possible to be designed by changing the structure of grating (wire dimension and the grating field).

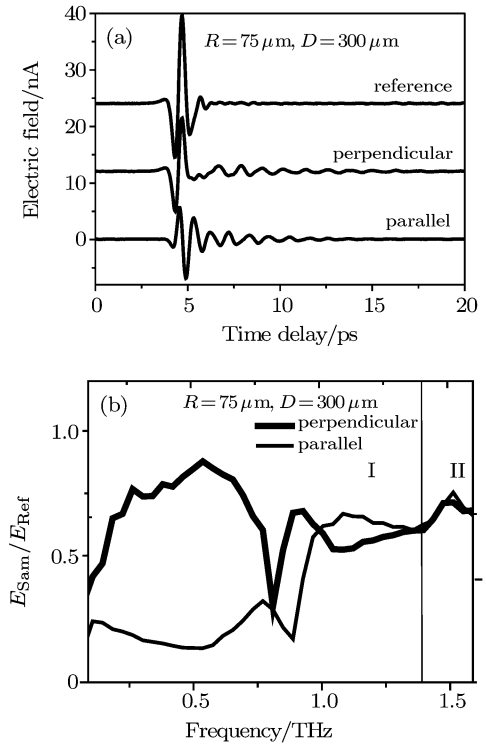


Fig.2. (a) Temporal waveforms of THz pulses transmitting through the grating. (b) Corresponding spectra of THz pulses transmitting through the grating.

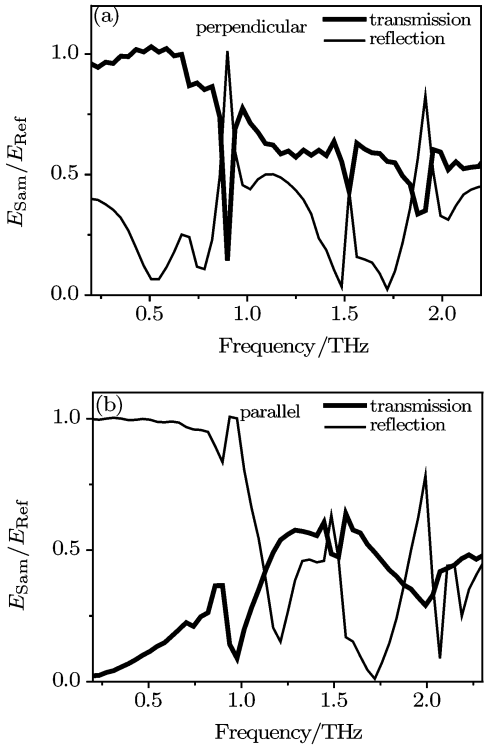


Fig.3. Theoretical calculations of transmission and reflection spectra for the grating: (a) perpendicular grating location; (b) parallel grating location.

In Fig.4, we plot the electric field distribution at time from 1.2 ps to 2.0 ps, and the starting calculation time is hypothesized as the THz pulses radiate incidence on the grating. And the Poynting vector is plotted in Fig.5 at 1.4 ps. It is clearly seen that the electromagnetic fields for the perpendicular condition are more concentrated on the wire walls, compared to parallel condition in which the electromagnetic fields are positioned towards the center of the spacing.[12] Also, it can be seen that the resonant excitation is associated with significantly more field enhancement for the perpendicular grating location as compared to the parallel location. Two additional differences between the characteristics of THz pulse incident on these grating structures are worth noting. First, the two grating location conditions both have cavity modes occurring due to the different electromagnetic boundary conditions at the metal/dielectric interfaces.[7,13] Second, for the perpendicular location the energy of the peak transmission and amount of transmission may be strongly enhanced due to the interactions between the cavity modes and the surface plasmons.[13,14]

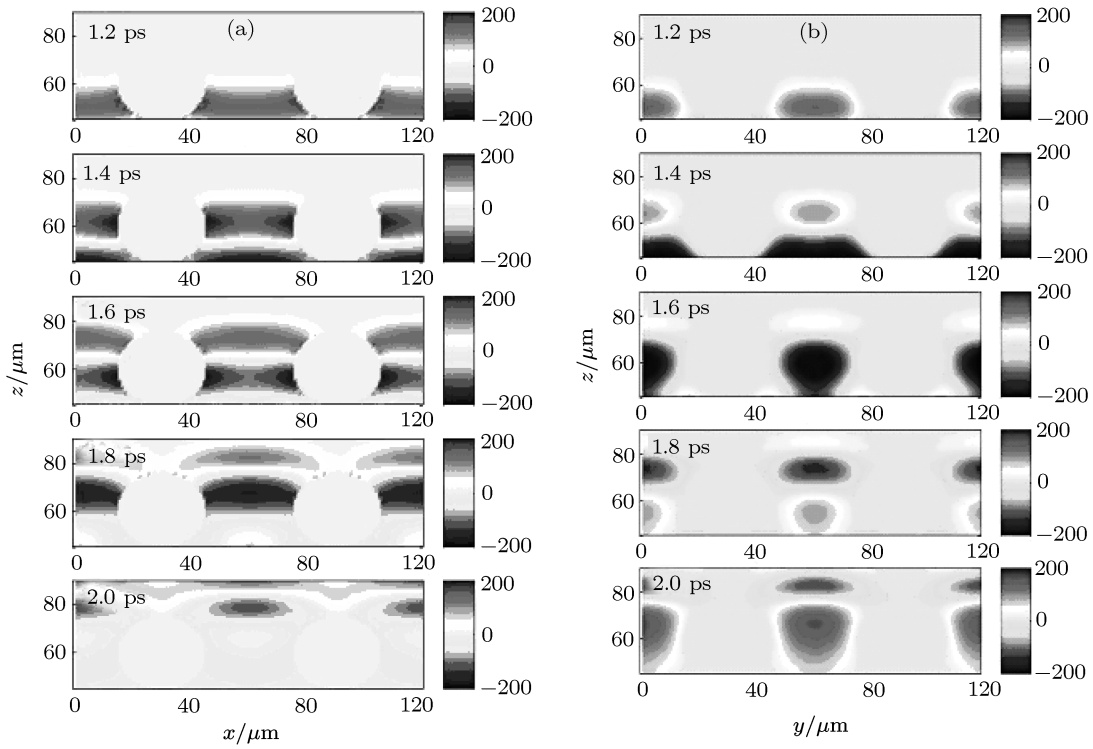


Fig.4. (a) The magnitude of the electric field produced by incident THz radiation perpendicular to grating at times from 1.2 ps to 2.0 ps. (b): The magnitude of the electric field produced by incident THz radiation parallel to grating at times from 1.2 ps to 2.0 ps.

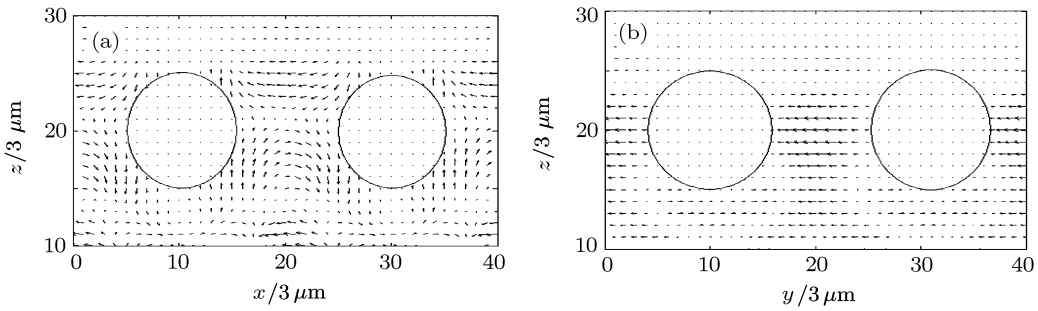


Fig.5. (a) The Poynting vector for incident THz radiation perpendicular to grating at 1.4 ps. (b) The Poynting vector for incident THz radiation parallel to grating THz at 1.4 ps.

5. Conclusion

By THz-TDS, we detected the transmission of THz pulse through the metallic cylindrical gratings, which are made of sub-wavelength brass wires. With perpendicular or parallel grating location conditions relative to the THz electric vector, discrepantly sharp resonances and an extraordinary transmission are observed. The FDTD was used to simulate the feature of the transmission, and we demonstrated that the resonances in the perpendicular grating location is attributed to the combined effects of the surface plasmons and cavity modes resonances, which could enhance the transmission to near 1.

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