Chapter 1

Terahertz (THz) Spectroscopy: A Cutting-Edge Technology

William Ghann and Jamal Uddin

Additional information is available at the end of the chapter

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1. Introduction

Terahertz (THz) represents the portion of the electromagnetic radiation between the microwave and the infrared region as displayed in **Figure 1**. It is within the frequency range of 0.1–10 THz, corresponding to wavelengths of radiation from 3000 to 30 μm. Terahertz radiation is also known as terahertz gap, terahertz waves, T-waves, terahertz light, T-light, or T-lux. This form of electromagnetic radiation is less known, due to the limited access to technology for generating and detecting radiation [1]. There are a number of reviews on the different technologies for generating and detecting terahertz [2, 3]. Terahertz waves are nonionizing, noninvasive, and penetrable to many materials with a depth of penetration lower than that of microwave radiation. Terahertz radiation also tends to be very sensitive to various kinds of resonances such as vibrational, translational, rotational, torsional, and conformational states, enabling it to provide information on molecules that are inaccessible with other analytical and imaging techniques. These unique characteristics make them suitable for identifying, analyzing, or imaging a variety of materials.

Unlike Raman and Infrared spectroscopy, the development of techniques for generating, manipulating, and detecting terahertz radiation is still in its early stages. Although terahertz radiation was deemed suitable for imaging and other applications, technologies to harness such capabilities were practically nonexistent [4]. On one hand, high terahertz frequencies do not lend themselves to be estimated with electronic counters employed in the detection of optical waves; instead various properties of wavelength and energy are harnessed to characterize terahertz radiation [5]. On the other hand, at such higher frequencies electronic devices utilized in generation and manipulation of radio waves and microwaves become less efficient. Thus with the exception of the terahertz gap, technology for the generation, manipulation, and everyday application of a vast majority of the electromagnetic spectrum has been developed. Significant progress made in terahertz technology has led to an increase in the different types of terahertz instrumentation available on the market with application for diverse fields. This review focuses on the generation, characterization, and application of terahertz radiation.

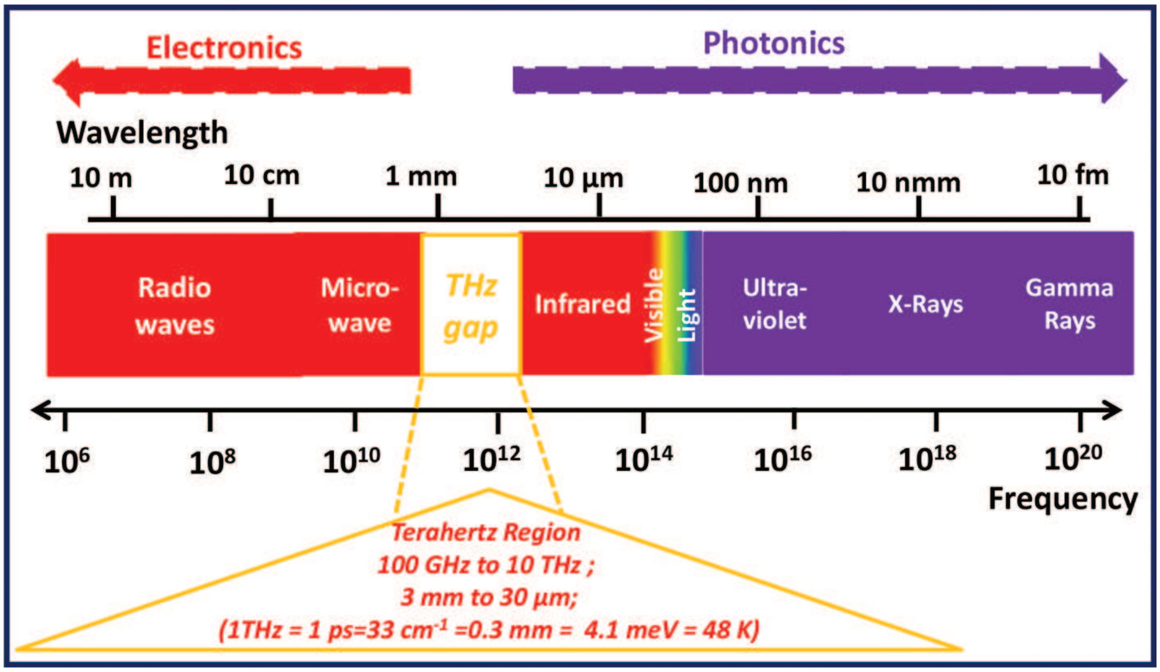

Figure 1. Frequency and wavelength regions of the electromagnetic spectrum.

2. Generation and detection of terahertz radiation

A typical terahertz system, in a majority of cases, consists of a source, components, and a detector. Some terahertz system may possess two or more of these components. A terahertz source generates a wide range of terahertz radiation; components such as lenses, mirrors, and polarizers manipulate the radiation; and a detector measures the radiation reaching it. R. A. Lewis list six main types of terahertz sources [6]. These include thermal [7, 8], vacuum electronic [9–11], solid-state electronic [12, 13], lasers [14, 15], sources pumped by lasers [16, 17], and mechanical-excitation types of terahertz radiation sources [18, 19]. Sources pumped by lasers employ either continuous or pulsed lasers. We will discuss the generation of terahertz radiation using a source pumped by continuous-wave (CW) diode lasers using an electro-optic dendrimer. In this method, an electro-optic dendrimer generates terahertz radiation through the difference-frequency technique (DFG). Rahman et al. pioneered work on the generation of terahertz radiation using this technique. The technique uses two continuous lasers to pump an electro-optic dendrimer emitter to give a combined pump power capable of generating a stable terahertz radiation from 0.1 THz to approximately 10 THz at room temperature.

Dendrimers are highly branched synthetic polymers composed of a central core, a treelike interior structure, and an external surface decorated with functional groups. Dendrimers have nanoscale dimensions and are radially symmetric molecules. The size of a dendrimer is dependent on its generation or the number of concentric shells around the core; the higher the generation, the larger the size. Their unique structure and size make them suitable for a variety of applications including their use as drug delivery agents, imaging agents, solubilizing agents, and radio-ligands. An electro-optic dendrimer has the capacity to generate terahertz radiation [8, 20]. When the structural features of dendrimers are carefully manipulated,

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the optical and electro-optic properties of the functional groups at the periphery of the dendrimers are enhanced in a very controlled manner. Dendrimers are able to form self-assembled multilayers. The thickness of such multilayer assemblies can be adjusted by controlling certain parameters such as the number of concentric layers or generation of the dendrimer. The surface and solution chemistry also affect the thickness of dendrimers.

Dendrimer dipole excitation (DDE) is the mechanism for the creation of the electro-optic dendrimer. Electro-optic properties are critical for applications that normally rely on nonlinear optical parameters such as electro-optic coefficient (EOC), and the second-order susceptibility, $\chi^{(2)}$. A third-generation dendrimer (**Figure 2a**) undergoes chromophore doping and poling to become an electro-optic dendrimer with high second-order susceptibility $\chi^{(2)}$ and a high electro-optic coefficient. A high $\chi^{(2)}$ is essential for both the up conversion and the bandwidth. The chromophore poling optimizes the dipole alignment of dendrimer film. There are a number of poling techniques including corona poling, optical poling, contact electrode poling, and photo-assisted poling. The electro-optic coefficient (r_{33}) is deduced from the difference in the refractive index (Δn) of poled and unpoled electro-optic dendrimer in accordance with the Pockel's law as shown in Eq. (1), where E_p is the poling field

$$|\Delta n| = \frac{1}{2} n^3 r_{33} \mathrm{E}_p \quad (1)$$

The electro-optic coefficient of dendrimers is significantly higher than inorganic crystalline materials since the second-order susceptibility is proportional to the relative electric constant (ε) and r_{33} as shown in Eq. (2):

$$\chi^{(2)} \propto \varepsilon^2 r_{33} \quad (2)$$

As displayed in **Figure 2(a)**, dendrimer doping creates a dipole moment (μ) distribution of charge (Q) carriers in the dendrimer such that the equation for dipole moment ($\mu = ql$) is adjusted to $\mu(r) = Ql(r)$. The separation (l) between the negative and positive charge centers is therefore a function of the coordinate, $l(r)$, of the charge centers. **Figure 2(c)** shows a schematic of the possible energy levels in an electro-optic dendrimer molecule that has undergone doping and poling.

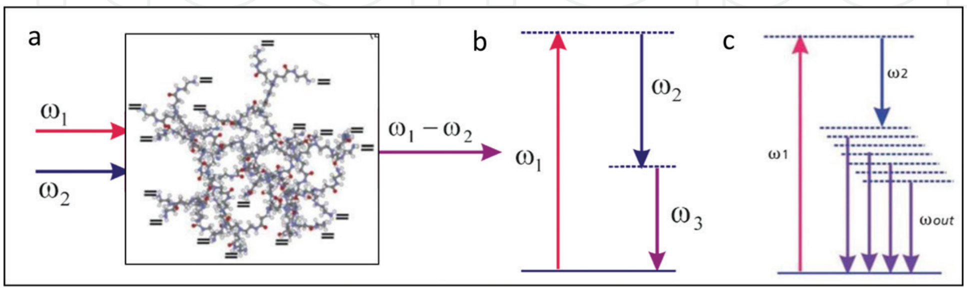

Figure 2. (a) Molecular structure of the third-generation dendrimer and interaction geometry for difference generation; (b) energy-level diagram of difference-frequency generation; (c) probable energy-level diagram in dendrimer molecule resulting from chromophore doping and poling. Adapted with permission from Ref. [20].

Difference-frequency generation (DFG) is used to generate terahertz radiation from the electro-optic dendrimers by a nonliner polarization as illustrated in Eq. (3).

$$P(\omega_1 - \omega_2) = 2\chi^{(2)} E_1 E_2^n \tag{3}$$

where E_1 and E_2 are the field strengths, ω_1 and ω_2 are the frequencies of the input lasers. **Figure 2** displays the energy-level diagram of the difference-frequency generation (panels a and b). Every photon created at the difference-frequency (Eq. (4)) requires the destruction of a photon at a higher input frequency (ω_1) and the creation of a photon at the lower input frequency (ω_2) to meet the requirements for energy conservation:

$$\omega_3 = \omega_1 - \omega_2 \tag{4}$$

A terahertz source generates the radiation, which goes through various components and reaches the detector. There are many methods used to detect terahertz radiation. The electro-optic sampling method of terahertz detection will be discussed in this section. Electro-optic sampling relies on the linear electro-optic effect, also known as the Pockel's effect. In the Pockel's effect, an externally applied electric field modulates the birefringence of an electro-optic material [17]. Typical components of this detection system include an electro-optic medium, a broadband quarter-wave plate, a Wollastron prism and differential detectors. When terahertz waves reach the detector, the incident THz pulse induces a birefringence in an electro-optic medium, which is proportional to the electric field of the pulse. The change in polarization state of a probe near-infrared probe pulse is measured with varying birefringence. The terahertz electric field can be mapped by measuring the degree of polarization rotation as a function of the delay between the terahertz pulse and the near-infrared probe pulse [17].

3. Applications of terahertz technology

The aforementioned distinctive capabilities of terahertz waves have been exploited in a plethora of applications in sensing and imaging. These applications of terahertz radiation are utilized in a variety of fields such as spectroscopy, photovoltaics, medicine, security screening, pharmacy, quality assurance, dentistry, communication, and astronomy (**Figure 3**).

3.1. Spectroscopic analysis

Terahertz has been used for the spectroscopic characterization of various materials. The sensitivity of terahertz radiation to resonances in different molecules has been exploited for the characterization of various compounds. Infrared spectroscopic techniques investigate intramolecular interactions but terahertz probes are unique in the sense that they probe the intramolecular and intermolecular interactions and provide information characteristic of a material. Huang et al. studied the terahertz time-domain spectroscopy of 1,3,5-trinitro-s-triazine. The results showed an absorption peak at 0.8 THz attributable to intermolecular action. The results were corrobo-

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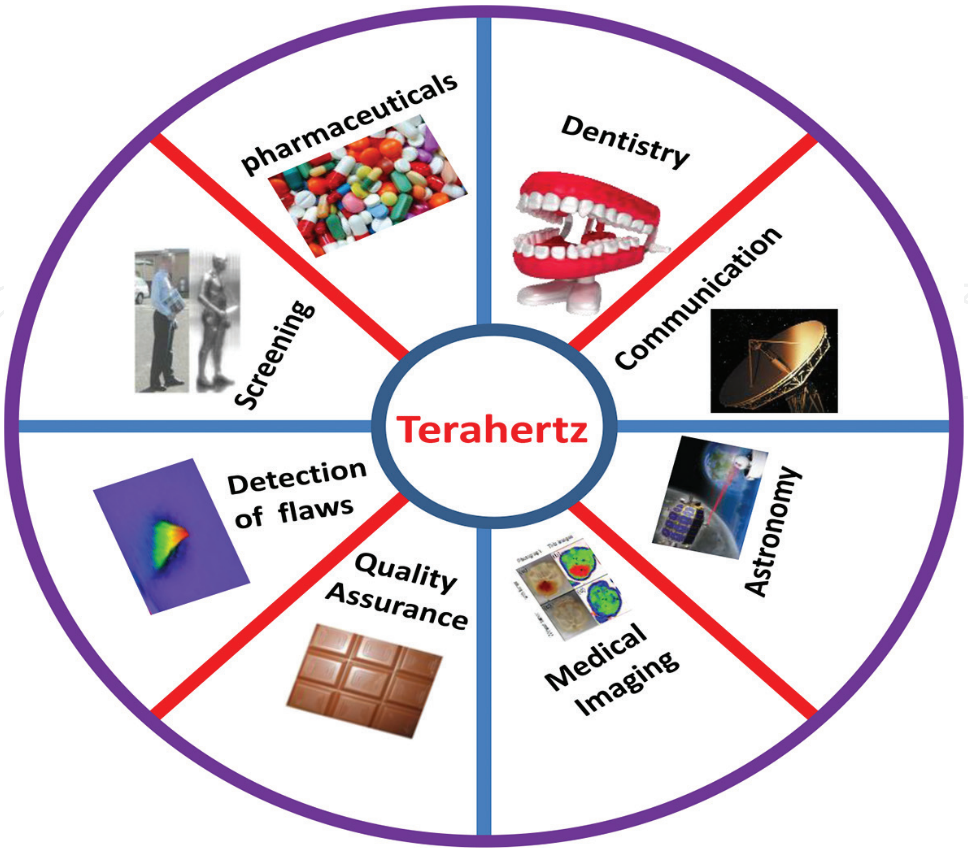

Figure 3. Examples of application of terahertz radiation (detection of flaws in photovoltaic materials, medical imaging, screening, pharmaceuticals, quality control, dentistry, communication, and astronomy).

rated with Fourier transform infrared spectroscopy (FTIR) study, which was carried out by the same researcher for comparison [21]. Upadhya et. al investigated the spectral features of glucose and uric acid using terahertz time-domain spectroscopy. It was found out that the unique features on the absorption spectra of the two biological molecules were as a result of the intermolecular vibrational modes existing in the molecules [22]. Terahertz spectroscopy has also been used to study the spectral absorption features of methamphetamine, a well-known illicit drug. Absorption spectra measured from 0.2 to 2.6 THz agreed with experimental data and were traced to the collective vibrational modes of the compound. Likewise, time-domain terahertz spectroscopic investigation of 2,4-dinitrotoluene carried out side by side with FTIR measurement of the same compound revealed a better correlation of results of two techniques at lower frequencies than at higher frequencies. The result obtained experimentally correlated well with theoretical study showing that terahertz spectroscopy is a powerful tool for studying the low-frequency modes of several compounds [23]. Other compounds that have been studied with terahertz spectroscopy include trialanine, short-chain polypeptides [24], and tryptophan [25].

3.2. Terahertz characterization of photovoltaics

We have used terahertz time-domain spectroscopy to obtain spectroscopic information on dye-sensitized titanium dioxide (TiO_2) films used in the fabrication of dye-sensitized solar cells [26]. **Figure 4** displays the probe setup used for this work. The dyes examined include two natural dyes, pomegranate and blackberry extract and a ruthenium bipyramidal complex. It was observed that the natural dyes, pomegranate and blackberry, had similar spectral features, which were different from that of the inorganic dye (rubpy).

In addition to the spectroscopic characterization of photovoltaic materials, terahertz reflectometry is also used to image photovoltaic material for detecting flaws and defects in the materials that could eventually affect the efficiency of solar cells. To confirm the unique capability of terahertz reflectometry to detect flaws present on the dye-sensitized TiO_2 films, dye-adsorbed TiO_2 films with size of 25 mm × 25 mm were scanned to examine any defects in an area of 14 mm × 14 mm. Pomegranate, blackberry, and rubpy dye-sensitized solar cell electrodes were scanned and with the measurements, 3D images, comparable to scanning electron microscopy images, were generated. As displayed in **Figure 5**, the cracks present in the TiO_2 films show up as large peaks on the surface plots due to the greater intensity of

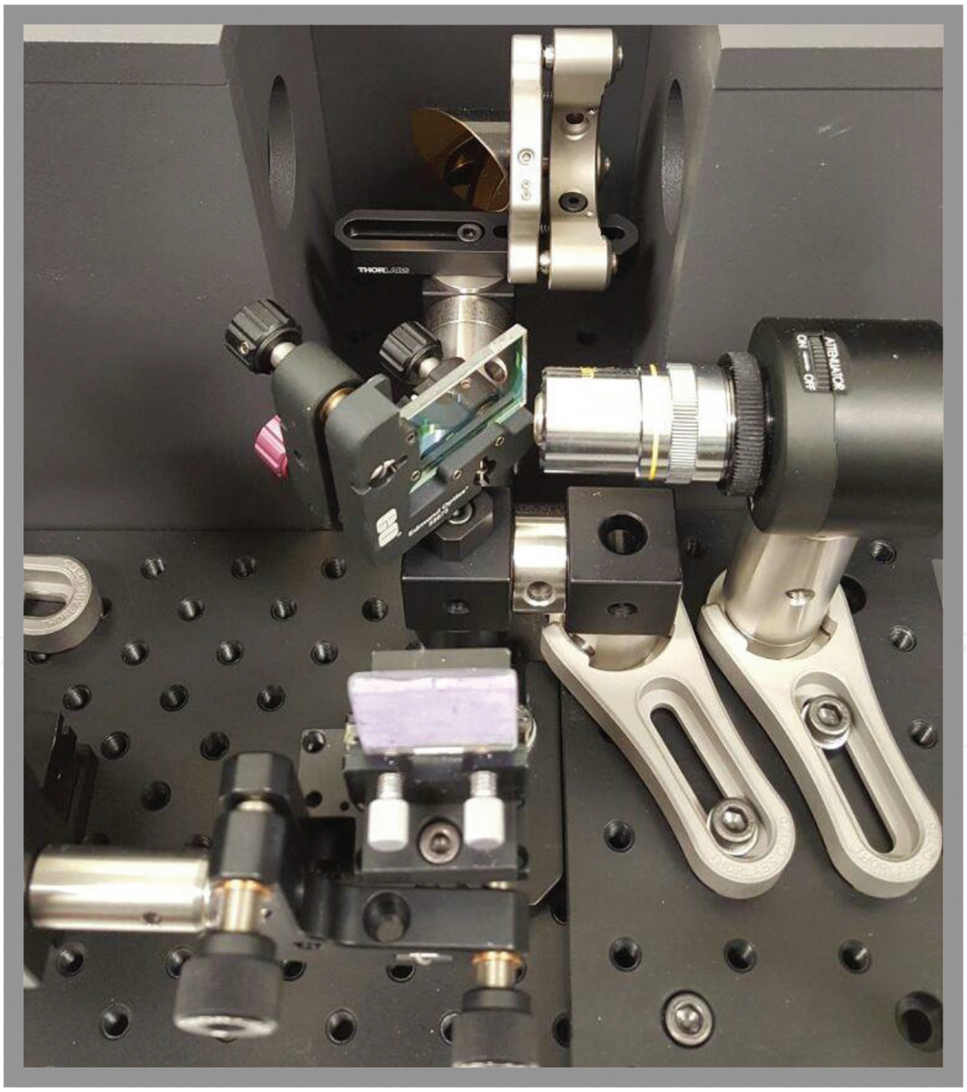

Figure 4. A typical terahertz probe setup used for reflectance measurement of photovoltaic materials.

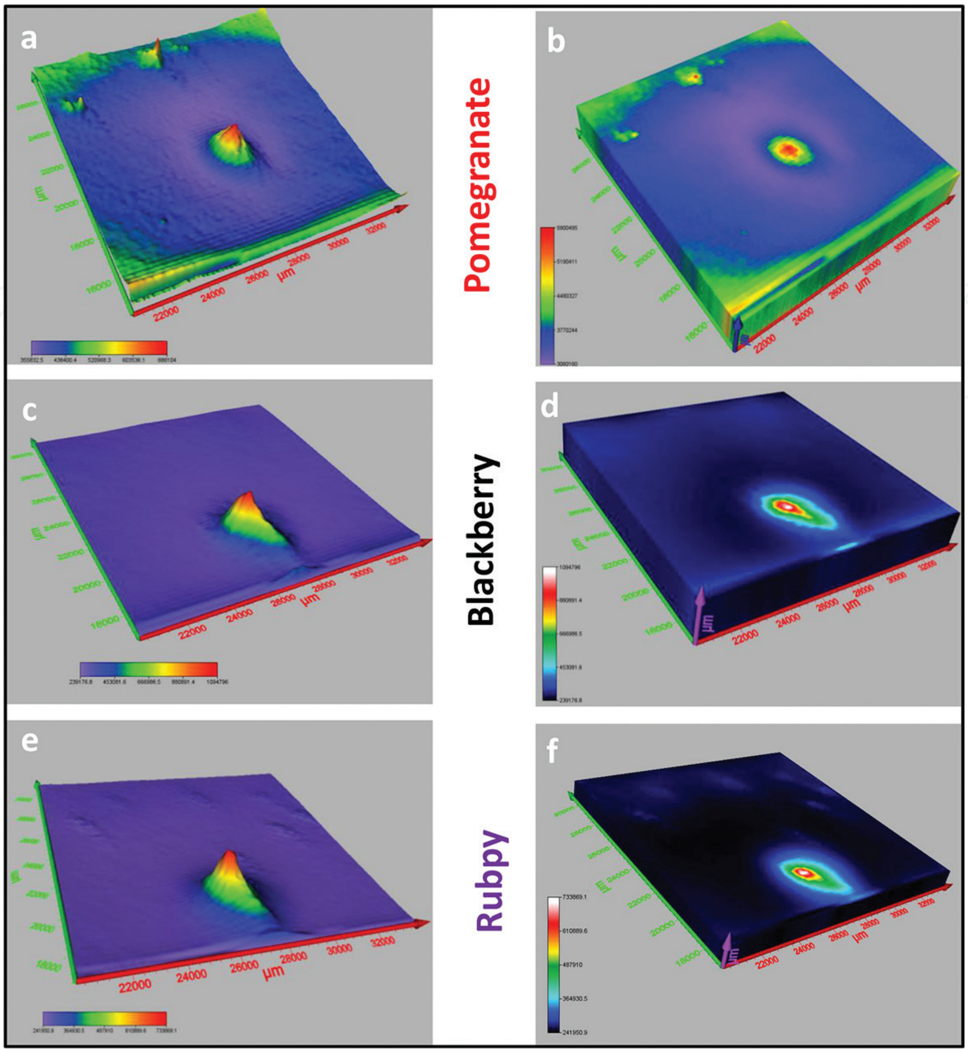

Figure 5. Comparison of terahertz surface (a, c, and e) plots and 3D (b, d, and f) images of Pomegranate (a and b), Blackberry (c and d), and Rubpy dye (e and f) sensitized TiO_2 film coated on FTO glass revealing defects present on these photovoltaic materials.

reflected light from the exposed glass surface. The magnitude of the peaks correlates with the size of the exposed surface area. Defects are easily noticeable as they reflect more light. As displayed in **Figure 5**, the protruding peaks in dye-sensitized TiO_2 film are the regions of higher light reflection occurring at the center of the 25 mm × 25 mm dye-sensitized TiO_2 film. These defects are partly attributed to the dye application and partly due to the lack of uniformity of the layer of TiO_2 on the glass substrate. The results demonstrate the unique defect detection capabilities of terahertz reflectometry. Terahertz reflectometry is therefore well suited to detect flaws and malfunctioning areas of solar cells.

Tiwana et al. used optical-pump terahertz to investigate the photo-induced conductivity dynamics of the semiconductor, titanium dioxide film, used in making the photoanode of dye-sensitized solar cells. In preparation of photoanode of dye-sensitized cell, a mesoporous titanium dioxide film is sensitized with the dye of interest. Upon absorption of radiant light, the dye molecules get excited to higher energy levels where they inject electrons into the conduction band of TiO_2. The injected electron travels through the mesoporous titanium dioxide layer to an external circuit via a conductive glass layer. The photoconductivity of the dye before and after dye adsorption was examined using the terahertz. The dye employed was a ruthenium bipyramidal complex. A biphasic charge injection with an initial sub-500 fs fast component and a slower 70–200 ps rise component was observed. Terahertz spectroscopy was also used to analyze the effect of $TiCl_4$ on the overall performance of the solar cell [27]. Similar work has been carried out by Nemec et al. where ultrafast studies were carried out on terahertz photoconductivity in nanocrystalline mesoporous titanium dioxide films. The transport of excited electron though the titanium dioxide film, prepared by the "brick and mortar" technology was enhanced upon calcination [28]. In addition to the studies involving the transport of excited electrons through the mesoporous titanium films, time-resolved terahertz spectroscopy has also been used to study the dynamics of interfacial charge transfer state and carrier separation in dye-sensitized solar cells [29].

3.3. Quality control

The role of quality inspection in industry cannot be overemphasized, and various techniques and methods are constantly being explored for the use in the quality control of various products. Terahertz time-domain spectroscopy has been used as a powerful tool for the analysis and characterization of various products. Rutz et al. utilized this technique in the evaluation of various polymeric compounds including a polyethylene compound with silver-coated titanium dioxide nanospheres and a glass-fiber-reinforced epoxy composite [30]. The water content in various materials could be estimated using terahertz radiation. Terahertz radiation is not transparent to water, and the attenuation of water to terahertz radiation has been exploited for quality control in the production of paper [31]. The humidity level of papers is evaluated using terahertz spectroscopy. In addition to the amount of water in papers, terahertz can also be used to assess the thickness and mass of paper. The ability of terahertz to measure the moisture or humidity in substances has been exploited in determination of the moisture content in leather as well as the thickness of the leather [32]. Various food processes have also been monitored using THz spectroscopic and imaging techniques [33].

3.4. Pharmaceutical applications of terahertz

Terahertz technology is exploited in the pharmaceutical industry owing to the uniqueness of its properties [34–36]. THz waves have the unique capability of penetrating different kinds of materials, which are usually not transparent to other forms of electromagnetic radiation. Some of the applications of terahertz in pharmaceutical industry include the identification and quantification of polymorphic forms or hydrates of new active pharmaceutical ingredients. This characterization makes it easy to optimize the stability, the bioavailability, and the production of drugs [3]. Russe et al. have used terahertz pulse imaging (TPI) for the quantification of the coating and thickness of coated pharmaceutical tablets. X-ray Microtomography, the traditional tomographic technique commonly used for the analysis of tablet coating, was used to validate the results of the terahertz pulsed imaging of the tablet coating. **Figure 6** depicts the results of the measurements of coating thickness of the coated pharmaceutical tablets comparing terahertz pulsed imaging to X-Ray Microtomography [37].

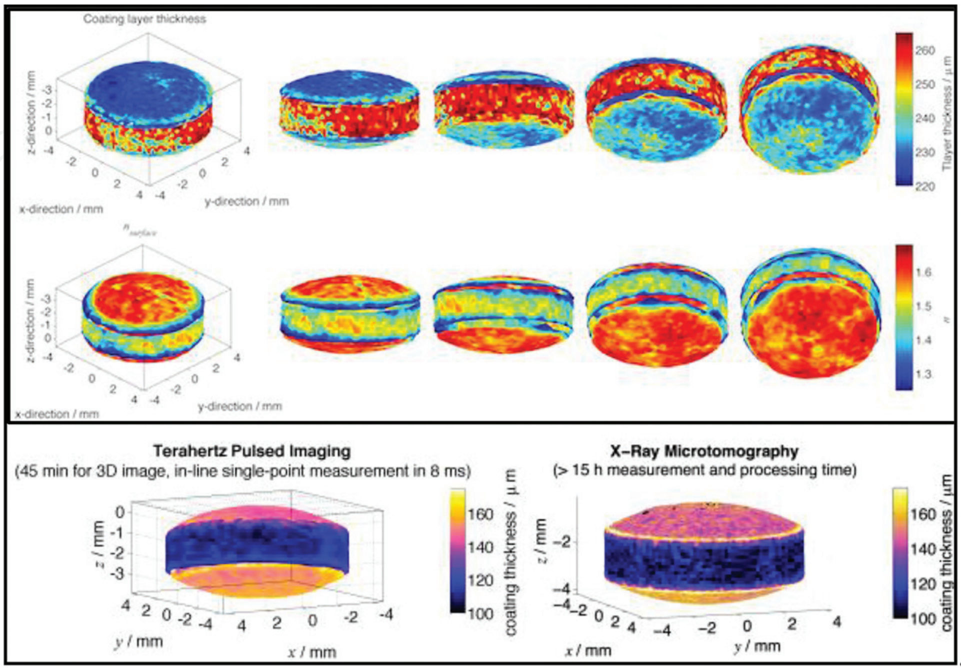

Figure 6. 3D maps of coating layer thickness (top) and surface refractive index (bottom) for a biconvex tablet. (Reprinted from http://thz.ceb.cam.ac.uk).

3.5. Medical applications of terahertz technology

The last couple of decades have seen the development of new terahertz techniques for imaging and sensing purposes. Like X-ray, terahertz radiation is capable of generating two-dimensional images of different kinds of objects owing to the fact that terahertz waves travel through certain materials such as semiconductors and plastics but are not transparent to others such as metallic and polarizing materials. Terahertz waves are preferable over X-rays for medical imaging since they are nonionizing and to a large degree harmless to the recipient. Terahertz waves are currently under investigation for use as an imaging modality to visualize cancerous tissues. According to the American Cancer Society, cancer is the second leading cause of death in the U.S., second only to heart disease, and accounts for nearly one in every four deaths. Early detection could mean the difference between life and death for many patients but there is a shortfall in the current imaging techniques. New terahertz spectroscopic studies on cancer could potentially provide novel techniques for the early detection of the disease. In fact, there has been a steady increase in the number of studies demonstrating the potential use of THz radiation for the imaging and detection of skin tissues and cancerous cells [20, 38–40]. Since terahertz radiation is readily absorbed by water and other polar liquids, the method lends itself well to imaging most organic tissue [38]. Water has intense absorption in the terahertz portion of the electromagnetic spectrum and with the concentration of water in cancerous cells significantly different from that in healthy cells, the variation in the water absorption of terahertz radiation becomes the basis of differentiation of normal cells from cancerous cells. Using THz pulse imaging, Woodward et al. were able to differentiate basal cell carcinoma, a type of skin cancer, from healthy tissues [39]. There have also been studies on the THz pulse imaging in breast cancer [41, 42].

A great number of biomolecules including DNA/RNA, carbohydrates, amino acids/peptides, proteins, cells, and tissues have been investigated using terahertz radiation [1]. The low-frequency internal helical vibration of DNA involving hydrogen bond of DNA base pairs is reflected in the terahertz frequency absorption spectra [43]. Such sensitivity of biomolecules to terahertz radiation has been utilized for the characterization of biological materials. Globus et al. used terahertz spectroscopy to probe DNA polymers in which they were able to prove the dependence of the mode strength on the polarization of the terahertz field with respect to the molecule alignment and thereby concluded that theoretical modeling, combined with measured data, may be used to directly assign vibrational modes to specific structural features of the macromolecule [43]. Using transmission time-domain terahertz spectroscopy and continuous wave terahertz imaging, Wahaia et al. were able to distinguish normal cells from cancerous cells and were, consequently, able to detect colon cancer [7].

3.6. Dental application of terahertz technology

X-ray imaging is the foremost imaging technique in dentistry. It is the principal tool employed to monitor caries and plan treatment for braces, dentures, extractions, and implants. However, X-rays are highly ionizing and frequent exposures are detrimental to health. Terahertz pulsed imaging (TPI) shows great potential as an alternative imaging technique in dental diagnosis [44–47]. It is low in energy, nonionizing, and less hazardous. Unlike other biological tissues with a huge percentage of water with the propensity for intensive absorption of terahertz radiation, teeth have a relatively low water content, which makes it convenient to image teeth samples using the terahertz pulsed imaging technique. Longbottom et al. employed a terahertz pulse imaging technique to perform *in vitro* experiments involving incisor teeth and concluded that terahertz has the ability to not only identify caries but also monitor erosion [48]. Using the transmission mode in a developed terahertz time-domain spectroscopy system, Kamburoglu et al. measured the properties of sliced teeth section. They analyzed the refractive and absorptive properties of primary and permanent teeth that were either healthy or had cavities in them and found the technique effective for characterizing dental structures [49].

Karagov et al. recently demonstrated how THz pulse imaging could be used to detect dental caries [50]. They employed a continuous wave (CW) and time-domain reflection mode raster scan THz imaging system to carry out 2D and 3D imaging of various teeth samples. The data were analyzed in both the spatial and frequency domains, and the results pointed to the sensitivity of terahertz pulse in detecting variations in the structure of teeth samples. Schirmer et al. conducted terahertz spectral imaging of teeth samples using a real-time terahertz color scanner [51]. To conduct the imaging studies, longitudinally sliced human molar specimen (**Figure 7a**) were heated to remove water molecules that could interfere with the measurements and then imaged to study differences in THz transmission in different part of the teeth samples. Spectral images of eight samples taken at different frequencies are displayed in **Figure 7(b)**.

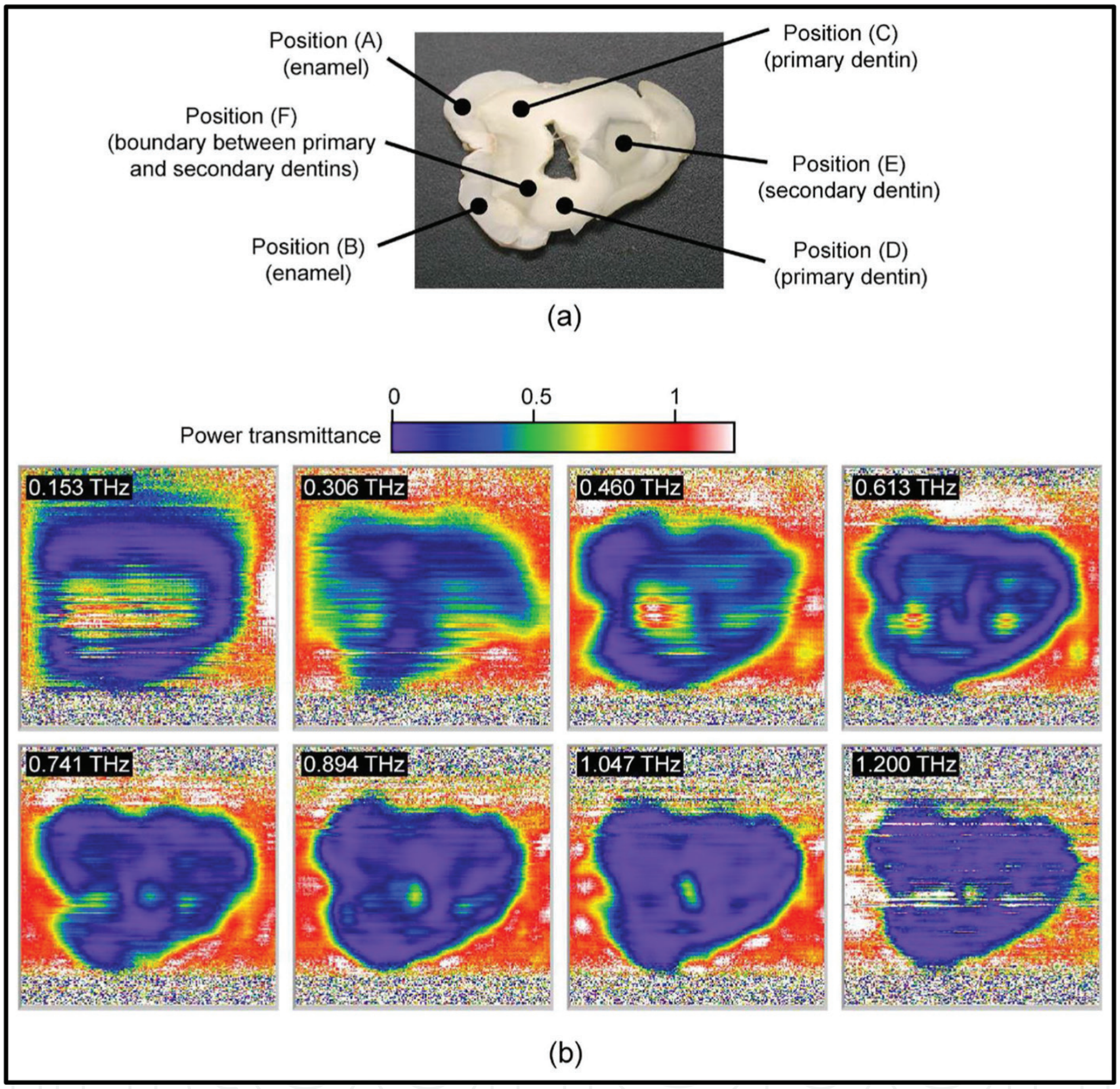

Figure 7. Visible and terahertz image of cavity in human tooth: (a) longitudinally sliced human molar specimen; (b) spectra images of eight samples taken at difference frequencies. (Reprinted from Markus Schirmer et al. "Biomedical applications of a real-time terahertz color scanner," Biomed. Opt. Express 1, 354–366, 2010) [51].

3.7. Security screening

Security screening is one of the most common applications of terahertz technology. Terahertz does not only give information about the presence of concealed items but also has the capacity to identify the composition of the materials in question. In recent years numerous investigations have been conducted on the capability of terahertz to detect explosives at airports and other sensitive places [52]. The advantage of terahertz radiation over X-ray, also used for security screening, is its low energy and nonionizing nature. The ionizing nature of X-rays makes the regular exposure of it harmful to people. The unique ability of Terahertz waves to penetrate a wide range of packaging materials makes it possible to detect weapons, explosives, and potentially explosive devices concealed within these materials [53]. **Figure 8** shows a terahertz image revealing a blade (c) and a metallic knife (d) concealed behind a cardboard and a thick dark cloth, respectively. Packaging materials such as cardboard, paper, plastics, and leather are all transparent to terahertz radiation.

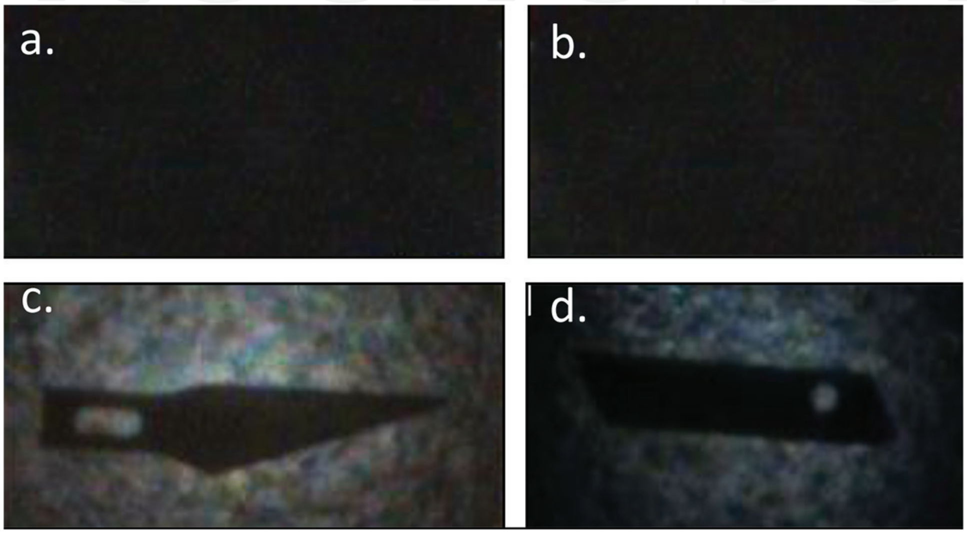

Figure 8. Security screening employing terahertz radiation: a hidden blade (c) behind a cardboard (a) is revealed with terahertz radiation; metallic knife (d) hidden behind a thick dark cloth (b) is revealed by the terahertz beam. Picture reprinted from Applied Research & Photonics, Inc.

3.8. Communication, remote sensing and astronomy

One other application of terahertz radiation is in the area of wireless data communication. The terahertz portion of the electromagnetic radiation has shown promise as a bandwidth suitable for data transmission. Ishagaki et al. have designed a terahertz oscillating resonate tunneling diode that has the ability to transmits signal at 542 GHz with a data transfer rate of 3 Gbit/s. This type of terahertz WIFI is limited to a region of 30 feet but has a potential to support data rates of up to 100 Gbit/s.

Remote sensing allows the acquisition of information about materials or locations from a distance, which could be from an aircraft or satellites. Terahertz spectroscopy is one of the promising tools for carrying out remote sensing. Lui et al. developed a technique based on broadband terahertz wave detection for remote sensing with which they were able to detect coherent terahertz wave at a distance of 10 m [54]. The technique has shown promise for the measurement of terahertz pulses at standoff distances with minimal water vapor absorption and unlimited directionality for optical signal collection. **Figure 9** shows a schematic of this terahertz wave remote sensing technique. The technique exploits the interaction between induced gas plasma and terahertz waves. Two lasers at different frequencies are focused at a target to induce gas plasma formation. Fluorescence emitted from the induced gas plasma is scattered in characteristic ways by the terahertz radiation of the material it hits. The terahertz wave sensing is then performed from remote distances [54]. The terahertz region of the electromagnetic radiation, furthermore, happens to be a very significant window for astronomical observation. Submillimeter astronomy is a branch of astronomy conducted with terahertz radiation providing a wide range of spectral lines useful for the investigation of many phenomena such as the formation of stars. It also holds spectral signatures of ions, atoms, and molecules that are necessary for understanding of the composition and origin of the Solar System, the evolution of matter in our Galaxy, and the star formation history of galaxies over cosmic timescales. The utility of these lines, their examples of the science they deliver, and the detail properties of successful low-resolution direct detection spectrometers for work in the THz regime have been reviewed by a number of researchers [55, 56].

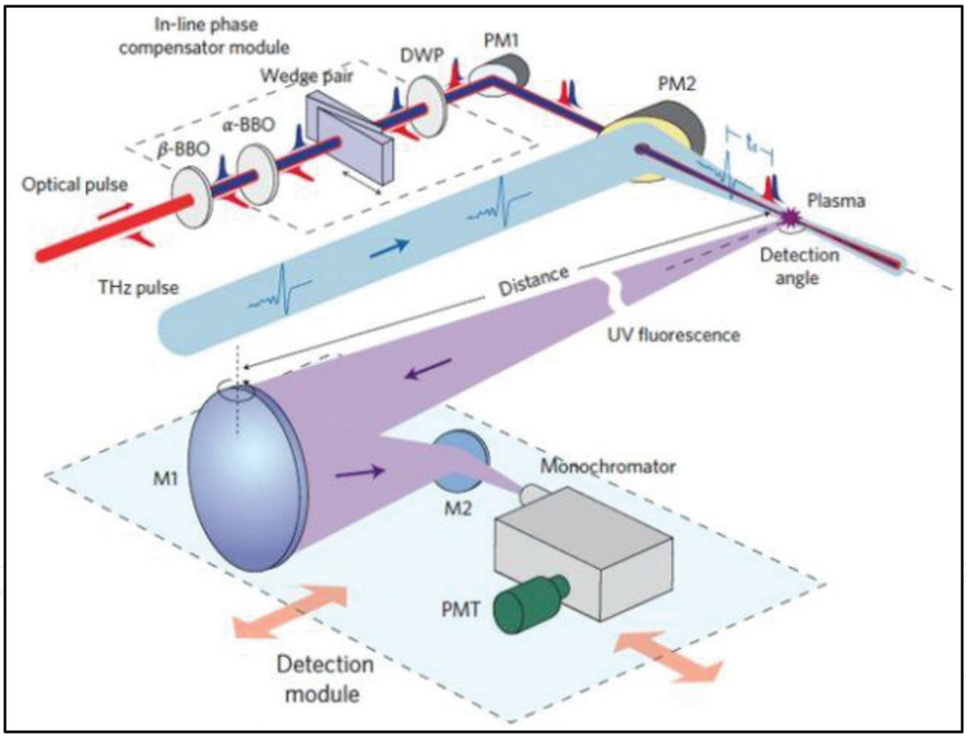

Figure 9. Schematic of the THz wave remote sensing technique (Obtained from Liu, J. et al, Nat. Photonic., 4, 627, 2010.) [54]. The 2ω pulse is generated by passing the fundamental beam through a type I β-BBO crystal. Both the fundamental and second-harmonic optical pulses are linearly polarized along a vertical direction. The relative phase change between the ω and 2ω pulses is tuned by the lateral translation of fused silica wedges in the optical beam path after the α-BBO. The two optical pulses are focused by a parabolic mirror (effective focal length, 150 mm) into air to generate plasma. The time delay t_d is defined as the delay between the optical pulse peak and terahertz pulse peak. The fluorescence detection system consists of a UV concave mirror (M1; diameter, 200 mm and focal length, 500 mm), a UV plane mirror (M2), a monochromator and a photomultiplier tube (PMT). The distance of remote sensing is varied by moving the fluorescence detection system with respect to the plasma. DWP, dual-band waveplate.

3.9. Other applications

Metamaterials are materials that are structurally adjusted to interact in a specific way to electromagnetic radiation. Terahertz spectroscopy is frequently used to characterize metamaterials. Metamaterials that are specifically fabricated to interact with terahertz frequencies are referred to terahertz metamaterials. They are artificial materials that are carefully engineered to provide a desired electromagnetic response. Metamaterial have a basic lattice structure composed of rudimentary elements and possess the characteristics of a crystal structure. These rudimentary elements are relatively bigger in size than atoms or individual molecules. Metamaterial can be used in making THz metamaterial sensors for the detection of an array of materials and systems. It has been used for the detection of microorganisms such as fungi and bacteria with high sensitivity [57].

Terahertz spectroscopy also has the potential to detect oil spills in water bodies [58, 59]. Using terahertz transmission spectroscopy, Gorenflo et al. determined the amount and structure of water in oil-water complexes by monitoring changes in absorption coefficient and refractive index [58]. Cunnell et al. carried out similar measurements using terahertz quantum cascade laser to quantify water in industrial water-oil emusions [59].

3.10. Conclusion

A remarkable progress has been made in the last couple of decades on the technology for the generation, manipulation, and detection of terahertz radiation leading to ever-increasing applications of this technology in industry and research. We have reviewed the applications of terahertz technology in spectroscopic analysis, photovoltaic characterization, pharmaceutical testing, security screening, biomedical, astronomy, oil spill characterization, pharmaceutical and quality control. With the exponential growth in research in the terahertz regime, we anticipate more advances in application of terahertz technology in the society.

Author details

William Ghann and Jamal Uddin*

*Address all correspondence to: juddin@coppin.edu

Center for Nanotechnology, Department of Natural Sciences, Coppin State University, Baltimore, MD, USA

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