frontiers in Physics

EDITORIAL
published: 07 February 2022
doi: 10.3389/fphy.2022.855623

Check for updates

Editorial: Advances in Terahertz Detection and Imaging

Meng Chen[1], Yingxin Wang[1], Xinke Wang[2] and Lianhe Li[3]*

[1]National Engineering Laboratory for Dangerous Articles and Explosives Detection Technologies, Department of Engineering Physics, Tsinghua University, Beijing, China, [2]Department of Physics, Beijing Key Lab for Metamaterials and Devices, Capital Normal University, Beijing, China, [3]School of Electronic and Electrical Engineering, University of Leeds, Leeds, United Kingdom

Keywords: terahertz detection, terahertz imaging, functional devices, terahertz technology, terahertz applications

Editorial on the Research Topic

Advances in Terahertz Detection and Imaging

Terahertz waves have many unique properties and show great potential for both fundamental scientific research and applications in various fields, such as astronomy, communication, biomedicine, and security inspection [1–3]. Terahertz detection is a process of converting terahertz signal into a measurable electrical signal. It can be used to obtain the amplitude, phase, spectroscopic, temporal, or polarization information of the THz signal, which may reveal rich physical phenomena about the interaction of terahertz waves with matter. Effective detection of terahertz signal is crucial for realizing real-world applications of terahertz technology, especially for the passive techniques [4]. Terahertz waves show good capability of penetration through objects which are usually opaque to infrared and visible light, and their appropriate wavelengths may yield a higher spatial resolution than microwave. Many organic substances exhibit fingerprint absorption spectra in this frequency range, enabling identification of different materials. Therefore, imaging with terahertz waves allows one to see through an object with millimeter- or submillimeter-scale resolution and even spatially resolve its chemical composition [5, 6]. Nowadays, terahertz detection and imaging are two fundamental and hot topics in the area of terahertz science and technology, and a series of significant advances have emerged in recent years.

Limited by the cut-off frequency of conventional electronic devices and the relatively large bandgap of conventional photonic devices, detection of terahertz waves at room temperature (RT) is still a challenge. For terahertz detection, the underlying mechanisms can be generally classified into three categories: thermal effect, electronic effect and photonic effect. Thermal detectors, relying on the temperature change of the photoactive materials induced by the incident radiation, have a broadband photoresponse (theoretically covering the entire terahertz range). Bolometers are the most widely used thermal detectors and their focal-plane arrays have been commercially available. At cryogenic temperatures, bolometers show very high sensitivities, with noise-equivalent power (NEP) levels on the order of $fW/\sqrt{Hz}$ or below, and have been successfully applied to astronomical observation and personnel screening [4, 7]. Thermal response is usually slow (of about milliseconds). However, the hot-carrier assisted photothermoelectric effect occurring in graphene is an exception, which is capable of reaching the picosecond level [8]. Electronic detectors, relying on the interaction of terahertz waves with the collective motion of electrons or induces an electron transition (across a potential barrier) [9], have a fast response but low-frequency operation (typically below 1 THz). Photonic detectors, relying on the generation of electron-hole pairs in narrow bandgap semiconductors upon terahertz photoexcitation, usually require cryogenic cooling to reduce the background thermal noise. Nevertheless, after years of development, exciting progress has been achieved in terahertz detection techniques [9, 10]. Benefiting from novel photoactive materials, optimized device structure design and refined fabrication process, terahertz detector performances,

Edited and reviewed by:
Lorenzo Pavesi,
University of Trento, Italy

****Correspondence:***
Yingxin Wang
wangyingxin@tsinghua.edu.cn

Specialty section:
This article was submitted to Optics and Photonics, a section of the journal Frontiers in Physics

Received: *15 January 2022*
Accepted: *19 January 2022*
Published: *07 February 2022*

Citation:
Chen M, Wang Y, Wang X and Li L (2022) Editorial: Advances in Terahertz Detection and Imaging. Front. Phys. 10:855623. doi: 10.3389/fphy.2022.855623

in term of sensitivity, speed, bandwidth, working temperature and integrability, have been remarkably improved.

Since the first demonstration of terahertz transmission imaging based on a time-domain spectroscopy (TDS) system [11], different modalities have been proposed to achieve better imaging performance or to provide new physical information for understanding of light-matter interactions at terahertz frequencies. The spatial resolution of conventional terahertz imaging is on the order of terahertz wavelength, limited by diffraction. Using near-field technique [12] or sub-diffraction optics [13], imaging with subwavelength resolution becomes viable. From pixel-by-pixel scanning to real-time 2D imaging, faster image acquisition can be realized with the advent of focal plane array detectors [14, 15] and computational imaging based on a single-pixel detector [16, 17]. Broadband pulses, frequency-tunable continuous-wave sources or frequency combs enables spectroscopic or hyperspectral imaging, which is appealing for acquiring both the structure and composition information of the object from multiple spectral bands [5, 18, 19]. When combining the techniques of interferometeric, holographic or self-mixing, phase images can be measured or reconstructed to reveal the terahertz wave front and the object depth information quantitatively [20–23]. In addition, imaging systems for radar, personnel screening and non-destructive evaluation applications have been well established and some even become commercially available.

Through this Research Topic, we aim to present the research advances in terms of new mechanisms, technical improvements, functional devices, and signal processing methods developed for terahertz detection and imaging. The first sub-topical area of this topic is terahertz detection, which serves as a basis of terahertz science and technology. Terahertz quantum-well photodetectors (QWP) have high sensitivity and fast response. In the article by Shao et al. the authors describes QWP theory and review the research progress for imaging and communication applications. In the work by Bai et al. QWP is integrated with a light-emitting diode to upconvert terahertz radiation into near infrared emission for broadband upconversion terahertz detection and pixelless imaging. Hou et al. present theoretical studies on the neon glow discharge characteristics and the interaction between the discharge plasma with terahertz waves so as to develop low cost, RT operation and user-friendly detectors. Photoactive materials are vital for RT terahertz bolometers. Jiang et al. report that the Nb_5N_6 thin film coupled with a radio frequency choke-enhanced dipole antenna enables a $pW/\sqrt{Hz}$ level NEP and a response time below 10 μs. Photoconductive antennas (PCAs) are widely used detectors in TDS systems. By fabricating a PCA array with a special substrate micromachining process to eliminate the reverse current between adjacent antenna, Shi et al. report an enhanced synthesis efficiency. Layered MoS2 crystals are promising materials for novel optoelectronic devices. Using optical pump-terahertz probe technique—a powerful tool for investigating the ultrafast process in semiconductors, Yang et al. present a study on their photo-generated carrier dynamics.

As for terahertz imaging, Zhang et al. report the non-contact and non-invasive characterization of Chinese lacquerware by terahertz reflection imaging. The layer structures of a lacquer-covered ornamental wood panel are clearly resolved by the time-of-flight of terahertz pulses. Wang et al. report the spatiotemporal distribution measurement of terahertz wave generated from two-color-induced plasma by focal plane imaging, allowing one to fully understand the characteristics of terahertz emission from plasma. To improve the terahertz image quality for nondestructive testing of composite materials, Li et al. propose an image enhancement method based on wavelet unsharp masking and guided filtering. Experimental results show that different types of defects can be accurately identified using this method. For self-mixing imaging by quantum cascade laser (QCL), interferometric signal extraction and analysis plays a key role. Ge et al. present a theoretical model to study the self-mixing interference in complex coupled distributed feedback THz QCLs, which is valuable for further development of terahertz self-mixing imaging technique.

In detection and imaging systems, functional devices play an important role in manipulating terahertz waves. Liu et al. report a flexible broadband terahertz modulator based on a strain-sensitive MXene film. Under a stretching force, the device can efficiently change terahertz transmission amplitude. Furthermore, a sensitive terahertz intensity change measurement is desirable for a sensor. Wang et al. design a composite device consisting of a carbon nanotube metasurface and a microfluidic channel to monitor the refractive index of the analyte with a high sensitivity for biological and chemical sensing applications. Besides amplitude modulation, polarization control also deserves special attention. Wang et al. propose an electronically tunable graphene composite metasurface to actively control the terahertz wave polarization state. By changing the chemical potential of graphene, they achieved the interconversion among linear, circular and elliptical polarizations of the THz signal. Wang et al. investigates the focusing and dispersive properties of circularly polarized terahertz vortex beams, which is promising for the applications in terahertz imaging and microscopy.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

REFERENCES

1. Tonouchi M. Cutting-Edge Terahertz Technology. *Nat Photon* (2007) 1: 97–105. doi:10.1038/nphoton.2007.3
2. Dhillon SS, Vitiello MS, Linfield EH, Davies AG, Hoffmann MC, Booske J, et al. The 2017 Terahertz Science and Technology Roadmap. *J Phys D Appl Phys* (2017) 50:043001. doi:10.1088/1361-6463/50/4/043001
3. Lu X, Venkatesh S, Saeidi H. A Review on Applications of Integrated Terahertz Systems. *China Commun* (2021) 18:175–201. doi:10.23919/JCC.2021.05.011

4. Grossman E, Dietlein C, Ala-Laurinaho J, Leivo M, Gronberg L, Gronholm M, et al. Passive Terahertz Camera for Standoff Security Screening. *Appl Opt* (2010) 49:E106–20. doi:10.1364/AO.49.00E106
5. Kawase K, Ogawa Y, Watanabe Y, Inoue H. Non-Destructive Terahertz Imaging of Illicit Drugs Using Spectral Fingerprints. *Opt Express* (2003) 11: 2549–54. doi:10.1364/OE.11.002549
6. Mittleman DM. Twenty Years of Terahertz Imaging [Invited]. *Opt Express* (2018) 26:9417–31. doi:10.1364/OE.26.009417
7. Siegel PH. THz Instruments for Space. *IEEE Trans Antennas Propagat* (2007) 55:2957–65. doi:10.1109/TAP.2007.908557
8. Cai X, Sushkov AB, Suess RJ, Jadidi MM, Jenkins GS, Nyakiti LO, et al. Sensitive Room-Temperature Terahertz Detection via the Photothermoelectric Effect in Graphene. *Nat Nanotech* (2014) 9:814–9. doi:10.1038/NNANO. 2014.182
9. Lewis RA. A Review of Terahertz Detectors. *J Phys D Appl Phys* (2019) 52: 433001. doi:10.1088/1361-6463/ab31d5
10. Rogalski A, Sizov F. Terahertz Detectors and Focal Plane Arrays. *Opto-electron Rev* (2011) 19:346–404. doi:10.2478/s11772-011-0033-3
11. Hu BB, Nuss MC. Imaging with Terahertz Waves. *Opt Lett* (1995) 20:1716–8. doi:10.1364/OL.20.001716
12. Cocker TL, Jelic V, Hillenbrand R, Hegmann FA. Nanoscale Terahertz Scanning Probe Microscopy. *Nat Photon* (2021) 15:558–69. doi:10.1038/ s41566-021-00835-6
13. Zhao F, Li Z, Dai X, Liao X, Li S, Cao J, et al. Broadband Achromatic Sub-Diffraction Focusing by an Amplitude-Modulated Terahertz Metalens. *Adv Opt Mater.* (2020) 8:2000842. doi:10.1002/adom.202000842
14. Lee AW, Hu Q. Real-Time, Continuous-Wave Terahertz Imaging by Use of a Microbolometer Focal-Plane Array. *Opt Lett* (2005) 30:2563–5. doi:10.1364/ OL.30.002563
15. Guerboukha H, Nallappan K, Skorobogatiy M. Toward Real-Time Terahertz Imaging. *Adv Opt Photon* (2018) 10:843–938. doi:10.1364/AOP.10.000843
16. Chan WL, Charan K, Takhar D, Kelly KF, Baraniuk RG, Mittleman DM. A Single-Pixel Terahertz Imaging System Based on Compressed Sensing. *Appl Phys Lett* (2008) 93:121105. doi:10.1063/1.2989126
17. Stantchev RI, Yu X, Blu T, Pickwell-MacPherson E. Real-Time Terahertz Imaging with a Single-Pixel Detector. *Nat Commun* (2020) 11:1–8. doi:10. 1038/s41467-020-16370-x
18. Bandyopadhyay A, Sengupta A. A Review of the Concept, Applications and Implementation Issues of Terahertz Spectral Imaging Technique. *IETE Tech Rev* (2021) 38:1–19. doi:10.1080/02564602.2020.1865844
19. Sterczewski LA, Westberg J, Yang Y, Burghoff D, Reno J, Hu Q, et al. Terahertz Hyperspectral Imaging with Dual Chip-Scale Combs. *Optica* (2019) 6:766–71. doi:10.1364/OPTICA.6.000766
20. Wang Y, Zhao Z, Chen Z, Zhang L, Kang K, Deng J. Continuous-Wave Terahertz Phase Imaging Using a Far-Infrared Laser Interferometer. *Appl Opt* (2011) 50:6452–60. doi:10.1364/AO.50.006452
21. Petrov NV, Kulya MS, Tsypkin AN, Bespalov VG, Gorodetsky A. Application of Terahertz Pulse Time-Domain Holography for Phase Imaging. *IEEE Trans Thz Sci Technol* (2016) 6:464–72. doi:10.1109/TTHZ.2016.2530938
22. Wang X, Xiong W, Sun W, Zhang Y. Coaxial Waveguide Mode Reconstruction and Analysis with THz Digital Holography. *Opt Express* (2012) 20:7706–15. doi:10.1364/OE.20.007706
23. Dean P, Valavanis A, Keeley J, Bertling K, Leng Lim Y, Alhathlool R, et al. Coherent Three-Dimensional Terahertz Imaging through Self-Mixing in a Quantum cascade Laser. *Appl Phys Lett* (2013) 103:181112. doi:10.1063/1. 4827886

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.