# THz Image Processing and Its Applications

**Bidyut Kumar Kundu and Pragti**

**Abstract** This chapter labels the recent advances of terahertz (THz or $10^{12}$ Hz) technology-based image processing and its applications. In short, the sandwiched regime between infrared and microwaves, bridging the gap amid optics and electronics is renowned as the THz. THz image processing deals with the interaction of matters in the sub-millimetre wavelength band (*ca.* 300 GHz to 3 THz) of a distinct electromagnetic spectrum indistinguishable from the other spectroscopic techniques. The THz regime also known as the "THz gap" for a long time as neither microwave nor optical devices could entirely subjugator this mysterious realm with its countless unseen scientific assets. Thus, the discovery of THz imaging techniques becomes successful to fill the gap. In general, the traditional THz technology can simultaneously acquire both image and spectral information to address various fields such as security, aerospace industries, medicine, materials science, biomedical imaging and others. The development and commercialization of THz imaging systems are now broadly accepted as the accessible alternative roots, such as electron lasers, Smith-Pur-cell emitters, backward wave oscillators, synchrotrons, are relatively expensive components. Therefore, THz image processing tries to find the solution through its generation, manipulation and detection of THz radiation to expand its usability as check-up tool for various imaging applications. For example, higher sensitivity of THz wave is convenient to investigate the specific behaviour of bio-molecules. In addition, advanced digital image processing algorithms in association with THz pulsed imaging (TPI) are effective for screening, diagnosis and treatment to examine the 3D structures of biological samples like cancer tumours.

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A. Acharyya et al. (eds.), *Generation, Detection and Processing of Terahertz Signals*, Lecture Notes in Electrical Engineering 794,
https://doi.org/10.1007/978-981-16-4947-9_9

Apart from that, THz spectrum might not only impact wireless network architectures (e.g. WLAN/WPAN/D2D) or security screening but also in aerospace industries using diode detectors through non-ionizing radiation. In contrast to X-rays, THz wave is completely harmless that can pass through clothing, objects and packages to recognize the inside materials and substances. At a glance, THz imaging along with detection technology contributes to identify opaque objects with clear borders, shaping this book a must-read for anybody in the arena of digital imaging and biomedical engineering.

**Keywords** THz spectroscopy · THz technology · THz image processing · THz applications

## 1 Introduction

In the recent decade, Terahertz science has progressively common day by day owing to the most part to the arrival of ultrashort-pulse optical device based time-domain spectroscopic analysis (TDS), that permits it conceivable for researchers to convey time-resolved "far-infrared" (FIR) lessons and to get spectroscopic analysis and their applications in the field of imaging and image processing within the sub-millimetre wavelength range (Fig. 1) [1, 2].

The development and commercialization of THz imaging systems are now broadly accepted as the accessible alternative roots, such as electron lasers, Smith-Pur-cell

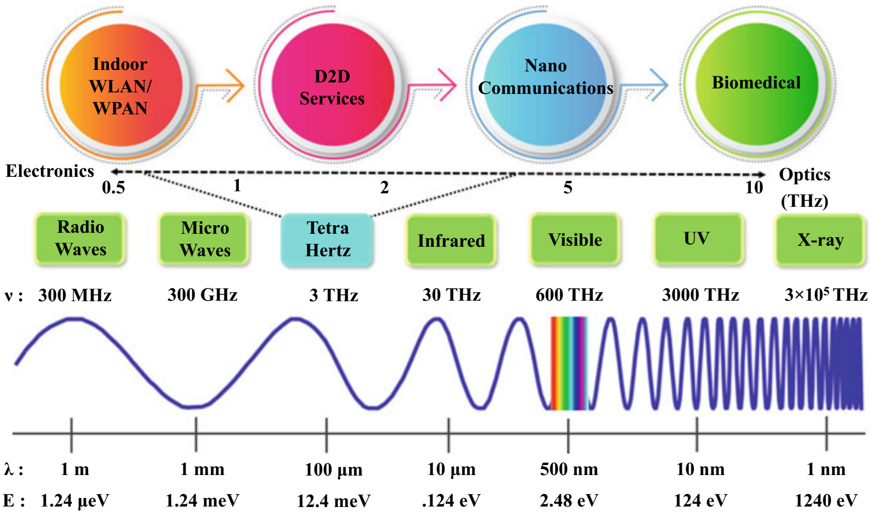


**Fig. 1** Electromagnetic spectrum

emitters, backward wave oscillators, synchrotrons, are relatively expensive components. Therefore, THz image processing tries to find the solution through its generation, manipulation and detection of THz radiation to expand its usability as check-up tool for various imaging applications.

Terahertz event surveys fundamental scientific benefits. Introduction of THz imaging systems can provide the answer to many spectroscopic limitations. The general objectives of this chapter are to assess the elementary theories of diverse kinds of THz foundations and detectors that are now thoughtful with THz radiation. The terahertz investigations are essential to be considered to accompanying crucial information. Thus, keeping in mind the growing interest in THz spectroscopy, this chapter will be sequenced as follows: Sect. 2 describes the background of THz spectroscopy. Sect. 3 briefly introduces Terahertz technology followed by THz image processing in the Sect. 4. This will follow up with THz technology-based applications in Sect. 5 that will be followed by conclusion in Sect. 6.

## 2 THz Spectroscopy

Terahertz wave is very sensitive to bio-molecules in the sub-millimetre wavelength band (*ca.* 300 GHz to 3 THz) [3], which offer several crucial medical applications. Moreover, the pulses of electromagnetic wave with an average power of 100 nW and a full-width half-maximum of 0.3 ps generally used for terahertz pulsed imaging (TPI) [4]. Fourier-transformed pulse or a photoconductive device can be convenient to coherently detect the pulses that provide a working frequency regime of 0.1–3.0 Terahertz [5]. While various methods like x-ray and ultrasound are failed to provide unique spectral information, terahertz imaging can be a proper solution furnishing a key advantage that is found that can possibly be employed to differentiate between the types of tissue [6]. The spectroscopic data may also be helpful for pharmaceutical applications—THz spectrographic analysis is ready to tell apart among polymorphic varieties of medicines. In fact, carbamazepine, a drug on the whole operated to deal with sufferers having psychological syndromes, transforms from shape III to shape I in a temperature-based method [7] (Fig. 2).

Terahertz radiations are non-invasive, penetrable and non-ionizing to numerous objects with a complexity of diffusion inferior to that of microwave radiation. THz spectra additionally tend to be terribly sensitive to numerous forms of resonances such as torsional, rotational, translational, vibrational and conformational states, empowering it to offer details on compounds, which are unapproachable with other imaging and analytical procedures (Fig. 3). These precise traits lead them to be appropriate for recognizing, analyzing, or imaging numerous materials. Despite Infrared and Raman spectroscopy, the improvement of strategies for generating, manipulating and detecting THz waves remains in its primary phases. However, THz wave was believed appropriate for image processing and other implementations, technologies to connect such competencies were realistically non-staying. On the other, the high frequency of terahertz cannot be estimated by an electronic counter used to record

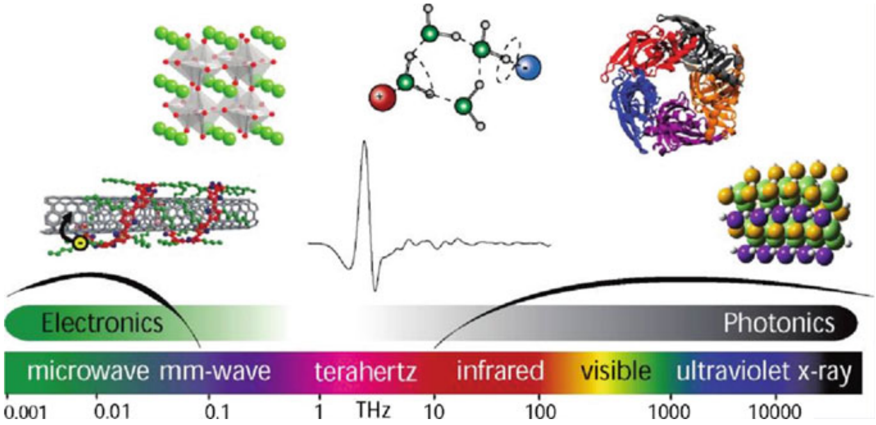


**Fig. 2** The THz scale based on the electromagnetic spectrum, with pictures featuring the large assortment of materials, molecules and phenomena, which THz spectroscopy can explore. Some examples of this kind are nano-materials and correlated electron materials; the charge carrier dynamics in semiconductors, hydration of solutes and liberational fashions in water and other liquids; and cooperative approaches in amino acid crystals and proteins. Reprinted with permission from [8]

optical radiations. Instead, different properties of wavelength and energy are used to characterize THz spectra. Significant advances in terahertz technology have led to more and more types of terahertz devices for different applications appearing for commercialization. This chapter introduces the use of THz image processing and the application of THz spectroscopy.

## 3 THz Technology

Although there is no precisely defined terahertz range, the accepted terahertz range is 300 to 3 GHz [3]. This parallels to wavelengths of 100 μm to 1 mm. This is a relatively unknown part of the electromagnetic spectrum called the "terahertz gap". Until recently, this gap was mainly due to the lack of light source and detector technology. Electromagnetic radiation (EM) with a wavelength longer than terahertz, antenna and waveguide tools can be presented for many years. Whereas for the wavelengths shorter than THz, optoelectronic and optical technologies have been applied for decades. These two technologies must be transported together to capture and study the THz regime, also stated as the far-infrared region.

THz radiation synthesis has been made conceivable by the advancement of three different strategies. These are:

1. Direct emission from far-infrared incoherent sources.
2. Up-conversion to terahertz frequencies from microwave frequencies [9].

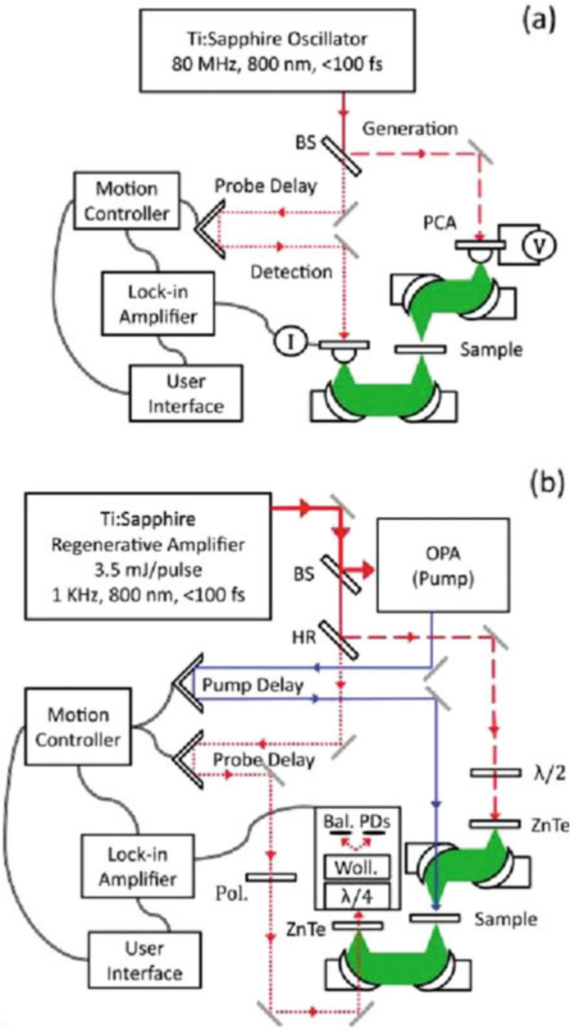


**Fig. 3** Characteristic transmission spectrometer flowchart of arrangements for **a** THz-TDS with photoconductive antennas and **b** TRTS with electro-optic production and recognition. Reprinted with permission from [8]

3. Coherent lasers down-conversion functioning in the adjacent IR to the THz band [10].

Figure 2 represents the THz-TDS in association to photoconductive antennas having characteristic transmission spectrometer configurations for TRTS generation and detection.

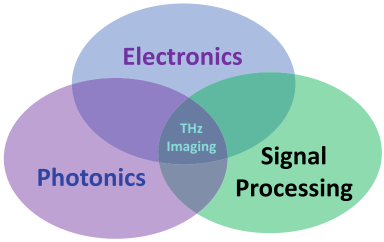


**Fig. 4** Counterparts for THz image processing

## 4 THz Image Processing

The components required for fruitful development of THz imaging is summarized in Fig. 4. It comprises the convergence of three units: electronics, photonics and signal processing.

Undoubtedly a portion of exertion has been devoted in the areas of electronics and photonics through the progress of production and identification technologies. Signal processing of THz data is the part that is least established [11]. Following are the main outcomes of this assignment, in this favour of THz spectroscopic imaging:

1. For significant development in THz image processing or THz imaging the key signal processing subjects that prerequisite to be talked about have been recognized and prospective lines of examination have been projected.
2. Introductory mathematical simulation and formulation outcomes have been gained for signal processing difficulties in Terahertz image modernization.

Moreover, in the typical working range of 0.3–5 THz, focal plane detector arrays are not yet accessible [12]. Antenna array mediated imaging by means of signal processing techniques is thus of great fit. Researchers established mathematical equations and primary explanations for complementary interferometric image modernization complications with antenna arrays [13]. Using MATLAB phantoms, computer simulations have also been achieved for tomographic renovation of complex-valued predictions.

## 5 THz Technology Applications

The aforesaid idiosyncratic competencies of terahertz radiations have been subjugated in a spare of applications in imaging and sensing. In general, THz wave applications are exploited in diverse areas including spectroscopy, photovoltaics, pharmacy, quality assurance, dentistry, medicine, communication, security screening and astronomy as depicted in Fig. 5.

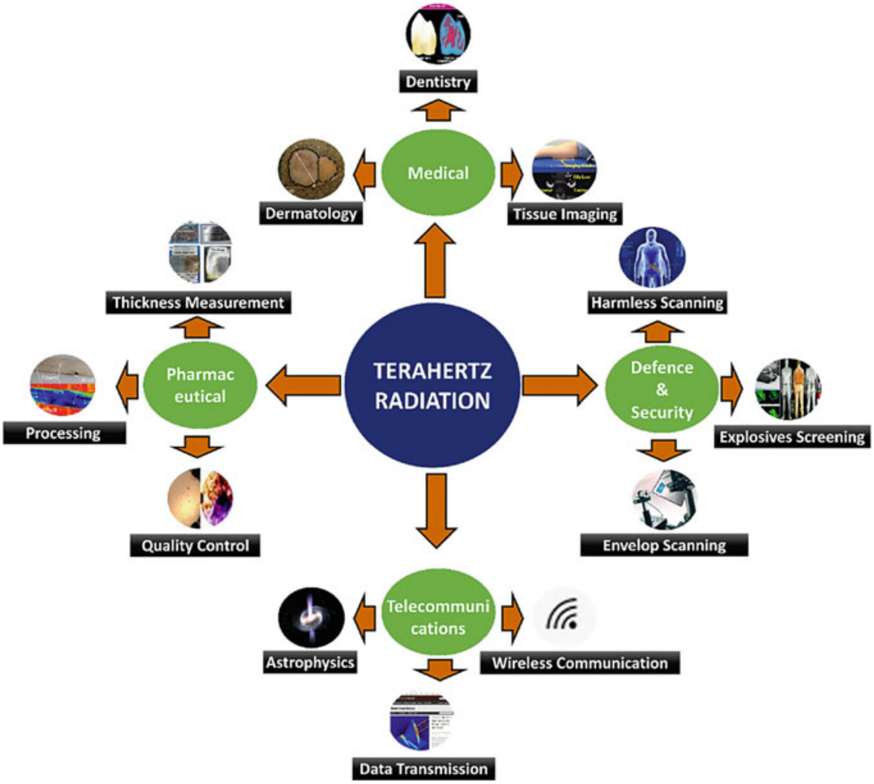


**Fig. 5** Applications of THz image processing. Reprinted with permission from ref [14]

## 5.1 THz Technology in Spectroscopic Analysis

Spectroscopic characterization of numerous materials can be analyzed by using Terahertz radiation. The characterization of various compounds has been exploited by introducing the sensitivity and resonances effect of terahertz radiation in different molecules. Moreover, intra-molecular connections can be investigated with the help of Fourier transform infrared (FTIR) spectroscopic techniques but THz probes are exclusive in the intelligence that they probe the intermolecular and intra-molecular interactions and deliver characteristic information of material. In a recent report, terahertz time-domain spectroscopy of 1,3,5-trinitro-s-triazine has been studied by Huang et al. which displayed an absorption peak at 0.8 THz accountable to intermolecular accomplishment [15].

In addition, infrared spectroscopy (FTIR) was introduced to corroborate the results with THz study, which was approved by the same researcher for assessment [15]. Using terahertz time-domain spectroscopy, the spectral topographies of uric acid and glucose has been investigated Upadhya et al. The results show that the absorption spectra of the two organic molecules were having unique features as a consequence of the intermolecular vibrational modes present in the compounds [16]. The spectral absorption topographies of a well-acknowledged illicit drug viz. methamphetamine has also been applied to study by Terahertz spectroscopy. Absorption spectra were traced to the cooperative vibrational modes estimated in the range of 0.2–2.6 THz corroborated with the experimental outcome of the molecule. Similarly, the investigation of time-domain THz spectroscopic measurement of 2,4-dinitrotoluene experimented for the same molecule in parallel with FTIR recording, which disclosed an improved association of outcomes of two procedures at lower frequencies range than at longer frequencies. The consequence gained experimentally interrelated well with theoretical analysis displaying that THz spectroscopy is an influential tool for perusing the low frequency modes of various molecules [17]. Apart from that, terahertz spectroscopy has been used to estimate some other compounds such as tryptophan [18] and trialanine, short-chain polypeptides [19].

Besides, the infrared spectra based on protein (bovine serum albumin, BSA)-complex interaction has been reported in one of our recent reports [20]. Though the information was not corroborated with THz spectral analysis. But, in a report, amplitude transmittance spectra of native-conformation and thermally denatured BSA protein interpreted using a THz-TDS system (Fig. 6).

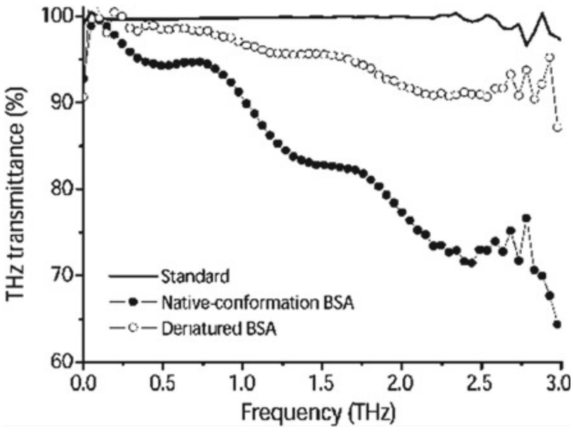


**Fig. 6** Applications to protein (here BSA) conformational analysis using a THz-TDS system. A standard sample with the solid curve shows THz transmittance without BSA, that of thermally denatured is denoted by open circles and the native conformation of BSA signified with solid circles. Reprinted with permission from ref [8]

## 5.2 THz Technology in Quality Control (QC)

The character of quality checks in the industry cannot be exaggerated and many methods and techniques are always being sight seen for use in the quality control of countless products. The analysis and characterization of numerous products can be done with the help of a powerful tool viz. THz time-domain spectroscopy. The assessment of several polymeric molecules along with a glass-fibre-reinforced epoxy composite and a polyethylene compound with silver-coated titanium dioxide nanospheres was utilized by Rutz et al. [21]. Terahertz radiation can also be useful for estimating the water content in various materials. The reduction of water to it has been subjugated for quality control in the paper manufacture process and the THz wave is also not clear to water [22]. Terahertz spectroscopy can also be introduced to evaluate the humidity level of papers. In addition, THz can also be applied to the measured mass of paper and thickness besides the access to the amount of water in papers [23]. THz imaging and spectroscopic techniques can also be helpful to monitor various food processes [24].

## 5.3 THz Technology in Photovoltaics

The construction of dye-sensitized solar cells on dye-sensitized titanium dioxide ($TiO_2$) can be analyzed through THz time-domain spectroscopy to acquire detailed spectroscopic information of the films [25]. Blackberry and pomegranate are the two natural dyes, which were inspected and extract an inorganic dye namely ruthenium bipyramidal complex (rubpy). From the observation, it was found that these two natural dyes having comparable spectral properties, which were dissimilar to that of the inorganic dye (rubpy).

THz reflectometry is also used in accumulation to the spectroscopic classification of photovoltaic compounds, to image photovoltaic compounds for identifying defects and flaws in the compounds, which could ultimately govern the competence of solar cells.

## 5.4 THz Technology in Pharmaceutical Industry

THz technology is oppressed in the pharmaceutical industry due to the exclusivity of its features [26–28]. THz radiations have the exceptional aptitude of powerful different classes of compounds, which are typically not clear to other procedures of electromagnetic fallout. The detection and quantification of hydrates or polymorphic systems can be explored by the applications of THz in pharmaceutical industry including novel active pharmaceutical constituents. The bioavailability, stability and production of drugs makes it easy to optimize the characterization via THz image processing [29]. The thickness of coated pharmaceutical tablets and the quantification of the coating can be used by THz pulse imaging (TPI), which is reported by Russe et al. The common tomographic procedure and X-ray Micro tomography were screened to authenticate the outcomes of the tablet coated THz pulsed imaging.

## *5.5 THz Technology in Biomedical Applications*

The development of imaging and sensing purposes of new THz techniques have seen for the last couple of decades. Like X-ray, THz wave is proficient in producing 2D pictures of diverse types of matters owing to the circumstance that THz waves transportable through some materials like plastics and semiconductors but are not clear to the others such as polarizing and metallic materials. For medical imaging, THz radiations are superior over X-rays because they are non-ionizing and to a large degree innocuous to the receiver. THz radiations are presently beneath examination for routine as an imaging modality to envisage tumour or cancerous tissues. Cancer is the second foremost reason of death in the U.S. after cardiovascular disease as per the American Cancer Society and notes for approximately one in every four deaths. The current imaging methods are no sufficient to study early detection of disease, which could mean the variance between life and death for countless patients but there is a gap. Herein, novel THz spectroscopic lessons on cancer could possibly offer new procedures for the initial recognition of the disease. Indeed, THz radiation-based imaging and detection of cancerous cells and skin tissues thus has been a sharp upsurge in the amount of studies signifying its potential use [30–33]. The technique lends itself glowing to imaging utmost organic tissue as THz wave is voluntarily absorbed by polar liquids and/or water [31]. Furthermore, Woodward et al., able to discriminate basal cell carcinoma, a type of skin cancer, from healthy tissues with the help of Terahertz pulse imaging [32]. Breast cancer studies are also an example, which has also been tested through the THz pulse imaging [34]. Terahertz radiation is very essential to investigate an excessive quantity of bio-molecules such as proteins, amino acids/peptides, carbohydrates, RNA/ DNA, cells and tissues [35]. The absorption spectra in the terahertz frequency can be reflected in the low-frequency core helical vibration of DNA involving hydrogen bond of DNA base pairs [36]. Thus, for the characterization of biological compounds or bio-molecules, THz radiation can be utilized to get extreme level of sensitivity towards the study of bio-molecules.

**Dental Application**: Imaging with X-ray is the leading imaging method in dentistry. This is the key technology used to watch dental caries and set up treatment for implants, extractions, dentures and braces. Nevertheless, X-rays are especially ionizing and common contacts are negative to health. Thus, as an alternative imaging technique, Terahertz pulsed imaging (TPI) express inordinate prospective in dental diagnosis [37–40]. On the other, THz radiations are less hazardous, non-ionizing and low in energy. In contrast to different organic tissues with a large percent of water with the inclination for extensive absorption of THz wave, tooth have an enormously

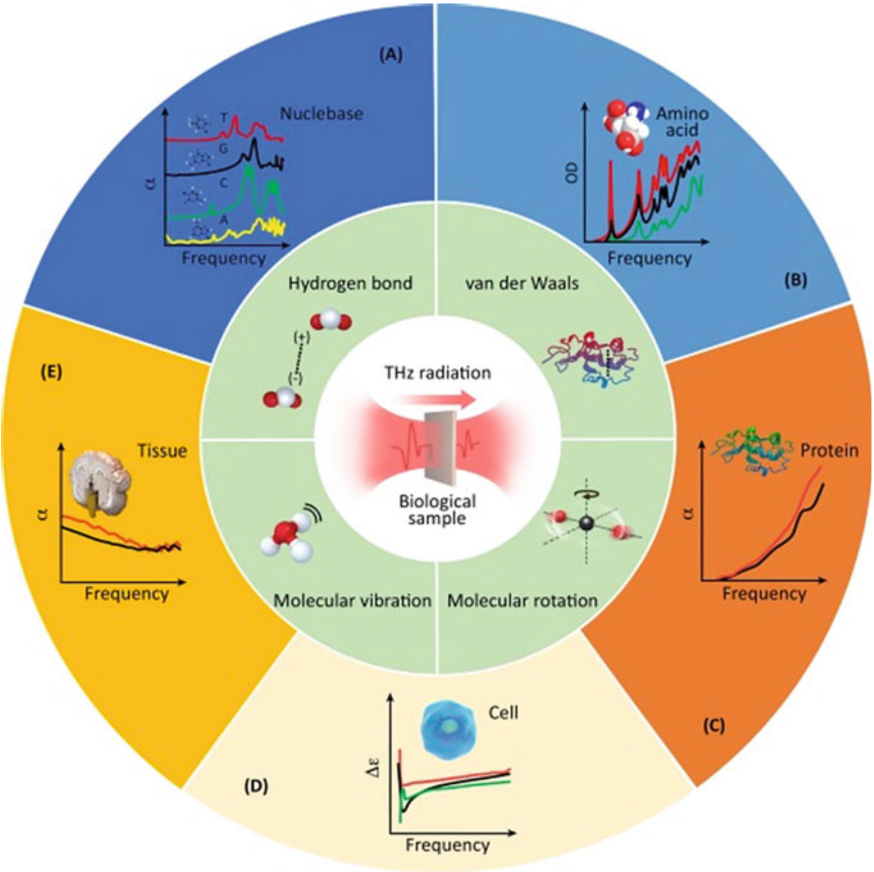


**Fig. 7** Terahertz spectroscopy in biomedical applications and image processing. Reprinted with permission from ref [41]

small water proportion, which drives it handy to photo tooth samples the usage of the THz pulsed imaging method (Fig. 7).

## *5.6 THz Technology in Security Screening*

Security screening is the most usual place programs of THz technology and image processing. Terahertz does nowadays no longer most effective supply statistics approximately the existence of hid objects however additionally has the ability to become aware of the composition of the substances as per requirement. In latest years several examinations have been performed at the functionality of terahertz to hit upon explosives at airports and different touchy places [42]. The gain of THz wave over

X-ray, extensively utilized for security screening because of its non-ionizing nature and low energy. The ionizing behaviour of X-rays forms the ordinary acquaintance of it, which by means is dangerous to people. The particular ability of Terahertz radiations to impale an extensive variety of packaging substances drives it feasible to hit upon explosives, weapons and doubtlessly explosive devices hid inside those substances [43].

### 5.7 THz Technology in Communication, Remote Sensing and Astronomy

One different use of THz spectra is inside the place of wireless statistics communication. The THz radiation part of the electromagnetic radiations has proven to undertake as a bandwidth appropriate for statistics transmission. Ishagaki et al. have planned a THz oscillating resonate tunnelling diode that has the capacity to transmits a signal at 542 GHz with a statistics switches price of 3 Gbit/s. This kind of THz WIFI is constrained to a vicinity of 30 ft however has an ability to aid statistics fees of as much as a hundred Gbit/s. Remote sensing lets in the purchase of data approximately substances or places from a span, which will be from a plane or satellites. Terahertz radiation is one of the potential equipment for sporting out far off sensing. Lui et al. advanced a method primarily based on broadband THz radiation identification for far off sensing with which they had been capable of coming across coherent THz radiation at a separation of 10 m [44].

### 5.8 THz Technology in Some Other Applications

Meta materials are substances that can be structurally regulated to have interaction in a selected manner to electromagnetic waves. Meta materials can also be represented by THz spectroscopy in a regular manner. Meta materials that can be mainly counterfeited to have interaction with THz radiation are mentioned to THz meta materials. THz spectroscopy additionally has the capacity to hit upon oil spills in water bodies [45, 46]. Gorenflo et al. decided the quantity and shape of water in oil-water complexes with the help of terahertz transmission spectroscopy, via way of means of tracking modifications in refractive index and absorption coefficient [45].

## 6 Summary

In the last couple of decades, a noteworthy development has been made on the Tetrahertz mediated technology for the production, manipulation and identification of

THz wave resulting in ever-growing applications of this technology in the research and industry. Herein, this chapter contributes towards the role of Terahertz image processing and THz technology along with its applications in numerous areas such as spectroscopic analysis, biomedical, pharmaceutical testing, oil spill characterization, astronomy, photovoltaic characterization, security screening, quality control and pharmaceutical industry. With the exponential development in analysis within the THz region, a tendency has been developed to anticipate additional proceedings in the implementation of THz technology within society.

**Acknowledgements** The first author gladly thanks his mother, Mrs. Champa Kundu for her constant moral support and encouragement to carry out this work.

## References

1. Safian R, Ghazi G, Mohammadian N (2019) Review of photomixing continuous-wave terahertz systems and current application trends in terahertz domain. Opt Eng 58:110901
2. Castro-Camus E, Alfaro M (2016) Photoconductive devices for terahertz pulsed spectroscopy: a review. Photonics Res 4:A36–A42
3. Ghasempour Y, Shrestha R, Charous A, Knightly E, Mittleman DM (2020) Single-shot link discovery for terahertz wireless networks. Nat Commun 11:1–6
4. Huang S, Wang Y, Yeung D, Ahuja A, Zhang Y, Pickwell-MacPherson E (2008) Tissue characterization using terahertz pulsed imaging in reflection geometry. Phys Med Biol 54:149
5. Spies JA, Neu J, Tayvah UT, Capobianco MD, Pattengale B, Ostresh S, Schmuttenmaer CA (2020) Terahertz spectroscopy of emerging materials. J Phys Chem C 124:22335–22346
6. Afsah-Hejri L, Hajeb P, Ara P, Ehsani RJ (2019) A comprehensive review on food applications of terahertz spectroscopy and imaging. Compr Rev Food Sci Food Saf 18:1563–1621
7. Kiang Y-H, Huq A, Stephens PW, Xu W (2003) Structure determination of enalapril maleate form II from high-resolution X-ray powder diffraction data. J Pharm Sci 92:1844–1853
8. Baxter JB, Guglietta GW (2011) Terahertz Spectroscopy. Anal Chem 83:4342–4368
9. Shi M, Yu M, Li G, Wang M (2020) A THz fourth-harmonic conversion system expanding microwave to THz band. Infrared Phys Technol 107:103217
10. Pistore V, Nong H, Vigneron P-B, Garrasi K, Houver S, Li L, Davies AG, Linfield EH, Tignon J, Mangeney J (2021) Millimeter wave photonics with terahertz semiconductor lasers. Nat Commun 12:1–7
11. Khabibullin RA, Morozov OG, Sakhabutdinov AJ, Nureev II, Kuznetsov AA (2018) Two-frequency radiation forming on chirped FBG for tuning terahertz carriers generation. In: 2018 Systems of signals generating and processing in the field of on board communications, IEEE, pp 1–4
12. Oda N, Kurashina S, Miyoshi M, Doi K, Ishi T, Sudou T, Morimoto T, Goto H, Sasaki T (2015) Microbolometer terahertz focal plane array and camera with improved sensitivity in the sub-terahertz region. J Infrared Millim Terahertz Waves 36:947–960
13. Guerboukha H, Nallappan K, Skorobogatiy M (2018) Toward real-time terahertz imaging. Adv Opt Photonics 10:843–938
14. Yakasai IK, Abas PE, Begum F (2021) Review of porous core photonic crystal fibers for terahertz waveguiding. Optik 229:166284
15. Huang F, Schulkin B, Altan H, Federici JF, Gary D, Barat R, Zimdars D, Chen M, Tanner D (2004) Terahertz study of 1, 3, 5-trinitro-s-triazine by time-domain and Fourier transform infrared spectroscopy. Appl Phys Lett 85:5535–5537

16. Upadhya P, Shen Y, Davies A, Linfield E (2003) Terahertz time-domain spectroscopy of glucose and uric acid. J Biol Phys 29:117–121
17. Chen Y, Liu H, Deng Y, Schauki D, Fitch MJ, Osiander R, Dodson C, Spicer JB, Shur M, Zhang X-C (2004) THz spectroscopic investigation of 2, 4-dinitrotoluene. Chem Phys Lett 400:357–361
18. Yu B, Zeng F, Yang Y, Xing Q, Chechin A, Xin X, Zeylikovich I, Alfano R (2004) Torsional vibrational modes of tryptophan studied by terahertz time-domain spectroscopy. Biophys J 86:1649–1654
19. Kutteruf M, Brown C, Iwaki L, Campbell M, Korter T, Heilweil E (2003) Terahertz spectroscopy of short-chain polypeptides. Chem Phys Lett 375:337–343
20. Kundu BK, Pragti, Mobin SM, Mukhopadhyay S (2020) Studies on the influence of the nuclearity of zinc(ii) hemi-salen complexes on some pivotal biological applications. Dalton Trans 49:15481–15503
21. Rutz F, Koch M, Khare S, Moneke M, Richter H, Ewert U, Waves M (2006) Terahertz quality control of polymeric products. Int J Infrared 27:547–556
22. Banerjee D, Von Spiegel W, Thomson M, Schabel S, Roskos H (2008) Diagnosing water content in paper by terahertz radiation. Opt Express 16:9060–9066
23. Hernandez-Serrano A, Corzo-Garcia S, Garcia-Sanchez E, Alfaro M, Castro-Camus E (2014) Quality control of leather by terahertz time-domain spectroscopy. Appl Opt 53:7872–7876
24. Gowen AA, O'Sullivan C, O'Donnell C (2012) Technology, Terahertz time domain spectroscopy and imaging: emerging techniques for food process monitoring and quality control. Trends Food Sci 25:40–46
25. Ghann W, Rahman A, Rahman A, Uddin J (2016) Interaction of sensitizing dyes with nanostructured TiO 2 film in Dye-Sensitized solar cells using terahertz spectroscopy. Sci Rep 6:1–11
26. Uddin J (2017) Terahertz (THz) spectroscopy: a cutting-edge technology. Wiley, Hoboken, NJ, USA, 2006
27. Taday PF (2004) Applications of terahertz spectroscopy to pharmaceutical sciences. Philos Trans R Soc London. Ser: Math Phys Eng Sci 362:351–364
28. Shen Y-C (2011) Terahertz pulsed spectroscopy and imaging for pharmaceutical applications: a review. Int J Pharm 417:48–60
29. McIntosh AI, Yang B, Goldup SM, Watkinson M, Donnan RS (2012) Terahertz spectroscopy: a powerful new tool for the chemical sciences? Chem Soc Rev 41:2072–2082
30. Rahman A, Frenchek S, Kilfoyle B, Patterkine L, Rahman A, Michniak-Kohn B (2012) Diffusion kinetics permeation concentration of human stratum corneum characterization by terahertz scanning reflectometry. Drug Dev Delivery
31. Pickwell E, Cole BE, Fitzgerald AJ, Pepper M, Wallace VPJPiM (2004) Biology, In vivo study of human skin using pulsed terahertz radiation. Phys Med 49, 1595
32. Woodward RM, Wallace VP, Pye RJ, Cole BE, Arnone DD, Linfield EH, Pepper M (2003) Terahertz pulse imaging of ex vivo basal cell carcinoma. J Investig Dermatol 120:72–78
33. Woodward RM, Cole BE, Wallace VP, Pye RJ, Arnone DD, Linfield EH, Pepper M (2002) Terahertz pulse imaging in reflection geometry of human skin cancer and skin tissue. Phys Med Biol 47:3853
34. Ashworth PC, Pickwell-MacPherson E, Provenzano E, Pinder SE, Purushotham AD, Pepper M, Wallace VP (2009) Terahertz pulsed spectroscopy of freshly excised human breast cancer. Opt Express 17:12444–12454
35. Plusquellic DF, Siegrist K, Heilweil EJ, Esenturk O (2007) Applications of terahertz spectroscopy in biosystems. Chem Phys Chem 8:2412–2431
36. Globus T, Woolard D, Khromova T, Crowe T, Bykhovskaia M, Gelmont B, Hesler J, Samuels A (2003) THz-spectroscopy of biological molecules. J Biol Phys 29:89–100
37. Crawley DA, Longbottom C, Cole BE, Ciesla CM, Arnone D, Wallace VP, Pepper M (2003) Terahertz pulse imaging: a pilot study of potential applications in dentistry. Caries Res 37:352–359

38. Crawley DA, Longbottom C, Wallace VP, Cole BE, Arnone DD, Pepper M (2003) Three-dimensional terahertz pulse imaging of dental tissue. J Biomed Opt 8:303–307
39. Sim YC, Park JY, Ahn K-M, Park C, Son J-H (2013) Terahertz imaging of excised oral cancer at frozen temperature. Biomed Opt Express 4:1413–1421
40. Kamburoğlu K, Yetimoĝlu N (2014) Applications of terahertz imaging in medicine. OMICS J Radiol 3, e127
41. Yang X, Zhao X, Yang K, Liu Y, Liu Y, Fu W, Luo Y (2016) Biomedical applications of terahertz spectroscopy and imaging. Trends Biotechnol 34:810–824
42. Shen Y, Lo AT, Taday P, Cole B, Tribe W, Kemp M (2005) Detection and identification of explosives using terahertz pulsed spectroscopic imaging. Appl Phys Lett 86, 241116
43. Davies AG, Burnett AD, Fan W, Linfield EH, Cunningham JE (2008) Terahertz spectroscopy of explosives and drugs. Mater Today 11:18–26
44. Liu J, Dai J, Chin SL, Zhang X-C (2010) Broadband terahertz wave remote sensing using coherent manipulation of fluorescence from asymmetrically ionized gases. Nat Photonics 4:627
45. Gorenflo S, Tauer U, Hinkov I, Lambrecht A, Buchner R, Helm H (2006) Dielectric properties of oil–water complexes using terahertz transmission spectroscopy. Chem Phys Lett 421:494–498
46. Cunnell R, Luce T, Collins J, Rungsawang R, Freeman J, Beere H, Ritchie D, Gladden L, Johns M, Zeitler J (2009) Quantification of emulsified water content in oil using a terahertz quantum cascade laser. In: 2009 34th international conference on infrared, millimeter, and terahertz waves. IEEE, pp 1–2