The potential of THz Microscopy for Non-Destructive Evaluation Applications

E.J.Y. Magaway[1a], M. Navarro-Cía[1,2]

[1] School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom
[2] Department of Electronic, Electrical and System Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom
[a]*Email: EJM727@student.bham.ac.uk*

Abstract

TeraHertz (THz) radiation, f = 0.1 to 10 THz, falls between microwave and infrared in the electromagnetic spectrum. This spectral range harbours several key benefits that are relevant for applications in non-destructive evaluation (NDE), namely, many optically opaque materials are transparent for THz, including packaging material, it is non-ionising, and it is a spectral rich fingerprint region for substances found in pharmaceutical and explosive substances. Prominent THz technologies, such as THz time-domain spectroscopy and imaging, are described and their current uses in various industries (safety, aviation and automation, cultural heritage, and food) as an NDE tool are discussed. Despite its potential for NDE applications, one of the challenges faced by THz technologies is its relatively low spatial resolution compared to light technologies. Methods being developed for enhancing the resolution of THz tools such as near-field modalities, and the relevance this could have for non-destructive testing are outlined. In addition, the challenges that must be overcome before these near-field techniques can be incorporated into pre-existing THz NDE tools are highlighted.

Keywords: *Terahertz, THz Microscopy, THz near-field, Terahertz NDE*

1. INTRODUCTION

Exhibiting frequencies in the range of 0.1 to 10 THz, TeraHertz (THz) radiation is situated between infrared and microwave in the electromagnetic (EM) spectrum (1). These frequencies harbour several unique characteristics; renders many common materials transparent (paper, ceramics, fabrics, cardboard), better spatial resolution than microwaves, non-ionising, and spectral fingerprint-rich region of the EM spectrum. These attributes have resulted in the THz field garnering increasing interest from several industries and has allowed it to be solidified as a significant emerging area of research (2).
Following efforts in producing coherent THz sources in the latter end of the 20th century, several technologies have been developed that allow access to this spectral region (3). Hence, in recent years the focus has shifted from hardware to developing applications of THz technologies. One industry, among many, that has shown great interest in the development of THz research is the non-destructive evaluation (NDE) industry. With its spectroscopic capabilities and mm to μm spatial resolution, THz time-domain spectroscopy (THz-TDS) systems have displayed promise in complementing pre-existing tools in the field of non-destructive testing (4).

1.1. THz-Based Analytical Tools

Terahertz Time-Doman Spectroscopy

THz-TDS is arguably the most established technique in the domain of THz analysis. First conceptualised in 1989 by Grischkowsky *et al*. (5), having been made possible with the advent of femtosecond lasers, THz-TDS is a powerful spectroscopic tool that is typically used for the direct measurement of dielectric properties (refractive index (n), and absorption coefficient (α) or, equivalently, permittivity (ε) and loss tangent (tanδ)). Looking at these characteristics of an object, substance or material can give an indication of its composition without the need for dismantling it.

Schematics of two configurations possible with a typical commercial THz-TDS system is presented in

Figure 1, with Figure 1(a) being used for transmission configuration. configuration and Figure 1(b) for reflection

These systems work under a pump-probe configuration wherein a femtosecond laser beam, in the near-infrared (NIR – red in Fig. 1) range, is split into two beams, via a beam splitter, with one being the pump beam (purple in Fig. 1) which hits the emitter and the other, the probe (orange in Fig. 1) that is directed to the receiver. In the case of THz generation and detection through photoconductive antennas (PCAs), both transmitter and receiver consist of electrodes placed on a highly resistive semiconductor material, such as that shown in Figure 2. Typically, this material is Gallium-Arsenide (GaAs), Indium-Gallium-Arsenide (InGaAs) or Gallium-Bismuth-Arsenide (GaBiAs).

For the transmitter, the pump illuminates an area of the semiconductor present between the two electrodes. The photon energy provided by the beam is greater than the bandgap of the semiconductor resulting in electron-hole pairs. These free carriers are accelerated in opposite directions by a bias voltage leading to a photocurrent which emits a single-cycle THz pulse (6).

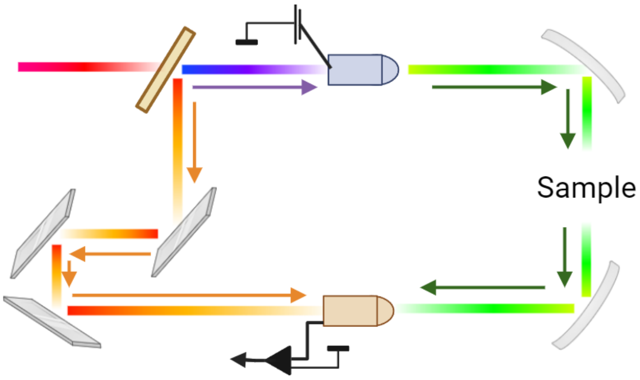

Figure 1(a): Schematic of a typical THz-TDS transmission setup.

The emitted THz pulse interacts with a sample and is then detected by the receiver. For detection there is no external bias voltage applied, instead the free carriers created by the probe beam are accelerated by the electric field of the incoming THz pulse, creating a current. The strength of the current generated through this interaction is proportional to the strength of the electric field of the incoming THz pulse. The use of PCAs for these systems is prolific owing to their relative simplicity, ease of use and reliability.

Standard order of operation for THz-TDS systems is composed of two measurements, one is of a reference ($E_{ref}(t)$) that captures the system response and the other of the sample ($E_s(t)$) which captures the system and sample response. For transmission setups the reference is the signal obtained from free space and for reflection the signal reflected from a perfect mirror. A Fast Fourier Transform is applied to both responses to convert them into the frequency domain. The converted sample signal, $E_s(\omega)$, is normalised by the reference signal, $E_{ref}(\omega)$ to de-embed the system response and thus, single out the sample response. The amplitude and phase of the resulting spectrum can be used to determine the dielectric properties of the sample. Though not discussed with in the scope of this document, the equations and subsequent steps for obtaining properties is well documented, if interested refer to (7,8).

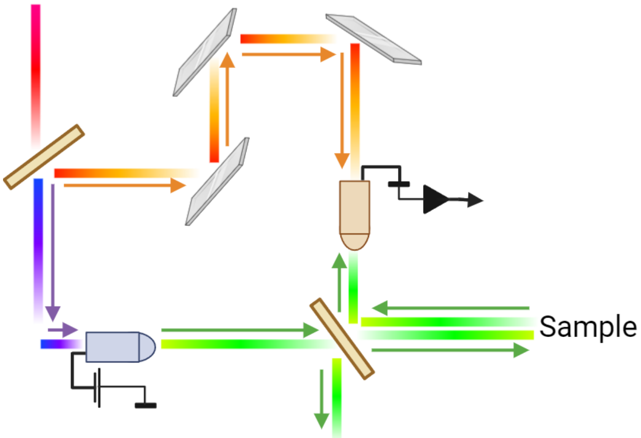

Figure 1(b): Schematic of a typical THz-TDS reflection setup.

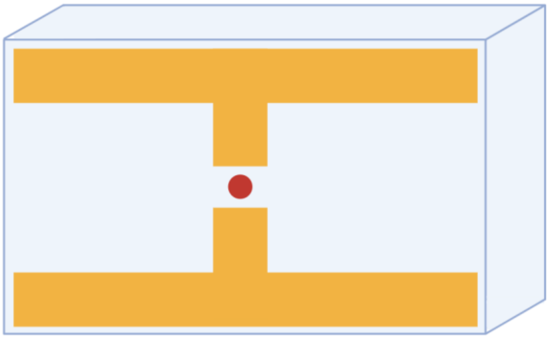

Figure 2: Photoconductive antenna used for THz generation and detection. Red circle represents where excitation occurs.

The choice between transmission and reflection setups is highly dependent on the samples being tested. Transmission measurements are often preferred due to the simplicity of the setup and post-processing with the caveat being the thickness of the sample must be known and it cannot be used if the sample is too absorbent. In such cases, reflection must be used which does not consider the sample thickness though post-processing becomes more complex especially if normal incidence is not utilised.

The combination of a developed spectroscopic technology and post-processing method, along with frequencies rich with the absorbance peaks of several substances of interest and the fact that many non-metallic materials are transparent at THz frequencies emphasises the relevance of THz technologies in the field of non-destructive evaluation (9).

THz Imaging

The potential of THz radiation as a tool for NDE is not limited to spectroscopy but also extends to imaging. The same setups depicted in Figures 1(a, b) can be used to take images of samples with a spatial resolution as low as ~150 µm at 1 THz, conditional on the system used. The most basic method for imaging using transmission or reflection configurations is through raster scanning of a sample and measuring the intensity of transmitted or reflected THz radiation at each point in the scan. Mapping out these points will highlight areas of high or low absorbance that could indicate different material types within the sample or different thicknesses. These concepts can then be used, for example, to detect cracks or measure thicknesses in a machine part or pipe work, as will be seen in the following section. THz imaging also has the advantage of access to phase response which can provide additional information beneficial to identification or classification of materials.

To dive into more details, the reader is referred to (10,11) which discuss, in detail, the rapid development undergone by the research area of THz imaging in recent decades since the first images were captured using THz radiation in the late 1970s to the present day and the possible future alleys that could be taken.

1.2. Applications of Far-Field THz-TDS for NDE

Several industries, such as chemistry, security, medicine, agriculture, and engineering, acknowledge the potential of THz technologies for NDE and quality control purposes and aim to incorporate it into their arsenal of NDE techniques (12). The goal of the following subsections is to highlight some of the work that has been carried out from several key industries on their route to realising a method for THz-based NDE. Note that these are just a few examples from a vast pool of literature available.

Drugs & Explosive Substances

Due to their proximity in the EM spectrum, the spectroscopic capability of THz is often compared to that of infrared. Techniques such as Fourier Transform Infrared (FTIR) spectroscopy can be used to gain information on the interactions within a molecule due to intra-molecular vibrations having strong absorption peaks in the infrared region. On the other hand, absorption peaks at THz frequencies are dominated by intermolecular vibrations (13) exhibited by movements of large numbers of atoms and molecules. The latter is a characteristic that proves extremely useful when probing the crystalline properties of materials as well as trying to identify substances that can undergo crystal polymorphism, a phenomenon in which crystals constructed from the same molecules undertake different forms depending on intermolecular arrangements (14).

The literature on THz-TDS for pharmaceutical application is vast; there are plenty of reviews that compile these studies together. Reviews by Shen Y., Bawuah *et al*., Patil *et al*., and Huang *et al*. focus on the ability of THz-TDS to differentiate between different crystal structures, chiral molecules and to determine tablet coating thickness (15–18). Work by Bawuah *et al*., Lu *et al*., and Naftaly *et al*. show porosity calculations of tablets (19–21).

Not only does THz-TDS have potential pharmaceutical quality control but there has also been some work on detecting explosives and other hazardous chemical agents (22). Work by Campbell *et al*., aimed to evaluate the ability of THz-TDS in identifying 3 common explosive substances: Semtex, Composition 4 (C4) and pentaerythritol tetranitrate (PETN). It was found that the technique exhibited some promise in detecting these materials in both bulk and aerosol forms (23). Later research by Chen *et al*., carried out a similar test but with a greater sample size of 14 common explosive substances and comparing results with those of an FTIR. Results found good agreement between both techniques. Several more examples are highlighted in conference proceedings by Gao *et al*. (24). This proves extremely useful as it would be possible to test packages that are suspected of containing explosives without the need for unboxing.

Automotive & Aviation

For the automotive and aviation industries, the interest in THz comes from the desire in developing a tool for detecting defects, such as cracks, in moving parts of a vehicle and measuring paint and coating thicknesses. In this case, THz radiation offers the spatial resolution that microwaves cannot provide whilst still having a safe photon energy unlike X-rays. Experiments conducted by Picot et al., and Chopard et al. show contactless THz techniques that are used to measure paint thickness (25,26). In both cases it is explained that in cases of single layer paint, thickness determination is straightforward if the refractive index of the paint is known, however, as is typically the case, there is a multilayer of paint, hence the measurement of thickness becomes non-trivial. Both papers offer their solutions, mainly based on simulations, with some success in both cases.

Imaging of defects is a more direct application of THz, as is shown by Hsu et al., and Ospald et al. who imaged several samples of composites used in aeronautics and wind turbine blades (27,28). The results show THz imaging having good detection rates for defects. The most notable work was carried out by X.-C. Zhang's team, who used THz imaging to deduce that the presence of air pockets between thermal tiles and the cabin of the space shuttle, Columbia, was the reason for its disintegration upon re-entry (29).

A review by Ellrich et al., provides a good summary of areas within the automotive and aviation industries that THz technologies could be implemented in as an NDE method (4).

Cultural Heritage & Architecture

Similar to the automotive and aviation industries, the field of cultural heritage conservation and architecture aim to take advantage of the spatial resolution, penetrative capability and low energy offered by THz radiation as a non-destructive tool. Again, here, several reviews exist that compiles the current state of the art and its potential direction. A document by Jackson et al., collate work that focuses on different THz imaging techniques to form 2D and 3D images of various art and archaeological pieces. With these techniques it was shown that it was possible to view "hidden layers" of a painting, underdrawings and contents of a container that would have not been possible to view without taking the piece apart (30). Similar studies are shared in a later work by Jackson et al., but with the focus being archaeology, as well as reviews by Consentino A. and Krügener et al. (31–33). The quantity of literature serves as good evidence of the interest in THz as an NDE technique within this area.

Food & Agriculture

The food and agriculture industries are other areas with stringent regulations in terms of the quality of the product. As such, it is vital to have tools capable of determining the state of food and crop quality without contact as this could contribute to accelerated spoilage.

Although the literature available on the usage of THz for non-destructive testing in these industries is not as abundant as those discussed previously, there has been notable progress made that showcase the growing interest in the techniques. For instance, work by Alomainy et al. reasoned that due to the sensitivity of THz radiation to water, it can be an instrument capable of expressing the moisture content of fruits, a metric known to indicate the quality of fresh produce (34). In this study the moisture content and THz transmission response of slices of apple and pear were measured in parallel, and results compared.

Zidane et al. illustrated how a combination of machine learning and THz-TDS can be used for fruit quality control (35). In this study a support vector machine (SVM), a form of machine learning algorithm, was trained to identify good and bad apples and peaches and then to separate them. The SVM was trained using permittivity data obtained at THz frequencies. The study showed promising results with a mean accuracy of 98%.

A compressive review of available literature around the use of THz tools for food and water quality assurance was carried out by Ren et al (36). It discusses methods such as moisture content detection and permittivity measurements such as those detailed in the previous studies presented, as indicators for food quality, but also details alternative uses like detecting foreign objects in foods. The review also includes the open challenges facing THz techniques prior to being accepted as a tool for NDE within the industry.

2. THz MICROSCOPY

In Section 1.1 the use of THz for imaging was discussed and it was mentioned that the spatial resolution limit is dependent on the system used. However, the value of 150 μm at 1 THz quoted is the absolute limit that can be achieved regardless of the system. It represents a physical limit, known as the

diffraction limit, that states that when taking measurements in the far-field, the maximum spatial resolution that can be theoretically achieved is half the wavelength (λ) of the radiation being used.
There would be several benefits to accessing subwavelength resolution at THz frequencies; for imaging, finer details could be resolved while for spectroscopy, smaller molecules can be interrogated, which would be extremely interesting because, as stated previously, the THz frequency range is rich with spectral fingerprints. These reasons have led many to develop methods for overcoming the Abbe limit.

2.1. THz Microscopy Techniques – Achieving Sub-Wavelength Resolution

Several techniques can be employed to achieve sub-wavelength resolution at THz frequencies but broadly speaking they can be classified into two main categories: aperture-type and scattering-type.

Aperture-Type THz Microscopy

A straightforward way to circumvent the diffraction is to essentially squeeze the THz radiation through an aperture whose size determines the resolution (a simplified diagram is shown in Figure 3). A detector is then placed very close to the aperture exit to detect the near-field signal.

Due to its simplicity, there is a variety of adaptations that can be found in literature. One of the earliest works was carried out by Mitrofanov *et al*, who placed a PCA just below an aperture of size 30 x 30 μm^2 and was able to achieve a spatial resolution of 40µm (λ/3.75) (37). With further development this has been brought down to single digit µm (38,39) and has been used for non-destructive evaluation of waveguides (40), dielectric µm-particles (41), conductive µm fibers (42) and metamaterials (43). Work carried out by Li *et al*, utilized a commercially available aperture-type detector to image single cells and in a later work, take images and spectroscopic measurements of cells (44,45).

Though the use of subwavelength apertures allow access to super-resolution, it does come with the caveat of high signal attenuation. Subwavelength apertures have high-pass properties that allow frequencies above a certain value (known as the cut-off frequency) to propagate through without significant changes to amplitude whilst lower frequencies experience increasing attenuation (46).

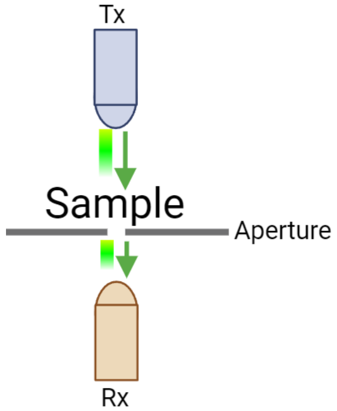

Figure 3: Setup for aperture-type THz Microscopy, Tx = Transmitter, Rx = Receiver.

Though the use of subwavelength apertures allow access to super-resolution, it does come with the caveat of high signal attenuation. Subwavelength apertures have high-pass properties that allow frequencies above a certain value (known as the cut-off frequency) to propagate through without significant changes to amplitude whilst lower frequencies experience increasing attenuation (46).

Scattering-Type THz Microscopy

This method takes the mechanisms used in optical techniques such as atomic force microscopy (AFM) and carries it out at THz frequencies. THz Scattering-type near-field scanning-type optical microscopy (THz s-NSOM) employs an AFM probe tip to scatter and reflect THz waves at the tip-sample region which can then be detected to provide information on the sample. This technique has been shown to achieve even nanoscale resolution with THz.

A typical THz s-NSOM is shown in Figure 4. Briefly, THz is used to illuminate the AFM tip; this creates a localized “hot spot”, an area where radiation is focused to a nanoscale near-field spot. As a sample is placed near the tip, the electric field of the radiation incites a near-field interaction between the tip and the sample. Dielectric properties of the sample are encoded in the electric field of the back scattered THz waves. It is often the case that back scattered waves are directed onto the path of the oncoming illumination beam which can be problematic for extracting information from the scattered signals. To overcome this, the AFM tip is modulated at some frequency, Ω and the detected signal de-modulated at higher harmonics, nΩ (47,48). It is worth noting that

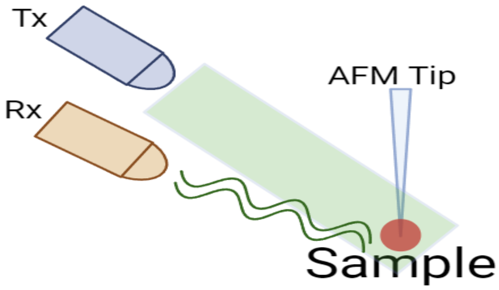

Figure 4: Schematic of a standard THz s-NSOM setup, Tx = Transmitter, Rx = Receiver.

despite the oscillation of the AFM tip designed to reduce background noise, standard THz s-NSOM is considered to have low SNR in comparison to aperture-type THz microscopy.

There is a plethora of accessible literature on the use of the method outlined above to achieve subwavelength resolution. With works by Van der Valk et al, Chen et al, Chen et al, boasting resolutions of 18 μm (λ/8), 0.15 μm (λ/1000), 0.1 μm (λ/1500), respectively, as examples (49–51). There have also been some tests done by Yang et al, and Yang et al, which do not specify the resolution achieved but were able to image single proteins using THz s-NSOM which can range from 1 – 100 nm in length (52,53).

The minimum resolution achievable for THz s-NSOM systems is a function of the tip radius. It is, however, an optimization problem as, while decreasing the radius improves resolution it has the effect of diminishing SNR (54).

Commercial THz Microscopy systems

To the knowledge of the author there are currently only two companies producing THz near-field systems. Protemics GmbH (Aachen, Germany) (https://www.protemics.com) which has several products of aperture-based microprobes and Neaspec GmbH (Haar, Germany) (https://neaspec.com) that produces scattering-type systems.

2.2. Potential Applications of THz Microscopy for NDE

With all the beneficial characteristics of THz radiation discussed previously coupled with the growing range of techniques to enhance resolution, THz microscopy is likely to show itself as a promising and formidable tool for NDE, at least in lab settings.

Incorporating near-field technologies in pre-existing THz systems in industries would provide more details about what is present in the sample, both chemically and physically. In sectors where THz is used for quality assurance, such as in the aviation and automotive industries, a near-field setup would allow for smaller defects to be resolved. For areas such as cultural heritage and architecture better resolution could reveal further “hidden layers” or provide more information on layers already viewed.

Giving a more specific example, Work by True *et al*, presents the argument for THz near-field tools for assurance purposes of several electrical components such as transistors, printed circuit boards (PCB) and semiconductors (55). For example, PCBs are carriers for several components, any of which could be defective. FR4, a common material for fabricating PCBs is transparent at THz frequencies and so THz spectroscopy and imaging could be used to identify any defective components within the PCB. However, since electrical parts are small, a higher resolution would be required than what far-field THz tools can provide hence the importance of near-field techniques. As current trends for electrical appliances shifts towards miniaturisation, the ability to resolve finer and finer features will only grow in relevance and consequently so too will the relevance of THz microscopy.

3. CHALLENGES OF THz MICROSCOPY FOR NDE APPLICATIONS

Though showcasing great potential and relevance to the field of NDE, THz near-field technologies still have several hurdles to overcome, namely, the acquisition time of images and control of distance from the sample. The combination of these two barriers limits them to lab environments for the time being.

The commercially available near-field systems discussed in Section 2.1 require probes to be in close proximity to the sample; in the order of tens of μm. This poses an issue due to several reasons; probes can be fragile and sensitive thus any accidental contact with samples could lead to decreased sensitivity or breakage. Similarly, contact with the probe could cause some deformation of the sample which is undesirable for a non-destructive testing tool. On-market translation stages provide a typical movement error of ± 5 μm, far too large to be used in near-field systems. There is also the added complexity of non-uniform samples which would require constant adjustment of distance during measurements. A possible solution utilises lasers and a feedback loop to control the distance between probe and sample, but this proves to be a costly fix. There is, therefore, a need for either more robust near-field setups or an economical method for manipulating sample-probe distance.

The concern around image acquisition time is not unique to THz near-field but is a major topic within the wider scope of THz research. Imaging using THz, in far- or near-field, currently involves raster scanning the sample by moving either the sample or the emitter and detector via a motorised stage. This, depending on averaging of traces, size of steps, area of desired image, can take several seconds to a considerable number of hours. Work by Mittleman et al., Stantchev et al., and Penketh et al., highlights some of the research being done to obtain greater acquisition time using large-area electro-optic crystals, THz quantum cascade lasers (QCLs) and single-pixel detectors (56–58). Using these techniques near real-time imaging has been achieved. Available literature on this topic does not yet extend into the near-field but it would be the next logical step to further develop the imaging capability of THz technologies. For THz techniques to be able to compete with current NDE tools, there needs to be a significant decrease in acquisition time.

It is also worth noting that the two problems go hand in hand. Acquiring an image in near-field using raster scanning would cause issues without an automatic adaptive system that could adjust probe-sample distance when imaging samples with features.

4. CONCLUSIONS

The work introduces TeraHertz radiation and describes its useful characteristics (low ionisation energy, good penetration through common materials and spectral fingerprint-rich region of the EM spectrum). THz far-field spectroscopic and imaging techniques were described and their relevance within the scope of non-destructive evaluation was highlighted. However, before THz-based tools can be used effectively several challenges must be overcome, namely, relatively low spectral resolution, acquisition time of images and distance control from samples. Whilst the latter two remain yet unanswered, the document discusses the existing methods being used to achieve subwavelength resolution at THz frequencies which would allow THz tools to become more effective in detecting finer details, chemically and physically, within samples. The benefits to several industries, namely for electrical component quality assurance, of having subwavelength resolution was presented. Overall, whilst currently, far-field THz tools are already being used, developing these techniques into the near-field could provide further assurance to the quality of products in several industries.

5. REFERENCES

[1] Naftaly M. Terahertz Metrology. Artech House; 2015. 64–65 p.
[2] Leitenstorfer A, Moskalenko AS, Kampfrath T, Kono J, Castro-Camus E, Peng K, et al. The 2023 terahertz science and technology roadmap. J Phys D Appl Phys. 2023 Jun 1;56(22).
[3] Lewis RA. A review of terahertz sources. J Phys D Appl Phys. 2014 Sep 17;47(37).
[4] Ellrich F, Bauer M, Schreiner N, Keil A, Pfeiffer T, Klier J, et al. Terahertz Quality Inspection for Automotive and Aviation Industries. J Infrared Millim Terahertz Waves. 2020 Apr 1;41(4):470–89.
[5] Van Exter M, Fattinger C, Grischkowsky D. Terahertz time-domain spectroscopy of water vapor. Opt Lett. 1989;14(20).
[6] Bacon DR, Madéo J, Dani KM. Photoconductive emitters for pulsed terahertz generation. Journal of Optics. 2021 Jun 1;23(6).
[7] Withayachumnankul W, Naftaly M. Fundamentals of measurement in terahertz time-domain spectroscopy. J Infrared Millim Terahertz Waves. 2014;35(8):610–37.
[8] Freer S, Sui C, Hanham SM, Grover LM, Navarro-Cía M. Hybrid reflection retrieval method for terahertz dielectric imaging of human bone. Biomed Opt Express. 2021 Aug 1;12(8):4807.
[9] Fischer BM, Helm H, Jepsen PU. Chemical recognition with broadband THZ spectroscopy. In: Proceedings of the IEEE. Institute of Electrical and Electronics Engineers Inc.; 2007. p. 1592–604.
[10] Guerboukha H, Nallappan K, Skorobogatiy M. Toward real-time terahertz imaging. Adv Opt Photonics. 2018 Dec 31;10(4):843.
[11] Valušis G, Lisauskas A, Yuan H, Knap W, Roskos HG. Roadmap of terahertz imaging 2021. Sensors. 2021 Jun 2;21(12).
[12] Nsengiyumva W, Zhong S, Zheng L, Liang W, Wang B, Huang Y, et al. Sensing and Nondestructive Testing Applications of Terahertz Spectroscopy and Imaging Systems: State-of-the-Art and State-of-the-Practice. IEEE Trans Instrum Meas. 2023;72.
[13] Shen YC. Terahertz pulsed spectroscopy and imaging for pharmaceutical applications: A review. Int J Pharm. 2011 Sep 30;417(1–2):48–60.
[14] Ajito K, Nakamura M, Tajima T, Ueno Y. Terahertz Spectroscopy Methods and Instrumentation. In: Encyclopedia of Spectroscopy and Spectrometry. Elsevier; 2017. p. 432–8.
[15] Shen YC. Terahertz pulsed spectroscopy and imaging for pharmaceutical applications: A review. Int J Pharm. 2011 Sep 30;417(1–2):48–60.

[16] Bawuah P, Zeitler JA. Advances in terahertz time-domain spectroscopy of pharmaceutical solids: A review. TrAC - Trends in Analytical Chemistry. 2021 Jun 1;139.

[17] Patil MR, Ganorkar SB, Patil AS, Shirkhedkar AA. Terahertz Spectroscopy: Encoding the Discovery, Instrumentation, and Applications toward Pharmaceutical Prospectives. Crit Rev Anal Chem. 2022;52(2):343–55.

[18] Huang S, Deng H, Wei X, Zhang J. Progress in application of terahertz time-domain spectroscopy for pharmaceutical analyses. Front Bioeng Biotechnol. 2023;11:1219042.

[19] Bawuah P, Markl D, Farrell D, Evans M, Portieri A, Anderson A, et al. Terahertz-Based Porosity Measurement of Pharmaceutical Tablets: a Tutorial. J Infrared Millim Terahertz Waves. 2020 Apr 1;41(4):450–69.

[20] Lu X, Sun H, Chang T, Zhang J, Cui HL. Terahertz detection of porosity and porous microstructure in pharmaceutical tablets: A review. Int J Pharm. 2020 Dec 15;591.

[21] Naftaly M, Tikhomirov I, Hou P, Markl D. Measuring open porosity of porous materials using THz-TDS and an index-matching medium. Sensors. 2020 Jun 1;20(11).

[22] Fu X, Liu Y, Chen Q, Fu Y, Cui TJ. Applications of Terahertz Spectroscopy in the Detection and Recognition of Substances. Front Phys. 2022 May 12;10.

[23] Campbell MB, Heilweil EJ. Non-invasive detection of weapons of mass destruction using THz radiation. 2003; Available from: www.sparta.com

[24] Gao W, Degang X, Jianquan Y. Review of Explosive Detection Using Terahertz Spectroscopy Technique. In: 20I I International Conference on Electronics and Optoelectronics (ICEOE 201 I). 2011.

[25] Picot M, Ballacey H, Guillet JP, Cassar Q, Mounaix P. Terahertz Paint Thickness Measurements: from lab to automotive and aeronautics industry. 2017; Available from: http://www.ndt.net/?id=22188

[26] Chopard A, Sleiman JB, Cassar Q, Fauché P, Guillet JP, Mounaix P, et al. Contactless Terahertz Paint Thickness Measurements: specificity of aeronautics industry. 2019; Available from: http://www.ndt.net/?id=25028

[27] Hsu DK, Lee KS, Park JW, Woo YD, Im KH. NDE inspection of terahertz waves in wind turbine composites. International Journal of Precision Engineering and Manufacturing. 2012 Jul 1;13(7):1183–9.

[28] Ospald F, Zouaghi W, Beigang R, Matheis C, Jonuscheit J, Recur B, et al. Aeronautics composite material inspection with a terahertz time-domain spectroscopy system. 2014; Available from: http://www.dotnac-project.eu

[29] Zhong H, Karpowicz N, Xu J, Deng Y, Ussery W, Shur M, et al. Inspection of space shuttle insulation foam defects using a 0.2 THz Gunn diode oscillator. In: Conference Digest of the 2004 Joint 29th International Conference on Infrared and Millimeter Waves and 12th International Conference on Terahertz Electronics. 2004. p. 753–4.

[30] Jackson JB, Bowen J, Walker G, Labaune J, Mourou G, Menu M, et al. A survey of terahertz applications in cultural heritage conservation science. IEEE Trans Terahertz Sci Technol. 2011 Sep;1(1):220–31.

[31] Jackson JB, Labaune J, Bailleul-Lesuer R, D'Alessandro L, Whyte A, Bowen JW, et al. Terahertz pulse imaging in archaeology. Frontiers of Optoelectronics. 2015 Mar 1;8(1):81–92.

[32] Cosentino A. Terahertz and Cultural Heritage Science: Examination of Art and Archaeology. Technologies. 2016 Feb 18;4(1):6.

[33] Krügener K, Ornik J, Schneider LM, Jäckel A, Koch-Dandolo CL, Castro-Camus E, et al. Terahertz inspection of buildings and architectural art. Applied Sciences. 2020 Aug 1;10(15).

[34] Alomainy A, Yang K, Imran MA, Yao XW, Abbasi QH. Nano-electromagnetic communication at terahertz and optical frequencies. Nano-Electromagnetic Communication at Terahertz and Optical Frequencies: Principles and Applications. Institution of Engineering and Technology; 2019. p. 1–206.

[35] Zidane F, Lanteri J, Marot J, Brochier L, Joachimowicz N, Roussel H, et al. Nondestructive control of fruit quality via millimeter waves and classification techniques: Investigations in the automated health monitoring of fruits. IEEE Antennas Propag Mag. 2020 Oct 1;62(5):43–54.

[36] Ren A, Zahid A, Fan D, Yang X, Imran MA, Alomainy A, et al. State-of-the-art in terahertz sensing for food and water security – A comprehensive review. Trends Food Sci Technol. 2019 Mar 1;85:241–51.

[37] Mitrofanov O, Brener I, Harel R, Wynn JD, Pfeiffer LN, West KW, et al. Terahertz near-field microscopy based on a collection mode detector. Appl Phys Lett. 2000 Nov 27;77(22):3496–8.

[38] Macfaden AJ, Reno JL, Brener I, Mitrofanov O. 3 μm aperture probes for near-field terahertz transmission microscopy. Appl Phys Lett. 2014 Jan 6;104(1).

[39] Mitrofanov O, Brener I, Luk TS, Reno JL. Photoconductive Terahertz Near-Field Detector with a Hybrid Nanoantenna Array Cavity. ACS Photonics. 2015 Dec 16;2(12):1763–8.

[40] Navarro-Cía M, Vitiello MS, Bledt CM, Melzer JE, Harrington JA, Mitrofanov O. Terahertz wave transmission in flexible polystyrene-lined hollow metallic waveguides for the 25-5 THz band. Opt Express. 2013 Oct 7;21(20):23748.

[41] Navarro-Cía M, Natrella M, Dominec F, Delagnes JC, Kužel P, Mounaix P, et al. Terahertz imaging of sub-wavelength particles with Zenneck surface waves. Appl Phys Lett. 2013 Nov 25;103(22).

[42] Khromova I, Navarro-Cía M, Brener I, Reno JL, Ponomarev A, Mitrofanov O. Dipolar resonances in conductive carbon micro-fibers probed by near-field terahertz spectroscopy. Appl Phys Lett. 2015;107(2).

[43] Mitrofanov O, Todorov Y, Gacemi D, Mottaghizadeh A, Sirtori C, Brener I, et al. Near-field spectroscopy and tuning of sub-surface modes in plasmonic terahertz resonators. Opt Express. 2018 Mar 19;26(6):7437.

[44] Li Z, Yan S, Zang Z, Geng G, Yang Z, Li J, et al. Single cell imaging with near-field terahertz scanning microscopy. Cell Prolif. 2020 Apr 1;53(4).

[45] Li Z, Zang Z, Wang J, Lu X, Yang Z, Wang H, et al. In Situ Cell Detection Using Terahertz Near-Field Microscopy. IEEE Trans Terahertz Sci Technol. 2022 Sep 1;12(5):457–63.

[46] Mitrofanov O, Lee M, Hsu JWP, Pfeiffer LN, West KW, Wynn JD, et al. Terahertz pulse propagation through small apertures. Appl Phys Lett. 2001 Aug 13;79(7):907–9.

[47] Aghamiri NA, Huth F, Huber AJ, Fali A, Hillenbrand R, Abate Y. Hyperspectral time-domain terahertz nano-imaging. Opt Express. 2019 Aug 19;27(17):24231.

[48] M. Wiecha M, Soltani A, G. Roskos H. Terahertz Nano-Imaging with s-SNOM. In: Terahertz Technology. IntechOpen; 2022.

[49] van der Valk NCJ, Planken PCM. Electro-optic detection of subwavelength terahertz spot sizes in the near field of a metal tip. Appl Phys Lett. 2002 Aug 26;81(9):1558–60.

[50] Chen HT, Kersting R, Cho GC. Terahertz imaging with nanometer resolution. Appl Phys Lett. 2003 Oct 13;83(15):3009–11.

[51] Chen X, Liu X, Guo X, Chen S, Hu H, Nikulina E, et al. THz Near-Field Imaging of Extreme Subwavelength Metal Structures. ACS Photonics. 2020 Mar 18;7(3):687–94.

[52] Yang Z, Tang D, Hu J, Tang M, Zhang M, Cui HL, et al. Near-Field Nanoscopic Terahertz Imaging of Single Proteins. Small. 2021 Jan 1;17(3).

[53] Yang Z, Li D, Chen L, Qiu F, Yan S, Tang M, et al. Near-Field Terahertz Morphological Reconstruction Nanoscopy for Subsurface Imaging of Protein Layers. ACS Nano. 2023;18(14).

[54] Cocker TL, Jelic V, Hillenbrand R, Hegmann FA. Nanoscale terahertz scanning probe microscopy. Nat Photonics. 2021 Aug 1;15(8):558–69.

[55] True J, Xi C, Jessurun N, Ahi K, Asadizanjani N. Review of THz-based semiconductor assurance. Optical Engineering. 2021 Jun 3;60(06).

[56] Mittleman DM. Twenty years of terahertz imaging [Invited]. Opt Express [Internet]. 2018;26(8):9417. Available from: https://www.osapublishing.org/abstract.cfm?URI=oe-26-8-9417

[57] Stantchev RI, Yu X, Blu T, Pickwell-MacPherson E. Real-time terahertz imaging with a single-pixel detector. Nat Commun. 2020 May 21;11(1):2535.

[58] Penketh H, Ergoktas MS, Lawrence CR, Phillips DB, Cunningham JE, Hendry E, et al. Real-time millimeter wave holography with an arrayed detector. Opt Express. 2024 Feb 12;32(4):5783.