文章编号:1001-9014(2012)03-0197-06 DOI:10.3724/SP.J.1010.2012.00197

Design of a T-shaped terahertz imager

GAO Xiang[1,2,3], LI Chao[1,2*], GU Sheng-Ming[1,2,3], FANG Guang-You[1,2]
(1. Institute of Electronics, Chinese Academy of Sciences, Beijing 100190, China;
2. Key Laboratory of Electromagnetic Radiation and Sensing Technology, Chinese Academy of Sciences, Beijing 100190, China;
3. Graduate University of Chinese Academy of Sciences, Beijing 100190, China)

Abstract: To achieve relatively high frame rates with relatively low costs, a T-shaped terahertz imaging system with beam-scanning function is presented. The system employs two orthogonally oriented co-polarized scanning fan-beam antennas arranged in a T-shaped configuration. Both transmitting and receiving antennas consist of a pyramid horn feed, a fixed elliptical main-reflector to generate thin fan beam, and a rotating sub-reflector to realize beam scanning function, all of which are embedded between two parallel metal plates. In this paper, specific design details of such a system were discussed, especially for the systematic method proposed to design a fan-beam scanning antenna with high performance. In addition, some experimental imaging results were shown, which demonstrated the capability of the system.

Key words: T-shaped terahertz imager; beam-scanning; elliptical main-reflector; rotating sub-reflector
PACS: 84.40.-x

一种T形太赫兹成像系统的设计

高 翔[1,2,3], 李 超[1,2,*], 谷胜明[1,2,3], 方广有[1,2]
(1. 中国科学院电子学研究所,北京 100190;2. 中国科学院电磁辐射与探测技术重点实验室,北京 100190;
3. 中国科学院研究生院,北京 100190)

摘要:为了获得较高的帧速率以及降低成本,提出了一种带有波束扫描功能的T形太赫兹成像系统.系统包含两个共极化扇形波束扫描天线,它们以T字形正交摆放.收发天线具有基本相同的内部结构,由角锥喇叭馈源、产生扇形波束的椭圆主反射体以及用于实现波束扫描功能的旋转次反射体构成,而所有这些元件都镶嵌在两个平行金属板之间.给出了T形太赫兹成像系统的具体设计,提出了设计高性能扇形波束扫描天线的系统化方法,最后给出了一些实验的成像结果,以论证系统的功能.

关 键 词:T形太赫兹成像系统;波束扫描;椭圆主反射体;旋转次反射体
中图分类号:TN958.94 **文献标识码**:A

Introduction

Because of its unique property different from the optical or infrared radiation: being able to 'see through' obscuring materials with relatively little loss, terahertz imaging has attracted great attention in the non-destructive testing[1-2] and security areas[3-4]. To exploit the potential applications of terahertz imaging, two typical approaches have been used to implement available terahertz imagers. The first is the focal-plane-array system[5-6], which can acquire an entire image at once. However, the high cost of the terahertz receivers makes the focal-plane-array system difficult to be widely used. The second approach is the scanned-antenna system[7], which mainly builds up an image over a two-dimensional plane through

Received date: 2011-04-18, **revised date**: 2012-01-18 **收稿日期**:2011-04-18, **修回日期**:2012-01-18
基金项目:国家自然科学基金(11174280);中国科学院知识创新工程(YYYJ-1123)
Foundation item: Supported by the National Natural Science Foundation of China (11174280); Knowledge Innovation Program of Chinese Academy of Sciences (YYYJ-1123)
Biography: GAO Xiang (1985-), male, Suzhou, China, Ph. D. Candidate. Research fields focus on terahertz antenna and terahertz imager. E-mail: guijianchou100@yahoo.com.cn.
* **Corresponding author**: E-mail: cli@mail.ie.ac.cn.

mechanically scanning an antenna with a single receiver. Hence, the scanned-antenna approach is usually accompanied by very low frame rates owing to the quite long scanning time. To achieve relatively high frame rates with relatively low costs, an effective way is to develop a terahertz imaging system with beam-scanning function[8-9]. In such a system, the beams of the transmitting and receiving antennas can scan without moving or rotating the whole antenna or system, which guarantees a quick imaging speed.

In this paper, a T-shaped terahertz imaging system with fan-beam scanning antennas is designed for the near field application. As an important component of the system, each antenna features a fixed elliptical main-reflector, a rotating sub-reflector and a pyramid horn feed, all of which are embedded between two parallel conducting plates. To reasonably design and implement such a terahertz imager, one of the important targets is to design and optimize the beam-scanning antennas with high performance. In this paper, A reversed ray tracing algorithm (RRTA) was introduced to minimize the aberration of the beam-scanning antenna and to determine the optimum positions and dimensions of the sub-reflector and the pyramidal horn. To further analyze and verify the performance of the antenna, a modified physical optics method based on discrete real mirror image theory (DRMI-PO) was developed to analyze the field patterns of the antenna with enough precision and reasonable computation complexity. Combined with a continuous wave source emitter and a Schottky diode detector, a T-shaped imager is designed and fabricated. Besides, imaging results of some typical objects with the imager are measured and discussed.

1 System scheme and antenna design

1.1 Imaging scheme and beam-scanning antenna

Fig. 1 shows the imaging scheme of the T-shaped terahertz imager. The system employs two orthogonally oriented co-polarized scanning fan-beam antennas arranged in a T-shaped configuration. The transmitting antenna has a fan-beam lying along y direction and scanning in z direction, while the receiving antenna has an orthogonal fan-beam lying along z direction and scanning in y direction. Hence, it's possible to cover a 2-D plane in a relatively short time as the intersection of the two beams moves.

Fig. 2 shows the inner structure of a fan-beam scanning antenna. It consists of two cylindrical reflectors and a pyramid horn feed. For the near field application, the fixed main-reflector is chosen as an elliptic reflector to focus the reflecting beam at a certain distance. The sub-reflector is a rotating one with small dimension, which is able to change the beam's direction by quick rotating. All the above components are sandwiched between two parallel metal plates. With small aperture size in z direction and focusing property in x-y plane, the antenna can produce a fan-beam lying along z direction and scanning in y direction, corresponding to the vertical antenna's beam shown in Fig. 1.

1.2 Design and optimization of the antenna with RRTA

According to high frequency approximation, the

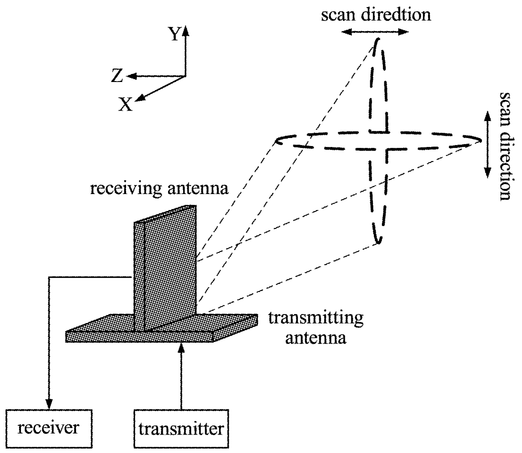

Fig. 1 Imaging scheme of the T-shaped terahertz imaging system
图1 T形太赫兹成像系统的成像体制

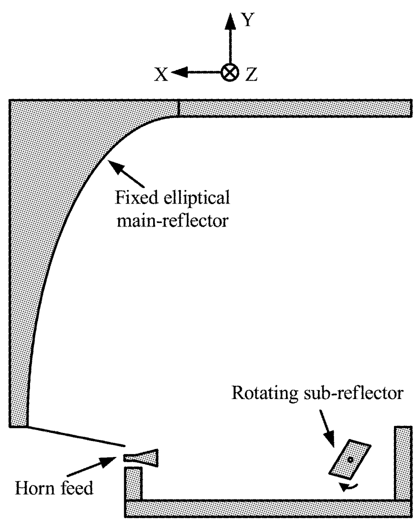

Fig. 2 Inner structure of a fan-beam scanning antenna
图2 扇形波束扫描天线的内部结构

beam generated from the horn feed and then reflected by the sub-reflector, can be considered as one directly transmitted by the mirror image of the horn feed to the sub-reflecting plane. During the sub-reflector's rotation, if the contour of the mirror image lies nearby one focus of the elliptical main-reflector, the final reflected beams will certainly converge near another focus of the ellipse. However, zero-aberration case only occurs when the mirror image of the horn is exactly situated at one focus of the ellipse. To simultaneously meet the requirements of beam focusing and scanning with aberration as little as possible for different scanning angles, a Reversed Ray Tracing Algorithm (RRTA) is introduced to derive the optimum contour of the mirror image.

Figure 3 shows the basic schematic of RRTA. The main idea of RRTA can be summarized as following: In the geometrical optics approximation, assume there are a bundle of incident rays, emitted reversely from a point on the imaging plane, shining upon the elliptical reflector and then reflected. If there exists a point in the first focal region which makes the mean square distance between itself and all the reflecting rays get minimal value, the point is reasonably to be chosen as the optimum position of the mirror image. For every point on the imaging plane, the corresponding optimum position of the mirror image can be found in the same way. With the optimum contour of the mirror image determined, the antenna parameters including the positions and dimensions of the sub-reflector and horn feed can be optimized through some optimization algorithms.

1.3 Analysis and verification of the antenna with DRMI-PO

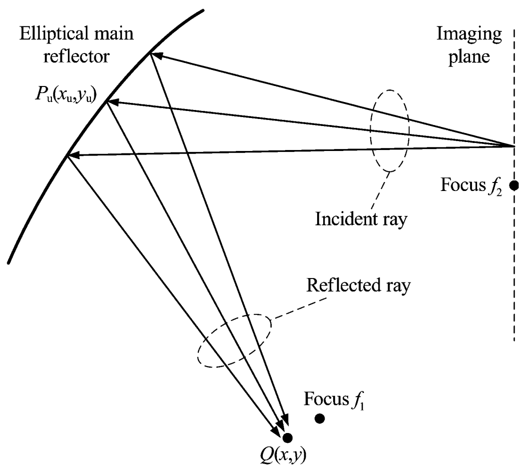

Fig. 3 Schematic of reversed ray tracing algorithm
图3 反向射线追踪法的原理图

With RRTA to minimize the aberration of the beam-scanning antenna, we have determined the optimum positions and dimensions of the sub-reflector and the feed horn. Next, we further analyzed and verified the performance of the antenna with electromagnetic simulation. Owing to the existing of two large metal plates in the antenna structure, traditional physical optics (PO) appears to be inapposite because it usually deals with standard 3D problem. Moreover, if the full wave method is applied, run time and memory requirements will be prodigious. To analyze this special antenna structure with enough precision and reasonable computation complexity, a modified physical optics method based on discrete real mirror image theory (DRMI-PO) is proposed here.

To start with, we may find that all the electromagnetic field between the two parallel metal plates can be solved based on the equivalent currents on the aperture of the horn. As shown in Fig. 4, based on the traditional discrete real mirror image theory (TDRMI), the current densities $\vec{J}$ and $\vec{M}$ inside two parallel metal plates can be equivalently transformed to an infinite summation of their images. However, due to the unique antenna structure with large electrical dimensions in x-y directions and small size in z direction, the field solutions in form of infinite summation derived from the equivalent currents usually converge quite slowly. To overcome the disadvantages of TDRMI, a modified version of the real mirror image theorem is developed as following.

First of all, it may be noted that equivalent currents $\vec{J}'$ and $\vec{M}'$ (infinite summation) are both a periodic function with respect to z, whose period is $2d$. Hence, they can be expanded into Fourier series

$$J'_\kappa(x,y,z) = \sum_{m=-\infty}^{\infty} J'_{m,\kappa}(x,y)e^{\frac{jm\pi z}{d}} , \quad (1a)$$

$$M'_\kappa(x,y,z) = \sum_{m=-\infty}^{\infty} M'_{m,\kappa}(x,y)e^{\frac{jm\pi z}{d}} , \quad (1b)$$

where subscript $\kappa = x,y,z$ represents the components

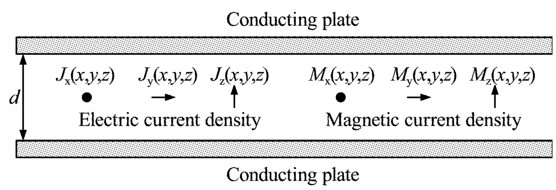

Fig. 4 Schematic showing the currents between two parallel metal plates
图4 两个平行金属板之间的电流和磁流示意图

in x, y and z direction, respectively. Besides, the coefficient $\vec{J}'_{m,\kappa}$ and $\vec{M}'_{m,\kappa}$ can be derived as the integrals of the original currents in the finite region[−d/2 d/2]. Due to the similarity of the field distribution on the aperture of a pyramid horn to the TE10 mode of its feeding waveguide, the series in (1) converge rapidly at small number of terms m = N. In the design of the antenna for the THz imager in this paper, N = 3 is enough for achieving desired precision.

Because that both the sub-reflector and the main-reflector have uniform structures along z direction, the vector potentials induced by each term of equivalent currents $\vec{J}'$ and $\vec{M}'$ degenerate to a two dimensional problem as

$$\nabla_{xy}^2 A_{m,\kappa}^J(x,y) + k_m^2 A_{m,\kappa}^J(x,y) = -\mu J'_{m,\kappa}(x,y) \quad , \quad (2a)$$

$$\nabla_{xy}^2 A_{m,\kappa}^M(x,y) + k_m^2 A_{m,\kappa}^M(x,y) = -\varepsilon M'_{m,\kappa}(x,y) \quad , \quad (2b)$$

where $k_m^2 = k^2 - \frac{m^2\pi^2}{d^2}$.

Finally, the total vector potential induced by the equivalent currents $\vec{J}'$ and $\vec{M}'$ can be expressed by the summation of small amount of terms with good convergence.

$$A_\kappa^{J,M}(x,y,z) = \sum_{m=-N}^{N} A_{m,\kappa}^{J,M}(x,y) e^{\frac{jm\pi z}{d}} \quad . \quad (3)$$

Based on the total vector potential, the electromagnetic fields can be derived.

Owing to the large dimensions of the structures in x-y directions, we can apply standard 2D physical optics for each term and then linearly combine them into the total fields. We named such a method as the modified physical optics method based on discrete real mirror image theory (DRMI-PO).

2 System design and experimental results

2.1 Design of the T-shaped terahertz imager

Based on the design methods which have been discussed in section 1, the T-shaped terahertz imager can be designed and fabricated based on two orthogonally oriented co-polarized scanning fan-beam antennas. Both of the antennas are made from stable aluminium alloy to minimize warping of the large parallel metal plates. The dimension of the transmitting antenna is approximately 750 mm × 830 mm × 55mm with an aperture of 680 mm × 5 mm. The receiving antenna has a total dimension of 747 mm × 860 mm × 56. 8 mm with an aperture of 680 mm × 6. 8 mm.

The two antennas have been elaborately designed and configured to make the centers of their scanning regions exactly overlap. Fig. 5 shows the configuration of the two beam-scanning antennas. With an offset of 361 mm from the fringe, the vertical receiving antenna is placed below the transmitting antenna, which is almost horizontal with 5. 7° declination. Based on such a configuration, the resulted imager can produce a 60 cm × 60 cm imaging region at the distance of 2. 33 m.

To design a T-shaped imager for a state-of-proof purpose, an incoherent detection is used to get the amplitude of the returning terahertz wave. Fig. 6 shows the working schematic of the T-shaped terahertz imaging system. The 100 GHz signal, generated by a Gunns oscillator, is modulated with a tunable modulator and converted to a 0. 2THz output signal by a frequency doubler. After a certain extent of attenuation, the 0. 2 THz signal is then transmitted by the horizontal beam-scanning antenna. The reflected signal from the objects is received by the vertical beam-scanning antenna, detected by a Schottky diode detector, and then amplified at the intermediate frequency. After being filtered and digitalized, the detected signal is sent to a PC for data processing and imaging processing. In addition, a scanning control system is constructed to make the two sub-reflectors rotate in specific sequence. Fig. 7 shows the scanning manner of the T-shaped terahertz imaging system. Based on the quick rotation of the sub-reflector inside the transmitting antenna with the max speed of 20 cycles per second, the scanning of the vertical fan-beam in the horizontal direction can be repeated rapidly with equivalent maximum speed of 40 rows per second due to the symmetry of the sub-reflector. Synchronously, the sub-reflector inside the receiving antenna rotates with a relatively low speed to realize the gradually moving of the intersection of the two beams in the

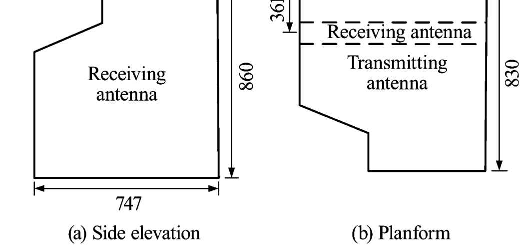

Fig. 5 Schematic showing the configuration of the two beam-scanning antennas
图5 波束扫描收发天线的配置示意图

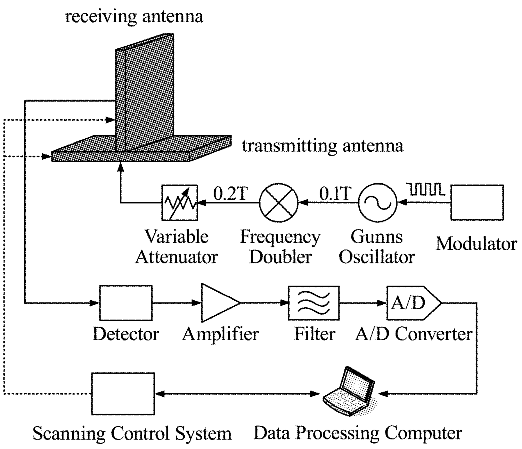

Fig. 6 Schematic of the T-shaped terahertz imaging system
图6 T形太赫兹成像系统的系统框图

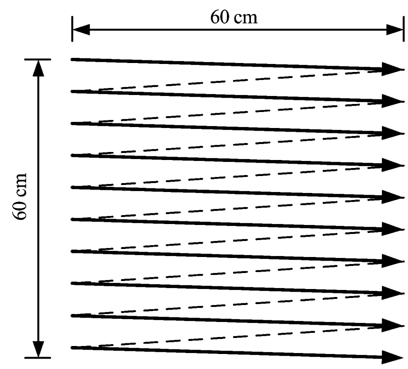

Fig. 7 Scanning manner of the T-shaped terahertz imaging system
图7 T形太赫兹成像系统的扫描方式

vertical direction from up to down only once during the whole time of imaging. The resulted scanning trace which is effective to the imaging is illustrated as the solid lines in Fig. 7.

Regardless of the receiver's sensitivity, such an imager can produce very high frame rates in potential. However, the practical imaging speed of the whole system is still limited by the sensitivity of the receiver which employs the G-band detector as its essential component. Due to the existence of the flicker noise at the output of the detector at the intermediate frequency, the signal-to-noise ratio (SNR) will be affected by the modulation frequency. Since the flicker noise matches the $1/f$ shape in theory, the SNR will decrease in the low frequency band where the flicker noise plays the main role rather than thermal noise [10]. We found that, the impact of the flicker noise on the SNR can be reduced to a negligible extent as the modulation frequency being increased higher than 10 kHz. Therefore, the frequency to modulate the Gunns oscillator in our imaging system is finally chosen to be 10 kHz, to obtain an optimized sensitivity with not very high data rate. The band width of the intermediate frequency bandpass filter is chosen as 2 kHz to make a compromise between the noise bandwidth and the edge blur for the 0.2 THz images of the objects. Based on the above configurations, a 60 cm × 60 cm image can be obtained at a distance about 2.3 m within 20 s. The corresponding maximum SNR is about 900, and the spatial resolution is about 1.5 cm.

2.2 Imaging results and discussion

Fig. 8 shows the imaging results of several test objects with the T-shaped terahertz imager. The upper section of every sub-figure is the photograph of the specific object such as a knife, a spanner, a metal bottle with a metal cap, two little metal bottles with plastic caps, a back cover of a cell phone and a metal letter H target; the lower section shows the corresponding imaging result of every test object. The experimental results demonstrate the capability of the T-shaped terahertz imager to detect objects.

The imperfections of the images can be observed by comparing them with the realistic objects. This may result from complex factors, including the non-uniform distribution of the fan beam, the different orientations in the different parts of an object with respective to the incident waves, and contribution of the scattering at the sidelobes of the beam. By offsetting appropriately the above effects in the further imaging processing procedure, the imaging quality can be further improved, especially in a system with coherent detection which can obtain the phases of the reflecting waves to realize more advanced and effective imaging algorithms.

3 Conclusion

Design of a T-shaped terahertz imager with fan-beam scanning antennas has been presented in this article. The RRTA and DRMI-PO are both proposed and developed to effectively design and efficiently analyze the antenna with special structures and electrical large dimensions, which is essential for the imager. Based on the incoherent detection, a 0.2 THz imager with state-of-proof purpose is developed to verify the effectiveness of the imaging scheme and the design procedure. To further improve the imaging quality and the speed, coherent detection with higher sensitivity and phase information can be applied.

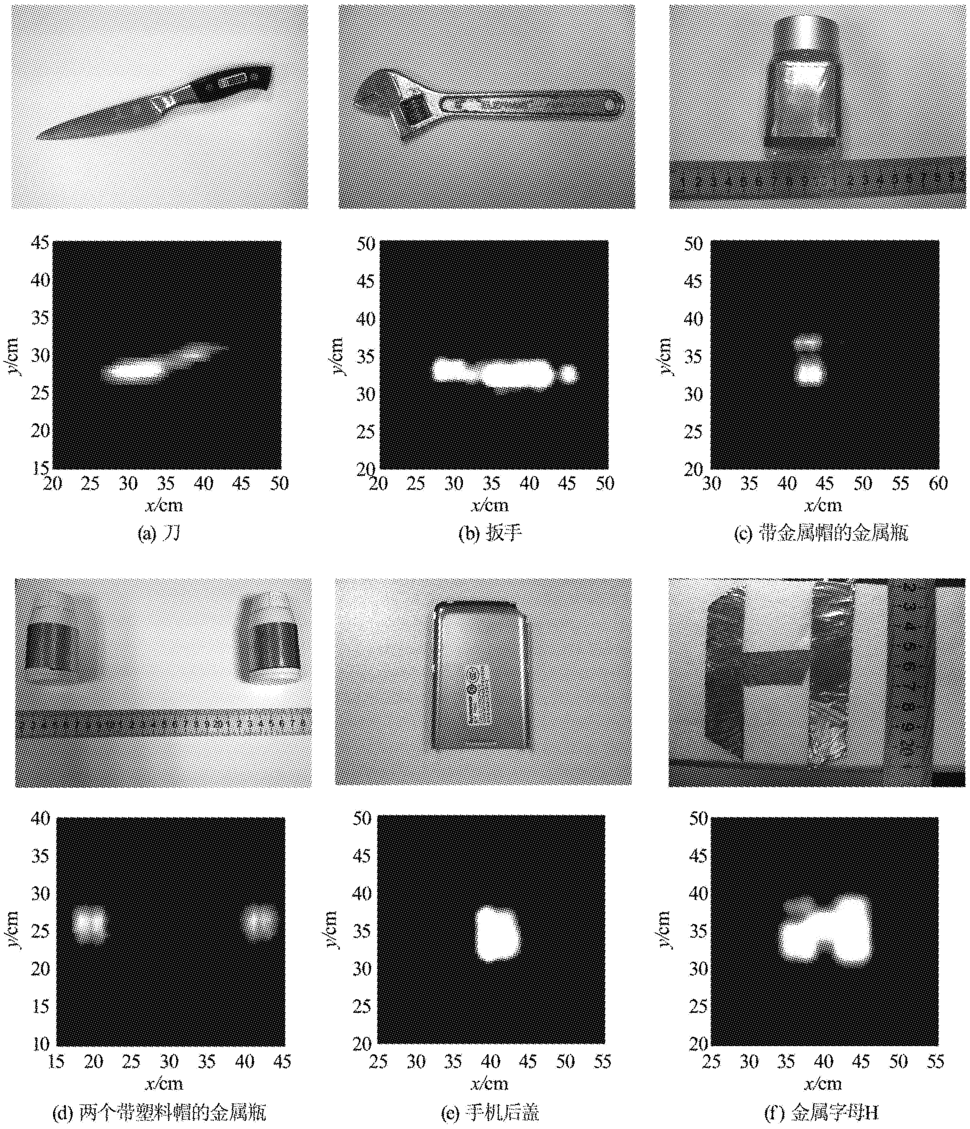

Fig. 8 Photograph and imaging results of several test objects
图8 几个测试目标的实物照片和成像结果

REFERENCES

[1]ZHOU Yan, MU Kai-Jun, LU Mei-Hong, *et al.* Characteristics and application of terahertz imaging non-destructive detection[C]. 31*st International conference on IRMMW-THz*,2006:156.

[2]Fitzgerald A, Cole B, Taday P. Non destructive analysis of tablet coating thicknesses using terahertz pulsed imaging[J]. *Journal of Pharmaceutical Sciences*, 2005, **94**: 177－183.

[3]Appleby R, Bruce W H. Standoff detection of weapons and contraband in the 100GHz to 1Thz region[J]. *IEEE Trans Antennas Propagat.* ,2007,**55**(11):2944–2956.

[4]Vizard R D, Doyle R. Advances in millimeter wave imaging and radar systems for civil applications[C]. *International Microwave Symposium Digest*,2006:94–97.

[5]Goldsmith F P, Hsieh T C, Huguenin R G. Focal Plane Imaging Systems for Millimeter Wavelengths[J]. *IEEE Trans. Microwave Theory Tech*,1993,**41**(10):1664–1675.

[6]Robert W H, Dennis H B, Robert J B. Multi-beam millimeter-wave focal plane array airbone imaging system[C]. *SPIE vol.* 2211:302–312.

[7]Smith R, Sundstorm B, Belcher B. Radiometric one second camera (ROSCAM) airborne evaluation[C]. *in Proc. Int. soc. Opt. Eng.* ,1999,**3703**:2 - 12.

[8]Schulwitz L, Mortazawi A. A broadband millimeter-wave dual polarized phased array for radar front end applications[C]. *International Microwave Symposium Digest*,2005.

[9]Frank G, Hue P T, Jochen W, *et al.* Optimization of a fast scanning millimeter-wave short range SAR imaging system[C]. *European Radar Conference*,2007,24–27.

[10]A van der Ziel. Noise in solid-state devices and lasers[C]. *Proceedings of the IEEE.* , 1970, **58** (8): 1178－1206.