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State-of-the-Art Terahertz Sensing for Food and Water Security – A Comprehensive Review

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Abstract—**Past few years have witness a dramatic change in the field of terahertz (THz) technology. The recent advancements in the technology for generation, manipulation and detection exploiting THz radiation have brought revolution in the field. Many researchers around the world have been inspired by the potential of invaluable new applications of THz sensing for food and water contamination detection. The microbial pollution in water and food is one the crucial issues with regard to the sanitary state for drinking water and daily consumption of food. To address this risk, the detection of microbial contamination is of utmost importance since the consumption of insanitary or unhygienic food can lead to catastrophic illness. This paper presents a first-time review of the open literature focused on the advances in the THz sensing for microbiological contamination of food and water and state-of-the-art network architectures, applications, industrial trends and recent developments. Finally, open challenges and future research directions are presented with in the field.**

Index Terms—**Terahertz technology, contamination detection, food products, water, THz spectroscopy**

I. INTRODUCTION

Electromagnetic radiation in the range of 0.3 THz to 3 THz has unique properties that make it particularly attractive for various applications including biomedical imaging, packaged goods inspection, food inspection, water contamination detection and so on. However, generating radiation at terahertz level presents many practical challenges. In recent years, several techniques for generating both continuous-wave and pulsed terahertz radiation have been developed [1]. In turn, these are spawning the early development of terahertz applications, particularly in microbial pollution in water and food. New trends, discoveries and applications have been observed in diverse fields, especially in the field of photonics and nanotechnology. The first demonstration of THz wave time-domain spectroscopy using femtosecond laser sources to generate and detect freely propagating THz pulses were developed by Auston at Bell Labs and Grischkowsky at IBM in 1980s [2]. The development of optimized techniques for THz pulse generations, particularly the optimized non-collinear beam geometry [3], the production of THz pulses using the energy of few microjoules or even higher values which has the potential to access the 2nd or 3rd order non-linearities [4][6] is a standard followed in almost every laboratory settings.

Matthias C Hoffmann et al.[5] generated the highest-energy ultrashort THz pulses by optical rectification of femtosecond pulses in $LiNbO_3$ using the tilted-pulse-front pumping technique, which is inherently scalable to increase the available THz pulse energy and field strength. The THz radiation has many advantages over other imaging modalities in many aspects including non-ionizing [7], classifying species of tissue [8], and scattering and water absorption for porosimetry [9]. As a result, the terahertz radiation has shown widespread potential applications in diverse areas to address the real-world problems including genomics [10], medical diagnostics [11], pharmacology [12], healthcare applications [13][14], Body-Area Networks (BAN) [15][16], wireless communication [17][18], environmental monitoring [19], agriculture [20] and food analysis [21][22], defence and security [23]-[25].

The recent research work on THz radiation generation, detection, and the spectroscopic and imaging tools, such as THz time-domain spectroscopy (THz-TDS) [26]-[29] that can be operated in the time and spatial domain to process the data obtained from the transmitted or reflected THz beam, opens up new ventures by applying the particular technology for food or water contamination detection [30]. The core idea is food and liquid have unique physical features and presents a unique spectral imprint when exposed in the THz frequency domain [31]-[44]. The food quality and safety monitoring [38] comprising microbiological contamination detection including toxic metals[44], pesticides[39], veterinary drug residues, organic pollutants, radionuclides and mycotoxins, is a pressing issue for public health and wellbeing. Several studies have focused on different types of food additives, such as flour and talc mixtures [40], melamine in milk powders [41], which indicate that the absorption spectra of the pure and mixed products were by and large distinct. The strong absorbing nature of THz radiation by water, the intramolecular vibrational modes of hydrogen bonds located in the THz region presents limitations on the application of THz technology considering the detection of concealed cases [45][46]. However, the absorbing nature does not pose challenge to the applications of THz imaging in the detection of moisture or humidity in

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different materials. There are several methods that can resolve limited penetration depth issue, for example the paraffin-embedding technique, freezing technique and terahertz penetration-enhancing agents (THz-PEAs) [11]. There are several existing sensing techniques that can be used for contamination detection at THz level [47]. The existing studies on the THz sources and processing methods, such as the spectral signatures of food and agricultural products in the THz region, enable the integration of THz sensing systems into real-world.

This paper examines the recent trends observed in THz technology, THz detection techniques and uncovers various issues that need to be addressed in order to apply THz sensing for food and water contamination detection. In this regard, the paper contribution of this paper is as follows:

In section II, we present the application, architecture and techniques for implementing THz systems. Section III describes the THz detection techniques and the associated technologies. Section IV illustrates the THz sensing for food and water contamination detection techniques. The open challenges for food and water contamination detection are discussed in section V. Section VI presents the conclusion drawn from existing literature.

II. TERAHERTZ COMPONENTS AND APPLICATION SYSTEMS

The Terahertz sources, components, detectors, and application-oriented goals are the main focus of the development of THz technologies. Fig. 1 indicates the typical THz configuration that consists of multiple sources, components and detectors. The available THz photoconductors that has a sensitivity between 100μm to 15μm (in wavelength), and is more compact than the Ti-sapphire laser solid-state [48] and fiber lasers in the spectral range [49], much attention has been paid to the systematic study in photoconductive THz components [50]-[52]. The development of solid-state mode-locked and quantum cascade lasers (QCL), which can provide a powerful continuous-wave THz source, also the technological breakthrough in laser-based THz time-domain spectroscopy (THz-TDS) and microelectronic fabrication have led to the realization of several significant THz devices and systems as in [53]-[55].

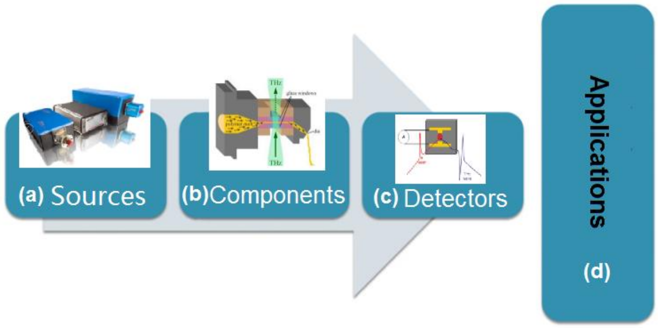


Fig. 1. Typical terahertz configuration. (a) Sources, (b) Components, (c) Detectors, (d) Applications, such as spectroscopy and imaging. (reproduced from [60])

A. The THz Sources

The THz electromagnetic spectrum falls between the infrared wavelengths on the higher frequency side and microwaves on the lower frequency side has unique and important properties [56]-[58]. A terahertz source generates a wide range of radiation [59]. R. A. Lewis [60] presents six types of THz sources which include thermal [61][62], vacuum electronic [63]-[65], solid-state electronic [66][67], lasers [68][69], sources pumped by lasers (including continuous [70][71], pulsed [72][73]) and mechanical excitation sources [74][75].

In recent years, several new THz source methods have been put forward. For examples, terahertz source techniques were summarized by Robert Bogue as in [76]. An InAs/GaAs Quantum-Dot (QD) Laser Source [77] can be ultracompact, tunable in room temperature and its experimental setup involves a QD based photomixer resonantly pumped by a compact, broadly-tunable dual-wavelength QD laser in the double-grating quasi-Littrow configuration. A high peak power THz source for ultrafast electron diffraction was constructed operating at the wavelength ranging between 50-200μm [78][79]. Fig 2 shows model of a device, which consisted of electron source and terahertz low-gain free electron laser (THz-FEL) oscillator [80][82]. The THz radiation source based on electron linear accelerator (linac) was introduction in [81][83]. In order to simultaneously stabilize a series of terahertz (THz) source devices [88], a frequency reference source based on the optical combs was proposed in [84]. The optical combs, which provide equally-spaced CW lights with high accuracy, can be produced using combination of a planar comb generator (MZ-FCG) based on a Mach-Zehnder modulator and a highly nonlinear dispersion-shifted fiber.

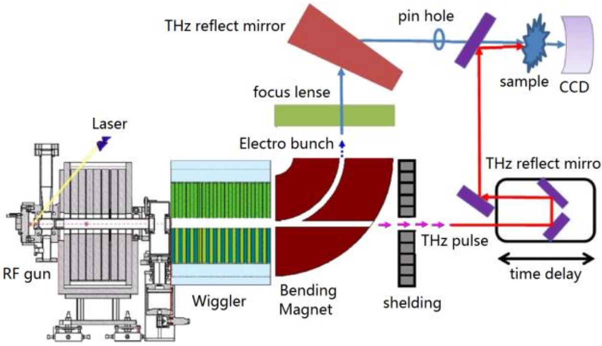


Fig. 2. Schematic diagram of high peak power THz source and pump-probe experiment (reproduced from [80])

B. The THz components

All THz components such as mirrors, lenses, and polarizers manipulate the specific radiation. Conventionally, the THz mirrors were made of metals such as aluminum, silver, copper and gold. In order to achieve maximum reflectivity characteristics from these metals, the thickness of the metal coating should be at least two skin depths at the frequency of the incident beam[85]. Recent innovations in THz mirror technology include semiconductor[86], hybrid mirrors[87], and the tunable mirrors are based on photonic crystals (PCs)[88][89]. Terahertz lenses are typically made of plastics such as polyethylene or TPX. Recently, the significant innovations allow the rapid production of a large number of lenses[90]that include Fresnel zone plates[91], plasmonic resonances[92], variable focal length lenses[93], 3D printed diffractive lenses[94], and even THz lenses made of paper[95]. Polarizers are essential components in THz imaging, communications, and spectroscopy. Wire-grid polarizers are simpler to realize in the THz than in the visible region[96]. Recently, reconfigurable polarizers in [97] and carbon nanotube fiber polarizers in [98] have been reported.

C. The THz Detectors

The THz detectors that can measure the THz radiation upon reception, play a significant role in many areas including astrophysics, biological, chemistry and explosions detection, imaging, astronomy applications and so on [99][100]. F. Sizov et al. [99] discussed various types THz radiation detectors, including basic direct [101] and heterodyne detectors [102][103], Schottky barrier diodes [104][105], pair braking photon detectors [106], thermal detectors [107] and field-effect transistor detectors [108].

JL Hesler et al. introduced the design and testing of broadband quasi-light THz Schottky diode detectors [109], which can be used as a set of waveguide detectors to provide a reference point at the same location of a source beam [109]. K. Ikamas et al.[110] presented a broadband bow-tie antenna-coupled THz detector on a 90nm silicon CMOS FET (TeraFET) for the detection of free-space THz radiation, which was optimized using an in-house developed physics based circuit model and the THz detection well beyond 2THz with an optical responsivity of 45mA/W (or 220V/W) [111]. Fig3 illustrates the micrographs and the layout of this detector, and Fig. 4 presents the simulated intrinsic.

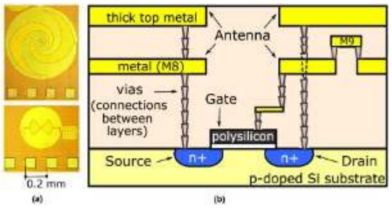


Fig. 3. The micrographs and the simplified layout of TeraFETs detector. (a) Micrographs of TeraFETs with log-spiral (top) and bow-tie antenna (bottom), which has an opening angle of 90o and the length of each leaf is 105µm. (b) A simplified cross-sectional view of the transistor region of the TeraFET [110]

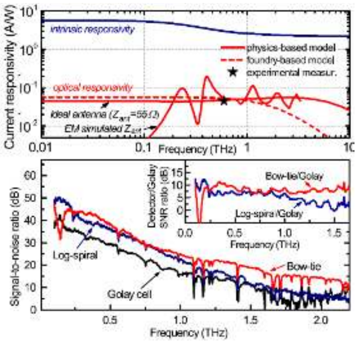


Fig. 4. Top: simulated and measured current responsivity vs. radiation frequency for TeraFET at Vg=0.45V. Black star denotes the responsivity of the TeraFET with a bow-tie antenna measured at 600 GHz. Bottom: comparison of the frequency-dependent SNR of the THz detectors (Vg=0.45V) and the comparation with the Golay cell inserted (reproduced from [110]).

D. The THz Systems and Applications

The THz radiation has broad range of applications and can be mainly divided into four groups: sensing, imaging, spectroscopy and communication [113][112], and can also be applied in preventive health care to quality control, surgery, and non-destructive evaluation [114] as shown in Fig. 5.

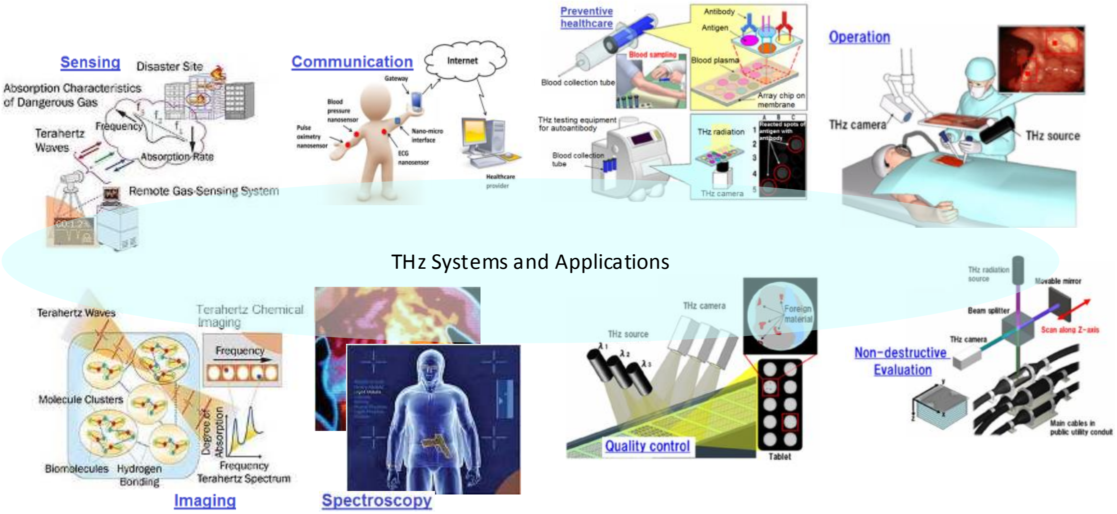


Fig. 5. Envisioned applications for THz radiation (reproduced from [112], [114] and [115])

The diverse areas of application of terahertz technology have been summarized in [22] and in [116], especially the applications in the safety and quality control of food products are shown in Table I. The table indicates that the potential of THz technologies in the food and water detection fields and presents various other aspects such as the detection of foreign bodies, determination of pesticide and antibiotic residues, characterization of edible oil and discrimination of transgenic crops, and so on [22]. For example, the detection of unwanted and potentially hazardous objects in food is extremely important in the food industry [54]. The THz technologies can be used to detect both the metallic and non-metallic contamination [117]. The characteristic absorption peaks of melamine could be found at the same frequencies in different food matrices. Also, the THz images were distinguishable from food components with or without the packaging materials used [118]. With regard to the advantages of non-destructive, non-invasive, and non-ionizing nature, the THz technologies have been considered as alternative methods for sensing food or water safety control and contamination detection.

TABLE I: Overview of the applications of terahertz technology for food and water detection

Types	Methods	Detected materials
Food products	THz-TDS	● Melamine detection in foods[118]
		● Detection of a carbamate insecticide in food matrices[119]
		● Moisture content in wheat grain[120] and wafers[121].
		● Pesticide detection in food powders[122]
		● Antibiotic detection in food and feed matrices[123]
		● Discrimination of transgenic crops[130][131]
	THz-FDS ^{a}	● Recognition of CCH ^{b} and TCH ^{c} in soil, chicken and rice[135]
	Imaging	● Metallic and nonmetallic foreign bodies in chocolate[124]
		● Foreign body detection in chocolate[125]
Water (including beverages)	THz-TDS	● Characterization of optical properties of vegetable oil[126]
		● Prediction of sugar and alcoholic content in beverages and liquors[127]
		● Characterization of the dielectric properties of water solutions[128][136]
		● Identification of adulterated dairy product[132]
		● Detection of harmful chemical residues in honey[133]
	TD-ATR ^{d}	● Dielectric constants determination of distilled water and sucrose solution[134]
	Imaging	● Sugar detection in beverages[129]

Note: ^{a} THz-FDS: Terahertz Frequency-Domain Spectroscopy
^{b} CCH: Chlortetracycline hydrochloride
^{c} TCH: Tetracycline hydrochloride
^{d} TD-ATR: Terahertz Time-Domain Attenuated Total Reflection spectroscopy

III. TERAHERTZ DETECTING METHODS AND THEIR ENABLING TECHNOLOGIES

The field of science and technology in terahertz has changed dramatically in the past few years. The research work on terahertz technology has greatly promoted the generation and development of many new technologies such as terahertz time-domain spectroscopy, terahertz radiation, and terahertz imaging. These technologies have been widely studied and applied in various fields.

A. *Time-domain spectroscopy*

The terahertz time-domain spectroscopy (THz-TDS) can be configured in three modes including transmission, reflection and attenuated total reflection (ATR) modes. A typical setup of THz-TDS system and three modes are shown in Fig. 6. Compared with transmission and reflection modes, ATR THz-TDS is more sensitive and suitable for measuring high moisture samples [22][141]. The TDS system can get a direct measurement of the field amplitude and phase as the function of time by sweeping out the transient field of the THz pulse. The THz spectrum is the obtained by appying Fourier transformation on the time-domain data.

As an effective means of detecting material spectra information in the THz region by employing ultrafast laser technology, THz-TDS has comparatively high signal-to-noiseratio due to the wider frequency band, and can be used to detect material composition and subtle structure changes [137]-[140]. F. F. Qu et al.[142] detected the molecular characterization and fingerprint peak of three plant growth regulators including 2,4-Dichlorophenoxyacetic acid, forchlorfenuron and indole-3-acetic acid. Baek et al. [118]investigated the feasibility of detecting melamine in foodstuffs and found the characteristic absorption peaks of melamine at 2, 2.26, and 2.6 TH. Zhang et al. [143] quantified the percentage contributions of the intermolecular and intramolecular vibrations to the normal mode by using THz vibrational spectroscopy to molecular characterization of saccharide molecules. Cheon et al.[144] presented THz molecular resonance fingerprints of DNA methylation in cancer DNA, which could be quantified to identify the types of cancer cells. M Mieloszyk et al. [146] detected the different pollutants such as oil, gypsum and water with the glass fibre reinforced composites materials and showed that the wave propagation velocity is slower in contamination region.

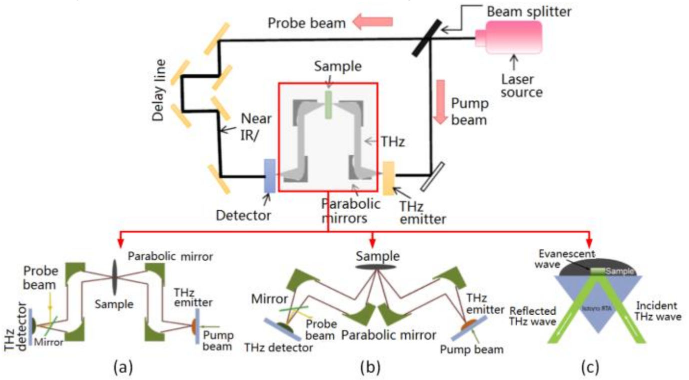


Fig. 6. Schematic of a typical THz time-domain spectroscopy system. (a) transmission mode, (b) reflection mode, (c) attenuated total reflection (ATR) mode. (reproduced from [22][145]).

B. *Terahertz radiation*

Terahertz radiation refers to the electromagnetic radiation region between 0.1THz and 10 THz in frequency range and between millimeter wave and infrared wave. The resulting T-ray has a broad application prospect in object imaging, medical diagnosis, environmental detection and communication. However, in the frequency range of terahertz radiation, the absorption and group velocity dispersion (GVD) of water vapor controls the propagation of THz waves in the atmosphere[147].

In the field of communication, Fitch M J et al. [148] presented an overview of THz technology for communications, which consisted of discussion on the sources, detectors, and modulators required for a practical THz communications system. The disadvantages of the THz communication caused by the strong atmospheric absorption of THz radiation can be seen in Fig. 7, which shows the enormous variation of THz power attenuation (dB/km) for the frequency range from 0.1THz to 2THz.

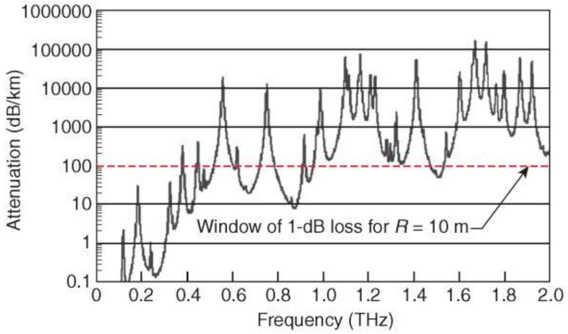


Fig. 7. Atmospheric attenuation in the THz frequency range [148].

C. *Terahertz Imaging*

The terahertz imaging is an emerging and significant non-destructive evaluation (NDE) technique used for safety checks [149]-[151], quality control [152]-[155], and even fanciful applications, such as using terahertz image detection technology to count almond chocolates in bars. One of the great advantages of terahertz in the field of image processing is that terahertz radiation has a unique ability to penetrate ordinary packaging materials, so it can provide spectral information of internal materials.

Yildirim et al.[151] introduced an active terahertz imaging autonomous biometric security access control and tracking gate system consisting of the THz scanning/ imaging, autonomous transition and X-Ray modules, which can detect the concealed object on the human body. Momivama et al. [152] constructed a swept source optical coherence tomography (SS-OCT) system with operating frequency of 600-665GHz, which can be used for quality control. Ryu W et al. [156] presented a compact and portable THz imaging system using Single Mode Fabry-Perot Laser Diodes (SMFPLD), which has the simple structure and low cost. E. Stübling et al. [157] proposed a THz tomography system with the 3D scanner, which allows for the reflection THz tomography image of the sample with arbitrary surface shape by placing the transmitter and receiver on the robotic arm and can be used to study variety of non-planar objects, including biological specimens, mummies, cultural heritage and industrially made parts.

IV. FOOD AND WATER CONTAMINATION DETECTION METHODS

A. *Terahertz for food contamination detection*

The unprecedented quality or safety concerns of food productsmakes the quality evaluation of food products ever more important and challenging. The efficient ways to evaluate the contents of food-material, to recognize contaminated food, and to detect poison (pesticide residues, veterinary drug residue, herbicide residue, additives, aflatoxin, etc.) and foodborn pathogens in foodstuffs are of utmost importance. Conventual testing methods including eyeballing, degustation, knocking or other physical ways were used to determine compliance, and non-traditional techniques such as near-infrared spectroscopy (NIR), NIR imaging, bioassays (chromatographic purity for example), molecular imprint-based sensors were investigated for their ability to differentiate products or provide additional quality information [158]. The IR spectroscopy is a rapid and non-destructive technique for the authentication of food samples. Analyzing a food sample with the MIR spectrum (4000-400cm^{-1}) reflects information about the molecular bonds present and also provides details of the types of molecules present in the food sample. The NIR spectroscopy uses the spectral range from 14,000cm^{-1} to 4000 cm^{-1}and offers much more complex structural information about the vibrational behavior in combinations of bonds. These techniques are suited for use in an industrial setting due to their ease of use and the relatively low financial cost of obtaining and running the equipment. As powerful analytical techniques, the IR analysis has been successfully employed in classification studies for wide range of food products. These techniques can be used for both qualitative and quantitative analysis [159]. The THz waves lie between microwaves and the far infrared, and can be transmitted through e variety of substances. The THz radiation is non-ionizing and nondestructive, hence it is safe for the biomaterials and the agricultural products. The range of potential applications has possibility to expand even further by the increased availability of many absorption spectra (i.e. fingerprint spectra) peculiar to specific chemicals, including vitamins, sugars, pharmaceuticals, agricultural chemicals, etc. discovered in the THz wave region. The worth of a practical far-infrared imaging system has been proved in a wide range of applications, because of its unique features to biomaterials, having stated above, the THz spectroscopy is a novel, fast, accurate, and economical technique available to the food industry for compositional analysis.

1) *Detection by analyzing moisture content*

The relatively high permittivity of liquid water contrasted to other materials in the terahertz (THz) range, which enables a contrast mechanism for the detection and imaging of moisture [165]. In this section, spatial mapping of moisture and liquid detection by THz imaging are reviewed. Analysis of the moisture content is discussed with a double Debye model for liquid water and effective medium models for the permittivity of the dry and 'wet' materials of interest. Examples in food and agriculture products, diffusion rates and diffusion maps from THz images are also reviewed.

Quality control of Pecans: A non-destructive evaluation technique for pecan nuts has been explored using THz imaging [160]. The pecan nuts are fairly transparent to THz radiation because the water content of the nutmeats inside of the shell are low, which may indicate the presence of a defective product with enhanced THz absorbance. One common defect in pecans is the presence of living insects which feed on the nutmeat. Since living insects mostly contain 70-80% water while the water content of nutmeats is typically less than 10%, THz absorbance based on the presence of water could be used to identify product contamination.

Quality control of damaged fruit: It is explored for tomatoes caused by pressure on the outer surface of the fruit to use THz imaging to assess the damage [161]. The pressure damages the fruit cell walls which causes a local filling with water. Over time, the damaged area looses moisture resulting in a brownish color to the fruit surface. Measurements on damaged tomatoes show a decrease in THz reflectivity from regions where there was sligh press. However, a detailed analysis of the change in permittivity was not discussed. The authors proposed that the decrease in reflection resulted from the increase in absorbance by water which fills the damaged area[163]. As shown in Fig.8, when one considers the effective permittivity of a medium, an increase in water content should lead to an increase rather than a decrease in reflectance. Another effect which makes the reflectance measurement complicated is the fact that the surface of the tomato is curved, leading not only to a Gouy phase shift in reflection [162], but also the need to treat the curvature and changes in curvature of the fruit as an effective curved mirror in the optical analysis of the THz reflection system.

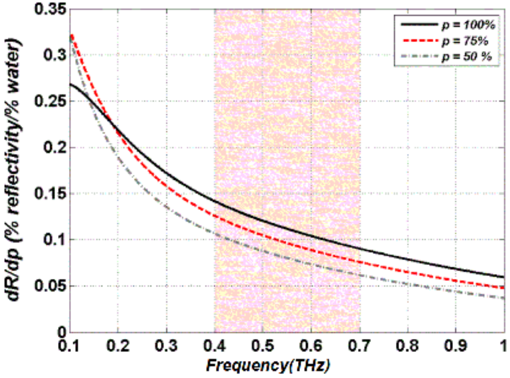


Fig. 8. Hydration sensitivity (change in reflectance per change in water concentration) as a function THz illuminating frequency for 100% (solid line), 75% (dashed line) and 50% (dotted line) water concentration. Adapted from [163].

Dried food[165]: The moisture content in dried food can be measured with THz techniques. The moisture affects food quality properties such as taste, texture, mechanical strength, bacterial growth, and shelf-life [166]. Water strongly absorbs terahertz radiation, while other constituents such as proteins are typically 100 times less absorptive than water. Fats and lipids typically exhibit absorption coefficients 20 times lesser than water. Moreover starch has roughly 50 times lower absorbance than water. A quantitative demonstration of moisture measurements in dried food was performed by Parasoglou et al. [167][168]. In this work, the samples pf starch wafers were used, which are commonly used in the confectionary food industry. The wafers exhibit low moisture content and porous structure. As discussed in [168], THz measurements are dominated by absorption because of moisture content, assuming that scattering in that holes and pores in the food are small. The THz absorbance is relatively immune to small fluctuations in the concentration of other constituents of the food sample since the relative absorbance of water is higher than the other constituents. Another advantage of using THz measurements is that the minimal THz power does not produce any significant heating in the sample. Parasoglou et al. measured a linear relationship between the moisture content in the wafers and the normalized peak-to-peak amplitude of the THz time-domain pulse. While the data is analyzed in the frequency domain, there is a linear relationship between the transmission amplitude and moisture content in the region between 0.2-0.6 THz. Above 0.6 THz, the attenuation of the THz signal is dominated by scattering of pores in the food wafer rather than by the presence of moisture. A complete analysis of the measured THz absorbance would require the inclusion of scattering, as shown in equation (1) and equation (2).

Jördens et al. [169] included the effect of interface roughness of a leaf into their analysis by defining an effective attenuation coefficient of the leaf, a_{total}, as a sum of absorptive and scattering losses, a_{abs} and a_{acat}:

$$\mathrm{a}_{total} = a_{abs} + a_{acat} \tag{1}$$

where the THz wavelength dependent scattering coefficient is

$$\mathrm{a}_{scat}(\lambda) = \frac{1}{D}\left[\left(\sqrt{\varepsilon_L(\lambda)}-1\right)\left(\frac{4\pi\Gamma\cos\theta}{\lambda}\right)\right]^2 \tag{2}$$

where D is the thickness of the leaf, Γ is the standard deviation of the height profile (measure of surface roughness), θ is the angle of incidence, λ is the THz free space wavelength, and ε_L is the wavelength dependent permittivity of the leaf.

2) Detection by inspecting food

Inspecting foods is one of the potential applications of terahertz (THz) technology [116]. For this purpose, an imaging system using a coherent source operating at 0.3 THz was developed [170]. The 0.3 THz imager has a diffraction limited resolution of 1 mm, and has real-time capability. The imager is able to detect foreign bodies such as plastics, glass shards, and insects in chocolate boxes and milk powder. However, the THz waves at 0.3 THz penetrate only several millimeters into foods with a moisture content of higher than 14 % such as wheat flour, indicating that the absorption of THz waves by moisture strongly limits the kind and thickness of foods inspected.

In order to ease the above limitations for foods, a dual-polarization imaging system using a THz noise source operating at 0.1 THz band has been newly developed. The absorption coefficient at 0.1 THz is theoretically one third lower than that of at 0.3 THz. In general, the shapes of foreign bodies are different from those of foods, and have different polarization anisotropies[171]. Therefore, dual polarization imaging can enhance discrimination of foreign bodies from foods even when having similar dielectric constants.

The 0.1 THz band imaging system was developed assuming that foods carried by a conveyor belt are inspected. As shown in Fig. 9, this system thus consists of a THz source, polyethylene lenses, a linear stage (conveyor), a one-dimensional detector array, and a computer for system control or image processing. The THz source is a uni-traveling-carrier photodiode (UTC-PD) driven by an amplified spontaneous emission (ASE) light source [172]. The source provides low coherence THz noise signals with frequency components between 0.075 THz and 0.11 THz. The output power is 1.2 mW.

In Fig.17, the objective lens has a diameter of 400 mm and its magnification is unity [173]. The detector array is composed of 60 Schottky barrier diodes (SBD). The array pitch is 5 mm and the total length is 300 mm. The two SBD arrays with a spacing of 3.5 mm were used to take THz images of objects for horizontal and vertical polarization waves independently and simultaneously. The measured dynamic range of the THz imaging system was approximately 30 dB. The minimum acquisition time of one-line data (60 pixels x 2) is 0.1 millisecond, which corresponds to a conveyor velocity of 60 m/min when the data acquisition step is 0.1 mm.

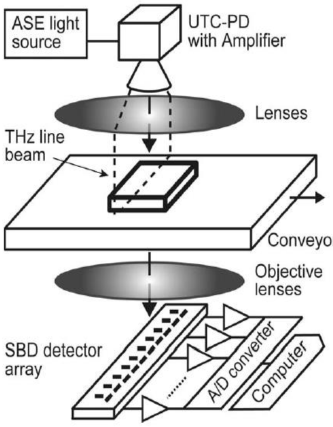
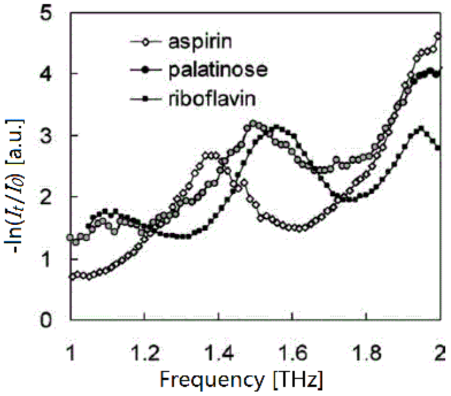


Fig. 9. Schematics diagram of the 0.1 THz imaging system [173].

3) *Detection by chemical recognition with THz pulses*

The detection of minute amounts of chemical and biological substances has been a major goal in bio-analytical technology. Theoretical calculations and experiments have demonstrated that many chemicals and bio-molecules have intrinsic resonance because of vibration or rotation level transitions, which allows THz sensing technique as a potential tool for the noninvasive and label-free detection of chemicals and bio-molecules. THz spectroscopy has been proposed to enable identification and investigation of a wide range of substances. The T-ray imaging technique is to detect chemical compositions in an object. Y. Watanabe et al. figured out inspection of chemical mixtures by THz spectroscopic imaging using known spectral data of the pure chemical components [174]. This method can determine the existence of chemicals, identify them, map the spatial distribution of each component, and measure the associated content in a target, which is based on principle component analysis. It was determined qualitatively and quantitatively that the components were present not only in pure chemical samples but also in mixtures. The content of each component determined experimentally comes in agreement with their respective known contents. Fig.10 shows the THz spectral data of aspirin, palatinose, and riboflavin.



ig. 10. The THz spectral data of aspirin, palatinose, and riboflavin. [174].

B Fischer et al. demonstrated how spatially resolved THz-TDS could be used as a general method for detection of chemicals hidden in sealed containers transparent to THz radiation [175]. The contrast mechanism that allows a distinction between the different chemicals is highly specific free induction decay signal, which is emitted coherently by the sample subsequent to excitation of collective vibrational modes of the crystal lattice by the ultra-short, broadband THz pulse. In the THz frequency range transitions between vibrational states of the crystalline compound mainly arise from lattice modes, which are specific to the crystalline structure as well as the molecular structure, and hence form a unique fingerprint of the substance.

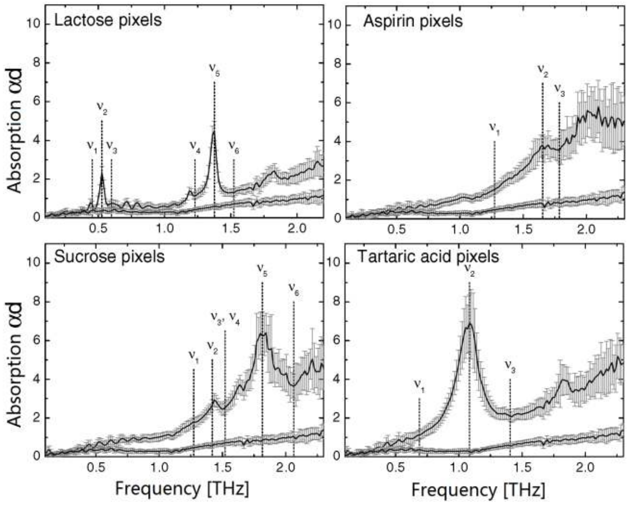


Fig. 11. Solid lines show the average absorption of lactose (top, left), aspirin (top, right), sucrose (down, left) and tartaric acid (down, right) in the sample. The lower curve in each panel shows the absorption of the packing material. The error bars represent one standard deviation from the mean of typically 20-30 measurements. The indicated frequencies are used for chemical recognition [175].

Fig.11 shows the absorption spectra of lactose, aspirin, sucrose and tartaric acid, which are extracted from the THz pulses transmitted through the relevant regions of the sample [175]. The vertical axis, αd, is the product of absorption α and sample thickness d which can be used in equation (3) to increase the specificity in more than one clear spectral feature situation.

Regarding the background absorption of the packing material, a recognition coefficient R proportional to the height of a spectral feature can be defined:

$$\mathrm{R} = \alpha\mathrm{d}(v_2) - (\alpha\mathrm{d}(v_1) + \alpha\mathrm{d}(v_3))/2 \tag{3}$$

We can see the suitability of these spectral fingerprints as a key in chemical recognition. Contemporary computational chemistry can assist to understand the origin of these modes, and in the future the far-infrared spectra of compounds may even be accurately predicted by numerical calculations. A key issue is the inclusion of periodic boundary conditions in the calculation of vibrational frequencies.

B. Terahertz for water contamination detection

1) Detection by chemical recognition with THz pulses

The high permittivity of liquid water is typically the dominate contrast mechanism for moisture detecting by THz imaging [165]. For example, typical real indices of refraction n and absorption coefficients α at 1 THz for wood [176] (n about 1.3, α about 15 cm^{-1}), leaves (solid material) [169] (n about 1.7, α about 40 cm^{-1}), polyamide plastic [177] (n about 1.75, α about 10 cm^{-1}), and cork cell walls [178] (n about 1.2, α about 10 cm^{-1}), are smaller than that of water (n about 2, α about 230 cm^{-1}). Note that the absorption coefficients for liquid water are typically an order of magnitude or larger than most other materials. The permittivity of liquid water in the THz range exhibits very broad spectral features. Consequently, the addition of water to a host material typically increases the overall absorbance at all THz frequencies without introducing any strong/narrow spectral features. There is a slight difference in the permittivities of free liquid water and water molecules which are weakly bound to the adjacent material.

2) THz response of water – Debye model

There have been numerous papers and review articles on the frequency dependent THz permittivity of liquid water. A good overview of the topic including the Debye model is given in [163][164][179]. In the THz range, the complex permittivity of liquid water is typically described as a sum of low pass filters which represent a sum of relaxation times. For the THz range, the sum is limited typically to two terms and called a double Debye model. In this model, the complex frequency dependent permittivity is termed as:

$$\varepsilon_{\mathrm{w}}(v) = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_1}{1 \pm i2\pi v\tau_1} + \frac{\varepsilon_1 - \varepsilon_\infty}{1 \pm i2\pi v\tau_2} \tag{4}$$

where ε_∞ is the high frequency limit of the permittivity, ε_0 and ε_1 are constants, while the time constants refer to temperature-dependent slow (τ_1), and fast (τ_2) relaxation processes. Below 100 GHz, a single Debye term is sufficient to describe water [180]. The ± signs in equation (4) are included to highlight the fact that definitions of the equations for the complex dielectric coefficient and complex refractive index will vary in the scientific literature. As a result of the different definitions, the resulting imaginary contribution to the permittivity can either be positive or negative depending upon the definitions of (4).

The permittivity of water is modeled using equation (4) assuming Debye parameters for 'free' liquid water. However, it has been recognized that polar water molecules may interact and weakly bond to polar functional groups on the surface of the host material. The weak bonding of 'bound' water to the host's surface modifies the vibrations of the water molecules leading to a lower refractive index and absorption coefficient. There are challenges including both the bound and free water contributions into an effective medium model: It is difficult to experimentally separate the contributions of bound and free water to the permittivity. In certain cases, such as water absorption by polyamide and wood-plastic composite, the measurement is simplified by the fact that only bound water exists in these materials assuming that one is well below the fiber saturation point [177].

3) Application of water contamination detection

Although there are many studies on the detection of food using terahertz technology, limited research has been done on water contamination detection. Two papers about water contamination detection are introduced in the following sections.

W. Sun et al. [181] used a reflective pulsed terahertz system to monitor the oil pollution. The authors utilized reflective terahertz imaging technology to analyze a layer of water covered with sesame oil, which simulate oil contamination monitoring. The reflective terahertz pulses are used to compute the optical thickness of sesame oil, and two-dimensional transverse reflection terahertz images determine clearly the diffuse areas of sesame oil with different densities. Abdul-Munaim et al. [183] used the THz-TDS system to discriminate water contamination levels (0%, 0.1%, and 0.2%) in diesel engine oil (SAE 15W-40). In addition, pure water has been studied using different techniques to observe its properties at THz frequencies [182]. This research discovered that the absorption coefficient performs significantly different at three water contamination levels across the 1.111 to 1.332 THz and 1.669 to 1.934 THz ranges. Each water contamination level was significantly different from the other two at each of these frequency ranges. Hence the differences of the refractive indices were used for discrimination of water contamination.

V. SOME OPEN CHALLENGES AND RESEARCH DIRECTIONS

Terahertz non-destructive detection technology in food inspection and water (or liquid, such as juice, beverages, and alcohol) contamination detection is emerging as a new area of study. With unique superiority, terahertz non-destructive detection technology has attracted many researchers in this field. This field has made great progress, however, it is still at an initial stage and there are still many challenges that need to be addressed. Some of the most important challenges are given as follows:

A. Distraction and Absorption of Water

Terahertz non-destructive detection for food and water contamination detection is limited by water due to the strong absorption of terahertz radiation by water. Therefore, a major challenge is the overwhelming attenuation of terahertz radiation by water. For example, in food detection terahertz technology is not suitable for detecting high humidity products with a thickness greater than 1mm. The inability of terahertz technology to monitor biomolecular interactions in solution is the major hurdle facing terahertz further applications. Methods for overcoming this challenge are given in the following research.

One method that applies to both food and water contamination is terahertz time-domain spectroscopy (THz-TDS) [184][186]. The THz-TDS system can obtain the amplitude and phase information of the terahertz pulse simultaneously [185]. Moreover, by applying the Fourier transform on the time waveform, the optical parameters of the sample can be directly obtained such as the absorption coefficient and refractive index. For food detection, many researchers proposed several methods using a broadband terahertz system or performing the measurement in the low-frequency terahertz region [187][173]. For water contamination detection, a method with reflective pulsed terahertz tomography is proposed in [181].

B. Low penetration depth

Another challenge of terahertz technology is the low penetration depth of terahertz radiation, especially measuring the liquid and meat products. This problem can be addressed using the penetration-enhancing agents, the use of graphene composite, and strengthening the intensity of terahertz source.

Hwayeong et al. -presented that the penetration depth can be enhanced using penetration-enhancing agents [188]. In [189], it was demonstrated that a new graphene composite with a double circularmetal ring array deposited on graphene can enhance the terahertz absorption. Terahertz power enhancement is also an effective way to increase penetration depth [190].

C. Scattering effects

Scattering effects is also a common problem in terahertz time-domain spectroscopy transmission measurements of solid state samples, especially for irregular granular samples. To reduce or remove the scattering effects, plasma and metamaterial are used. In addition, some better algorithms can also be used, such as wavelet transform and Monte Carlo method, to extract spectral data to minimize the scattering effects.

A novel method by coating plasma and metamaterial is presented to reduce the scattering effects of target, which has a better performance than coated with plasma [191]. Also, a modified Monte Carlo method is utilized to exclude or reduce the scattering effects [192].

D. More compact systems at higher powers

Because of the requirement of integration and miniaturization, a challenge that the need for more compact systems at higher powers has emerged. Terahertz area expects more compact systems, more terahertz power, and higher dynamic range. To overcome this challenge, engineering homework and sufficient fundings are required. With the availability of higher-power terahertz sources, materials that partially absorb terahertz radiation or thicker objects can be investigated.

E. Equipment costs

Equipment cost is one of the main obstacles to the universalization and commercialization of a technology. Currently, the cost of a terahertz system is higher than that of existing infrared and microwave technology. The continuous advancement and development of laser sources, integrated optics, and industrial-grade terahertz hardware will allow the exploitation of low-cost equipment with high performance [193]. Furthermore, due to the sensitivity to the environment parameters, enhancing the signal-to-noise ratio of the THz equipment is another challenge for future engineering researchers.

VI. CONCLUSION

The recent advancements in the terahertz technology has a high potential benefit to society, particularly for the public health and environmental protection. Therefore, there is a need of thorough research on the contamination detection of food products and liquid water matters. In this paper, various studies have been analyzed, examined and discussed covering the various aspects of terahertz systems, components, terahertz spectroscopy and imaging technologies. In addition, we have highlighted the terahertz detecting technologies and different potential applications that can be effectively used for food and water contamination detection and linked those to future directions. We have also presented some of the open challenges such as distraction and absorption of water, low penetration depth, scattering effect, compact system and equipment cost that need to be address. In a nutshell, the findings of this review paper are expected to be useful for researchers, engineers, health professionals, and policymakers working in the area THz domain for healthcare, fitness and wellness.

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