High efficiency terahertz diffraction grating with trapezoidal elements*

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A newly designed grating used in terahertz region is proposed, which is composed of the trapezoidal elements repeated successively along one dimension of the substrate, and uniform interval (the grating period) repeated along the other dimension. The transmission of the grating owns a designable trapezoidal profile dependent on the geometric dimensions of the element. The far-field diffraction patterns of a designed grating at incident broadband terahertz frequencies, with element dimensions of upper, lower side and period of 50, 250, and 300 μm, respectively, are simulated by the scalar diffraction theory. The simulation results indicate that the terahertz grating exhibits a property of single-order diffraction, and the diffraction efficiency of the first order reaches 6.6%, exceeding that of a traditional sinusoidal amplitude grating with identical period and duty cycle. Owing to the regular architecture and the high single-order diffraction efficiency, the grating is easy to fabricate and shows great potential applications in single-shot spectral measurements of weak broadband terahertz pulse.

Keywords: grating, terahertz, trapezoidal element, high efficiency

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1. Introduction

Using the common approaches to terahertz spectral measurements, such as the terahertz time domain spectroscopy (THz-TDS) and Fourier transform spectroscopy (FTS), we usually acquire first the terahertz temporal signals in time domain, which is based on scanning of stable repetitive pulses or continuous signals, and then obtain the corresponding spectra in frequency domain.[1–3] These approaches are not practical or need trimming in spectral measurement of single-shot broadband terahertz pulse carrying abundant physical information. Improved single-shot electro-optical sampling is often employed in THz-TDS technique to acquire the terahertz temporal signal, and then gain the terahertz spectrum.[4,5] The upper measurable frequency limits in electro-optical sampling technique depend on the duration of probe pulse, the crystal absorption and the phase-matching conditions between probe and terahertz pulse in crystal. Some crystals, like GaSe, reaches several tens of THz, owning to the high absorption limit and excellent phase-matching extent.[6] However, as a crystal used most in electro-optical sampling, ZnTe has a lower frequency measuring limit due to the crystal absorption, which is not enough to measure the ultrabroadband terahertz signals, for example, the terahertz radiation with spectral components up to several tens of THz generating from interaction of single-shot intense femtosecond laser pulse with solid target.[5,7]

Since the terahertz region essentially contains electromagnetic waves, which own the propagation properties of wave optics, it is natural to attempt the spectral measurement by employing a traditional black-white terahertz grating as a dispersive element. Delsim-Hashemi *et al.* measured indirectly the broadband spectrum of transition terahertz radiation generating from single-shot electron bunch in FLASH facility, in order to diagnose on a single-shot basis the longitudinal profile of electron bunches.[8] They employed two traditional gratings with line grooves of 2.5 lp/mm and 0.5 lp/mm, respectively, to measure in subsection the corresponding band, and obtained finally the actual whole spectrum through combining the two bands. However, in order to obtain the final actual spectrum, it usually needs subsequent complicated spectrum analyses after acquiring first the spectral patterns diffracted from grating, since the traditional grating presents inherently high diffraction orders, which causes spatial overlapping among diffraction orders. In the case of broadband terahertz radiation, it needs more complicated spectral analyses to obtain actual spectra when tradition terahertz grating is adopted, since the terahertz radiation spreads over almost the whole terahertz region.

The above approaches cannot gain directly the spectrum of single-shot broadband terahertz pulse. We proposed a terahertz diffraction grating composed of quasi-random circular elements to handle this problem, thereby simplifying the procedure of spectral measurement.[9] However, the diffraction

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efficiency of the grating reached only the level of one in a thousand, which confined its application in spectral measurements of weak terahertz pulse. It is urgent to enhance the diffraction efficiency.

In this paper, inspired by the unique grating with trapezoidal line structures originally proposed for the spectral resolving of soft x-ray region,[10] which functions well as a single-order dispersive element owing to its trapezoidal transmission profile, we get an idea of extending its applications into the terahertz regime to resolve the problem of single-shot terahertz spectral measurements. A new terahertz grating with high diffraction efficiency composed also of trapezoidal elements is designed to realize on a single-shot basis the spectral measurements of weak broadband terahertz radiation, which exhibits the property of single-order diffraction in ultrabroadband terahertz region. For simple fabrication, we make minor changes to the original grating structure, with successively repeated trapezoidal elements, instead of the alternating elements. The rest of this paper is organized as follows. The grating structure is introduced in Section 2, and its diffraction patterns in terahertz region are numerically simulated in Section 3. Discussions about the grating are given in Section 4, and finally some conclusions are drawn from the present study in Section 5.

2. Structure of grating

As shown in Fig. 1, grating line structure with no coating distributes periodically on a substrate nearly transparent to terahertz waves, and the remaining area of the substrate is coated with highly reflective film in terahertz region. Each grating line is composed of successive trapezoidal elements with identical dimensions. The geometric dimensions of the upper side, lower side and height of the trapezoidal element are denoted as a, b, and h. The spacing between the lines is d, which is the grating period.

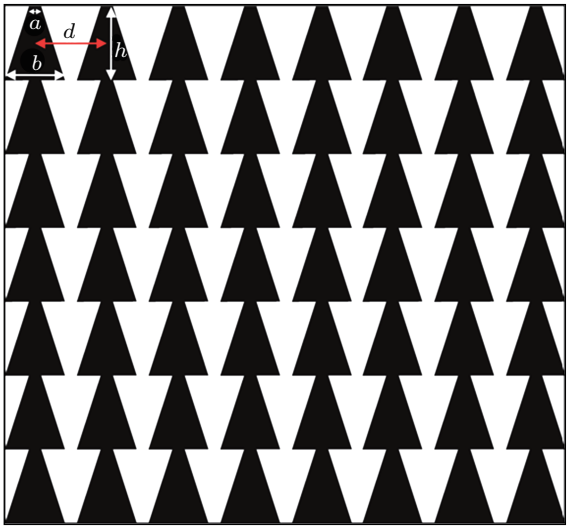


Fig. 1. (color online) Structure of terahertz diffraction grating.

According to the deduction of one-dimensional (1D) transmission function along the period direction of the trapezoidal grating, its spatial transmission profile is also a trapezoidal function, which depends on the geometric parameters of the trapezoidal element.

3. Diffraction simulations

In order to simulate the dispersive properties of the grating, scalar diffraction procedure is adopted to calculate the far-field diffraction patterns in the traditionally defined terahertz regime: (0.1–10) THz. The simulation parameters adopted are given in Table 1. The symbols ν, N, L denote, respectively, the incident terahertz frequencies, the number of grating lines and the diffraction distance. According to the deduction of the transmission function,[10] optimal result to suppress the high diffraction orders is achieved when the parameters satisfy the following equations: $a+b=d$, $a=d/6$, and $b=(5d)/6$.

Table 1. Simulation parameters for terahertz grating diffraction.

ν/THz	a/μm	b/μm	d/μm	h/μm	N	L/mm
0.1∼10	50	250	300	300	30	300

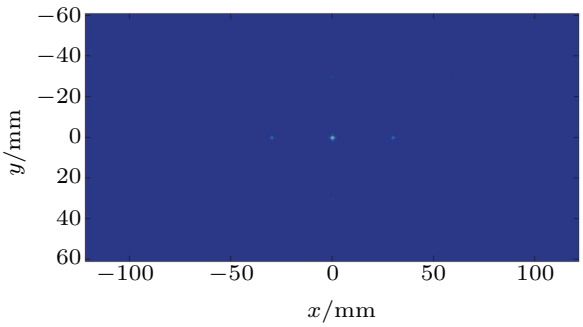


Fig. 2. (color online) The simulated far-filed diffraction patterns at 10 THz.

Figure 2 shows the diffraction pattern at an incident wave frequency of 10 THz, and figure 3 displays the 1D spatial intensity distribution corresponding to the diffraction pattern in Fig. 2. It is found that there exist mainly the zero- and first-diffraction orders, while the intensities of second- and higher-orders are suppressed effectively to a level of several orders of magnitude lower than the first-order, which means that the diffraction grating exhibits nearly a property of single-order diffraction. Meanwhile, after calculation, we find that the absolute diffraction efficiency of 6.6% is achieved for the first-order, which is greatly higher than the absolute diffraction efficiency of our previous grating (0.1%) and exceeds the absolute diffraction efficiency in the case of sinusoidal amplitude grating (6.25%). We ascribe it to the fact that the appropriate trapezoidal transmission function owning linear variation of transmission profile, demonstrates an effective suppression of high diffraction orders and is a more efficient transmission profile in designing this type of diffraction gratings.

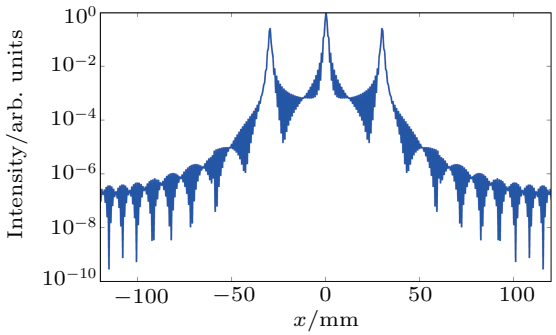


Fig. 3. (color online) Corresponding 1D spatial intensity profile (logarithm, normalized).

At other terahertz frequencies, the far-field diffraction patterns are also simulated and the results are similar to those in the case of 10 THz.

In practical spectral measurements, the incident spectrum is a composite spectrum with a certain bandwidth. To demonstrate the dispersive properties of the grating, we make far-field diffraction simulations on the grating owning the same parameters as those in Table1. The incident composite spectrum is chosen to contain relatively high frequency components. Figure 4 shows the simulation results. It is seen that the composite spectrum is spatially resolved into corresponding components, which are distinctly separate and can be easily distinguished from the spectrum captured by terahertz detector.

Consequently, the new grating exhibits a property of single-order diffraction in terahertz region, which is not dependent on the incident spectrum. The grating can act as a dispersive element in terahertz region and obtains directly the spectra of ultrabroadband terahertz radiation through measuring the first-order diffraction.

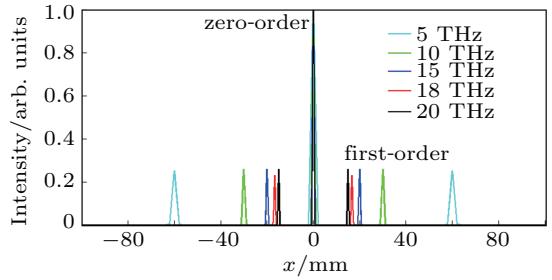


Fig. 4. (color online) Dispersive properties of the grating with composite incident spectrum for different frequencies (5–20) THz. Diffraction distance: 300 mm.

4. Discussion

According to the grating equation in the case of normal incidence: $d\sin\theta = m\lambda$, since the grating owns the property of single-order diffraction ($m = 1$), we can easily gain the incident spectra through measuring the spatial intensity distribution of far-field first-order diffraction dispersive from the grating with no need of making complicated spectral analyses.

When adopting an effective terahertz detector, for example, the spatially distributed multi-channel or focal-plane-array pyroelectric terahertz detector to capture the first-order diffraction pattern, the measurable wavelength coverage theoretically ranges from $(0 \sim d)$. As regards the grating period parameter (d) chosen in above simulations, it is in a range of (0–300) μm, corresponding to a wide frequency coverage of (1–several tens) THz, which brings an advantage of ultrabroadband spectral measurement over the terahertz time-domain spectroscopy (TDS) approach, since the latter owns inherently relatively low frequency upper limit arising from the electro-optical crystal.

Actually, the bandwidth of THz optoelectronics has been enhanced dramatically to cover an ultrabroadband ranging up to even several tens of THz, which exceeds the traditionally defined terahertz regime of (0.1–10) THz. In physical interaction of intense single-shot femtosecond laser pulse with solid target, terahertz radiation with spectral components up to several tens of THz is generated. However, the grating can still be used to resolve the high frequency components in the first-order, since the property of single-order diffraction is not dependent on the incident spectrum.

As regards the resolution in grating spectral measurements, it can be expressed as $\Delta\lambda \approx (d \cdot \Delta x)/f$, in the case of normal incidence and small diffraction angle, and is schematically shown in Fig. 5. Here, d denotes the grating period, Δx the spatial resolution of terahertz detector, and f the focal length of terahertz lens placing closely behind the grating. When the grating and focusing lens are determined, the spectral resolution will depend directly on the spatial resolution of detector. Typically, when using a lens with a focal length f of 50 mm and a terahertz detector with a spatial resolution of 25 μm in the experiment, the spectral resolution will achieve 0.6 μm, corresponding to a frequency resolution of 20 GHz at the central frequency of 1 THz, which is equivalent to the spectral resolution of terahertz time-domain spectral approach.

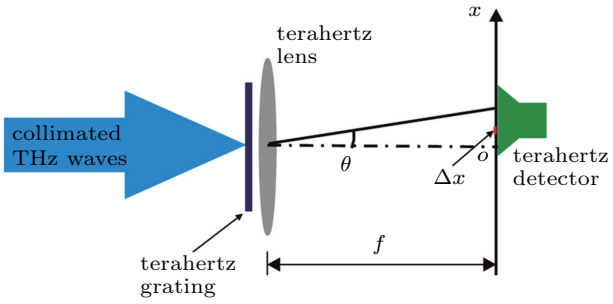


Fig. 5. (color online) Spectral resolution of terahertz grating.

5. Conclusions

A new diffraction grating designed for single-shot terahertz spectral measurement is designed, which is composed of trapezoidal line structure. Its far-field diffraction pattern is numerically simulated and the results indicate that the grating ex-

hibits the property of single-order diffraction and high diffraction efficiency in ultrabroadband terahertz region. When it is used as a dispersive element, the spectral information of ultrabroadband terahertz signals can be obtained directly through the first diffraction order with no need of making complicated spectral analyses in the case of traditional grating. Meanwhile, due to the high diffraction efficiency, relatively weak terahertz signals can be detected and thus the detector sensitivity can be released. Considering the two points, the direct single-shot spectral measurement of weak broadband terahertz signals becomes feasible.

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