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An Optical Camera Design and Application for the Terahertz Spectrum Analysis

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Abstract

To improve the accuracy of Terahertz spectrum analysis, the design idea of optical-mechanical integration was adopted. Firstly, with the help of Zemax's optical analysis and optimization functions, a secondary aspheric TPX plano-convex lens was designed to improve the lens's ability to focus Terahertz beams; then 4 identical TPX plano-convex lenses were used to build a Terahertz beam shaping optical system, so that the most Terahertz spot size focused on the sample was just 0.81mm; finally, an optical camera used for Terahertz spectrum analysis was designed based on the complete optical system, and the camera was used in the Terahertz time-domain spectroscopy system. Terahertz spectroscopy tests were performed on moxifloxacin hydrochloride and levofloxacin. The results showed that the optical camera achieves emission and detection of Terahertz signal. The obvious differentiated data can be seen after the signals collected by the lens were processed, providing a basis for the non-destructive identification of substances.

Keywords

Terahertz; Optical camera; Spectrum analysis.

1. INTRODUCTION

Terahertz waves are the general term for electromagnetic waves which are between microwaves and infrared, with frequencies ranging from 0.1 THz to 10 THz and wavelengths from 0.03 mm to 3 mm [1]. The weak interaction forces (hydrogen bonds, van der Waals forces), skeleton vibrations and dipole rotations within or among macromolecules are just in the Terahertz range, therefore, in the Terahertz range, different macromolecular materials exhibit specific absorption characteristics and dispersion, that is "fingerprint spectrum", the characteristics can be used for the non-destructive identification of substances [2] [3].

Generally, when performing the Terahertz spectrum tests, a wide-range Terahertz photoconductive antenna is used, and the antenna emits a Terahertz beam with a certain divergence angle. Therefore, it is necessary to design a corresponding optical camera to shape the Terahertz beam, thus to improve the Terahertz energy density of the sample penetrated and increase the accuracy of sample identification [4][5].

2. DESIGN OF TERAHERTZ BEAM SHAPING OPTICAL SYSTEM

Currently, the most widely used commercial Terahertz photoconductive antenna is MenloSystems' 1560nm fiber-coupled antenna module [6]. This article uses TERA15-TX-FC as a wide-range Terahertz source and TERA15-RX-FC as a Terahertz signal detector. The Terahertz beam divergence angle of TERA15-TX-FC is ±12.5°, and the electrode gap on the crystal is 100μm, while the TERA15-RX-FC's Terahertz beam acceptance angle is ±12.5°, and the electrode gap on the crystal is 10μm. Therefore, the Terahertz source and detector can be regarded as the point source and point detector, and the divergence angle and reception angle are both ±12.5°. A transmissive optical system is used to shape the Terahertz beam [7].

2.1. Section Headings

Polymethylpentene (TPX) is the lightest material among all known polymers, it is optically transparent in the UV, visible and Terahertz ranges, it's refractive index is about 1.46 and is relatively independent of wavelength [8]. Therefore, TPX is generally regarded as the manufactured material of Terahertz lens, TPX lens can be molded by mold, and the surface quality is stable [9].

In order to reduce the processing cost and installation difficulty of the single lens and the optical system, four identical plano-convex lenses are used to form the Terahertz beam shaping optical system. A plano-convex lens is a lens with a positive focal length and with a flat surface and a convex surface, it is generally used for beam collimation or focusing, and at the same time, in order to reduce spherical aberration, the parallel light is generally placed on the convex side and the focused light is placed on the plane side.

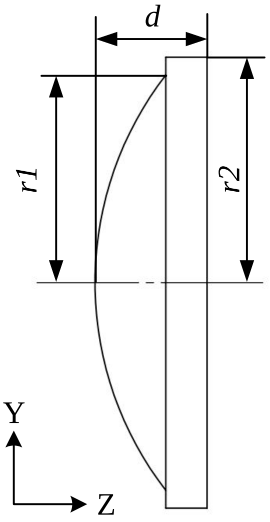

Fig 1. Structure parameters of the plano-convex lens

In order to increase the Terahertz energy density focused on the sample, the aspherical coefficients are introduced into the plano-convex lens to further enhance the focusing ability of the lens. The expression of the quadratic aspheric equation follows:

$$z(x,y)=\frac{c(x^2+y^2)}{1+\sqrt{1-(1+k)c^2(x^2+y^2)}} \tag{1}$$

Where c is the radius of curvature, k is the conic surface constant, when k=0, the equation (1) is the spherical equation where the center of the sphere coincides with the origin of the coordinate.

Since the main function of the plano-convex lens in the Terahertz optical path is to collimate and focus the Terahertz beam, in the single lens design, the beam parallel to the optical axis is used as the incident light and the focused spot size is used as the inspection standard. Considering the beam parameters of the Terahertz source, the optical path layout, and the lens installation. The initial focal length l is 50mm during the design of the initial structure of the plano-convex lens. Establish TPX materials in the Zemax glass library, and select three typical ranges of 300μm (1.0 THz), 3000μm (0.1 THz), and 30μm (10.0 THz), and among them, 0.1~1.0 THz is also the area with the largest wide-range Terahertz energy ratio. Focusing spot was taken directly as the optimization target, and the best set of lens parameters was found through the combination of local optimization and Hammer Optimization.

Table 1. Optimization parameters of the plano-convex lens

r1/mm	r2/mm	d/mm	c/mm	k	l/mm
lens parameters before optimization					
17.55	19.05	9.5	28	0	50
lens parameters after optimization					
17.55	19.05	9.5	27.315	-0.574	52.641

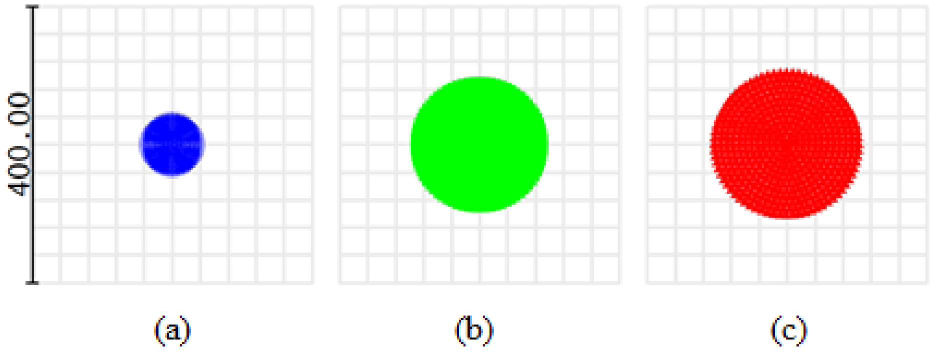

Fig 2. Single lens focus spot size

(a) is the spot size of 300μm wavelength (1.0 THz) with a diameter of 0.08mm; (b) is the spot size of 3000μm wavelength (0.1 THz) with a diameter of 0.18mm; (c) is the spot size of 30μm wavelength (10.0 THz) with a diameter of 0.20mm.

2.2. Design of Optical System

A symmetrical structure of the Terahertz beam shaping optical system is designed based on 4 identical plano-convex lenses, and the symcenter is test sample. The conical divergent beam from the Terahertz point source is collimated by the first plano-convex lens, then focused on the sample by the second plano-convex lens. The Terahertz beam that passes through the sample and carries sample information is collimated by the third plano-convex lens, then focused on the crystal in the Terahertz detector by the fourth plano-convex lens.

The above-mentioned optical system was simulated by Zemax, then the spatial position of each lens was optimized to obtain the final optical system structure.

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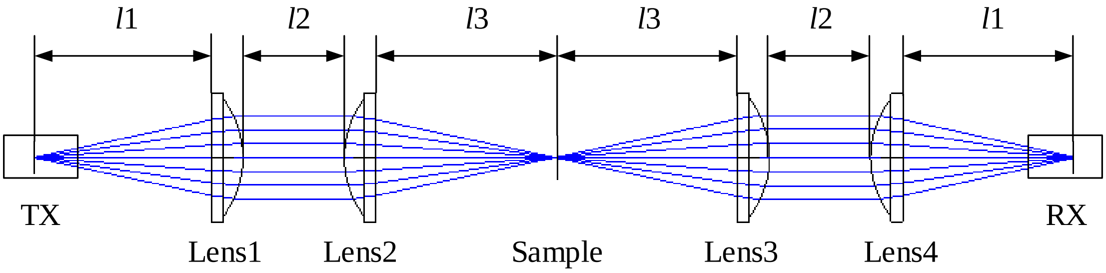
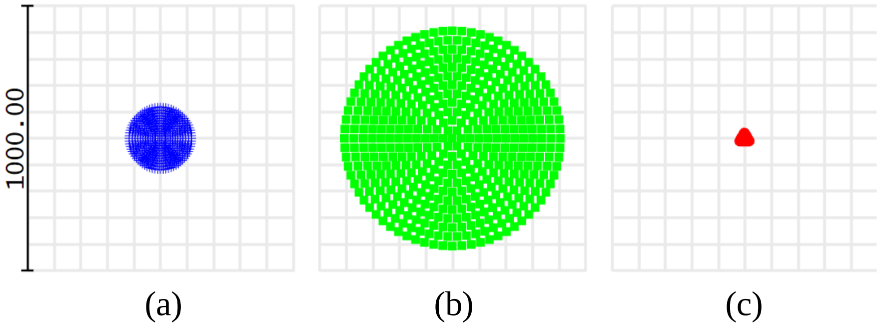


Fig 3. Terahertz beam shaping optical system

TX is a Terahertz source, RX is a Terahertz detector, Lens1 and Lens3 are collimating lenses, Lens2 and Lens4 are focusing lenses; after optimization, l1=52.641mm, l2=30mm, l3=53.598mm.



(a) (b) (c)

Fig 4. The size of the focused spot on the sample surface

(A) is the spot size of 300μm wavelength (1.0 THz) with a diameter of 0.23mm; (b) is the spot size of 3000μm wavelength (0.1 THz), with a diameter of 0.81mm; (c) is the spot size of 30μm wavelength (10.0 THz) with a diameter of 0.04mm.

3. DESIGN OF TERAHERTZ CAMERA

At present, in most of the Terahertz transmission optical paths, the Terahertz source, detector and lens are fixed by optical rails and movable brackets, and adjusted manually. This scheme is difficult to install and adjusts, and the stability of the optical path is poor. Therefore, the optical-mechanical integration design idea was adopted, and corresponding installation structural parts were designed for the completed optical system to form a special optical camera for Terahertz, which overcomes the above shortcomings. At the same time, the axial distance between each optical component in the camera can be adjusted through the thread to rectify the component processing error.

4. TERAHERTZ SPECTRUM TEST AND DATA PROCESSING

The Terahertz optical camera was installed on the optical rails and connected with the Terahertz time-domain spectroscopy system (THz-TDS), and then fine-tune the axial distance of each component to make the detected Terahertz signal the strongest. Moxifloxacin hydrochloride and Levofloxacin were made into 1.25mm thick solid compression to be used as the test samples.

The Terahertz time-domain signals not passed through samples and passed through samples were collected respectively. The Terahertz signal not passed through samples was used as the reference signal; the Terahertz frequency domain signals were obtained by Fourier transform which can be used to extract the optical parameters of samples.

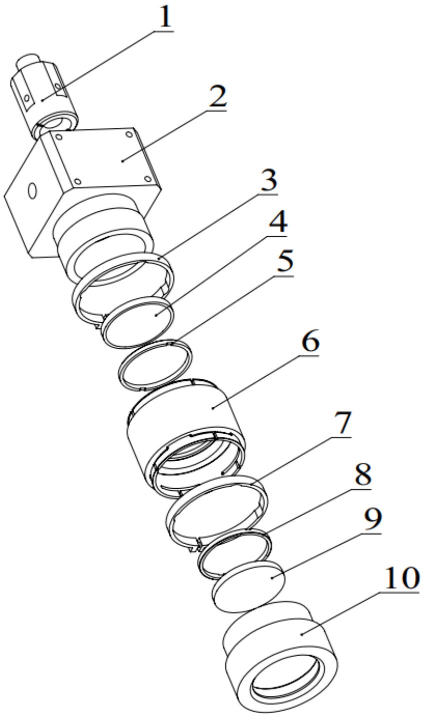


Fig 5. Exploded view of Terahertz camera

1- Terahertz source/detector; 2- antenna mounting; 3- first fastening ring; 4- first lens; 5- first pressing ring; 6-first lens barrel; 7- second fastening ring; 8-Second pressing ring; 9- Second lens; 10-Second lens barrel

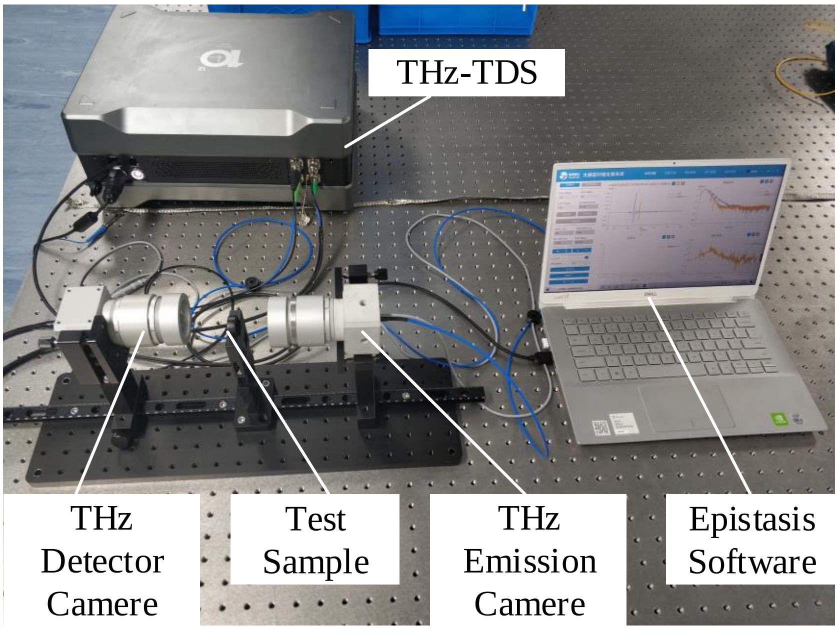
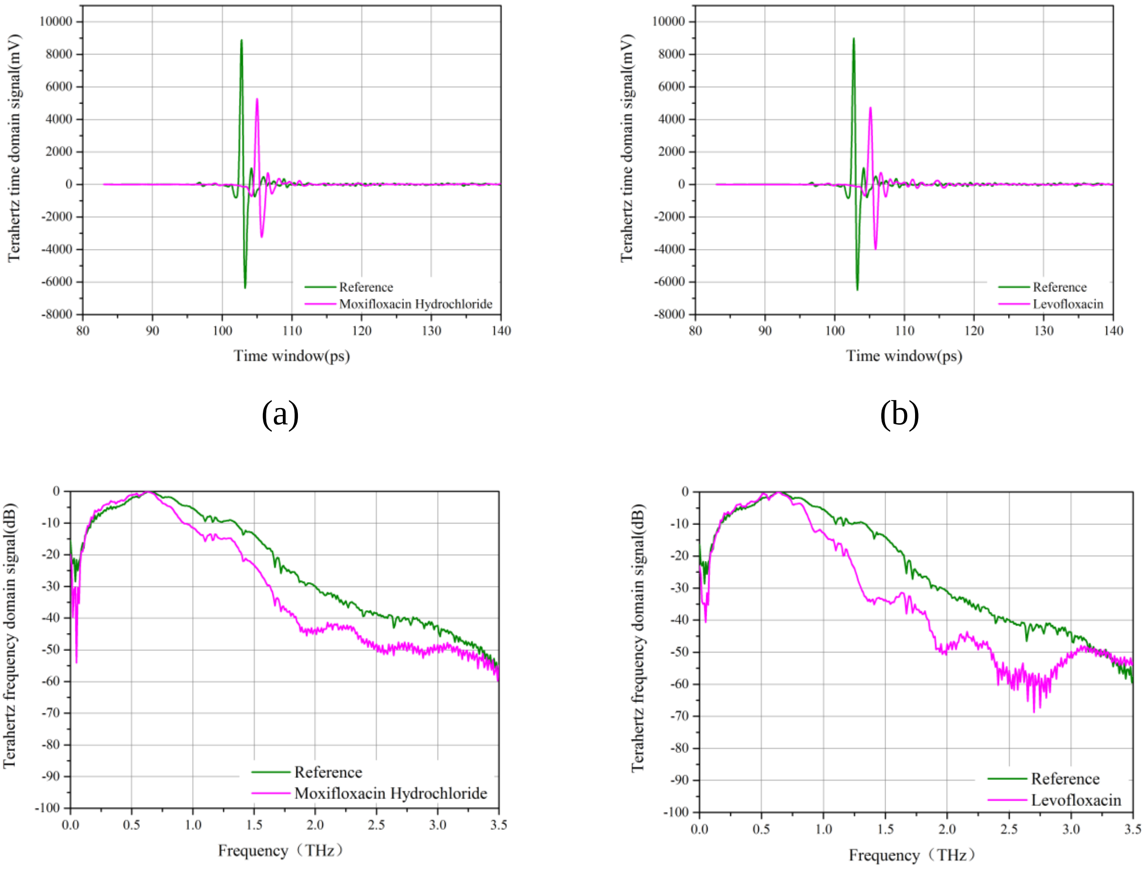


Fig 6. Terahertz spectrum test site



(a) (b)

(c) (d)

Fig 7. Terahertz time-domain and frequency-domain signals

(a) and (b) are the time-domain reference signal and time-domain sample signal of Moxifloxacin hydrochloride and Levofloxacin, with a time window of 83~140ps and a step of 0.05ps; (c) and (d) are the frequency-domain reference signal and frequency-domain sample signal of Moxifloxacin hydrochloride and Levofloxacin, and the frequency range displayed is 0~3.5THz.

In the case that only the main Terahertz peak signal is extracted, and the reflected signal is not considered, and the Terahertz signal is incident to the sample perpendicularly, the negative transmission function of the Terahertz signal passing through the sample can be expressed as:

$$T(\omega)=\frac{E_{sam}(\omega)}{E_{ref}(\omega)}=\frac{4\tilde{n}(\omega)}{[1+\tilde{n}(\omega)]^2}\exp\left\{\frac{-j[\tilde{n}(\omega)-1]\omega d}{c}\right\} \tag{2}$$

$$\tilde{n}(\omega)=n(\omega)-j\kappa(\omega) \tag{3}$$

Here $E_{sam}(\omega)$ is the Terahertz signal passing through the sample, $E_{ref}(\omega)$ is the reference signal, $\tilde{n}(\omega)$ is the complex refractive index of the sample, $n(\omega)$ is the real refractive index of the sample, $\kappa(\omega)$ is the extinction coefficient of the sample, d is the thickness of the sample, and c is the speed of light in vacuum, 3×10^8 m/s.

The complex transmission function is expressed to the form of mode and argument:

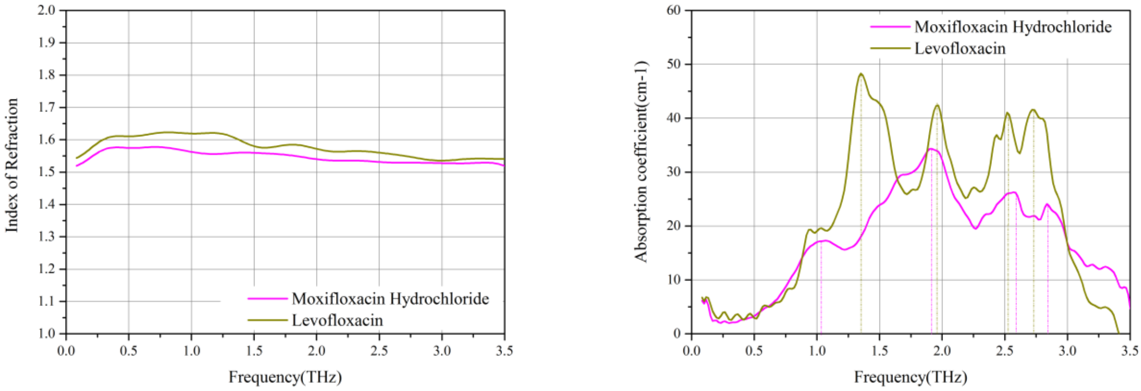
$$\begin{cases} T(\omega)=\rho(\omega)\exp[-j\phi(\omega)] \\ \rho(\omega)=\dfrac{4n(\omega)}{[n(\omega)+1]^2}\exp[-\kappa(\omega)\omega d/c] \\ \phi(\omega)=\dfrac{[n(\omega)-1]\omega d}{c} \end{cases} \tag{4}$$

The refractive index $n(\omega)$ and absorption coefficient $\alpha(\omega)$ of the sample can be extracted from those:

$$n(\omega)=\frac{\phi(\omega)c}{\omega d}+1 \tag{5}$$

$$\alpha(\omega)=\frac{2}{d}\ln\left\{\frac{4n(\omega)}{\rho(\omega)[n(\omega)+1]^2}\right\} \tag{6}$$

According to the above formula, the optical parameters of Moxifloxacin hydrochloride and Levofloxacin were extracted, and their refractive indexes and absorption coefficients were obtained.



(a) (b)

Fig 8. Frequency-domain curves about the refractive index and absorption coefficient of Moxifloxacin hydrochloride and Levofloxacin

(a) shows the refractive index curve of Moxifloxacin hydrochloride and Levofloxacin, here the refractive index of Levofloxacin is higher than Moxifloxacin hydrochloride in the range of 0.1~3.5THz, and the change of the refractive index of Moxifloxacin hydrochloride is more gentle than Levofloxacin; (b) shows absorption coefficient curve of Moxifloxacin hydrochloride and Levofloxacin. The absorption peaks of Moxifloxacin hydrochloride are 1.03THz, 1.92THz, 2.58THz, 2.84THz, and the absorption peaks of Levofloxacin are 1.35THz, 1.96THz, 2.52THz, 2.73THz.

5. CONCLUSION

The difficulty of the assembling and the adjustment of the Terahertz optical system can be reduced, and the accuracy of sample spectrum test can be improved by designing a dependable optical structure and a camera. The unique fingerprint spectrum in the Terahertz range of macromolecular samples provides an effective method for non-destructive identification of the samples. The results of this paper show that the refractive index and absorption of Moxifloxacin hydrochloride and Levofloxacin are different in the Terahertz range, which can be used as an important evidence for substance identification. However, the population of the samples selected in this paper is not sufficient, it is necessary to increase the number of samples tested and construct a complete database of samples.

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