Hindawi Publishing Corporation
Active and Passive Electronic Components
Volume 2007, Article ID 63139, 4 pages
doi:10.1155/2007/63139

Research Article

Transmission Properties of Metallic Grating with Subwavelength Slits in THz Frequency Region

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Received 11 September 2007; Accepted 10 October 2007

Recommended by Yalin Lu

This paper presents a fully experimental and theoretical study on transmission properties of a deep metallic grating with subwavelength slits in THz frequency region by using THz time domain spectroscopy (THz-TDS). The grating exposed to p-polarized incident wave exhibits enhanced nonresonant transmission in the long-wavelength region where the incident wavelength is larger than the grating period. Wood anomalies are observed when the wavelength is comparable to the grating period. Strict theory is given to explain the experimental results and the two are in good agreement. It is proposed that the Wood dips may be considered a criterion and a tool to judge and control the uniformity or fabricating accuracy of the grating period.

1. INTRODUCTION

Since 1998 when Ebbesen et al. discovered enhanced transmission of light through subwavelength hole arrays made in a thin metal film [1] there has been a renewed interest in exploiting dielectric response of subwavelength metallic periodic structures in different frequency regions including the optical [2–4], microwave [5], and terahertz region [6–12]. These structures possess abilities to confine incident light into a small spatial domain or to transmit light very efficiently. Thus, subwavelength metallic structures have great potential in subwavelength photonics apart from the fundamental physics.

In this letter, we experimentally investigated the transmission properties of a metallic grating with subwavelength slits by using THz-TDS [13]. The grating is exposed to p-polarized incident wave which is also called transverse magnetic (TM) with its electric field vector E perpendicular to the slit direction. The delay of the terahertz pulses and the nonresonant transmission spectrum through the samples were observed. Here, "nonresonant" corresponds to the case where the depth of the metallic grating in our experiment is much larger than the time window of the sampling terahertz radiation signal by using THz-TDS so that only a single pass of the terahertz pulses through the sample could be detected. Therefore, there was no Fabry-Perot-like resonant transmittance. Enhanced transmission in the long-wavelength was observed, as well as Wood anomalies which may act as a criterion and a tool to judge and control the fabricating accuracy of the sample grating. Theoretical explanation is then given by employing the effective refractive index of the metallic grating in the long wavelength and the nonuniformity of the grating period. Experimental results agree well with theoretical calculation.

2. EXPERIMENTAL SETUP AND RESULT

The sample was constructed using $250 \pm 5\,\mu$m thick steel blades, which were aligned vertically in a metallic frame with air spacers of the thickness of $70 \pm 15\,\mu$m. The grating was 3 mm in depth. In Figure 1, we show a schematic view of the sample with the parameters: the period of the grating (p), the width (w), and the depth (h) of the grating. The sample was placed between two off-axis parabolic mirrors in the collimated path of a standard THz-TDS with ZnTe-based emitter and detector. Linearly polarized and near single-cycle

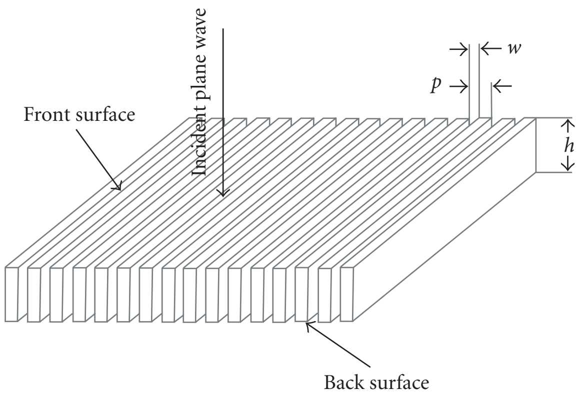

FIGURE 1: Schematic view of the metallic grating with subwavelength slits.

broadband terahertz pulses with a bandwidth from 0.3 to 3 THz were generated using 50 femtoseconds pulses from a mode-locked Ti: sapphire laser (average output power of 300 mW, repetition rate of 100 MHz).

The linearly polarized terahertz pulses through around 20 mm diameter aperture were impinged perpendicularly on the grating surface. All the system was sealed in a plastic box purged with pure nitrogen to mitigate absorption by water vapor.

The reference signal was obtained without the sample in the collimated beam path. We adjusted the metallic grating to make sure that the THz pulses were incident perpendicularly upon the grating surface in p-polarized state. Time domain signals with and without the metallic grating are given in Figure 2(a); while their corresponding spectra are shown Figure 2(b). Also, it can be seen in Figure 2(a) that the amplitude of transmission signal is nearly one third of that of the incident THz pulse, and that transmission pulse exhibits a time delay compared to the reference signal. The additional structures on the spectra curves in Figure 2(b) arise from absorption of the residual water vapor in the plastic box. The transmittance or transfer function of the grating can be derived by dividing the transmission spectrum by the reference spectrum as shown in Figure 2(c).

3. DISCUSSION

According to the modal expansion method proposed by Sheng et al. [14] and the effective Fabry-Perot model given in [15], and considering that metal can generally be treated as a perfect electrical conductor (PEC) in the THz frequency region, the expressions of transmittance or transfer function for normal incidence may be written as

$$T(\omega) = \frac{4\Gamma}{(1+f)^2}, \tag{1}$$

where $\Gamma = w/p$ is the area filling factor of the slits. Function f can be written as

$$f = \Gamma \sum_{n=-\infty}^{+\infty} \frac{s_n^2}{\beta_n}, \tag{2}$$

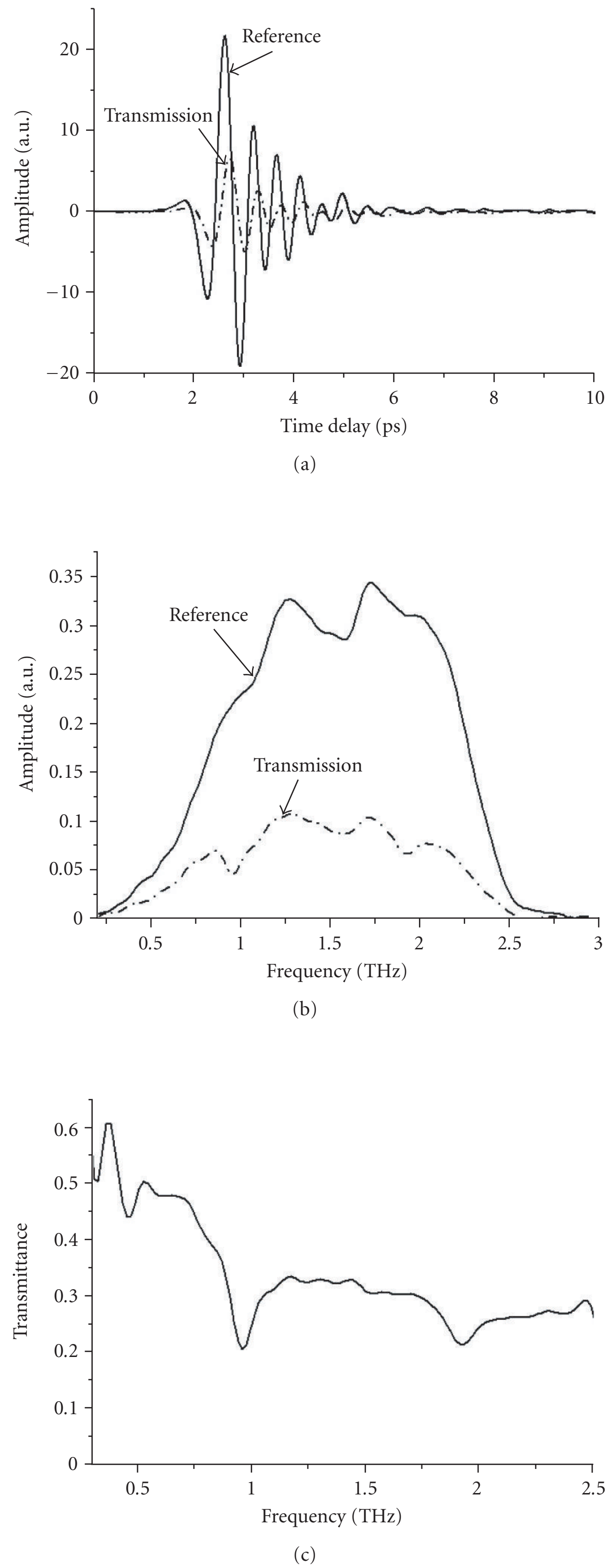

FIGURE 2: Nonresonant terahertz transmission properties of the grating exposed to p-polarized incident wave with grating period $p = 320 \pm 15\,\mu$m, slit width $w = 70 \pm 5\,\mu$m, and grating depth $h = 3$ mm. (a) Time domain traces of terahertz pulses. (b) Corresponding Fourier spectra. (c) Transmittance.

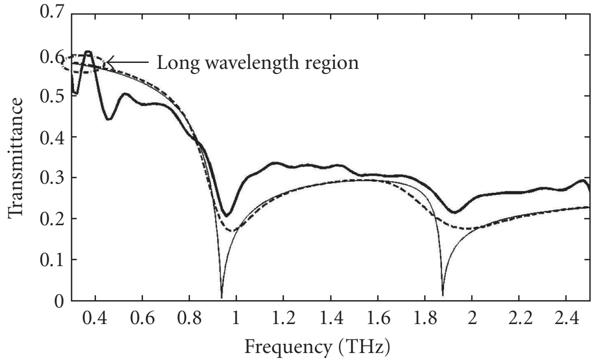

Figure 3: Comparison between experimental result and theoretical calculation. The thick solid line shows the experimental transmittance as indicated in Figure 2(c). The thin solid line denotes the theoretical transmittance of the grating with uniform period $p = 320\,\mu$m. The dashed line is a theoretical simulation assuming the grating period fulfills normal distribution with mean $320\,\mu$m and standard deviation $20\,\mu$m. The circle marks the transmittance in the long-wavelength region.

where s_n with integer n can be expressed as

$$s_n = \frac{\sin\,(k_0\gamma_n w/2)}{(k_0\gamma_n w/2)} \tag{3}$$

with

$$\gamma_n = n\frac{\lambda}{p}, \qquad \beta_n^2 = 1 - \gamma_n^2. \tag{4}$$

Regular spaced transmission minima, called Wood anomalies [16, 17], can be observed when a new diffraction order emerges from the surface, which is $\gamma_n = 1$ corresponding to Wood frequencies:

$$\nu_n = \frac{nc}{p}, \tag{5}$$

where c and n are the vacuum speed of light and an integer number, respectively. The experimental positions of the minima in the transmission spectrum agree well with the theoretical expectation as illustrated in Figure 2(c) with frequencies equal to 0.94 THz and 1.88 THz.

It should be pointed that the minima at frequencies 0.94 THz and 1.88 THz are expected to be zero according to (1), (2), and (4) as shown by the thin solid line in Figure 3 but the experimental result (thick solid line in Figure 3) only exhibits dips at such frequencies. The difference may be attributed to the nonuniformity of the period of the sample grating we fabricated. The grating period is randomly distributed in the vicinity of $320\,\mu$m with a fabrication error of $20\,\mu$m. As we know, the positions of the minima are subject to the grating period. Different periods correspond to different positions of the minima so that the comprehensive effect is to form dips in the transmittance curve other than zeros at Wood frequencies.

A model is proposed to demonstrate our point of view. Assuming the grating period fulfills normal distribution $N(p)$ with mean p_0 of $320\,\mu$m and standard deviation σ of $20\,\mu$m, which is

$$N(p) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(p-p_0)^2/2\sigma^2}. \tag{6}$$

Thus, the average transmittance $\overline{T}(\omega)$ can be rewritten as

$$\overline{T}(\omega) = \int_{-\infty}^{+\infty} N(p)T(\omega)dp, \tag{7}$$

where $T(\omega)$ is given by (1). The dashed line in Figure 3 denotes the curve of $\overline{T}(\omega)$ The theoretical simulation of the average transmittance demonstrates the formation of the dips at Wood frequencies. More importantly, the dips provide us a basis to judge the uniformity or fabricating accuracy of the metallic grating. The grating period can be judged by the position of the dips; and the fabricating accuracy may be judged by the width and depth of the dips. The narrower and deeper the dips are, the more accurate the grating period is.

The theoretical deviation from the experiment is mainly attributed to two reasons. The first is that the actual distribution of the grating period does not exactly fulfill the normal distribution. The second one is that the signal-to-noise ratio (SNR) increases when the frequency is below 0.5 THz, which leads to fluctuation of the transmittance in the long-wavelength region shown in Figure 3.

Then, we mainly focus on the long-wavelength region where the incident wavelength λ is much larger than the grating period p. Therefore,

$$f = \Gamma \sum_{n=-\infty}^{+\infty} \frac{s_n^2}{\beta_n} = \Gamma\left(1 - \frac{2ip}{\lambda}\sum_{n=1}^{\infty}\frac{\operatorname{sinc}(n\pi\Gamma)}{n}\right) \approx \Gamma. \tag{8}$$

The transmittance can thus be approximated by the expression

$$T(\omega) = \frac{4\Gamma}{(1+\Gamma)^2} = \frac{4}{(1/\Gamma+1)^2}. \tag{9}$$

However, (9) implies that the transmittance is only related to the area filling factor of the slits in the long-wavelength region. By comparing (9) with the transmittance of a plane wave incident normally on a dielectric slab with refractive index n and thickness of h/n,

$$T = \frac{4}{(n+1)^2}, \tag{10}$$

we can easily extract an effective refractive index $n = 1/\Gamma = p/w$, namely, the metallic grating with subwavelength slits can be treated as a dielectric slab. In fact, the effective index reflects the surface phase retardation of the metallic grating because the slits bring no time delay to the THz pulse compared to the reference signal. Assuming that the grating period keeps constant, the narrower the slits are, the more time the incident wave spends in getting into and out of the slits, which corresponds to a larger refractive index. As we can see in Figure 2(a), there is a time delay in the time traces of the transmitted THz pulses compared to reference traces, which is a proof of the surface retardation of the grating.

The transmission efficiency t exceeds unit when normalized to the field directly impinging on the slits:

$$t = \frac{T(\omega)}{\Gamma} = \frac{4}{(1+\Gamma)^2}. \tag{11}$$

As indicated by (11), t ranges from 1 to 4 for $0 < \Gamma < 1$. Obviously, the larger Γ factor, the larger the effective index and the larger the transmission efficiency we can get. For $\Gamma \to 0$, t tends to reach its maximum 4. This conclusion is different from the resonant transmission condition described in [1, 3]. For condition $\Gamma \to 1$, where the grating actually becomes air or vacuum, $t = 1$ corresponding to no enhanced transmission. For our sample grating with period $p = 320\,\mu$m and slit width $w = 70\,\mu$m, transmittance $T = 0.59$ agrees well with the experimental result shown by the circle in Figure 3.

4. CONCLUSION

The nonresonant transmission properties through a metallic grating with subwavelength slits in the THz frequency region were investigated. The grating was exposed to p-polarized incident THz radiation. The minima attributed to Wood anomalies were observed at wavelengths equal to fractions of the grating period. The nonuniformity of the grating period led to dips other than zeros at Wood frequencies. Normal distribution of the grating period was used to simulate the formation of the dips. These results provide us a criterion and a tool to judge and control the fabricating accuracy of the metallic grating. As for the long-wavelength region, an effective index of the grating was extracted based on the effective Fabry-Perot model to explain the enhanced transmission in this region. The experimental results are in good agreement with the theoretical calculations.

ACKNOWLEDGMENTS

This work was partly supported by National Key Basic Research Special Foundation of China through Grant No.2007CB310408, National Natural Science Foundation of China (No.60578037), NSFC-RFBR program 2007-2008, and “985” program of Tianjin University.

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