New terahertz dispersive device for single-shot spectral measurements of terahertz pulse*

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A new terahertz dispersive device designed for single-shot spectral measurements of broadband terahertz pulses is proposed. With two-dimensional quasi-randomly distributed element design, the device exhibits approximately the dispersive property of single-order diffraction in far field. Its far-field diffraction pattern is experimentally verified employing a continuous terahertz source centered at 2.52 THz and a pyroelectric focal-plane-array camera, which is in good agreement with the numerical result. The device provides a new approach for direct single-shot spectral measurements of broadband terahertz waves.

Keywords: terahertz, diffraction, single-shot, spectral measurement

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1. Introduction

The intense terahertz waves emission from laser plasma interaction of intense ultrashort laser pulses with gas or solid target, due to its unique features of sub-picosecond duration, high peak power, and broadband spectral coverage, attracts significant attention.[1–5]

Since the spectral distribution of terahertz emission from the laser plasma interaction contains important information related to the interaction process, it becomes an effective approach to diagnose the interaction by measuring the emission spectrum of single-shot broadband terahertz source.[6] Hereby, it is necessary to gain on a single-shot basis the spectral distribution of broadband terahertz source.

Conventional approaches for terahertz spectral measurements, such as Fourier transform spectroscopy (FTS)[1] and terahertz time-domain-spectroscopy (THz-TDS),[7] are realized by obtaining first the temporal terahertz signal through sequential optical-delay-line scanning (electro–optic sampling in THz-TDS) and then transforming it to frequency domain. Obviously, it is not applicable in the case of single-shot terahertz pulse. Adopting improved single-shot electro–optic sampling, Tilborg had measured the temporal profile of single terahertz pulse and retrieved from it the corresponding spectrum.[6] However, the eventual spectral coverage reaches only 4 THz, limited by intrinsic cut-off frequency of electro–optic crystal (ZnTe, with a transverse optical phonon resonance frequency of 5.31 THz) and phase mismatch between propagating terahertz waves and optical probe beam in the crystal, which is not wide enough for measuring broadband terahertz waves up to 10 THz.

Delsim-Hashemi measured on a single-shot basis the spectrum of broadband terahertz radiation employing two stages of conventional black–white transmission grating.[8] However, since inherent high-order diffraction of conventional black–white grating impose intractable interferences on the useful first diffraction order, it is not convenient to acquire the actual spectrum of terahertz pulse from just the first diffracted order, and usually needs complicated spectral decoding process.

Based on the above analyses, in this article, we propose a new terahertz dispersive device used for single-shot spectral measurements of broadband terahertz pulse, free of complicated spectral decoding, which is uniquely designed in Section 2 to own the property of single-order diffraction. Experiment and discussion are presented in Section 3.

2. Terahertz dispersive device

The geometry of the dispersive device is illustrated in Fig. 1(a). A piece of thin square substrate completely opaque to terahertz waves is diced uniformly into $N \times N$ small squares with side length (d) (actually the period of the device), and each square cuts out randomly a circular through-hole as the element (with diameter of a) within its area to transmit terahertz waves. Generally, the diameter of all elements (a) is chosen as half of the side length (d) and is much larger than the wavelength of incident terahertz waves, i.e. $a = d/2$ and $a \gg \lambda$. Thus, the device is composed of $N \times N$ two-dimensional

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(2D) quasi-randomly distributed transmissive holes (elements) on a piece of substrate completely opaque to terahertz waves.

According to the deduction of amplitude transmission coefficient of the designed device,[9] when the number of rows of the transmissive holes (N) is large enough, the amplitude transmission coefficient within one period (d) can be expressed as:

$$t(x)=\begin{cases}\dfrac{1}{8}\left[\dfrac{\pi}{2}-\arcsin\left(1-\dfrac{4x}{d}\right)-\left(1-\dfrac{4x}{d}\right)\sqrt{1-\left(1-\dfrac{4x}{d}\right)^2}\right], & x\in[0,\,d/2],\\ \dfrac{1}{8}\left[\dfrac{\pi}{2}+\arcsin\left(3-\dfrac{4x}{d}\right)-\left(3-\dfrac{4x}{d}\right)\sqrt{1-\left(3-\dfrac{4x}{d}\right)^2}\right], & x\in[d/2,\,d].\end{cases} \tag{1}$$

Figure 1(b) illustrates the amplitude transmission profile within a period, which peaks and is symmetric at half of the period: $x=d/2$.

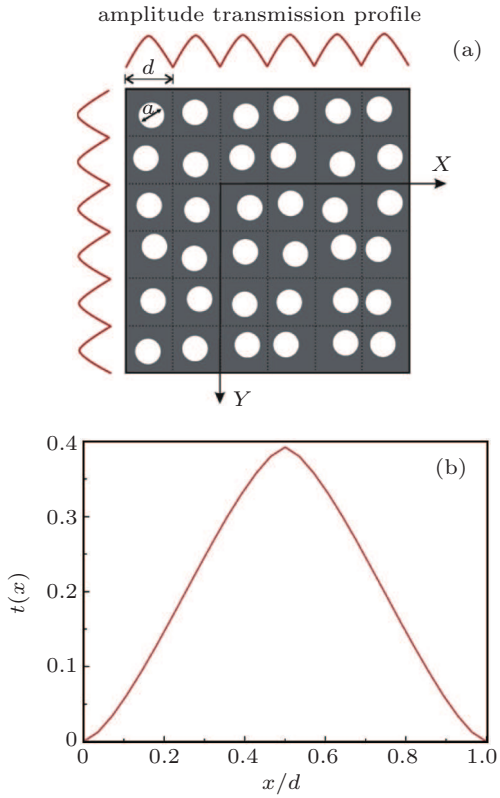


Fig. 1. (color online) (a) Geometry of dispersive device; (b) profile of the amplitude transmission coefficient within one period.

In order to analyze the diffracted orders induced by this amplitude transmission profile, equation (1) is expanded with Fourier series corresponding to diffracted orders as shown in Eq. (2), and thus gain respectively the amplitude transmission coefficient: $f(0)=0.1963$, $f(1)=-0.1804$, $f(3)=-0.009965$, $f(5)=-0.002693$, …, while $f(2)$, $f(4)$, $f(6)$, …, $f(2n)$ equal zero owning to the symmetric profile, i.e., even diffracted orders disappear in the diffraction pattern.

$$\begin{aligned}t(x) &= \sum_m f(m)\cos\left(\frac{2\pi x}{d}m\right)\\ &= f(0)+f(1)\cos\left(\frac{2\pi x}{d}\right)+\cdots,\end{aligned}$$

$$m=0,\pm1,\pm2,\pm3,\ldots. \tag{2}$$

Considering the intensity contrast among different diffracted orders, it is found the maximal intensity of the first order is 21% that of the zeroth order, while two orders of magnitude (327 times) higher than that of the third order, and at least three orders of magnitude than the fifth and higher diffracted orders. In other words, the zeroth and first diffracted orders are dominant in diffraction pattern, which is similar to that of ideal sinusoidal transmission grating. As is known for the ideal sinusoidal transmission grating, there exist only the first far-field diffracted orders except the zeroth, i. e., it owns the property of pure single-order diffraction. Its amplitude transmission coefficient can be expressed as:

$$t(x)=\frac{1}{2}+\frac{2}{\pi}\cos\left(\frac{2\pi x}{d}\right). \tag{3}$$

It is evident that equation (2) is in form approximate to Eq. (3) if neglecting those minor Fourier series. Hereby, it is anticipated the far-field diffraction of the proposed device approximate that of the sinusoidal grating, which is critical for spectral resolving of broadband terahertz waves with the device.

In the same way, when the number of columns along axis Y is large enough, the device exhibits the same amplitude transmission profile as axis X. Therefore, the device will exhibit in 2D case the same dispersive property.

According to the grating equation with normal incidence: $d\sin\theta=m\lambda$ ($m=1$), we can gain, theoretically, the spectral distribution of broadband terahertz waves by measuring just the first diffracted order, free of the complicated spectral decoding process.

3. Experiments and discussion

Based on above analyses on the diffraction property of the device, an experiment to evaluate its far-field diffraction was conducted. We prepared a piece of device with 30 × 30 elements (with diameter a of 500 μm, period d of 1200 μm) on 1-mm-thick aluminum plate, as shown in Fig. 2.

The experimental setup is schematically shown in Fig. 3. The incident source was CO_2-laser-pumped continuous terahertz gas laser, which generated a collimated monochromatic terahertz beam centered at 2.52 THz. The terahertz beam propagated to cover the terahertz device at normal incidence. A terahertz focusing lens (with a focal length of f 50 mm) was placed tightly behind the device to image the far-field diffraction patterns onto a pyroelectric focal-plane-array (FPA) camera (with 124×124-pixels).

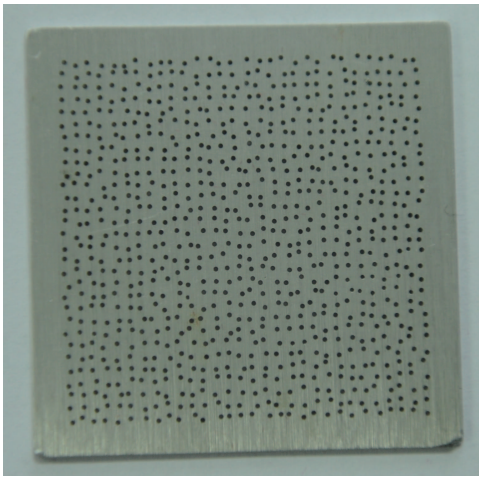


Fig. 2. (color online) Terahertz dispersive device.

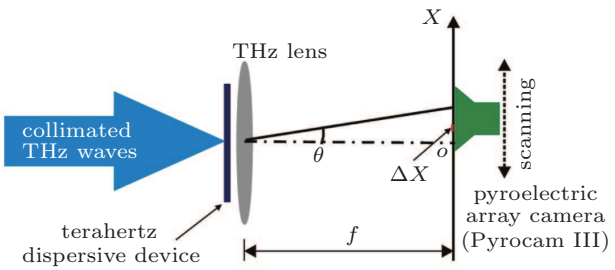


Fig. 3. (color online) Experimental setup for diffraction verification.

Since the number of pixels of FPA camera was not large enough, it was impossible to capture four or more orders of diffracted patterns within the limited sensor area. Hence, we captured the diffraction patterns by scanning along axis X. According to the theoretical far-field diffraction position of the m-th order expressed below by grating Eq. (4), since the period (d), incident wavelength (λ), and focal length (f) are all known, different orders of diffraction patterns can be located and captured by the camera.

$$x = f\tan\left(\sin^{-1}\left(\frac{m\lambda}{d}\right)\right) \quad m = 0, \pm1, \pm2, \pm3, \ldots \quad (4)$$

Figure 4(a) illustrates the diffracted patterns captured at position $x = 0$. Owing to relatively high noise level of the pyroelectric camera, the captured diffraction order is not easy to be recognized. However, the spatial patterns of the zeroth and first order marked within yellow quadrate frames, and the diffraction gap between the zeroth and first orders, which measures as 5.0 mm, are both agree well with the far-field numerical simulation given in Fig. 4(b). After a careful examination at the theoretical diffraction positions, the second, third and higher diffracted orders were not found, which is consistent with the above analyses on diffraction property of the device as mentioned in Section 2.

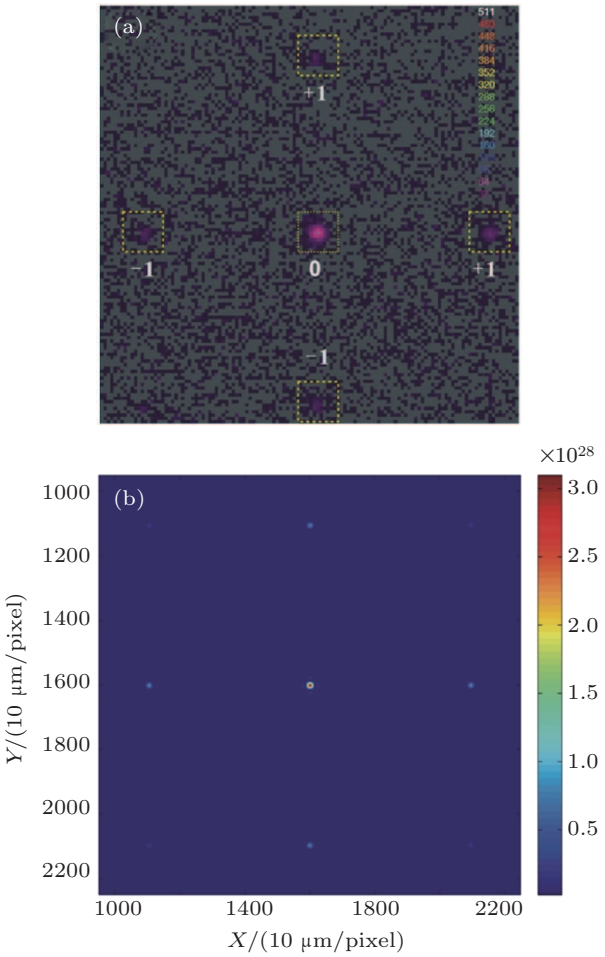


Fig. 4. (color online) Diffracted patterns of terahertz dispersive device at 2.52 THz: (a) experimental; (b) simulation.

The conventional sinusoidal grating is feasible and perfect to spectral dispersion in visible spectra, since only the zeroth and useful first order appears in diffraction pattern. However, in terahertz band, considering the particularity of the spectral region and different material response, no such ideal grating is available currently. Thereby, the device proposed in the paper aims to provide a dispersive device used in THz band, which exhibits a spatial diffracted patterns close to the sinusoidal grating in visible region, and thus acts the critical dispersive device in THz spectral measurements. Compared with conventional grating, since inherent high diffracted orders of conventional grating impose interferences on the useful first diffracted order, one cannot acquire the actual spectrum of

terahertz waves from just the first diffracted order, and usually needs complicated spectral decoding process. The advantage of this device is that a feasible THz dispersive device with near single-order diffraction like sinusoidal grating is provided in spectral measurements of THz waves, one can easily acquire the spectra through the diffracted first order pattern, free of complicated spectral decoding.

According to the grating equation, within the first diffraction angle (θ): $0^\circ \sim 90^\circ$, the spectral coverage of single-order diffraction device achieves, theoretically, λ: $0 \sim d$. Thereby, a terahertz wavelength region of 30 μm $\sim$ 1200 μm is desired to be resolved by the dispersive device, corresponding to a maximal terahertz region 0.25 THz$\sim$10 THz.

As to the spectral resolution of the device, when the diffraction angle (θ) is small, the spectral resolution can be expressed as: $\Delta\lambda \approx d \cdot \Delta x / f$, where d, Δx, f denote, respectively, the period of device, the spatial resolution of diffracted patterns on focal plane and focal length of terahertz focusing lens. When d and f are determined, the spectral resolution depends on the spatial resolution of diffraction patterns (Δx). In our experiment, a pyroelectric array camera with 100-μm spatial resolution was employed, then the spectral resolution is 2.4 μm, corresponding to a frequency resolution ($\Delta\nu$) of 80 GHz at the central frequency (ν) of 1 THz, which is equivalent to that of THz-TDS approach.

4. Conclusion

A new terahertz dispersive device owning the property of near single-order diffraction is proposed and experimentally validated, which provides an approach for direct single-shot spectral measurement of terahertz waves. Combined with appropriate terahertz detectors, the terahertz dispersive device can be used to measure the broadband spectrum of single-shot terahertz pulse.

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