Frontiers in Biomedical Technologies Vol. 13, No. 1 (Winter 2026) 255-265

REVIEW ARTICLE

Terahertz Computed Computed Tomography and Imaging Challenges

Masoumeh Mohamadian *, **Masoumeh Hosseini**

Energy Engineering and Physics Department, Amirkabir University of Technology, Tehran, Iran

*Corresponding Author: Masoumeh Mohamadian

Received: 31 December 2023 / Accepted: 02 March 2024

Email: mohamadian@aut.ac.ir

Abstract

Purpose: Terahertz imaging has emerged as a promising technique for non-destructive evaluation and imaging applications, offering unique advantages over traditional imaging modalities. This paper presents an overview of the current state of Terahertz Computed Tomography and highlights the challenges faced in its implementation.

THz-CT utilizes electromagnetic waves in the terahertz frequency range to reconstruct three-dimensional images of objects with high resolution and penetration capabilities. The ability to visualize internal structures without the use of ionizing radiation has significant implications for various fields.

Materials and Methods: Despite its potential, it faces several challenges that need to be addressed for its widespread adoption. Firstly, the limited availability and complexity of THz sources and detectors hinder the practical implementation of THz-CT systems. Efforts are being made to develop compact, efficient, and cost-effective THz sources and detectors to overcome these limitations.

Secondly, THz waves are highly susceptible to scattering and absorption by various materials. This poses challenges in achieving accurate and artifact-free reconstructions, especially in applications involving biological samples.

Results: Furthermore, the relatively long acquisition times required for THz-CT imaging limit its real-time applications. Efforts are underway to develop faster acquisition methods to reduce acquisition times while maintaining image quality.

Lastly, the lack of standardized protocols and benchmarks for THz-CT imaging hinders the comparison and reproducibility of results across different systems and studies.

Also, in addition to its various applications, terahertz medical imaging and medical microbiological detection play a significant role in the diagnosis of several types of cancers.

Conclusion: In conclusion, THz-CT holds great promise for various imaging applications, but several challenges need to be overcome for its widespread adoption. Addressing the limitations associated with THz sources, scattering and absorption effects, acquisition times, and standardization will pave the way for the realization of the full potential of THz-CT in the future.

Keywords: Terahertz Imaging; Terahertz Computed Tomography; Terahertz Sources; Acquisition Times.

DOI: https://doi.org/10.18502/fbt.v13i1.20791

Frontiers in BIOMEDICAL TECHNOLOGIES

1. Introduction

Terahertz Computed Tomography (THz-CT) is an emerging imaging technique that holds great promise in various scientific and technological fields. It utilizes terahertz radiation, which lies between the microwave and infrared regions of the electromagnetic spectrum, to generate detailed images of objects with high resolution and non-destructive capabilities. This technology has garnered significant attention due to its potential applications in medical imaging, security screening, material characterization, and many other areas [1-3].

The unique properties of terahertz radiation make it particularly suitable for imaging purposes. Unlike X-rays and other ionizing radiation, terahertz waves are non-ionizing and non-destructive, making them safe for use in medical and biological applications. Additionally, terahertz radiation can penetrate various materials, such as clothing, plastics, ceramics, and even biological tissues, enabling the visualization of internal structures without the need for invasive procedures [4].

However, despite its numerous advantages, THz-CT still faces several challenges that need to be addressed for its widespread adoption and further development. One of the main challenges is the limited availability of efficient terahertz sources and detectors. Terahertz radiation is challenging to generate and detect due to its relatively low energy and the lack of suitable materials for efficient conversion. Overcoming this limitation is crucial to enhancing the imaging capabilities and overall performance of THz-CT systems [5-8].

Another significant challenge lies in the computational aspects of terahertz computed tomography. The reconstruction of three-dimensional images from terahertz projection data requires advanced algorithms and computational power [9]. The complex nature of terahertz wave propagation and scattering necessitates the development of sophisticated image reconstruction techniques to ensure accurate and reliable results. Furthermore, the large amount of data generated during the imaging process poses computational challenges that need to be addressed for real-time imaging applications [10-11].

Moreover, terahertz radiation is highly sensitive to environmental conditions, such as temperature and humidity. These factors can affect the propagation and absorption of terahertz waves, leading to distortions in the acquired images. Therefore, robust calibration methods and environmental control systems are essential to mitigate these effects and ensure the reliability and reproducibility of THz-CT imaging results [12].

In this scientific paper, we aim to provide a comprehensive overview of the current state-of-the-art in terahertz computed tomography and discuss the existing challenges that hinder its widespread adoption. We will delve into the technical aspects of terahertz radiation generation, detection, and imaging systems, highlighting the limitations and potential solutions. Additionally, we will explore the computational challenges associated with terahertz image reconstruction and discuss the advancements in this field. Finally, we will address the environmental factors that affect terahertz imaging and propose strategies to overcome these challenges [13-14].

By understanding and addressing these challenges, we can pave the way for the successful implementation and advancement of terahertz computed tomography, unlocking its full potential in various scientific, medical, and industrial applications.

1.1. Current State-of-the-Art in Terahertz Computed Tomography

The current state-of-the-art in THz-CT encompasses several advancements in terahertz technology, image reconstruction algorithms, and applications. These developments have significantly improved the imaging capabilities and expanded the potential applications of THz-CT [15-20].

In terms of terahertz sources, researchers have made significant progress in developing efficient and compact terahertz emitters. One notable advancement is the development of terahertz quantum cascade lasers (QCLs), which provide high-power terahertz radiation in a compact and tunable form. QCLs have enabled the generation of terahertz waves with a wide range of frequencies, improving the flexibility and versatility of THz-CT systems.

Furthermore, advancements in terahertz detectors have contributed to the improvement of THz-CT imaging. The development of high-sensitivity and high-speed terahertz detectors, such as bolometers, pyroelectric detectors, and photoconductive antennas, has enhanced the signal-to-noise ratio and enabled faster data acquisition [21-22]. These detectors have also facilitated the implementation of real-time THz-CT imaging systems, allowing for dynamic imaging of moving objects or biological processes [11, 23].

In terms of image reconstruction, researchers have developed advanced algorithms to overcome the challenges associated with terahertz wave propagation and scattering. Iterative reconstruction algorithms, such as filtered back projection and algebraic reconstruction techniques, have been adapted and optimized for terahertz imaging, enabling the reconstruction of high-resolution three-dimensional images from terahertz projection data. Additionally, machine learning techniques, such as deep learning and neural networks, have been explored to improve the speed and accuracy of image reconstruction in THz-CT [9].

The applications of THz-CT have also expanded in recent years. In the field of medical imaging, terahertz technology has shown potential for non-invasive imaging of biological tissues, including early detection of skin cancer, imaging of dental structures, and monitoring of wound healing processes [7, 24]. THz-CT has also found applications in material characterization, such as the inspection of pharmaceutical tablets, the detection of concealed objects in security screening, and the analysis of artworks and cultural heritage objects [25].

Despite these advancements, several challenges remain in the field of terahertz computed tomography. These include the need for further improvements in terahertz sources and detectors, the development of more efficient image reconstruction algorithms, and the enhancement of environmental control systems to mitigate the effects of temperature and humidity on terahertz imaging [9]. Addressing these challenges will contribute to the continued advancement and adoption of THz-CT in various scientific, medical, and industrial applications.

1.2. Existing Challenges, Limitations, and Potential Solutions

Existing challenges that hinder the widespread adoption of THz-CT can be categorized into three main areas: terahertz radiation generation, detection, and imaging systems. Let's delve into each of these areas, highlighting the limitations and potential solutions.

2. Terahertz Radiation Generation

Generating terahertz radiation is a challenging task due to the relatively low energy of terahertz waves and the lack of efficient terahertz sources. Terahertz sources can be classified into electronic solid-state sources, vacuum electronic sources, laser and photonics sources, photoconductive antennas, optical rectification, laser-plasma interaction, Wakefield scheme, beating scheme, and laser-nanostructure interaction [26-28]. The limitations in terahertz radiation generation include:

a. Limited power output: Terahertz sources often have low power outputs, which can result in low signal-to-noise ratios and limited penetration depth. Increasing the power output of terahertz sources is crucial for improving the imaging capabilities of THz-CT systems [29]. Potential solutions include the development of more efficient terahertz emitters [30-31], such as terahertz quantum cascade lasers (QCLs) [32], which can provide higher power outputs in a compact form.

b. Limited tunability: Many terahertz sources have limited tunability, meaning they can only generate terahertz waves at specific frequencies. This limits the flexibility and versatility of THz-CT systems. Solutions to this limitation include the development of tunable terahertz sources, such as QCLs with wide tunability ranges [9], or the use of frequency conversion techniques to generate terahertz waves at desired frequencies [33, 34].

In this regard, several methods have been investigated for the generation of stable terahertz radiation. Yuelin Li in [35] discusses the generation of a train of pre-bunched electron beams to produce coherently enhanced terahertz radiation. The proposed scheme involves using picosecond laser pulses to drive a photoemission gun and generate a train of 50 keV electron pulses. They also discuss the coherence factor, space charge effect, and the potential applications of the proposed scheme in terahertz radiation generation. Additionally, they explore the use of an echelon lens to generate a pulse train from a single laser pulse and the potential for generating non-relativistic bunch trains with a bunch rate in the terahertz regime [35].

Also, Qi Jin *et al.* [36] discusses the generation of THz waves from liquid water using femtosecond laser pulses. The study demonstrates the critical dependence of the THz field on the relative position between the water film and the laser beam's focal point. It also compares the characteristics of THz radiation from liquid water with those from air plasmas, highlighting differences in pulse duration, polarization, and excitation energy. The findings suggest potential applications in the fields of THz and infrared radiation, contributing to the exploration of laser-liquid interactions and their future as THz sources [36-37].

The source of THz radiation with long Josephson junctions of the BSCCO type refers to a specific type of superconductor material known as BiSrCaCuO (BSCCO) being used to create Josephson junctions, which are long in length. When a current is passed through these long Josephson junctions, they can emit terahertz (THz) radiation. This type of radiation is useful for various applications such as medical imaging, security screening, and communication technology. The unique properties of BSCCO and the design of long Josephson junctions make this source of THz radiation particularly efficient and effective for generating high-frequency electromagnetic waves [38].

Among other methods of THz generation, utilizing semiconductor technology, such as quantum cascade lasers, uni-travelling carrier photodiodes, nonlinear photonic waveguides, and photoconductors, would be a suitable approach for THz generation. Additionally, the use of CMOS-based and heterojunction bipolar transistors for electronic terahertz sources represents another viable option [37, 39-40].

3. Terahertz Detection

The receivers or detectors are another important component of these systems. There are some basic models of receivers which can be divided into two main categories: photonic THz receivers, such as photoconductors [41], and electronic terahertz receivers, such as Schottky barrier diode detectors [42], heterodyne receivers [43], and field effect transistors [44-45].

Additionally, there are other dispersed ideas for THz receivers, such as Alvydas Lisauskas *et al.*, who discuss the use of silicon MOSFETs as detectors of terahertz (THz) radiation. They summarize three lines of development and investigation, including efficient detection at frequencies as high as 9 THz, imaging with enhanced sensitivity in heterodyne mode, and an all-electronic raster-scan imaging system for 220 GHz. They also explore the potential for real-time imaging at 600 GHz with a 12x12 detector array and the use of CMOS technology for THz photonics. Additionally, they discuss the advantages of heterodyne detection and the potential for an all-CMOS imaging system. They highlight the potential impact of silicon MOSFET technology on THz imaging and photonics [46].

Detecting terahertz waves with high sensitivity and speed is another challenge in THz-CT. The limitations in terahertz detection include:

a. Limited sensitivity: Terahertz detectors often have low sensitivity, resulting in weak signals and reduced image quality. Enhancing the sensitivity of terahertz detectors is crucial for improving the signal-to-noise ratio and overall imaging performance. Potential solutions include the development of high-sensitivity detectors, such as bolometers or superconducting detectors, or the use of signal amplification techniques, such as heterodyne detection [47].

b. Limited speed: Terahertz detectors typically have slow response times, which can limit the acquisition speed of THz-CT systems. Improving the speed of terahertz detectors is important for real-time imaging applications [11]. Potential solutions include the development of high-speed detectors, such as photoconductive antennas or field-effect transistors, or the use of parallel detection schemes to increase the data acquisition rate [48-52].

4. Terahertz Imaging Systems

Terahertz imaging systems are advanced technologies that utilize terahertz waves to create detailed images of objects and materials. This capability allows terahertz imaging systems to provide high-resolution images and even reveal the chemical composition of objects. Furthermore, the progress in terahertz imaging modalities, which encompasses enhanced spatial resolution and spectroscopic imaging, along with a focus on functional devices and signal processing methods, has led to significant improvements in terahertz imaging systems [53-55].

The technical aspects of terahertz imaging systems also present challenges in THz-CT. These limitations include:

a. Computational complexity: The reconstruction of three-dimensional images from terahertz projection data requires advanced algorithms and significant computational power. The complex nature of terahertz wave propagation and scattering adds to the computational complexity. Potential solutions include the development of optimized image reconstruction algorithms, such as iterative reconstruction techniques or machine learning-based approaches, and the utilization of parallel computing architectures to accelerate the reconstruction process [9].

b. Environmental effects: Terahertz radiation is highly sensitive to environmental conditions, such as temperature and humidity. These factors can affect the propagation and absorption of terahertz waves, leading to distortions in the acquired images. Robust calibration methods and environmental control systems are essential to mitigate these effects and ensure the reliability and reproducibility of THz-CT imaging results [56-57].

Addressing these challenges requires interdisciplinary efforts from researchers in physics, engineering, and computer science. Continued advancements in terahertz technology, image reconstruction algorithms, and environmental control systems will contribute to overcoming these limitations and promoting the widespread adoption of terahertz computed tomography in various applications [32].

5. Biological Effects of Terahertz Radiation

Terahertz (THz) radiation has been observed to have a significant impact on biological organisms, resulting in a wide range of effects such as changes in protein activity and epigenetic modifications that can lead to altered metabolism or reproduction. These effects are categorized as thermal and non-thermal, with the former attributed to THz's ability to induce localized thermal changes, while the latter involves more intricate interactions with the macromolecules of cells, which are not yet fully understood. The capacity of terahertz radiation to enhance actin polymerization and modify gene expression suggests potential applications in agriculture, where increased growth rates have been observed in certain plant species post-exposure, and in medicine, where it may potentially slow down the rapid division of cancer cells [23, 58-60].

5.1. Computational Challenges of Terahertz Image Reconstruction

THz-CT involves the acquisition of multiple projections of an object using terahertz radiation and the reconstruction of a three-dimensional image from these projections. The reconstruction process is computationally intensive and involves solving a system of linear equations to obtain the attenuation coefficients of the object at each voxel. The computational challenges associated with terahertz image reconstruction can be categorized into two main areas: the complexity of terahertz wave propagation and scattering, and the large amount of data generated during the acquisition process [61].

5.1.1. Complexity of Terahertz Wave Propagation and Scattering

Terahertz waves are highly sensitive to the geometry and composition of the object being imaged, as well as the surrounding environment [62]. The complex nature of terahertz wave propagation and scattering presents computational challenges in image reconstruction, including:

a. Non-linear and non-local effects: Terahertz waves exhibit non-linear and non-local effects, such as dispersion, absorption, and scattering, which can lead to distortions in the acquired projections. These effects need to be accurately modeled and accounted for in the reconstruction process, which can be computationally demanding [63-65].

b. Limited data availability: Terahertz radiation has limited penetration depth and can be strongly absorbed by certain materials, resulting in incomplete projection data. This can lead to artifacts and errors in the reconstructed image, which need to be minimized through advanced image reconstruction algorithms [66].

5.1.2. Large Amount of Data

THz-CT generates a large amount of data, which requires efficient storage and processing. The limitations in data processing include:

a. Memory and processing power: The large amount of data generated during the acquisition process requires significant memory and processing power for image reconstruction. This can be a challenge for systems with limited computational resources [67-68].

b. Data transfer and storage: THz-CT systems generate large amounts of data, which need to be transferred and stored efficiently. This requires advanced data compression and transfer protocols to minimize data loss and ensure data integrity [69-70].

Recent advancements in terahertz image reconstruction have focused on addressing these computational challenges. These advancements include:

1. Advanced Image Reconstruction Algorithms

Several advanced image reconstruction algorithms have been developed to overcome the limitations of traditional reconstruction methods, such as filtered back projection. These algorithms include iterative reconstruction techniques, such as Algebraic Reconstruction Techniques (ART) and Simultaneous Algebraic Reconstruction Techniques (SART), which can improve the accuracy and robustness of image reconstruction [71-72].

2. Machine Learning-Based Approaches

Machine learning-based approaches have shown promise in terahertz image reconstruction, particularly in addressing the limited data availability and non-linear effects of terahertz waves. These approaches include deep learning-based algorithms, such as convolutional neural networks (CNNs) and Generative Adversarial Networks (GANs), which can learn complex features and patterns from limited data and improve the accuracy and speed of image reconstruction [73-74].

3. Parallel Computing Architectures

Parallel computing architectures, such as graphics processing units (GPUs) and field-programmable gate arrays (FPGAs), have been utilized to accelerate the image reconstruction process [75-76]. These architectures can handle large amounts of data and perform complex computations in parallel, leading to significant improvements in reconstruction speed and efficiency.

In conclusion, terahertz image reconstruction presents several computational challenges, including the complexity of terahertz wave propagation and scattering, and the large amount of data generated during the acquisition process. Recent advancements in image reconstruction algorithms, machine learning-based approaches, and parallel computing architectures have shown promise in addressing these challenges and improving the accuracy, speed, and efficiency of terahertz image reconstruction.

6. Environmental Factors and Propose Strategies

Environmental factors can significantly impact the performance and reliability of terahertz imaging systems. Some of the key environmental challenges in terahertz imaging include temperature variations, humidity, and atmospheric absorption. Here are strategies to overcome these challenges:

6.1. Temperature Variations

Terahertz radiation is sensitive to temperature variations, which can affect the propagation and absorption of terahertz waves [77-78]. To overcome this challenge:

- Environmental Control: Implementing temperature control systems, such as temperature stabilization chambers or enclosures, can help maintain a stable and controlled environment for terahertz imaging. This ensures consistent and reproducible results.

- Calibration: Regular calibration of the terahertz imaging system is crucial to account for temperature variations. Calibration can be done using temperature-sensitive reference materials or by incorporating temperature sensors within the system [79-80].

6.2. Humidity

Humidity can also impact terahertz imaging as water vapor in the atmosphere strongly absorbs terahertz waves [81-82]. To mitigate this challenge:

- Environmental Control: Similar to temperature control, humidity control systems can be employed to maintain a stable humidity level during terahertz imaging. This helps minimize the effects of water vapor absorption on the acquired images.

- Atmospheric Compensation: Advanced algorithms can be developed to compensate for the effects of atmospheric absorption and scattering. These algorithms can be based on physical models or machine learning approaches to estimate and correct for the distortions caused by humidity.

6.3. Atmospheric Absorption

Terahertz waves are subject to absorption by atmospheric gases, such as water vapor and oxygen. This absorption can limit the penetration depth of terahertz radiation [83-85]. Strategies to overcome this challenge include:

- Frequency Selection: Choosing frequencies with lower absorption by atmospheric gases can help improve the penetration depth and image quality. This requires careful consideration of the target application and the specific absorption characteristics of the gases present in the environment.

- Gas Compensation: Similar to atmospheric compensation for humidity, algorithms can be developed to compensate for the effects of atmospheric absorption. These algorithms can estimate and correct for the distortions caused by the absorption of terahertz waves by atmospheric gases.

- Gas Sensing: Incorporating gas sensing capabilities within the terahertz imaging system can provide real-time information about the composition and concentration of atmospheric gases. This information can be used to adjust the imaging parameters or apply appropriate correction algorithms to account for the absorption effects [86].

Overall, strategies to overcome environmental challenges in terahertz imaging involve environmental control, calibration, advanced algorithms for compensation, and real-time monitoring of environmental parameters. These approaches can help ensure the reliability, reproducibility, and accuracy of terahertz imaging in various applications [87].

7. Conclusion

Terahertz computed tomography has emerged as a promising imaging technique with unique capabilities for non-destructive and non-invasive imaging. However, the computational challenges and environmental factors discussed in this paper highlight the need for further research and development to fully harness the potential of THz-CT.

Advanced image reconstruction algorithms, machine learning-based approaches, and parallel computing architectures have shown great promise in overcoming the computational challenges associated with THz-CT. These advancements have the potential to improve the accuracy, speed, and efficiency of image reconstruction [88], enabling real-time imaging and analysis of terahertz data.

Additionally, strategies to address environmental factors, such as temperature variations, humidity, and atmospheric absorption, are crucial for ensuring reliable and accurate terahertz imaging. Environmental control systems, calibration techniques, and compensation algorithms can help mitigate the effects of these factors, enabling consistent and reproducible results.

By overcoming these challenges, THz-CT can find widespread applications in fields such as materials science, biomedical imaging [89], security screening, and industrial quality control [55]. The ability to visualize and characterize materials and structures at terahertz frequencies can provide valuable insights and enable advancements in diverse areas, including pharmaceutical research, cancer detection, and non-destructive testing [29, 32, 90-91].

In conclusion, terahertz computed tomography holds immense potential for revolutionizing imaging technologies. However, to fully realize this potential, it is crucial to address the computational challenges and environmental factors that impact THz-CT. The advancements in image reconstruction algorithms, machine learning-based approaches, and parallel computing architectures, along with strategies to mitigate environmental factors, will play a pivotal role in unlocking the full capabilities of THz-CT in scientific, medical, and industrial applications. Continued research and development in these areas will pave the way for the widespread adoption and advancement of THz-CT, leading to discoveries, improved diagnostics, and enhanced quality control in various fields [55].

References

1- X. Yin, Brian W-H Ng, Derek Abbott, Xiaoxia Yin, Brian W-H Ng, and Derek Abbott, "Terahertz Computed Tomography." *Terahertz Imaging for Biomedical Applications: Pattern Recognition and Tomographic Reconstruction,* pp. 179-89, (2012).

2- W.-Tai Su, Yi-Chun Hung, Po-Jen Yu, Chia-Wen Lin, and Shang-Hua Yang, "Physics-Guided Terahertz Computational Imaging: A tutorial on state-of-the-art techniques." *IEEE Signal Processing Magazine,* Vol. 40 (No. 2), pp. 32-45, (2023).

3- S Wang and XC Zhang, "Pulsed terahertz tomography." *Journal of Physics D: Applied Physics,* Vol. 37 (No. 4), p. R1, (2004).

4- X. Li, Jingxi Li, Yuhang Li, Aydogan Ozcan, and Mona Jarrahi, "High-throughput terahertz imaging: progress and challenges." *Light: Science & Applications,* Vol. 12 (No. 1), p. 233, (2023).

5- M. Gezimati and Ghanshyam Singh, "Terahertz cancer imaging and sensing: open research challenges and opportunities." *Optical and Quantum Electronics,* Vol. 55 (No. 8), p. 727, (2023).

6- Y.-Chun Hung, Ta-Hsuan Chao, Pojen Yu, and Shang-Hua Yang, "Terahertz spatio-temporal deep learning computed tomography." *Optics Express,* Vol. 30 (No. 13), pp. 22523-37, (2022).

7- J. Paul Guillet *et al.*, "Review of terahertz tomography techniques." *Journal of Infrared, Millimeter, and Terahertz Waves,* Vol. 35, pp. 382-411, (2014).

8- I. Malhotra and Ghanshyam Singh, "Terahertz Imaging Terahertz Imaging Modalities: State-of-the Art and Open Challenges." in *Terahertz Antenna Technology for Imaging and Sensing Applications*: *Springer*, (2021), pp. 39-73.

9- H. Richter H. W. Hübers, M. Wienold, X. Lü, L. Schrottke, and H. T. Grahn, "Terahertz spectroscopy using quantum-cascade lasers." *Photoniques,* Vol. 101, pp. 27–32, (2020).

10- D. Wang, Ran Ning, Gaochao Li, Jie Zhao, Yunxin Wang, and Lu Rong, "3D image reconstruction of terahertz computed tomography at sparse angles by total variation minimization." *Applied Optics,* Vol. 61 (No. 5), pp. B1-B7, (2022).

11- H. Guerboukha, Kathirvel Nallappan, and Maksim Skorobogatiy, "Toward real-time terahertz imaging." *Advances in Optics and Photonics,* Vol. 10 (No. 4), pp. 843-938, (2018).

12- R.-Cristian Bucur-Portase, "Introduction to the Biological Effects of Terahertz Radiation." *Trends in Terahertz Technology,* (2023).

13- DJ Roth, S Reyes-Rodriguez, DA Zimdars, RW Rauser, and WW Ussery, "Terahertz computed tomography of NASA thermal protection system materials." in *AIP Conference Proceedings*, (2012), Vol. 1430 (No. 1): *American Institute of Physics*, pp. 566-72.

14- Q. Li, Yun-Da Li, Sheng-Hui Ding, and Qi Wang, "Terahertz computed tomography using a continuous-wave gas laser." *Journal of Infrared, Millimeter, and Terahertz Waves,* Vol. 33, pp. 548-58, (2012).

15- V. Anitha, Ankur Beohar, Anveshkumar Nella, "THz imaging technology trends and wide variety of applications: a detailed survey." *Plasmonics,* Vol. 18 (No. 2), pp. 441-83, (2023).

16- K Humphreys *et al.*, "Medical applications of terahertz imaging: a review of current technology and potential applications in biomedical engineering." in *The 26th annual international conference of the IEEE engineering in medicine and biology society*, (2004), Vol. 1: *IEEE*, pp. 1302-05.

17- Y. Singh *et al.*, "Topological data analysis in medical imaging: current state of the art." *Insights into Imaging,* Vol. 14 (No. 1), pp. 1-10, (2023).

18- Y. Zhang *et al.*, "Continuous-wave THz imaging for biomedical samples." *Applied Sciences,* Vol. 11 (No. 1), p. 71, (2020).

19- Ch. Booz, "State-of-the-Art Research: Current Developments in CT Imaging." Vol. 13, ed: *MDPI*, (2023), p. 2305.

20- A. D'Arco, Marta Di Fabrizio, Valerio Dolci, Massimo Petrarca, and Stefano Lupi, "THz pulsed imaging in biomedical applications." *Condensed Matter,* Vol. 5 (No. 2), p. 25, (2020).

21- A. Leitenstorfer *et al.*, "The 2023 terahertz science and technology roadmap." *Journal of Physics D: Applied Physics,* Vol. 56 (No. 22), p. 223001, (2023).

22- J.-Paul Guillet *et al.*, "Low-frequency noise effect on terahertz tomography using thermal detectors." *Applied optics,* Vol. 54 (No. 22), pp. 6758-62, (2015).

23- Bucur-Portase, Robin-Cristian. "Introduction to the biological effects of terahertz radiation." Trends in Terahertz Technology, Book chapter, IntechOpen**.** doi: 10.5772/intechopen.111416, (2023).

24- M. Gezimati and Ghanshyam Singh, "Terahertz cancer imaging and sensing: open research challenges and opportunities." *Optical and Quantum Electronics,* Vol. 55 (No. 8), p. 727, (2023).

25- X. Ruan X. Ruan, Hai Huang, "Application of terahertz spectroscopy in medical microbiological detection." *Journal of Physics ICSCAS,* (2022).

26- T. Punia, "Nanostructures based terahertz emission." *Indian Institute of Technology,* (2022).

27- I. Alekseevna Pilipenko N. Sadykov, Semyon Evgenievich Jolnirov, "Terahertz Radiation Generation Process In The Medium Based On The Array of The Elongated Nanoparticles." *Research square,* (2022).

28- G. Hernandez-Cardoso F. Taleb, Enrique Castro-Camus, Martin Koch, "Transmission, Reflection, and Scattering Characterization of Building Materials for Indoor THz Communications." *IEEE Transactions on Terahertz Science and Technology,* Vol. 13 (No. 5), (2023).

29- P. Fosodeder, Simon Hubmer, Alexander Ploier, Ronny Ramlau, Sandrine van Frank, and Christian Rankl, "Phase-contrast THz-CT for non-destructive testing." *Optics Express,* Vol. 29 (No. 10), pp. 15711-23, (2021).

30- E. R. Brown M. Martin "Photoconductive materials for THz generation at 1550 nm: ErAs: GaAs vs InGaAs based materials." *Proc. SPIE,* Vol. 9362, pp. 16–23, (2015).

31- S. Makhlouf *et al.*, "Terahertz Sources and Receivers: From the Past to the Future." (2023).

32- J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum cascade laser," *Science*, Vol. 264 (No. 5158), pp. 553–556, (1994).

33- H. W. Hübers, R. Eichholz, S. Pavlov, and H. Richter, "High resolution terahertz spectroscopy with quantum cascade lasers," *J. Infrared, Millimeter, Terahertz Waves*, Vol. 34, pp. 325–341, (2013).

34- G. Xu et al., "Efficient power extraction in surface-emitting semiconductor lasers using graded photonic heterostructure." *Nature Commun,* Vol. 3 (No. 1.952), (2012).

35- Y. Li and Kwang-Je Kim, "Nonrelativistic electron bunch train for coherently enhanced terahertz radiation sources." *Applied Physics Letters,* Vol. 92 (No. 1), (2008).

36- Q. Jin, Kaia Williams, Jianming Dai, and X-C Zhang, "Observation of broadband terahertz wave generation from liquid water." *Applied Physics Letters,* Vol. 111 (No. 7), (2017).

37- Kitae Lee M. Kumar, Seong Hee Park, Young Uk Jeong, and Nikolay Vinokurov, "Terahertz radiation generation by nonlinear mixing of two lasers in a plasma with density hill." *Physics of Plasmas* Vol. 24 (No. 033104), (2017).

38- V. Pierro G. Filatrella, N. F. Pedersen, M. P. Sørensen, "Negative Differential Resistance due to Nonlinearities in Single and Stacked Josephson Junctions." *IEEE Transactions on Applied Superconductivity,* Vol. 24 (No. 6), pp. 1-7, (2014).

39- T. Seifert et al., "Efficient metallic spintronic emitters of ultrabroadband terahertz radiation." *Nature Photon,* Vol. 10 (No. 7), pp. 483–88, (2016).

40- O. Moutanabbir N. Brett Carnio, Abdulhakem Y. Elezzabi, "Nonlinear Photonic Waveguides: A Versatile Platform for Terahertz Radiation Generation (a Review)." *Laser Photonics Rev.,* (No. 2200138), (2023).

41- A. d. J. F. Olvera et al., "Frequency selective optoelectronic down conversion of a terahertz pulse using ErAs: In (Al) GaAs photoconductors." *IEEE Access,* Vol. 9, pp. 95391–400, (2021).

42- I. Capan, "4H-SiC Schottky barrier diodes as radiation detectors: A re1view." *Electronics,* Vol. 11 (No. 4), p. Art. no. 532, (2022).

43- M. Jarrahi Y.-J. Lin "Heterodyne terahertz detection through electronic and optoelectronic mixers." *Rep. Prog. Phys.,* Vol. 83 (No. 6), p. Art. no. 066101, (2020).

44- M. Dyakonov and M. Shur, "Shallow water analogy for a ballistic field effect transistor: New mechanism of plasma wave generation by DC current." *Phys. Rev. Lett.,* Vol. 71 (No. 15), p. Art. no. 2465, (1993).

45- M. Dyakonov and M. Shur, "Detection, mixing, and frequency multiplication of terahertz radiation by two-dimensional electronic fluid." *IEEE Trans. Electron Devices,* Vol. 43 (No. 3), pp. 380–87, (1996).

46- A. Lisauskas, "Exploration of Terahertz Imaging with SiliconMOSFETs." *J Infrared Milli Terahz Waves,* Vol. 35, pp. 63–80, (2014).

47- Z. Ya, "Fast and sensitive bolometric terahertz detection at room temperature through thermomechanical transduction." *Journal of Applied Physics,* Vol. 125 (No. 15), (2019).

48- E. F. Nichols H. Rubens "Heat rays of great wave length." *Phys. Rev. (Ser. I),* Vol. 4 (No. 4), p. Art. no. 314, (1897).

49- F. Sizov, "Brief history of THz and IR technologies." *Semicond. Phys., Quantum Electron. Optoelectron,* Vol. 22 (No. 1), pp. 67–79, (2019).

50- T. Nagatsuma, "Terahertz technologies: Present and future." *IEICE Electron. Exp.,* Vol. 8 (No. 14), pp. 1127–42, (2011).

51- Yasushi Koyama *et al.*, "A high-power terahertz source over 10 mW at 0.45 THz using an active antenna array with integrated patch antennas and resonant-tunneling diodes." *IEEE Transactions on Terahertz Science and Technology,* Vol. 12 (No. 5), pp. 510-19, (2022).

52- N. Yang A. Shafie, Chong Han, Josep Miquel Jornet, Markku Juntti, and Thomas Kurner, "Terahertz Communications for 6G and Beyond Wireless Networks: Challenges, Key Advancements, and Opportunities." *IEEE Network,* Vol. 37 (No. 3), pp. 162-69, (2023).

53- Yingxin Wang M. Chen, Xinke Wang, Lianhe Li, " Advances in Terahertz Detection and Imaging." *Frontiers in Physics* (2022).

54- Sina Shahbazmohamadi K. Ahi, Navid Asadizanjani, "Quality control and authentication of packaged integrated circuits using enhanced-spatial-resolution terahertz time-domain spectroscopy and imaging." *Optics and Lasers in Engineering,* pp. 1–11, (2017).

55- K. Humphreys et al., " Medical applications of terahertz imaging: a review of current technology and potential applications in biomedical engineering." *The 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, San Francisco, CA, USA,* pp. 1302-05, (2004).

56- H. Hassan A., "Effects of environmental conditions on the ultrafast carrier dynamics in graphene revealed by terahertz spectroscopy." *Physical Review B,* Vol. 95 (No. 16), p. 165428, (2017).

57- B. Alexei, and Boris Gelmont. "The influence of environment on terahertz spectra of biological molecules." *The Journal of Physical Chemistry B* 114.38, pp. 12349-12357, (2010).

58- C. Olga P., et al. "Cellular effects of terahertz waves." *Journal of Biomedical Optics,* Vo. 26(No, 9), pp. 090902, (2021).

59- M. Gezimati and Ghanshyam Singh, "Advances in terahertz technology for cancer detection applications." *Optical and Quantum Electronics,* Vol. 55 (No. 2), p. 151, (2023).

60- W. Yunxia, "The biological effects of terahertz wave radiation-induced injury on neural stem cells." *Iscience,* Vol. 26 (No. 10), (2023).

61- Q. Guo, Tianying Chang, Guoshuai Geng, Chengyan Jia, and Hong-Liang Cui, "A high precision terahertz wave image reconstruction algorithm." *Sensors,* Vol. 16 (No. 7), p. 1139, (2016).

62- Yi, H., et al, *Full-Wave Simulation and Scattering Modeling for Terahertz Communications.* IEEE Journal of Selected Topics in Signal Processing, 2023.

63- S. Narendar, S.R., and S. Gopalakrishnan, *Study of non-local wave properties of nanotubes with surface effects.* Computational Materials Science, 56, 2012.

64- Hebling, J., et al, *High-power THz generation, THz nonlinear optics, and THz nonlinear spectroscopy.* IEEE Journal of Selected Topics in Quantum Electronics 14.2, 2008.

65- Tuchin, V.V., *Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnostics, Third Edition.* Spie Press Book, 2016.

66- W. Tianyi, e.a., *Virtual unrolling technology based on terahertz computed tomography.* Optics and Lasers in Engineering 151, 2022.

67- C. Si-Chao, e.a., *All-optically driven memory device for terahertz waves.* Optics Letters 45.1, 2020.

68- L. Xueguang, e.a., *Two-channel vo2 memory meta-device for terahertz waves.* Nanomaterials 11.12, 2021.

69- K. Ostmann, T., and Tadao Nagatsuma, *A review on terahertz communications research.* Journal of Infrared, Millimeter, and Terahertz Waves 32, 2011.

70- A. Ian F., J.M.J., and Chong Han, *Terahertz band: Next frontier for wireless communications.* Physical communication 12, 2014.

71- A. Anders H., A. A.C.K., *Simultaneous algebraic reconstruction technique (SART): a superior implementation of the ART algorithm.* Ultrasonic imaging 6.1.

72- J. Ming, A.G.W., *Convergence of the simultaneous algebraic reconstruction technique (SART).* IEEE Transactions on Image Processing 12.8, 2003.

73- J. Yuying, e.a., *Machine learning and application in terahertz technology: A review on achievements and future challenges.* IEEE Access 10, 2022.

74- H. Sara, e.a., *Signal processing and machine learning techniques for terahertz sensing: An overview.* IEEE Signal Processing Magazine 39.5, 2022.

75- K. Soufiene, G.T., and René Beigang, *Advanced GPU-based terahertz approach for in-line multilayer thickness measurements.* IEEE Journal of Selected Topics in Quantum Electronics 23.4 2016.

76- M. Hasantha, e.a., *FPGA-Based FDTD Accelerators for 2DEG Plasma-Wave Device Modeling at THz.* International Applied Computational Electromagnetics Society Symposium (ACES). IEEE, 2019.

77- S. Kono, G., P., Tani, M. et al, *Temperature dependence of terahertz radiation from n-type InSb and n-type InAs surfaces.* Appl Phys B 71, 901–904, 2000.

78- S. C. Howells, S.D.H., L. A., *Schlie Infrared wavelength and temperature dependence of optically induced terahertz radiation from InSb.* Appl. Phys, 1994.

79- M. Slavenko A. Svetlitza, T. Blank, I. Brouk, S. Stolyarova and Y. Nemirovsky, "THz Measurements and Calibration Based on a Blackbody Source." *IEEE Transactions on Terahertz Science and Technology,* Vol. 4 (No. 3), pp. 347-59, (2014).

80- F. Zarrinkhat, B., M. Lamberg, J. Tamminen, A. Nefedova, I. Ala-Laurinaho, J. Khaled, E.E.M. Rius, J.M. Romeu, J. Taylor, Z. *Calibration Alignment Sensitivity in Corneal Terahertz Imaging.* 2022.

81- T. Yuan, H.L., Jingzhou Xu, Fatemeh Al-Douseri, Ying Hu, Xi-Cheng Zhang, *Terahertz time-domain spectroscopy of atmosphere with different humidity.* Proc. SPIE 5070, Terahertz for Military and Security Applications, 2003.

82- F. Taleb, A.-G., M., Al-Dabbagh, M.D. et al, *Propagation of THz radiation in air over a broad range of atmospheric temperature and humidity conditions.* Sci Rep 13, 2023.

83- M. David Slocum, E.J.S., Robert H. Giles, and Thomas M. Goyette, *Atmospheric absorption of terahertz radiation and water vapor continuum effects.* Quantitative Spectroscopy and Radiative Transfer, 2013. 127.

84- D. Moltchanov, P.K., and Yevgeni Koucheryavy, *Analytical approximations for interference and SIR densities in terahertz systems with atmospheric absorption, directional antennas, and blocking.* Physical Communication, 2018. 26.

85- M. David Slocum, T.M.G., Elizabeth J. Slingerland, Robert H. Giles, and William E, *Terahertz atmospheric attenuation and continuum effects.* 2013.

86- P. Hillger, J.G., Ritesh Jain, Ullrich R. Pfeiffer, *Terahertz Imaging and Sensing Applications with Silicon-Based Technologies.* IEEE Transactions on Terahertz Science and Technology, 2019. 9.

87- B. Ewers, A.K., Axel Lange, Manfred P, *Terahertz Spectral Imaging Techniques in NDT: Topography and Computed Tomography.* BAM The Federal Institute for Materials Research and Testing.

88- Y. Deng, R.S., Wenquan Liu, Yuanfu Lu, Guangyuan Li, *High efficiency terahertz single-pixel imaging based on a physics-enhanced network.* Optics Express 2023. 31.

89- Mavis Gezimati and Ghanshyam Singh, "Advances in terahertz technology for cancer detection applications." *Optical and Quantum Electronics,* Vol. 55 (No. 2), p. 151, (2023).

90- Peter Fosodeder, Simon Hubmer, Alexander Ploier, Ronny Ramlau, Sandrine van Frank, and Christian Rankl, "Phase-contrast THz-CT for non-destructive testing." *Optics Express,* Vol. 29 (No. 10), pp. 15711-23, (2021).

91- Hannah Lindley-Hatcher, RI Stantchev, X Chen, Arturo I Hernandez-Serrano, Joseph Hardwicke, and Emma Pickwell-MacPherson, "Real time THz imaging—opportunities and challenges for skin cancer detection." *Applied Physics Letters,* Vol. 118 (No. 23), (2021).