

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,800

Open access books available

122,000

International authors and editors

135M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Terahertz Pulse Detection Techniques and Imaging Applications

Sung-Liang Chen and L. Jay Guo

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/67089>

Abstract

Recent years have witnessed successful developments of detection techniques of terahertz (THz) pulse radiation and its imaging applications such as security, medicine and environmental sensing, to name an important few. Progress of detection techniques has been made in many aspects, including detection sensitivity, real-time detection, room-temperature operation, detection bandwidth and dynamic range, spatial (wavefront) and temporal profiles and so on. New detection techniques utilizing cutting-edge materials, sensors, systems and even novel detection mechanisms contribute to advances in terahertz pulse detection. While detection techniques continuously improve, terahertz pulsed imaging (TPI) also finds broad and intriguing applications. For instance, TPI has shown applications in nondestructive evaluation in pharmaceuticals, biomedical characterization of tissues, medical diagnosis of cancers, identification of explosive hazards and examination of art and archeology. The chapter highlights recent progress of terahertz pulse detection techniques and imaging applications.

Keywords: Terahertz, Detection, Imaging, pulsed terahertz detection, terahertz pulsed imaging

1. Introduction

Terahertz (THz) electromagnetic spectrum from 0.1 to 10 THz (3 mm–30 μm wavelength) is a scientifically rich frequency band that involves research in physics, chemistry, material science, biology and medicine. In the past five years, there has been a prosperous rise of research activity related to THz pulses, partly due to the advancement of various new technologies. There is a range of applications based on the study of the interaction between matter (solid, liquid, or gaseous) and THz pulses. To achieve further understanding and utilization of THz

pulses, it is essential to advance THz pulse detection techniques. Furthermore, there is a need to develop novel and reliable THz pulse detectors that can facilitate diverse THz pulse applications. Another motivation for ameliorating detection techniques is the applications of THz pulsed imaging (TPI). TPI has exceptional potential for applications in security, nondestructive evaluation, biological sciences and medicine.

The objective of this chapter is to review the state-of-the-art technology for THz pulse detection and imaging developed in recent five years. A search in the Web of Knowledge (Thomson Reuters) with “THz pulse” in “Title” has returned 589 articles during 2011–2015, while the number of articles returned is 379 during 2006–2010 (the search was conducted on June 24, 2016). Another search on Google Scholar with the same keyword “THz pulse” generates 4020 and 2540 articles for the five years 2011–2015 and 2006–2010, respectively. The two results show an increase of 55% and 58%, respectively, in the total number of publications between the two five-year periods, which indicates the increasing interest in the area of THz pulses. As stated earlier, the research field of THz pulse detection and TPI is of unique significance. Therefore, the chapter is limited to, what the authors consider, the most interesting recent research findings in the area of THz pulse detection techniques and TPI applications including THz spectroscopy. The chapter is presented in the following arrangement: Section 2 will elaborate on the significance of pulsed THz technology, Section 3 will present recent THz pulse detection techniques, Section 4 will focus on recent TPI applications and Section 5 will provide a summary and future outlook in this field.

2. Significance of THz pulses

The THz pulse radiation is of great interest by several unique features. First, the use of a short THz pulse enables the study of THz fields and the collection of information in time domain, which is the underlying principle of THz time-domain spectroscopy (THz-TDS). A variety of physical phenomena and material characteristics can be studied utilizing short THz pulses [1]. For example, by studying the absorption of THz photons in doped semiconductors, carrier dynamics can be studied [2]. For intrinsic semiconductors, the complex permittivity or THz absorption coefficient and refractive index can be determined [3]. Second, since a single-cycle THz pulse can be intense and short, it is experimentally possible to tap into the regime of extreme nonlinear optics [4] where the usual approximation (e.g., the conditions for complete state transfer) no longer holds. THz pulse radiation with high energies has found many applications such as nonlinear spectroscopy [5], high harmonic generation [6], molecular alignment [7] and charged particle acceleration [8, 9], to name an important few. Third, the spectral bandwidth of pulsed THz waves can be of the order of several hundred percent of the center frequency and therefore, pulsed THz waves show promise in short-distance data transmission at high bit rates.

Conventionally, optical sampling is used to perform time-resolved measurement of THz responses. Free-space electro-optic (EO) sampling is one of the most common sampling

techniques. Another common technique for detecting THz pulses is photoconductive antennas [10, 11]. The single-cycle THz pulse can cover a wide spectral range (0.1–50 THz). The two detection schemes are ideal for THz-TDS to investigate the spectral response of materials. On the other hand, commercially available thermal detectors such as bolometers, pyroelectric detectors and Golay-cell detectors are generally used for measuring THz pulse energy. The three devices are maturely developed and can provide stable performance. However, bolometer provides high sensitivity, but cryogenic cooling is necessary, while the other two detectors show low sensitivity at room temperature, restricting detailed measurement. The rapid development of THz pulse detection techniques such as time-domain profile detection and energy measurement offers many advantages and will be discussed in Section 3.

One primary application of THz pulse detection is TPI, which can provide a three-dimensional (3D) map of the object by using the time of flight of THz pulses [12]. TPI can be regarded as an extension of the THz-TDS. TPI can acquire not only valuable spectral information but also 3D images. In image acquisition, a THz pulse is launched to the sample and the reflected echo is measured in amplitude and/or phase. The time-of-flight information of the echo pulse indicates the presence of the boundaries or inner structures along the propagation direction of the THz, which extracts the one-dimensional depth profile. By performing a two-dimensional (2D) scan from pixel to pixel, a 3D image of the target can be visualized. Thus, TPI is possible to provide 3D views into a layered structure. Unlike THz CW imaging, TPI can attain distinctive knowledge of the target, such as the spectral and depth information, by using the acquired amplitude and phase information of THz waves in the time domain. The critical benefit renders TPI valuable for diverse applications, such as detection of breast cancer [13] and inspection of pharmaceutical tablets [14–17], to name but a few.

Note that in the subject of THz pulses, there are issues relating to generation and detection, devices and systems and applications. We focus our discussion on recent development, basically in five years, in THz pulse detection techniques and TPI applications.

3. Terahertz pulse detection techniques

In order to attain the potential offered by pulsed THz technology, the generation and characterization of THz pulses play an important role in THz pulse applications. There are many methods for THz pulse emission, such as photoconductive antenna [18], optical rectification [19] and laser-induced plasma [20–24]. On the other hand, several approaches for THz pulse measurement are well established because of historically long-term needs in detection technologies such as radio astronomy. The newly developed technology for THz pulse detection in recent years will be described in this section. The progress has been made due to the advance of novel detection mechanism and material science.

3.1. Time-domain THz sampling

In recent years major efforts have been made to improve the performance of photoconductive and EO sampling of pulsed THz wave. Photoconductive and EO methods are able to provide large detection bandwidth for THz pulses, which is useful for spectroscopy. As for photoconductive sampling, there are many studies and promising results [25–32]. (i) The sensitivity, THz bandwidth and dynamic range of THz pulse detection are improved by fabricating photoconductive antennas on InGaAs/InAlAs multilayer heterostructures [25, 26]. (ii) A nanowire-based detector can be well suited for near-field THz sensing [27]. (iii) The detection of highly confined THz fields is demonstrated by employing nanostructure of optical materials [28]. (iv) Plasmonic contact electrodes are used to enhance THz detection sensitivity [29]. (v) Novel optical gating technique is used to realize subpicosecond temporal resolution in pulse detection [30]. (vi) Some work is related to adapting photoconductive THz detectors to THz-TDS systems [31, 32]. As for EO sampling, similarly, there are various progress such as improvement of detection efficiency [33, 34] and dynamic range [35], polarization sensing of THz pulses [36] and a new detection scheme based on the amplitude variation of optical pulse [37].

3.2. Energy or power measurement

One important need in THz pulse applications is to measure the energy or power of THz pulses. Recently there have been many investigations on new technologies.

We demonstrated a novel scheme based on photoacoustic conversion of carbon nanotube (CNT) nanocomposite to realize efficient and real-time measurement of THz pulse energy [38]. Conventionally used thermal detectors utilize continuous heat integration to measure the power of pulsed THz radiation. The power can be converted to energy with the pulse repetition frequency (PRF). Due to the mechanism of heat integration, most thermal detectors have slow response times, which limit the characterization of energy of each THz pulse at high values of PRF. Unlike conventional thermal detectors, we utilize photoacoustic effect to realize real-time detection of THz pulse energy. Specifically, the transient and localized heating in an absorber by the absorption of THz pulse energy produces ultrasound, which is subsequently detected by a sensitive acoustic sensor. Moreover, our method responds only to the pulse excitation while rejecting other continuous radiations. In other words, in THz pulse detection, the ultimate sensitivity will not be restricted by the background continuous radiation, thus showing the potential for the efficient detection of THz pulse energy. In order to achieve efficient detection, it is essential to optimize the efficiency for photoacoustic conversion and subsequent acoustic sensing. We choose a CNT-polydimethylsiloxane (PDMS) nanocomposite to achieve efficient THz-to-ultrasound conversion. This is because CNTs can efficiently absorb THz radiation and then convert it into heat via THz absorption capability and low specific heat of CNTs, while PDMS has a high thermal coefficient of volume expansion. On the other hand, we employ a photonic device, a polymer microring resonator, as a highly sensitive acoustic sensor. The resonator has a high optical quality (Q) factor of 1.3×10^5 . The acoustic pressure impinges on the microring resonator, thus changing its effective refractive index

and the resonance wavelength. To enable sensitive conversion of the ultrasound pulse to the modulated optical intensity, we identify a wavelength where the local slope in the transmission spectrum is high and then probe the microring using this wavelength. The modulated optical intensity is further recorded by a low-noise high-speed photodetector. A high Q factor of the resonator correlates with a high slope in the transmission spectrum and therefore high sensitivity of ultrasound detection. The setup of the PA detection of THz pulses is shown in **Figure 1**. A two-color air ionization scheme is used to generate broadband THz pulses. The noise-equivalent detectable energy of the technique is calibrated as ~ 220 pJ. We expect that three orders-of-magnitude improvement in sensitivity are possible by configuring the nano-composite in the form of an acoustic lens as well as employing a microring resonator with a higher Q factor. The fast response time less than $0.1 \mu\text{s}$ is achieved, which is several orders faster than that of a commercial pyroelectric detector (~ 0.1 s). In addition, the novel method possesses other advantages such as room-temperature operation, compact detector size in mm scale and wide spectral response for THz spectroscopy.

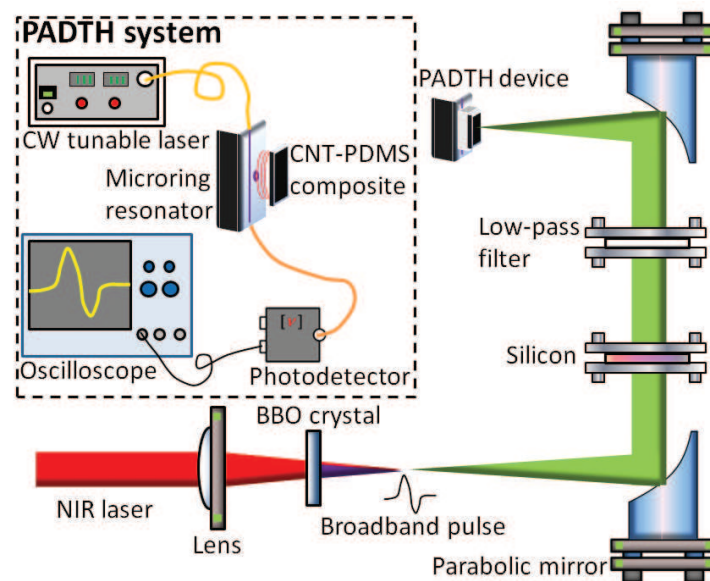


Figure 1. Experimental setup for the photoacoustic detection of THz (PADTH) pulse radiation. Using a β -barium borate (BBO) crystal, we can obtain a second-harmonic laser field from its fundamental one. Then, mixing the fundamental and the second-harmonic laser fields at the focus produces a broadband THz pulse radiation. We use a parabolic mirror to collect and also collimate the THz radiation from the focus, and then we use a silicon wafer and a low-pass filter in order to choose THz radiation with frequencies less than 6 THz. Finally, the THz radiation is refocused using another parabolic mirror for detection test of the PADTH device, consisting of a CNT-PDMS composite for high-efficiency THz-to-ultrasound conversion, ultrasound gel for sound coupling, and an optical microring resonator for sensitive ultrasound detection. In the PADTH system, a CW tunable laser is used to probe the microring resonator at a high-slope region in its transmission spectrum, and a high-speed photodetector is used to record the temporal optical intensity, which duplicates the temporal acoustic pressure. Reprinted with permission from Ref. [38].

Sensitive room-temperature detection of THz radiation is highly difficult. A detection mechanism based on the hot-electron photothermoelectric effect in graphene can be a promising approach [39]. First, photo-excited carriers thermalize rapidly due to strong

electron-electron interactions but lose energy to the lattice slowly. Next, the electron diffusion due to the electron temperature gradient, as well as asymmetry or dissimilar contact metals, produces a net current by the thermoelectric effect. **Figure 2** shows optical and atomic-force micrographs of the graphene THz detector made by microfabrication technologies. Each of the two metal electrodes consists of partially overlapping Cr and Au regions and contacts the monolayer graphene flake. Electron temperature gradient ΔT is produced across the device, then resulting in potential gradient ΔV . The photoresponse is obtained by integrating ΔV over the length of the device. The graphene thermoelectric THz detector shows sensitivity exceeding 10 V/W (700 V/W) at room temperature and noise-equivalent power less than 1100 pW/ $\sqrt{\text{Hz}}$ (20 pW/ $\sqrt{\text{Hz}}$), referenced to the incident (absorbed) power. The sensitivity is comparable with that of the best room-temperature THz detectors. Further improvements on orders-of-magnitude sensitivity is possible indicated by studying a model of the response including contact asymmetries. A fast intrinsic response time of 10.5 ps due to electron-phonon relaxation is estimated for THz time-domain measurements.

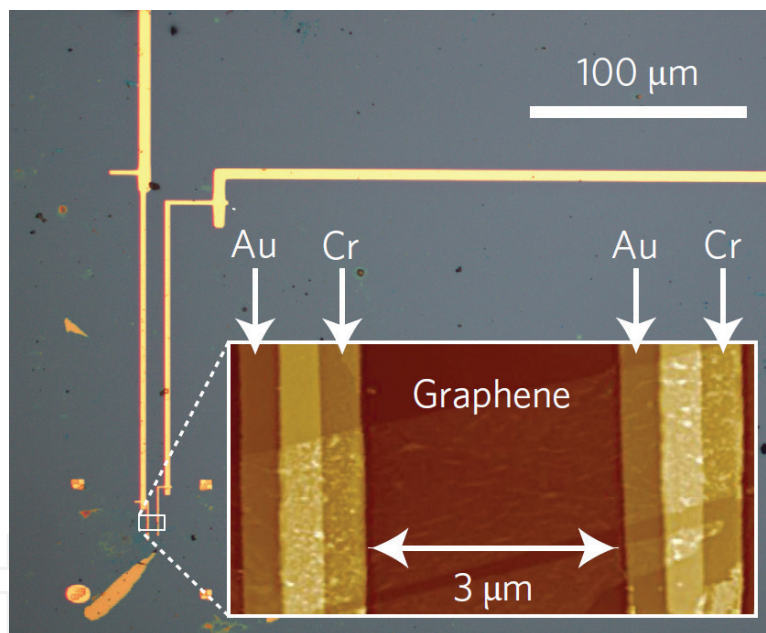


Figure 2. Graphene photothermoelectric detector device. The optical micrograph shows electrical contacts; the atomic-force micrograph in inset shows bimetallic contacts connected to an exfoliated graphene layer. Reprinted with permission from Ref. [39].

There are more examples besides the above two highlights. (i) Sensitive THz pulse energy detection is demonstrated by wavelength conversion from THz waves to near-IR light using LiNbO_3 crystals [40]. (ii) Sensitive THz detection is possible through THz light amplification in optically pumped graphene [41]. (iii) A THz line array detector with 20 elements is demonstrated with an average noise equivalent power of 106.6 pW/ $\sqrt{\text{Hz}}$ and the -3-dB bandwidth of 0.18 THz [42]. (iv) A fast response time of 45 ps allowing the measurement of ultrashort

THz pulses is achieved [43]. (v) Electroluminescence effect is utilized to develop a low-cost, probe-beam-free THz detection system [44].

3.3. Other sensing works

There are some intriguing research works for THz pulse sensing. We incorporate some examples here. (i) THz detection capable of acquiring the entire spatiotemporal profile of THz radiation in a single laser shot is demonstrated, which is based on space-to-time grading by using a converging probe intensity front [45]. The approach does not require any specially designed optics or precise alignment. The scheme has several merits such as a simple setup, high temporal resolution and fast acquisition. Compared to the conventional EO sampling, the technique reduces the time taken for data acquisition and thus may offer a decent option for real-time detection of THz radiation. (ii) The wavefront characterization of THz pulses is presented [46], which is realized by using a Hartmann sensor associated with a 2D EO imaging system composed of a ZnTe crystal and a CMOS camera. The wavefront sensing is crucial to applications such as optimization of far-field intensity distribution of time-domain imaging or enhancement of the peak power of intense THz sources. (iii) Measurement of spectra of THz pulses is realized by using a system consisting of channels for measuring amplitudes of pulses and an algorithm based on the iteration method or the amplitude-frequency method [47]. The spectrum measurement is essential to THz-TDS applications.

4. Terahertz pulsed imaging applications

THz imaging systems have been improved in recent years. The systems are intrinsically safe, nondestructive and noninvasive and can answer many of the questions left unresolved by complementary techniques, such as optical, Raman and infrared imaging [48]. Two types of imaging, TPI and THz CW imaging, are used with their respective strengths and weaknesses [49]. TPI renders data richer in information. Specifically, depth information can be retrieved in TPI, while THz CW imaging acquires intensity image data without depth information. In this section, recent progress on the development of TPI systems will be introduced. Besides, we will give an overview over a broad range of TPI applications such as medical imaging and diagnosis, evaluation of tablets in pharmaceuticals, painting investigation for art and archeology, material characterization and detection of concealed weapons.

4.1. THz pulsed imaging system

TPI system has shown progress in different aspects such as development of a compact system design suited to specific applications and enhancement of system performance including resolution, imaging time and dynamic range. For example, the performance of THz computed tomography (CT) is improved [50, 51]. THz CT can acquire and render 3D images in the THz frequency range, as in the optical, infrared, or X-ray regions of the electromagnetic spectrum [50]. A THz CT system using an injection-seeded parametric source for frequency-tunable, Fourier transform-limited and high-power THz emission and a heterodyne detector

for sensitive THz detection is demonstrated, as shown in **Figure 3** [51]. This system covers a frequency range of 0.95–2.7 THz and achieves a dynamic range greater than 90 dB, enabling high-resolution 3D THz CT images of samples with strong THz absorption. For illustration, 3D imaging of a pencil and a plastic product is obtained. The hidden lead as the internal structure of the pencil and the internal defect of the plastic product can be successfully revealed, demonstrating the system's capability and potential in nondestructive testing and evaluation of a variety of industrial products, such as semiconductors, pharmaceuticals, plastics and ceramics.

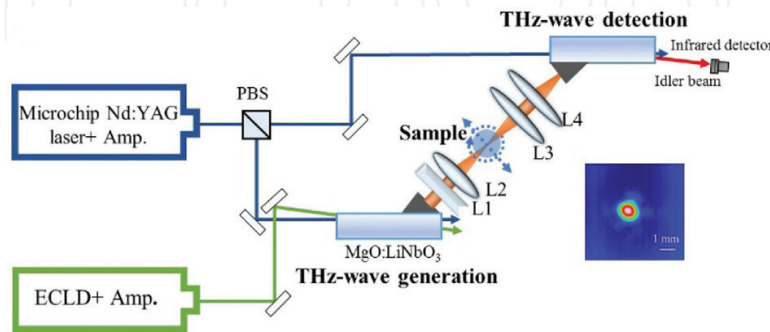


Figure 3. A 3D THz wave CT configuration. A THz image shown in inset is taken at the focal point using a THz imager (IR/VT0831, NEC Corp.). ECLD, external cavity laser diode. Reprinted with permission from Ref. [51].

Besides the above highlight, there are more examples. We discuss some here. (i) A THz InGaAs Schottky barrier diode array detector with 20 elements is built for real-time, compact and portable scanners in a TPI system [42]. (ii) Another real-time TPI system is built using a palm-size THz camera that contains a microbolometer array and a compact quantum cascade laser (QCL) [52]. (iii) A real-time transmission-type THz microscope is proposed by employing a THz penetration-enhancing agent, glycerol, to improve the THz penetration depth in tissues because the glycerol has low absorption of THz waves compared with water [53].

The use of novel THz sources, waveguides and detectors is valuable for THz imaging systems. The QCL in THz frequency is a compact source of THz radiation with high power and high spectral purity. As such, the source is useful for many TPI applications such as long-range imaging and materials analysis. The QCL-based THz imaging approaches and their key advancements are reviewed [54]. Another example is that by utilizing a split tapered waveguide with a subwavelength aperture, near-field THz imaging is accomplished [55].

4.2. Biomedical applications

Interest in biomedical THz research is growing rapidly [56, 57]. THz radiation has very low photon energy and thus does not cause any ionization hazard for biological tissues. Unique absorption spectra over the THz band have been found in different biological tissues. The feature makes THz attractive for biomedical applications because THz can provide

complementary information to existing techniques. TPI or THz-TDS is one essential approach in biomedical THz research. In the following, we will describe TPI in various biomedical imaging applications.

Studies of cancer by THz imaging or spectroscopy have gained increasing interests in recent years [58]. First, the presence of cancer often induces increased blood supply to the affected tissues and a local increase in tissue water content, which can be utilized as contrast for THz imaging of cancer. For instance, a sample of dehydrated human colon tissues embedded in paraffin is studied [59]. The results demonstrate the potential of THz imaging to distinguish adenocarcinoma-affected colon areas and the ability to image dehydrated tissues. Second, the structural changes in affected tissues can also be an important sign for diagnosis and can be observed by THz imaging. As another example, a reflection THz imaging system is used to identify tumors in freshly excised whole brain tissue from normal brain tissue based on structural observation [60]. Because the THz reflection intensity is higher in brain tumors than in normal tissue, the difference in the THz reflection intensity between the normal and tumor brain tissues can be adopted for the diagnosis of cancer. **Figure 4** shows the visual, THz and MR images of fresh whole brain tissues with and without tumors. **Figure 4(a)–(c)** shows the brain tissue with tumors and **Figure 4(d)** shows the normal brain tissue. The tumor boundaries in the THz images agree well with those visible images, indicating that the THz imaging technique could be useful for diagnosing brain tumors. Potentially, THz imaging could be employed as a complementary label-free technique allowing surgeons to determine tumor margins in real time. In addition, THz image contrast differences are also observed in the normal brain tissue image in **Figure 4(d)** and these correspond to the gray and white matter areas, showing the ability of THz imaging to study brain structure. Furthermore, this study shows that the THz signals correspond to the cell density when water was removed. In other words, the THz contrast between normal and cancerous brain tissues can be distinguished not only by differences in the water content but also by differences in the cell density.

One other promising application of TPI is the study of breast cancer, which has been explored extensively. (i) Breast tumor phantoms that match the refractive indices and absorption coefficients in the THz band are developed to facilitate the study of breast cancer THz imaging [61]. Phantom properties are verified through THz-TDS. (ii) THz-TDS and TPI are used for characterization of paraffin-embedded breast cancer tissue [62]. (iii) A pulsed THz system is used to enact a quick and reasonable estimation of the breast cancer margin thickness of embedded breast cancer tissue [63]. (iv) A similar work investigates TPI for the application of surgical margin assessment of breast cancer in 3D, where the depth information is retrieved using time-of-flight analysis [64]. (v) A linear sampling algorithm can be applied to TPI data for identifying breast cancer tumor margins [65]. (vi) THz measurement of normal and breast cancer tissue in the range of 0.1–4 THz is presented [66], showing the ability of THz technology for characterization of cancerous and normal breast tissue. (vii) A clinical study that fifty-one samples from patients in Cambridge and Guy's Hospital in London is conducted [67], showing the ability of THz technology to classify tumor and normal breast tissue with good accuracy.

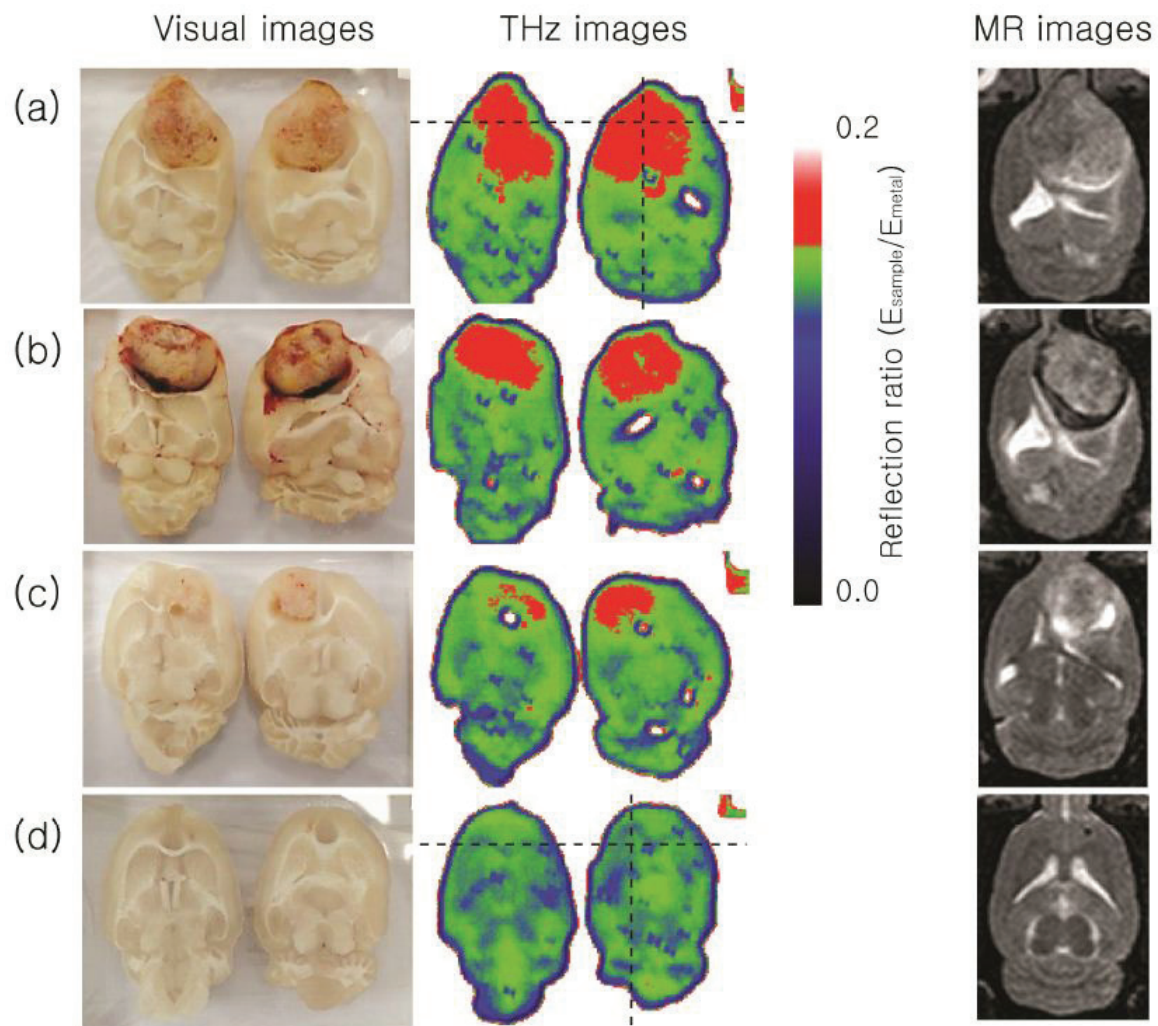


Figure 4. Whole brain images with (a–c) and without (d) tumors by visual, THz, and MR imaging. For THz images, the size is $4 \times 3 \text{ cm}^2$ and scanning resolution is $250 \mu\text{m}$. Reprinted with permission from Ref. [60].

4.3. Pharmaceutical applications

Pharmaceutical applications are one of the emerging opportunities offered by TPI and THz pulsed spectroscopy [68]. Solid dosage forms are the pharmaceutical drug delivery systems of choice for oral drug delivery [69]. These solid dosage forms are often coated to modify the properties of the active pharmaceutical ingredients, in order to help release kinetics [69, 70]. The critical coating attributes such as coating thickness, uniformity and density have chief influence on the tablet performance; advanced quality control techniques are required. TPI is an emerging nondestructive method to quantitatively characterize coating quality. Compared with established imaging techniques, e.g., near-infrared and Raman spectroscopy, TPI has the advantage to enable structural features of coated solid dosage forms at depth by the ability of THz radiation to penetrate many pharmaceutical materials. A typical THz time-domain waveform used for characterization of a single-layer coated tablet is illustrated in **Figure 5** [69].

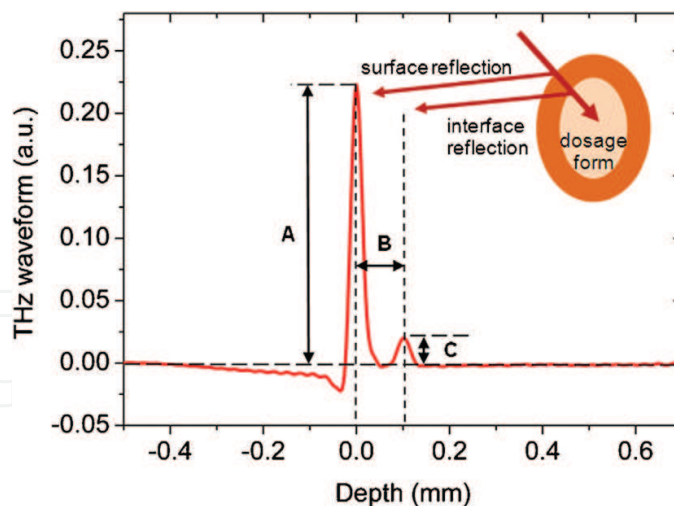


Figure 5. Characterization of coating attributes of a tablet by a THz time-domain waveform. At a depth of 0 mm in the THz waveform, the positive peak with a magnitude of A represents the difference in the refractive indices of the air and the outer surface of the coating layer (Interface 1). At a depth of ~0.1 mm, the next positive peak with a magnitude of C is caused by the boundary between the inner surface of the coating layer and the tablet core (Interface 2). One can retrieve parameters from the THz waveform: (1) the changes of the refractive index due to Interface 1, and the signal scattering can be obtained from the magnitude “A”; (2) the coating thickness can be calculated from the time delay, “B,” between the reflection of Interface 1 and that of Interface 2; (3) the changes of the refractive index due to Interface 2 can be obtained from the magnitude “C.” Reprinted with permission from Ref. [69].

A number of studies have been done recently. (i) TPI is used for nondestructive evaluation of film-coated tablets by deriving parameters such as film thickness, film surface reflectance and interface density differences between the film layer and core tablets [71]. (ii) Spectral domain optical coherence tomography (OCT) and TPI for quantifying film coating thickness of tablets are studied [72]. The finding shows that OCT is suitable for characterizing pharmaceutical dosage forms with thin film coatings, whereas TPI is suited for thick coatings. (iii) To ensure robust measurements, the evaluation of film coating thickness using TPI should take some factors into account, such as signal processing of the raw data and signal distortions that can occur at tablet edges or areas with defects [73]. (iv) Enteric coatings in tablets are widely used to reduce gastrointestinal side effects and to control the release properties of oral medications. TPI is used to identify structural defects within enteric coating tablets with poor acid resistance [74]. (v) TPI is used for evaluation of the intra tablet and inter tablet coating uniformity and identification of critical process parameters in a coating process [75, 76]. (vi) TPI can also be used in evaluating the effect of coating equipment on tablet film quality [77]. (vii) TPI is used to quantify the hardness and surface density distribution of tablets [78]. (viii) TPI is a feasible and rapid tool to characterize ribbon density distributions [79], which are important parameters in dry granulation process in pharmaceutical industries. (ix) Tablet dissolution is crucial in medication and is strongly affected by swelling and solvent penetration into its matrix. A reflection mode TPI is used to measure swelling and solvent ingress in pharmaceutical compacts [80]. (x) Layer separation is a crucial defect in many bilayer tablets. TPI is used to provide a precise estimate of the layer separation risk [81].

4.4. Art and archeology

Examination of art and archeology is important for cultural heritage scientists to understand artistic materials and to devise better conservation procedures [82]. THz presents a number of valuable features specifically for the investigation of art and archeology such as no radiation risk with deep penetration (**Figure 6**), low power and noncontact mode. Recent progress shows that THz technology for art investigation is an efficient, convenient and affordable approach. We introduce several examples. (i) TPI is used to image apsidal wall painting in 3D to provide subsurface features at depths up to 1 cm from the surface [83]. Characterization of subsurface features is useful in conservation of art history as well as in building archeology. (ii) TPI is used as a technique to image obscured mural paintings [84]. Image processing can be used to solve the issue due to an uneven surface, enabling the visualization of the obscured painting. (iii) THz reflective tomography is used to identify the preset defects in a plaster [85]. (iv) A portable THz-TDS system is used to image panel paintings from a lab and a museum, offering useful information on the internal structure of the paintings and on their conditions [86]. (v) TPI is also used to image an oil canvas painting by Pablo Picasso and the multilayer structure is clearly revealed [87]. (vi) An artwork attributed to the Spanish artist Goya painted in 1771 is imaged and analyzed by THz time-domain system [88]. The study indicates that THz images present features that cannot be seen with optical inspection.

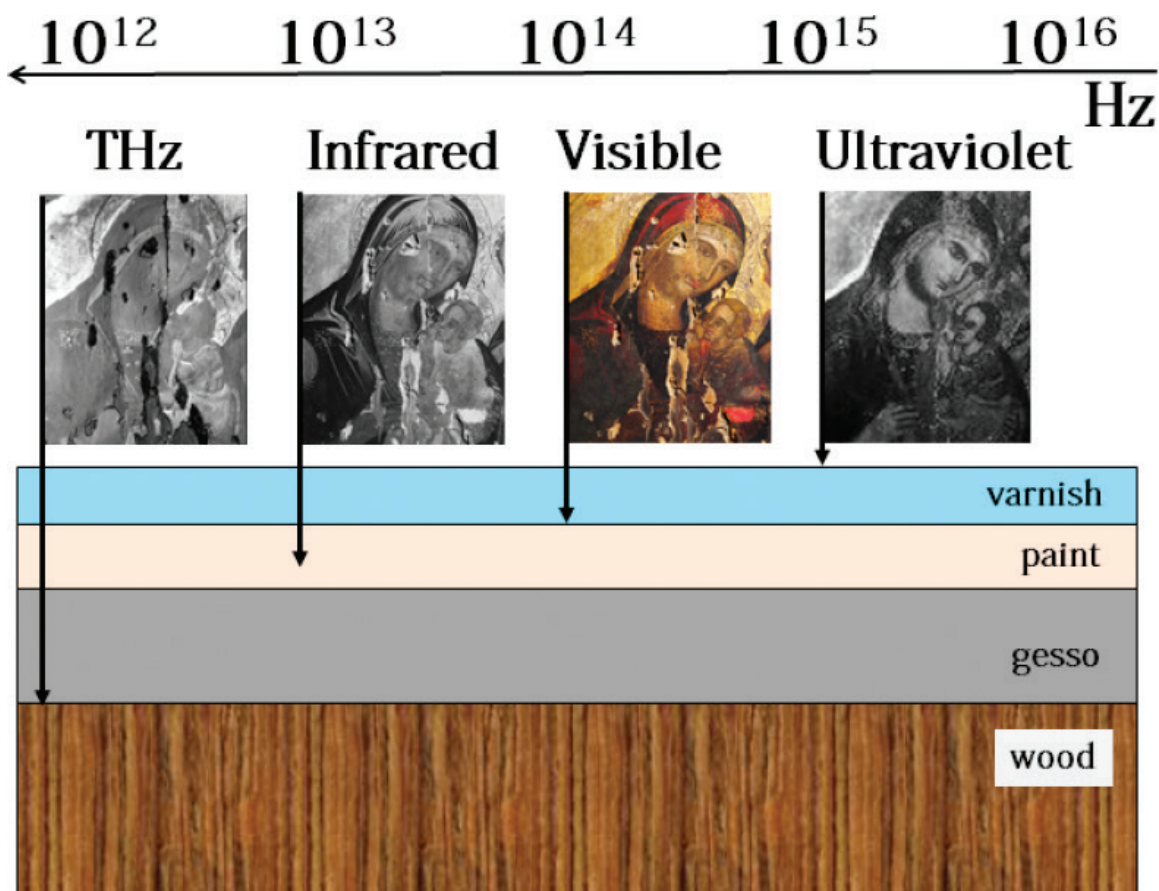


Figure 6. Paintings studied by THz radiation. For painting inspection, a panel painting can be penetrated deeper using THz and X-ray radiography than using other traditional approaches such as infrared radiation. Although THz and X-ray radiations can provide deep penetration into paintings, only THz promises safe and nonionizing 3D imaging of paintings. Reprinted with permission from Ref. [82].

4.5. Other applications

There are still a variety of TPI applications in the fields of architecture, chemistry, material science, environmental protection and homeland security. (i) TPI and THz-TDS are employed in characterization of construction and building materials [89]. Different types of thermal building insulation materials are analyzed [90]. (ii) TPI and THz-TDS are used to identify wheat grains at different stages of germination [91]. Specifically, the inner chemical structure during germination can be revealed from the THz spectra. (iii) TPI and THz-TDS are also explored to identify features such as coating, pores and cracks in polymer materials [92]. Another study employs TPI to study glass fiber-reinforced composite laminates in polyetherimide resin [93]. (iv) Reflective pulsed THz tomography can be a tool to monitor oil pollution. A cup of water covered by a layer of sesame oil with different densities is devised to simulate oil spills [94]. The results show that different densities can be determined by THz images. (v) The spectral fingerprint of high explosive material is investigated using THz-TDS [95]. Besides, the explosive material concealed in an opaque envelope can be identified using TPI.

5. Conclusions and future prospects

In summary, a number of detection techniques of THz pulse radiation and applications based on TPI and THz-TDS are presented in this chapter. We first elaborate the significance of THz pulses. Pulsed THz technologies bring about useful information from the interaction between THz radiation and matters. The applications based on pulsed THz technologies in part heavily rely on the technological advancement in THz pulse detection. We review the recent rapid development of THz pulse detection techniques in various aspects such as using novel materials, adopting innovative designs of detectors and even employing new detection mechanisms. These will open up new fields of applications or carry out particular tasks that cannot be attained previously. Of particular interest are the applications using TPI as well as THz-TDS. Development and test of TPI systems have shown steady progress in recent years. In addition, a wide range of TPI or THz-TDS applications including the fields of medical imaging and diagnosis, pharmaceuticals, art and archeology, material science, architecture and so on has been intensively investigated by researchers and scientists. The exploration of THz pulsed detection technology and imaging applications will eventually lead to commercial products and systems for specific purposes, which is expected to have a profound impact on our lives. The substantial improvements over the past few years lay foundation for extending THz technology to new and potentially groundbreaking realms.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (no. 61405112), the National High Technology Research and Development Program of China (863 Program) (no. 2015AA020944) and the Shanghai Pujiang Program (no. 14PJ1404400).

Author details

Sung-Liang Chen^{1*} and L. Jay Guo²

*Address all correspondence to: sungliang.chen@sjtu.edu.cn

1 University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China

2 Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan, United States

References

- [1] Jepsen PU, Cooke DG, Koch M. Terahertz spectroscopy and imaging—modern techniques and applications. *Laser & Photonics Reviews* 2011;**5**:124–166.
- [2] Zhang W, Azad Abul K, Grischkowsky D. Terahertz studies of carrier dynamics and dielectric response of n-type, free standing epitaxial GaN. *Applied Physics Letters* 2003;**82**:2841.
- [3] Grischkowsky D, Keiding S, Exter Mv, Fattinger C. Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors. *Journal of the Optical Society of America B* 1990;**7**:2006–2015.
- [4] Wegener M. *Extreme Nonlinear Optics: An Introduction*. Springer-Verlag Berlin Heidelberg; 2005. ISBN 978-3642060908.
- [5] Hebling J, Yeh KL, Hoffmann MC, Nelson KA. High-power THz generation, THz nonlinear optics and THz nonlinear spectroscopy. *IEEE Journal of Selected Topics in Quantum Electronics* 2008;**14**:345–353.
- [6] Balogh E, Kovacs K, Dombi P, Fulop JA, Farkas G, Hebling J, Tosa V, Varju K. Single attosecond pulse from THz-assisted high-order harmonic generation. *Physical Review A* 2011;**84**:023806.
- [7] Fleischer S, Zhou Y, Field RW, Nelson KA. Molecular orientation and alignment by intense single-cycle THz pulses. *Physical Review Letters* 2011;**107**:163603.
- [8] Wong LJ, Fallahi A, Kärtner FX. Compact electron acceleration and bunch compression in THz waveguides. *Optics Express* 2013;**21**:9792.
- [9] Palfalvi L, Fülöp JA, Toth G, Hebling J. Evanescent-wave proton postaccelerator driven by intense THz pulse. *Physical Review ST-Accelerators and Beams* 2014;**17**:031301.
- [10] Ezdi K, Heinen B, Jördens C, Vieweg N, Krumbholz N, Wilk R, Mikulics M, Koch M. A hybrid time-domain model for pulsed terahertz dipole antennas. *Journal of European Optical. Society-Rapid Publications* 2009;**4**:09001.

- [11] Dietz RJB, Gerhard M, Stanze D, Koch M, Sartorius B, Schell M. THz generation at 1.55 μm excitation: six-fold increase in THz conversion efficiency by separated photoconductive and trapping regions. *Optics Express* 2011;**19**:25911–7.
- [12] Takayanagi J, Jinno H, Ichino S, Suizu K, Yamashita M, Ouchi T, Kasai S, Ohtake H, Uchida H, Nishizawa N, Kawase K. High-resolution time-of-flight terahertz tomography using a femtosecond fiber laser. *Optics Express* 2009;**17**:7549–7555.
- [13] Fitzgerald AJ, Wallace VP, Jimenez-Linan M, Bobrow L, Pye RJ, Purushotham AD, Arnone DD. Terahertz pulsed imaging of human breast tumors. *Radiology* 2006;**239**:533–540.
- [14] Shen YC, Taday PF. Development and application of terahertz pulsed imaging for nondestructive inspection of pharmaceutical tablet. *IEEE Journal of Selected Topics in Quantum Electronics* 2008;**14**:407–415.
- [15] Fitzgerald AJ, Cole BE, Taday PF. Nondestructive analysis of tablet coating thicknesses using terahertz pulsed imaging. *Journal of Pharmaceutical Sciences* 2005;**94**:177–183.
- [16] Maurer L, Leuenberger H. Terahertz pulsed imaging and near infrared imaging to monitor the coating process of pharmaceutical tablets. *International Journal of Pharmaceutics* 2009;**370**:8–16.
- [17] Ho L, Müller R, Römer M, Gordon KC, Heinämäki J, Kleinebudde P, Pepper M, Rades T, Shen YC, Strachan CJ, Taday PF, Zeitler JA. Analysis of sustained-release tablet film coats using terahertz pulsed imaging. *Journal of Controlled Release* 2007;**119**:253–261.
- [18] Tani M, Herrmann M, Sakai K. Generation and detection of terahertz pulsed radiation with photoconductive antennas and its application to imaging. *Measurement Science and Technology*. 2002;**13**:1739–1745.
- [19] Auston DH, Cheung KP, Valdmanis JA, Kleinman DA. Cherenkov radiation from femtosecond optical pulses in electro-optic media. *Physical Review Letters* 1984;**53**:1555–8.
- [20] Kim KY, Taylor AJ, Glowacki JH, Rodriguez G. Coherent control of terahertz supercontinuum generation in ultrafast laser–gas interactions. *Nature Photon* 2008;**2**:605–609.
- [21] Thomson MD, Blank V, Roskos HG. Terahertz white-light pulses from an air plasma photo-induced by incommensurate two-color optical fields. *Optics Express* 2010;**18**:23173–23182.
- [22] Petersen PB, Tokmakoff A. Source for ultrafast continuum infrared and terahertz radiation. *Optics Letters* 2010;**35**:1962–1964.
- [23] Fuji T, Suzuki T. Generation of sub-two-cycle mid-infrared pulses by four-wave mixing through filamentation in air. *Optics Letters* 2007;**32**:3330–3332.
- [24] Dai J, Liu J, Zhang XC. Terahertz wave air photonics: terahertz wave generation and detection with laser-induced gas plasma. *IEEE Journal of Selected Topics in Quantum Electronics* 2011;**17**:183–190.

- [25] Kostakis I, Saeedkia D, Missous M. Terahertz generation and detection using low temperature grown InGaAs-InAlAs photoconductive antennas at 1.55 μm pulse excitation. *IEEE Transactions on Terahertz Science and Technology* 2012;**2**:617–622.
- [26] Dietz RJB, Globisch B, Roehle H, Stanze D, Göbel T, Schell M. Influence and adjustment of carrier lifetimes in InGaAs/InAlAs photoconductive pulsed terahertz detectors: 6 THz bandwidth and 90 dB dynamic range. *Optics Express* 2014;**22**:19411–19422.
- [27] Peng K, Parkinson P, Fu L, Gao Q, Jiang N, Guo YN, Wang F, Joyce HJ, Boland JL, Tan HH, Jagadish C, Johnston MB. Single nanowire photoconductive terahertz detectors. *Nano Letters* 2015;**15**:206–210.
- [28] Mitrofanov O, Brener I, Luk TS, Reno JL. Photoconductive terahertz near-field detector with a hybrid nanoantenna array cavity. *ACS Photonics* 2015;**2**:1763–1768.
- [29] Berry CW, Wang N, Hashemi MR, Unlu M, Jarrahi M. Significant performance enhancement in photoconductive terahertz optoelectronics by incorporating plasmonic contact electrodes. *Nature Communications* 2013;**4**:1622.
- [30] Muraviev A, Gutin A, Rupper G, Rudin S, Shen X, Yamaguchi M, Aizin G, Shur M. New optical gating technique for detection of electric field waveforms with subpicosecond resolution. *Optics Express* 2016;**24**:12730–12739.
- [31] Vieweg N, Rettich F, Deninger A, Roehle H, Dietz R, Göbel T, Schell M. Terahertz-time domain spectrometer with 90 dB peak dynamic range. *Journal of Infrared Millimeter and Terahertz Waves* 2014;**35**:823–832.
- [32] Urbanowicz A, Pačebutas V, Geižutis A, Stanionyte S, Krotkus A. Terahertz time-domain spectroscopy system based on 1.55 μm fiber laser and photoconductive antennas from dilute bismides. *AIP Advances* 2016;**6**:025218.
- [33] Tani M, Kinoshita T, Nagase T, Horita K, Que CT, Estacio E, Yamamoto K, Bakunov MI. Non-ellipsometric detection of terahertz radiation using heterodyne EO sampling in the Cherenkov velocity matching scheme. *Optics Express* 2013;**21**:9277–9288.
- [34] Tani M, Horita K, Kinoshita T, Que CT, Estacio E, Yamamoto K, Bakunov MI. Efficient electro-optic sampling detection of terahertz radiation via Cherenkov phase matching. *Optics Express* 2011;**19**:19901–19906.
- [35] Ibrahim A, Férachou D, Sharma G, Singh K, Kirouac-Turmel M, Ozaki T. Ultra-high dynamic range electrooptic sampling for detecting millimeter and sub-millimeter radiation. *Scientific Reports* 2016;**6**:23107.
- [36] Oguchi K, Iwasaki H, Okano M, Watanabe S. Polarization-sensitive electro-optic detection of terahertz wave using three different types of crystal symmetry: toward broad-band polarization spectroscopy. *Applied Physics Letters* 2016;**108**:011105.
- [37] Kovalev SP, Kitaeva GK. Two alternative approaches to electro-optical detection of terahertz pulses. *JETP Letters* 2011;**94**:91–96.

- [38] Chen SL, Chang YC, Zhang C, Ok JG, Ling T, Mihnev MT, Norris TB, Guo LJ. Efficient real-time detection of terahertz pulse radiation based on photoacoustic conversion by carbon nanotube nanocomposite. *Nature Photonics* 2014;**8**:537–542.
- [39] Cai X, Sushkov AB, Suess RJ, Jadidi MM, Jenkins GS, Nyakiti LO, Myers-Ward RL, Li S, Yan J, Gaskill DK, Murphy TE, Drew HD, Fuhrer MS. Sensitive room-temperature terahertz detection via the photothermoelectric effect in graphene. *Nature Nanotechnology* 2014;**9**:814–819.
- [40] Minamide H, Hayashi S, Nawata K, Taira T, Shikata J, Kawase K. Kilowatt-peak terahertz-wave generation and sub-femtojoule terahertz-wave pulse detection based on nonlinear optical wavelength-conversion at room temperature. *Journal of Infrared Millimeter and Terahertz Waves* 2014;**35**:25–37.
- [41] Otsuji T, Watanabe T, Tombet SAB, Satou A, Knap WM, Popov VV, Ryzhii M, Ryzhii V. Emission and detection of terahertz radiation using two-dimensional electrons in III–V semiconductors and graphene. *IEEE Transactions on Terahertz Science and Technology* 2013;**3**:63–71.
- [42] Han SP, Ko H, Park JW, Kim N, Yoon YJ, Shin JH, Kim DY, Lee DH, Park KH. InGaAs Schottky barrier diode array detector for a real-time compact terahertz line scanner. *Optics Express* 2013;**21**:25874–25882.
- [43] Probst P, Scheuring A, Hofherr M, Rall D, Wunsch S, Il'in K, Siegel M, Semenov A, Pohl A, Hübers HW, Judin V, Müller AS, Hoehl A, Müller R, Ulm G. YBa₂Cu₃O_{7- δ} quasi-optical detectors for fast time-domain analysis of terahertz synchrotron radiation. Citation: *Applied Physics Letters* 2011;**98**:043504.
- [44] Shin J, Jin Z, Nosaka Y, Nakazawa T, Kodama R. Probe beam-free detection of terahertz wave by electroluminescence induced by intense THz pulse. *Journal of Physics: Conference Series* 2016;**688**:012108.
- [45] <http://arxiv.org/abs/1602.05739>.
- [46] Abraham E, Cahyadi H, Brossard M, Degert J, Freysz E, Yasui T. Development of a wavefront sensor for terahertz pulses. *Optics Express* 2016;**24**:5203–5211.
- [47] Glyavin MY, Goykhman MB, Gromov AV, Palitsin AV, Panin AN, Rodin YV, Fil'chenkov SE. A waveguide high-pass filter system for measuring the spectrum of pulsed terahertz sources. *Infrared Physics & Technology* 2016;**76**:11–20.
- [48] Pawar AY, Sonawane DD, Erande KB, Derle DV. Terahertz technology and its applications. *Drug Invention Today* 2013;**5**:157–163.
- [49] Yin X, Ng BWH, Abbott D. *Terahertz Imaging for Biomedical Applications*. Springer-Verlag New York; 2012. ISBN: 978-1-4614-1820-7.
- [50] Guillet JP, Recur B, Frederique L, Bousquet B, Canioni L, Manek-Hönninger I, Desbarats P, Mounaix P. Review of terahertz tomography techniques. *Journal of Infrared Millimeter and Terahertz Waves* 2014;**35**:382–411.

- [51] Tripathi SR, Sugiyama Y, Murate K, Imayama K, Kawase K. Terahertz wave three-dimensional computed tomography based on injection-seeded terahertz wave parametric emitter and detector. *Optics Express* 2016;**24**:6433–6440.
- [52] Oda N, Lee AWM, Ishi T, Hosako I, Hu Q. Proposal for real-time terahertz imaging system with palm-size terahertz camera and compact quantum cascade laser. *Proceedings of SPIE 8363, Terahertz Physics, Devices, and Systems VI: Advanced Applications in Industry and Defense*; 2012. 83630A.
- [53] Oh SJ, Kim SH, Jeong K, Park Y, Huh YM, Son JH, Suh JS. Measurement depth enhancement in terahertz imaging of biological tissues. *Optics Express* 2013;**21**:21299–21305.
- [54] Dean P, Valavanis A, Keeley J, Bertling K, Lim YL, Alhathloul R, Burnett AD, Li LH, Khanna SP, Indjin D, Taimre T, Rakić AD, Linfield EH, Davies AG. Terahertz imaging using quantum cascade lasers—a review of systems and applications. *Journal of Physics D: Applied Physics* 2014;**47**:374008.
- [55] Liu S, Mitrofanov O, Nahata A. Near-field terahertz imaging using sub-wavelength apertures without cutoff. *Optics Express* 2016;**24**:2728–2736.
- [56] Ouchi T, Kajiki K, Koizumi T, Itsuji T, Koyama Y, Sekiguchi R, Kubota O, Kawase K. Terahertz imaging system for medical applications and related high efficiency terahertz devices. *Journal of Infrared Millimeter and Terahertz Waves* 2014;**35**:118–130.
- [57] Fan S, He Y, Ung BS, Pickwell-MacPherson E. The growth of biomedical terahertz research. *Journal of Physics D: Applied Physics* 2014;**47**: 374009.
- [58] Yu C, Fan S, Sun Y, Pickwell-MacPherson E. The potential of terahertz imaging for cancer diagnosis: a review of investigations to date. *Quantitative Imaging in Medicine and Surgery* 2012;**2**:33–45.
- [59] Faustino F, Kasalynas I, Venckevicius R, Seliuta D, Valusis G, Urbanowicz A, Molis G, Carneiro F, Silva CDC, Granja PL. Terahertz absorption and reflection imaging of carcinoma-affected colon tissues embedded in paraffin. *Journal of Molecular Structure* 2016;**1107**: 214–219.
- [60] Oh SJ, Kim SH, Ji YB, Jeong K, Park Y, Yang J, Park DW, Noh SK, Kang SG, Huh YM, Son JH, Suh JS. Study of freshly excised brain tissues using terahertz imaging. *Biomedical Optical Express* 2014;**5**:2837–2842.
- [61] Walter A, Bowman T, El-Shenawee M. Development of breast cancer tissue phantoms for terahertz imaging. *Proceedings of SPIE 9700, Design and Quality for Biomedical Technologies IX*; 2016. 970003.
- [62] Bowman T, El-Shenawee M, Campbell L. Regional spectroscopy of paraffin-embedded breast cancer tissue using pulsed terahertz transmission imaging. *Proceedings of SPIE 9706, Optical Interactions with Tissue and Cells XXVII*; 2016. 97061W.

- [63] Bowman T, El-Shenawee M, Campbell L. Time of flight estimation for breast cancer margin thickness using embedded tumors. *Proceedings of SPIE 9706, Optical Interactions with Tissue and Cells XXVII*; 2016. 97061V.
- [64] Bowman T, Walter A, El-Shenawee M. Margin assessment of three-dimensional breast cancer phantoms using terahertz imaging. *Proceedings of SPIE 9700, Design and Quality for Biomedical Technologies IX*; 2016. 97000J.
- [65] Bowman T, Hassan A, El-Shenawee M. Terahertz imaging of breast cancer margin using the linear sampling method. *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)*; 2013. 538–539.
- [66] Bowman T, El-Shenawee M, Sharma SG. Terahertz spectroscopy for the characterization of excised human. *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*; 2014. 1–4.
- [67] Fitzgerald AJ, Pinder S, Purushotham AD, O’Kelly P, Ashworth PC, Wallace VP. Classification of terahertz-pulsed imaging data from excised breast tissue. *Journal of Biomedical Optics* 2012;**17**:016005.
- [68] Shen YC. Terahertz pulsed spectroscopy and imaging for pharmaceutical applications: a review. *International Journal of Pharmaceutics* 2011;**417**:48–60.
- [69] Haaser M, Gordond KC, Strachane CJ, Radesf T. Terahertz pulsed imaging as an advanced characterisation tool for film coatings—a review. *International Journal of Pharmaceutics* 2013;**457**:510–520.
- [70] Haaser M, Karrouf Y, Velghe C, Cuppok Y, Gordon KC, Pepper M, Siepmann J, Rades T, Taday PF, Strachan CJ. Application of terahertz pulsed imaging to analyse film coating characteristics of sustained-release coated pellets. *International Journal of Pharmaceutics* 2013;**457**: 521–526.
- [71] Dohi M, Momose W, Yoshino H, Hara Y, Yamashita K, Hakomori T, Sato S, Terada K. Application of terahertz pulse imaging as PAT tool for non-destructive evaluation of film-coated tablets under different manufacturing conditions. *Journal of Pharmaceutical and Biomedical Analysis* 2016;**119**:104–113.
- [72] Lin H, Dong Y, Shen Y, Zeitler JA. Quantifying pharmaceutical film coating with optical coherence tomography and terahertz pulsed imaging: an evaluation. *Journal of Pharmaceutical Sciences* 2015;**104**:3377–3385.
- [73] Brock D, Zeitler JA, Funke A, Knop K, Kleinebudde P. Critical factors in the measurement of tablet film coatings using terahertz pulsed imaging. *Journal of Pharmaceutical Sciences* 2013;**102**:1813–1824.
- [74] Niwa M, Hiraishi Y, Terada K. Evaluation of coating properties of enteric-coated tablets using terahertz pulsed imaging. *Pharmaceutical Research* 2014;**31**:2140–2151.

- [75] Brock D, Zeitler JA, Funke A, Knop K, Kleinebudde P. Evaluation of critical process parameters for intra-tablet coating uniformity using terahertz pulsed imaging. *European Journal of Pharmaceutics and Biopharmaceutics* 2013;**85**:1122–1129.
- [76] Brock D, Zeitler JA, Funke A, Knop K, Kleinebudde P. Evaluation of critical process parameters for inter-tablet coating uniformity of active-coated GITS using terahertz pulsed imaging. *European Journal of Pharmaceutics and Biopharmaceutics* 2014;**88**:434–442.
- [77] Haaser M, Naelapaa K, Gordon KC, Pepper M, Rantanen J, Strachan CJ, Taday PF, Zeitler JA, Rades T. Evaluating the effect of coating equipment on tablet film quality using terahertz pulsed imaging. *European Journal of Pharmaceutics and Biopharmaceutics* 2013;**85**:1095–1102.
- [78] May RK, Su K, Han L, Zhong S, Elliott JA, Gladden LF, Evans M, Shen Y, Zeitler JA. Hardness and density distributions of pharmaceutical tablets measured by terahertz pulsed imaging. *Journal of Pharmaceutical Sciences*; **102**:2179–2186.
- [79] Zhang J, Pei C, Schiano S, Heaps D, Wu CY. The application of terahertz pulsed imaging in characterising density distribution of roll-compacted ribbons. *European Journal of Pharmaceutics and Biopharmaceutics* 2016;**106**:20–25.
- [80] Yassin S, Su K, Lin H, Gladden LF, Zeitler JA. Diffusion and swelling measurements in pharmaceutical powder compacts using terahertz pulsed imaging. *Journal of Pharmaceutical Sciences* 2015;**104**:1658–1667.
- [81] Niwa M, Hiraishi Y, Iwasaki N, Terada K. Quantitative analysis of the layer separation risk in bilayer tablets using terahertz pulsed imaging. *International Journal of Pharmaceutics* 2013;**452**:249–256.
- [82] Cosentino A. Terahertz and cultural heritage science: examination of art and archaeology. *Technologies* 2016;**4**:6.
- [83] Dandolo CLK, Jepsen PU. Wall painting investigation by means of non-invasive terahertz time-domain imaging (THz-TDI): inspection of subsurface structures buried in historical plasters. *Journal of Infrared and Millimeter and Terahertz Waves* 2016;**37**:198–208.
- [84] Walker GC, Bowen JW, Matthews W, Roychowdhury S, Labaune J, Mourou G, Menu M, Hodder I, Jackson JB. Sub-surface terahertz imaging through uneven surfaces: visualizing Neolithic wall paintings in Çatalhöyük. *Optics Express* 2013;**21**:8126–8134.
- [85] Yuan M, Sun W, Wang X, Wang S, Zhang Q, Ye J, Zhang Y. Investigating murals with terahertz reflective tomography. *Proceedings of SPIE 9625, 2015 International Conference on Optical Instruments and Technology: Terahertz Technologies and Applications*; 2015. 962507.
- [86] Picollo M, Fukunaga K, Labaune J. Obtaining noninvasive stratigraphic details of panel paintings using terahertz time domain spectroscopy imaging system. *Journal of Cultural Heritage* 2015;**16**:73–80.

- [87] Fukunaga K, Ikari T, Iwai K. THz pulsed time-domain imaging of an oil canvas painting: a case study of a painting by Pablo Picasso. *Applied Physics A* 2016;**122**:106.
- [88] Seco-Martorell C, López-Domínguez V, Arauz-Garofalo G, Redo-Sanchez A, Palacios J, Tejada J. Goya's artwork imaging with terahertz waves. *Optics Express* 2013;**21**:17800–17805.
- [89] Abina A, Puc U, Jeglič A, Zidanšek A. Applications of terahertz spectroscopy in the field of construction and building materials. *Applied Spectroscopy Reviews* 2015;**50**:279–303.
- [90] Abina A, Puc U, Jeglič A, Zidanšek A. Structural characterization of thermal building insulation materials using terahertz spectroscopy and terahertz pulsed imaging. *NDT&E International* 2016;**77**:11–18.
- [91] Jiang Y, Ge H, Lian F, Zhang Y, Xia S. Early detection of germinated wheat grains using terahertz image and chemometrics. *Scientific Reports* 2016;**6**:21299.
- [92] Pastorelli G, Trafela T, Taday PF, Portieri A, Lowe D, Fukunaga K, Strlič M. Characterisation of historic plastics using terahertz time-domain spectroscopy and pulsed imaging. *Analytical and Bioanalytical Chemistry* 2012;**403**:1405–1414.
- [93] Dong J, Kim B, Locquet A, McKeon P, Declercq N, Citrin DS. Nondestructive evaluation of forced delamination in glass fiber-reinforced composites by terahertz and ultrasonic waves. *Composites Part B* 2015;**79**:667–675.
- [94] Sun W, Wang X, Zhang Y. A method to monitor the oil pollution in water with reflective pulsed terahertz tomography. *Optik* 2012;**123**:1980–1984.
- [95] Liu J, Fan WH, Chen X, Xie J. Identification of high explosive RDX using terahertz imaging and spectral fingerprints. *Journal of Physics: Conference Series* 2016;**680**:012030.

