



Research Progress on Terahertz Quantum-Well Photodetector and Its Application

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Compared with other typical terahertz (THz) detectors, the quantum-well photodetector (QWP) has the advantages of high detection sensitivity, fast response, mature fabrication, small size, and easy integration. Therefore, it is suitable for high-speed detection and imaging applications at the THz band. Researchers, both domestic and overseas, have systematically studied material design and device performance of the THz QWP. The design of the device is such that the peak frequency error is within 8%, the maximum peak responsivity is 5.5 A/W, the fastest response speed is 6.2 GHz, the best noise equivalent power is $\sim 10^{-13}$ W/Hz^{0.5}, and the spectrum range is 2.5–6.5 THz. In this article, firstly the basic principles and theoretical calculations of the THz QWP are described, and then the research progress of the THz QWP in our research group at imaging and communication is reviewed, which looks forward to its future development.

Keywords: terahertz detection, terahertz imaging, terahertz communication, terahertz, terahertz quantum-well photodetector

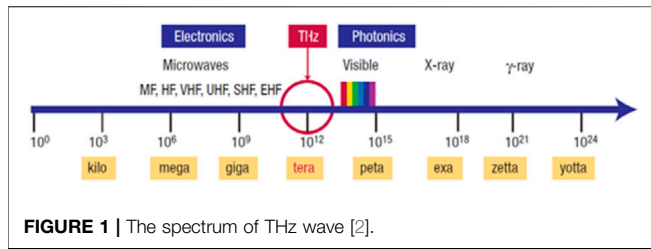
INTRODUCTION

1 Terahertz Quantum-Well Photodetector

Terahertz (THz) waves are electromagnetic waves falling between the millimeter and infrared [1, 2] spectrum as shown in **Figure 1**. This region ranges in frequency from about 0.1 to 10 THz (30–1000 μm). It has the advantages of strong dielectric penetration and weak ionization. It has a broad application prospect in material research, environmental monitoring, nondestructive testing, medical diagnosis, wireless communication, and other fields.

1.1 Working Principle

THz detectors have been studied since 1960s [3]. THz quantum-well photodetector (QWP) is the natural expansion of quantum-well infrared detector (QWIP) at the THz band [4–7]. The THz QWP material system is GaAs/AlGaAs, which is usually composed of many quantum wells. When THz wave radiation is incident on the THz QWP, the electrons in the bound state of the quantum well absorb THz photons and transit to the continuous state, forming a photocurrent under the external bias voltage, so as to complete the detection of the THz waves [8]. Compared with the QWIP, the energy between the bound and the continuous state in the THz QWP is just 20 meV, and the doping in the quantum well is lower, which directly leads to the decreasing absorption efficiency and the responsibility. In 2004, H.C. Liu and coworkers [9] developed a quantum-well detector working in the THz band by reducing the barrier height and doping in the quantum well. Reference 40 used the THz QWP to demonstrate THz communication. Professor Hu



Qing, an authoritative expert in the THz field at the Massachusetts Institute of Technology, believes that THz QWP may improve the speed and sensitivity of THz imaging. The main problem of the THz QWP [10, 11] is that the energy difference between the first bound sub-band in the quantum well and the quasi-continuous state is less than 30 meV. The signal-to-noise ratio (SNR) of the device needs to be improved by limiting the thermally excited electrons, such that the device needs to work at a low temperature (<20 K). According to the differences in the active structure, internal charge distribution, and carrier transport mode of the detector, the QWP is divided into photoconductive detector and photovoltaic detector. The active region and conduction band structure of the photoconductive THz QWP are shown in **Figure 2**.

1.2 Theoretical Design

Due to the high degree of freedom of the multiparticle system, the many-body effect can only be approximated [12, 13]. Considering the interaction between electrons, we established on the basis of density functional theory, combined with the local density approximation (LDA), meanwhile considering including exchange self-energies effect, depolarization-shift effect, and excitonic effect, between the depolarization and exciton interaction contributes to the optical many-body effect. The many-body effect is an electronic collective effect. When the wavelength is extended to the THz region because of the small carrier transition energy involved in the detection process, the influence of the many-body effect cannot be ignored, which needs to be considered during device design.

The THz QWP design needs to satisfy the following **Equation (9)** [14], [15]:

1) The Schrodinger equation is as follows:

$$-\frac{\hbar^2}{2} \frac{d}{dz} \frac{1}{m^*(z)} \frac{d}{dz} \psi(z) + V(z)\psi(z) = E\psi(z), \quad (1)$$

$$V(z) = V_0(z) + V_{ex}(z) + V_H(z), \quad (2)$$

where, $V_0(z)$ is the original potential distribution without extra electric field and doping:

$$V_0(z) = \begin{cases} V_w = 0 \\ V_B = 0.67 \times 1.247x = 0.12532eV \end{cases} \quad (3)$$

$V_{ex}(z)$ in **Equation 2** is the potential distribution caused by the extra electric field.

$$V_{ex}(z) = |e|F(L_p - z) = |e| \times \frac{0.064}{L_p} \times (L_p - z) \quad (4)$$

where, F is the extra field intensity, e is the electron charge, and $L_p = 52.4nm$ is the whole-period width. $V_H(z) = -|e|\varphi(z)$, $\varphi(z)$ is the field potential caused by the doped impurities.

The Poisson equation is as follows:

$$\frac{d}{dz} \left[\epsilon(z) \frac{d}{dz} \right] \varphi(z) = -|e|[N_D(z) - N_A(z) + p(z) - n(z)], \quad (5)$$

where, $\epsilon(z)$ is the dielectric constant of the material,

$$\begin{cases} \epsilon_w = 12.9\epsilon_0 \\ \epsilon_B = (12.9 - 2.84x)\epsilon_0 = 12.474\epsilon_0 \end{cases} \quad (6)$$

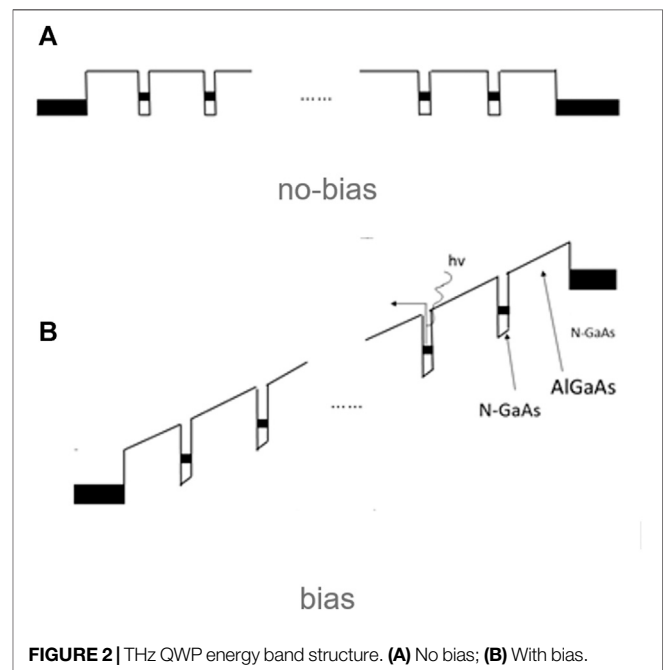
where, ϵ_0 is the dielectric constant of the material. $n(z)$ and $p(z)$ are, respectively, the concentrations of electrons and holes. For the type N-doped quantum-well structure, where $N_D(z)$ and $N_A(z)$ are respectively the concentrations of donor impurities and acceptor impurities; $n(z)$ and $p(z)$ are respectively the concentrations of electrons and holes; concentration effect can be ignored:

$$\frac{d}{dz} \left[\epsilon(z) \frac{d}{dz} \right] \phi(z) = -|e|[N_D(z) - n(z)] \quad (7)$$

2) For the THz QWP (consider many-body), the Hamilton function is as follows:

$$H = p \frac{1}{2m^*(z)} p + V_{QW}(z) + V_H(z) + V_{xc}(z) \quad (8)$$

where, p is the momentum, V_{QW} is the limited potential of the well, V_H is the Hartley potential, and V_{xc} is the exchange correlation potential; m^* is the effective quality of the electrons. The expression of V_{xc} is as follows:



$$V_{xc}(z) = \frac{e^2}{4\pi^2 \epsilon_0 \epsilon_B r_s(z)} \sqrt[3]{\frac{9}{4}} \pi \times \left\{ 1 + 0.0545 r_s(z) \ln \left[1 + \frac{11.4}{r_s(z)} \right] \right\} \quad (9)$$

Considering the condition of the Schrodinger equation,

$$\left\{ -\frac{\hbar^2}{2} \frac{\partial}{\partial z} \left[\frac{1}{m^*(z)} \frac{\partial}{\partial z} \right] + V_{QW}(z) + V_H(z) + V_{xc}(z) \right\} \varphi_{l,k_z}(z) = \epsilon_{l,k_z} \varphi_{l,k_z}(z) \quad (10)$$

Electronic charge is $E_{k,l} = \frac{\hbar^2 k_l^2}{2m^*} + \epsilon_{k_z,l}$

Electronic density is $\rho_e(z) = |e| \sum_{k,l} f(E_{k,l}, \epsilon_F, T) |\varphi_{l,k_z}(z)|^2$,

where, e is the electron, f is the Fermi distribution function, and T is the temperature.

When the electron density is known, the Hartley potential can be obtained by solving the Poisson equation $\frac{\partial^2}{\partial z^2} V_H(z) = \frac{\rho_e(z) - \rho_d(z)}{\epsilon}$

In this study, researches were carried out based on the density functional theory. When the energy dispersion relations and wave functions can be obtained by Fermi's golden rule, the relationship between them is as follows:

$$\begin{aligned} \eta(\omega) &= \frac{\pi e^2}{\epsilon_0 c n_0 \omega m^{*2}} \sum_j \int \frac{dk}{(2\pi)^3} | \langle j | p_z | 0 \rangle |^2 [f(E_{k,0}, \epsilon_F, T) \\ &- f(E_{k,j}, \epsilon_F, T)] \delta(\Delta \tilde{E}_{k,l,0} - \hbar\omega) \Delta \tilde{E}_{k,l,0}^2 \\ &= \Delta E_{k,l,0}^2 (1 + \alpha_{k,l,0} - \beta_{k,l,0}), \alpha_{k,l,0} \\ &= \frac{2e^2 \rho_{2D}}{\epsilon \Delta E_{k,l,0}} \int dz \left[\int_{-\infty}^z dz' \varphi_{k_z,l}(z') \varphi_{k_z,0}(z') \right]^2, \beta_{k,l,0} \\ &= -\frac{2\rho_{2D}}{\Delta E_{k,l,0}} \int dz \varphi_{k_z,l}(z)^2 \varphi_{k_z,0}(z)^2 \frac{\partial V_{xc}[\rho(z)]}{\partial \rho(z)}. \end{aligned} \quad (11)$$

2 TERAHERTZ QUANTUM-WELL PHOTODETECTOR IMAGING TECHNOLOGY

Compared with electromagnetic waves in other bands, the THz waves have many excellent characteristics, such as good penetrability to nonpolar substances, characteristic spectrum of biological macromolecules, and non-damage to human body [15–21]. THz waves have been used for imaging applications since 1990. The principle of THz imaging [22–26] is to obtain a THz image of the sample by collecting the amplitude, phase, and polarization information reflected or transmitted at different positions of the sample, and transforming the collected THz information into parameters that can reflect the physical and chemical properties of the sample, then corresponding to the spatial position parameters of the sample, combining with image restoration technology. THz imaging has many classification methods. According to the different ways of acting on the sample, it can be divided into transmission imaging and reflection imaging. According to the different

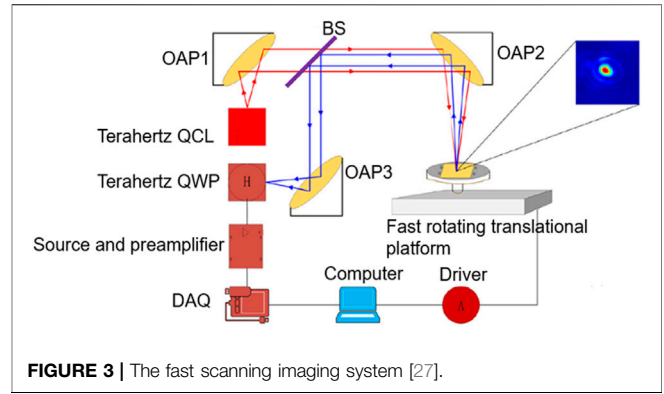


FIGURE 3 | The fast scanning imaging system [27].

working modes of the THz light source, it can be divided into continuous-wave imaging and pulse imaging. According to the imaging speed, it can be divided into scanning imaging and real-time imaging. According to whether the hidden wave effect is considered, it can be divided into far-field imaging and near-field imaging.

2.1 Imaging Modes

2.1.1 Scanning Imaging

Tan Zhiyong et al. from the Shanghai Institute of Microsystem and Information Technology (SIMIT) developed the fast scanning imaging system based on THz quantum devices [27]. The system used 4.3 THz quantum cascade laser (QCL) as the THz light source and a high-speed THz QWP with matching frequency. A rotating scanning platform was used to realize rapid scanning of the sample (Figure 3), so as to improve the imaging speed of the system. The system used a new pulse signal acquisition method and a practical image restoration program to obtain THz images of blades and shaving blades under different shelters within 5 s. In addition, the system also used an image processing algorithm to deal with the noise problem during practical application, which improves the quality of the THz images.

2.1.2 Reflection Imaging

Wang Chang from SIMIT set up a reflective THz fast confocal imaging system [28](Figure 4). The THz light source used was 4.3 THz QCL, with a THz QWP and fast-rotating translation platform to complete the fast scanning imaging of the sample. The imaging optical path adopts confocal microscopy. Two 200- μm pinholes were placed at the two conjugate focuses to filter out the scattered light of the system and improve the spatial resolution of the imaging system. Finally, lateral resolution better than 110 μm and axial resolution about 320 μm were achieved. The two-dimensional THz imaging of common metal samples and toothpicks was carried out by using the rapid confocal microscopy imaging system, and a high-contrast image of the samples was obtained within 5 s. Finally, using the high axial resolution of the system, three-dimensional slice imaging of the sample was carried out. The imaging results are clearly visible, and the thickness of the sample could be measured.

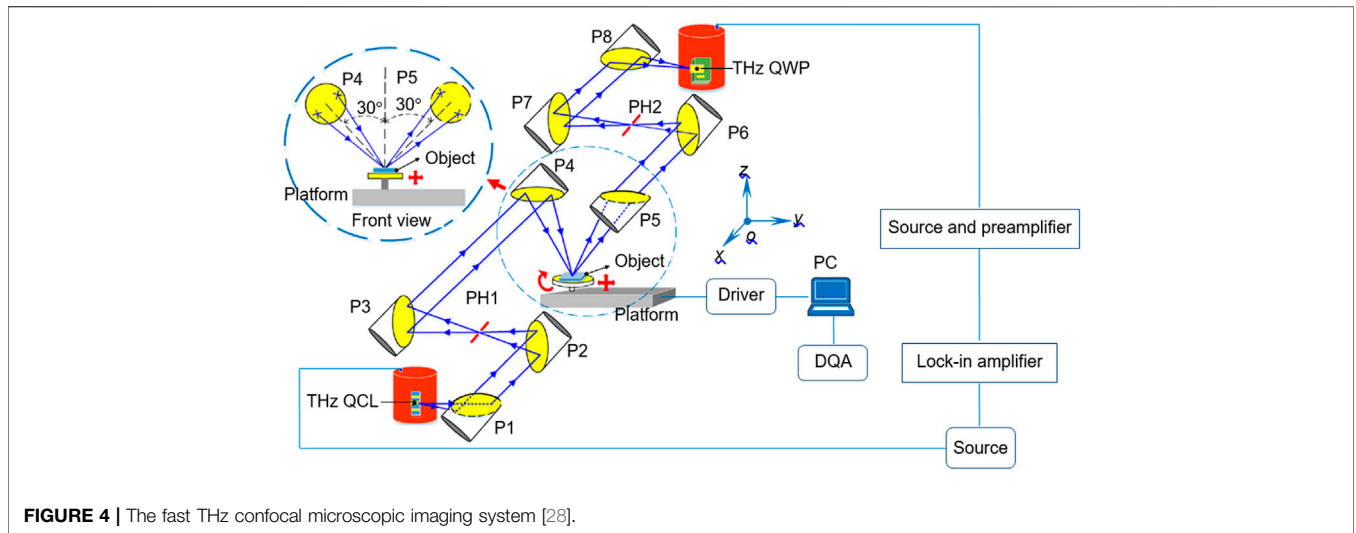


FIGURE 4 | The fast THz confocal microscopic imaging system [28].

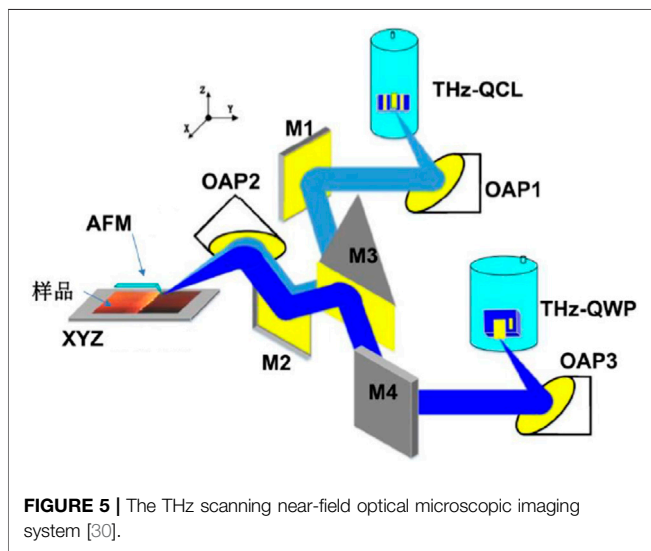


FIGURE 5 | The THz scanning near-field optical microscopic imaging system [30].

2.1.3 Near-Field Imaging

Qiu Fucheng [30] established a scattering-type scanning near-field optical microscopy system based on the THz QCL and THz QWP. Using the self-developed THz QCL and THz QWP, the low-bias continuous-wave THz QCL laser source module and THz QWP high-sensitivity detection module were developed for near-field microscopic imaging, and the scattering-type scanning near-field optical microscopic imaging system was built. The demodulation of the THz near-field signal was completed by using signal high-order demodulation technology. The THz imaging system with THz scattering-type scanning near-field optical microscopy was used to image pure gold samples with scratches. The minimum resolution of the system was calculated to be about 200 nm (Figure 5).

2.1.4 Pixel-less Imaging

In 2016, Z.L. Fu et al. from SIMIT fabricated the THz frequency up-conversion device (THz QWP-LED) formed by stacking THz

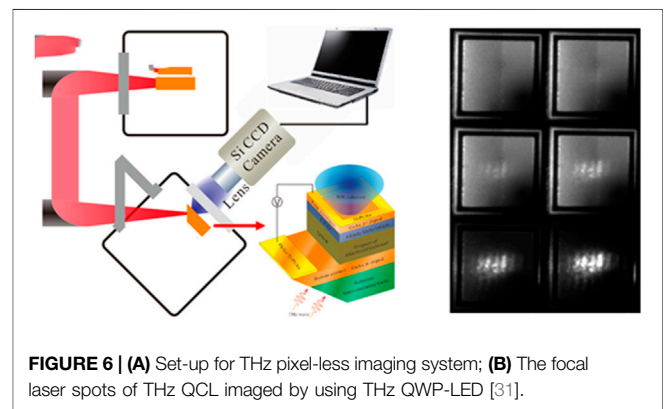


FIGURE 6 | (A) Set-up for THz pixel-less imaging system; **(B)** The focal laser spots of THz QCL imaged by using THz QWP-LED [31].

QWPs and the light-emitting diode (LED) and using this device for pixel-less imaging. The 45-degree coupled THz QWP-LED imaging system is shown in Figure 6A. The peak frequency is 5.2 THz, the peak responsibility is 0.22 A/W, the noise equivalent power is $5.2 \times 10^{-12} \text{ W/Hz}^{0.5}$, and the operating temperature is 3.5 K. The frequency point of THz QCL RF is 4.3 THz. Figure 6B shows the imaging results of THz QWP-LED for THz QCL with different laser powers. The imaging resolution is better than 0.05 mm; the SNR is better than 10,000; and the imaging time is 1 s. At present, the one-dimensional and two-dimensional metal grating coupling devices with normal incidence have achieved real-time imaging. The two-dimensional metal grating coupling device can rapidly image the THz QCL laser spot within 10 μs . The energy of the imaging spot is Gaussian distribution, which is basically consistent with the results of long imaging time. This experiment shows that the frequency up-conversion device based on THz QWP has high-resolution and high-speed imaging ability.

2.2 Imaging Applications

Terahertz is used in various imaging scenes, such as in intelligence, security, crime detection, biology, and medicine

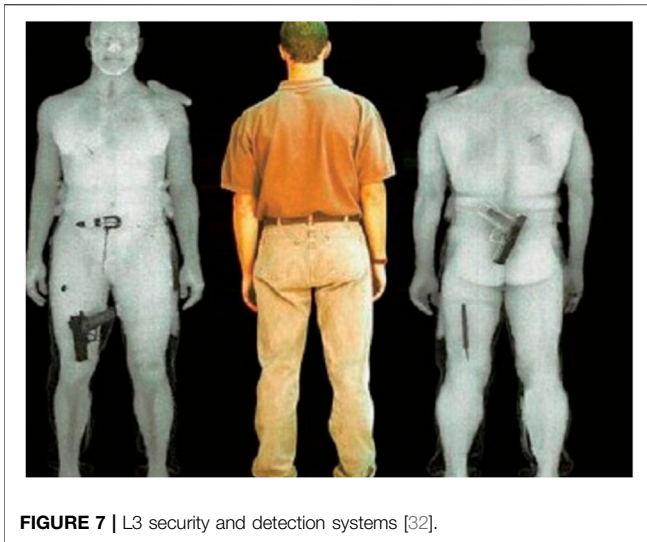


FIGURE 7 | L3 security and detection systems [32].

[32–35]. At present, some THz passive imaging security products have been released, such as the ThruVision series released by Digital Barriers. It works at 0.25 THz; the detection distance is 4–10 m; and the imaging speed can reach 6 frames/s. The device can effectively compensate for the limitations of slightly poor light transmittance, macromolecules that cannot penetrate, imaging contrast, and so on when visible light and X-rays are used for imaging. The application of THz imaging can supplement these disadvantages. THz waves have no ionization characteristics, and they can safely and nondestructively detect the human body through clothing. Therefore, these can be used for human security and the security of some prohibited items (Figure 7), and also for the identification of ancient cultural relics. The most popular is THz tomography (THz CT), which can scan molecules such as materials and samples.

In the field of medicine, THz radiation is used for low-energy, nondestructive detection and minimizes radiation damage to the human body. Compared with X-rays, THz waves do little damage to cells and objects and can be applied for organ identification and in gene research. They can also be used in dental treatment, examination of skin cancer and other diseases, real-time imaging in surgery, medical diagnosis, biomedical engineering, and other medical fields.

In terms of environmental monitoring, THz waves can analyze and characterize the chemical components of solid, liquid, gas, and other states. It can also be used for pollutant detection, such as compound leakage, problems caused by microorganisms, food quality problems, and the detection of harmful substances in decoration materials.

3 TERAHERTZ QUANTUM-WELL PHOTODETECTOR COMMUNICATION

Terahertz waves have great potential in high spectrum bandwidth, more information can be carried, low photon

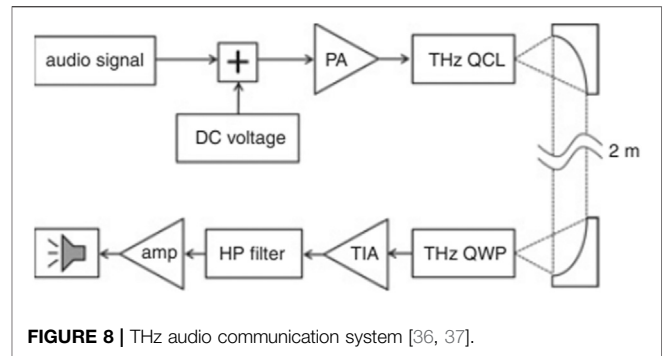


FIGURE 8 | THz audio communication system [36, 37].

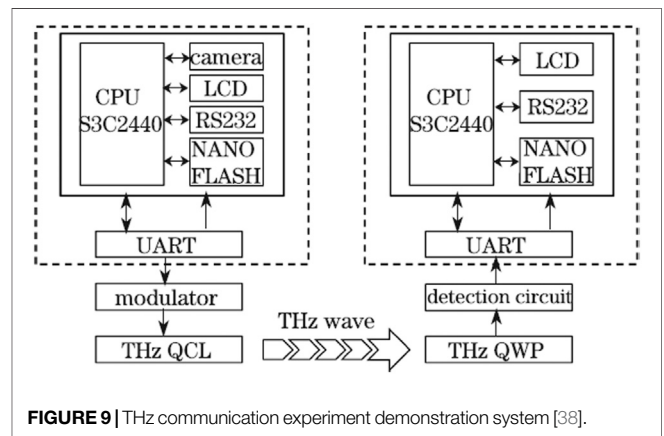


FIGURE 9 | THz communication experiment demonstration system [38].

energy, and high security, which has the significant advantage of the future communication to achieve ultra-wideband and high rate [35]. Compared with microwave frequency communication, terahertz for high-speed communications application has a very rich frequency resource, has a workable bandwidth as high as dozens of GHz, and is the sixth generation of carrier wave communication technology.

In 2009, H.C. Liu group of the Institute of Microstructure Science of the National Research Institute of Canada built a THz communication system based on THz QCL and THz QWP and realized audio signal transmission at 3.8 THz frequency points. Other researchers also actively follow up the wireless communication project research based on THz QCL and THz QWP and carry out the demonstration experiment of using THz carrier to transmit analog audio signals with THz QCL as the transmitting source and THz QWP as the receiver. The frequency point of THz waves is 4.1 THz. The communication system using THz QCL and THz QWP as transmitter and detector, respectively, has great development potential.

Tan Zhiyong from SIMIT demonstrated a wireless transmission system of THz waves with a transmission distance of 2 m (Figure 8) and detailed the circuit design of the transmitter and receiver. The system uses THz QCL working in continuous-wave mode as the transmitter and THz QWP as the detector. By means of intensity modulation/direct detection, we use this system to transmit analog signals such as sine wave,

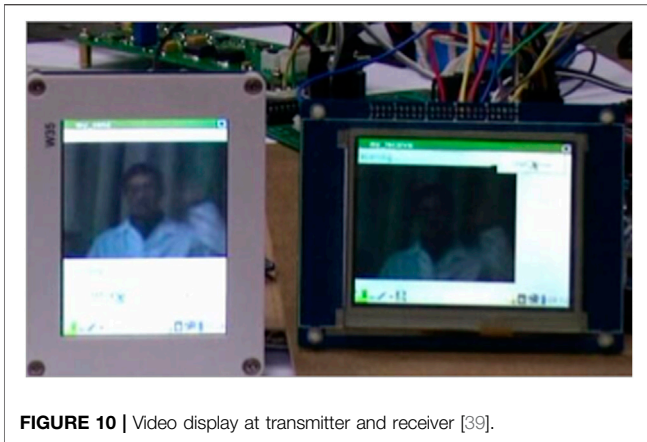


FIGURE 10 | Video display at transmitter and receiver [39].

triangle wave, and audio signal. The system is capable of transmitting signals at a -3 dB cutoff frequency of about 750 kHz. Theoretically, both THz QCL and THz QWP have modulation and detection bandwidths of tens of GHz if the circuit design and packaging of the devices are optimized. But in our experiment, the modulation bandwidth is mainly limited by the external modulation circuit and a detection circuit.

Gu Li et al. from SIMIT used THz QCL and THz QWP working in continuous mode to build the THz communication system, as shown in **Figure 9**. In this system, the digital signal to be transmitted from the signal generator is sent to the drive circuit to drive THz QCL, and the radiated THz light is transmitted through the optical path and is detected at the receiving end of the THz QWP. The THz QWP converts the received THz light into photocurrent of corresponding intensity, and the receiving end circuit amplifies the photocurrent and converts it into voltage signal, which is output in the oscilloscope.

The framework of the THz wave wireless communication system with transmission distance of 2.2 and 6 m, using THz QCL as transmitter and THz QWP as a detector, is presented in **Figure 10**. The experimental results show that the rate of the 2.2-m communication system is less than 16 Mbps and the bit error rate is 0. The rate is less than 22 Mbps, and the error rate is less than 10^{-3} . The rate of the 6-m communication system is less than 8 Mbps, and the bit error rate of the transmission system is 0. The maximum transmission rate can reach 14 Mbps. Meanwhile, the OOK modulation real-time digital video transmission is realized by using the 2.2-m THz wireless communication link platform. The transmission rate is 5 Mbps, and the video signal transmission is stable. The video picture can be played smoothly on the display screen of both the transmitter and the receiver.

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4 CONCLUSION

THz technology is a very important cross-cutting frontier, showing enormous potential application and practical value in astrophysics, plasma physics, spectroscopy, biology, medical imaging, environmental science, and other fields. In this article, the new terahertz detector, THz QWP, is reviewed. The development history, design principle, imaging application, and communication application of the detector are introduced. The THz QWP imaging system indicators are resolution, area, speed, and SNR. In the future, we can study the influence of off-axis parabolic mirrors with different parameters and sub-millimeter holes of different sizes on the spatial resolution of the system, so that the spatial resolution of the imaging system can break through the diffraction limit. In the mechanical scanning module, the accuracy of mechanical scanning can be optimized and the scanning range of mechanical scanning can be improved by controlling image distortion and improving the size of the imaging area. The imaging speed can be further improved by increasing the scanning speed and data acquisition speed. The SNR of imaging is mainly limited by the stability of the light path, stability of light source power, power of the light source, and sensitivity of the detector. Developing high-performance THz devices (lasers and detectors) to solve THz signal modulation and signal processing is the key to THz communication research. In the future, through the efforts of researchers, THz QWPs will become the mainstream detector of THz just as the corresponding band of QIWP and promote the development of THz technology and application.

AUTHOR CONTRIBUTIONS

DS proposed and wrote this manuscript; ZF, ZT, CW modified this manuscript; FQ, LG, WW performed the experiment; JC helped perform the analysis with constructive discussions.

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