Advances in CODE V design in terahertz imaging system

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Abstract. The band of terahertz (THz) spans from microwave to infrared bands, which belongs to the transition band from macro-electronics to micro-photonics, possessing peculiarities different from electromagnetic waves in other bands. THz technology with the characteristics of high penetration, broadband, high resolution and transient are employed in various fields, such as space remote sensing, nondestructive detection biomedical imaging and near-field microscopy. These broad applications, in turn, provide incentive to further improve the basic performance of THz technology. Aiming at the application of terahertz technology in the imaging field, this novel mainly discussed the basic principle, key devices, system composition, technical advantages and future development trend of terahertz imaging system. The application status of CODE V optical design software in designing scanning lens systems for terahertz imaging, such as free-form surfaces, non-free surfaces and multi-lens groups are further discussed in this paper.

Keywords: terahertz; imaging system; non-free surface; CODE V.

1. Introduction

Terahertz (THz ,1 THz=1012 Hz) wave is usually a general term for electromagnetic waves with a frequency range of 0.1~10 THz, and the corresponding wavelength range is 3 mm~30 μm[1]. The frequency of THz wave is between millimeter wave and infrared light (as shown in fig.1), is a special electromagnetic wave segment that transits from macroscopic electromagnetic field theory to microscopic quantum theory.

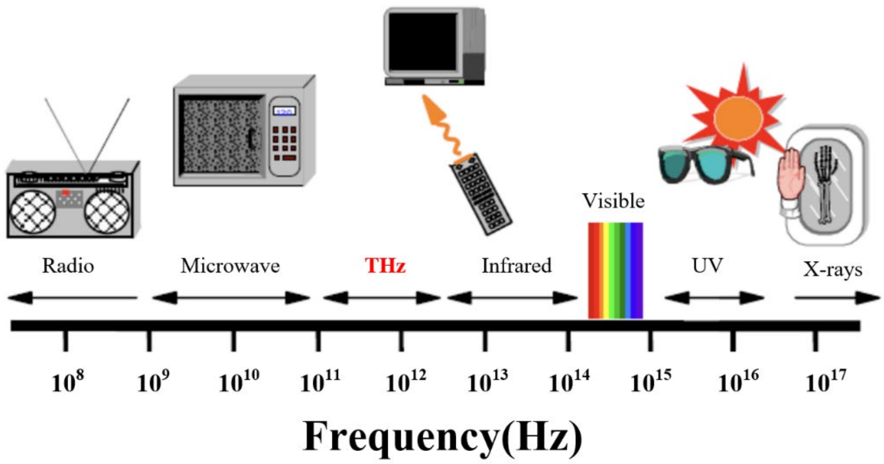

Fig. 1. THz waveband in spectrum

Terahertz wave, which is between millimeter wave and infrared light, is a special electromagnetic wave segment transiting from macroscopic electromagnetic field to microscopic quantum theory. This unique wave-band was discovered at the beginning of last century. However, due to the lack of effective methods to generate and detect THz waves, the research of this band can neither be completely explained by the classical microwave theory nor by the physical-optical principle[2]. For a long time, although the research on the microwave and infrared bands on both sides of the THz band has been mature, until the 1980s, the related research on the terahertz band was still extremely poor, so that this band was long called the terahertz gap in the electromagnetic spectrum by scientists. Since 1980s, ultrafast laser technology and research on semiconductor materials have made rapid progress, which provided a reliable emitter for generating broadband and stable terahertz pulses.

These technologies enabled the rapid development of terahertz technology and set off a worldwide upsurge of terahertz wave research.

Terahertz technology is an important frontier interdisciplinary subject. Compared with other electromagnetic wave bands, THz waves have many unique properties. The time-domain spectrum signal-to-noise ratio of terahertz waves is much stable and much higher than the infrared spectrum, which can reach greater than 104 and therefore suitable for THz imaging technology application[3]. The instantaneous bandwidth of terahertz wave is very wide, usually the frequency band of a single pulse is 0.1~10 THz, which is very suitable for high-speed communication technology and is also beneficial to analyze the spectral properties of substances. In remote sensing applications, molecules in the atmosphere such as H2O, CO, CO2 and O2 have strong absorption peaks for millimeter wave and terahertz wave[4].The THz absorption characteristics can be used to detect the water vapor layer and temperature in the atmosphere, so as to forecast the weather (for example, water molecules have absorption peaks around 28 GHz and 89 GHz).

In radio astronomy, since there are a large number of millimeter wave and terahertz radiation backgrounds in the universe, electromagnetic waves in this range can be used to study the formation of celestial bodies and the evolution of the universe, and also to measure the background radiation of the universe[5]. Presently, many domestic and foreign research institutions have established astronomical observatories using millimeter wave and terahertz, including Arecibo Observatory located in Puerto Rico Island (which collapsed in December 2020), ALAM Astronomical Telescope and FAST Observatory in China (millimeter wave band has not yet been opened). At present, in terms of application, some passive and active imaging products have appeared in terahertz imaging. T3000, T5000, 94 GHz imager used in American airport security inspection, and products of many domestic units.

A remarkable advantage of terahertz imaging is that its spatial resolution is stronger than microwave, and its penetration is better than that of light wave. Furthermore, compared with X-ray imaging, it belongs to non-ionizing radiation and is safer[6]. In military applications, millimeter wave and terahertz technology can be used for radar and guidance. The outstanding advantages of millimeter-wave radar are narrow beam, high angular resolution, small volume, light weight, ability to penetrate fog and smoke, and anti-interference ability. In the above application systems, reception, transmission and processing of millimeter-wave and terahertz are involved. In the traditional transmission method, the transmission line theory is used to analyze the signal. However, an obvious defect of transmission line in millimeter wave and terahertz frequency band lies in its loss and size. With the frequency increased, the loss per unit length of transmission line will increase accordingly. At the same time, the physical size of the corresponding transmission line will be reduced accordingly, which brings higher requirements for processing. In addition, due to the decrease of size, the power of system will also decrease at the speed of square rate (proportional to the cross-sectional area of the transmission line). Furthermore, the polarization processing ability of transmission lines is limited, such as rectangular waveguide. Finally, the transmission line has a certain working bandwidth, while the frequency band from millimeter wave to terahertz is always wide.

In this review, the principle of THz and its advantages in application are summarized, and the typical structure, basic principle and application scenarios of THz imaging system are introduced. Aiming at the application of CODE V software in the design of THz imaging system, this paper mainly introduces the optical design of THz microscope and THz telescope system. Furthermore, the future development of THz and the design of optical system are prospected.

2. Terahertz imaging

2.1 Terahertz imaging system

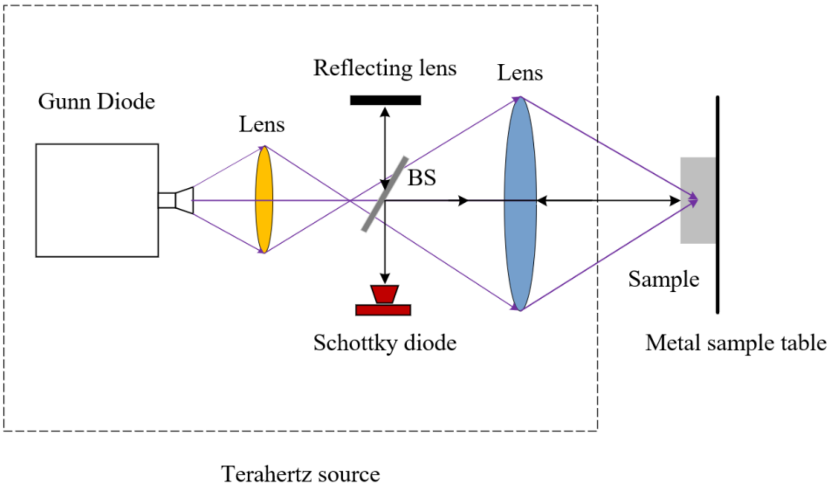

Fig. 2. Typical schematic of THz imaging system

THz imaging can be divided into two categories: continuous wave and pulse wave imaging. As shown in fig. 2, THz wave signals was collected and then wave amplitude information were obtained for real-time imaging. Gunn diode is served as the radiation source and the THz waves radiated by Gunn diode passes through the beam splitter (BS) then focused on the sample by the lens to be measured. Finally, the signal is detected by Schottky diode and oscillator, which both amplitude and phase information for imaging can obtain. THz system has two common modes: transmission mode and reflection mode. THz pulse will carry information after irradiating the sample, and at this time it will react on the detector together with the detection pulse to realize signal acquisition. According to the equivalent time-interval sampling theory, the time-domain THz wave signal will be restored to realize the detection of THz pulse.

2.2 Terahertz imaging principle

Two-dimensional images can be obtained by moving the sample and scanning point by point. Presently, some researchers have proposed that the frequency modulation of continuous THz waves based on the principle of triangular wave modulation can achieve acquisition of different depth information in the sample. According to the diffraction effect, in the process of optical imaging, a point object is not a point image after passing through the optical system, which fundamentally limits the imaging performance of the optical system.

Continuous imaging system uses THz signal intensity information to image, and when THz pulse acts on the sample, it can obtain its transmitted or reflected waveform. Among them, the refractive index, absorption coefficient and thickness of the measured sample will change the pulse amplitude and phase of THz wave[7]. By translating the sample, THz waveforms at different points can be obtained, so that a complete THz image of the measured sample can be constructed pixel by pixel. Because each pixel contains a complete time domain waveform, the maximum amplitude, minimum amplitude or arrival time of THz time domain waveform can be used to reconstruct a two-dimensional image, and the amplitude or phase of a single frequency point can also be used to reconstruct the image after Fourier transform.

Internal structure of three-dimensional objects can be imaged by the THz tomography. Taking the amplitude of time domain waveform at a specific time point as the imaging feature, the two-dimensional image can be reconstructed, and the three-dimensional image of the measured object can be reconstructed by stacking the two-dimensional images at different time points. The time resolution of THz pulse is in the order of picoseconds, so the time-of-flight method can determine the position of the interface with micron resolution, and can also obtain the refractive index information of the substance by analyzing the reflectivity at the interface.

3. CODE V design in terahertz imaging system

CODE V software has contributed significantly to important technological advances across a wide spectrum of fields such as projection displays, medical instrumentation, advanced military technology and space exploration. CODE V has been instrumental in the development of highly advanced optical systems, sometimes with profound effects on business and culture. It has been used in the development of revolutionary applications[8]. CODE V algorithms are a key and dominant technology in the design of the micro lenses.

In terahertz optical systems, the lens group is often not a standard lens but a combination of multiple free-form surfaces. Free-form surfaces in optics refer to surfaces that cannot be represented by spherical or aspherical coefficients, mainly including any unconventional surfaces, asymmetric surfaces, micro-structure array surfaces and surfaces of any shape represented by parameter vectors[9]. Free-form surfaces of any shape represented by parameter vectors are used, including Bessel surfaces, B-spline surfaces and non-uniform rational B-spline surfaces. In the process of designing and manufacturing free-form surfaces, interferometer is used to measure the surface of the machined optical element, and the machining error represented by the polynomial of the interference pattern is obtained. Based on the function of the CODE V interferogram file, the polynomial corresponding to the interference pattern is introduced into a specific surface as error data, so that the surface shape error or wavefront aberration is added to the optical surface[10]. By analyzing the optical evaluation parameters change before and after introducing errors, the influence of surface error or wavefront aberration on the imaging performance of optical system is quantified. Adopted the above method, different distribution forms of errors are added to a specific optical surface, and various optical parameters are integrated to explore the error distribution forms that are beneficial to improving the imaging performance of the optical system.

However, it is still difficult to design an optical system with free-form surfaces by optical design software[11]. XY polynomials can be used to describe free-form surfaces in CODE V, and UDS module in CODE V can be attached to design optical systems with free-form surfaces. Since bicubic B-spline surface is intuitive and easy to control shape, the number of mesh vertices and the order of surface are independent and easy to modify locally, thus bicubic B-spline surface is applied to describe free-form surface. The characteristic mesh of bicubic B-spline surface consists of control vertices V, and its equation is usually expressed by the following formula 1.1:

$$P(u,w) = UBVB^T W^T \tag{1}$$

Where $V = \begin{bmatrix} V_{11} & V_{12} & V_{13} & V_{14} \\ V_{21} & V_{22} & V_{23} & V_{24} \\ V_{31} & V_{32} & V_{33} & V_{34} \\ V_{41} & V_{42} & V_{43} & V_{44} \end{bmatrix}$, U and W are parameter matrices of u and w.

In freeform surface design, it is usually necessary to design a new surface based on a prototype surface. Therefore, it is necessary to reverse the polygon mesh based on a prototype surface, and then constantly modify the polygon mesh to finally obtain a satisfactory surface. Since no existed prototype surface appeared previously, interpolation inverse calculation is needless. When describing free-form surfaces in CODE V, we directly give control vertices and directly simulate them according to the equation of bicubic B-spline surfaces.

This paper mainly focus on imaging system as microscope and telescope in THz imaging, listed as two examples. In 2008, Sunmi Kim group reported a laser terahertz (THz) emission microscope

(LTEM) uses terahertz (THz) emission excited by femtosecond (fs) laser pulses for two-dimensional mapping[12]. For high resolution imaging, the combination of hemispherical solid immersion lens (SIL) and LTEM with transmission detection mode is adopted. Both the detected fs laser pulse and the generated terahertz emission use the same optical elements. The optical elements on the incident side of the sample are only used to manipulate the fs pulse, while the optical elements on the transmission side are only used to manipulate the terahertz emission, four typical methods were shown in fig 3(a-d). At 780 nm, the spatial resolution can be improved within 1.5μm by combining a hemispherical SIL with refractive index n = 1.98 with an objective lens.

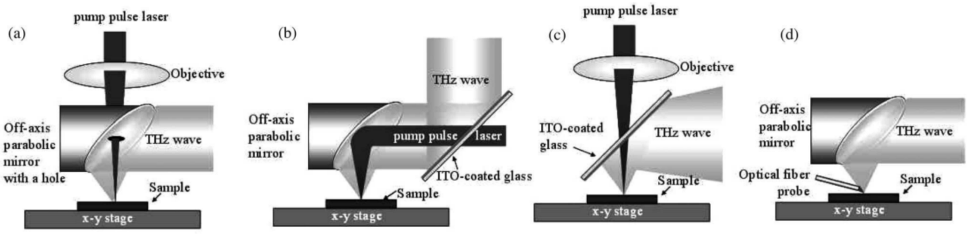

Fig. 3. (Ref. [12]) Structures for irradiating a laser and collecting THz wave using (a) the off-axis parabolic mirror with a hole, (b) the off-axis parabolic mirror without a hole and the ITO-coated glass, (c) the objective lens and the ITO-coated glass, (d) the optical fiber probe and the off-axis parabolic mirror.

Research group from University of Auckland [13] designed aspheric lenses system used in THz imaging, then evaluate the different lens designs using Kirchhoff's scalar diffraction theory and experiment. They used a terahertz time domain spectroscopy (THz-TDS) device to verify the results of Kirchhoff's scalar diffraction theory. Terahertz source is a surface emitter, pumped by Ti:S laser (80 fs, 800 nm pulses), while detector is a commercial terahertz antenna from EKSPLA, gated by delayed pulses from the same laser. The focal length of oapm for THz beam collimation with f = 75 mm. The phase-locked amplifier is used to record the current generated by terahertz wave in the antenna. The THz spectrum extends from 0.1 THz to 1.5 THz, and the peak value is about 0.4 THz. The entire frequency range can be evaluated by scanning the time delay between the pump pulse and the probe pulse once, shown in fig. 4(a). Three types of lens are used to ensure wavefront from a collimated incident beam converges into a focal spot and each 'ray' travels the same optical distance, while lens design with no spherical aberration, shown in fig.4(b-d) respectively.

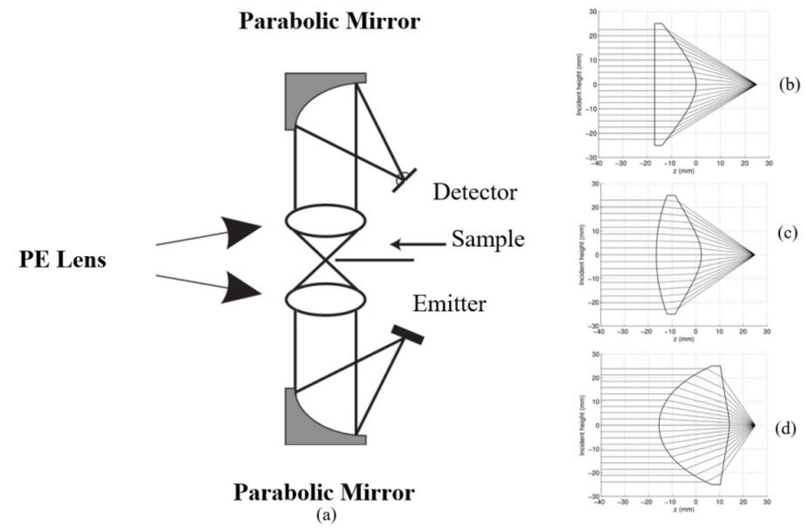

Fig. 4. (Ref. [13]) Schematic of THz scanning system(a), the planar-hyperbolic (p-h) lens(b), the elliptical-aspheric (e-a) lens(c), the symmetric-pass (s-p) lens(d).

A double pinhole (two holes in 80μm thick brass sheet) is used as a sample. The hole diameter is 0.25 mm, and the hole spacing is 0.4mm. Terahertz images of pinholes were measured by performing x-y scanning (step size of 50 μm in each direction) on the focal planes of three different lenses. According to Rayleigh criterion, when the light intensity at the saddle point is less than 81%, the images of two pinholes can be distinguished, so only the s-p lens pair can clearly distinguish the two pinholes. In the experiment, both e-a and s-p lenses can distinguish images, but the performance of s-p lens is much better, shown in fig.5.

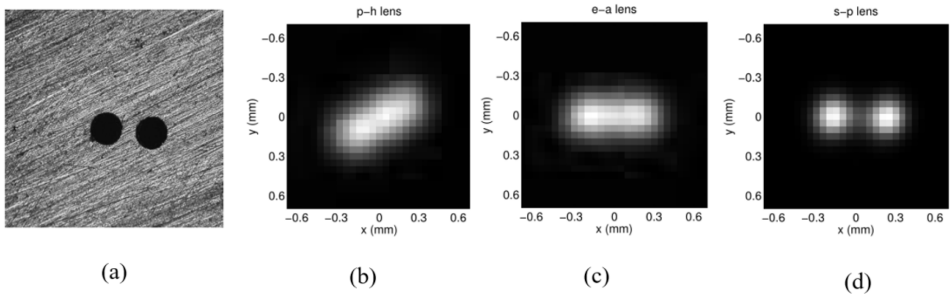

Fig. 5. (a) Double pinhole used as the imaging sample; (b) Imaging result for p-h lens; (c) Imaging result for e-a lens; (d) Imaging result for s-p lens.

In 2021, NASA designed the Orbiting Astronomical Satellite for Investigating Stellar Systems[14] (OASIS), which is a 17 meters class space observatory performed heterodyne and high spectral resolution observations ranging from 81 to 659 micrometers at terahertz wavelength. The telescope has to be highly efficient over the wavelength range. As is shown in fig 4, the surface of the inflatable main antenna A1 is Henky surface, 4th or higher order deformation of reflector surface which is corrected by following 3-mirror correction optics. In order to realize this rapid turnaround of measurement and manufacturing process, it is necessary to consider the optical design of correcting optical elements. The design with thin reflective field lens or all refractive design increases overall photon throughput while accommodating broad band spectral range.

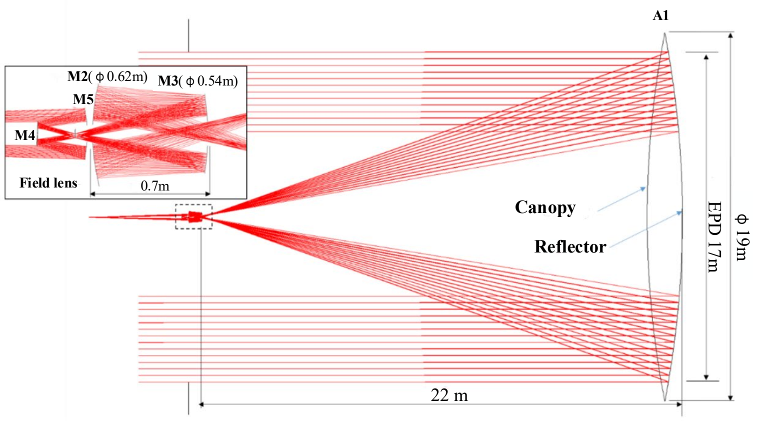

Fig. 6. (Ref. [14]) The design of OASIS optical system, collection area is > 120 m2 field of view (FOV) of ± 0.05 deg with a scanner and over 0.2 degrees.

4. Conclusion

Terahertz imaging field has developed from a promising curiosity to a booming research discipline, with increasing commercial application and scientific influence. Advances in both hardware and signal processing continue to open new frontiers. The future research direction of THz imaging mainly includes the following aspects. (1) High-power THz source is one of the keys to improve the stability of imaging system. Therefore, the research and development of real-time, large depth of field and super-resolution imaging system combined with THz quantum cascade laser technology is the focus of all fields; (2) Integrating programmable technology with metamaterials, and further moving towards THz frequency band; (3) AI algorithm is introduced into THz band to establish the model, and the information mapping relationship of THz conventional imaging optical system is established by deep learning method to realize the system construction. In the above development directions, the optical design software is vital important for the design and processing of optical systems, so the integration and improvement of CODE V software will help to improve the accuracy and efficiency of design.

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