

Development and Optimization of Terahertz Detection Systems

by

Rui Zhou

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Systems Design Engineering

Waterloo, Ontario, Canada, 2025

© Rui Zhou 2025

Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner: Prof. Luca Pierantoni
Dipartimento di Ingegneria dell'Informazione
Università Politecnica delle Marche

Supervisor(s): Prof. John T.W. Yeow
Department of Systems Design Engineering
University of Waterloo

Internal Member: Prof. Ning Jiang
Department of Systems Design Engineering
University of Waterloo

Internal Member: Prof. Shi Cao
Department of Systems Design Engineering
University of Waterloo

Internal-External Member: Prof. Dayan Ban
Department of Electrical and Computer Engineering
University of Waterloo

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This section presents the peer-reviewed research cited in this thesis for which I have made significant contributions.

For the publications where I am the first author, I was fully responsible for all aspects of the work, including experimental design, chip and system design, fabrication, device characterization, measurements, data analysis, and manuscript preparation. These works were carried out under the supervision of Prof. John T.W. Yeow, whose continuous support and expert guidance played a critical role in shaping the scientific direction and ensuring the quality of the outcomes. The co-authors provided essential materials, assisted in manuscript review, and offered valuable feedback throughout the process.

Additionally, I contributed substantially to a comprehensive review paper published during the early phase of my Ph.D. studies under the supervision of Prof. Ning Jiang. In this work, I led the literature review effort by screening over 3,000 studies and conducting detailed analysis of more than 100 relevant publications. I was also responsible for classifying, summarizing, and synthesizing the findings and independently prepared the first full draft of the manuscript.

Research presented in Chapter 2:

N. Li, R. Zhou, B. Krishna, A. Pradhan, H. Lee, J. He, and N. Jiang, “Non-invasive techniques for muscle fatigue monitoring: a comprehensive survey,” *ACM Computing Surveys*, vol. 56, no. 9, pp. 1–40, 2024.

R. Zhou and J. T. Yeow, “Innovations in bolometer technology for enhanced terahertz detection,” *IEEE Nanotechnology Magazine*, 2024.

Research presented in Chapter 3:

R. Zhou, Z. Xie, J. Wang, G. Lu, Y. Yuan, S. Chen, and J. T. Yeow, “Graphene-integrated microbolometer array imaging system: a novel approach for fast and sensitive terahertz detection in biomedical applications,” *ACS Applied material & interfaces*, vol. 17, no. 6, pp. 9103–9114, 2025.

Research presented in Chapter 4:

R. Zhou, J. Wang, Z. Xie, Y. Sun, G. Lu, and J. T. Yeow, “Superior terahertz radiation detection through micro circular log-periodic antenna engineered with an advanced evolutionary neural network algorithm,” *Microsystems & Nanoengineering*, vol. 11, no. 1, p. 160, 2025.

Abstract

[Terahertz \(THz\)](#) technology, occupying the spectral range between microwaves and infrared radiation (0.1–10 THz), has rapidly emerged as a compelling focus of scientific and engineering research. Characterized by its non-ionizing nature, strong penetration through non-metallic materials, and high sensitivity to molecular composition and water content, THz radiation offers significant potential across a broad spectrum of applications.

THz detection systems form the foundational core of THz technology platforms, serving the critical function of converting incident terahertz radiation into quantifiable electrical signals. The effectiveness and applicability of THz technology depend heavily on the performance of these detection systems. However, current THz detection technologies remain limited in several critical aspects, including sensitivity, accuracy, temporal resolution, and scalability. Specifically, weak interaction between THz waves and detectors often restricts signal detection, while environmental noise and material inconsistencies reduce measurement fidelity. Furthermore, the relatively slow response times hinder the real-time capture of dynamic biological and communicational processes. These challenges pose substantial barriers to the development of high-performance THz systems, constraining the practical implementation of THz technology’s immense potential across various fields.

In response to these challenges, this research presents a comprehensive exploration of advanced THz detection strategies, introducing multiple technological innovations aimed at achieving accurate, sensitive, fast, compact, and cost-effective THz detection solutions. Central to this work is the design of a novel graphene-integrated microbolometer, forming the core of a THz [Microbolometer Array Imaging System \(MAIS\)](#). This microbolometer features an optimized structural design and tailored material composition, significantly improving responsivity, detectivity, and response time. This innovative microbolometer

design not only significantly enhances the THz detection performance, but also establishes a solid foundation for advancing THz imaging applications. Complementing detection methodology development, a [Micro Circular Log-Periodic Antenna \(MCLPA\)](#) was designed and optimized using a custom-developed [Evolutionary Neural Network \(ENN\)](#). This algorithm-driven approach enables efficient optimization of the sophisticated antenna design, resulting in a compact structure with broad bandwidth, high gain, and optimal impedance matching. This ENN-driven MCLPA represents a significant breakthrough in THz antenna engineering, introducing a transformative design paradigm that synergistically integrates algorithmic intelligence with structural innovation.

In conclusion, this work significantly contributes to overcoming key limitations in THz detection by integrating advancements in novel device architecture, advanced material engineering, and innovative algorithm-driven design methodology. These innovations collectively enhance sensitivity, accuracy, response speed, system compactness and cost-effectiveness, representing a considerable step forward in the performance of THz detection systems. Beyond technical improvements, the results provide a solid foundation for practical implementation in biomedical and other high-impact applications. Overall, the contributions made herein substantially advance the development of THz technology and offer promising pathways for its transformative application across scientific, industrial and clinical fields.

Acknowledgements

First, I would like to express my sincere gratitude to my supervisor, Prof. John T.W. Yeow, for the invaluable opportunity to join the Advanced Micro-/Nano-Devices Laboratory and to pursue my Ph.D. under his supervision. I am truly thankful for his generous financial support, which allowed me to fully focus on my studies and research. His insightful feedback has consistently helped me improve the quality of my work, and his guidance has been a source of both inspiration and confidence throughout my projects. His trust, patience, and encouragement allow me to explore research directions aligned with my interests, supporting both my academic and personal development. The experience and growth I achieved under his mentorship is the treasure I will always carry with me and be thankful for.

I am also grateful to Prof. Jiang for his insightful mentorship and careful guidance during the early stages of my Ph.D. research, to Prof. Cao for his continuous encouragement in articulating the broader significance of my studies, to Prof. Ban for his valuable advice that helped me critically refine my research direction and for generously providing essential equipment for my experimental work, and to Prof. Pierantoni for graciously traveling from Italy to participate in my defense and for offering insightful feedback.

I would also like to thank my colleagues for the cooperation and shared learning over the years. From late-night debugging sessions to casual conversations that sparked new ideas, their presence made this experience both productive and memorable. I will always remember the challenges we faced together and how their support turned obstacles into progress. I genuinely hope our friendship and collaboration will continue to grow.

Finally, no words suffice to convey my gratitude to my family. Their steady and unconditional support has been the strongest foundation throughout this journey - quiet,

unwavering, and always present. They remained by my side during moments of uncertainty, encouraged my curiosity, and helped illuminate the path forward when I felt lost. Without their presence, patience, and constant support, I could not have walked this far with confidence and resolve.

Table of Contents

Examining Committee	ii
Author’s Declaration	iii
Statement of Contributions	iv
Abstract	vi
Acknowledgements	viii
List of Figures	xiv
List of Tables	xix
List of Abbreviations	xx
1 Introduction	1
1.1 Motivation	1
1.2 Thesis outline	5

2	Background	7
2.1	Terahertz Gap	7
2.2	Terahertz Applications	10
2.2.1	Security screening	10
2.2.2	Material characterization	12
2.2.3	Spectroscopy	12
2.2.4	Biomedical monitoring	13
2.2.5	Non-destructive testing	21
2.2.6	Wireless communication	23
2.3	Terahertz Detectors	26
2.3.1	Electronics-based THz detector	27
2.3.2	Optics-based THz detector	34
3	Graphene-Integrated Microbolometer Design	37
3.1	Aims and Highlights	37
3.2	Methods	41
3.2.1	Structure design	41
3.2.2	Fabrication process	43
3.2.3	Characterization	45
3.2.4	Materials	46
3.3	Results and Discussion	47

3.3.1	Absorption	47
3.3.2	Resistance-temperature relationship	53
3.3.3	Response time	55
3.3.4	Optical measurements	57
3.3.5	Durability	59
3.3.6	Performance comparison	60
3.3.7	Imaging system	61
3.4	Chapter Summary	68
4	Novel Micro Circular Log-Periodic Antenna Design	70
4.1	Aims and Highlights	70
4.2	Methods	73
4.2.1	Fabrication	73
4.2.2	Characterization	74
4.3	Results and Discussion	75
4.3.1	Design of MCLPA	75
4.3.2	Architectural of ENN	79
4.3.3	Performance characteristics	87
4.3.4	Array configuration	97
4.4	Chapter Summary	100

5	Summary and Future Work	103
5.1	Principle Contributions	103
5.2	Future Wrok	106
5.2.1	Integration of the microbolometer and the antenna	106
5.2.2	Development of differential microbolometer system	107
5.2.3	Utilization of Advanced Materials	109
5.2.4	Prospective developments in AI-driven devices design	111
5.2.5	Potential Applications	112
	References	114

List of Figures

2.1	Frequency Spectrum [1].	8
2.2	black-body radiation spectrum [2].	9
2.3	Classification of THz detectors [3, 2, 4, 5, 6, 7, 8, 9, 10, 11].	26
2.4	Structure of traditional (a) Bolometer [12]; (b) Pyroelectric Detector [13]; (c) Thermopile [14], and (d) Golay Cell [15].	28
2.5	Cross section diagrams of (a) CMOS THz Detector [10]; (b) HBT THz Detector [9].	30
2.6	Cross section diagrams of (a) SBD THz Detector [16]; (b) SIS Mixer THz Detector [17]; (c) HEB THz Detector [18].	32
2.7	Schematic diagrams of representative (a) THz antenna [12]; (b) THz optical rectification [8].	34
3.1	Structure of our novel microbolometer. (a) 3-Dimensional schematic dia- gram of the microbolometer design. (b) Cross-section illustration of the microbolometer structure.	42

3.2	Sequential fabrication processes of the graphene-integrated microbolometer.	
	(a-h) Sequential fabrication of the graphene-integrated microbolometer, detailing the cross-sectional development from substrate to final assembly. . .	43
3.3	The Raman spectrum of pure graphene and this device-incorporated graphene.	
		44
3.4	Microstructural characterization of the graphene-integrated microbolometer. (a) Optical imaging of the microbolometer. (b) Scanning electron microscope (SEM) image revealing the precise architecture of the overall microstructure. (c) Side-view SEM image of the microbolometer.	45
3.5	1 - 5 THz radiation absorption spectrum across cavity thicknesses ranging from 10 μm to 50 μm	48
3.6	THz absorption spectra with cavity thicknesses varying from 10 μm to 50 μm in 10 μm intervals across the frequency range of 1 - 5 THz.	49
3.7	Angle-dependent THz absorption spectra of the microbolometer simulated at 20° intervals from 0° to 80°.	50
3.8	THz absorption characteristics of the microbolometer verified through ten validations ($n = 10$), with comparative absorption spectra using graphene, TiO_2 , A-Si, and VO_2 as absorptive layers.	52
3.9	Analysis of resistance and temperature coefficient of resistance in microbolometers in response to variations in blackbody source temperature.	54
3.10	Comparative output voltages of microbolometers with different absorptive materials across varied blackbody source temperatures.	55
3.11	Characterization of microbolometer response dynamics to periodic THz radiation.	56

3.12	Optical characteristics of the microbolometer's (a) Responsivity and (b) Detectivity, with twenty data points collected at each measurement step. .	58
3.13	Long-term stability assessment of microbolometers: Consistent turn-on voltage and response time observed in durability tests conducted over an eight-week period.	60
3.14	Microbolometer array imaging system, detailing the integrated imaging process from THz radiation capture to the final image output.	62
3.15	(a) Schematic diagram of the dual layer Al readout circuit. (b) Visual representation of THz radiation detected by the MAIS. (c) Optimized imaging performance.	64
3.16	(a) Operational block diagram of our MAIS; (b) Demonstration of the MAIS in a practical bio-detection application, capturing the shape and size of foreign objects on the skin surface.	66
3.17	Exhibition of the MAIS's accurate biomedical imaging capability. Six distinct metal letter models on human skin-representative of the University of Waterloo Advanced Micro-Nano Devices Lab (UWAMND) are precisely visualized, showcasing the MAIS's ability to accurately detect and image the anomalies on human skin.	67
4.1	(a) presentative implementation diagram of a log-periodic antenna in practical applications. (b) Schematic diagram of linear log-periodic antenna configuration. (c) Geometric parameters illustration of linear log-periodic antenna.	75

4.2	(a) Total width and total length comparison across linear and circular LPAs with increasing elements. (b) Size variation in LPAs with increasing elements, proving MCLPA's compactness.	77
4.3	(a) Top view layout of circular log-periodic antenna, showing the total length and total width (L_t , W_t), angles(α_1 , α_2) and element lengths (L_1 - L_n). (b) Geometric parameters of circular log-periodic antenna elements, detailing radii (R_1 - R_n) and elements widths (W_1 - W_n).	78
4.4	Flowchart illustrating the ENN algorithm for antenna design: from initialization to optimal geometry selection.	80
4.5	Optimal geometric parameters of the MCLPA.	82
4.6	Comparative analysis of ENN and DNN algorithms. (a) Progression of fitness for ENN and DNN models over training epochs. (b) Comparison of the trends in training and testing losses.	83
4.7	(a) Optical imaging showing the scale representation of our MCLPA. (b) SEM image revealing the precise microstructure of the MCLPA.	84
4.8	Comprehensive statistical analysis of MCLPA performance metrics aggregated from 4,000 evaluated configurations. The plots illustrate the optimization dynamics of geometric parameters across successive generations, demonstrating their impact on key performance indicators including gain, S_{11} , Y-parameter, and VSWR, as well as the resulting composite fitness scores.	86
4.9	(a) Peak gain of our MCLPA in the frequency range 0.1-0.6 THz. (b) S_{11} response across the target THz frequency spectrum.	90

4.10	(a) Y-parameter frequency response over the target THz range. (b) VSWR profile over the target THz frequency range.	91
4.11	Comparative radiation patterns of THz antenna across 0.1 to 0.6 THz: E-plane and H-plane performance analysis.	92
4.12	(a) Block diagram of the testing experimental setup. (b) Experimental Setup for THz Antenna Performance Evaluation: From THz Radiation Source to Read-Out System.	93
4.13	(a) Current-Voltage characteristics of our MCLPA. (b) Voltage response to increasing radiation source temperature.	95
4.14	(a) SNR as a function of radiation source temperature. (b) Incidence radiation angular dependence of output voltage for MCLPA.	96
4.15	(a) Time-domain voltage response under periodic THz radiation exposure. (b) Peak directivity and radiation efficiency of the MCLPA over 0.1-0.6 THz.	97
4.16	(a) Radiation patterns in E-Plane for the 8x8 MCLPA array configuration. (b) S_{11} and Y-parameter spectrum of the 8x8 MCLPA array configuration.	98
5.1	Differential Microbolometer System	108

List of Tables

2.1	Advantages and Limitations of Current Biomedical Detection Technologies	19
2.2	Evolution of Wireless Communication Technologies Towards the Terahertz Band	24
2.3	Key Parameters of Representative THz Communication Technologies . . .	25
2.4	Comparative Analysis of the Advantages and Limitations of Existing THz Detectors	36
3.1	The parameter comparisons between our study and the state-of-the-art devices.	61
4.1	Performance comparison of state-of-the-art THz antennas.	99
5.1	Advantages and Disadvantages of Materials in THz Detection	110

List of Abbreviations

ADC Analogue-to-Digital Converter [63](#), [94](#)

CMOS Complementary Metal Oxide Semiconductor [30](#)

CT Computed Tomography [37](#)

E-beam electron Beam [44](#), [73](#)

EMG Electromyography [16](#), [17](#), [19](#)

ENN Evolutionary Neural Network [vii](#), [4](#), [5](#), [72](#), [105](#)

FET field-effect transistor [60](#)

FP Fabry-Perot [41](#)

HBT Heterojunction Bi-polar Transistor [30](#)

HEB Hot Electron Bolometer [32](#)

HF High Frequency [23](#), [36](#)

IPA Isopropanol [44](#), [73](#)

LNA Low Noise Amplifier [94](#)

LPA Log-Periodic Antenna [75](#)

MAIS Microbolometer Array Imaging System [vi](#), [4](#), [5](#), [40](#)

MCLPA Micro Circular Log-Periodic Antenna [vii](#), [4](#), [5](#), [72](#), [105](#)

MEMS Micro-electromechanical systems [38](#)

MMG Mechanomyography [17](#), [19](#)

MRI Magnetic Resonance Imaging [14](#), [19](#), [20](#), [37](#)

NDT Non-Destructive Testing [21](#), [113](#)

NETD Noise Equivalent Temperature Differences [39](#)

NIRS Near Infrared Spectroscopy [18–20](#)

PECVD Plasma Enhanced Chemical Vapor Deposition [43](#)

PET Positron Emission Tomography [37](#)

PTE photothermoelectric [60](#)

SBD Schottky Barrier Diode [32](#)

SEM Scanning Electron Microscope [45](#), [74](#)

SIS Semiconductor-Insulator-Semiconductor [32](#)

SNR Signal-to-Noise Ratio [72](#), [109](#)

THz Terahertz [vi](#), [1](#), [7](#), [37](#), [70](#), [103](#)

UHF Ultra High Frequency [23](#)

US Ultrasound [15](#), [19](#)

VHF Very High Frequency [23](#)

VSWR Voltage Standing Wave Ratio [81](#), [111](#)

Chapter 1

Introduction

1.1 Motivation

The electromagnetic spectrum has long served as the foundation of modern detection, imaging, and communication systems. Technologies operating in the microwave and infrared regimes, which are adjacent to the THz band, have matured into powerful and widely adopted tools. In contrast, the THz region remains comparatively underexplored and is often described as the “THz technological gap” [19]. In recent years, however, THz technology has attracted increasing academic and industrial interest due to its unique properties and broad application potential, providing a complementary and expandable solution to overcome the limitations of existing approaches. From the spectral perspective, the THz range not only rests on solid theoretical foundations but also offers considerable promise for technological advancement.

The recent developing trend of THz technology is evidenced by increasing market investment and the converging trajectory of operational bands, particularly in biomedical

detection and wireless communication, which together signal an inevitable progression toward the THz regime [20, 21]. This shift has been further accelerated by the growing demand for advanced sensing, imaging, and communication, supported by breakthroughs in device physics, the emergence of novel materials, and advances in fabrication techniques. Within the broader context of Moore’s Law and the continuing trend of device miniaturization, the transition to THz operation represents both a natural and necessary stage in the evolution of modern technologies [22, 23]. With sustained global investment and growing technical maturity, THz technology is poised to become an indispensable enabler of future innovations across various domains.

The THz spectral region exhibits unique physical properties that make it highly appealing for both scientific research and industrial applications. Different from ionizing radiation such as X-rays, THz waves are non-ionizing and thus safer for biological tissues and long-term exposure. Owing to their shorter wavelengths, THz waves offer higher spatial resolution than microwaves while retaining the ability to penetrate a wide range of non-metallic and non-polar materials, including plastics, ceramics, and biological tissues. In addition, many biomolecules exhibit characteristic vibrational and rotational modes within the THz range, enabling label-free chemical and structural identification via THz spectroscopy. Their strong interactions with water molecules and hydrogen bonds result in high sensitivity to variations in hydration levels, protein conformations, and cellular microstructures, all of which are critical for the detection of pathological changes. Furthermore, the ultrafast speed and ultra-broad bandwidth of the THz band hold great potential to overcome the emerging performance challenges of current communication systems and provide a promising pathway toward next-generation communication technologies [24, 25, 1, 26].

Owing to its distinct physical and electromagnetic properties, THz radiation supports

a broad spectrum of high-impact applications across scientific, industrial, and clinical domains. In security screening, its non-ionizing and penetrative nature facilitates the safe detection of concealed objects beneath clothing or within packages. In spectroscopy, THz waves enable label-free molecular identification by probing characteristic vibrational and rotational modes, offering a powerful tool for chemical and material sensing. In addition, THz demonstrate exceptional sensitivity to biomolecules, tissue composition, and microstructural anomalies, positioning them as promising modalities for non-invasive biomedical detection and early disease diagnostics. For non-destructive testing, THz radiation allows internal inspection of non-metallic materials such as polymers, ceramics, and composites without structural damage, which is beneficial in sectors such as aerospace and advanced manufacturing. Additionally, in wireless communication, the high carrier frequency and large bandwidth of the THz band make it a strong candidate for future 6G systems, promising ultra-high-speed data transfer. Together, these diverse applications demonstrate the significant potential of THz technology as a next-generation platform for innovation [27, 28, 29, 30].

In practical applications, the THz detection system serves as the central element of any THz-based setup, converting incident THz radiation into measurable electrical signals. The overall efficiency, accuracy, and reliability of THz imaging or sensing platforms are fundamentally constrained by the detection systems performance. However, existing THz detection systems face several persistent limitations. Sensitivity remains insufficient due to the inherently weak interaction between THz photons and conventional materials, which is an issue further exacerbated in biomedical environments where tissue scattering and ambient noise significantly attenuate the signal. Accuracy is often compromised by thermal drift, electronic noise, and the difficulty of isolating relevant signals in real time. Response speed poses another major challenge, particularly in applications involving dy-

dynamic biological processes that demand high temporal resolution. Furthermore, limited scalability and poor system integration hinder the development of compact, portable, and cost-effective THz detection systems suitable for practical deployments [31, 32, 33].

These limitations present a fundamental barrier to the advancement of THz technology and severely constrain its translational potential in critical application domains. Recognizing this gap, the primary motivation of this research is to develop high-performance THz detection systems that overcome the aforementioned challenges and establish a robust platform for next-generation THz detection systems. Specifically, this research aims to significantly enhance the sensitivity, accuracy, and response speed of THz detection systems through a twofold approach. Two fundamentally distinct yet complementary detection methodologies have been proposed and established in this research. In addition to their individual innovations and advantages, they exhibit strong integration compatibility, enabling synergistic enhancement of detection sensitivity and the realization of high-precision measurements. First, a novel microbolometric THz detector is developed using a graphene-integrated architecture, followed by the design of a **MAIS** built upon this detector to enable advanced THz imaging capabilities. Second, an ultra-broadband **MCLPA** is designed and optimized using a customized **ENN** framework. Together, the proposed subsystems form the foundation of a highly integrated and scalable THz detection platform. Their synergistic design ensures enhanced sensitivity, accuracy, and speed, thereby directly addressing the key limitations currently hindering THz detection systems performance. The broader significance of this work lies not only in the technical advancements it achieves but also in the foundational contributions it makes toward the practical realization of THz technology in biomedical, communication and other high-impact applications.

In conclusion, the motivation for this research is grounded in the urgent need to unlock the full potential of THz technology through the development of high-performance detec-

tion systems. By addressing key technical challenges through structural design, material innovation, and algorithmic development, this thesis advances the field of THz detection and provides valuable insights to guide future research and applications. The contributions presented herein constitute a substantive step toward narrowing the THz technological gap and unlocking the potential of this emerging spectral region.

1.2 Thesis outline

This thesis will be organized in the following paragraphs.

Chapter 2 provides a comprehensive review of the theoretical background, representative applications, and the current landscape of THz detector technologies. This contextual analysis not only establishes a solid foundation for the research presented in this thesis but also underscores the necessity and significance of this research to unlock the scientific and practical impact of THz technology.

Chapter 3 introduces a novel graphene-integrated microbolometer featuring a fundamentally restructured architecture. The innovative configuration enables seamless integration of a graphene absorptive layer, significantly enhancing both the sensitivity and response speed of THz detection. Additionally, a fully integrated THz [MAIS](#) is proposed and evaluated for practical imaging applications.

Chapter 4 presents the design and optimization of a [MCLPA](#) tailored for high-performance THz radiation detection. The sophisticated antenna structure is optimized using a custom-developed [ENN](#), which substantially accelerates the design process while maintaining superior operational bandwidth, gain, and efficiency.

Finally, Chapter 5 summarizes the principle contributions of this work and outlines

several future research directions that are currently under active investigation. Some of these efforts, including ongoing experiments, have already yielded preliminary progress. These directions encompass continued advancements in structural innovation, system integration, application-oriented development, and other related areas, aiming to further push the boundaries of THz detection technologies.

Chapter 2

Background

2.1 Terahertz Gap

THz is one of the fluctuation frequency units, it is typically used to indicate the frequency which is 10^{12} Hz. The THz gap denotes a frequency range within the electromagnetic spectrum, typically between 0.1 and 10 THz, lying between microwaves and infrared frequencies, as illustrated in Figure 2.1 [3, 34]. This range, also known as the sub-millimeter wave or far-infrared region, is characterized by unique physical properties, positioning THz radiation research as a transition area from macroscopic classical theory to microscopic quantum theory [35, 36].

The gap not only reflects the fact that THz is a range of spectrum that physically exist, but also emphasizes the difficulties in efficiently generating, detecting, and manipulating THz radiation using traditional electronic and photonic technologies for various applications, such as imaging, communication, and sensing. As a result, the THz range has been relatively underexplored and underutilized compared to neighboring regions of the electro-

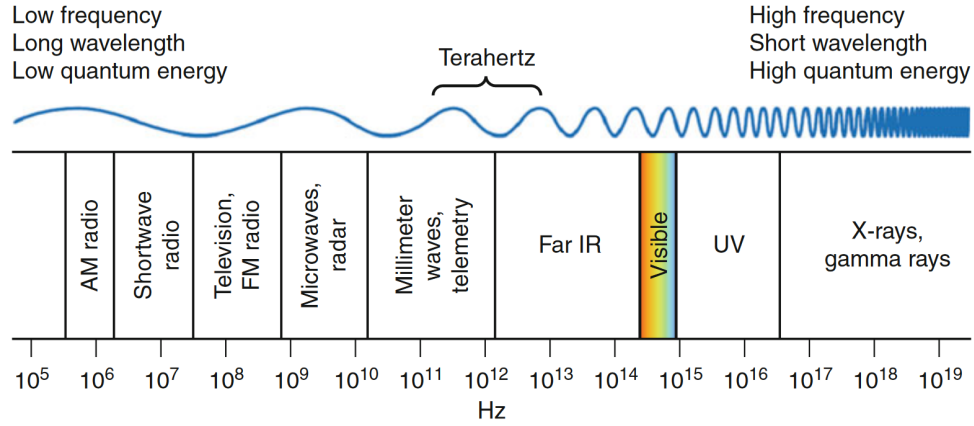


Figure 2.1: Frequency Spectrum [1].

magnetic spectrum, highlighting both its physical significance and the challenges faced in its study.

The THz gap exists primarily due to technological limitations in both electronic and photonic devices, as the frequency range falls between the traditional domains of electronic and optical devices. In electronics, conventional semiconductor technologies, such as Transistor and Diode, become less effective at generating and detecting signals at THz frequencies, as the devices' performance tends to degrade due to the scaling of their physical dimensions and increasing parasitic effects [37, 3]. On the other hand, in photonics, THz frequencies are difficult to manipulate using standard optical components such as lenses and mirrors, as the wavelength of THz radiation is significantly longer than that of visible and near-infrared light. Additionally, THz radiation is strongly absorbed by water vapor in the atmosphere, which poses challenges for the development of long-range communication and sensing systems operating in this frequency range [38, 15, 39, 40].

The electromagnetic waves with frequencies within the THz range is typically regarded as THz radiation. As a component of black-body radiation, THz radiation is emitted by

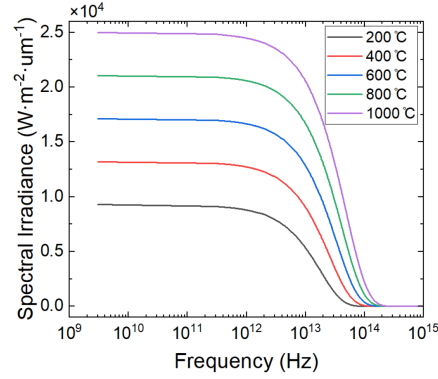


Figure 2.2: black-body radiation spectrum [2].

any object with a temperature above absolute zero. This emission occurs as a result of the conversion of a body's internal energy into electromagnetic energy, serving as a natural mechanism for radiative entropy dispersion [2]. The black-body radiation spectrum, including THz radiation, is illustrated in Figure 2.2. THz radiation exhibits a multitude of distinctive properties, rendering it highly attractive for numerous applications across diverse fields. Its ability to penetrate various non-conductive materials, such as plastics, ceramics, and foams, while being absorbed by metals and water, renders it suitable for non-destructive testing, imaging, and security screening applications. As a non-ionizing form of radiation, THz radiation is safer for human exposure compared to ionizing radiation sources such as X-rays or gamma rays, making it suitable for biomedical applications [3]. Additionally, many molecules display unique and characteristic absorption or emission spectra within the THz frequency range, facilitating material identification, chemical analysis, and quality control. The short wavelength of THz radiation enables high-resolution imaging capabilities, which can be harnessed in applications such as concealed object detection, art restoration, and biomedical imaging. Moreover, its large bandwidth and high-frequency properties hold the potential to facilitate ultra-high-speed wireless communication systems,

paving the way for the development of advanced communication networks [41, 42, 43]. Owing to the unique properties of THz radiation, it holds considerable promise for numerous applications across various domains.

Although addressing the challenges associated with the THz gap remains a challenging task, the distinct attributes of THz radiation persistently garner research interest in this field. In recent years, there have been significant advancements in the development of THz detection systems driven by new materials, detectors, and techniques. Continued research and development in this field are expected to further bridge the THz gap and unlock the potential of this frequency range for various applications [42, 43, 40].

2.2 Terahertz Applications

Owing to the distinct electromagnetic properties such as non-ionizing radiation, high sensitivity to molecular signatures, and the ability to penetrate non-metallic materials, THz radiation enables a wide range of applications across multiple scientific and engineering domains. The following sections provide a detailed overview of representative THz applications, demonstrating their underlying principles, technological implementations, and practical significance.

2.2.1 Security screening

THz technology presents a compelling solution for modern security screening due to its unique combination of physical properties, including high spatial resolution, non-ionizing radiation, and strong material penetration capabilities. THz waves are biologically safe and non-destructive, making them suitable for repeated use in high-traffic environments

such as airports, government buildings, and public transportation hubs. Operating in the high frequency range, THz radiation penetrates common concealment materials such as clothing, plastics, and paper, allowing for the non-contact detection of concealed objects without compromising personal privacy. Furthermore, THz waves provide higher spatial resolution than microwaves, enabling the visualization of fine structural details that are critical for distinguishing concealed items.

In addition to imaging, THz spectroscopy exploits the frequency-selective absorption characteristics of many chemical substances, including explosives, narcotics, and chemical agents. These materials exhibit distinct spectral signatures in the THz range due to their molecular vibrational and rotational modes, allowing for label-free, material-specific identification. THz systems can operate in both active and passive modes, providing adaptability to diverse deployment contexts. Recent advancements in source generation, detector sensitivity, and real-time image reconstruction have significantly improved system performance, while integration with machine learning algorithms enhances automated threat recognition and reduces reliance on manual interpretation.

Collectively, the ability to combine material discrimination, high-resolution imaging, and safe operation positions THz technology as a transformative tool for next-generation security infrastructure. As further progress is made in system miniaturization, cost reduction, and environmental robustness, THz-based security screening is expected to play an increasingly central role in ensuring public safety through accurate, efficient, and non-invasive threat detection.

2.2.2 Material characterization

Owing to the distinctive spectral range (0.1–10 THz) of THz radiation, it can penetrate a wide variety of non-metallic and non-polar materials while providing rich spectroscopic information associated with molecular vibrations, phonon modes, and intermolecular interactions. These characteristics make THz systems particularly suitable for identifying material composition, detecting structural defects, and monitoring phase transitions with high spatial and spectral resolution. Moreover, the non-ionizing nature of THz waves ensures that the characterization process remains safe, preserving the physical and chemical integrity of the sample. Recent advances in THz generation and detection, along with the integration of time-domain and frequency-domain spectroscopy, have significantly expanded the applicability of THz techniques across diverse fields such as polymer inspection, semiconductor analysis, pharmaceutical quality control, and composite material evaluation. As a result, THz-based material characterization is increasingly recognized as a crucial methodology in both industrial quality assurance and fundamental materials research [44, 45].

2.2.3 Spectroscopy

The study of the interaction of matter with electromagnetic waves as a function of frequency or wavelength, often based on the emission or absorption characteristics of the matter, is known as spectroscopy [46]. A helpful approach for obtaining this information from a specific material is spectroscopy. A substance’s reaction to electromagnetic waves reveals a wealth of physical and chemical information about the material.

THz technology has been proved to have great potential in spectroscopy from many aspects, which involves the measurement of the interaction of THz radiation with matter.

Spectroscopy is used to identify and analyze the chemical and physical properties of materials by studying their spectral response to electromagnetic radiation. THz spectroscopy provides a unique opportunity to study the spectral region between microwave and infrared wavelengths, which can provide valuable information about the molecular structure, composition, and dynamics of materials[35].

2.2.4 Biomedical monitoring

Biomedical imaging plays a vital role in modern healthcare by enabling non-invasive visualization of internal organs and structures, facilitating accurate diagnosis and effective treatment planning. While existing modalities have significantly advanced medical diagnostics, they still face limitations including exposure to ionizing radiation, low sensitivity to certain tissue types, and challenges in achieving high-contrast imaging. Consequently, there is a growing demand for alternative technologies that are both safe and capable of providing enhanced sensitivity and resolution.

Recent advancements in sensor architecture, signal processing algorithms, and data analytics have significantly improved the precision, efficiency, and adaptability of non-invasive biomedical diagnostics. These innovations have enabled real-time monitoring of vital physiological signals, metabolic fluctuations, neural activity, and tissue-specific properties. A diverse array of non-invasive modalities including bioelectrical signal acquisition, optical spectroscopy, ultrasound imaging, and magnetic resonance techniques has been extensively developed and clinically implemented to support accurate disease detection and health monitoring. While these established technologies have each demonstrated distinct advantages, they also present inherent limitations in terms of spatial resolution, penetration depth, signal specificity, or cost-effectiveness. As biomedical diagnostics continue to

shift toward more personalized, efficient, and minimally invasive solutions, it is essential to evaluate the strengths and constraints of these existing methods.

In the following sections, we provide a comparative overview of several widely used bio-detection modalities with THz technology, briefly describe their operational principles, diagnostic capabilities, and application boundaries [47, 48].

X-ray imaging is one of the most widely used non-invasive diagnostic techniques, offering detailed visualization of internal anatomical structures based on the differential absorption of ionizing radiation by biological tissues. Operating in the energy range of 10–300 keV, X-rays penetrate soft tissue and are absorbed to varying degrees depending on tissue density and atomic number. Dense structures such as bone absorb more radiation and appear bright on radiographs, whereas softer tissues display lower contrast in varying shades of gray. This imaging principle is primarily governed by the photoelectric effect and Compton scattering. Although X-ray imaging is not typically used for real-time functional monitoring, it can indirectly assess physiological changes. For example, CT imaging can quantify muscle atrophy, fat infiltration, or volumetric changes in response to disease or fatigue. Emerging technologies like dynamic digital radiography further extend its capability to capture joint movement, respiratory mechanics, and cardiac function, bridging the gap between structural and functional imaging [49]. Despite its strengths including rapid acquisition, high spatial resolution, and compatibility with automated analysis, X-ray imaging still has limitations. These include exposure to ionizing radiation, particularly concerning in pediatric or frequent-use cases, and relatively poor soft tissue contrast compared to modalities like MRI or ultrasound. Nonetheless, due to its diagnostic reliability and broad clinical adoption, X-ray imaging remains a foundational tool for structural assessment, injury evaluation, and large-scale screening in modern healthcare [50, 51].

Magnetic Resonance Imaging (MRI) is a highly versatile modality that leverages

the nuclear magnetic resonance properties of hydrogen protons in biological tissues to produce high-resolution images. Typically operating at magnetic field strengths of 1.5–7 Tesla, MRI aligns hydrogen nuclei in water and fat molecules using a strong magnetic field. When exposed to radiofrequency pulses, these protons are temporarily displaced; their subsequent relaxation emits signals characterized by T1 (longitudinal) and T2 (transverse) relaxation times. Variations in these relaxation properties across tissue types enable MRI’s exceptional soft tissue contrast [52].

MRI is particularly effective for imaging the brain, spinal cord, musculoskeletal structures, and internal organs. A variety of pulse sequences (e.g., T1-weighted, T2-weighted) allows tailored visualization of specific tissue characteristics. Clinically, MRI is extensively used to evaluate neurological disorders, tumors, cardiovascular anomalies, and musculoskeletal injuries. In neuromuscular diagnostics, MRI facilitates the assessment of muscle volume, fatty infiltration, edema, and fiber orientation, enabling early detection of pathological changes associated with fatigue, denervation, or disease progression. Compared to other modalities introduced this section, MRI offers comprehensive anatomical and functional data without depth limitations or operator dependence. Quantitative approaches, including T2 mapping, fat fraction analysis, and MR elastography, further enhance diagnostic precision by detecting subtle biochemical and mechanical changes prior to the onset of clinical symptoms. Despite its strengths, MRI has notable limitations: it is costly, time-intensive, and prone to motion artifacts. Contraindications also exist for patients with metallic implants or severe claustrophobia. Nevertheless, MRI remains a cornerstone of modern biomedical imaging due to its superior soft tissue contrast and multiparametric capabilities, making it indispensable for advanced diagnostics and longitudinal patient monitoring [53, 54].

Ultrasound (US) is another advanced biomedical imaging modality that employs

high-frequency mechanical sound waves (typically 2–10 MHz) to assess internal tissue structure and properties. These waves, generated by piezoelectric transducers, travel through biological tissues and undergo reflection, scattering, or absorption based on acoustic impedance differences. The returning echoes are processed to reconstruct images and evaluate tissue morphology, elasticity, and dynamic behavior [55]. US provides real-time visualization of anatomical and functional changes in soft tissues, including muscles, tendons, and connective structures. Various imaging modes such as A-mode (amplitude), B-mode (brightness), and E-mode (elastography) support detailed assessment of tissue depth, thickness, cross-sectional area, fiber orientation, and stiffness. These parameters are particularly valuable for detecting neuromuscular activity, contractile function, and fatigue-related changes. A-mode offers compact, high-temporal-resolution monitoring ideal for wearable or portable applications; B-mode delivers two-dimensional structural imaging; and E-mode (including strain and shear-wave elastography) quantifies tissue stiffness, serving as a proxy for muscle contractile state and fatigue. Despite its strengths including high temporal-spatial resolution, real-time feedback, and accessibility, US is limited by a restricted field-of-view, depth-dependent signal degradation, and operator-dependent variability [56, 57].

Electromyography (EMG) is an emerging non-invasive electrophysiological technique used to assess neuromuscular activity by detecting electrical signals generated during muscle contractions. These signals arise from the summation of action potentials within motor units, comprising a motor neuron and its innervated muscle fibers, and are captured via electrodes placed either on the skin (surface EMG) or within the muscle (intramuscular EMG) [58]. Surface EMG, particularly in high-density configurations, has gained traction for its ability to non-invasively monitor spatially distributed muscle activation with minimal discomfort, making it well-suited for wearable applications and continuous mon-

itoring. EMG provides detailed physiological insights into motor unit recruitment, firing patterns, and neuromuscular integrity. Signal preprocessing such as filtering, rectification, and normalization is essential to reduce noise, motion artifacts, and powerline interference, ensuring reliable interpretation [59]. Clinically, EMG is widely applied in diagnosing neuromuscular disorders, monitoring rehabilitation progress, and enabling biofeedback in prosthetic and human-machine interface systems. It is particularly effective in assessing muscle fatigue, motor coordination, and functional recovery. However, EMG faces challenges in dynamic or ambulatory contexts due to signal variability, motion artifacts, and cross-talk from adjacent muscles. Additionally, accurate interpretation requires standardized protocols and skilled analysis. Despite these limitations, EMG remains a powerful tool for real-time, quantitative assessment of neuromuscular function in both clinical and research settings [60, 61].

Mechanomyography (MMG) offers a mechanically based alternative to conventional neuromuscular assessment by capturing surface vibrations generated during muscle contractions. These micro-vibrations, caused by intramuscular pressure fluctuations and motor unit activity, provide direct insights into muscle fiber displacement, contraction dynamics, and oscillatory behavior. MMG signals are acquired using a variety of sensors including accelerometers, piezoelectric transducers, microphones, and laser displacement devices, each capable of detecting subtle biomechanical responses [62]. Unlike EMG, which records electrical activity, MMG reflects the physical manifestation of muscle contractions. Its signal characteristics, including amplitude and frequency, correlate with motor unit firing patterns and the mechanical state of the muscle, making it useful for evaluating activation timing, recruitment strategies, and fatigue. MMG is less susceptible to issues like skin impedance or precise electrode placement, requires minimal setup, and demonstrates robustness in dynamic or ambulatory conditions, making it well-suited for wearable

applications and long-term monitoring [63]. This modality has been employed in various biomedical scenarios, including rehabilitation, prosthetic control, and real-time analysis of electromechanical delay. While challenges remain in optimizing sensor design, improving signal fidelity, and ensuring consistent performance across different muscle groups, MMG's capacity to non-invasively decode neuromuscular mechanics highlights its potential as a valuable complement to traditional electrophysiological methods in modern biomedical diagnostics [64].

Near Infrared Spectroscopy (NIRS) is an optical technique that provides real-time monitoring of tissue oxygenation and hemodynamic responses by measuring the differential absorption of near-infrared light by chromophores such as hemoglobin and myoglobin. Grounded in the Beer-Lambert Law, NIRS estimates concentrations of oxygenated and deoxygenated forms, offering insight into local vascular supply, oxygen consumption, and metabolic activity. NIRS is particularly effective for assessing muscle oxygen saturation, blood volume, and perfusion under various physiological conditions, including isometric, dynamic, and electrically evoked muscle contractions. Its high sensitivity to fluctuations in oxygen delivery and utilization enables evaluation of neuromuscular function, fatigue, and vascular responses. Recent advancements in frequency- and time-domain NIRS have enhanced its precision by enabling absolute quantification of chromophore concentrations and tissue scattering properties[65, 66]. Clinically and in research, NIRS has been employed to monitor muscle health, tailor rehabilitation protocols, and guide interventions such as electrical stimulation through real-time oxygenation feedback. Its key advantages include continuous data acquisition, portability, and compatibility with motion, making it well-suited for dynamic assessments. However, limitations include susceptibility to motion artifacts, signal degradation in individuals with high adiposity or darker skin tones, and variability due to tissue heterogeneity [67].

Table 2.1: Advantages and Limitations of Current Biomedical Detection Technologies

Technology	Advantages	Limitations
X-Ray	Fast and widely available Relatively inexpensive Effective for imaging bones	Uses ionizing radiation Limited soft tissue contrast
MRI	Non-invasive High spatial resolution Multi-planar imaging	Expensive and Time-consuming Patient discomfort
US	Non-invasive and radiation-free Real-time imaging Portable and relatively inexpensive Useful for various applications	Limited penetration depth Operator-dependent image quality Less detailed
EMG	Non-invasive or minimally invasive Real-time evaluation	Limited to electrical activity Uncomfortable to wear
MMG	Non-invasive and radiation-free Directly measure mechanical activity Less affected by skin impedance	Sensitive to motion artifacts Lower signal amplitude and SNR Limited spatial resolution
NIRS	Non-invasive and radiation-free Functional information available Inexpensive	Limited penetration depth Lower spatial resolution Susceptible to scattering
THz	Non-invasive and radiation-free Sensitive to hydration levels label-free molecular detection	Limited penetration depth Underdeveloped detection systems

As summarized in Table 2.1, a comparative overview of the strengths and limitations of current biomedical imaging technologies highlights the unique value proposition of THz systems. Despite the significant advancements in biomedical detection technologies, each modality remains constrained by inherent limitations. Structural imaging techniques such as X-ray and MRI provide high-resolution anatomical insights but suffer from drawbacks including ionizing radiation exposure, high cost, and limited portability. Functional approaches like EMG and MMG enable real-time monitoring of neuromuscular activities but are hindered by low spatial resolution, susceptibility to motion artifacts, and a lack of morphological or biochemical information. Similarly, optical methods such as NIRS offer dynamic assessment of tissue oxygenation but face challenges including shallow penetration depth, scattering, and limited specificity in heterogeneous tissues. Collectively, these limitations underscore the pressing need for a new modality that combines structural, functional, and biochemical sensitivity while remaining safe, label-free, and non-invasive.

THz technology has emerged as a promising candidate in this context due to its non-ionizing nature, low photon energy, and strong sensitivity to water content. THz waves can penetrate various non-metallic materials and biological tissues while avoiding the harmful effects associated with ionizing radiation. This makes THz imaging particularly suitable for biomedical applications requiring high safety standards and tissue selectivity. One of the key advantages of THz radiation lies in its ability to distinguish healthy and diseased tissue based on water content, which is a property that has been leveraged for detecting skin cancers, breast tumors, and protein anomalies in tissue samples [28].

Several representative biomedical applications highlight the unique strengths of THz imaging. First, fine-grained diagnosis of soft tissue abnormalities like brain diseases or cancers is possible through the high-resolution contrast in THz transmission and reflection between lesioned and healthy tissue. Second, detection of hard tissues like teeth and bones

is achievable due to the relatively low water content in these structures, enabling early detection of conditions such as dental caries and bone fractures. Third, direct imaging of soft tissues like corneal can be performed without extensive sample preparation, owing to the linear relationship between THz reflectance and tissue water content. Lastly, the integration of THz detectors with flexible substrates supports the development of wearable real-time diagnostic systems, allowing for continuous monitoring with minimal user burden. The passive design and compact footprint of advanced THz sensors further enhance their viability for portable, energy-efficient biomedical devices [41, 68].

Collectively, these capabilities position THz technology as a next-generation biomedical detection platform that effectively overcomes key limitations of conventional imaging techniques, while also opening new frontiers in non-invasive, real-time, and high-precision diagnostics. Building on the emergence of THz technology as a powerful tool for non-invasive biomedical detection, it is important to situate it within the broader context of existing diagnostic modalities. Non-invasive techniques have revolutionized biomedical detection by enabling the monitoring of physiological and pathological states without breaching the skin or disturbing internal tissues. These approaches offer significant advantages in both clinical and wearable healthcare settings by reducing patient discomfort, minimizing infection risks, and supporting continuous or remote monitoring [69, 70, 71].

2.2.5 Non-destructive testing

THz technology has attracted significant attention in the field of [Non-Destructive Testing \(NDT\)](#) due to its ability to examine internal structures and material composition without requiring physical contact or causing damage. THz radiation corresponds to photon energies in the millielectronvolt range, which align with vibrational and rotational modes

in molecular and crystalline lattices. This spectral compatibility enables the detection of subtle internal features such as delamination, microcracks, voids, and inhomogeneities in a wide range of materials, including polymers, ceramics, composites, and coatings.

A key advantage of THz-based NDT lies in its ability to generate material-specific spectral fingerprints through absorption or transmission analysis. These signatures facilitate the identification and differentiation of chemical and structural compositions, which is crucial for quality control and defect detection. Furthermore, THz radiation can penetrate various non-metallic and non-polar materials, including plastics, foams, and fabrics. Compared to microwave-based methods, THz waves provide higher spatial resolution due to their shorter wavelengths, enhancing the precision of subsurface imaging.

THz time-domain spectroscopy further expands diagnostic capabilities by enabling simultaneous measurement of both amplitude and phase. This allows for the extraction of intrinsic material parameters such as refractive index, dielectric permittivity, and electrical conductivity, all of which are vital for assessing structural integrity and functionality. The non-ionizing nature of THz radiation also ensures safety for both users and fragile samples.

Despite limitations such as signal attenuation in water-rich environments and sensitivity to ambient noise, recent advancements in THz sources, detector sensitivity, and integrated system design are driving the development of compact, portable, and high-performance NDT platforms. Overall, THz technology offers a powerful, label-free, and real-time diagnostic solution, with broad applicability across industries such as aerospace, electronics, automotive manufacturing, and cultural heritage preservation.

2.2.6 Wireless communication

The evolution of wireless communication technologies has been characterised by a continuous expansion in frequency utilisation and application complexity, progressing from early analogue systems to anticipated terahertz-based communication paradigms as demonstrated in Table 2.2. Beginning with early radio communication in the kilohertz range for maritime and broadcast applications, the introduction of [Very High Frequency \(VHF\)](#) and [Ultra High Frequency \(UHF\)](#) bands in the mid-20th century facilitated FM radio, radar, and television services. The commercial deployment of first-generation (1G) mobile networks in the late 1970s marked the onset of mobile voice communication, followed by second-generation (2G) systems which introduced digital voice and text messaging. Subsequent generations from 3G, 4G, to 5G brought transformative capabilities, including mobile internet, high-definition media streaming, and ultra-reliable low-latency communication, by expanding frequency usage into the gigahertz and millimetre-wave domains. The current trajectory, represented by the anticipated sixth-generation (6G) systems, envisions operation in the sub-terahertz range (0.1–1 THz), enabling ultra-high data rates, holographic communication, and pervasive connectivity. This trend illustrates a clear shift towards higher frequencies to meet the escalating demand for bandwidth, latency reduction, and novel applications, positioning the THz band as the next frontier in wireless communication [72, 73, 74, 75, 76, 77, 78].

Many recent studies have forecasted that future 6G communication systems will operate predominantly within the THz frequency band, underscoring the immense potential of THz technology for next-generation wireless networks. The exceptionally broad spectral window and ultra-high frequency ([High Frequency \(HF\)](#)) characteristics of the THz band facilitate substantially larger bandwidth allocations, thereby supporting the trans-

Table 2.2: Evolution of Wireless Communication Technologies Towards the Terahertz Band

Generation	Frequency Range	Inception Time	Development Era	Characteristics	Ref
Early Radio	kHz-30 MHz	1900	1900s–1950s	Broadcasting, maritime communication	[72]
VHF	30-300 MHz	1930s	1930s–1960s	FM broadcasting, aeronautical communication	[73]
UHF	0.3-1 GHz	1940s	1940s–1980s	Television broadcasting, radar, GSM	[74]
1G	800-900 MHz	1979	1980s–1990s	Analogue voice	[79]
2G	0.9-1.8 GHz	1991	1990s–2000s	Digital voice, SMS	[75]
3G	1.8-2.5 GHz	2001	2000s–2010s	Mobile data, video calling	[76]
4G	2-6 GHz	2009	2010s–2020s	HD video, mobile broadband	[80]
5G	6-40 GHz	2019	2020s	High bandwidth, low latency, mMTC	[77]
6G	0.01-1 THz	2030	2030s	Tbps data rates, holographic communication	[78]

mission of significantly greater data volumes per unit time and enabling ultra-fast network throughput. Consequently, in terms of carrier frequency and data rates, 6G is anticipated to outperform 5G by nearly an order of magnitude [81, 82].

From this perspective, the THz band emerges as a particularly promising and strategic candidate, not only surpassing the capabilities of the upcoming millimetre-wave (mmWave) spectrum but also vastly exceeding the performance limits of the current dominant 1–2 GHz frequency range. In light of its technical merits, numerous countries and research institutions have initiated large-scale investments in THz wireless communication technologies. A selection of representative advancements and their associated performance metrics is summarised in Table 2.3 [83, 26].

Table 2.3: Key Parameters of Representative THz Communication Technologies

Institutions	Frequency (THz)	Symbol Time Delay (ps)	Communication Rate (Gbps)	Technology
IAF Germany	0.22	-	0.01	TMIC
IEMN France	0.2	-	1	PD
NTT, Italy	2.5	3	10^{-3}	THz QCL/HEB
Bell, USA	0.625	10	2.5	Multiplier/SBD
	0.1-0.25	1	10^{-3}	THz TDS
IoP, China	0.14	500	10	SHM
	0.14	$2.1 * 10^4$	5	
	0.34	50	3	
NTT, Japan	0.125	800	10	UTC-PD/MMIC
	0.125	$5.8 * 10^3$	10	MMIC/MMIC
	0.2	-	60	-
	0.34	500	24	UTC-PD/SBD

2.3 Terahertz Detectors

In the preceding section, the extensive array of applications for THz technology was discussed, validating the critical role high-performance THz detectors play in realizing these applications. As essential components of THz technology, THz detectors are responsible for converting THz radiation into measurable signals [84].

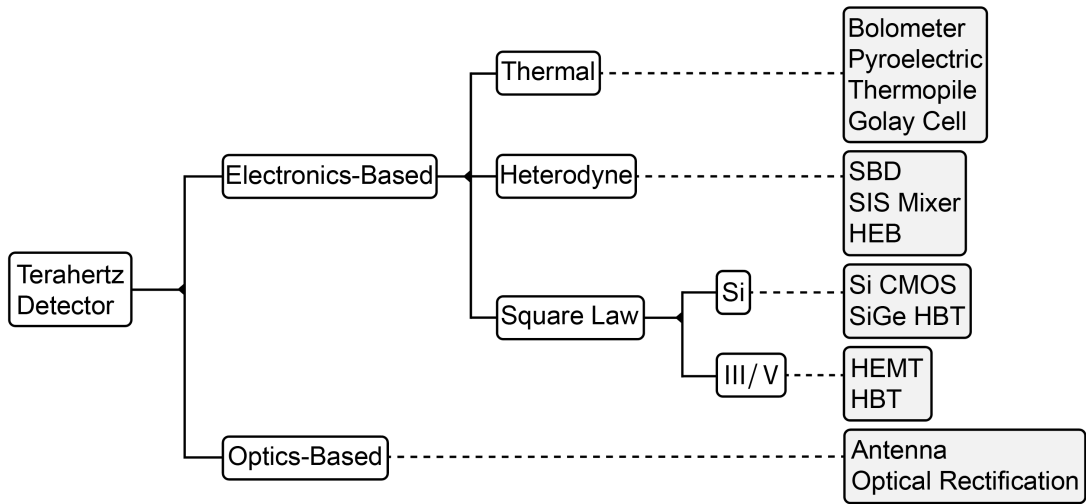


Figure 2.3: Classification of THz detectors [3, 2, 4, 5, 6, 7, 8, 9, 10, 11].

The THz region of the electromagnetic spectrum had remained predominantly unexplored for a considerable duration, mainly due to the scarcity of high-performance detectors. Existing THz detectors exhibit limitations in sensitivity, response time, and detection range. To overcome these limitations and facilitate novel THz applications, the development of advanced THz detectors is imperative. For instance, sophisticated THz detectors can yield higher resolution images with enhanced contrast, facilitating early disease detection and more accurate diagnoses in biomedical imaging. In communication, such detectors can support faster data transfer rates, leading to more efficient communication networks.

In material characterization, advanced THz detectors can enable more accurate measurements of material properties, resulting in superior quality control and improved materials design. Furthermore, cutting-edge THz detectors can foster the emergence of innovative THz applications, including THz sensing and imaging of biomolecules, THz spectroscopy for material analysis, and THz sensing for security and environmental monitoring [85]. Consequently, advancing THz detector technology is crucial for the continued progress of THz technology.

In the exploration of THz technology, a variety of detectors originally adapted from neighboring spectral bands have been further expanded and developed for THz applications. This chapter presents a comprehensive investigation of existing THz detectors and provides an overview of these established designs, as illustrated in the accompanying Figure 2.3 [3, 2, 4, 5, 6, 7, 8, 9, 10, 11].

2.3.1 Electronics-based THz detector

- **Thermal Detector**

Thermal THz detectors are a class of devices that detect and measure THz radiation by converting the absorbed THz energy into heat, resulting in a temperature change or a voltage signal. These detectors are characterized by their broad spectral range, simplicity, and ease of integration with various readout systems. When employing thermal detectors, the temperature rise resulting from the absorption of THz waves is leveraged for evaluating the magnitude of incident power.

There are four typical thermal-based THz detectors: **Bolometer** is a commonly utilized detector for THz radiation detection [12, 86]. By converting the temperature increase

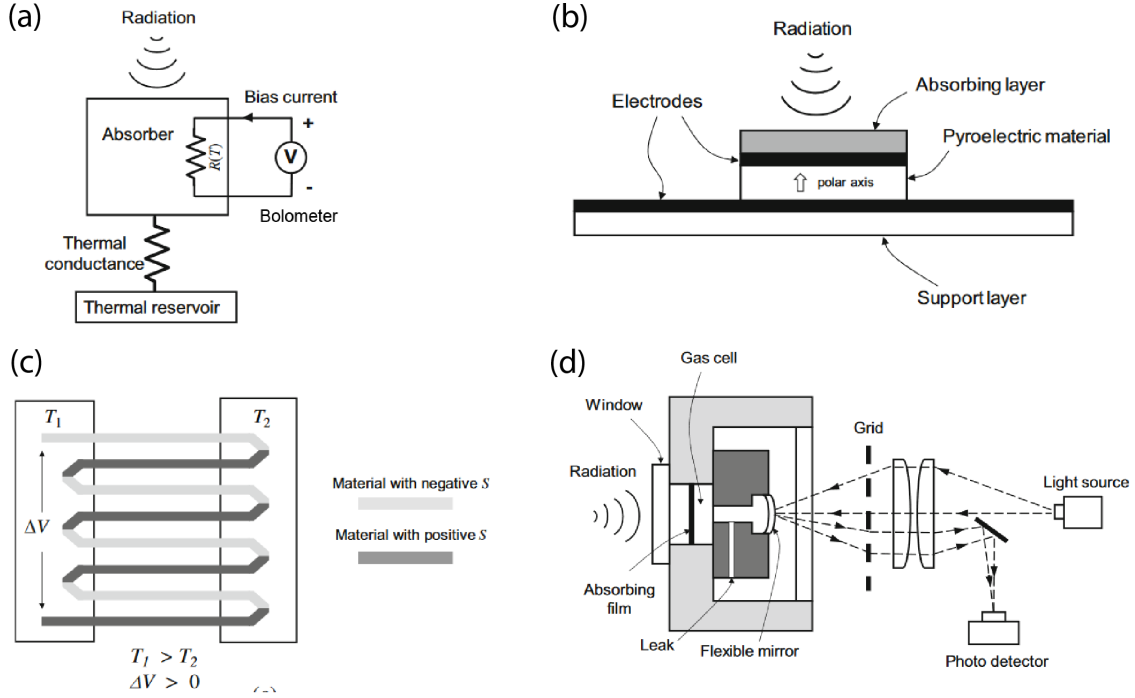


Figure 2.4: Structure of traditional (a) Bolometer [12]; (b) Pyroelectric Detector [13]; (c) Thermopile [14], and (d) Golay Cell [15].

into a change in the constituent material's resistance, bolometers may measure electrical quantities like current or voltage. In **pyroelectric detectors**, the temperature change brought on by light results in a change in the polarisation property of the pyroelectric materials, which may then be translated into a change in voltage across a slab of these materials and detected [87, 13]. By shining THz waves on one side of a material, **Thermopile** creates a temperature differential that is then translated by the Seebeck effect into a voltage difference [14, 88]. Another well-known THz detector is the **Golay cell**, which inflates as the temperature of the gas within rises in response to THz wave irradiation, changing the route of light reflection off the cell surface owing to the surface's distorted state [15]. Although the specifics vary depending on the device type, these heat detectors

may be conceptualised as electrical approach detectors. The structure schematics of all the thermal detectors are presented in Figure 2.4.

Thermal THz detectors present several advantages. These detectors are characterized by their broad spectral response, which enables the detection of a wide range of THz frequencies. Additionally, they exhibit a linear response to incident THz radiation, allowing for accurate measurements of signal intensities. Furthermore, thermal THz detectors are less susceptible to interference from ambient radiation, making them a great fit for operation in diverse environments.

However, thermal THz detectors also have some drawbacks. The most significant limitation is their relatively slow response time compared to other types of THz detectors, which restricts their utility in high-speed applications. Secondly, these detectors often suffer from lower sensitivity, particularly at higher frequencies, limiting their ability to detect weak signals. Thirdly, their reliance on temperature stabilization or calibration to maintain consistent performance add complexity to their operation. Lastly, the limited spectral selectivity of thermal THz detectors can hinder their capacity to discern specific frequency components within the THz radiation, potentially affecting their suitability for applications requiring high-resolution spectral information [2, 4, 5, 6, 7].

• Transistor THz Detector

Transistor THz detectors are one of the typical electrically-based devices that detect THz radiation by modulating the conductance through the interaction between the incident THz field and the transistor's gate-channel region. These detectors generate an output signal proportional to the input signal, offering high sensitivity and fast response times. They are known for their compatibility with integrated circuit technology, facilitating the development of compact and cost-effective THz systems.

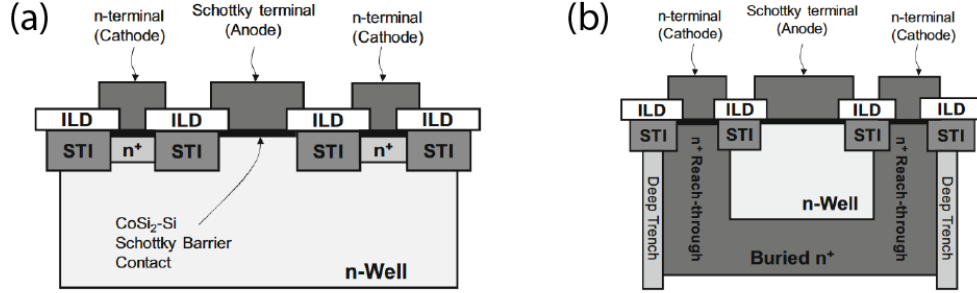


Figure 2.5: Cross section diagrams of (a) CMOS THz Detector [10]; (b) HBT THz Detector [9].

The most representative transistor THz detectors are [Complementary Metal Oxide Semiconductor \(CMOS\)](#) and [Heterojunction Bi-polar Transistor \(HBT\)](#), they can be employed for detecting THz radiation through direct detection or heterodyne mixing [89]. The cross section diagrams of the mentioned detectors are exhibited in Figure 2.5. **CMOS** detectors leverage the plasma-wave resonances in the channel of field-effect transistor, converting THz radiation into an electrical signal [10]. **HBTs**, on the other hand, use their high-speed properties to detect THz radiation through heterodyne mixing, where the incoming THz signal is combined with a local oscillator signal to generate an intermediate frequency. Both CMOS and HBT technologies provide the potential for developing compact, low-cost, and highly-integrated THz detectors [9].

However, the transistor THz detectors have several limitations that may impact their performance or suitability for certain applications. Firstly, transistor THz detectors might possess a limited dynamic range compared to other THz detector types, potentially leading to diminished performance when detecting signals with high or rapidly varying intensity levels. Secondly, these detectors are frequently sensitive to ambient temperature changes, resulting in performance fluctuations. Consequently, temperature stabilization or calibration may be required to guarantee consistent and accurate results. Thirdly, transistor THz

detectors may exhibit higher noise levels, particularly at lower frequencies, compared to other THz detector types. This could negatively impact the signal-to-noise ratio and limit their capacity to detect weak signals. Fourthly, the fabrication process for transistor THz detectors, especially when integrated with other components on a chip, can be complex and costly. This may influence their scalability and cost-effectiveness in large-scale applications. Furthermore, transistor THz detectors typically display limited spectral selectivity, rendering them potentially unsuitable for applications necessitating precise identification or analysis of specific frequency components within the THz radiation. Lastly, transistor THz detectors may be susceptible to interference from other electronic components or radiation sources. This vulnerability may necessitate additional shielding or filtering measures to ensure accurate and reliable detection. Understanding these limitations is crucial when selecting the most appropriate THz detector for a specific application or for guiding future research to address these challenges [90, 89, 10].

While transistor THz detectors have their advantages, these limitations make them less suitable for certain biomedical detection applications, where precise spectral information, temperature stability, large dynamic range, ultra-high sensitivity, and low noise levels are of paramount importance.

• Diode Detector

Diode THz detectors are another class of electrically-based detecting device, which detect THz radiation by leveraging the nonlinear properties of diodes to rectify the incident THz signal, converting it into a measurable DC voltage. These detectors are known for their high sensitivity and fast response times. Diode THz detectors are widely used in various applications, such as imaging, spectroscopy, and communication systems.

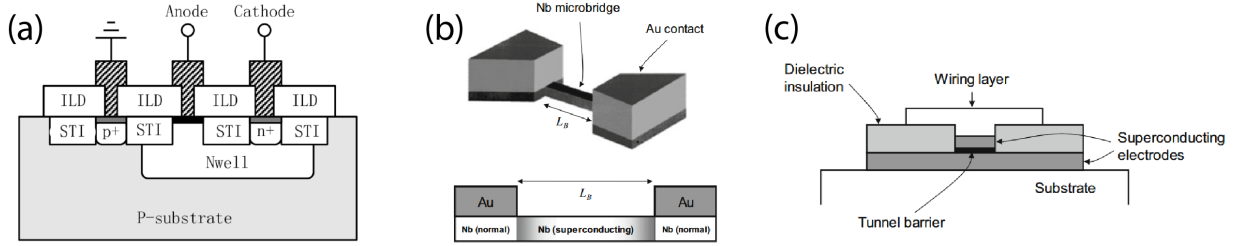


Figure 2.6: Cross section diagrams of (a) SBD THz Detector [16]; (b) SIS Mixer THz Detector [17]; (c) HEB THz Detector [18].

Schottky Barrier Diode (SBD), Semiconductor-Insulator-Semiconductor (SIS) mixers, and Hot Electron Bolometer (HEB) represent three distinct and representative detectors for detecting THz radiation, each employing unique mechanisms [11]. The structure diagrams of the above three Diode THz detectors is shown in Figure 2.6 below. **SBDs** capitalize on the non-linear current-voltage characteristics of metal-semiconductor junctions to rectify incoming THz signals into a proportional DC voltage, offering rapid response, low noise, and broad bandwidth [16, 11]. **SIS** mixers utilize a tunnel junction's highly non-linear current-voltage relationship to generate an intermediate frequency output when combined with a local oscillator signal, providing excellent sensitivity and low noise performance suitable for high-resolution spectroscopy and imaging applications [17]. Meanwhile, **HEBs** exploit the temperature-dependent electrical properties of a superconducting thin film, converting incident THz radiation into measurable changes in electrical resistance, thereby offering ultrafast response times and high sensitivity for applications necessitating rapid signal detection and high spectral resolution [18]. Collectively, these diverse THz detection technologies serve a range of applications and performance requirements, demonstrating their significant potential in advancing the field of THz technology.

Despite their advantages, diode THz detectors exhibit several inherent limitations that may impact their performance and suitability. Firstly, the reliance on the nonlinear prop-

erties of diodes for rectification of the incident THz signal introduces distortion, particularly when detecting signals with high or rapidly varying intensity levels, which may compromise the detector’s performance in specific applications. Secondly, similar to other semiconductor-based devices, diode THz detectors are sensitive to changes in ambient temperature. Temperature fluctuations can adversely affect the detector’s performance, necessitating temperature stabilization or calibration to ensure accurate and consistent results. Thirdly, diode THz detectors typically possess limited spectral selectivity, hindering their capacity to precisely identify or analyze specific frequency components within the THz radiation. This limitation could impact their suitability for applications requiring high-resolution spectral information, such as material identification or chemical analysis. Furthermore, the manufacturing process for diode THz detectors, particularly when integrated with other components on a chip, can be complex and expensive, potentially affecting the scalability and cost-effectiveness of these detectors for large-scale applications. Lastly, diode THz detectors may exhibit higher noise levels compared to some other types of THz detectors, especially at lower frequencies. Elevated noise levels can negatively influence the signal-to-noise ratio, limiting the detector’s ability to measure weak signals or subtle changes in the sample. Consequently, understanding these limitations is crucial when selecting the most appropriate THz detector for a specific application or for guiding future research to address these challenges [91, 11, 92].

In summary, diode THz detectors offer high sensitivity and fast response times, making them suitable for various applications. However, limitations such as nonlinearity, temperature sensitivity, limited spectral selectivity, fabrication complexity, and noise levels can impact their performance and suitability for certain applications. Understanding these limitations is crucial when selecting the most appropriate THz detector for a specific application or for guiding future research to address these challenges.

2.3.2 Optics-based THz detector

THz detectors based on optical effects remain comparatively challenging to implement, primarily due to the intrinsically low photon energy of THz radiation. Photon energy is directly proportional to frequency, as described by Equation 2.1:

$$E = hf \quad (2.1)$$

where E is the photon energy, h is Planck's constant, and f is the frequency. As a result, THz photons carry relatively low energy, leading to subtle interactions with materials and correspondingly modest signal levels. However, this characteristic offers unique opportunities for developing highly sensitive detection strategies that exploit optical effects, thereby enabling innovative pathways for advancing THz detection.

Despite the above mentioned challenge, optical approaches such as **antenna-based detection** and **optical rectification** have gained considerable attention because of their distinctive operating principles and promising performance [12, 8].

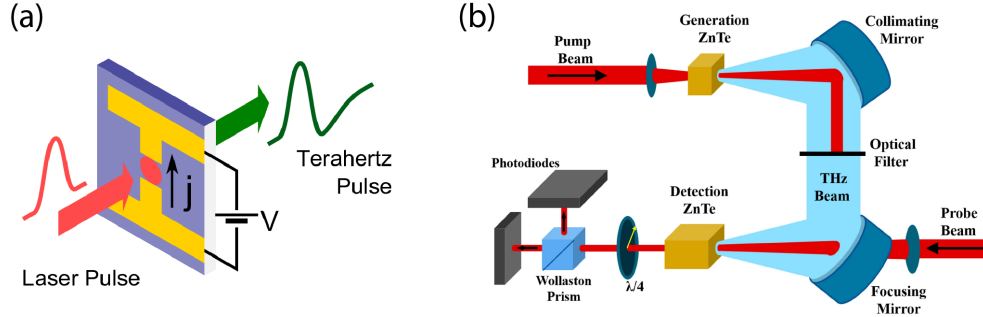


Figure 2.7: Schematic diagrams of representative (a) THz antenna [12]; (b) THz optical rectification [8].

As demonstrated in Figure 2.7 (a), **antenna-based detectors** function by coupling incident THz radiation into resonant structures that enhance local electromagnetic fields,

thereby improving sensitivity and enabling integration with a wide range of electronic and photonic components. Their performance can be further advanced through optimized geometrical design, broadband scaling strategies, and the incorporation of novel low-loss materials, which collectively enhance detection bandwidth and coupling efficiency [10]. In contrast, **optical rectification** relies on the second-order nonlinear response of non-centrosymmetric crystals to convert incident THz radiation into detectable signals as presented in Figure 2.7 (b). This method offers intrinsic advantages of ultrafast response time and compatibility with ultrashort laser sources, making it highly suitable for time-resolved THz spectroscopy. Ongoing progress in nonlinear material engineering, phase-matching optimization, and device miniaturization continues to improve its efficiency and scalability [93, 9]. Both approaches thus hold considerable promise for next-generation THz detection, with the potential to advance applications in biomedical imaging, security screening, and high-speed wireless communication.

In summary, each THz detector technology exhibits distinct advantages and limitations as summarized in Table 2.4 [88, 94, 95, 96, 97, 98, 99, 100, 101, 33, 102]. The selection of an appropriate detector is collectively determined by several factors such as accuracy, sensitivity, response time, size, operational frequency range, cost, and system complexity, together with the specific demands of the intended practical applications. Following the comprehensive review of existing THz detectors, this research focuses on two fundamentally distinct yet complementary methodologies: the microbolometer and the micro-circular antenna. The selection of these two approaches is motivated by their demonstrated strengths in THz detection, which are investigated and discussed in detail in Chapters 3 and 4. Importantly, these mechanisms are not mutually exclusive; when integrated, they offer the potential to synergistically enhance detection sensitivity and achieve superior measurement precision.

Table 2.4: Comparative Analysis of the Advantages and Limitations of Existing THz Detectors

Mechanisms	Categories	Detector Structure	Advantages	Limitations
Electronics-Based	Thermal	Bolometer	Broadband detection Good sensitivity	Slow response time Instability Large size
		Pyroelectric	Room-temperature operation Broadband detection	Slow response time Low sensitivity
		Thermopile/ Golay Cell	Room-temperature operation Broadband detection	Slow response time Low sensitivity
	Transistor	CMOS	Scalability Low cost	Poor performance at HF Lower sensitivity
		Integration with other electronics		
		HBT	Better high-frequency performance Cost-effective	Not competitive at HF Sensitivity limitations
	Diode	SBD	High sensitivity Fast response time	Poor performance at HF High Noise
		SIS Mixer	Low noise High sensitivity	Cryogenic cooling Complex fabrication
		HEB	Wideband detection High sensitivity	Cryogenic cooling Slow response time
	Optics-Based	Antenna	Fast response time High sensitivity Time-domain	Limited spectral range Poor portability Cooling requirement
Optical Rectification		Broadband detection High conversion efficiency Non-contact	Complex fabrication Limited sensitivity Optical setups requirement	

Chapter 3

Graphene-Integrated Microbolometer Design

3.1 Aims and Highlights

Biomedical imaging has traditionally depended on modalities such as X-ray[25], [Computed Tomography \(CT\)](#) [103], [MRI](#) [104], and [Positron Emission Tomography \(PET\)](#) [105]. These technologies have driven significant advancements in medical diagnostics, providing enhanced tissue contrast, real-time biomedical imaging, and the ability to detect metabolic changes. However, the reliance on ionizing radiation in these modalities poses considerable health risks to human body [106, 107, 108]. In contrast, [THz](#) biomedical imaging presents a non-ionizing alternative with substantial benefits. It mitigates the risks of DNA and cellular damage and offers unique non-invasive tissue penetration capabilities, setting the stage to potentially revolutionize biomedical imaging [109, 110].

The THz domain, situated between microwave and infrared on the electromagnetic

spectrum, has attracted substantial attention, particularly in the biomedical field [27]. With its non-ionizing nature, capability to penetrate non-conductive materials, and potential to derive critical bio-spectral information, THz imaging is becoming an essential tool for biomedical detection [28, 41, 111, 69]. The integration of THz imaging systems with [Micro-electromechanical systems \(MEMS\)](#) technology has initiated a shift towards system miniaturization, enabling the development of portable devices and expanding the scope of THz applications [112]. Despite these advancements, developing THz imaging systems that combine precision, sensitivity, rapid response, and seamless materials integration continues to be a significant challenge, one that our research aims to address [113, 114, 19, 115].

The THz detector is critical to the operation of THz imaging systems, serving as the fundamental component that captures and translates THz radiation into analyzable information [116, 24, 117]. Extensive research underscores that the effectiveness of a THz imaging system is closely tied to the performance characteristics of its THz detector [118]. Owing to the THz band’s unique position between the microwave and infrared spectra, numerous THz detectors have been historically adapted from technologies initially developed for these adjacent spectral ranges [31]. Prominent among these THz detectors are schottky diodes, golay cells, and pyroelectric detectors [11, 33, 101]. Schottky diodes are prized for their swift response and low noise profile, rendering them suitable for high-frequency applications. Nevertheless, their dependency on local oscillator pumps adds complexity to the system design, and their efficacy frequently diminishes at room temperature in the absence of cooling mechanisms. In contrast, golay cells are lauded for their adept room-temperature functionality and their sensitivity across a wide THz spectrum. Their bulkiness, stemming from the pneumatic detection mechanism, and their sluggish response impede their utility in dynamic scenarios. Pyroelectric detectors, which convert thermal variance into electrical signals, offer the advantages of ambient operability and expansive

THz frequency detection. However, these detectors are plagued by lower detectivity and require the modulation of the incident THz radiation to facilitate effective detection. Within this context, the microbolometer has emerged as an innovative THz detector, representing substantial advancements and attracting considerable academic interest. [112, 32]. By leveraging thermal-induced resistance changes, it converts THz radiation into quantifiable electrical signals [119, 120]. The microbolometer’s commendable uncooled operation dispenses with the need for elaborate cooling apparatus, positioning it as a cost-effective and user-friendly detection modality. Its extensive spectral response and compatibility with array integration enhance its prospects for producing high-resolution, real-time THz images. These features collectively elevate the microbolometer to a pivotal role in the advancement of pragmatic THz imaging systems.

Despite the promising applications of microbolometers in biomedical imaging and detection, several challenges inhibit their broader implementation. Primary among these is the lengthy thermal time constant of these devices, constraining their frame rate and accuracy in capturing fast-evolving scenes [120, 121]. Furthermore, microbolometers typically exhibit lower sensitivity compared to their counterparts, resulting in higher Noise Equivalent Temperature Differences (NETD) that degrade image quality in applications requiring high precision [122, 112]. Additionally, the variability in pixel response across devices necessitates intricate calibration processes, adding to the system’s complexity and cost [123]. Lastly, the advanced micromachining techniques and specialized materials necessary for microbolometer fabrication present significant barriers to mass production and commercialization [119].

In this study, we present a novel microbolometer design featuring an innovative structure integrated with graphene, aimed at overcoming the challenges previously outlined. Graphene is distinguished by its monolayer configuration of carbon atoms arranged in

a two-dimensional honeycomb lattice, celebrated for its exceptional electronic, thermal, and mechanical properties [124, 125]. Its outstanding electrical conductivity, robustness, and adaptability facilitate its integration with the microbolometer structure, significantly improving the device’s electrical and thermal conductance and enabling a more compact design. Within the 1 - 5 THz operational bandwidth, our graphene-integrated novel microbolometer attains remarkable performance at a specific frequency, with an average response time of 0.246 s, reaching a peak responsivity of $8.95 \times 10^5 \text{ V W}^{-1}$, and achieving an optimal detectivity of $5.97 \times 10^8 \text{ cm Hz}^{1/2} \text{ W}^{-1}$. This peak performance significantly enhances its applicability, particularly in the fields of non-invasive and high-precision biomedical imaging.

Centered around this novel microbolometer, our MAIS is adept at the fast and sensitive THz detection, as well as the corresponding imaging. The system’s augmented sensitivity facilitates the precise identification of weak signals and minute changes in THz radiation, and its swift response is crucial for fast signal processing and real-time visualization. To ascertain the effectiveness of our proposed system, we performed comprehensive experiments using the microbolometer array. These evaluations involved detecting metal letter models positioned on human skin, and the outcomes of these experiments confirm the MAIS’s ability to accurately detect and delineate subtle variations in THz radiation, thereby enabling precise imaging of the targets.

This study marks a pivotal advancement in THz technology, particularly in its application to biomedical imaging. The strategic integration of graphene into our innovative microbolometer structure design marks the emergence of a new generation of THz detection technology, distinguished by their heightened sensitivity and accelerated response capabilities. Furthermore, our MAIS establishes new benchmarks for non-invasive and real-time biomedical imaging. This research not only positions our MAIS at the cutting edge of THz

detection technologies but also establishes a robust foundation for continued advancements in the field of biomedical imaging.

3.2 Methods

3.2.1 Structure design

The novel microbolometer design we introduce in this research is depicted in Figure 3.1(a). By incorporating a microfluidic architecture into the microbolometer framework, the thermal management of the microbolometer is significantly improved, leading to a noteworthy enhancement in the device’s performance across a broad operational temperature range. Specifically, the microfluidic channel allows for the efficient dissipation of heat generated from radiation absorption through the fluidic chamber, thereby inducing a swift cooling effect. This advancement enables our microbolometers to attain exceptionally rapid response times, essential for precise and instantaneous imaging [126]. Additionally, the microfluidic channel also acts as a Fabry-Perot (FP) resonant cavity. Upon exposure to THz radiation, the microbolometer’s absorptive layer captures a major portion of the energy, which is then directed into the resonant cavity. This cavity boasts a distinctive capability to selectively bolster THz absorption within a predetermined spectral region. To fully exploit this resonance effect, precise adjustment of the thickness of cavity is crucial to induce an optimal FP resonance as shown in Figure 3.1(b) [127]. Leveraging this advanced design strategy, the microbolometer achieves effective coupling with targeted incident radiation, thus enhancing its absorptive efficiency across designated frequency spectrum. Additionally, this approach enhances the fabrication yield and streamlines the manufacturing process, representing a significant leap in the development of the THz detection

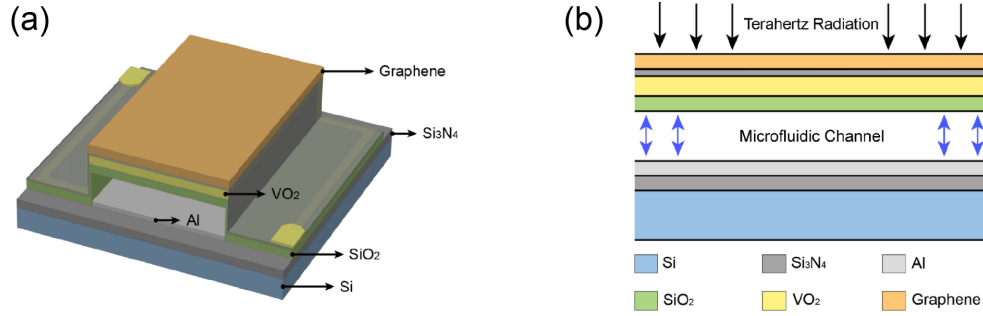


Figure 3.1: Structure of our novel microbolometer. **(a)** 3-Dimensional schematic diagram of the microbolometer design. **(b)** Cross-section illustration of the microbolometer structure.

technology. This novel structural design underscores the potential for advanced THz detection techniques, paving the way for more accurate, efficient, and convenient biomedical imaging.

This configuration is built upon a silicon substrate. A silicon nitride (Si_3N_4) layer is shielded on the substrate, serving a protective role for subsequent fabrication steps. Positioned atop the Si_3N_4 layer, an aluminum (Al) reflective layer acts as the lower boundary of the FP resonant cavity. This Al film enhances microbolometer's absorption by reflecting incident radiation back towards the absorptive layer. Above the Al reflective interface lies a stable silicon dioxide (SiO_2) bridge, SiO_2 is selected for the supporting structure due to its mechanical strength, appropriate thermal properties and ease of fabrication, offering both physical support and thermal insulation. The VO_2 , known for its phase-change characteristics and a high temperature coefficient of resistance (TCR), is chosen as the sensitive element due to its exceptional responsiveness to temperature variations [128]. Graphene, situated at the apex of the structure, functions as the primary absorptive layer. The selection of graphene for this layer is driven by its exceptional THz absorption and superior thermal conductivity, which contribute significantly to augmenting the microbolometer's

thermal sensitivity [125]. The integration of VO₂ and graphene synergistically enhances their collective properties, optimizing the collection and conversion of radiation into heat and subsequently into electrical signals. This innovative integration markedly improves the detection capabilities of the microbolometer, heralding advancements in the field of THz detection technology.

3.2.2 Fabrication process

The fabrication process of the microbolometer, as illustrated in Figure 3.2(a-h), represents a comprehensive approach that integrates advanced materials and methodologies.

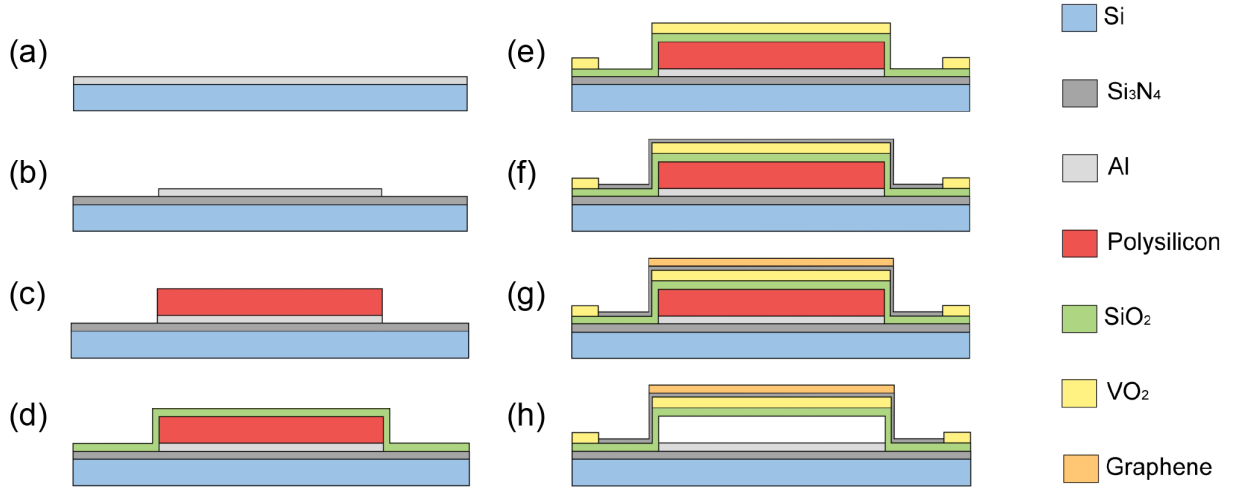


Figure 3.2: Sequential fabrication processes of the graphene-integrated microbolometer. (a-h) Sequential fabrication of the graphene-integrated microbolometer, detailing the cross-sectional development from substrate to final assembly.

The process started with depositing a Si₃N₄ film on a silicon substrate through Plasma Enhanced Chemical Vapor Deposition (PECVD), serving as a protective layer. The Al

film was then deposited through [electron Beam \(E-beam\)](#) deposition as the base reflective layer. Subsequent fabrication involved the deposition of SiO_2 via PECVD, setting the stage for subsequent layers and crafting the gap to facilitate access to sacrificial etch channels. At the heart of this microbolometer structure is the sensitive layer comprised of VO_2 , applied through magnetron sputtering. Right after the sensitive layer, a thin Si_3N_4 film was deposited through PECVD to protect the existing structure. The next processes included the dispersion of graphene within an [Isopropanol \(IPA\)](#) solution at a concentration of 0.5 mg/mL, followed by ultrasonication to achieve a homogeneous mixture. The device was then subjected to plasma treatment to enhance adhesion before the spin-coating of the graphene layer. Finally, subsequent curing was adopted to solidify the depositions. Corresponding Raman spectral characteristics of the well-fabricated microbolometer are illustrated in Figure 3.3.

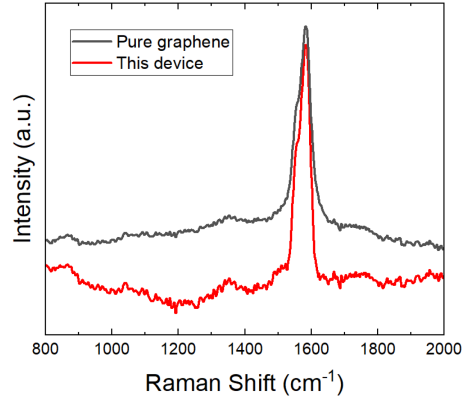


Figure 3.3: The Raman spectrum of pure graphene and this device-incorporated graphene.

The Raman spectra exhibit distinct D (1350 cm^{-1}) and G (1585 cm^{-1}) bands for graphene, reflective of defect-associated vibrations and sp^2 carbon atom vibrations, respectively. Post-device integration, an intensification of both bands suggests augmented

defect density and stronger interactions between the sp^2 carbon regions upon bonding to the device, potentially from substrate interactions. Concurrently, the redshift of the bands indicates altered graphene-substrate interactions, with the electronic properties of graphene remain essentially unchanged.

Figure 3.4(a) presents a comprehensive view of the constructed microbolometer, measuring $4 \times 4 \text{ mm}^2$. Furthermore, Figure 3.4(b) provides detailed [Scanning Electron Microscope \(SEM\)](#) imagery of the tilted view, illustrating the microbolometer's distinct design. Characterized by its compact architecture, the microbolometer incorporates a central microfluidic channel as demonstrated in Figure 3.4(c).

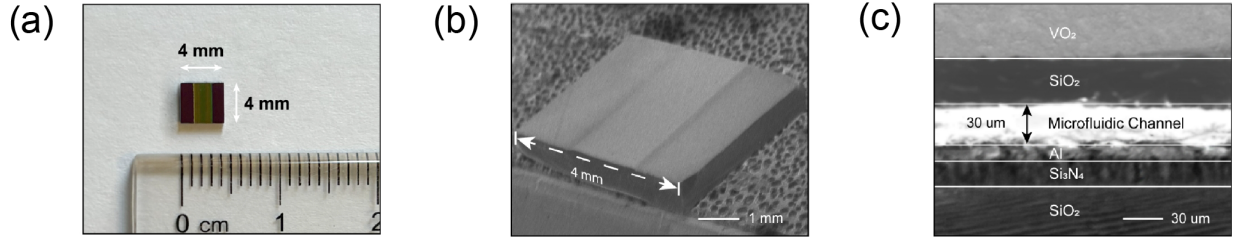


Figure 3.4: Microstructural characterization of the graphene-integrated microbolometer. (a) Optical imaging of the microbolometer. (b) Scanning electron microscope (SEM) image revealing the precise architecture of the overall microstructure. (c) Side-view SEM image of the microbolometer.

3.2.3 Characterization

To characterize the morphology of our microbolometer, we employed a JEOL JSM-7200F SEM with settings of 10.0 kV voltage and a 10 nA beam current. Raman spectroscopy was conducted using a Bruker Senterra-2 system, equipped with a 780 nm laser and a 1 mW power setting. For radiation stimulation, a Newport Oriel 67030 blackbody

source was adopted, complemented by a optical cutoff lens that filtered out non-targeted wavelengths, thereby minimizing heat-related disturbances and ensuring the presence of only desired radiation for detailed microbolometer analysis. The measurement equipments comprised a Keithley Model 6500 digital multimeter and a LeCroy LT322 oscilloscope, which ensured precision data acquisition. The experimental setup maintained a 10 cm distance between the microbolometer and the source throughout the experiments.

3.2.4 Materials

All the materials utilized in this study were procured from reputable suppliers to ensure quality and consistency in the experimental procedures. Graphene was sourced from Graphene Laboratories Inc., while VO_2 was obtained from Sigma-Aldrich Co. The ALD/PECVD Cluster system from Oxford Instruments facilitates the utilization of both materials and PECVD fabrication processes, enabling the deposition of both Si_3N_4 and SiO_2 . Al was obtained from Goodfellow Cambridge Ltd. and was pre-filled in an Angstrom Engineering Amod model. Each of the materials was selected in consultation with the respective manufacturers, adhering to specific purity and compositional requirements dictated by the experimental design. Before integration into the fabrication process, all materials were subjected to standard pre-treatment procedures as per the manufacturers' guidelines, ensuring that they met the necessary criteria for the subsequent experimental steps.

3.3 Results and Discussion

3.3.1 Absorption

In the domain of radiant detection, absorption is a critical attribute that indicates the detector's efficiency in capturing radiant energy. It is defined as the ratio of absorbed to incident radiant power, quantitatively evaluates a device's ability to absorb radiation [129]. In this specific design of microbolometer, the absorption (A) is expressed by the following equation [4]:

$$A = \frac{4}{D} \{ [f_s(f_r + 1) + f_r] \sin^2 \theta + (f_r + f_s) \cos^2 \theta \},$$

(3.1)

where

$$D = [(f_s + 1)(f_r + 1) + 1]^2 \sin^2 \theta + (f_r + f_s + 2) \cos^2 \theta$$

herein, $f_r = \frac{120\pi}{\sigma_r}$, $f_s = \frac{120\pi}{\sigma_s}$, and $\theta = 2\pi d_{eff}/\lambda$, where λ is the wavelength of the incident radiation, σ_r is the sheet resistance of a thin Al reflective layer, σ_s is the sheet resistance of the absorptive layer, and d_{eff} is the thickness of microfluidic cavity. By integrating the specific microfluidic cavity structure into microbolometer designs, improved THz radiation absorption can be achieved across an extensive frequency range. This enhanced broadband THz absorption is facilitated by the strategic coupling of absorption peaks, which is realized through the incorporation of FP cavity structures. Such advancements demonstrate the feasibility of implementing this design in microbolometers, offering an effective approach for broadband THz detection at room temperature [121].

Figure 3.5 effectively illustrates the absorption intensity within the microbolometer using a color gradient, with blue indicating lower absorption levels and red denoting higher absorption. This color scheme reflects systematic variations in absorption peaks and troughs,

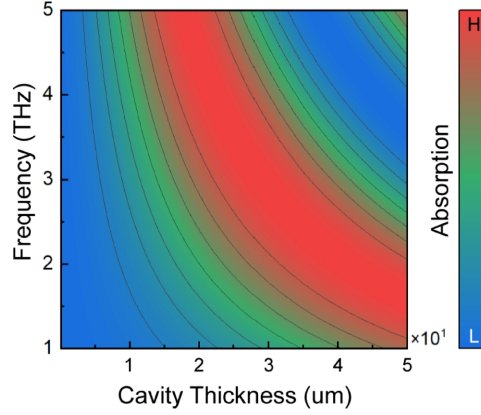


Figure 3.5: 1 - 5 THz radiation absorption spectrum across cavity thicknesses ranging from 10 μm to 50 μm .

which are influenced by changes in both the cavity thickness and the radiation wavelength. Such patterns reveal the microbolometer's tunability, demonstrating how its physical dimensions can be adjusted to optimize absorption properties. Additionally, the absorption spectrum here has enabled a easier and more precise determination of the optimal FP cavity thickness for our target frequency range (1 - 5 THz), enhancing the device's functional adaptability to specific biomedical applications.

In the typical Fabry–Perot structure, constructive interference is typically achieved when the cavity thickness satisfies the condition:

$$d = \frac{\lambda}{2n} \quad (3.2)$$

where d is the cavity thickness, λ is the free-space wavelength of the targeted frequency, and n is the refractive index of the cavity medium. However, when functional materials are introduced or when light enters the cavity at non-perpendicular incidence, the effective optical path is modified, and the cavity thickness can no longer be determined solely

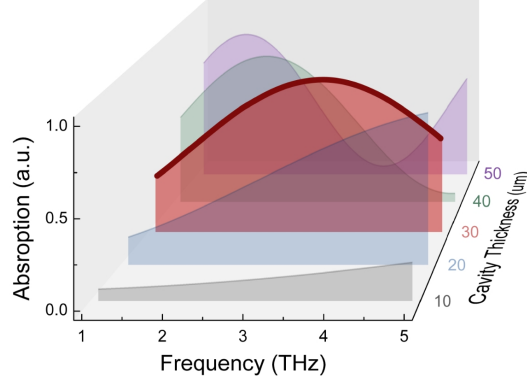


Figure 3.6: THz absorption spectra with cavity thicknesses varying from 10 μm to 50 μm in 10 μm intervals across the frequency range of 1 - 5 THz.

by the conventional half-wavelength rule. In our experiment, VO_2 was employed, which exhibits metamaterial-like characteristics that allow modulation of the phase of incident electromagnetic waves rather than functioning solely as the sensitive dielectric. This additional phase shift effectively reduces the optical path length, thereby requiring the cavity thickness to be smaller than the nominal $\lambda/2n$. Such adjustment ensures constructive interference and efficient resonance coupling, thereby enhancing absorption across the 1–5 THz spectral band, particularly under practical detection scenarios where radiation arrive from multiple directions.

To determine the optimal cavity thickness, we investigated the absorption spectra of microbolometers across our target frequency range using five discrete resonant cavity thicknesses, varying from 10 μm to 50 μm . Figure 3.6 illustrates these characteristics, with each colored layer representing the absorption profile of our microbolometer with different cavity thicknesses. A distinct trend is observed where increasing cavity thickness leads to a shift in the absorption peaks towards lower frequencies in 1 - 5 THz range. This behavior is the typical characteristic highly related to the resonant cavities, where physical dimensions

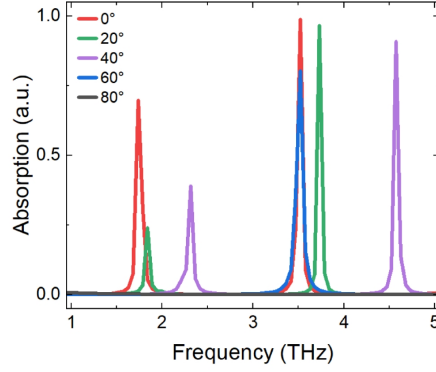


Figure 3.7: Angle-dependent THz absorption spectra of the microbolometer simulated at 20° intervals from 0° to 80°.

are inversely related to resonant frequencies. The experimental results indicate that microbolometers with thinner cavities resonate at higher frequencies, while those with thicker cavities resonate at lower frequencies. Notably, the absorption spectrum for a cavity thickness of 30 μm in the figure shows a near-normal distribution within 1 - 5 THz, signifying its optimal performance of radiation absorption in this range. Quantitative analysis of ten experiments revealed that the average absorption values of THz radiation at cavity thicknesses of 10 μm , 20 μm , 30 μm , 40 μm , and 50 μm are 0.074, 0.470, 0.680, 0.542, and 0.485, respectively. The microbolometer with cavity thickness of 30 μm exhibited the highest average absorption, further confirming its optimal effectiveness for THz absorption. These results affirm that adjusting the cavity thickness is an effective strategy for tuning the spectral response of our novel microbolometer, thereby enhancing its suitability for THz applications. Consequently, we have refined our microbolometer design by adjusting the cavity thickness to 30 μm to optimize the THz absorption performance.

While the broad THz absorption spectrum of our microbolometer was observed under practical application scenarios, where THz radiation impacts the device from multiple

directions, Figure 3.7 provides a detailed simulation results of the microbolometer’s absorption characteristics across specific incident angles ranging from 0° to 80° , with the cavity thickness of $30\text{ }\mu\text{m}$. These outcomes are corroborated by five experimental repetitions, with the figure displaying the average results of these measurements. These results clearly demonstrates sharp resonant peaks that shift with the angle of incidence, underscoring the device’s sensitivity to angular changes due to constructive interference within its cavity structure. These shifts in resonance, influenced by changes in the path length through the cavity at different incident angles, affect the phase relationships and interference patterns of the THz waves, resulting in distinct absorption peaks at specific frequencies. Additionally, the analysis reveals that from an incident angle of $0 - 60$ degrees, the THz radiation consistently exhibits at least one absorption peak within the examined frequency range. The presence of these peaks ensures robust absorption across a broad spectrum in $1 - 5\text{ THz}$ range. The directional sensitivity demonstrated by the microbolometer supports its potential for a range of applications, including precise prediction of the angle or wavelength of incident radiation, enhancing its practical utility. This thorough analysis confirms the device’s potential for advanced THz applications, showcasing its versatility and applicability in diverse operational conditions.

Following the structural optimization of the microbolometer, particularly the adjustment of cavity thickness, we evaluated various materials for the absorptive layer to enhance the absorption characteristics our novel microbolometer. Figure 3.8 displays the THz absorptivity of the microbolometer across different absorbing materials, with the results verified through ten validations to ensure both accuracy and reliability. We conducted a comparative analysis using four prominent materials typically used for THz radiation detection: graphene [130], titanium dioxide nanoparticles (TiO_2) [129], amorphous silicon (A-Si) [131], and vanadium dioxide (VO_2) [132]. The microbolometer demonstrates high

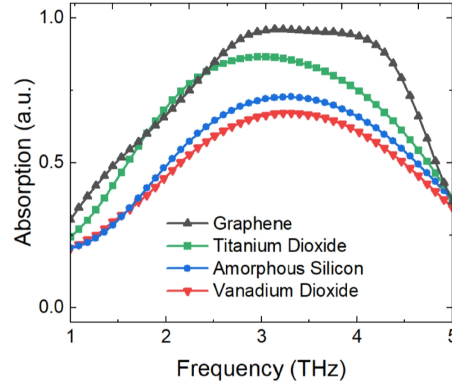


Figure 3.8: THz absorption characteristics of the microbolometer verified through ten validations ($n = 10$), with comparative absorption spectra using graphene, TiO_2 , A-Si, and VO_2 as absorptive layers.

absorption within the target THz band, with a pronounced absorption peak between 2 and 3 THz across all tested materials. Graphene, in particular, showed consistently superior THz absorption throughout the frequency spectrum, attributable to its unique electronic properties and exceptional thermal conductivity, which enhance energy absorption efficiency. Conversely, Titanium Dioxide, although inferior to graphene, presented absorption rates noticeably higher than A-Si and VO_2 . A-Si rendered moderate absorption efficiency, its potential impeded by its amorphous structure, which restricts the availability of free carriers essential for absorption. Nevertheless, devices' absorption utilizing these three materials outperformed those employing VO_2 as the absorptive layer. The experimental outcomes underscore the significant advantages and essential role of graphene as the absorptive layer in our innovative microbolometer design. By seamlessly integrating graphene, we have adeptly harnessed its inherent properties, enhancing THz radiation absorption effectively. This integration not only improves the device's performance but also represents a pioneering advancement in the development of highly efficient THz detectors. Such enhancements hold profound implications for imaging applications, marking a significant step forward in

THz imaging field.

3.3.2 Resistance-temperature relationship

The accuracy of THz detection in microbolometers is contingent upon two fundamental parameters: the resistance-temperature (R-T) relationship and the temperature coefficient of resistance (TCR). These parameters are vital in determining the operational characteristics of the microbolometer design.

The TCR, which quantifies the change in resistance in response to temperature variations, is calculated using the following equation [133]:

$$TCR = \frac{1}{R} \frac{dR}{dT} = \frac{1}{R} \frac{\Delta R}{\Delta T} \quad (3.3)$$

where R refers to the resistance and T is the temperature. TCR is crucial for evaluating the microbolometer's effectiveness and thermal sensitivity. Higher absolute TCR values indicate superior detection of minute temperature variations, a highly prized feature in radiation inspection. The high TCR is fundamental to the advancement of microbolometers, enhancing both the quality and precision of THz detection produced by our microbolometers. The experimental approach involved situating the fabricated microbolometers on the stage, carefully calibrated for optimal THz radiation detection. The ambient conditions were strictly maintained at a constant room temperature of 23 °C, and the radiation intensity variation was controlled to a thermal range from 300 to 900 °C in increments of 10 °C. To assure accuracy in the R - T and TCR - T profiles, each temperature set-point was affirmed by an ensemble average of twenty individual data readings.

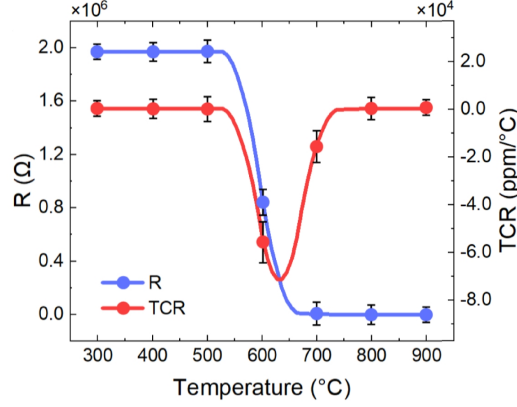


Figure 3.9: Analysis of resistance and temperature coefficient of resistance in microbolometers in response to variations in blackbody source temperature.

Figure 3.9 displays the $R - T$ relationship and the TCR profile of the device, with standard deviation intervals set at 100 °C to improve clarity of representation. The device demonstrates a thermistor-like behavior, maintaining a constant resistance of 1.973 MΩ with a zero temperature TCR across the blackbody source's temperature range from 300 to 530 °C. This stability confirms the device's robustness against thermal fluctuations within this specific range. Beyond this temperature threshold, the resistance profile exhibits a marked inflection point, characterized by a significant decrease in resistance and a corresponding increase in absolute TCR, reaching a peak at approximately 630 °C. As the temperature continues to rise, the absolute TCR progressively decreases toward zero, while the resistance levels off at a lower value. This distinctive behavior is indicative of the intrinsic properties of the VO₂ sensitive layer, illustrating the microbolometer's dynamic response to the THz radiation.

Furthermore, Figure 3.10 presents a detailed comparative analysis of output voltages across the range of blackbody source temperatures from 200 to 1000 °C for microbolometers

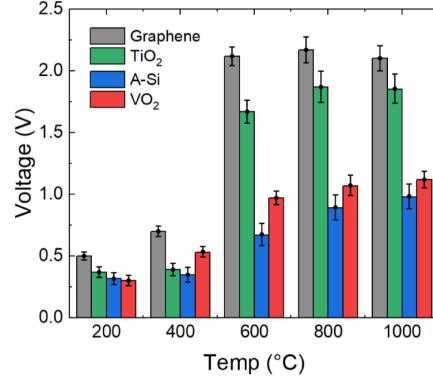


Figure 3.10: Comparative output voltages of microbolometers with different absorptive materials across varied blackbody source temperatures.

fabricated with four different absorptive materials: graphene, TiO₂, A-Si, and VO₂. We performed five measurements of output voltage at 200 °C intervals for microbolometers constructed from each material. Notably, the device incorporating graphene as the absorptive layer exhibited the highest output voltages throughout the temperature spectrum, surpassing those of devices using TiO₂, A-Si, and VO₂. This enhanced performance underscores the exceptional TCR and stability of the graphene-based microbolometer, making our novel microbolometer particularly effective for applications requiring precise THz detection.

3.3.3 Response time

Improving the response time of microbolometers is crucial for their efficacy in THz detection and imaging, as a fast response time enables the microbolometer with the capability to accurately capture and delineate radiation instant changes with high precision. This capability is critical for the real-time processing of transient THz signals, which is indispensable in a variety of dynamic THz detection.

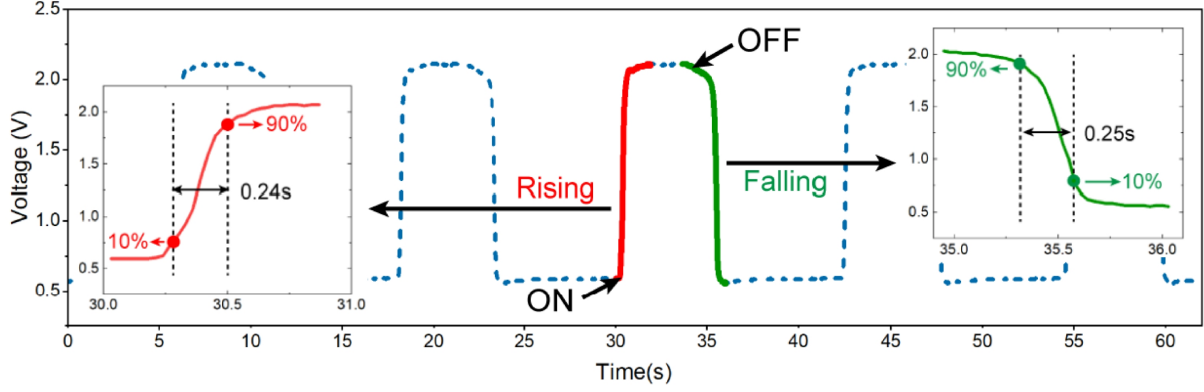


Figure 3.11: Characterization of microbolometer response dynamics to periodic THz radiation.

To ensure the accuracy of our measurements, we strictly calibrated the microbolometer and the radiation source prior to initiating experiments, and kept the experimental setup consistently at the room temperature. The radiation source was set to an optimal temperature of 630°C, a regime known to induce the maximum TCR from the microbolometer. Following calibration, we continuously monitored the voltage across the microbolometer until it achieved the stable state. Then the radiation source was periodically obstructed to record the output signals of the microbolometer. The corresponding output voltage is illustrated in Figure 3.11. Within this experimental context, we defined response time as the duration required for the output signal to transition from 10% to 90% of its saturation level following an increase in radiation stimulus, or from 90% to 10% upon a decrease in radiation stimulus. Analysis of the data obtained demonstrates that the microbolometer's response times for the rising and falling edges were approximately 0.240 s and 0.248 s, respectively. An average response time of 0.246 s was calculated from a comprehensive series of 100 cycles, affirming the microbolometer's capability to rapidly response to changes in THz radiation.

The superior response time of our microbolometer is attributed to the integration of a microfluidic structure and graphene as the absorptive layer. This innovative combination provides the device with several essential attributes, including efficient thermal transduction, swift changes in electrical properties, and robust thermal isolation of critical components. Graphene enables the rapid capture of radiation and its effective transformation into thermal energy, which leads to an immediate change in resistance within the sensitive VO₂ layer, enhancing the device's reactivity. Simultaneously, the microfluidic framework of the microbolometer substantially strengthens thermal management by enabling swift heat evacuation, ensuring maximum absorption of THz radiation while ensuring heat dissipation. This thoughtful integration of pioneering design features presents a substantial leap forward in THz detection technology, offering a refined solution to the dual objectives of improved thermal management and accelerated response time.

3.3.4 Optical measurements

To advance microbolometer design, we conducted a comprehensive analysis of the device's optical response across the target radiation frequencies. Particular emphasis was placed on evaluating the efficiency of converting THz radiation into electrical signals, an improvement enabled by the innovative structural design. We employed the voltage responsivity (R_v) to delineate the relationship between the single microbolometer's output voltage signal and the its corresponding incident radiation power, the mathematical representation of R_v is [134]:

$$R_v = \frac{I_b R \eta}{G \sqrt{1 + \omega^2 T_{th}^2}} \quad (3.4)$$

here, I_b denotes the bias current, R represents the device resistance, η is the absorptivity, G is the thermal conductivity, ω captures the radiation modulation frequency, and T_{th} is

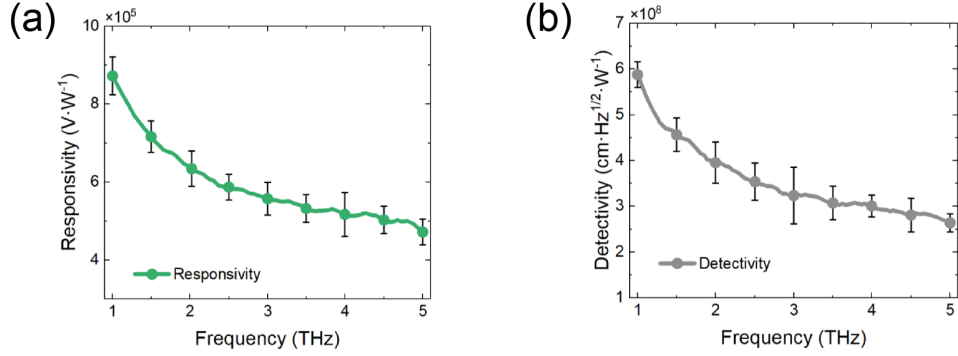


Figure 3.12: Optical characteristics of the microbolometer's (a) Responsivity and (b) Detectivity, with twenty data points collected at each measurement step.

the response time. Our results, as illustrated in Figure 3.12(a), robustly demonstrate the high responsivity of our meticulously engineered device across the 1 - 5 THz range. To ensure precise data representation, measurements were taken at every 0.1 THz increment, with twenty data points collected at each step. For clarity in statistical presentation, the standard deviation of the results are aggregated and displayed at 0.5 THz intervals within the figure. Despite some variability, the device's average responsivity consistently ranges between 4.56 and $8.95 \times 10^5 \text{ V W}^{-1}$ across the target frequency range, underscoring the structure's promise in augmenting detection capabilities.

Voltage detectivity (D^*) serves as another critical metric for evaluating the microbolometer's optical performance, providing a measure to describe the detector's capability to detect weak signals [135]:

$$D^* = \frac{R_v \sqrt{\Delta f A}}{V_n} \quad (3.5)$$

in this formula, Δf is the frequency bandwidth procured from the dynamic signal analyzer, while A is the area of the detector's sensitive element and V_n embodies the aggregate noise voltage, this noise levels were accurately derived using Fourier Transformation (FT) of

time-domain noise signals in our experiments. Our microbolometer demonstrated exceptional detectivity, as depicted in Figure 3.12(b). The results with values ranging from 2.57 to $5.97 \times 10^8 \text{ cm Hz}^{1/2} \text{ W}^{-1}$, reflecting the device’s superior performance in the relevant frequency spectrum. The detectivity data were systematically collected at 0.1-THz intervals, with the standard error reported for each 0.5-THz interval, and all frequency points was substantiated by twenty data points.

The outstanding optical properties of our microbolometer demonstrate its superior performance, particularly in the target THz spectral range. Enhanced responsivity and detectivity enable the precise detection of THz radiation, facilitating accurate measurements even with slight variations in radiation. These capabilities yield images of greater clarity and higher contrast, essential for applications demanding exacting image quality, such as non-destructive testing (NDT) and biomedical imaging.

3.3.5 Durability

The data presented in Figure 3.13 illustrate the robustness of the device’s turn-on voltage and response time over an eight-week period. Each test was measured 5 times to ensure statistical reliability with minor standard deviation, as detailed in the figure. The turn-on voltage, consistently hovering just above the 2.15 V mark with negligible variance, corroborates the stability of the device’s electrical attributes over the analyzed timeframe. Simultaneously, the response time remains steadfast, with an average value proximate to 0.246 s. The compact dispersion of data points in both metrics underscores the device’s operational reliability. The absence of progressive deviation signifies a high degree of precision and reproducibility, bolstering the device’s suitability for enduring utilization. Consequently, the depicted performance stability offers substantial evidence of the device’s

sustained efficacy and enduring reliability.

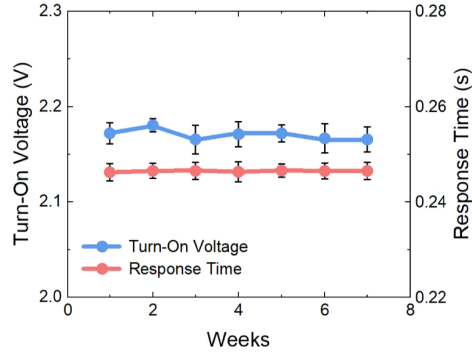


Figure 3.13: Long-term stability assessment of microbolometers: Consistent turn-on voltage and response time observed in durability tests conducted over an eight-week period.

3.3.6 Performance comparison

In examining the presented microbolometer’s THz detection performance relative to state-of-the-art devices, several noteworthy distinctions become evident. As presented in Table 3.1, our design showcases exceptional responsivity ($8.95 \times 10^5 \text{ V W}^{-1}$), which substantially outperforms many existing models, especially in the [field-effect transistor \(FET\)](#) and [photothermoelectric \(PTE\)](#) categories. This elevated responsivity signifies our system’s aptitude for efficiently transducing weak optical signals into pronounced voltage outputs, an invaluable trait for practical deployments. Another pivotal metric where our system excels is detectivity, with a commendable value of $5.97 \times 10^8 \text{ cm Hz}^{1/2} \text{ W}^{-1}$, emphasizing its robust capability to discern faint signals. Importantly, the ability of our microbolometer to operate optimally at room temperature (23°C) positions it as an advantageous alternative to models requiring more intricate and costly cooling provisions. The response time of our

Table 3.1: The parameter comparisons between our study and the state-of-the-art devices.

Mechanism	Frequency (THz)	Responsivity (V W^{-1})	Detectivity ($\text{cm Hz}^{1/2} \text{ W}^{-1}$)	Response time (s)	T ($^{\circ}\text{C}$)	Ref
PTE	2.52	> 10.0	1.9×10^5	1.10×10^{-7}	23	[118]
PTE	~ 0.30	> 1.1	1.0×10^6	2.0×10^{-3}	23	[116]
FET	~ 0.30	> 1.2	2.3×10^7	2.5×10^{-3}	23	[24]
FET	~ 0.30	> 30.0	3.0×10^8	5.0×10^{-6}	23	[117]
FET	0.15	> 400.0	3.5×10^8	2.00×10^{-5}	23	[113]
Bolometer	~ 0.30	7.8	1.2×10^7	1.00×10^{-3}	23	[120]
Bolometer	0.30 - 1.60	N/A	3.3×10^9	$< 1.00 \times 10^{-4}$	-270	[122]
This work	1.00	8.95×10^5	5.97×10^8	2.46×10^{-1}	23	—

microbolometer is recorded at a commendable 0.246 seconds, facilitating swift responsiveness in practical applications without compromising essential performance metrics such as responsivity and detectivity. All these superior characteristics are underpinned by the innovative design of our microbolometer. This integration of features highlights the considerable potential and extensive implications of our work within the dynamically evolving field of THz detection.

3.3.7 Imaging system

Building on the innovative microbolometer, we have further developed the MAIS to optimize microbolometer’s application in practical biomedical detection. The architecture of the MAIS, depicted in Figure 3.14, represents a comprehensive strategy for THz imaging, demonstrating a substantial advancement in the field.

The system’s configuration permits precise control of blackbody radiation via an ad-

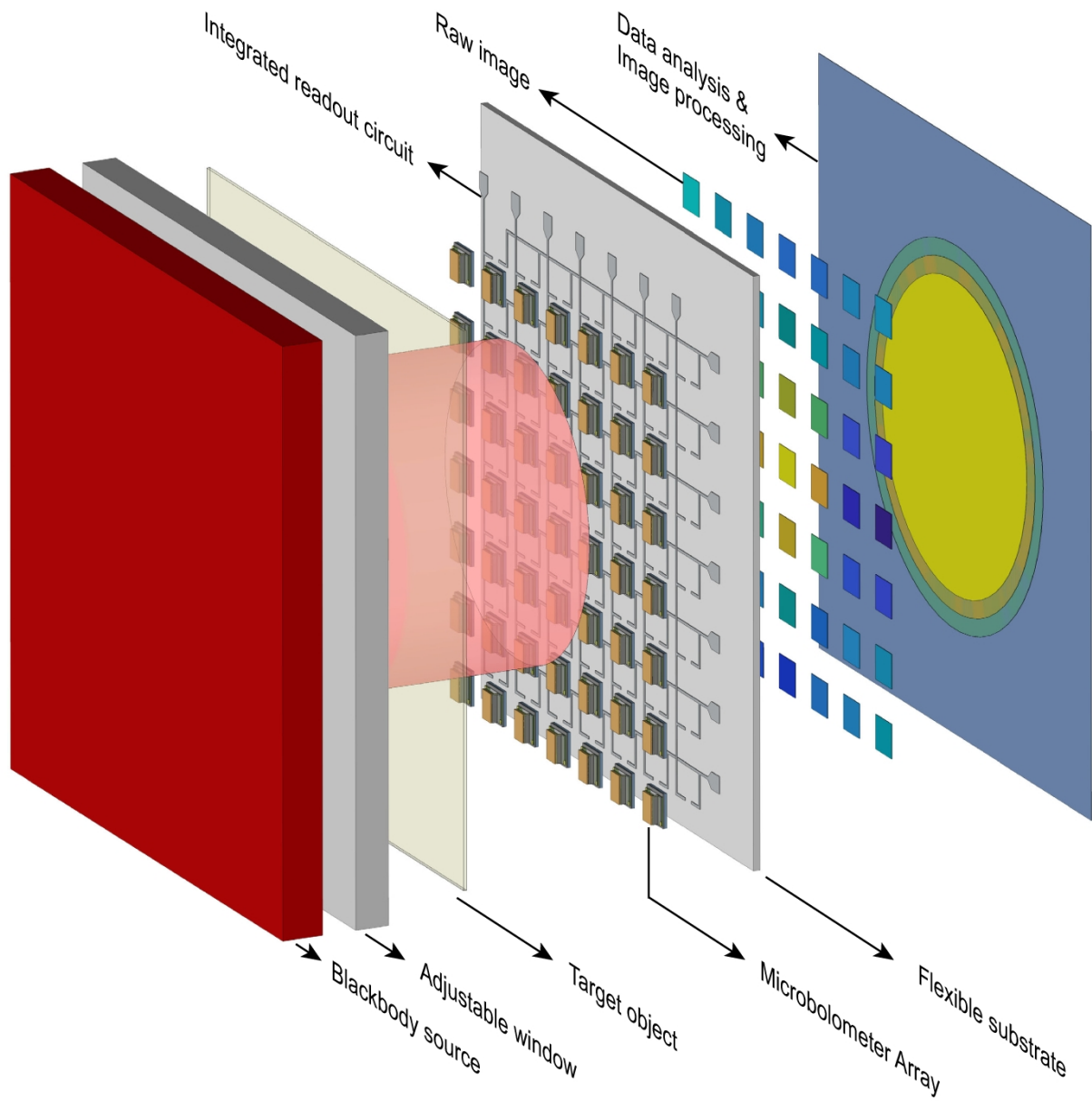


Figure 3.14: Microbolometer array imaging system, detailing the integrated imaging process from THz radiation capture to the final image output.

justable window, carefully positioned during experiments to optimize the incident radiation on the microbolometer array. This precise alignment ensures each microbolometer's absorption of THz radiation, resulting in measurable resistance changes across the microbolometer array. The strictly pre-fabricated circuit is integral to the exceptional efficacy of our MAIS. The circuit has been thoughtfully engineered for perfect compatibility with our microbolometers. It features a dual-layer aluminum deposition strategy, carefully formulated to reduce signal interference between input and output components for enhanced electrical signal transmission. Furthermore, the circuit is optimized to minimize thermal accumulation, thereby boosting both circuit's performance and reliability. This efficient design facilitates the implementation of an $m \times n$ detector array, requiring only $m + n$ interconnections, markedly simplifying the overall complexity of our MAIS. In our specific application, this approach is exemplified by a streamlined 14-pin configuration for the 7×7 microbolometer array, with the dimension of $70 \times 70 \text{ mm}^2$. Such simplification not only decreases reliance on extensive external circuitry but also significantly reduces the potential for signal crosstalk between channels. Consequently, there is a notable improvement in both the stability and reliability of the MAIS detection process.

Employing a consistent external power supply, we measured the voltage differential across the microbolometer array (as depicted in Figure 3.15(a)), allowing us to monitor the THz radiation intensity at each pixel. During imaging tests, the object under tests was situated between the blackbody source and the microbolometer array to assess the system's imaging capabilities. We employed the Arduino Mega to capture the output signals from the detector array, and subsequently convert the analogue readout signals into digital values using its integrated 10-bit [Analogue-to-Digital Converter \(ADC\)](#). By configuring the ADC to operate at a refresh rate of 10 Hz, the digital values, which precisely represent the actual output voltage at each pixel, are rapidly transmitted to the computer

for subsequent analysis and imaging.

Subsequently, we converted the outputs from individual microbolometers into RGB values, thereby facilitating an accurate visual representation of the objects detected by the MAIS. During the development of the THz MAIS, a critical challenge became apparent in the initial imaging results, as illustrated in Figure 3.15(b). The images displayed pronounced non-uniformity among pixels, leading to fragmented and inconsistent image quality. Overcoming this issue was essential for achieving the high-quality imaging necessary for our applications. Consequently, we adopted a dual-faceted strategy, focusing on both hardware optimization and software algorithm enhancements. This comprehensive approach was crucial and efficient to address the inherent complexities and improve the overall performance of the MAIS.

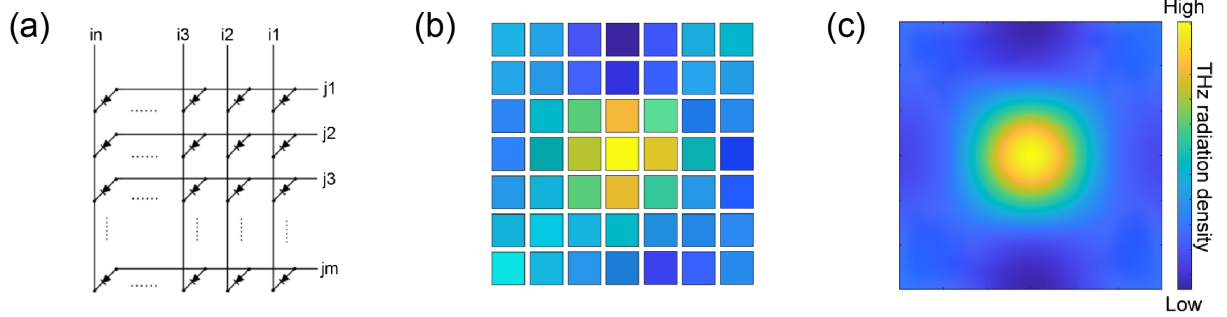


Figure 3.15: **(a)** Schematic diagram of the dual layer Al readout circuit. **(b)** Visual representation of THz radiation detected by the MAIS. **(c)** Optimized imaging performance.

On the hardware front, the thorough refinement of the fabrication process was undertaken, aiming to achieve uniformity in pixel dimensions, morphology, and material attributes. This meticulous process included precise control over deposition processes, strict adherence to lithography parameters, and comprehensive quality assessments. Despite

these efforts, some variability remained inherent to the fabrication process, thereby underscoring the necessity for software-based compensatory strategies. To mitigate these disparities, we also developed advanced optimization algorithms designed to enhance THz imaging quality. We implemented a custom calibration algorithm focused on offset and gain corrections, significantly contributing to image smoothing and noise reduction. By employing this optimization algorithm, we precisely calculated and implemented calibrated gain and offset adjustments for each pixel, ensuring optimal imaging performance. Figure 3.15(c) displays an exemplary real-time imaging result. In this illustration, the microbolometer array is centrally exposed to blackbody radiation, producing a distinct yellow highlight at the most intense detection point. In contrast, areas not receiving radiation are shown in blue, indicating the lowest radiation levels within the array. These impressive results not only demonstrate the excellent performance of the device, but also its potential for imaging applications. The synergistic solutions from both hardware and software effectively addressed the challenges of non-uniformity in microbolometer detector arrays and marked significant technological advances in real-time THz imaging. The advanced processes and algorithms we adopted hold significant promise for future applications, showcasing the potential impacts of our research.

In this study, we have further applied the functionalities of our MAIS to encompass bio-detection, showcasing its accuracy and effectiveness in practical scenarios. Figure 3.16(a) presents the operational block diagram that details the MAIS’s configuration for applied uses.

Our experimental setup involved placing metal letter models on human skin and precisely aligning the THz detector array as depicted in Figure 3.16(b). The THz detector array features a resolution of 7×7 pixels over an area of $70 \times 70 \text{ mm}^2$, and each letter model measuring $50 \times 50 \text{ mm}^2$. By leveraging the human body’s inherent radiation emis-

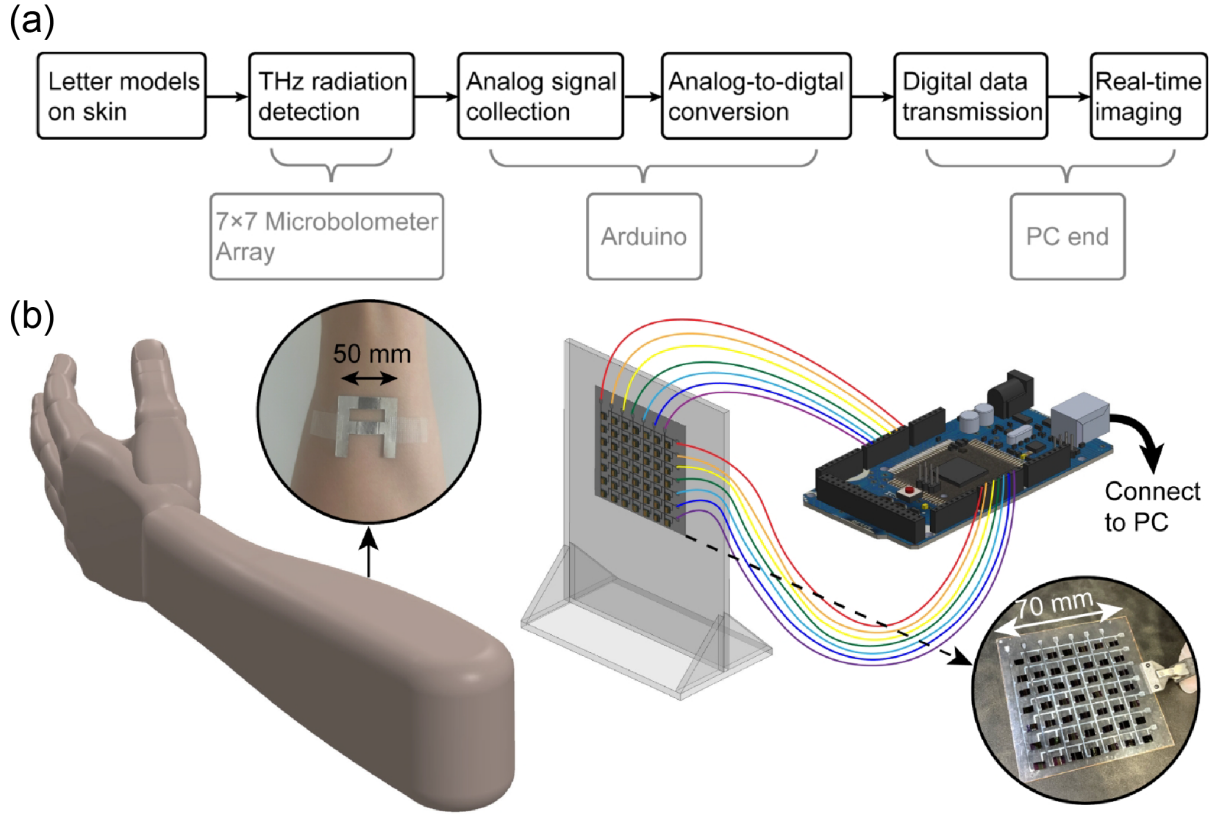


Figure 3.16: (a) Operational block diagram of our MAIS; (b) Demonstration of the MAIS in a practical bio-detection application, capturing the shape and size of foreign objects on the skin surface.

sion characteristics within the THz spectrum, the MAIS quickly and effectively detected THz radiation emanating from the skin, thus facilitating the identification of foreign objects in real-time.

To validate this application, we conducted experiments using six unique models named after the first six letters of our research facility, the University of Waterloo Advanced Micro-Nano Devices Lab (UWAMND). The outcomes of the imaging were displayed in

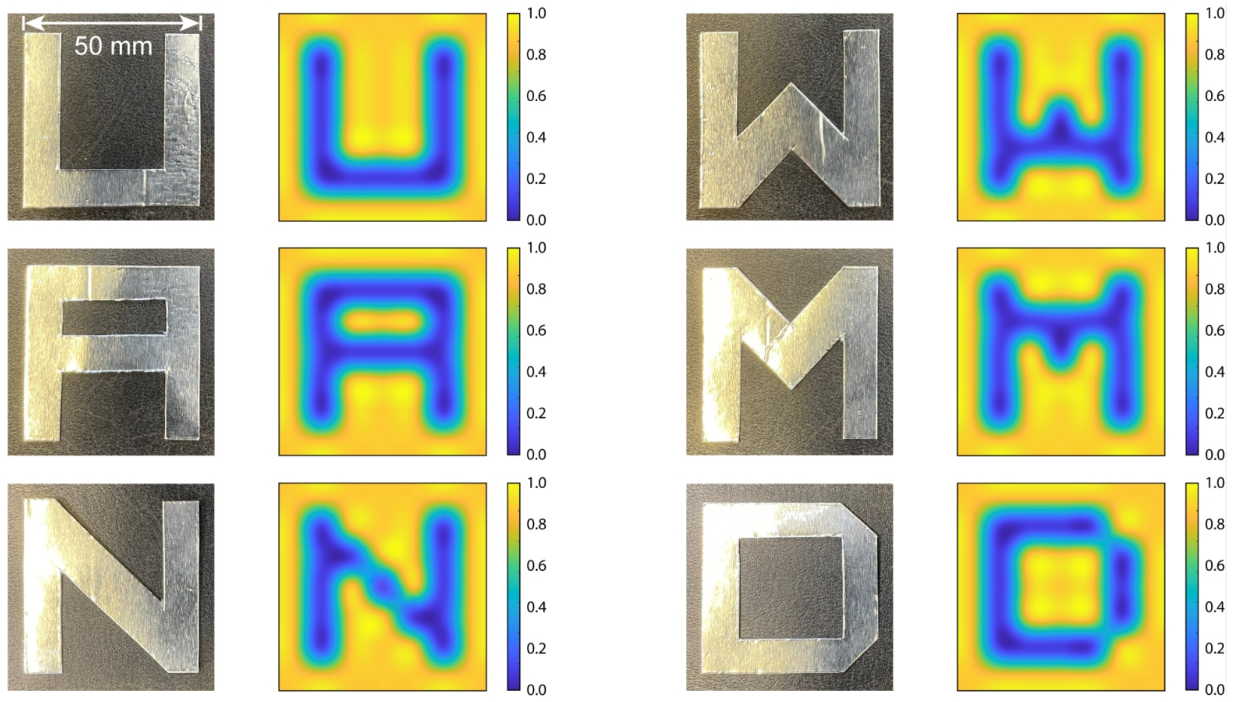


Figure 3.17: Exhibition of the MAIS's accurate biomedical imaging capability. Six distinct metal letter models on human skin-representative of the University of Waterloo Advanced Micro-Nano Devices Lab (UWAMND) are precisely visualized, showcasing the MAIS's ability to accurately detect and image the anomalies on human skin.

real-time with the refresh rate of 10 Hz, detailed in Figures 3.17, demonstrate the system’s capability to rapidly produce accurate images.

The exceptional imaging results reveal the unique attributes of the microbolometer’s structural design, fabrication techniques, and material composition, reinforcing its practical performance and reliability. These key elements of the microbolometer have led to significant improvements in the accuracy, speed and sensitivity of our innovative MAIS, particularly effective in the precise detection of anomalies in the surface or even deeper layers of the human skin. These advancements significantly bolster the biomedical imaging functionalities of the innovative MAIS, representing a notable advancement in the field of THz technology.

3.4 Chapter Summary

This study marks a significant advancement in THz imaging technology, primarily attributable to the development of the novel graphene-integrated microbolometer and the microbolometer array imaging system (MAIS). The microbolometer’s innovative structure design, enhanced by the strategic integration of graphene, has markedly improved its response speed and sensitivity. This is demonstrated by its rapid average response time of 0.246 s, a peak responsivity of $8.95 \times 10^5 \text{ V W}^{-1}$, and an optimal detectivity of $5.97 \times 10^8 \text{ cm Hz}^{1/2} \text{ W}^{-1}$, across a broad operational bandwidth of 1 - 5 THz. These advancements significantly boost the speed and precision of our MAIS, making it particularly effective for non-ionizing and non-invasive biomedical applications within the THz spectrum. Additionally, the MAIS’s capability to detect subtle variations in THz radiation with high accuracy underscores its potential utility in critical areas such as skin disease diagnostics and extensive biomedical imaging applications. Future studies will concentrate on validat-

ing the microbolometer’s performance across varied real-world settings, with an emphasis on improving portability, accessibility, and reliability to enhance its applicability in extreme conditions. In conclusion, this research not only addresses existing challenges in THz detection but also establishes a solid foundation for advancing THz imaging technologies. The significant advancements achieved herein facilitate the future creation of cost-effective, high-performance THz detection and imaging solutions in various biomedical applications.

Chapter 4

Novel Micro Circular Log-Periodic Antenna Design

4.1 Aims and Highlights

THz radiation, situated between microwave and infrared bands, exhibits a unique set of electromagnetic properties that distinguish it from other spectral regions. THz is known for their non-ionizing characteristics, making them intrinsically safe for interaction with biological tissues and sensitive materials. Additionally, THz radiation can penetrate a wide variety of non-metallic and non-polar materials while remaining highly responsive to changes in material composition and structure. This dual capability of transmission and sensitivity enables precise probing of internal features without destructive impact [136, 137]. Furthermore, THz waves are characterized by their short wavelengths, which support high spatial resolution in imaging and enable the miniaturization of integrated systems. From a spectral standpoint, many molecules and crystalline structures exhibit distinctive

vibrational and rotational resonances in the THz range, offering rich spectral information for material identification and structural analysis. The inherently broad bandwidth and large available spectrum also make THz frequencies highly attractive for high-capacity signal transmission [35, 138]. Collectively, these attributes define THz technology as a powerful platform for advanced sensing, precise imaging, and high-speed communication applications. The ongoing exploration and development of THz technology are catalyzing significant advancements across multiple disciplines, opening new avenues for scientific research and practical applications [139, 140, 141].

Despite the remarkable potential of THz technology across various domains, its successful integration into practical systems hinges on the development of highly efficient and precisely engineered components, particularly in THz antenna design. As the primary interface for emitting and capturing electromagnetic radiation, the antenna exerts a decisive influence on key system attributes, including physical dimensions, operational bandwidth, and overall system performance [142, 143]. However, the high-efficient THz antenna design continues to pose a major technical challenge, constrained by persistent limitations that hinder both scientific advancement and industrial deployment [144, 145]. One fundamental issue stem from the extremely short wavelength of THz waves, which necessitate physically miniature antenna structures. These size constraints not only complicate fabrication but also degrade radiation efficiency due to increased material and surface losses [146, 147]. In addition, achieving broadband operation across the THz spectrum is particularly difficult, as traditional antenna geometries often exhibit narrowband responses and poor frequency agility. The gain and impedance matching of conventional THz antennas are typically sub-optimal, further limited by intrinsic material losses and the complexity of integrating them with other microscale or on-chip components [137, 148, 149]. These limitations indicate an urgent need for innovative antenna architectures that can simultaneously achieve compact-

ness, broadband high gain, effective impedance matching, and enhanced radiation control. Addressing these challenges is essential for realizing the full potential of THz technology in next-generation sensing, imaging, and high-speed communication systems.

To effectively address the aforementioned challenges, we introduce a novel **MCLPA** architecture, structurally designed and optimized using an advanced **ENN** algorithm. The ENN algorithm has been extensively adapted and tailored in our study to suit the specific demands of THz antenna design, enabling efficient and precise tuning of critical variables. This advanced algorithm-driven design framework enables automated optimization of MCLPA structure, ensuring miniaturization, broadband operation and stable impedance matching across the targeted THz frequency range. The proposed ENN-guided MCLPA demonstrates an exceptional performance profile, achieving a wide 372 GHz bandwidth (0.135-0.507 THz), a peak gain of 5.51 dBi, an optimal S-parameter (S_{11}) of -13.68 dB, and the maximum radiation efficiency of 82.39%, comprehensively demonstrating its broadband operation and efficient signal transmission. The compact architecture, coupled with the substantial overall system performance, enables highly responsive and reliable THz radiation detection. Comprehensive experimental evaluations including radiation-dependent electrical responses and **Signal-to-Noise Ratio (SNR)** analysis further validate the antenna's high sensitivity and robust performance under realistic operational conditions. Additionally, the time-domain measurements validate rapid and consistent response of MCLPA to THz radiation, reinforcing the MCLPA's suitability for advanced THz detection and imaging platforms. Moreover, the design's inherent scalability, particularly in array configurations, significantly amplifies its gain and directional responsiveness, paving the way for integration into high-resolution and high-throughput THz systems.

By leveraging the geometric flexibility of the MCLPA architecture alongside the intelligent global optimization capabilities of the ENN framework, this study introduces an

advanced, scalable and high-efficiency design paradigm that accelerates antenna development while preserving exceptional electromagnetic performance. The synergistic integration of structural innovation and advanced algorithmic optimization not only enhances the reliability and adaptability of THz antenna designs but also significantly improves design efficiency and cost-effectiveness. This innovation establishes a new benchmark in THz antenna engineering, offering a powerful and flexible framework for the development of next-generation THz sensing, imaging, and communication platforms across a wide range of scientific and industrial applications.

4.2 Methods

4.2.1 Fabrication

Our MCLPA features dual-material architecture, combining a Cu-based radiating structure and feedline with an Al circular ring reference element. This configuration strategically exploits the high electrical conductivity of Cu for efficient THz absorption, while utilizing Al's lightweight properties to maintain structural balance and integration flexibility. A low-loss PCB with a pre-deposited high-frequency connector interface was cleaned using an ultrasonic IPA bath, followed by nitrogen drying to remove surface contaminants. The Al circular reference ring was deposited using E-beam evaporation at a rate of approximately 2 Å/s under a vacuum pressure of 3.9×10^{-7} Torr, yielding a uniform thickness of 200 nm. The antenna geometry was precisely defined through a custom-designed mask, allowing accurate pattern transfer of the MCLPA structure onto the substrate. The Cu antenna layer was subsequently deposited via E-beam evaporation, forming a 300 nm thick film. Post-deposition, the antenna undergoes a final cleaning process to eliminate residual

chemicals or particulates, thereby preserving surface quality and electrical integrity. The Cu feedline is then connected to the connector using the high-conductivity solder to ensure stable electrical interfacing. The completed device is mounted on a dielectric holder to minimize external interference. Final inspection includes [SEM](#) imaging to verify the fidelity of geometric alignment and deposition accuracy. This robust and reproducible fabrication workflow ensures high-performance, application-ready THz antennas with excellent mechanical stability, optimized impedance matching, and integration compatibility for advanced THz systems.

4.2.2 Characterization

To characterize the structure of our MCLPA, we employed a JEOL JSM-7200F SEM with settings of 10.0 kV voltage and a 10 nA beam current. During the characterization process, a Newport Oriel 67030 blackbody source was used, and an optical cutoff lens was applied to filter frequencies, thereby minimizing spectral interference for the detailed MCLPA analysis. The measurement equipment comprised a Keithley Model 6500 digital multimeter and a LeCroy LT322 oscilloscope, which ensured precise data acquisition. The experimental setup maintained a 10 cm distance between the MCLPA and the source throughout the experiments.

4.3 Results and Discussion

4.3.1 Design of MCLPA

Traditional [Log-Periodic Antenna \(LPA\)](#), as illustrated in Figure 4.1(a) and (b), are composed of geometrically scaled elements that progressively decrease in size, enabling stable gain and impedance characteristics across a broad frequency spectrum [\[150, 151\]](#).

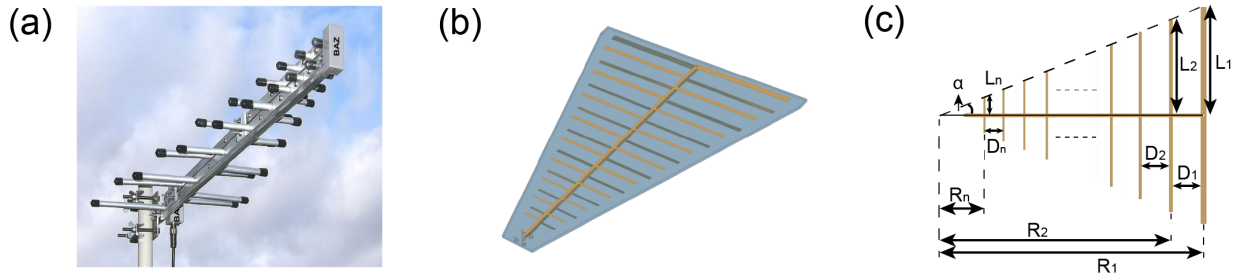


Figure 4.1: (a) presentative implementation diagram of a log-periodic antenna in practical applications. (b) Schematic diagram of linear log-periodic antenna configuration. (c) Geometric parameters illustration of linear log-periodic antenna.

The broadband functionality of LPAs arises from a precisely defined logarithmic scaling of element lengths and spacings, which ensures that each segment resonates within a specific frequency range as shown in Figure 4.1(c). The element lengths progress from L_1 to L_n , with each contributing to the overall spectral coverage. This geometric progression is quantitatively characterized by the scale factor τ [\[152\]](#):

$$\tau = \frac{L_{n+1}}{L_n} = \frac{R_{n+1}}{R_n} \quad (4.1)$$

Here, τ is always less than 1, indicating a proportional decrease in the size and space of successive elements [\[153\]](#). Correspondingly, the operational wavelength λ associated with

each antenna element adheres to a constant ratio [154]:

$$\frac{L_1}{\lambda_1} = \frac{L_2}{\lambda_2} = \dots = \frac{L_n}{\lambda_n} = C \quad (4.2)$$

This ratio C relates the length of each element to its operational wavelength, ensuring that each element remains resonant within its assigned frequency band [152]. Therefore, the frequency progression across the antenna elements utilizes logarithmic properties can be described by the relation [155]:

$$\ln f_{n+1} - \ln f_n = \ln \frac{1}{\tau} \quad (4.3)$$

This logarithmic decrement in frequency enhances the wideband characteristics of the antenna, which is essential for the practical applications requiring robust and continuous spectral coverage.

While conventional linear LPAs perform well over broad bandwidths, their adaptation to the THz regime introduces considerable challenges. Designed primarily for lower-frequency operation, these linear LPAs often require relatively large physical dimensions, complicating their integration into miniaturized systems, which is a key requirement in modern THz applications [156, 157]. Furthermore, maintaining high performance at THz frequencies demands extreme precision in element spacing and alignment, significantly increasing fabrication complexity and cost. These constraints limit the practical applicability of traditional LPAs in scenarios that demand both compactness and economic scalability [158, 159, 160]. To overcome these limitations, we introduce the MCLPA architecture that reconfigures the conventional linear layout into a compact circular topology. This structural innovation preserves the essential broadband characteristics of the original design while dramatically enhancing spatial efficiency and integration potential. As illustrated

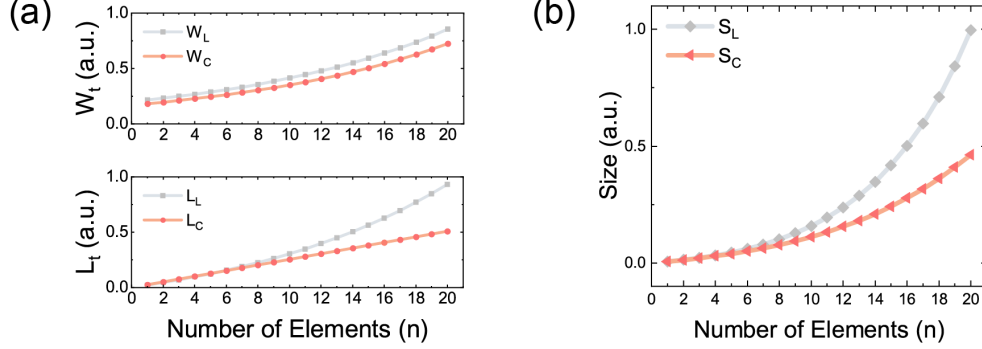


Figure 4.2: **(a)** Total width and total length comparison across linear and circular LPAs with increasing elements. **(b)** Size variation in LPAs with increasing elements, proving MCLPA's compactness.

in Figure 4.2(a) and (b), a comparative analysis reveals that when the minimum element lengths and the distance between the first two elements are aligned for both the linear and circular configurations, the circular design results in a significantly more compact size. Notably, for 20 elements, the linear LPA occupies nearly twice the area required by the circular counterpart, clearly demonstrating the spatial advantage of the MCLPA. This compact geometry not only reduces the physical dimensions but also enables seamless integration with state-of-the-art THz detectors, offering a practical solution to advance the deployment of high-performance THz technologies in portable and embedded systems.

Although the MCLPA differs geometrically from conventional linear LPAs, it retains the fundamental principles outlined in Equations 4.1, 4.2, and 4.3, comprising a sequence of scaled radiating elements to achieve wideband functionality. As illustrated in Figure 4.3(a) and (b), the proposed MCLPA architecture features a sophisticated design framework, defined by a high-dimensional set of interdependent parameters. These include the number of elements (n), the scale factor (τ), the element widths proportion ($\beta = \frac{W_n}{R_n - R_{n+1}}$), and a series of physical dimensions including lengths ($L_1, L_2, \dots, L_n$), radii ($R_1, R_2, \dots, R_n$), widths ($W_1, W_2, \dots, W_n$), as well as the angular parameters (α_1, α_2). While this intricate

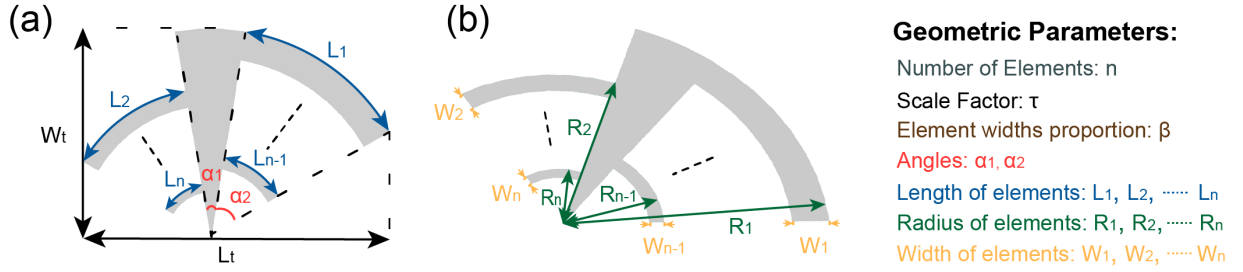


Figure 4.3: (a) Top view layout of circular log-periodic antenna, showing the total length and total width (L_t, W_t), angles(α_1, α_2) and element lengths (L_1-L_n). (b) Geometric parameters of circular log-periodic antenna elements, detailing radii (R_1-R_n) and elements widths (W_1-W_n).

configuration enables compact integration and broadband operation without compromising electromagnetic performance, it also introduces substantial design complexity, rendering conventional trial-and-error or manual tuning approaches less effective at THz frequencies [161, 162]. Leveraging recent advances in algorithmic intelligence, this study applies a customized ENN framework to address the complex design challenges associated with the MCLPA. While conventional approaches such as genetic algorithms (GA) and particle swarm optimization (PSO) have been explored in antenna design, their application to intricate THz MCLPA structures is hindered by substantial computational costs and slow convergence, which primarily due to their reliance on extensive full-wave simulations in high-dimensional, nonlinear parameter spaces [163, 164]. In contrast, the proposed ENN framework combines surrogate modeling with evolutionary strategies, substantially accelerating the optimization process while dramatically reducing the number of simulation evaluations required. This integrated approach enhances optimization efficiency, scalability, and robustness, making it particularly well-suited for the design of sophisticated THz MCLPA [165, 166, 167].

4.3.2 Architectural of ENN

The ENN algorithm, illustrated in Fig.4.4, facilitates the optimization of the MCLPA design through a dynamic and iterative evolutionary process. The optimization begins with the generation of an initial population of 20 individuals, each encoding a unique configuration defined by specific geometric parameters and performance characteristics of the MCLPA. Subsequent optimization is governed by standard evolutionary operators including crossover, mutation, performance evaluation, and selection. Crossover promotes the exchange of favorable traits between high-performing designs to explore beneficial configurations in the solution space, while mutation introduces controlled stochastic variations to enhance diversity and prevent premature convergence to local optima. After performance evaluation, the top 5 high-performing candidates are selected based on a predefined fitness function. These elite individuals are retained directly, and new offspring are generated by applying crossover and mutation operations on them to replenish the population back to its original size of 20. This strategy ensures a balance between exploration and exploitation, maintaining diversity while preserving high-quality solutions. Following each evolutionary iteration, all top-rated candidates are validated via high-fidelity COMSOL simulations. The simulation results are then used to iteratively retrain the ENN model, continuously refining its predictive accuracy and guiding the optimization process toward globally optimal MCLPA designs.

The proposed ENN model adopts an efficient architecture consisting of five input neurons n , τ , β and α_1, α_2 , which define the fundamental geometric parameters of the MCLPA. The corresponding element lengths, radii and widths can be subsequently calculated using the scaling laws described in Equations 4.1 and 4.2. During the optimization of the proposed MCLPA via the advanced ENN framework, a well-defined search space for the input

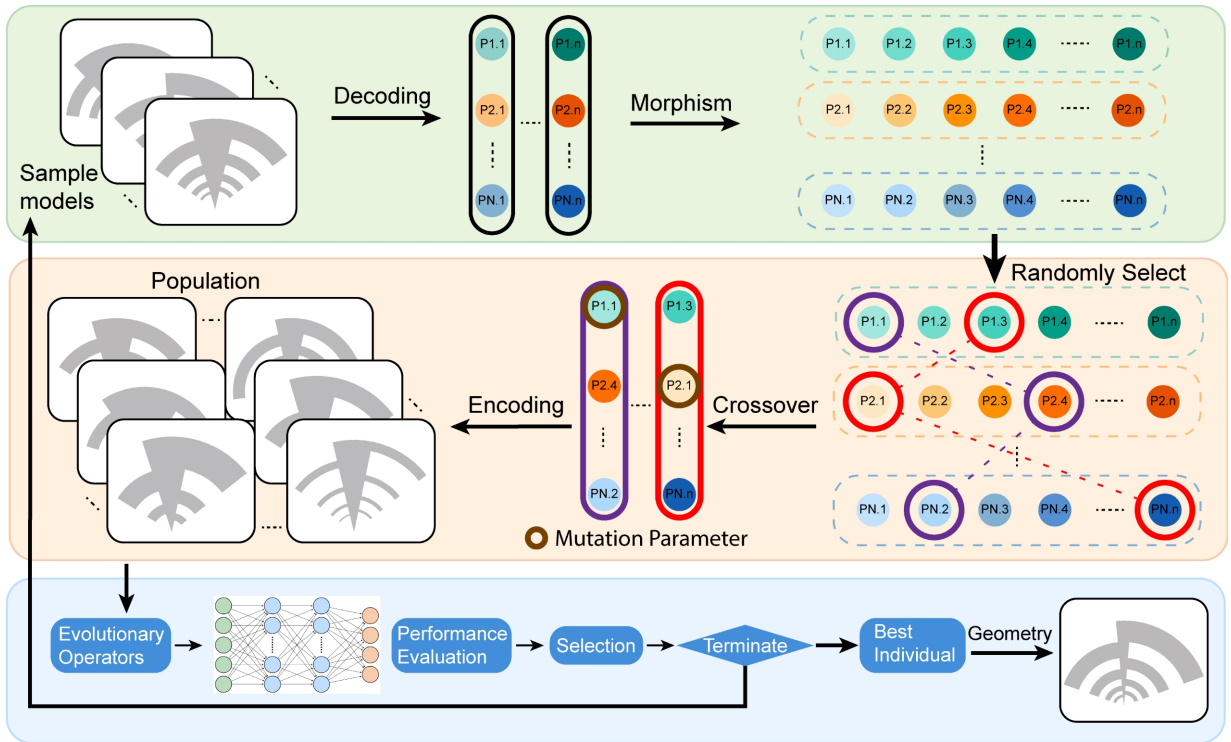


Figure 4.4: Flowchart illustrating the ENN algorithm for antenna design: from initialization to optimal geometry selection.

neurons was established to ensure convergence within practical manufacturing and operational constraints. Specifically, the number of elements n was restricted to the range of 1-10 to maintain structural compactness. The scale factor τ was restricted to the range of 0.7-0.95 to ensure the physically realizable progression of element dimensions. The element widths proportion β was limited to values below 1, satisfying the condition $W_n \leq R_n - R_{n+1}$, which ensures appropriate spacing between adjacent elements. The angular parameters α_1 and α_2 were confined within the range of 10 to 80 degree to preserve a balanced angular distribution. Furthermore, the aggregate angular coverage was constrained by the inequality $2\theta_1 + \theta_2 < \pi$, ensuring that the antenna geometry remains within a semi-circular domain. These carefully formulated search spaces guide the ENN's search trajectory, enabling the generation of high-performance MCLPA designs that are not only electromagnetically efficient but also practically realizable.

The neural network architecture comprises two hidden layers containing 64 and 32 neurons, respectively. Each layer employs the Rectified Linear Unit (ReLU) activation function, defined as $f(x) = \max(0, x)$. ReLU is chosen for its computational efficiency and its effectiveness in alleviating vanishing gradient problems during training [168, 169]. To enhance modularity and interpretability, the output layer is structured in two stages. The first stage comprises four linear neurons that independently predict key performance indicators, including gain, S_{11} , Y-parameter, and [Voltage Standing Wave Ratio \(VSWR\)](#). The second stage applies a fitness function F , which is formulated as a weighted combination of the key performance indicators, expressed as [161]:

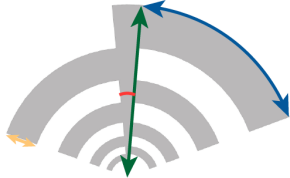
$$F = \sum_{i=1}^n w_i \cdot M_i \quad (4.4)$$

where w_i denotes the weighting factor applied to the average value of the i -th performance

metric M_i within the target frequency range. This fitness function serves as a comprehensive metric for evaluating the performance and suitability of each MCLPA configuration, guiding the evolutionary process by selecting high-fitness candidates for propagation in subsequent generations. The weighting coefficients within the fitness function were empirically calibrated through iterative experimentation to achieve an optimal trade-off between convergence efficiency and global optimization. These coefficients encode the relative priorities of key design objectives, including gain, S_{11} , Y-parameter, VSWR and n , thereby guiding the optimization toward a compact and high-performance MCLPA configuration. The final fitness function adopted in this study is defined as:

$$\text{Fitness} = \text{Gain} - 2 \times S_{11} - 100 \times |\text{Y-parameter} - 0.02| - 5 \times \text{VSWR} - 0.1 \times N^2 \quad (4.5)$$

Although fixed in the current implementation, the ENN framework offers considerable flexibility and can be effectively extended to application-specific tasks by adjusting the weight scheme and performance matrix.



Geometric Parameters	Values	Unit
Number of elements (n)	8	/
Scale factor (τ)	0.76	/
Element widths proportion (β)	1	/
Angles (α)	α ₁ =10, α ₂ =62	deg
Length of elements (L)	L ₁ =2.92, L ₂ =2.22, L ₃ =1.69, L ₄ =1.28, L ₅ =0.97, L ₆ =0.74, L ₇ =0.56, L ₈ =0.42	mm
Radius of elements (R)	R ₁ =2.70, R ₂ =2.05, R ₃ =1.56, R ₄ =1.19, R ₅ =0.90, R ₆ =0.68, R ₇ =0.52, R ₈ =0.40	mm
Width of elements (W)	W ₁ =0.65, W ₂ =0.49, W ₃ =0.37, W ₄ =0.29, W ₅ =0.22, W ₆ =0.16, W ₇ =0.12, W ₈ =0.09	mm

Figure 4.5: Optimal geometric parameters of the MCLPA.

The integration of a multi-objective fitness function within the ENN framework substantially enhances the optimization process by simultaneously assessing multiple performance metrics. This advanced approach subsequently enables each top-rated candidate antenna

configuration to undergo comprehensive performance evaluation and iterative refinement. The optimization process continues for a minimum of 200 epochs and terminates early if neither the fitness score nor the mean square error (MSE) loss shows significant improvement over twenty consecutive epochs. The optimal geometric outcomes of this robust ENN-enhanced optimization process are detailed in Figure 4.5, demonstrating the ENN algorithm's high efficacy and robustness in tailoring geometric parameters of MCLPA. To rigorously assess the performance of our antenna design methodology, we conducted a comparative analysis between the proposed ENN framework and a conventional deep neural network (DNN) comprising four hidden layers.

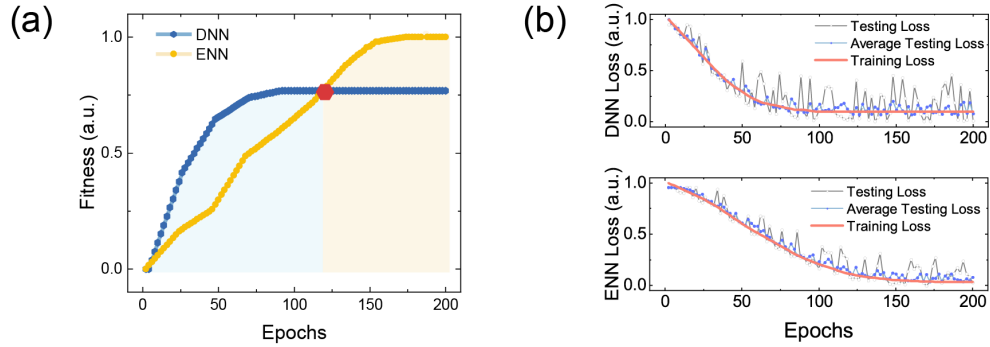


Figure 4.6: Comparative analysis of ENN and DNN algorithms. **(a)** Progression of fitness for ENN and DNN models over training epochs. **(b)** Comparison of the trends in training and testing losses.

As depicted in Figure 4.6(a), the fitness evolution in 200 training epochs demonstrates that the ENN achieves a steady and sustained improvement, ultimately surpassing the DNN at epoch 119. In contrast, the DNN exhibits a sharp initial increase in fitness but stagnates after epoch 75, indicating its susceptibility to premature convergence within the high-dimensional and nonlinear optimization landscape characteristic of the MCLPA design space. The training and testing loss trajectories for both models are presented in Figure 4.6(b). In this context, the MSE loss function quantifies the deviation between

the predicted and validated fitness values, guiding the model’s optimization process. Both models exhibit decreasing training and testing loss, reflecting improved predictive accuracy over time. However, the ENN demonstrates superior generalization, as evidenced by a continued reduction in testing loss until epoch 157, whereas the DNN’s testing performance plateaus after approximately 50 epochs. These findings underscore the ENN’s enhanced capability in navigating complex multi-objective design constraints and achieving robust optimization in THz antenna development.

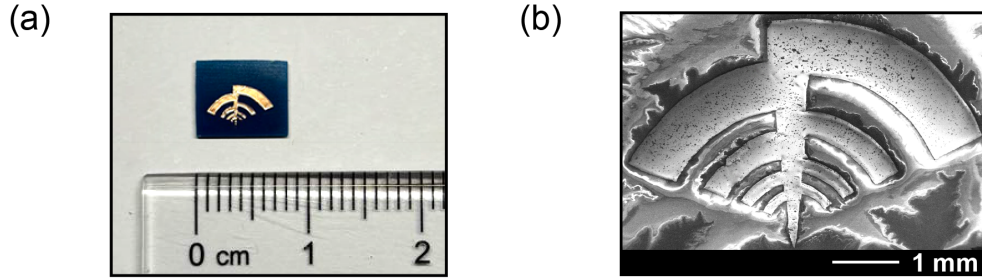


Figure 4.7: (a) Optical imaging showing the scale representation of our MCLPA. (b) SEM image revealing the precise microstructure of the MCLPA.

The practical realization of the proposed structure is illustrated in Figure 4.7(a), which presents the fabricated MCLPA prototype developed using the ENN framework. With a diameter near 5 mm, the antenna exhibits a highly compact form factor, demonstrating its potential for seamless integration into portable and space-constrained THz platforms. The SEM image in Figure 4.7(b) reveals the high-precision microfabrication of the antenna, characterized by logarithmically scaled radiating elements extending radially from the center. This finely structured geometry is instrumental in achieving broadband operation and enhanced sensitivity, which are crucial for efficient THz radiation capture and transmission in next-generation imaging, sensing, and communication systems.

Figure 4.8 presents a comprehensive statistical analysis of the evolutionary performance metrics over 200 training epochs for the ENN-optimized THz MCLPA. At each epoch, the critical performance indicators of all 20 unique antenna configurations were evaluated and recorded, including gain, S_{11} , Y-parameter, VSWR, and the overall fitness score. The resulting plots capture the distribution of these performance metrics across a total of 4000 evaluated MCLPA instances, with error bars representing standard deviations and central markers indicating mean values. Collectively, this analysis offers a multidimensional perspective on the influence of geometric parameters on antenna behavior across the THz spectrum, and the evolution of fitness serves as a critical indicator of the overall performance and adaptability of the MCLPA. As illustrated in the bottom row of Figure 4.8, each subplot presents the relationship between the fitness score and specific geometric parameters, including the number of elements (n), the scale factor (τ), the element width proportion (β), and the angular parameters (α_1, α_2). The fitness trajectory with respect to n reveals a generally increasing trend, reaching its maximum at $n = 8$. This observation indicates a positive correlation between the number of radiating elements and the antenna's overall performance within our experimental domain. The widening distribution of fitness values with increasing n further highlights the trade-off between performance improvements and the compactness or fabrication complexity of the antenna. For τ , the fitness response exhibits pronounced variability across the tested range, underscoring the critical influence of inter-element scaling on antenna behavior. A gradual rise in average fitness is observed up to around $\tau = 0.76$, beyond which performance declines. Although a partial recovery is noted after $\tau > 0.87$, the fitness values remain significantly below the earlier peak. Regarding β , the results reveal a generally increasing fitness trend with larger element widths proportion. This suggests that broader elements improve the an-

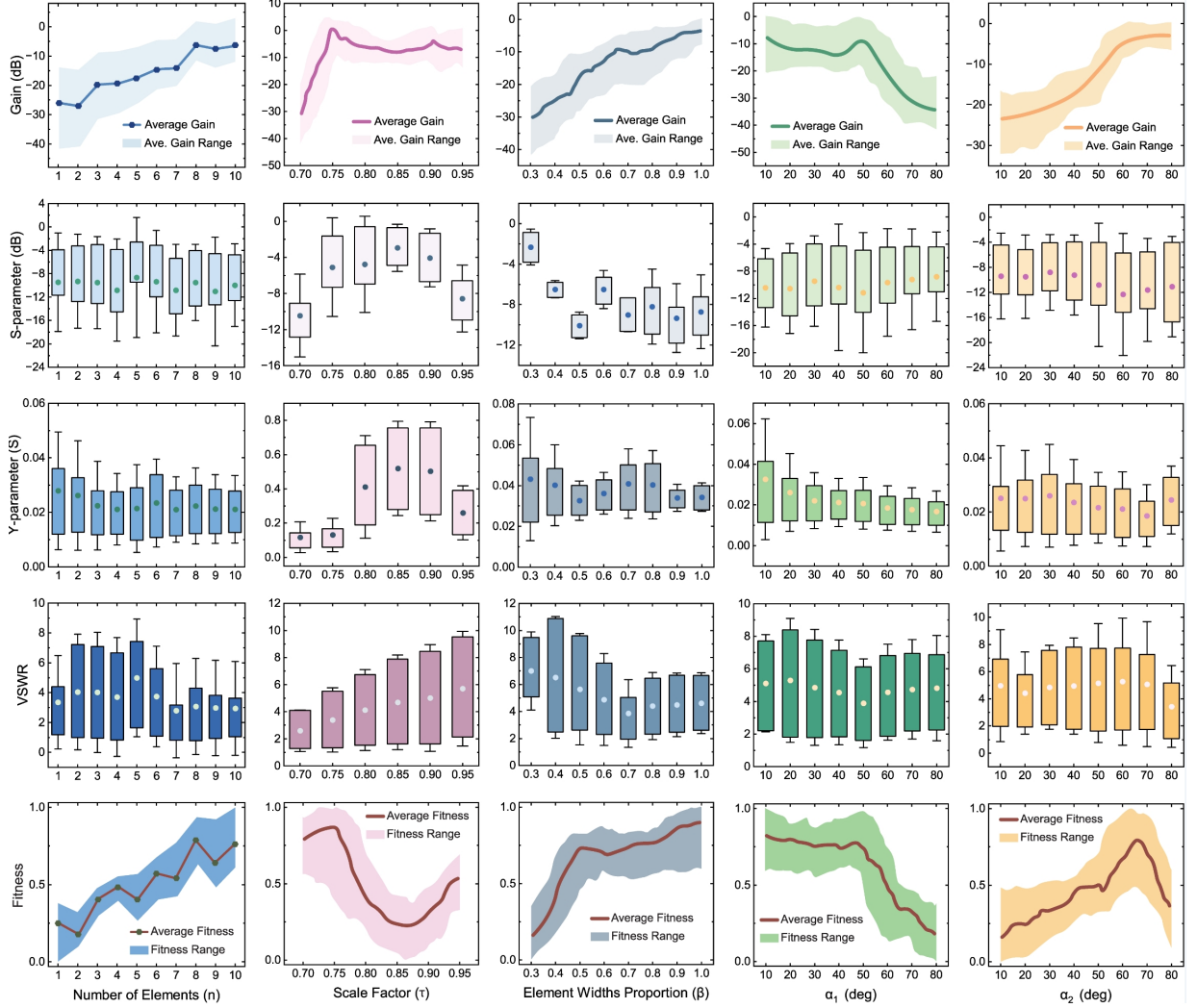


Figure 4.8: Comprehensive statistical analysis of MCLPA performance metrics aggregated from 4,000 evaluated configurations. The plots illustrate the optimization dynamics of geometric parameters across successive generations, demonstrating their impact on key performance indicators including gain, S_{11} , Y-parameter, and VSWR, as well as the resulting composite fitness scores.

tenna's efficiency in capturing THz radiation. The fitness distribution for α_1 reveals a distinct peak at 10 degree and remains relatively stable till 47.5 degree, beyond which the fitness values decline. This trend suggests that excessive α_1 configurations may impair the formation of efficient radiation patterns or degrade impedance matching. In contrast, the response to α_2 shows a global fitness maximum around 62 degree, with a high-performance window between 60 and 70 degree. The broad spread in fitness values within this range illustrates the antenna's sensitivity to variations in α_2 , reflecting its critical role in mediating electromagnetic interactions among the elements. The fitness metric serves as a comprehensive performance indicator, reinforcing the ENN's effectiveness in optimizing complex geometric parameters to achieve superior antenna functionality. The observed correlations between fitness and individual parameters substantiate the algorithm's capacity to converge toward optimal configurations, confirming the results previously illustrated in Figure 4.5. These findings underscore the ENN's precision and reliability in designing compact, broadband and high-performance antennas, marking a significant advancement in automated, algorithm-driven design methodologies. The successful implementation of this framework in the development of the MCLPA exemplifies a paradigm shift from conventional approaches to intelligent optimization strategies in THz antenna engineering.

4.3.3 Performance characteristics

In antenna engineering, gain serves as a primary metric for characterizing the efficiency of converting input power into radiated energy in a given direction. It is typically expressed in decibels relative to an isotropic radiator (dBi) and is calculated using the following relation [170]:

$$Gain = 10 \log_{10} \left(\frac{P_{\text{radiated}}}{P_{\text{isotropic}}} \right) \quad (4.6)$$

Where P_{radiated} represents the power radiated in a given direction and $P_{\text{isotropic}}$ is the power radiated by an isotropic source under the same conditions. A high gain indicates the effectiveness and efficiency of the antenna in practical applications.

Scattering parameter (S-parameter) is a fundamental metric used to characterize the reflection and transmission behavior of an antenna under incident excitation, typically expressed in decibels (dB). Among these, S_{11} is the most widely analyzed, quantifying the proportion of input power that is reflected back from the antenna. It is defined as [171]:

$$S_{11,\text{dB}} = 10 \log_{10} \left(\frac{P_{\text{reflected}}}{P_{\text{input}}} \right) \quad (4.7)$$

A lower S_{11} value indicates better impedance matching and minimal reflection, which are essential for efficient power transfer and optimal antenna performance in high-frequency communication systems.

The Y-parameter characterizes the admittance of an antenna, quantifying the ease with which current flows in response to an applied voltage and is expressed in siemens (S). It is mathematically defined as [172]:

$$Y = \frac{1}{Z} = \frac{1}{R + jX} \quad (4.8)$$

where R and X represent the resistive and reactive components of the antenna's impedance, respectively. In high-frequency communication systems, precise impedance matching between the antenna and transmission line is critical to minimize signal reflections and ensure efficient power delivery. The proposed design targets a Y-parameter around 0.02 S, indicative of effective impedance matching and stable operational performance across the THz band.

The Voltage Standing Wave Ratio (VSWR) quantifies impedance matching efficiency by measuring the ratio of the maximum to minimum voltage along a transmission line, arising from the superposition of incident and reflected waves. It is mathematically expressed as [173]:

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (4.9)$$

where $|\Gamma|$ denotes the magnitude of the reflection coefficient, defined as $\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$. Here, Z_L represents the load impedance of the antenna and Z_0 is the characteristic impedance of the transmission line. Maintaining a low VSWR is critical for optimizing signal integrity and transmission efficiency in THz systems, directly contributing to enhanced detection sensitivity and system reliability across diverse application environments.

To validate the structural robustness and material adaptability of the proposed MCLPA, we systematically evaluated its performance using two conventional antenna materials: copper (Cu) and aluminum (Al). A comprehensive comparative analysis was conducted throughout the characterization process as demonstrated in Figure 4.9 and Figure 4.10. In addition, we performed an extended tolerance analysis to assess the antenna's resilience to material property variations and fabrication imperfections. This included $\pm 10\%$ deviations in the conductivity of Cu and Al, $\pm 10\%$ changes in substrate permittivity, and $\pm 10\%$ geometric scaling of the MCLPA structure. The results reveal that while material and fabrication tolerances tend to have a more pronounced negative effect at higher frequencies, the MCLPA consistently maintains stable and reliable performance across the 0.1-0.6 THz range, indicating its robustness for practical implementation.

Figure 4.9(a) illustrates the frequency-dependent peak gain of the Cu- and Al-based MCLPAs across the 0.1-0.6 THz range. Both variants exhibit similar gain trends over the spectrum, with the Cu-based configuration consistently achieving slightly higher peak val-

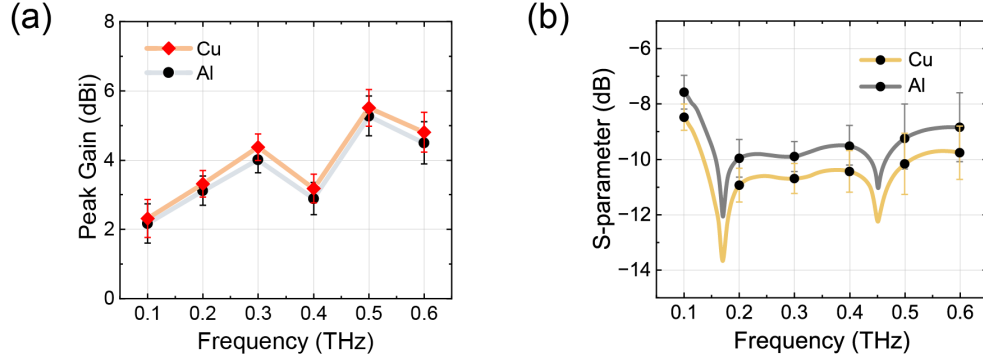


Figure 4.9: (a) Peak gain of our MCLPA in the frequency range 0.1-0.6 THz. (b) S_{11} response across the target THz frequency spectrum.

ues. Notably, the Cu implementation attains a maximum gain of approximately 5.51 dBi at 0.5 THz, indicating its superior radiative efficiency. Figure 4.9(b) presents the corresponding S_{11} performance. For both materials implementations, S_{11} consistently remains below -7.53 dB across the target THz band, indicating strong impedance matching. The Cu-based MCLPA demonstrates particularly strong performance, with S_{11} values maintained below -10 dB from 0.135 to 0.507 THz, signifying a wide operational bandwidth. Notably, a peak S_{11} of -13.68 dB is achieved, corresponding to 95.7% of the incident power being efficiently coupled into the antenna. These results highlight the MCLPA's excellent broadband impedance characteristics and confirm its suitability for high-efficiency THz applications.

Figure 4.10(a) displays the real part of the Y-parameter across the 0.1-0.6 THz frequency range. For the Cu-based MCLPA, the Y-parameter remains within 0.0165 to 0.0283 S, while for Al, it ranges from 0.0157 to 0.0260 S. On average, both configurations exhibit Y-parameter values centered around 0.02 S throughout the operational bandwidth. This stable input admittance is critical for consistent energy absorption and minimal transmission loss, thereby enhancing overall antenna efficiency across the target spectrum. Figure

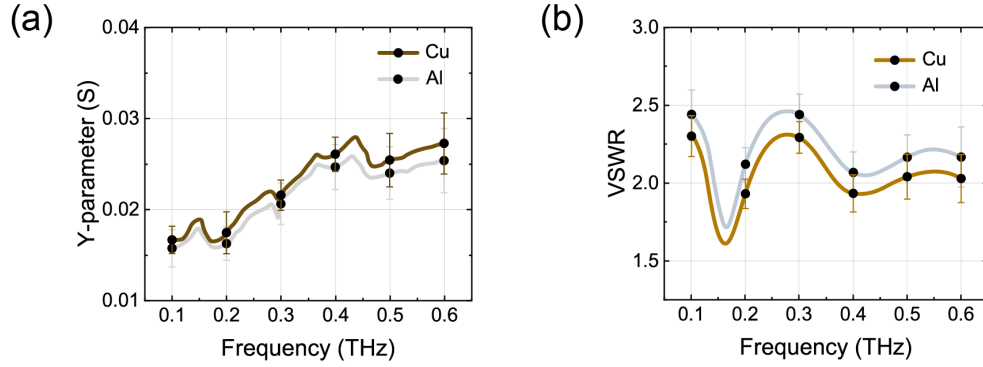


Figure 4.10: **(a)** Y-parameter frequency response over the target THz range. **(b)** VSWR profile over the target THz frequency range.

4.10(b) presents the practical VSWR observed during operation, which remains consistently around a value of 2. This stable impedance matching behavior reinforces the performance trends indicated by the S_{11} results. The minor deviation between the trends of S_{11} and VSWR arises from differences in their measurement perspectives, where S_{11} characterizes reflection at the port level, while VSWR represents impedance mismatches observed along the physical transmission line.

Figure 4.11 details the radiation patterns of the Cu-based MCLPA in both the E-plane and H-plane across six representative frequencies within the 0.1-0.6 THz range. While certain deviations from ideal pattern symmetry are observed particularly at higher frequencies, these variations are typical characteristics of broadband log-periodic structures, where multiple resonant elements contribute concurrently to the radiation. Despite this complexity, the antenna maintains a well-defined main lobe between 0.1 and 0.6 THz, with steady angular directivity and moderate side lobe levels. Notably, the gain remains consistently strong across the band, demonstrating the proposed design's robustness and applicability for high-resolution THz detecting systems that demand wideband operation.

Across the full 0.1-0.6 THz frequency range, the performance disparity between Cu-

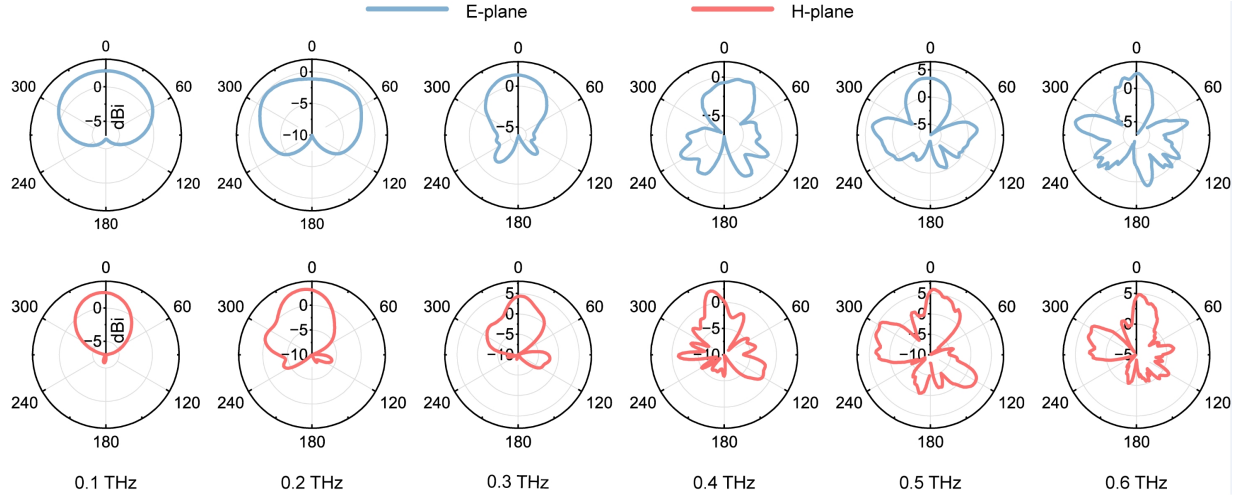


Figure 4.11: Comparative radiation patterns of THz antenna across 0.1 to 0.6 THz: E-plane and H-plane performance analysis.

based and AI-based MCLPAs remains minimal, verifying the structural robustness and material tolerance of the proposed design. This consistency affirms the antenna's reliability across commonly used THz conductor materials, ensuring broad applicability in diverse fabrication scenarios where material availability or compatibility may vary. Notably, the antenna maintains excellent impedance matching, stable admittance characteristics, and efficient signal transmission throughout the wide THz spectrum, these capabilities are a direct outcome of the advanced ENN-driven optimization framework, which enables precise tuning of complex geometric parameters to maximize electromagnetic efficiency. Collectively, the results position the proposed MCLPA as a broadband, high-performance, scalable solution for next-generation THz applications, exemplifying the practical and technical advantages of our ENN-driven antenna design strategy.

Following thorough evaluations, the novel MCLPA device, optimized using the advanced ENN algorithm, was fabricated for practical validation and testing. Figure 4.12(a) presents a schematic of the THz signal detection process, and Figure 4.12(b) details the

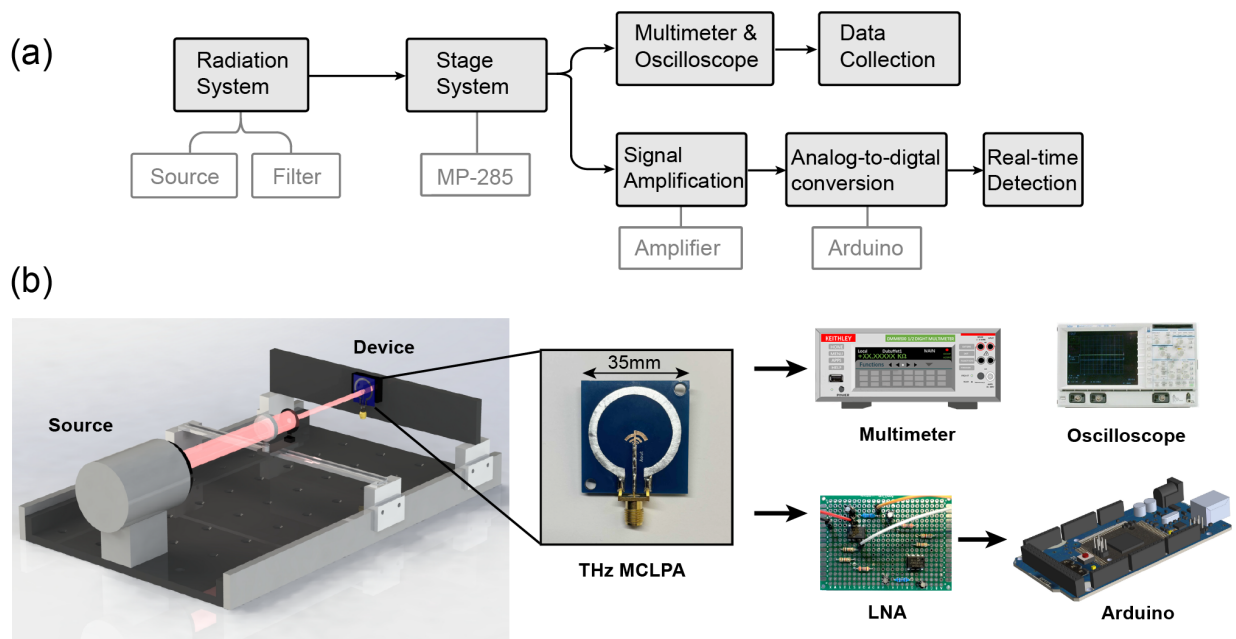


Figure 4.12: (a) Block diagram of the testing experimental setup. (b) Experimental Setup for THz Antenna Performance Evaluation: From THz Radiation Source to Read-Out System.

experimental setup, featuring meticulously arranged components applied to ensure precise THz signal capture and analyze. THz radiation was generated using a Newport Oriel 67030 blackbody source, with a radiation filter carefully positioned within the optical path to ensure that only radiation within the target spectrum range was received by the MCLPA. The MP-285 stage system facilitated precise positioning and angular adjustments of the device under tests, optimizing alignment with the THz radiation for accurate measurements. The MCLPA converts incident THz radiation into electrical signals, which are then transmitted to measurement devices including a Keithley 6500 multimeter and a LeCroy LT322 oscilloscope. On the other hand, to facilitate real-time detection and ensure precise time-domain analysis, weak electrical signals are initially amplified using our specially customized [Low Noise Amplifier \(LNA\)](#) for this MCLPA. The amplifier boosts signal amplitudes and reduces interference, incorporating a bandpass filter to minimize noise, thereby enhancing the clarity and quality of the detected signals. Subsequently, these enhanced signals are digitized via an [ADC](#) system, operated through an Arduino microcontroller. This digitization enables real-time signal processing and supports precise data collection and analysis, which are essential for evaluating and validating the antenna's performance.

Figure 4.13(a) displays the current-voltage (I-V) characteristics for the THz MCLPA fabricated from both Cu and Al. The linear I-V response from both materials confirms their ohmic behavior and excellent impedance matching. The Cu-based antenna shows a steeper I-V response than the Al-based antenna, indicating better electrical performance for THz applications. Figure 4.13(b) displays the voltage response of Cu and Al-based MCLPAs as a function of the THz radiation source temperature, ranging from 400°C to 900°C. The data demonstrates a distinct positive correlation between the source temperature and the voltage output for both materials. The Cu-based antenna consistently generates higher voltage outputs, with its voltage increasing from 7.86 μV to 13.90 μV as the radiation

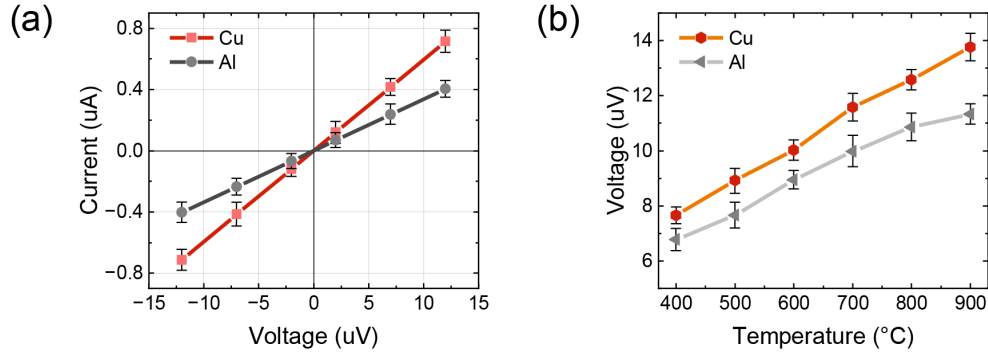


Figure 4.13: **(a)** Current-Voltage characteristics of our MCLPA. **(b)** Voltage response to increasing radiation source temperature.

source temperature rises. In contrast, the Al-based antenna exhibits a relatively slower voltage increase, peaking at approximately 11.37 μV . These results illustrate the typical response of THz radiation detection systems, where higher temperatures enhance radiation intensity, thereby boosting signal output.

Figure 4.14(a) illustrates the variation in SNR as a function of radiation temperature for our MCLPA. Both materials show a steady improvement in SNR with increasing source temperature, indicative of the antennas' effective design and performance. The Cu MCLPA demonstrates a notable SNR increase from 10.65 dB to 13.91 dB as radiation temperatures rise from 400°C to 900°C, and the Al MCLPA exhibits a growth from 10.25 dB to 12.88 dB in the same temperature range. The consistent growth in SNR across the temperature spectrum correlates with the increased intensity of THz radiation from the blackbody source, suggesting a stronger signal contribution relative to background noise as the source temperature rises. Figure 4.14(b) illustrates the directional detection performance of the fabricated MCLPAs under obliquely incident THz radiation. In the experimental setup, the antenna was initially positioned at a 30° angle relative to the incident wave and mounted on a high-precision rotational stage. Voltage outputs were systematically measured at

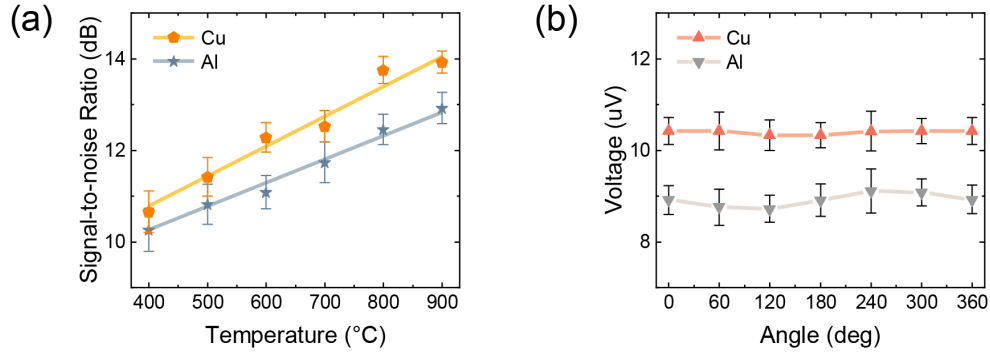


Figure 4.14: **(a)** SNR as a function of radiation source temperature. **(b)** Incidence radiation angular dependence of output voltage for MCLPA.

60° rotational increments to evaluate angular sensitivity. Despite observable variations across different orientations, the MCLPA exhibits consistently strong detection capability, with the Cu-based prototype delivering higher and more stable signal output. This responsiveness indicates the antenna’s robustness and adaptability, suggesting its potential for integration in practical THz imaging and communication platforms where dynamic angle-of-incidence performance is critical.

The results described in Figure 4.15(a) capture the time-domain response of the MCLPA to cyclic THz radiation exposure, effectively simulating on and off states. Using the MP-285 stage system, the MCLPAs were periodically positioned within and removed from the path of the radiation beam. The captured THz signals were amplified, digitalized and then recorded for detailed analysis. The experimental data reveals a rapid rise in output voltage for both materials upon radiation exposure, with the Cu-based MCLPA reaching a peak of approximately 14.46 mV and the Al-based counterpart peaking at 12.03 mV. After the radiation source was turned off, the voltage levels for both quickly dropped to nearly zero. These results reveal the MCLPA’s robust time-domain response and reliability, indicating its applicability in dynamic THz environments like real-time detection. Additionally, all

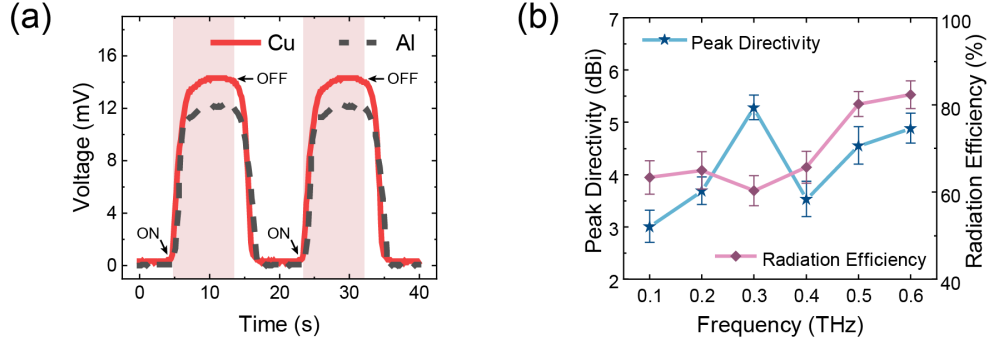


Figure 4.15: (a) Time-domain voltage response under periodic THz radiation exposure. (b) Peak directivity and radiation efficiency of the MCLPA over 0.1-0.6 THz.

the above comparative results between Cu and Al-based MCLPA indicate the potential for material optimization in THz antenna design. This reveals a promising direction for further enhancements in MCLPA performance, warranting detailed exploration in future studies. Figure 4.15(b) illustrates the MCLPA's performance across the target frequency range, with a peak directivity of 5.27 dBi at 0.3 THz, supporting THz detection in practical scenarios with multidirectional incident radiation. Alongside, the radiation efficiency achieves an exceptional average of 69.75% across the target frequency spectrum, with peaks reaching as high as 82.39%. This impressive efficiency underscores the innovative antenna design and the advanced optimization process, which refine energy utilization and enhance power transfer in our MCLPA.

4.3.4 Array configuration

By configuring the proposed MCLPA into an array architecture, we achieved a substantial enhancement in its peak gain and directivity. As shown in Figure 4.16(a), the E-plane radiation pattern of the 8×8 MCLPA array at 0.3 THz demonstrates the superior performance of our advanced MCLPA array. In this array configuration, each MCLPA is

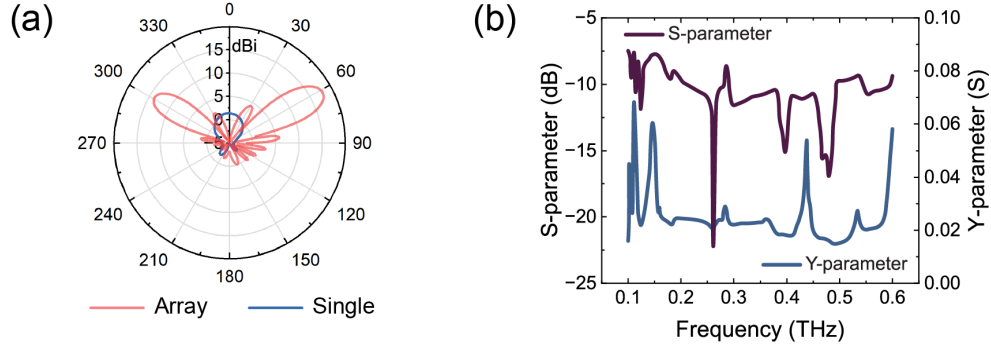


Figure 4.16: **(a)** Radiation patterns in E-Plane for the 8x8 MCLPA array configuration. **(b)** S_{11} and Y-parameter spectrum of the 8x8 MCLPA array configuration.

uniformly spaced by half the wavelength in both horizontal and vertical directions, forming a rectangular lattice. This layout represents a well-established compromise that effectively minimizes mutual coupling and suppresses sidelobes, as evidenced by the well-formed array radiation pattern and a main-to-side lobe ratio exceeding 11 dBi. Compared to the single-element MCLPA, the array demonstrates significantly enhanced angular selectivity and directional response, with a peak gain of 17.1 dBi attributed to the coherent radiation of multiple elements. This strategic-arranged MCLPA array also yields a well-formed radiation pattern with dual-lobe coverage, delivering an optimal balance of gain, directivity, and angular symmetry across a wide field. Figure 4.16(b) presents the analysis of the S_{11} and Y-parameter for an individual MCLPA element within the 8×8 array configuration across the 0.1-0.6 THz frequency range. The S_{11} remains consistently below -10 dB across a wide spectral range with pronounced minima surpassing -15 dB at multiple frequencies, indicating strong impedance matching and minimal reflection. Simultaneously, the Y-parameter maintains an average value near 0.02 S despite several fluctuations, reflecting stable input admittance and effective power coupling. The close alignment of low S_{11} , stable admittance values, and a well-formed array radiation pattern confirms that array integration does not introduce significant mutual coupling or impedance mismatch. These

Table 4.1: Performance comparison of state-of-the-art THz antennas.

Antenna Type	f (THz)	Bandwidth (GHz)	Gain (dBi)	S_{11} (dB)	Efficiency (%)	Ref.
Slotted Antenna	0.12	4.42	7.36	-42.41	99.75	[174]
Patch Antenna	0.76	31.00	3.71	-40.00	N/A	[143]
Slotted Patch Antenna	0.70	26.40	5.24	-50.95	N/A	[175]
Patch Antenna	0.68–0.70	24.00	6.79	-64.16	N/A	[142]
On-chip Antenna	0.36–0.59	229.00	4.00	N/A	93.00	[176]
Waveguide Antenna	0.61–0.68	70.00	13.05	-62.00	N/A	[177]
Microstrip Array	0.10	2.20	15.70	-26.04	52.00	[147]
Our work	0.14–0.51	372.00	5.51	-13.68	82.39	–

results affirm that the proposed array configuration preserves the intrinsic impedance characteristics of individual antenna elements while enhancing array-level performance in terms of gain and directionality. The broadband impedance integrity retained in the array further validates the effectiveness and robustness of the ENN-guided optimization strategy for both standalone and arrayed THz antenna systems.

Compared to previously reported state-of-the-art THz antenna architectures, the proposed MCLPA demonstrates a substantially broader operational bandwidth while maintaining strong gain performance and excellent impedance matching, underscoring its technical significance and practical applicability in advanced THz systems. As shown in Table 4.1, conventional THz antennas based on patch, slotted, and waveguide designs typically achieve bandwidths ranging from 4.42 to 229 GHz, often constrained by limited spectral coverage or elevated reflection losses. In contrast, our antenna achieves an expanded bandwidth of 372 GHz (0.135-0.507 THz), representing a notable advance in fractional

bandwidth among miniaturized THz antenna designs. This broad spectral range is realized alongside a peak gain of 5.51 dBi, an optimal S_{11} of -13.68 dB, and the highest radiation efficiency of 82.39% across the operational band, demonstrating superior and well-balanced performance in the miniaturized THz antenna domain.

These integrated performance advantages are realized through the synergistic combination of compact structural innovation and intelligent algorithmic optimization, demonstrating the effectiveness of the ENN framework in refining antenna functionality, accelerating the design cycle, and reducing computational cost. The resulting MCLPA not only ensures robustness and consistency across the target frequency band but also exhibits exceptional suitability for advanced THz applications, including high-resolution imaging, ultrafast wireless communications, and precision detection systems. The novelty and efficacy of the proposed design methodology establish a transformative foundation for scalable THz antenna technologies, positioning our MCLPA as a leading solution in the evolving landscape of broadband, high-performance THz systems.

4.4 Chapter Summary

This work presents a novel Micro Circular Log-Periodic Antenna (MCLPA), systematically optimized using an advanced Evolutionary Neural Network (ENN) framework, marking a significant advancement in the field of THz engineering. This novel methodology not only accelerates the antenna design process but also ensures robust and high-performance outcomes.

Extensive experimental validation demonstrates that the ENN-guided MCLPA achieves an exceptional balance of ultra-compact form factor, wideband operation, and superior performance. The close agreement between measured and simulated results validates the

reliability and predictive accuracy of the proposed design approach. Notably, the antenna achieves an remarkable 372 GHz bandwidth (0.135-0.507 THz) alongside a peak gain of 5.51 dBi, the optimal S_{11} of -13.68 dB, and maximum radiation efficiency of 82.39% across the operational band, establish a benchmark for miniaturized THz antennas with broad bandwidth. Further performance evaluations, including radiation radiation-dependent electrical responses, signal-to-noise ratio analysis and the time-domain response confirm the antenna’s high sensitivity and stable performance in real-world THz detection scenarios. Time-domain measurements also reveal rapid and reliable signal acquisition, reinforcing its suitability for advanced sensing and imaging applications. Comparative studies involving Cu- and Al-based prototypes underscore the design’s robustness and material adaptability, while the implementation of an 8×8 antenna array significantly enhances gain and directivity. These findings collectively establish the proposed ENN-optimized MCLPA as a highly scalable and efficient solution for next-generation THz systems, offering transformative potential in accurate THz detection.

Looking ahead, our research will focus on further refining the ENN framework to accelerate convergence and enhance precision of the optimization, thereby enabling broader adaptability across diverse design tasks. We also aim to seamlessly integrate the MCLPA with state-of-the-art THz detectors to establish a unified, high-efficiency platform for real-time detection and imaging. Furthermore, recognizing the influence of material-dependent properties, we will explore the use of advanced nanomaterials for micro-scale MCLPA fabrication. These materials are anticipated to unlock new regimes of sensitivity and operational efficiency, driving the development of intelligent, high-performance THz systems.

Overall, this work not only delivers a high-efficient antenna design paradigm for THz applications, but also exemplifies the transformative robustness and precision of integrating advanced algorithm in the sophisticated, multifunctional and customizable THz antenna

design. This synergistic methodology establishes a reliable and generalizable foundation for development in next-generation THz detection, imaging, and wireless communication systems.

Chapter 5

Summary and Future Work

5.1 Principle Contributions

This thesis presents a series of original contributions to THz detection systems, with focuses on structural innovation, methodological advancement, performance enhancement, and expanded application potentials. The key contributions are summarized as follows:

Critical reviews and forward-looking design proposals for THz detection technologies

This study presents comprehensive and systematic reviews of existing THz detection mechanisms, with a particular emphasis on bolometers and antenna. The analysis offers critical evaluations of key performance trade-offs, including sensitivity, response time, fabrication complexity, and scalability. Building on these insights, the work proposes strategic directions for future development, focusing on advancements in device architecture, innovative material selection, and system-level integration. Special attention is given to emerging

biomedical applications, thereby establishing a solid foundation for the design and implementation of next-generation THz detection systems.

Novel microbolometer design for enhanced THz detection

A novel microbolometer was conceived and realized, demonstrating a substantial advancement in terahertz detection technology. The innovation lies in the integration of structural engineering with material-level design, offering a significant step forward toward scalable, high-performance THz detection systems. The device exhibits markedly enhanced accuracy, sensitivity, and response speed, achieved through the systematic optimization of the thermal isolation architecture, radiation absorbing configuration, and material selection. This novel design not only enables efficient THz detection under practical conditions but also establishes a new framework for future microbolometer development.

Pioneering use of graphene in microbolometer development

This research represents the first successful integration of graphene into the microbolometer design process, marking a significant advancement in THz detection performance. The incorporation of this atomically thin material introduces superior thermal sensitivity and substantially improves THz absorption efficiency, thereby overcoming fundamental limitations of conventional designs. By demonstrating the feasibility and advantages of graphene-based THz detection elements, this work establishes a critical foundation and offers a new strategy for the development of next-generation THz detection systems.

Realization of the advanced microbolometer-based THz imaging system

An integrated THz imaging system incorporating the developed microbolometer was successfully designed and implemented, demonstrating the transition from device-level in-

novation to system-level functionality. This platform provides a robust proof of concept for the practical deployment of THz imaging, with particular relevance to biomedical diagnostics. By enabling fast, sensitive and safe real-time detection, the system forms an essential platform that significantly advances the potential of THz imaging in practical clinical and scientific applications.

Standardized design methodology for circular log-periodic antennas

The geometric configuration and design methodology of the [MCLPA](#) for THz detection were systematically formalized. A unified framework was developed to define key geometric parameters and spatial distribution principles, enabling both reproducibility and scalability in antenna design. This standardization not only ensures consistent performance but also provides a robust foundation for broadband THz applications, significantly improving the practicality and reliability of antenna technology in THz domain.

Development of an innovative antenna optimization algorithm

An innovative algorithmic framework was developed that integrates evolutionary strategies with neural network architectures to accelerate antenna optimization. This approach markedly improves design efficiency by enabling intelligent, data-driven exploration of the antenna parameter space, while simultaneously reducing computational overhead and fabrication costs. Beyond streamlining the development process, the algorithm establishes a powerful framework for broadband THz antenna design, offering a scalable and cost-effective pathway toward advanced high-performance detection systems.

Establishment of a flexible and tunable paradigm for hardware design

A flexible and generalizable evolutionary [ENN](#) paradigm was established to address a

broad range of hardware design and optimization tasks, demonstrating particular effectiveness in complex design scenarios. This robust paradigm allows for multi-parameter and multi-objective optimization, enabling the simultaneous consideration of diverse performance characteristics and physical constraints. This paradigm’s tunability and adaptability across diverse hardware systems illustrate its technical versatility, and establish it as a transformative methodology for hardware design. By providing this intelligent, scalable, and adaptive methodology, this paradigm advances the development of sophisticated devices and lays the groundwork for cutting-edge hardware innovation.

5.2 Future Wrok

5.2.1 Integration of the microbolometer and the antenna

One of the most promising directions for future work lies in the full integration of the microbolometer with the log-periodic antenna, aimed at developing a compact and high-performance THz detection system. While the current research has successfully optimized both the antenna structure and microbolometer design, the experimental validation has primarily focused on the individual performance of each component. Achieving effective coupling between the antenna and the microbolometer is critical for maximizing THz absorption, minimizing signal loss, and ensuring high spatial and spectral resolution. Future efforts should concentrate on the co-design and co-fabrication of the microbolometer and antenna on a shared substrate, taking into account the impedance matching, thermal isolation, and material compatibility between the two components. Moreover, the antenna geometry may need to be fine-tuned further to ensure optimal field confinement at the sensing region of the microbolometer, especially in light of its physical footprint and thermal

time constant.

From a fabrication standpoint, challenges such as precise alignment, layer thickness control, and thermal cross-talk suppression must be addressed through high-resolution lithography and robust thermal isolation strategies. For instance, incorporating low-thermal-conductivity materials or further optimizing micro-bridge architectures can improve the detector’s responsivity and Noise Equivalent Power (NEP). On the system level, the integration should support scalable array configurations, enabling multi-pixel THz imaging with sufficient uniformity and reduced inter-pixel interference. The integration must also consider readout circuitry design, possibly leveraging CMOS-compatible processes, to facilitate real-time signal acquisition and data processing.

Finally, a fully integrated antenna-microbolometer system would enable the demonstration of real-world biomedical or security imaging applications, which is essential for transitioning from device-level research to application-oriented prototypes. By completing this integration, the proposed THz detection systems can achieve a new level of miniaturization, functional synergy, and field applicability, paving the way for high-resolution, non-invasive, and real-time THz detection in biomedical diagnostics and beyond.

5.2.2 Development of differential microbolometer system

An important direction for future development in THz detection involves the implementation and refinement of differential microbolometer systems. Traditional single-ended microbolometer readout configurations are often vulnerable to common-mode noise, baseline drift, and parasitic interference, all of which compromise signal fidelity and detection sensitivity, especially in low-signal or high-noise environments. To address these limitations, we propose the advancement of a differential readout architecture specifically optimized for

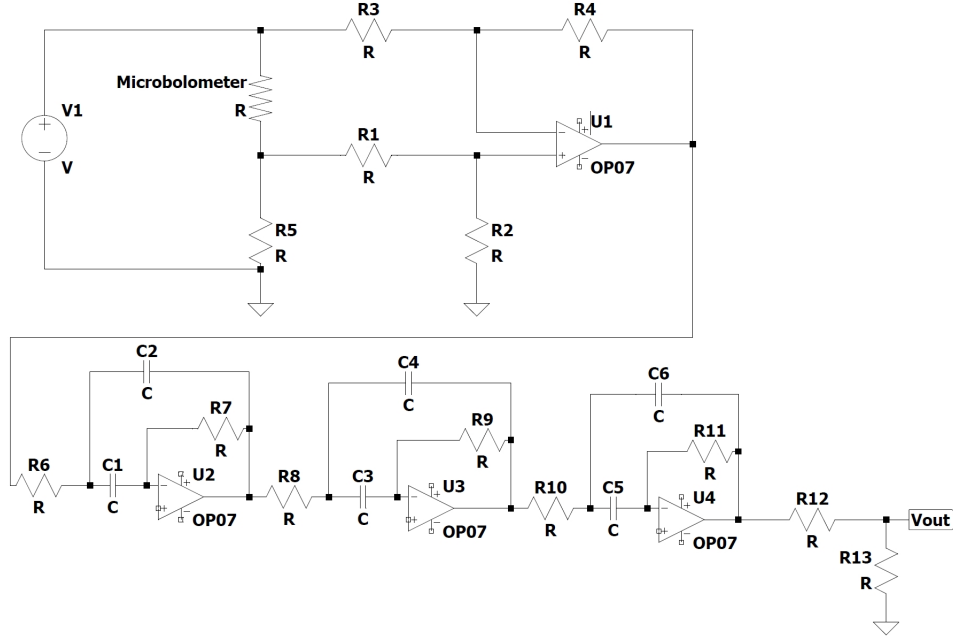


Figure 5.1: Differential Microbolometer System

THz microbolometers. As illustrated in Fig. 5.1, this system features a carefully designed differential network, incorporating a series of band-pass filtering stages, low-noise operational amplifiers, and matched resistive-capacitive components to achieve robust signal conditioning.

The circuit leverages several strategic advantages: differential signal acquisition ensures effective rejection of common-mode disturbances and environmental electromagnetic interference; active highpass filters isolate the frequency range of interest, thereby suppressing out-of-band noise and enhancing spectral resolution; and high-precision amplification stages improve overall signal detectability without introducing significant distortion or phase lag. Moreover, the modular configuration of the system supports scalability and adaptability, enabling it to accommodate array-based sensing layouts or application-specific tuning. This makes it particularly well-suited for biomedical imaging scenarios where sub-

tle variations in thermal or dielectric properties must be resolved with high fidelity.

Experimental validation has shown that this differential system achieves a significant reduction in both input-referred and output noise power, leading to improved SNR across the operating bandwidth. Notably, the design maintains linearity and gain stability under dynamic load conditions, demonstrating its potential as a high-performance readout solution for next-generation THz microbolometer systems. Continued refinement of this architecture through detector-circuit matching, precision layout, and low-power integration will be a key focus of future work, aiming at further improving sensitivity, noise control, and system integration for compact, real-time THz detection systems.

5.2.3 Utilization of Advanced Materials

Future research on THz detection system will place increasing emphasis on the strategic selection and engineering of materials to enhance the system's electromagnetic performance, mechanical reliability, and application versatility. As summarized and demonstrated in Table 5.1, while conventional detection systems are typically fabricated using metals such as copper or aluminum due to their excellent conductivity, emerging demands particularly in practical applications necessitate advanced materials that can offer improved performance in miniaturized or flexible platforms. Novel conductive materials such as nanomaterials and superconducting materials are being explored for their high-frequency response and compatibility with flexible substrates [178, 179, 180]. These materials allow for the development of THz detection system that can be integrated into wearable devices or embedded in non-planar surfaces. Additionally, dielectric substrates play a crucial role in influencing the impedance, bandwidth, efficiency, and structural integrity of the THz detection system. Future work will investigate high-performance dielectric materials with

Table 5.1: Advantages and Disadvantages of Materials in THz Detection

Material	Advantages	Disadvantages
Metal	Excellent electrical conductivity, Good mechanical stability, Effective thermal response	Higher noise levels, Sensitive to temperature fluctuations, Higher fabrication costs
Metal Oxide	High sensitivity, Good thermal stability, Strong environmental stability	Complex fabrication processes, Potential long-term stability issues, Slower response times
Semiconductor	Adjustable electronic properties, High temperature sensitivity, Wide bandgap features	Affected by temperature variations, Higher manufacturing costs, Reliability depends on material quality
Metal Silicide	High responsivity to infrared, Good thermal stability, High temperature tolerance	High production complexity, Higher cost, Sensitivity to impurities
Nanomaterial	Extremely high surface area to volume ratio, Exceptional electrical properties, High sensitivity	Complex preparation techniques, Challenges in large-scale manufacturing, Stability and uniformity issues
Superconducting Material	Very low noise levels, High sensitivity, Low energy consumption	Requires very low operating temperatures, High cooling costs, Technological complexity

low loss tangents and tailored permittivity profiles to optimize electromagnetic wave propagation while maintaining mechanical stability [181]. These innovations are particularly significant in scenarios requiring multi-band or adaptive operation. In addition, the compatibility of advanced materials with scalable and cost-effective fabrication processes such as inkjet printing, screen printing, or laser-assisted patterning will be a key consideration in future investigations [182, 183]. Overall, a materials-centric approach is expected to not only overcome current limitations in size, flexibility, and frequency response, but also enable the next generation of high-performance THz detection system tailored for compact, wearable, and multifunctional electromagnetic systems.

5.2.4 Prospective developments in AI-driven devices design

Building on the successful development and implementation of the ENN algorithm for THz antenna optimization, several promising research directions are proposed to further advance this work. Future efforts will concentrate on enhancing the algorithm’s capabilities, broadening the optimization scope, and extending its applicability to a wider range of high-performance micro- and nanoscale devices.

One key area of development involves expanding the input parameter space. In addition to core geometric and configuration variables, future models will incorporate material properties, fabrication tolerances, and environmental factors such as temperature and humidity. This expanded parameter set will enable more comprehensive optimization strategies that account for practical design constraints and real-world operating conditions. Equally important is the diversification of output performance metrics. Beyond conventional indicators such as gain, S_{11} , Y-parameters, and [VSWR](#), subsequent work will include additional criteria such as radiation efficiency, cross-polarization levels, sidelobe suppression, thermal

stability, and mechanical robustness. Integrating these metrics will facilitate the generation of designs optimized across a multidimensional performance space.

To further improve algorithmic performance, future work will incorporate enhancements such as adaptive learning rates, dynamic mutation strategies, parallel computing, and reinforcement learning frameworks. These improvements aim to accelerate convergence, increase prediction accuracy, and efficiently navigate complex, high-dimensional search spaces. Finally, the ENN-based methodology will be extended beyond antenna design to encompass other functional components, including resonators, modulators, photodetectors, and metamaterials. This expanded scope will enable innovations in emerging fields such as integrated photonics, flexible electronics, and quantum technologies.

Collectively, these research directions establish a forward-looking framework for intelligent, adaptive device design, reinforcing the transformative potential of AI-driven optimization in THz systems and beyond.

5.2.5 Potential Applications

A vital direction for future research lies in the comprehensive development of a functional THz detection and imaging system tailored for practical applications. While significant progress has been made in individual component optimization, the translation of these advancements into a cohesive, real-world platform remains a critical challenge. Future work will focus on system-level design considerations including source-detector alignment, detection path configuration, scanning mechanics, and data acquisition synchronization to enable precise and repeatable detection and image reconstruction. These efforts must balance resolution, imaging speed, and system compactness to meet the stringent requirements of practical environments.

Particular attention will be given to biomedical scenarios where THz imaging offers unique advantages over traditional modalities, such as high contrast in water-content differentiation and non-ionizing operation. Examples include non-invasive skin cancer diagnostics, intraoperative margin assessment, early-stage dental caries identification, and corneal hydration evaluation. To support these applications, the system must incorporate adaptive calibration algorithms, noise mitigation techniques, and real-time image processing modules capable of enhancing contrast and suppressing artifacts. The integration of flexible, wearable THz sensor arrays with conformal geometries may also be explored to expand diagnostic capabilities beyond stationary platforms, enabling applications in continuous monitoring and point-of-care diagnostics.

Another critical direction for future work lies in the [NDT](#). Potential applications include defect detection in composite materials, quality control in manufacturing, and the assessment of cultural heritage artifacts without causing physical damage. Future research should focus on improving system sensitivity, imaging speed, and penetration depth, as well as developing robust algorithms for defect recognition and quantitative analysis. These advancements would significantly enhance the practicality of THz-based NDT and establish it as a powerful complementary tool alongside conventional inspection methods.

Finally, an important application direction for future THz research lies in its potential contribution to 6G communication systems, particularly in supporting the Internet of Things (IoT). The high data rates and broad bandwidth of the THz spectrum provide promising pathway to mitigate capacity and latency limitations in existing communication, enabling large-scale device connectivity and real-time data exchange. Future work should focus on the development of energy-efficient THz detection systems, and scalable architectures tailored to heterogeneous device requirements.

References

- [1] Nira and A. Shukla, “Terahertz communication: merits, demerits, and future challenges regarding 6g wireless networks,” in *Security and Privacy: Select Proceedings of ICSP 2020*. Springer, 2021, pp. 163–174.
- [2] N. Oda, H. Yoneyama, T. Sasaki, M. Sano, S. Kurashina, I. Hosako, N. Sekine, T. Sudoh, and T. Irie, “Detection of terahertz radiation from quantum cascade laser using vanadium oxide microbolometer focal plane arrays,” in *Infrared Technology and Applications XXXIV*, vol. 6940. SPIE, 2008, pp. 982–993.
- [3] P. H. Siegel, “Terahertz technology,” *IEEE Transactions on microwave theory and techniques*, vol. 50, no. 3, pp. 910–928, 2002.
- [4] P. A. Silberg, “Infrared absorption of three-layer films,” *JOSA*, vol. 47, no. 7, pp. 575–578, 1957.
- [5] P. S. Stefanova, J. M. Hammler, A. K. Klein, A. J. Gallant, and C. Balocco, “Polymer-based micro-golay cells for thz detection,” in *2016 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*. IEEE, 2016, pp. 1–2.
- [6] R. Whatmore, “Pyroelectric devices and materials,” *Reports on progress in physics*, vol. 49, no. 12, p. 1335, 1986.
- [7] E. Betz-Güttner, N. Cefarin, S. Dal Zilio, and M. Lazzarino, “Graphene golay micro-cell arrays for a color-sensitive terahertz imaging sensor,” in *Workshop Co-chairs*, p. 45.
- [8] G. Gol’Tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, “Picosecond superconducting single-photon optical detector,” *Applied physics letters*, vol. 79, no. 6, pp. 705–707, 2001.

- [9] S. Subramania, K. Xu, S. K. Moser, D. Deng, J. Li, R. M. Feenstra, S. K. Fullerton-Shirey, and J. A. Robinson, “Engineering pn junctions in graphene/molybdenum disulfide heterostructures,” in *2019 Device Research Conference (DRC)*. IEEE, 2019, pp. 83–84.
- [10] M. Rahimi Azghadi, Y.-C. Chen, J. K. Eshraghian, J. Chen, C.-Y. Lin, A. Amirsoleimani, A. Mehonic, A. J. Kenyon, B. Fowler, J. C. Lee *et al.*, “Complementary metal-oxide semiconductor and memristive hardware for neuromorphic computing,” *Advanced Intelligent Systems*, vol. 2, no. 5, p. 1900189, 2020.
- [11] Z. Liu, P.-G. Li, Y.-S. Zhi, X.-L. Wang, X.-L. Chu, and W.-H. Tang, “Review of gallium oxide based field-effect transistors and schottky barrier diodes,” *Chinese Physics B*, vol. 28, no. 1, p. 017105, 2019.
- [12] R. Lewis, “A review of terahertz detectors,” *Journal of Physics D: Applied Physics*, vol. 52, no. 43, p. 433001, 2019.
- [13] J. W. Stewart, J. H. Vella, W. Li, S. Fan, and M. H. Mikkelsen, “Ultrafast pyroelectric photodetection with on-chip spectral filters,” *Nature materials*, vol. 19, no. 2, pp. 158–162, 2020.
- [14] X. Li, Z. Zhu, and K. Behnia, “A monomaterial nernst thermopile with hermaphroditic legs,” *Advanced Materials*, vol. 33, no. 20, p. 2100751, 2021.
- [15] M. J. Golay, “A pneumatic infra-red detector,” *Review of Scientific Instruments*, vol. 18, no. 5, pp. 357–362, 1947.
- [16] B. Chatterjee, A. Jayawardena, E. Heller, D. W. Snyder, S. Dhar, and S. Choi, “Thermal characterization of gallium oxide schottky barrier diodes,” *Review of Scientific Instruments*, vol. 89, no. 11, p. 114903, 2018.
- [17] H. Ekström, E. Kollberg, P. Yagoubov, G. Gol’tsman, E. Gershenzon, and S. Yngvesson, “Gain and noise bandwidth of nbn hot-electron bolometric mixers,” *Applied physics letters*, vol. 70, no. 24, pp. 3296–3298, 1997.
- [18] J. Yan, M. H. Kim, J. A. Elle, A. B. Sushkov, G. S. Jenkins, H. M. Milchberg, M. S. Fuhrer, and H. Drew, “Dual-gated bilayer graphene hot-electron bolometer,” *Nature nanotechnology*, vol. 7, no. 7, pp. 472–478, 2012.

- [19] C. Vicario, B. Monoszlai, M. Jazbinsek, S.-H. Lee, O.-P. Kwon, and C. Hauri, “Intense, carrier frequency and bandwidth tunable quasi single-cycle pulses from an organic emitter covering the terahertz frequency gap,” *Scientific reports*, vol. 5, no. 1, pp. 1–8, 2015.
- [20] J. Ajayan, S. Sreejith, M. Manikandan, W.-C. Lai, and S. Saha, “Terahertz sensors for next generation biomedical and other industrial electronics applications: A critical review,” *Sensors and Actuators A: Physical*, vol. 369, p. 115169, 2024.
- [21] A. A. Firoozi and A. A. Firoozi, “A comprehensive survey: The role of terahertz communication systems in urban infrastructure development,” *Measurement*, p. 117318, 2025.
- [22] J. Shalf, “The future of computing beyond moore’s law,” *Philosophical Transactions of the Royal Society A*, vol. 378, no. 2166, p. 20190061, 2020.
- [23] M. Al-Raei, “Trends in the applications of terahertz radiation in oral oncology treatments,” *Oral Oncology Reports*, vol. 10, p. 100402, 2024.
- [24] D. Spirito, D. Coquillat, S. L. De Bonis, A. Lombardo, M. Bruna, A. C. Ferrari, V. Pellegrini, A. Tredicucci, W. Knap, and M. S. Vitiello, “High performance bilayer-graphene terahertz detectors,” *Applied Physics Letters*, vol. 104, no. 6, p. 061111, 2014.
- [25] B. E. Warren, *X-ray Diffraction*. Courier Corporation, 1990.
- [26] M. Dai, C. Wang, B. Qiang, F. Wang, M. Ye, S. Han, Y. Luo, and Q. J. Wang, “On-chip mid-infrared photothermoelectric detectors for full-stokes detection,” *Nature Communications*, vol. 13, no. 1, p. 4560, 2022.
- [27] D. M. Mittleman, “Twenty years of terahertz imaging,” *Optics express*, vol. 26, no. 8, pp. 9417–9431, 2018.
- [28] E. Pickwell and V. Wallace, “Biomedical applications of terahertz technology,” *Journal of Physics D: Applied Physics*, vol. 39, no. 17, p. R301, 2006.
- [29] I. F. Akyildiz, A. Kak, and S. Nie, “6g and beyond: The future of wireless communications systems,” *IEEE access*, vol. 8, pp. 133 995–134 030, 2020.
- [30] V. Petrov, T. Kurner, and I. Hosako, “Ieee 802.15. 3d: First standardization efforts for sub-terahertz band communications toward 6g,” *IEEE Communications Magazine*, vol. 58, no. 11, pp. 28–33, 2020.

- [31] A. N. Grigorenko, M. Polini, and K. Novoselov, “Graphene plasmonics,” *Nature photonics*, vol. 6, no. 11, pp. 749–758, 2012.
- [32] I. Ryger, P. Lobotka, A. Steiger, S. Chromik, T. Lalinsky, Z. Raida, K. Pítra, J. Zehetner, M. Spankova, S. Gazi *et al.*, “Uncooled antenna-coupled microbolometer for detection of terahertz radiation,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 42, pp. 462–478, 2021.
- [33] M. Aleks, C. Jagtap, V. Kadam, G. Kolev, K. Denishev, H. Pathan *et al.*, “An overview of microelectronic infrared pyroelectric detector,” *Engineered Science*, vol. 16, pp. 82–89, 2021.
- [34] S. Dhillon, M. Vitiello, E. Linfield, A. Davies, M. C. Hoffmann, J. Booske, C. Paoloni, M. Gensch, P. Weightman, G. Williams *et al.*, “The 2017 terahertz science and technology roadmap,” *Journal of Physics D: Applied Physics*, vol. 50, no. 4, p. 043001, 2017.
- [35] J. El Haddad, B. Bousquet, L. Canioni, and P. Mounaix, “Review in terahertz spectral analysis,” *TrAC Trends in Analytical Chemistry*, vol. 44, pp. 98–105, 2013.
- [36] J. Uddin, *Terahertz Spectroscopy: A Cutting Edge Technology*. BoD–Books on Demand, 2017.
- [37] X. Tu, C. Jiang, P. Xiao, S. Zhai, X. Jia, Y. Wu, Q. Meng, B. Chen, L. Kang, J. Chen *et al.*, “Fabry–pérot cavity-coupled microbolometer terahertz detector with a continuously tunable air spacer gap,” *Optics Letters*, vol. 44, no. 4, pp. 1019–1022, 2019.
- [38] E. Putley, “The pyroelectric detector,” in *Semiconductors and Semimetals*. Elsevier, 1970, vol. 5, pp. 259–285.
- [39] M. Zhang and J. T. Yeow, “A flexible, scalable, and self-powered mid-infrared detector based on transparent pedot: Pss/graphene composite,” *Carbon*, vol. 156, pp. 339–345, 2020.
- [40] N. K. Nikolova, M. Ravan, and R. K. Amineh, “Substrate-integrated antennas on silicon,” in *Advances in Imaging and Electron Physics*. Elsevier, 2012, vol. 174, pp. 391–458.
- [41] S. Fan, Y. He, B. S. Ung, and E. Pickwell-MacPherson, “The growth of biomedical terahertz research,” *Journal of Physics D: Applied Physics*, vol. 47, no. 37, p. 374009, 2014.

- [42] N. Oda, A. W. Lee, T. Ishi, I. Hosako, and Q. Hu, "Proposal for real-time terahertz imaging system with palm-size terahertz camera and compact quantum cascade laser," in *Terahertz Physics, Devices, and Systems VI: Advanced Applications in Industry and Defense*, vol. 8363. SPIE, 2012, pp. 31–43.
- [43] A. Khoshakhlagh, "Design of a readout integrated circuit (roic) for infrared imaging applications," 2011.
- [44] M. Naftaly and R. E. Miles, "Terahertz time-domain spectroscopy for material characterization," *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1658–1665, 2007.
- [45] A. Veeraselvam, G. N. A. Mohammed, K. Savarimuthu, J. Anguera, J. C. Paul, and R. K. Krishnan, "Refractive index-based terahertz sensor using graphene for material characterization," *Sensors*, vol. 21, no. 23, p. 8151, 2021.
- [46] W. Kemp and W. Kemp, "Energy and the electromagnetic spectrum," *Organic spectroscopy*, pp. 1–17, 1991.
- [47] N. Li, R. Zhou, B. Krishna, A. Pradhan, H. Lee, J. He, and N. Jiang, "Non-invasive techniques for muscle fatigue monitoring: A comprehensive survey," *ACM Computing Surveys*, vol. 56, no. 9, pp. 1–40, 2024.
- [48] R. Zhou and J. T. Yeow, "Innovations in bolometer technology for enhanced terahertz detection," *IEEE Nanotechnology Magazine*, 2024.
- [49] J. A. Bearden, "X-ray wavelengths," *Reviews of Modern Physics*, vol. 39, no. 1, p. 78, 1967.
- [50] R. Jenkins, "X-ray techniques: overview," *Encyclopedia of analytical chemistry*, vol. 1, pp. 1–20, 2000.
- [51] P. J. Withers, C. Bouman, S. Carmignato, V. Cnudde, D. Grimaldi, C. K. Hagen, E. Maire, M. Manley, A. Du Plessis, and S. R. Stock, "X-ray computed tomography," *Nature Reviews Methods Primers*, vol. 1, no. 1, p. 18, 2021.
- [52] M. T. Vlaardingerbroek and J. A. Boer, *Magnetic resonance imaging: theory and practice*. Springer Science & Business Media, 2013.
- [53] G. Katti, S. A. Ara, and A. Shireen, "Magnetic resonance imaging (mri)—a review," *International journal of dental clinics*, vol. 3, no. 1, pp. 65–70, 2011.

- [54] T. Geva, “Magnetic resonance imaging: historical perspective,” *Journal of cardiovascular magnetic resonance*, vol. 8, no. 4, pp. 573–580, 2006.
- [55] G. Rizzatto, “Ultrasound transducers,” *European journal of radiology*, vol. 27, pp. S188–S195, 1998.
- [56] J. Chan, Z. Zheng, K. Bell, M. Le, P. H. Reza, and J. T. Yeow, “Photoacoustic imaging with capacitive micromachined ultrasound transducers: Principles and developments,” *Sensors*, vol. 19, no. 16, p. 3617, 2019.
- [57] D. Dalecki, “Mechanical bioeffects of ultrasound,” *Annu. Rev. Biomed. Eng.*, vol. 6, no. 1, pp. 229–248, 2004.
- [58] M. Cifrek, V. Medved, S. Tonković, and S. Ostojić, “Surface emg based muscle fatigue evaluation in biomechanics,” *Clinical biomechanics*, vol. 24, no. 4, pp. 327–340, 2009.
- [59] J. R. Cram and D. Rommen, “Effects of skin preparation on data collected using an emg muscle-scanning procedure,” *Biofeedback and Self-regulation*, vol. 14, no. 1, pp. 75–82, 1989.
- [60] O. Barzilay and A. Wolf, “A fast implementation for emg signal linear envelope computation,” *Journal of Electromyography and Kinesiology*, vol. 21, no. 4, pp. 678–682, 2011.
- [61] R. Merletti, M. Avenatti, A. Botter, A. Holobar, H. Marateb, and T. M. Vieira, “Advances in surface emg: recent progress in detection and processing techniques,” *Critical Reviews™ in Biomedical Engineering*, vol. 38, no. 4, 2010.
- [62] M. R. M. Ismail, C. K. Lam, K. Sundaraj, and M. H. F. Rahiman, “Fatigue effect on cross-talk in mechanomyography signals of extensor and flexor forearm muscles during maximal voluntary isometric contractions,” *Journal of musculoskeletal & neuronal interactions*, vol. 21, no. 4, p. 481, 2021.
- [63] P. Madeleine, H.-y. Ge, A. Jaskólska, D. Farina, A. Jaskólski, and L. Arendt-Nielsen, “Spectral moments of mechanomyographic signals recorded with accelerometer and microphone during sustained fatiguing contractions,” *Medical and Biological Engineering and Computing*, vol. 44, no. 4, pp. 290–297, 2006.
- [64] C. L. Camic, T. J. Housh, J. M. Zuniga, C. R. Hendrix, H. C. Bergstrom, D. A. Traylor, R. J. Schmidt, and G. O. Johnson, “Electromyographic and mechanomyographic responses across repeated maximal isometric and concentric muscle actions

- of the leg extensors,” *Journal of Electromyography and Kinesiology*, vol. 23, no. 2, pp. 342–348, 2013.
- [65] T. J. Barstow, “Understanding near infrared spectroscopy and its application to skeletal muscle research,” *Journal of applied physiology*, vol. 126, no. 5, pp. 1360–1376, 2019.
 - [66] R. Boushel and C. Piantadosi, “Near-infrared spectroscopy for monitoring muscle oxygenation,” *Acta Physiologica Scandinavica*, vol. 168, no. 4, pp. 615–622, 2000.
 - [67] S. Perrey and M. Ferrari, “Muscle oximetry in sports science: a systematic review,” *Sports Medicine*, vol. 48, no. 3, pp. 597–616, 2018.
 - [68] H. Banerjee, M. Suhail, and H. Ren, “Hydrogel actuators and sensors for biomedical soft robots: brief overview with impending challenges,” *Biomimetics*, vol. 3, no. 3, p. 15, 2018.
 - [69] Y. Zhang, C. Wang, B. Huai, S. Wang, Y. Zhang, D. Wang, L. Rong, and Y. Zheng, “Continuous-wave thz imaging for biomedical samples,” *Applied Sciences*, vol. 11, no. 1, p. 71, 2020.
 - [70] A. Gong, Y. Qiu, X. Chen, Z. Zhao, L. Xia, and Y. Shao, “Biomedical applications of terahertz technology,” *Applied Spectroscopy Reviews*, vol. 55, no. 5, pp. 418–438, 2020.
 - [71] Z. Xie, J. Wang, and J. T. Yeow, “Doped polyaniline/graphene composites for photothermoelectric detectors,” *ACS Applied Nano Materials*, vol. 5, no. 6, pp. 7967–7973, 2022.
 - [72] T. H. White, “United states early radio history,” at: earlyradiohistory.us/index.html (last consulted 2 June 2008), 2003.
 - [73] J. C. Cook, “Proposed monocycle-pulse very-high-frequency radar for air-borne ice and snow measurement,” *Transactions of the American Institute of Electrical Engineers, Part I: Communication and Electronics*, vol. 79, no. 5, pp. 588–594, 1960.
 - [74] O. R. Floody and D. W. Pfaff, “Communication among hamsters by high-frequency acoustic signals: Iii. response evoked by natural and synthetic ultrasounds.” *Journal of Comparative and Physiological Psychology*, vol. 91, no. 4, p. 820, 1977.
 - [75] M. Mouly and M.-B. Pautet, *The GSM system for mobile communications*. Telecom publishing, 1992.

- [76] H. Honkasalo, K. Pehkonen, M. T. Niemä, and A. T. Leino, “Wcdma and wlan for 3g and beyond,” *IEEE Wireless Communications*, vol. 9, no. 2, pp. 14–18, 2002.
- [77] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, “A survey of millimeter wave communications (mmwave) for 5g: opportunities and challenges,” *Wireless networks*, vol. 21, no. 8, pp. 2657–2676, 2015.
- [78] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, W. Chen, L. Li, and S. Li, “A survey on terahertz communications,” *China communications*, vol. 16, no. 2, pp. 1–35, 2019.
- [79] M. H. Sharifi and M. Arozullah, “A centralized multiple satellite network for real time global space, land, and mobile communications,” in *MILCOM 1987-IEEE Military Communications Conference-Crisis Communications: The Promise and Reality*, vol. 3. IEEE, 1987, pp. 0807–0811.
- [80] C. Cox, *An introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE and 4G mobile communications*. John Wiley & Sons, 2014.
- [81] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, “6g wireless communication systems: Applications, requirements, technologies, challenges, and research directions,” *IEEE Open Journal of the Communications Society*, vol. 1, pp. 957–975, 2020.
- [82] Ž. Lučev, I. Krois, and M. Cifrek, “Application of wireless intrabody communication system to muscle fatigue monitoring,” in *2010 IEEE Instrumentation & Measurement Technology Conference Proceedings*. IEEE, 2010, pp. 1624–1627.
- [83] W. Saad, M. Bennis, and M. Chen, “A vision of 6g wireless systems: Applications, trends, technologies, and open research problems,” *IEEE network*, vol. 34, no. 3, pp. 134–142, 2019.
- [84] J.-S. Rieh, *Introduction to Terahertz Electronics*. Springer Nature, 2020.
- [85] Z. Liu, Z. Liang, W. Tang, and X. Xu, “Design and fabrication of low-deformation micro-bolometers for thz detectors,” *Infrared Physics & Technology*, vol. 105, p. 103241, 2020.
- [86] P. Prudkovskii, A. Leontyev, K. Kuznetsov, and G. Kitaeva, “Towards measuring terahertz photon statistics by a superconducting bolometer,” *Sensors*, vol. 21, no. 15, p. 4964, 2021.

- [87] A. Odon and A. Szlachta, “Voltage response of a pyroelectric detector to a single rectangular optical radiation pulse,” *Sensors*, vol. 22, no. 16, p. 6265, 2022.
- [88] N. Zhou, X. Ding, H. Li, Y. Ni, Y. Pu, and H. Mao, “A thermopile detector based on micro-bridges for heat transfer,” *Micromachines*, vol. 12, no. 12, p. 1554, 2021.
- [89] A. Amirsoleimani, F. Alibart, V. Yon, J. Xu, M. R. Pazhouhandeh, S. Ecoffey, Y. Beilliard, R. Genov, and D. Drouin, “In-memory vector-matrix multiplication in monolithic complementary metal–oxide–semiconductor–memristor integrated circuits: Design choices, challenges, and perspectives,” *Advanced Intelligent Systems*, vol. 2, no. 11, p. 2000115, 2020.
- [90] A. Manasreh, “Design, optimization and simulation of iii-nitride power heterostructure field effect transistor,” *Journal of Engineering and Applied Sciences*, vol. 15, no. 6, pp. 1558–1563, 2020.
- [91] S. Glenz, M. Justen, P. Putz, R. Teipen, T. Tils, C. Honingh, and K. Jacobs, “Broadband nbtin based sis mixers for hifi band 2,” in *Twenty Seventh International Conference on Infrared and Millimeter Waves*. IEEE, 2002, pp. 257–258.
- [92] A. Shurakov, Y. Lobanov, and G. Goltsman, “Superconducting hot-electron bolometer: from the discovery of hot-electron phenomena to practical applications,” *Superconductor Science and Technology*, vol. 29, no. 2, p. 023001, 2015.
- [93] K. Li, G. Wan, G. Cheng, L. Meng, and J. Han, “Object detection in optical remote sensing images: A survey and a new benchmark,” *ISPRS journal of photogrammetry and remote sensing*, vol. 159, pp. 296–307, 2020.
- [94] H. Wu, S. Grabarnik, A. Emadi, G. De Graaf, and R. Wolffenbuttel, “Characterization of thermal cross-talk in a mems-based thermopile detector array,” *Journal of Micromechanics and Microengineering*, vol. 19, no. 7, p. 074022, 2009.
- [95] S. B. Mbarek, N. Alcheikh, and M. I. Younis, “Recent advances on mems based infrared thermopile detectors,” *Microsystem Technologies*, vol. 28, no. 8, pp. 1751–1764, 2022.
- [96] H. Hou, Q. Huang, G. Liu, and G. Qiao, “Enhanced performances of cmos-mems thermopile infrared detectors using novel thin film stacks,” *Infrared Physics & Technology*, vol. 102, p. 103058, 2019.

- [97] A. Bao, C. Lei, H. Mao, R. Li, and Y. Guan, “Study on a high performance mems infrared thermopile detector,” *Micromachines*, vol. 10, no. 12, p. 877, 2019.
- [98] T. Otsuji, “Trends in the research of modern terahertz detectors: Plasmon detectors,” *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 6, pp. 1110–1120, 2015.
- [99] K. Yamashita, A. Murata, and M. Okuyama, “Miniaturized infrared sensor using silicon diaphragm based on golay cell,” *Sensors and Actuators A: Physical*, vol. 66, no. 1-3, pp. 29–32, 1998.
- [100] A. Hossain and M. H. Rashid, “Pyroelectric detectors and their applications,” *IEEE Transactions on industry applications*, vol. 27, no. 5, pp. 824–829, 1991.
- [101] L. Fernandes, P. Kaufmann, R. Marcon, A. Kudaka, A. Marun, R. Godoy, E. Bor-tolucci, M. B. Zakia, and J. Diniz, “Photometry of thz radiation using golay cell de-tector,” in *2011 XXXth URSI General Assembly and Scientific Symposium*. IEEE, 2011, pp. 1–4.
- [102] M. Zhang and J. T. Yeow, “Flexible polymer–carbon nanotube composite with high-response stability for wearable thermal imaging,” *ACS applied materials & interfaces*, vol. 10, no. 31, pp. 26 604–26 609, 2018.
- [103] T. M. Buzug, “Computed tomography,” in *Springer handbook of medical technology*. Springer, 2011, pp. 311–342.
- [104] Z.-P. Liang and P. C. Lauterbur, *Principles of magnetic resonance imaging*. SPIE Optical Engineering Press Bellingham, WA, 2000.
- [105] D. L. Bailey, M. N. Maisey, D. W. Townsend, and P. E. Valk, *Positron emission tomography*. Springer, 2005, vol. 2.
- [106] J. F. Ward, “Dna damage produced by ionizing radiation in mammalian cells: iden-tities, mechanisms of formation, and reparability,” *Progress in nucleic acid research and molecular biology*, vol. 35, pp. 95–125, 1988.
- [107] W. W.-Y. Kam and R. B. Banati, “Effects of ionizing radiation on mitochondria,” *Free Radical Biology and Medicine*, vol. 65, pp. 607–619, 2013.
- [108] M. Zhu, M. Yang, J. Zhang, Y. Yin, X. Fan, Y. Zhang, S. Qin, H. Zhang, and F. Yu, “Immunogenic cell death induction by ionizing radiation,” *Frontiers in immunology*, vol. 12, p. 705361, 2021.

- [109] Y. Peng, C. Shi, Y. Zhu, M. Gu, and S. Zhuang, "Terahertz spectroscopy in biomedical field: a review on signal-to-noise ratio improvement," *Photonix*, vol. 1, pp. 1–18, 2020.
- [110] D. Samanta, M. Karthikeyan, D. Agarwal, A. Biswas, A. Acharyya, and A. Banerjee, "Trends in terahertz biomedical applications," *Generation, Detection and Processing of Terahertz Signals*, pp. 285–299, 2022.
- [111] W. Xu, L. Xie, J. Zhu, L. Tang, R. Singh, C. Wang, Y. Ma, H.-T. Chen, and Y. Ying, "Terahertz biosensing with a graphene-metamaterial heterostructure platform," *Carbon*, vol. 141, pp. 247–252, 2019.
- [112] L. Yu, Y. Guo, H. Zhu, M. Luo, P. Han, and X. Ji, "Low-cost microbolometer type infrared detectors," *Micromachines*, vol. 11, no. 9, p. 800, 2020.
- [113] C. Liu, L. Wang, X. Chen, J. Zhou, W. Hu, X. Wang, J. Li, Z. Huang, W. Zhou, W. Tang *et al.*, "Room-temperature photoconduction assisted by hot-carriers in graphene for sub-terahertz detection," *Carbon*, vol. 130, pp. 233–240, 2018.
- [114] C. Sirtori, "Bridge for the terahertz gap," *Nature*, vol. 417, no. 6885, pp. 132–133, 2002.
- [115] S. Zhong, "Progress in terahertz nondestructive testing: A review," *Frontiers of Mechanical Engineering*, vol. 14, pp. 273–281, 2019.
- [116] L. Vicarelli, M. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, V. Pellegrini, and A. Tredicucci, "Graphene field-effect transistors as room-temperature terahertz detectors," *Nature materials*, vol. 11, no. 10, pp. 865–871, 2012.
- [117] H. Qin, J. Sun, S. Liang, X. Li, X. Yang, Z. He, C. Yu, and Z. Feng, "Room-temperature, low-impedance and high-sensitivity terahertz direct detector based on bilayer graphene field-effect transistor," *Carbon*, vol. 116, pp. 760–765, 2017.
- [118] X. Cai, A. B. Sushkov, R. J. Suess, M. M. Jadidi, G. S. Jenkins, L. O. Nyakiti, R. L. Myers-Ward, S. Li, J. Yan, D. K. Gaskill *et al.*, "Sensitive room-temperature terahertz detection via the photothermoelectric effect in graphene," *Nature nanotechnology*, vol. 9, no. 10, pp. 814–819, 2014.
- [119] J. Tissot, C. Trouilleau, B. Fieque, A. Crastes, and O. Legras, "Uncooled microbolometer detector: recent developments at ulis," *Opto-Electronics Review*, vol. 14, pp. 25–32, 2006.

- [120] L. Viti, J. Hu, D. Coquillat, A. Politano, W. Knap, and M. S. Vitiello, “Efficient terahertz detection in black-phosphorus nano-transistors with selective and controllable plasma-wave, bolometric and thermoelectric response,” *Scientific Reports*, vol. 6, no. 1, p. 20474, 2016.
- [121] S. Fan, J. Gou, Q. Niu, Z. Xie, and J. Wang, “Broadband thz absorption of microbolometer array integrated with split-ring resonators,” *Nanoscale Research Letters*, vol. 15, pp. 1–7, 2020.
- [122] W. Miao, H. Gao, Z. Wang, W. Zhang, Y. Ren, K. Zhou, S. Shi, C. Yu, Z. He, Q. Liu *et al.*, “A graphene-based terahertz hot electron bolometer with johnson noise readout,” *Journal of Low Temperature Physics*, vol. 193, pp. 387–392, 2018.
- [123] H.-J. Song and N. Lee, “Terahertz communications: Challenges in the next decade,” *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 2, pp. 105–117, 2021.
- [124] C. Rao, K. Biswas, K. Subrahmanyam, and A. Govindaraj, “Graphene, the new nanocarbon,” *Journal of Materials Chemistry*, vol. 19, no. 17, pp. 2457–2469, 2009.
- [125] A. K. Geim, “Graphene: status and prospects,” *science*, vol. 324, no. 5934, pp. 1530–1534, 2009.
- [126] M. M. Hamed, A. Ainla, F. Güder, D. C. Christodouleas, M. T. Fernández-Abedul, and G. M. Whitesides, “Integrating electronics and microfluidics on paper,” *Advanced Materials*, vol. 28, no. 25, pp. 5054–5063, 2016.
- [127] M. Vaughan, *The Fabry-Perot interferometer: history, theory, practice and applications*. Routledge, 2017.
- [128] R. Zhou, T. Jiang, Z. Peng, Z. Li, M. Zhang, S. Wang, L. Li, H. Liang, S. Ruan, and H. Su, “Tunable broadband terahertz absorber based on graphene metamaterials and vo2,” *Optical Materials*, vol. 114, p. 110915, 2021.
- [129] M. A. Green, J. Xu, H. Liu, J. Zhao, K. Li, L. Liu, H. Qin, Y. Zhu, D. Shen, and X. Chen, “Terahertz absorption of hydrogenated tio2 nanoparticles,” *Materials Today Physics*, vol. 4, pp. 64–69, 2018.
- [130] Z. Huang, H. Chen, Y. Huang, Z. Ge, Y. Zhou, Y. Yang, P. Xiao, J. Liang, T. Zhang, Q. Shi *et al.*, “Ultra-broadband wide-angle terahertz absorption properties of 3d graphene foam,” *Advanced functional materials*, vol. 28, no. 2, p. 1704363, 2018.

- [131] S. K. Ghosh, S. Das, and S. Bhattacharyya, “Graphene based metasurface with near unity broadband absorption in the terahertz gap,” *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 30, no. 12, p. e22436, 2020.
- [132] Z. Song and J. Zhang, “Achieving broadband absorption and polarization conversion with a vanadium dioxide metasurface in the same terahertz frequencies,” *Optics express*, vol. 28, no. 8, pp. 12 487–12 497, 2020.
- [133] F. Warkusz, “The size effect and the temperature coefficient of resistance in thin films,” *Journal of Physics D: Applied Physics*, vol. 11, no. 5, p. 689, 1978.
- [134] P. W. Kruse, “Principles of uncooled infrared focal plane arrays,” in *Semiconductors and semimetals*. Elsevier, 1997, vol. 47, pp. 17–42.
- [135] A. Dubey, R. Mishra, Y.-H. Hsieh, C.-W. Cheng, B.-H. Wu, L.-J. Chen, S. Gwo, and T.-J. Yen, “Aluminum plasmonics enriched ultraviolet gan photodetector with ultrahigh responsivity, detectivity, and broad bandwidth,” *Advanced Science*, vol. 7, no. 24, p. 2002274, 2020.
- [136] M. A. Jamshed, A. Nauman, M. A. B. Abbasi, and S. W. Kim, “Antenna selection and designing for thz applications: suitability and performance evaluation: a survey,” *IEEE Access*, vol. 8, pp. 113 246–113 261, 2020.
- [137] N. M. Burford and M. O. El-Shenawee, “Review of terahertz photoconductive antenna technology,” *Optical Engineering*, vol. 56, no. 1, pp. 010 901–010 901, 2017.
- [138] K. Liu, X. Chen, M. Lian, J. Jia, Y. Su, H. Ren, S. Zhang, Y. Xu, J. Chen, Z. Tian *et al.*, “Nonvolatile reconfigurable electromagnetically induced transparency with terahertz chalcogenide metasurfaces,” *Laser & Photonics Reviews*, vol. 16, no. 4, p. 2100393, 2022.
- [139] X. Li, J. Li, Y. Li, A. Ozcan, and M. Jarrahi, “High-throughput terahertz imaging: progress and challenges,” *Light: Science & Applications*, vol. 12, no. 1, p. 233, 2023.
- [140] T. Nagatsuma, G. Ducournau, and C. C. Renaud, “Advances in terahertz communications accelerated by photonics,” *Nature Photonics*, vol. 10, no. 6, pp. 371–379, 2016.
- [141] Q. Cassar, A. Al-Ibadi, L. Mavarani, P. Hillger, J. Grzyb, G. MacGrogan, T. Zimmer, U. R. Pfeiffer, J.-P. Guillet, and P. Mounaix, “Pilot study of freshly excised breast tissue response in the 300–600 ghz range,” *Biomedical optics express*, vol. 9, no. 7, pp. 2930–2942, 2018.

- [142] S. Ullah, C. Ruan, T. U. Haq, and X. Zhang, "High performance thz patch antenna using photonic band gap and defected ground structure," *Journal of Electromagnetic Waves and Applications*, vol. 33, no. 15, pp. 1943–1954, 2019.
- [143] H. Wang, "A novel terahertz dual-band patch antenna based on double-t-slots," *Study on Optical Communications*, vol. 201, pp. 75–78, 2017.
- [144] P. Mukherjee and B. Gupta, "Terahertz (thz) frequency sources and antennas-a brief review," *International Journal of Infrared and Millimeter Waves*, vol. 29, no. 12, pp. 1091–1102, 2008.
- [145] I. Malhotra, K. R. Jha, and G. Singh, "Terahertz antenna technology for imaging applications: A technical review," *International Journal of Microwave and Wireless Technologies*, vol. 10, no. 3, pp. 271–290, 2018.
- [146] G. Christina, "A review on microstrip patch antenna performance improvement techniques on various applications," *Journal of Trends in Computer Science and Smart Technology*, vol. 3, no. 3, pp. 175–189, 2021.
- [147] M. S. Rabbani and H. Ghafouri-Shiraz, "Liquid crystalline polymer substrate-based thz microstrip antenna arrays for medical applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1533–1536, 2017.
- [148] W. Shihzad, S. Ullah, A. Ahmad, N. A. Abbasi, and D.-y. Choi, "Design and analysis of dual-band high-gain thz antenna array for thz space applications," *Applied Sciences*, vol. 12, no. 18, p. 9231, 2022.
- [149] X. C. Zhang, A. Shkurinov, and Y. Zhang, "Extreme terahertz science," *Nature photonics*, vol. 11, no. 1, pp. 16–18, 2017.
- [150] D. Dykaar, B. Greene, J. Federici, A. Levi, L. Pfeiffer, R. Kopf, M. Anzlowar, and K. West, "Log-periodic antennas for pulsed terahertz radiation," in *Quantum Electronics and Laser Science Conference*. Optica Publishing Group, 1991, p. JFB4.
- [151] R. S. Pavlov, A. G. Curto, and N. F. van Hulst, "Log-periodic optical antennas with broadband directivity," *Optics Communications*, vol. 285, no. 16, pp. 3334–3340, 2012.
- [152] G. De Vito and G. Stracca, "Comments on the design of log-periodic dipole antennas," *IEEE Transactions on Antennas and Propagation*, vol. 21, no. 3, pp. 303–308, 2003.

- [153] R. Carrel, “The design of log-periodic dipole antennas,” in *1958 IRE International Convention Record*, vol. 9. IEEE, 1966, pp. 61–75.
- [154] K. K. Mistry, P. I. Lazaridis, Z. D. Zaharis, M. O. Akinsolu, B. Liu, T. D. Xenos, I. A. Glover, and R. Prasad, “Time and frequency domain simulation, measurement and optimization of log-periodic antennas,” *Wireless Personal Communications*, vol. 107, no. 2, pp. 771–783, 2019.
- [155] L. C. Godara, “Applications of antenna arrays to mobile communications. i. performance improvement, feasibility, and system considerations,” *Proceedings of the IEEE*, vol. 85, no. 7, pp. 1031–1060, 1997.
- [156] F. González and G. Boreman, “Comparison of dipole, bowtie, spiral and log-periodic ir antennas,” *Infrared physics & technology*, vol. 46, no. 5, pp. 418–428, 2005.
- [157] A. Kyei, D.-U. Sim, and Y.-B. Jung, “Compact log-periodic dipole array antenna with bandwidth-enhancement techniques for the low frequency band,” *IET Microwaves, Antennas & Propagation*, vol. 11, no. 5, pp. 711–717, 2017.
- [158] D. Surender, T. Khan, F. A. Talukdar, and Y. M. Antar, “Rectenna design and development strategies for wireless applications: A review,” *IEEE Antennas and Propagation Magazine*, vol. 64, no. 5, pp. 16–29, 2021.
- [159] T. Lchhab and M. El Ghzaoui, “A circularly polarized wideband high gain antenna for thz wireless applications,” *Optical and Quantum Electronics*, vol. 54, no. 12, p. 787, 2022.
- [160] A. Rogalski, M. Kopytko, and P. Martyniuk, “Two-dimensional infrared and terahertz detectors: Outlook and status,” *Applied Physics Reviews*, vol. 6, no. 2, 2019.
- [161] A. Baldominos, Y. Saez, and P. Isasi, “On the automated, evolutionary design of neural networks: past, present, and future,” *Neural computing and applications*, vol. 32, no. 2, pp. 519–545, 2020.
- [162] Z. Qiu, W. Bi, D. Xu, H. Guo, H. Ge, Y. Liang, H. P. Lee, and C. Wu, “Efficient self-learning evolutionary neural architecture search,” *Applied Soft Computing*, vol. 146, p. 110671, 2023.
- [163] S. Katoch, S. S. Chauhan, and V. Kumar, “A review on genetic algorithm: past, present, and future,” *Multimedia tools and applications*, vol. 80, no. 5, pp. 8091–8126, 2021.

- [164] D. Wang, D. Tan, and L. Liu, “Particle swarm optimization algorithm: an overview,” *Soft computing*, vol. 22, no. 2, pp. 387–408, 2018.
- [165] A. Alexandridis, P. Patrinos, H. Sarimveis, and G. Tsekouras, “A two-stage evolutionary algorithm for variable selection in the development of rbf neural network models,” *Chemometrics and intelligent laboratory systems*, vol. 75, no. 2, pp. 149–162, 2005.
- [166] A. Gaspar-Cunha and A. Vieira, “A multi-objective evolutionary algorithm using neural networks to approximate fitness evaluations,” *Int. J. Comput. Syst. Signals*, vol. 6, no. 1, pp. 18–36, 2005.
- [167] Y. Sun, B. Xue, M. Zhang, and G. G. Yen, “Evolving deep convolutional neural networks for image classification,” *IEEE Transactions on Evolutionary Computation*, vol. 24, no. 2, pp. 394–407, 2019.
- [168] A. F. Agarap, “Deep learning using rectified linear units (relu),” *arXiv preprint arXiv:1803.08375*, 2018.
- [169] I. Daubechies, R. DeVore, S. Foucart, B. Hanin, and G. Petrova, “Nonlinear approximation and (deep) relu networks,” *Constructive Approximation*, vol. 55, no. 1, pp. 127–172, 2022.
- [170] W. L. Stutzman, “Estimating directivity and gain of antennas,” *IEEE Antennas and Propagation Magazine*, vol. 40, no. 4, pp. 7–11, 1998.
- [171] H. Cho and D. E. Burk, “A three-step method for the de-embedding of high-frequency s-parameter measurements,” *IEEE Transactions on Electron Devices*, vol. 38, no. 6, pp. 1371–1375, 1991.
- [172] A. R. Hambley, *Electrical engineering: principles and applications*. Prentice Hall, 2017, vol. 4.
- [173] D. M. Pozar, *Microwave engineering: theory and techniques*. John wiley & sons, 2021.
- [174] A. Youssef, I. Halkhams, R. El Alami, M. O. Jamil, and H. Qjjidaa, “A novel slotted antenna design for future terahertz applications,” *International Journal of Electrical & Computer Engineering (2088-8708)*, vol. 14, no. 3, 2024.

- [175] L. C. Paul and M. M. Islam, “Proposal of wide bandwidth and very miniaturized having dimension of μm range slotted patch thz microstrip antenna using pbg substrate and dgs,” in *2017 20th International Conference of Computer and Information Technology (ICCIT)*. IEEE, 2017, pp. 1–6.
- [176] S. Kiani, P. Rezaei, and M. Fakhr, “On-chip coronavirus shape antenna for wide band applications in terahertz band,” *Journal of Optics*, vol. 52, no. 2, pp. 860–867, 2023.
- [177] X. Ji, Y. Chen, J. Li, D. Wang, Y. Zhao, Q. Wu, and M. Li, “Design of high-gain antenna arrays for terahertz applications,” *Micromachines*, vol. 15, no. 3, p. 407, 2024.
- [178] F. B. Niesler, J. K. Gansel, S. Fischbach, and M. Wegener, “Metamaterial metal-based bolometers,” *Applied Physics Letters*, vol. 100, no. 20, 2012.
- [179] G. Chen, J. Seo, C. Yang, and P. N. Prasad, “Nanochemistry and nanomaterials for photovoltaics,” *Chemical Society Reviews*, vol. 42, no. 21, pp. 8304–8338, 2013.
- [180] G.-H. Lee, D. K. Efetov, W. Jung, L. Ranzani, E. D. Walsh, T. A. Ohki, T. Taniguchi, K. Watanabe, P. Kim, D. Englund *et al.*, “Graphene-based josephson junction microwave bolometer,” *Nature*, vol. 586, no. 7827, pp. 42–46, 2020.
- [181] M. Al-Haddad, N. Jamel, and A. N. Nordin, “Flexible antenna: A review of design, materials, fabrication, and applications,” in *Journal of Physics: Conference Series*, vol. 1878, no. 1. IOP Publishing, 2021, p. 012068.
- [182] M. Palandöken, “Artificial materials based microstrip antenna design,” *Microstrip antennas*, pp. 43–50, 2011.
- [183] R. Salvado, C. Loss, R. Gonçalves, and P. Pinho, “Textile materials for the design of wearable antennas: A survey,” *Sensors*, vol. 12, no. 11, pp. 15 841–15 857, 2012.