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Reflective scanning imaging based on a fast terahertz photodetector

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ABSTRACT

The fast detection of terahertz radiation is recognized as a key technology of terahertz imaging systems. We realize a terahertz imaging system employing a terahertz quantum-well photodetector (QWP) and a terahertz quantum cascade laser (QCL). The detector can rapidly detect the 4.3THz light generated from a pulsed electrically-pump terahertz QCL, which is used as the terahertz source of the imaging system. The object is placed on a rotary scanning platform to realize fast scanning. A practical detection method of the terahertz pulse signal is employed to extract the amplitude information from the terahertz signal and improve the signal-to-noise ratio (SNR) of the system. The electrical and optical performances of the fast terahertz QWP are characterized, and the results show that the terahertz QWP can completely meet the fast detection requirement of the terahertz imaging system. The terahertz images of some invisible objects are obtained with a high contrast within 5 s. The imaging system owns a resolution of 0.3 mm and a circular imaging region with a diameter of 100 mm. An image processing algorithm is applied in this system to solve the noise problem and improve the quality of the images. The imaging results indicate that terahertz QWP has a good application prospect in nondestructive inspection applications and the research of the fast physical or chemistry process.

1. Introduction

Terahertz imaging [1] is one of the most important application in terahertz research because of the great penetrability of nonpolar materials, such as plastics, ceramics and hardboard. Terahertz waves technologies [2] can be applied in security or non-destructive examination [3,4]. Nevertheless, the high-efficiency practical terahertz emitters and detectors are deemed as the huge bewilderment of terahertz researchers for a long time. Due to the obvious advantages of high output power, high-efficiency, minute extension, handiness and easy-integration, the terahertz quantum-cascade lasers (QCL) [5,6] become the popular research orientation in field of terahertz emitters. The superiority of quantum-well photodetector (QWP) [7,8] compared with common detectors (bolometers [9], Golay-cell [10], pyroelectrics [11], etc.) lies in a fast response time at the ps level, so the terahertz QWP can be utilized in fast terahertz imaging systems. The terahertz QCLs and the terahertz QWPs have been employed as the sources and detectors respectively in terahertz imaging systems [12].

The fast detection [13] of terahertz radiation is of great importance for various applications such as fast imaging, high speed communications, and spectroscopy. Faster imaging methods and the systems should be put forward to solve the time-consuming problem in practical application. As reported [14,15], some fast imaging systems have been used in practical research. Some imaging devices such as scanning Mirror [16], cost-efficient delay generator [17] and spinning mirrors [18] have been employed to shorten the time in the terahertz imaging systems. More effective imaging methods (block-based compressed sensing [19], sparse rotating array [20], single-pixel imaging technology [21], etc.) and some devices (plasmonic antenna arrays [22], quantum cascade amplifier [23], blazed diffractive gratings [24], etc.) have been applied to improve the detection speed of the terahertz radiation in the systems. But the imaging time or the SNR of these systems should be improved further. In this paper, a fast two-dimension imaging system based on a fast rotating translational platform are realized by employing a 4.3 THz terahertz QCL and a spectrally-matched terahertz QWP as the source and the detector, respectively. And the images of some invisible objects are obtained with the time of 5 s.

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2. Performances of the device

Firstly, the electrical and optical performances of the terahertz QWP are characterized. The device schematic and conduction band profile of a 45° facet coupled terahertz QWP [8] is shown in Fig. 1(a). A 45° facet coupled geometry is employed to improve the coupling efficiency of the terahertz radiation. A quantity γ [8] is defined to show the normalized coupling efficiency of a light coupler to that of a 45° facet coupling scheme

$$\gamma = \frac{2\iiint_{MQMs}\left|E_Z\right|^2 dv}{\iiint_{MQMs}\left|E_0\right|^2 dv} \tag{1}$$

where E_0 is the electric field intensity in the multiquantum-well (MQW) region of a terahertz QWP with a 45° facet coupling scheme. Due to the special device structure of quantum well, the terahertz QWP owns a high response rate. Fig. 1(b) plots the photoresponse spectra of the terahertz QWP and the emission spectra of the terahertz QCL, the spectra of the terahertz QWP is well-matched with the terahertz QCL at the frequency of 4.3 THz. Fig. 1(c) gives the dark current of the terahertz QWP as a function of bias voltage at 5 K. To obtain the moderate background noise, the terahertz QWP works at the low dark current of 10^{-7} A below 150 mV, both in up and down sweeping mode. Fig. 1(d) shows the peak responsivity versus bias voltage characteristics of the terahertz QWP, a peak responsivity of 0.5 A/W is obtained in the bias voltage range from 50 to 100 mV. A microwave rectification technique [13] is applied to investigate the high frequency characteristics of the QWP device, the 6.2-GHz modulated terahertz light emitted from a Fabry–Pérot terahertz QCL is successfully detected using the fast terahertz QWP. In our experiment, the similar terahertz QWP is utilized to detect the terahertz radiation. An oscilloscope is employed to show the drive signal of the terahertz QCL and the response signal of the terahertz QWP. As depicted in Fig. 3(b), the results show that the terahertz QWP can detect well the fast-modulated terahertz signal. The characteristics indicate the ability of the terahertz QWP for the sensitive and fast detection in the terahertz imaging system.

3. Experimental setup

The experimental setup of the fast terahertz imaging system is shown in Fig. 2. A pulsed terahertz beam at the frequency of 4.3 THz is emitted by the terahertz QCL which is operating at 11 K and driven by a 3.0 A current with a 5% duty cycle at 1 kHz. The terahertz beam passes through the two off-axis parabolic (OAP1 and OPA2) mirrors, with focus length of 76.2 mm and 127 mm respectively, and a beam splitter (BS) mirror, with a reflectance ratio of 46%. Then the beam is focused onto the object which is placed on a reflecting mirror installed on the fast rotating translational platform. Compared with the traditional step scanning mode, the platform can substantially shorten the imaging time by employing a fast continuous scanning mode. The reflected beam goes through the OAP2, the BS and OAP3, with a focal length of 100 mm, successively. Finally, the beam is detected by the terahertz QWP which is placed in a cryostat at 4.2 K and driven by a bias voltage of 70 mV.

The signal of the terahertz QWP is read out by the source and preamplifier [12], and collected by a data acquisition (DAQ) pad. The platform is driven by a servo driver connecting with the same computer which contains a LabVIEW program. The location information and the corresponding amplitude information of the object are collected by the servo driver and the DAQ pad, respectively. The LabVIEW program is applied to control the DAQ pad and the servo driver at the same time and gather the information to restore the object. Under the influence of Rayleigh diffraction limit, the limit resolution δ of terahertz imaging system can be written as

$$\delta = \frac{0.61\lambda}{\mathrm{n} * \sin\theta} \tag{2}$$

where λ is the wavelength of the terahertz wave and $\mathrm{n} * \sin\theta$ is the numerical aperture of the terahertz imaging system, so a resolution on submillimeter level can provided by the terahertz imaging system. In addition, the final resolution of the object is also determined by the quality of the real terahertz imaging system. In order to demonstrate the resolution of this system, the beam profile in the object plane are obtained by a terahertz array which has 320 × 240 pixels and a pixel size of 23.5 μm, as shown in the inset of Fig. 2. And the beam waist are measured to be 0.45 mm and 0.3 mm in the horizontal and vertical dimensions, respectively.

4. Detection method

In the experiment, in order to increasing the SNR of the imaging system and avoiding the bandwidth limitation of the lock-in amplifier, as shown in Fig. 3, a detection method of the pulse terahertz signal is employed to extract the amplitude information of the corresponding point. Fig. 3(a) shows the pulse signal coming from the source of the terahertz QCL with a 5% duty cycle at 1 kHz. Fig. 3(b) gives the drive signal of the terahertz QCL and the response signal of the terahertz QWP, which are shown in an oscilloscope. It is obvious that the response signal can completely meet the requirements of the pulse signal detection method in the imaging system. After passing the object, the information of the object is added to the amplitude of the terahertz pulse, and the terahertz waves are detected by the fast terahertz QWP. The current signal of the terahertz QWP is read out and translated into an amplified voltage signal by a low noise current preamplifier, the pulse signal coming from the preamplifier is plotted in Fig. 3(c).

The voltage signal is collected by the DAQ pad with a sampling rate of 100 kHz. It is worth noting that a maximum date compression process with a ratio of one to one hundred is employed in the DAQ pad. That is to say, the maximum of the pulse signal in one cycle is regarded as the amplitude information of the corresponding point, as shown in Fig. 3(d). Finally, the computer which contains a LabVIEW program will receives the pulse signal handled by the DAQ pad and restore the object. We can improve the pulse repetition frequency of the terahertz QCL, based on the fast detection of the terahertz QWP, to more than 10 kHz to obtain more amplitude information and increase the pixels of the images. The detection method of the terahertz pulse signal in the present work can also be combined with other faster imaging mode, introduced in Ref. [16], to further improve the SNR and shorten the imaging time at the same time in further research.

5. Results and discussion

In order to explore the performance of the terahertz imaging system, we obtained the reflective images of some hidden targets. As exhibited in Fig. 4, the terahertz images of a dry leaf with different shelters, a plastic bag and a polyethylene lid, are acquired within 5 s. The size of the terahertz images obtained by this rotary scanning system is a circular region with a diameter of 100 mm, which include 5000 pixels. Special image plotting arithmetic is employed to transform the location and the signal amplitude information into the final terahertz images. Fig. 4(a) shows the photographic images and the THz image of the leaf which is covered with the plastic bag. The leaf is easily distinguished in the THz image, including the slender petiole and the covered part. In Fig. 4(b), the normalized signal amplitude along the line "m" in the THz image of Fig. 4(a) is demonstrated. It is easy to clearly see that the average amplitude of the mirror covered with plastic bag, the leaf covered with plastic bag, the leaf, and the mirror is about 0.48, 0.11, 0.13, and 0.71, respectively. This indicates the high contrast of the terahertz image very well. In order to estimate the distinction of the size between the real object and the THz image, by measuring the full-width half maximum of the signal amplitude, the distance between point A and B (d1) are calculated to be 1.478 cm compared with the real 1.480 cm. The result is credible and relatively exact.

Another THz image of the leaf that is covered with a polyethylene lid is exhibited in Fig. 4(c), and the three holes in the lid is clearly