N° d'ordre :

الجمهورية الجزائرية الديمقراطية الشعبية

République Algérienne Démocratique et Populaire

وزارة التعليم العالي والبحث العلمي

Ministère de L'enseignement Supérieur et de La Recherche Scientifique

جامعة عين تموشنت بلحاج بوشعيب

Universite Ain Témouchent-Belhadj Bouchaib

Faculté : Sciences et technologie
Departement : Electronique et Télécommunications
Laboratoire : Structures intelligentes

THESE

Présentée pour l'obtention du **diplôme de DOCTORAT**
Domaine : Sciences et Technologies
Filière : Télécommunications
Spécialité : Système de Télécommunications
Par : MOULFI BOUCHRA

Intitulé

Etude et conception des nano-antennes optiques micro-rubans

Soutenue publiquement, le 10 / 07 /2024 devant le jury composé de :

Nom & Prénom(s)	Grade	Qualité	Etablissement de rattachement
Dr Sekkal Mansouria	MCA	Présidente	Université d'Ain Temouchent Belhadj Bouchaib
Dr Ferouani Souheyla	MCA	Rapporteur	Université d'Ain Temouchent Belhadj Bouchaib
Dr Ziani Kerarti Djalal	MCA	Co-rapporteur	Ecole Nationale Supérieure des Télécommunications et des Technologies de l'Information et de la Communication (ENSTTIC)
Dr Boukhobza Abdelkader	MCA	Examinateur	Université d'Ain Temouchent Belhadj Bouchaib
Dr Benosman Hayat	MCA	Examinateur	Université Abou Bekr Belkaid Tlemcen
Dr Bousalah Fayza	MCA	Examinateur	Université Abou Bekr Belkaid Tlemcen
Dr Moulessehoul Wassila	MCA	Invité	Université d'Ain Temouchent Belhadj Bouchaib

Année Universitaire : 2023 /2024

N° d'ordre :

الجمهورية الجزائرية الديمقراطية الشعبية

People's Democratic Republic of Algeria

وزارة التعليم العالي والبحث العلمي

Ministry of Higher Education and Scientific Research

جامعة عين تموشنت بلحاج بوشعيب

University Ain Temouchent Belhadj Bouchaib

Faculty of Science and Technology
Department of Electronic and Telecommunications
Smart Structures Laboratory

THESIS

Presented to obtain the 3rd cycle DOCTORAL diploma
Domain: Science and Technology
Sector: Telecommunications
Specialty: Telecommunications systems
By MOULFI BOUCHRA

Title of the thesis
Study and design of microstrip optical nano antennas

Supported publicly, the .../... /2024, in front of the jury composed of:

Name & first Names(s)	Grade	Quality	Establishment of attachment
Dr Sekkal Mansouria	MCA	President	University of Ain Temouchent Belhadj Bouchaib
Dr Ferouani Souheyla	MCA	Supervisor	University of Ain Temouchent Belhadj Bouchaib
Dr Ziani Kerarti Djalal	MCA	Co-Supervisor	National Higher School of Telecommunications and Information and Communication Technologies (ENSTTIC)
Dr Boukhobza Abdelkader	MCA	Examiner	University of Ain Temouchent Belhadj Bouchaib
Dr Benosman Hayat	MCA	Examiner	University of Abou Bekr Belkaid Tlemcen
Dr Bousalah Fayza	MCA	Examiner	University of Abou Bekr Belkaid Tlemcen
Dr Moulessehoul Wassila	MCA	Guest of Honor	University of Ain Temouchent Belhadj Bouchaib

Année Universitaire : 2023 /2024

Acknowledgements

In the first place, I thank Almighty God for not only fulfilling my dream, which seemed almost miraculous, but also for giving me the strength to endure and the courage to overcome all difficulties.

I would like to express my sincere gratitude to my thesis advisor, Dr. Souheyla Ferouani from the University of Ain Temouchent, for guiding my work throughout. She has always been attentive and highly available during the realization of my project. I warmly thank her for her valuable support and the time she willingly dedicated to me, without which this work would never have come to fruition. I also want to thank her for her constant kindness, trust in me, encouragement, and invaluable advice. I have learned a great deal from her technical expertise and her consistently sincere and coherent feedback.

I must also thank my co-Director, Djalal Ziani-Kerarti, from the Institute of Telecommunications and ICT of Oran, for his valuable advice.

I also thank Dr Sekkal Mansouria, MCA at University of Ain Temouchent Belhadj Bouchaib, for accepting to chair the jury. This demonstrates the trust he places in my work and honors me with his availability.

By agreeing to be part of my jury, Dr. Benosman Hayat, MCA at Abou Bekr Belkaid University of Tlemcen, Dr. Bousalah Fayza, MCA at Abou Bekr Belkaid University of Tlemcen, and Dr. Boukhobza Abdelkader and Dr. Moulessehoul wassila, MCA at University of Ain Temouchent Belhadj Bouchaib, have bestowed upon me a great honor. May they find heremy deepest gratitude.

I want to extend my heartfelt thanks to the friends and colleagues who have offered me their moral and intellectual support every step of the way.

Dedication

I dedicate this work to :

To my parents, whose sacrifices, love, tenderness, encouragement, and prayers have been unwavering throughout my studies.

To my dear grandmother,who dreamed and prayed to see me become a doctor and wished to be with me on that day .

To my dear sisters, for their encouragement, I wish them success and happiness in their lives.

To my esteemed mentor, Madame Souhayla Ferouani, for her sacrifices and efforts from the Master's degree to this day.

To my dear colleagues.

To all the professors who have generously imparted their knowledge and wisdom to us.

To everyone who has encouraged me and believed in my success.

Thank you from the bottom of my heart!

Bouchra Moulfi

ملخص

ظهرت الهوائيات الضوئية النانوية كتقنية واعدة لتطبيقات مختلفة في نطاق التيراهيرتز. الهدف الأول من هذه الأطروحة هو تصميم هوائيات نانوية بصرية قائمة على الغرافين مع ركائز ذات سماكة رقيقة توفر مزايا فريدة بسبب خصائص الغرافين الاستثنائية، مثل قابلية حمل الشحنات العالية والقابلية للتعديل وامتصاص النطاق الترددي. يمكن تصميم هذه الهوائيات للعمل في نطاق التيراهرتز، الذي يعتبر مناسباً بشكل خاص لتطبيقات الاتصال اللاسلكي . تعمل الركيزة ذات السماكة الرفيعة على تحسين أداء الهوائي من خلال توفير الدعم الميكانيكي وتسهيل الاقتران الفعال لإشعاع تيراهيرتز. الهدف الثاني من هذه الرسالة هو تصميم هوائيات بصرية نانوية القائمة على الذهب مع قواعد رقيقة للتطبيقات الطبية والتحليل الطيفي. يظهر الذهب ارتفاعاً قوياً في الترددات البلازمية في نطاق التيراهرتز، مما يجعله مثالياً لتعزيز التفاعلات بين الضوء والمادة . تعمل القواعد رقيقة كمنصة لدعم الذهب ويتيح التحكم الدقيق في هندستها وترتيبها. يتطلب تصميم وتحسين هذه الهوائيات دراسة متأنية لمختلف المعلمات لتحقيق عمل فعال في نطاق التيراهرتز، بما في ذلك أبعاد الهوائي، وخصائص المواد، وسمك الألواح، وكفاءة الاقتران.

كلمات مفتاحية: الهوائيات البصرية،هوائي الشريط المبكروي، هوائي نانوي، إلكترونيات ضوئية، الرنينات البلازمونية، الجسيمات النانوية المعدنية

Abstract

Nano-optical antennas have emerged as a promising technology for various applications in the terahertz band. The first objective of this thesis is to design nano-optical graphene-based antennas with thin epesser substrates that offer unique advantages due to the exceptional properties of graphene, such as its high carrier mobility, tunability, and broadband absorption. These antennas can be designed to operate in the terahertz frequency range, which is particularly suitable for wireless communication applications. The thin epesser substrate enhances the performance of the antenna by providing mechanical support and facilitating efficient coupling of the terahertz radiation. The seconde objective of this thesis is to design gold-based nano-optical antennas with thin epesser substrates for medical and spectroscopy applications. The Gold exhibit strong plasmonic resonances in the terahertz regime, making them ideal for enhancing light-matter interactions. The thin epesser substrate serves as a platform for supporting the gold and enables precise control over their geometry and arrangement. The design and optimization of these antennas require careful consideration of various parameters to achieve efficient operation in the terahertz band, including antenna dimensions, material properties, substrate thickness, and coupling efficiency.

Key words: *Optical Antennas,Microstrip Antenna,Nano-antenna, Optoelectronics,Plasmonic Resonances,Metallic Nanoparticles.*

Résumé

Les antennes nano-optiques sont apparues comme une technologie prometteuse pour diverses applications dans la bande térahertz. Le premier objectif de cette thèse est de concevoir des nano-antennes optiques à base de graphène avec des substrats d'épaisseur minces qui offrent des avantages uniques en raison des propriétés exceptionnelles du graphène, telles que sa mobilité élevée des porteurs, sa capacité de réglage et son absorption large bande. Ces antennes peuvent être conçues pour fonctionner dans la plage de fréquence terahertz, ce qui est particulièrement adapté aux applications de communication sans fil. Le substrat d'épaisseur minces améliore les performances de l'antenne en fournissant un support mécanique et en facilitant le couplage efficace du rayonnement terahertz. Le deuxième objectif de cette thèse est de concevoir des nano-antennes optiques à base d'or avec des substrats d'épaisseur minces pour des applications médicales et de spectroscopie. L'or présente de fortes résonances plasmoniques dans le régime terahertz, ce qui les rend idéales pour améliorer les interactions entre la lumière et la matière. Il sert de plateforme pour supporter l'or et permet un contrôle précis de leur géométrie et de leur disposition. La conception et l'optimisation de ces antennes nécessitent un examen minutieux de divers paramètres pour obtenir un fonctionnement efficace dans la bande térahertz, notamment les dimensions de l'antenne, les propriétés des matériaux, l'épaisseur du substrat et l'efficacité du couplage.

Mots clés : *Antennes Optique, Antenne microruban, nano-antenne, optoélectronique, résonances plasmoniques, nanoparticules métalliques.*

Contents

List of Figures

List of Tables

List of Abbreviations

Au: Gold.
Bp: Bandwidth.
CDV: chemical vapor deposition.
DC: Direct Current.
DGS: Defected Ground Structure.
dBi: Decibels per isotropic.
dB: Decibels.
eV: Electron-volts.
EM: Electromagnetic.
FCC: Federal Communications Commission.
InP: Indium Phosphid material.
IoT: Internet of Things.
IR: The infrared frequencies.
GaAs: Gallium arsenid material.
GPS: The Global Positioning System.
Gbps: Gigabit per second.
GHz: Gigahertz.
K: Unit kelvin.
MDMA Methylene-Dioxy-MetArnphetamine.
MIMO : Multiple-Input Multiple-Output.
RADAR: Radio Detection And Ranging.
SAR: Specific Absorption Rate.
SPP: Surface Plasmon Polariton.
S11: The return loss.
TRI: reflectometry imaging.
T-WLAN: Terabit Wireless Local Area Network.

T-WPAN: Terabit Wireless Personal Area Networks.
VSWR: Voltage Standing Wave Ratio.
PTFE: Teflon substrate.
WBAN: Wireless Body Area Networks.
WLANs: Wireless local area networks.
5G: The fifth generation.
NTT: Japan Nippon Telegraph and Telephone Compan.
fr : frequency.

General introduction

Introduction and backround

The realm of Nano Optical Antennas designed for Terahertz (THz) Applications stands as a dynamic and swiftly progressing domain of exploration, blending the frontiers of nanotechnology and photonics. Terahertz radiation, positioned amidst the electromagnetic spectrum between microwaves and infrared light, spanning the range from 0.1 to 10 THz, has emerged as a focal point of intense scrutiny. This radiation possesses extraordinary attributes that have captivated the imagination of researchers, offering boundless potential in arenas ranging from imaging, sensing, and communication to the realm of spectroscopy. However, terahertz waves are challenging to manipulate and transmit efficiently due to their long wavelength and weak interaction with matter. Nano optical antennas offer a promising solution to overcome these challenges by enhancing the interaction between terahertz waves and matter at the nanoscale. These antennas are typically made of metallic or dielectric materials and are designed to resonate at specific frequencies within the terahertz range.Through precise adjustments to the antennas' dimensions, morphology, and material constituents, scientists gain the ability to manipulate the characteristics of terahertz waves. These manipulations encompass controlling factors like absorption, scattering, and radiation properties. Crafting nano optical antennas optimized for terahertz transmission entails a multifaceted approach, encompassing theoretical modeling, numerical simulations, and experimental methodologies.In recent years, several fabrication techniques have been developed to realize nano optical antennas for terahertz transmission. Among these methodologies are electron beam lithography, focused ion beam milling, nanoimprint lithography, and self-assembly techniques. Each of these methods possesses distinct merits and constraints concerning factors such as resolution, scalability, and compatibility with materials.

Goals

The goals of this thesis are as follows:

1. **Design and Optimization:** Develop a comprehensive understanding of the design principles and optimization techniques for nano optical antennas operating in the THz

frequency range.

2. **Characterization:** Characterize the performance of nano optical antennas for THz applications, including their radiation patterns, resonant frequencies, and near-field interactions.

3. **Applications:**Explore and evaluate potential applications of nano optical antennas in THz communication, imaging and spectroscopy.

4. **Performance Enhancement:** Investigate methods to enhance the efficiency and functionality of nano optical antennas, including advanced materials, geometries, and fabrication techniques.

Thesis Outline

The thesis will be structured as follows:

Chapter 1:Terahertz domain and application

Chapter 1 will be devoted to the presentation of terahertz band and its properties, followed by its advantages, disadvantages and the different fields of applications used in this band.

Chapter 2:Nano optical terahertz antenna

Chapter 2 introduce optical antennas by discussing the choice and challenges of the terahertz band, as well as the type of materials chosen for this band and the way in which materials are used to manufacture nano-antennas. However, prior knowledge of antenna theory and characteristics is essential to enable us to propose compact, high-performance structures for terahertz band applications.

Chapter 3:Wireless applications THz antenna

Chapter 3 details the designed of nano optical antennas for wireless communications in terahertz band [0.1-10] THz using Graphene radiating element with polymer and High-Frequency Laminate substrates because of their flexibility, light weight and low cost to increase performances of antennas.

Chapter 4:WBAN THz antenna

Chapter 4 details the design of optical nano antennas for WBAN applications such as medical imaging and spectroscopy, combining different materials with high conductivity compatible with the terahertz band.

Chapter 1

Terahertz domain and application

1.1 Introduction

There has been increasing interest in terahertz optical waves due to their ability to provide more valuable information in fields such as wireless communication, imaging, spectroscopy, and security.

In this first chapter, the terahertz band and its properties are presented. We then discuss its advantages, disadvantages and the different fields of applications used in this band.

1.2 Terahertz band

The term terahertz (THz) consists of two words:

- The suffix hertz (Hz) refers to the International System of Units (SI) frequency unit, which is defined as the number of wave cycles per second.
- The prefix Tera (T) which means monster comes from the ancient Greek word Teras.

As a result, the latter increases by one trillion Hz units. Therefore, we can express 1 THz $=10^{12}$ Hz, which is equivalent to millions of millions. THz frequencies are a thousand times greater than the GHz frequencies utilized in microwave devices [1].

The terahertz (THz) frequency range is a part of the electromagnetic (EM) spectrum located between the infrared (IR) frequencies and the electronic microwave range. Terahertz waves are also called T-rays (T-rays) or far infrared waves due to their longer wavelengths than IR and smaller wavelengths than microwaves.

Specifically, the terahertz frequencies are between 0.1 and 10 THz, or in terms of wavelength between 1mm and 30 µm with data rates ranging from 10 to 160 Gbps with a transmission range of ten metres . It is possible to visualize where the THz spectrum is located in relation to the spectra of more known regions by observing the figure 1.1 [2]

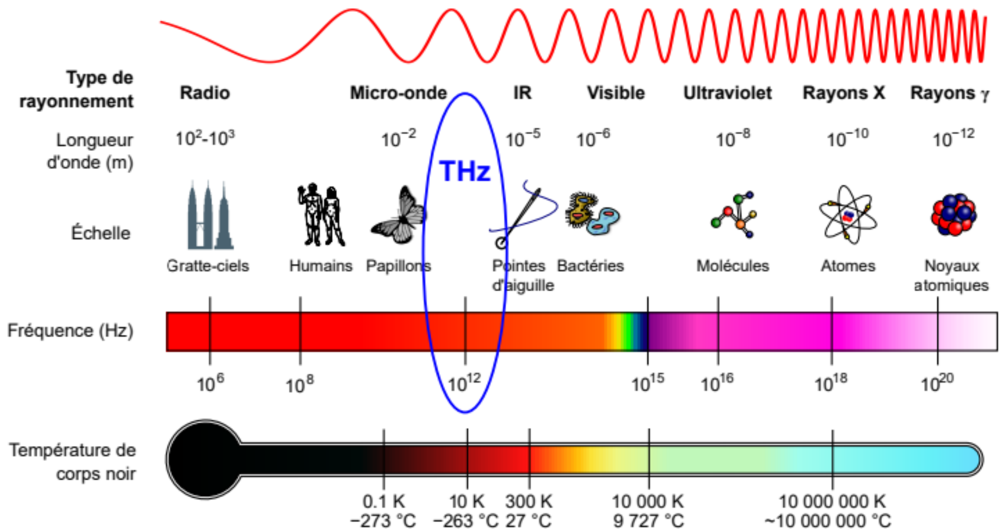


Figure 1.1: The terahertz domain in the electromagnetic spectrum [2].

In order to enhance spectral efficiency and increase data throughput within the terahertz (THz) band, it is imperative to develop new transceiver [3]. Furthermore, you can find a comprehensive estimated comparison in Table 1.1.

Technology	Frequency Ranges	Transmission Range	Peak Data Rate
Bluetooth Low Energy (BLE)	2.4 GHz	100 m	1 Mbps
Low Power Wide Area Network(LoRaWAN)	868 MHz, 0.9 Ghz, Sub 1 GHz	10 Km	50 Kbps
NarrowBand-Internet of Things (NB-IoT)	0.7 to 0.9 GHz	10 Km	200 Kbps
Millimeter Wave (mmWave) Communication	24 to 100 GHz	100 m	10 Gbps
THz Communication	0.1 THz -10 THz	10 m	10 Gbps to 160 Gbps

Table 1.1: Comparison between THz and other wireless technologies [4].

Only a limited number of researchers, primarily in fields such as chemical spectroscopy, astronomy, and solid-state physics, have explored this particular realm within the terahertz

(THz) spectrum. However, microwave bands suffer from a limitation in bandwidth, typically below 10 GHz. This results in a limited capacity for carrying data simultaneously. Thus, applications that require extremely high data rates and massive data transmission may find microwave bands insufficient. As a result, the evolution of microprocessing requires miniaturized antennas that are difficult to achieve in the GHz band.

To address this issue, researchers have turned to exploring millimetre frequency bands in electronics. The use of millimetre frequencies offers a solution to the growing demand for data rates in wireless communications, thanks to the wide bandwidths available at these frequencies. Additionally, the birth of nanotechnology has made it possible to achieve smaller sizes and less energy consumption [5]. For this reason, it is useful in many fields of applications including imaging and spectroscopy, biology and medicine, security and communication [6].

1.3 Advantages and Disadvantages of the terahertz THz band

1.3.1 Advantages of THz Band

The Terahertz communication offers several advantages over other systems (microwave and infrared). Here is a summary of these advantages:

- It offers a possibility of increasing the throughput and bandwidth, compared to other systems and can be used to transmit several channels simultaneously in high definition [7].
- Terahertz waves are non-ionizing and do not pose a health risk due to their previously mentioned low photon energy, which makes THz deployable with less strain than X-rays [1].
- Dielectric materials used in the terahertz band are less susceptible to Mie and Rayleigh scattering [8].

- The use of terahertz waves allows to obtain a higher resolution than microwaves due to their short wavelength [9].

- Can be considered as a secure communication for several reasons, among which the fact that the THz wave has a directional propagation and that it propagates on a distance limited to a few tens of meters, considering the strong absorption by water [8].

- Under certain atmospheric conditions, THz waves are less attenuated than infrared waves [10].

- The THz frequency band is not yet allocated, the band $0,275-0,450$ THz in the United States is reserved for mobile communication [11]. The frequencies above $0,275$ GHz in Europe are available for communication [12].

These advantages over the various existing technologies make THz an interesting choice for many applications.

1.3.2 Disadvantages of the terahertz THz band

Despite the incredible advantages, the terahertz band suffers from several challenges:

- Emitted terahertz waves are strongly absorbed by water vapor molecules, once transmitted through the Air [13] .

- *A great difficulty in manufacturing detectors sensitive to the optical band:* The Terahertz detectors must be able to convert electromagnetic waves at terahertz frequencies into detectable electrical signals. This requires specific materials and devices that can react sensitively to changes in the electromagnetic field at optical frequencies [14] .

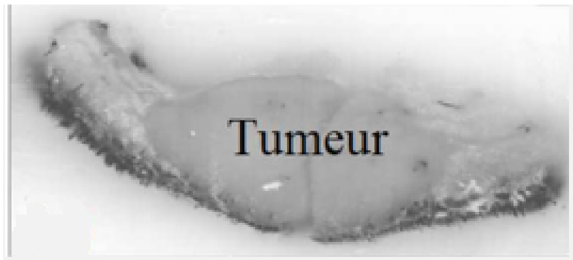
- *Great difficulty in manufacturing powerful, inexpensive, easy to integrate optical antennas:* Compared to conventional antennas used for radio frequency transmissions, optical nano antennas are substantially smaller [15]. so the fabrication and integration of these antennas necessitate advanced lithography techniques and specialized equipment to generate nano-scale structures, which is more expensive [16].

- *The absence of microscopic equipment to manufacture this nano antenna:* The terahertz (THz) range can present technical challenges due to the need to work at very fine scales. Fabrication of optical nano terahertz antennas requires advanced lithography techniques and specialized equipment capable of producing nano-scale structures [17].
- *The antenna range is limited :* The THz waves have an extremely short wavelength, on the order of a few hundred micrometers to a few millimeters. As a result of their short wavelength, the Terahertz waves are subject to strong attenuation and dispersion when they propagate through the air and encounter obstacles [18].

1.4 Applications Domain

1.4.1 The biomedical Applications

The reason for the low non-ionizing energy per photon makes far-infrared radiation of great interest for all medical applications because it poses no threat to biological media. In addition, the wavelengths in the terahertz band are shorter than those of microwaves, so THz radiation provides much lower spatial resolution than microwaves [19]. THz imaging thus allows to visualize objects in different ways with a better spatial resolution [6] than X-rays, which use photons with quantum energy higher than one hundred eV (molecular ionization requiring several eV) [20] . One of the most widely used applications is the identification of a tumor by measuring the reflection, diffraction and transmission indices of a biological tissue as shown in Figure 1.2 [21].



(a) Image optic.

(b) Absorption 2 THz.

(c) Absorption 0.6 THz .

Figure 1.2: (a) Optical image of a tumor tissue ; (b) 2 THz imaging by transmission ; (c) 0.6 THz transmission imaging [21].

Figure 1.3 showcased how THz reflectometry imaging (TRI) effectively differentiated between cancerous and normal regions within brain tissue . Regions with relatively high intensity (shown in red) exhibited a strong spatial correlation with the tumor areas identified in green [22].

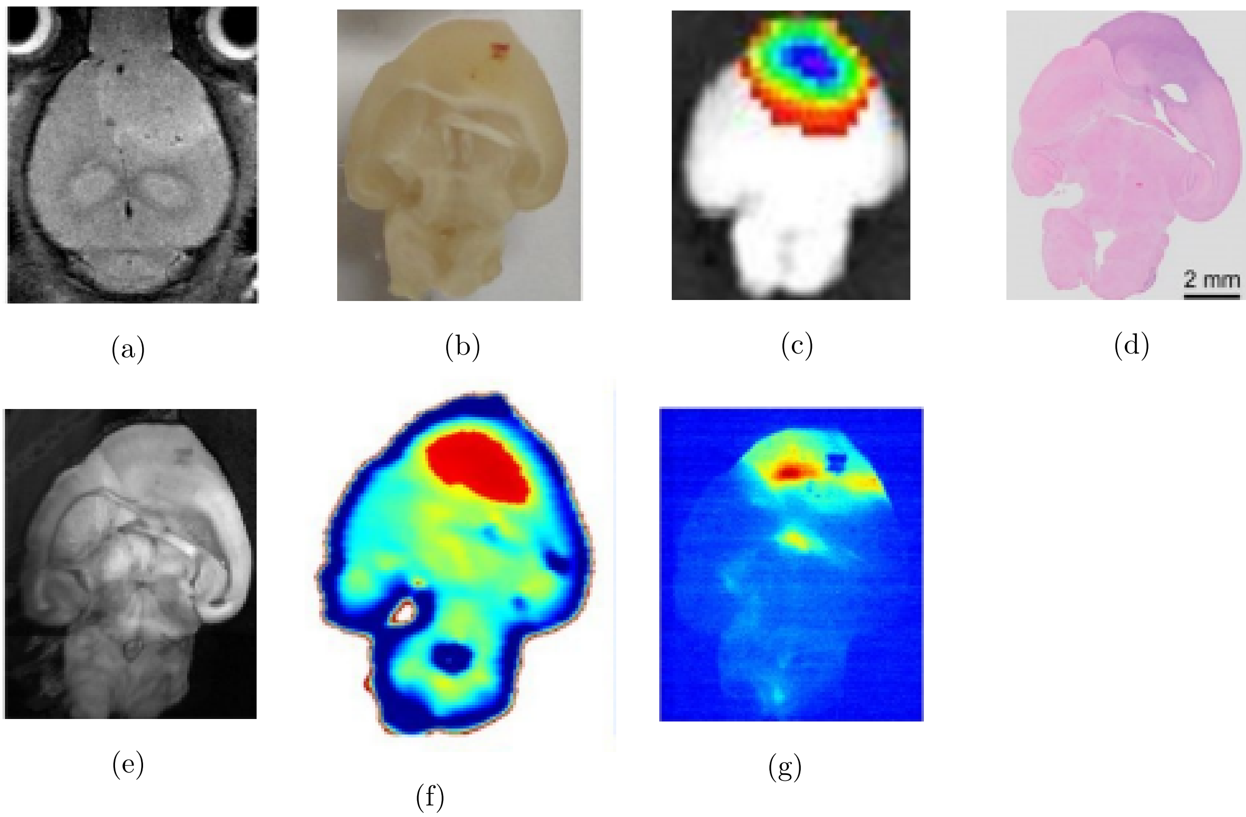


Figure 1.3: Distinguishing brain tumors using various imaging methods:(a) Magnetic Resonance Imaging (MRI) ; (b) White Light Imaging ; (c) Green Fluorescent Protein (GFP) Imaging ; (d) Hematoxylin and Eosin ($H\&E$) Stained Imaging ; (e) Optical Coherence Tomography (OCT) Imaging ; (f) Terahertz Reflectometry Imaging (TRI) ; (g) 5-Aminolevulinic Acid (5-ALA)-Induced ppIX Fluorescence Imaging [22].

THz radiation has the ability to penetrate organic materials to a shallow depth, making it valuable in certain fields of medicine and biology. This non-destructive characteristic makes THz radiation an advantageous alternative for studying living organisms. Medical applications for THz radiation include disease diagnosis, body monitoring, cancer detection, identification of protein structural states, and studying the effects of radiation on biological samples and processes [6].

1.4.2 Pharmaceutical applications

The pharmaceutical sector, dedicated to healing and treating ailments, cannot reasonably employ X-ray technology, which emits ionizing radiation, a known hazard to both human and animal well-being. In this context, Terahertz rays and THz-imaging emerge as distinctive and secure alternatives.

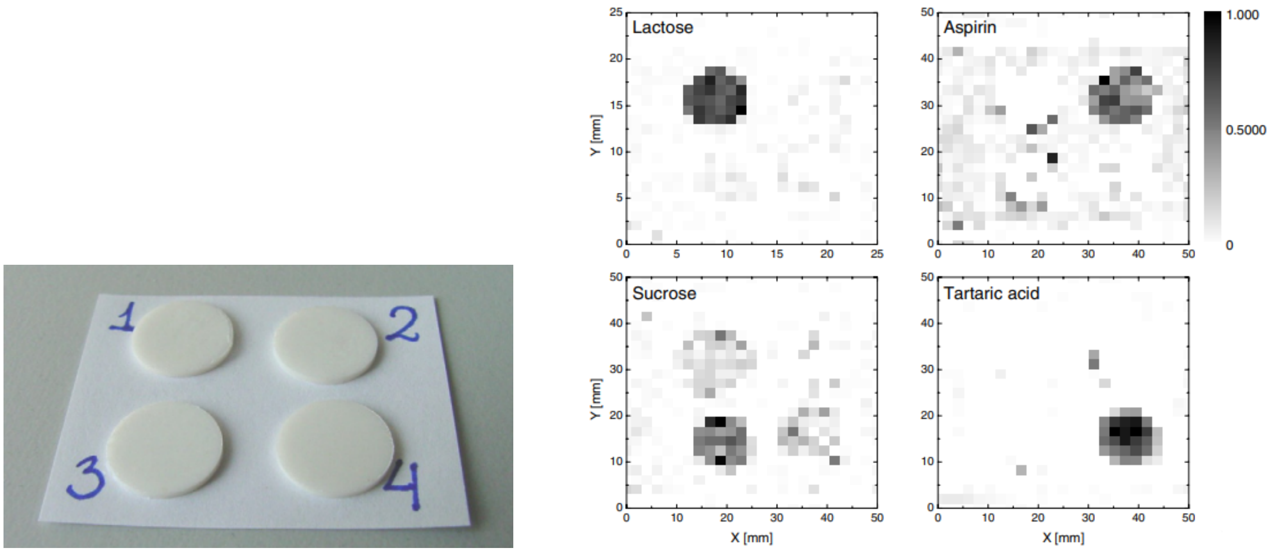
In 2003, the initial investigation into terahertz mapping of illicit drugs in Japan took place. During this study, spectral fingerprints at seven different frequencies were utilized to differentiate between 20 mg of methamphetamine, MDMA, and aspirin concealed within a polyethylene bag inside envelopes, as illustrated in Figure 1.4. The analysis involved applying component spatial pattern analysis to the seven spectral images, enabling the extraction of each of the three components independently [23].

(a) (b)

Figure 1.4: (a)From left to right, the small polyethylene bags contain MDMA, aspirin, and methamphetamine ; (b) The extracted spatial patterns for MDMA (yellow), aspirin (blue), and methamphetamine (red) are displayed. It's evident that all three drugs are distinctly discernible, with corresponding spatial patterns obtained for each [23].

A similar research effort employed pulsed terahertz technology in reflection mode to identify powders such as lactose and sucrose within the frequency range of [0-2] THz. This study revealed the potential to acquire the spatial distribution of individual chemical constituents within a mixture [24].

Conversely, a different study was conducted to distinguish between four chemical compounds using a transmission configuration through samples that were 1 cm thick, as depicted in Figure 1.5. The ability to differentiate the powders was achieved based on a coefficient that was directly related to a spectral feature's weight within the absorption spectra [25].



(a) (b)

Figure 1.5: (a) Image of the sample with four pellets containing various chemicals ; (b) An image depicting the amplitude of THz transmission [25].

1.4.3 The Security and defense Applications

Airport scanners are widely used for security purposes. Recently, newer systems that utilize frequencies near the THz range have been introduced to enhance image accuracy and resolution. These scanners are capable of detecting weapons or drugs by seeing through clothes. What sets these machines apart from X-rays is their ability to differentiate between various materials. Additionally, real-time imaging is possible due to the faster speed of terahertz radiation. It is worth noting that far-infrared waves have also been utilized in the military to identify potential targets, as depicted in the accompanying figures 1.6.

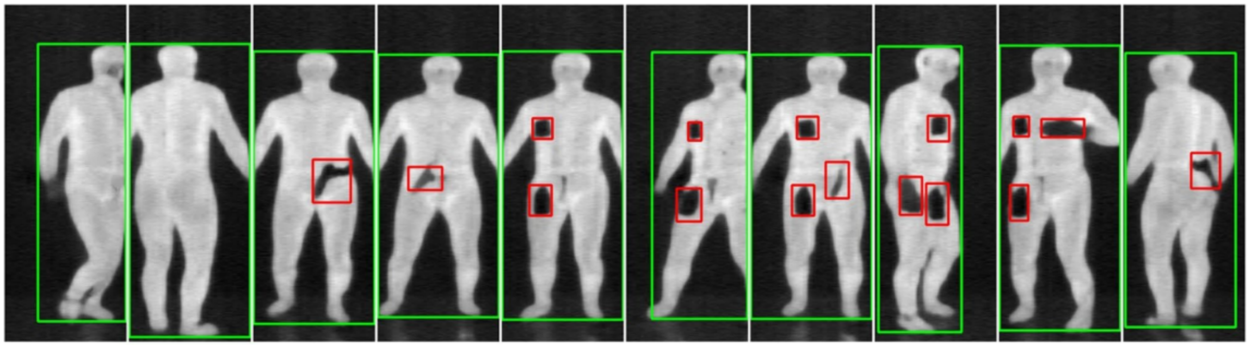


Figure 1.6: Automatic detection with terahertz RADAR for security applications [26].

The terahertz band provides fast transmission speed and high data rate, making it useful for a variety of applications including RADAR (Radio Detection And Ranging), target detection, precision guidance, and missiles. The directivity and energy concentration of terahertz waves allow for the development of high-resolution and elevation tracking radars. Additionally, the hardware imaging capability can detect hidden, obscured, or smoke-covered objects.

The optical RADAR higher precision imaging due to the wider bandwidth, can allows the control of people in an application. The scanning of a person with the far infra-red wave was effected with a fast speed of scanning minimum 5000 pixels/second, a distance more than 20 meters and a clear image that provides more security [27] ,as shown in Figure 1.7 An Example of an image of a razor blade hidden in a polyethylene foam, imaged at 0.650 THz [28].

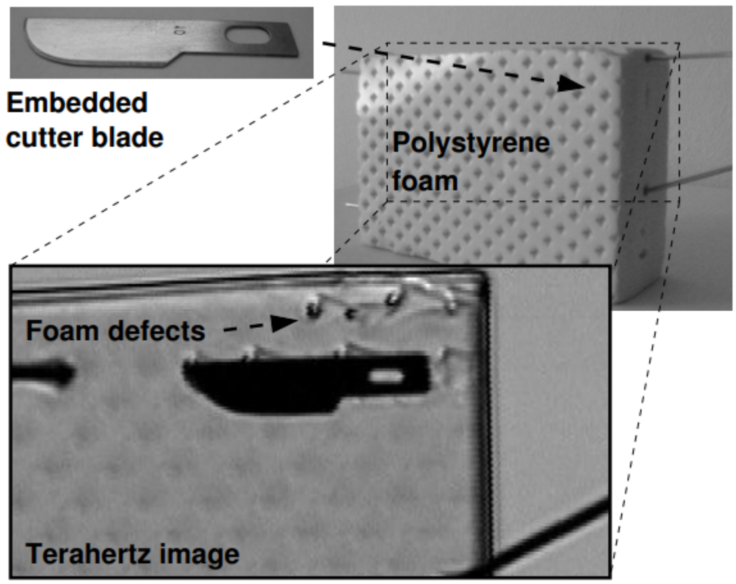
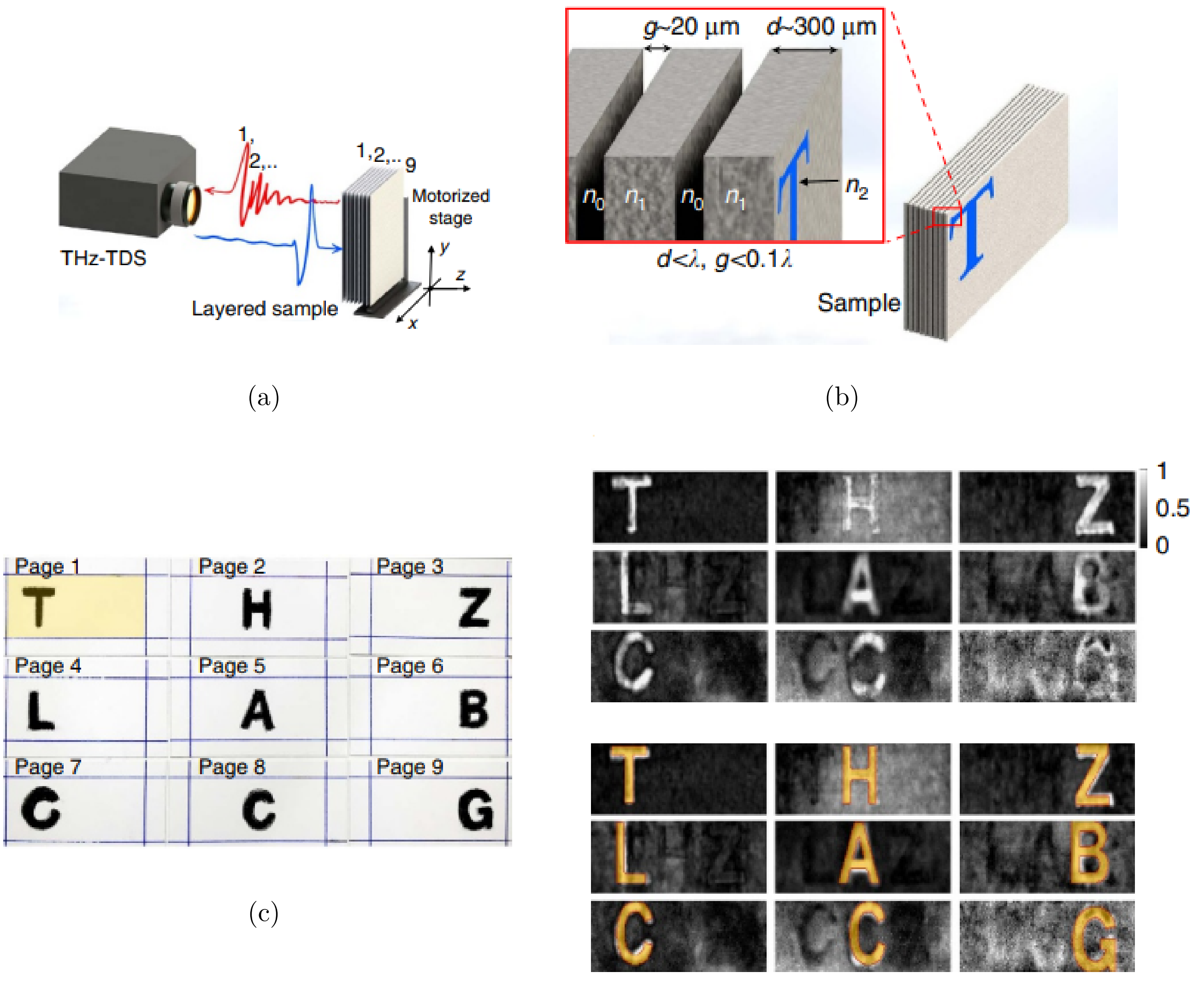


Figure 1.7: Image scanned at 650 GHz in transmission mode of a cutter blade embedded in polystyrene construction foam[28].

1.4.4 Archaeology applications

Terahertz radiation has a higher penetration capacity than X-rays and gamma rays in certain materials due to its specific electromagnetic properties. It can penetrate materials like plastics, textiles, paper, ceramics, and some paint layers without causing damage. This makes it possible to read books that have not been opened, including historical books that are impossible to access due to natural factors. This feature of the far-infrared zone is unique and valuable for accessing information that has been otherwise inaccessible [29] as shown in Figure 1.8.



(a) (b) (c) (d)

Figure 1.8: Explanatory scheme for reading a book its opening (a) The confocal terahertz (THz) time-domain spectroscopy (THz-TDS) measurement is conducted ;(b) The sample consists of nine compacted paper layers ;(c) Nine Roman letters, T, H, Z, L, A, B, C, C, and G, are written on the nine pages ;(d) The technique employs kurtosis of the time-gated Fourier transform to enhance the contrast of the content [29].

The examination of THz pictures gives insight into the painting process and the detection of characteristics that are not present in the visible image. The THz picture, in particular, delivers a "texture feel" of the painting, in which the strength of the stroke, the density of the paint, and the structural elements of the canvas all come together [30] as shown in Figure 1.9.

(a) Image in visible.

(b) 50 %visible,50% THz image.

(c) 100% THz image.

Figure 1.9: "Sacrifice to Vesta" composition at various transparency levels of visible and THz pictures [30].

1.4.5 The Wireless communications Applications

Recently, as wireless communications developed rapidly, traditional microwave communications have been unable to meet the need for high-speed wireless communications, while the terahertz optical band, which can transmit data at high speed, offers several advantages [31].

A future generation of cellular networks: The Terahertz Band transmission can be employed in future generations of small cells, such as hierarchical cellular networks or heterogeneous networks . The terahertz Spectrum will enable very small cells to communicate at ultra-high speeds within coverage spans of as long as 10 meters [32].Furthermore, directed optical Band lines are able to used to offer ultra-fast wireless transport to small cells as described in figure 1.10a [33].

Terabit Wireless Local Area Networks (T-WLAN): Represent a vision and plan for large-scale, ultra-fast Wi-Fi networks with terabit-per-second data rates. This speculative technology goes much beyond the capacities of current wireless networks [34].

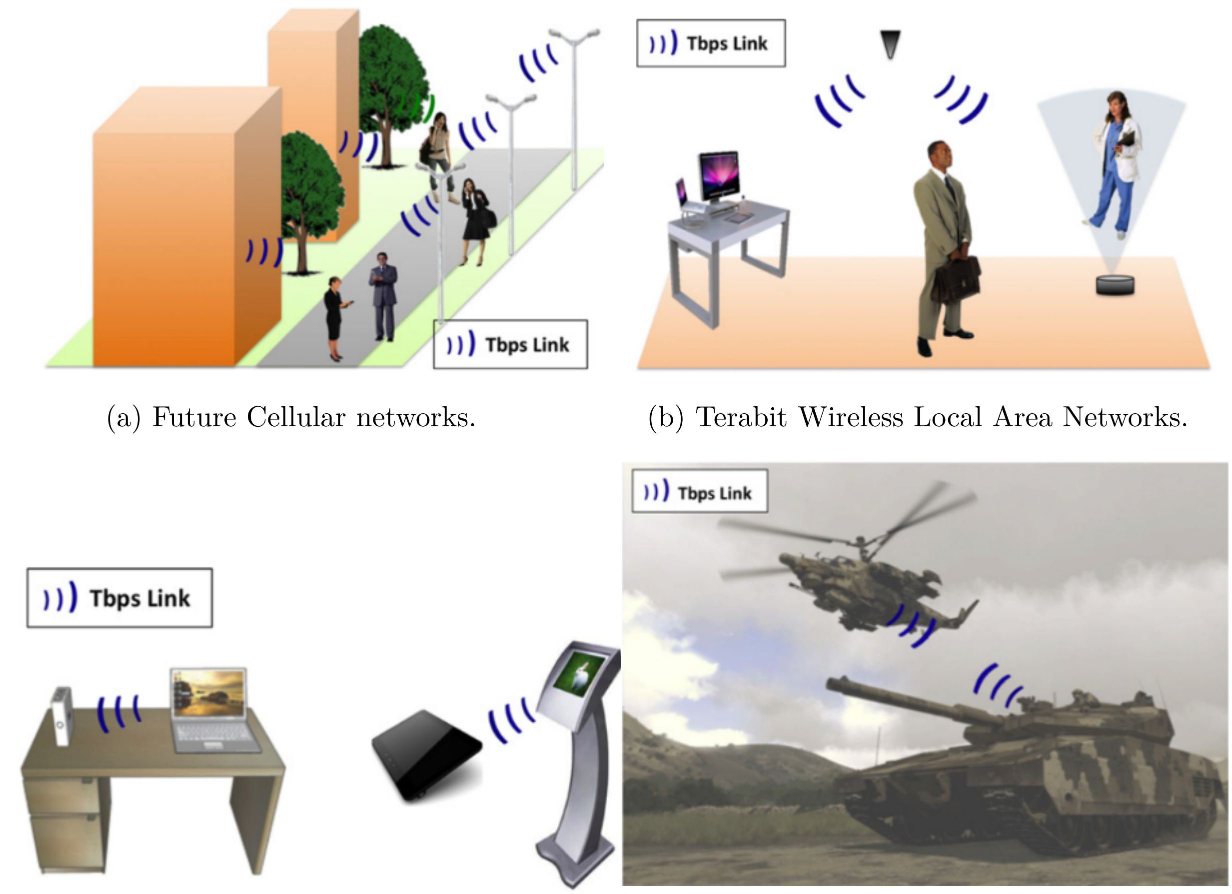
T-WLANs are frequently promoted as a future wireless networking solution, particularly in high-density environments such as urban areas, stadiums, shopping malls or university campuses. They could enable bandwidth-intensive applications such as virtual reality, online games with massively multi-player capabilities, massive real-time data transmissions, autonomous vehicles and more as shown in figure 1.10b [35].

Terabit Wireless Personal Area Networks (T-WPAN): Terabit-scale wireless personal area networks (T-WPANs) are a speculative application for ultra high-speed mobile networks in short-distance communications.T-WPANs, as opposed to terabit-scale wireless local area networks (T-WLANs), focus on small-scale communications between personal devices(figure 1.10c) [36].

T-WPANs are believed to be capable of much higher data rates, allowing for more bandwidth-intensive applications. This could include large Large transfers of data between personal devices, mobile virtual or augmented reality connections, short-range communications between autonomous vehicles, and many others [37].

Secure Terabit Wireless Communication: In the military and defense domains, the optical terahertz Band can also provides ultra-broadband secure communication networks [35].

The Terahertz optical band has promising features for ensuring communication security(figure 1.10d). Its signals are weakened by the atmosphere and barriers, making them less susceptible to interception and disturbance. This helps to strengthen communication security in situations where data privacy is vital [38].



(a) Future Cellular networks.

(b) Terabit Wireless Local Area Networks.

(c) Terabit Wireless Personal Area Networks.

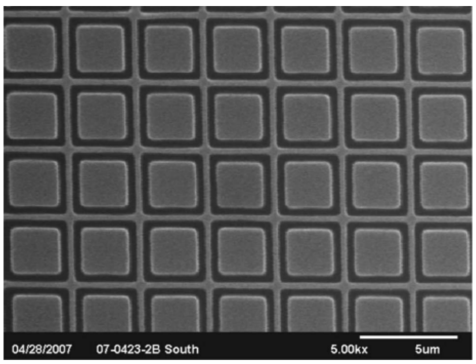
(d) Secure Terabit Wireless Communication.

Figure 1.10: The Wireless communications Applications domain [35].

1.4.6 Solar Energy collection Applications

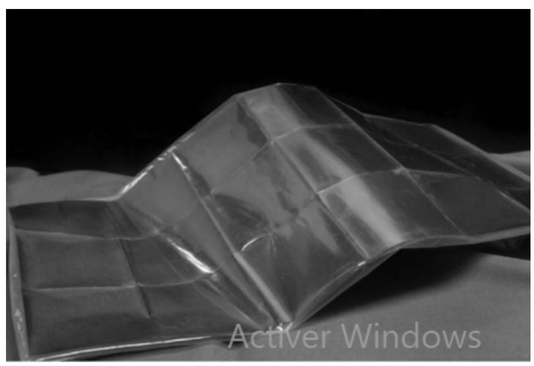
In a very general way, the solar panels use the incident solar radiation to generate electricity by exploiting the photovoltaic effect, that is to say by inducing an electric voltage between the two electrodes. Since the incident solar radiation is an electromagnetic wave with a terahertz wavelength, it can be captured with optical antennas, as is usually the case with radio waves and microwaves [39]. The Optical antennas is a device designed to used in the far infrared frequency range capable of converting freely propagating solar energy into localized energy [40].

To generate the electricity an electromagnetic wave from the sun is incident on a nanoantenna, An alternating current will be induced on the surface of this nano-antenna, and thus a voltage will be generated at the feed point of the terahertz antenna which contains an appropriate rectifier to obtain a direct current (DC), These types of systems that allows energy recovery are called "rectennas"; which essentially contains antennas connected to a rectifier is converts the received signal into direct current and produces electricity [41] as shown in the figure 1.11.



(a)

(b)



(c)

Figure 1.11: Solar Energy collection antenna [42].

1.5 Conclusion

The terahertz band's wide array of applications spans various domains, encompassing imaging and sensing, communication and wireless technology, spectroscopy, material characterization, security and defense, as well as biomedical applications. Continuous research and advancements in technology are poised to reveal even more possibilities in utilizing the distinctive attributes of terahertz waves. The next chapter looks at nano-optical antennas in the terahertz band, offering unique possibilities for manipulating and controlling terahertz radiation at the nanoscale.

Chapter 2

Nano optical terahertz antenna

2.1 Introduction

Nano optical antennas have gained significant attention in recent years due to their ability to manipulate light at the nanoscale. These antennas are designed to enhance the interaction between light and matter, enabling various applications in fields such as sensing, imaging, communication, and energy harvesting. In the terahertz (THz) frequency range, nano optical antennas offer unique opportunities for advancing THz technology by enabling efficient manipulation and control of THz waves.

The aim of this chapter is to introduce optical antennas by discussing the choice and challenges of the terahertz band, as well as the type of materials chosen for this band and the way in which materials are used to manufacture nano-antennas. However, prior knowledge of antenna theory and characteristics is essential to enable us to propose compact, high-performance structures for terahertz band applications.

2.2 Basic antenna theory

To start with the fundamentals of antennas, it is essential to gain an understanding of their fundamental characteristics in general. When designing an antenna (figure 2.1), there are several fundamental parameters that require exploration.

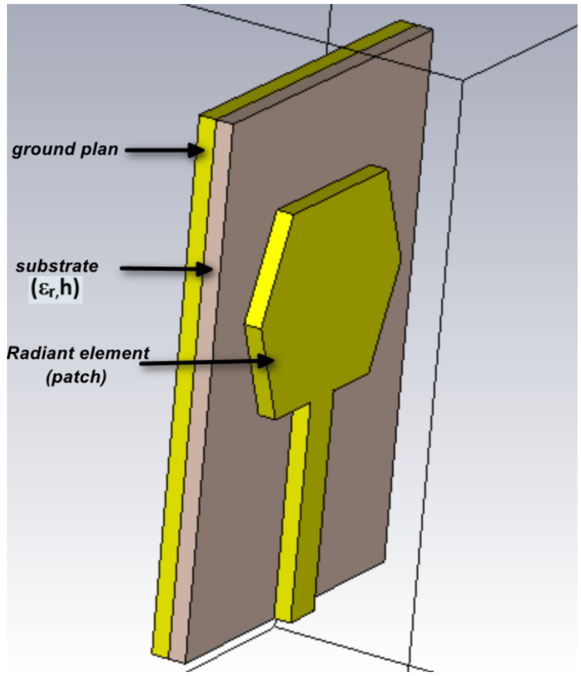


Figure 2.1: Antenna designing.

The specific parameters that need adjustment vary depending on the intended application, as different goals necessitate the tuning of different factors. This section provides an overview of some commonly discussed basic parameters in the context of antennas.

2.2.1 The impedance

Each antenna is characterized by its impedance Z_a, which consists of a real part Ra and an imaginary part X_a. The impedance is defined by the expression 2.1 [43]:

$$Z_a = R_a + jX_a \tag{2.1}$$

The real part as shown by the expression 2.2 consists of the resistance R_r corresponding to the energy radiated by the antenna, and the resistance R_l corresponding to conduction losses, dielectric losses, and surface wave losses of the antenna.

$$Z_a = R_r + R_l \tag{2.2}$$

In transmission, a generator connected to the antenna also has an output impedance Z_g, consisting of a real part R_g and an imaginary part X_g, as shown by the expression 2.3:

$$Z_g = R_g + jX_g \tag{2.3}$$

In most cases, we have: $R_g = 50\omega$ et $X_g = 0$.

2.2.2 Adaptation - Reflection coefficient (S11)

Adaptation is the process that allows the antenna, in transmission for example, to accept the maximum power provided by the generator. It is generally characterized by the parameter S11, which is the ratio of amplitude between the incident wave applied at the antenna's input (P_{inc}) and the wave reflected back to the source (P_{Pref}) due to discontinuities between the circuit and the antenna.

The reflection coefficient S11 is used to characterize the antenna's adaptation to the preceding circuit. The better the antenna is adapted, the lower this coefficient becomes. For instance, with a reflection coefficient at -10 dB, 90% of the power is transmitted to the antenna. The reflection coefficient is measured by a network analyzer as a function of frequency. Expressions 2.4 and 2.5 represent the value of S11 in linear and dB scale [44]. The reflection coefficient ranges between 0 and +1.

$$|S11|^2 = \Gamma = \frac{P_{ref}}{P_{inc}} \tag{2.4}$$

$$S11(dB)2 = 20\log\frac{P_{ref}}{P_{inc}} \tag{2.5}$$

2.2.3 Beamwidth

If G is the maximum gain of a given antenna in a specific plane, then its beamwidth in that plane is the angle between two directions in that plane that have half of the maximum gain (gain at -3 dBi), which is G/2.

2.2.4 Gain and Directivity

The gain G(θ, ϕ) of an antenna in a direction (θ, ϕ) is the ratio of the radiated power in a given direction P(θ, ϕ) to the power that would be radiated by an isotropic antenna with the same losses as in the case under consideration. Generally, the gain G is associated with the direction of maximum radiation (θ_0, ϕ_0). This property indicates the antenna's ability to focus radiated power in a specific direction. Therefore, the gain is given by the following expression 2.6 [45]:

$$G(\theta, \phi) = 4\pi \frac{P(\theta, \phi)}{P_A} \tag{2.6}$$

P_A:The average power density radiated by the lossy isotropic antenna (in W/m^2).

The directivity D(θ, ϕ) of an antenna in a direction (θ, ϕ) is calculated in the same way as the gain compared to a lossless isotropic antenna given by the following expression 2.7.

$$D(\theta, \phi) = 4\pi \frac{P(\theta, \phi)}{P_s} \tag{2.7}$$

P_s the average power density radiated by the lossless isotropic antenna (in W/m^2). The maximum gain is determined from the radiation patterns measured in an anechoic chamber.

2.2.5 Efficiency

Efficiency is the ratio of the power radiated by the antenna to the power supplied at the antenna's input. While total efficiency takes into account mismatch losses, radiated efficiency is an intrinsic parameter of the antenna. It depends solely on the geometric structure of the antenna, determined by its dimensions, shape, as well as the thickness and width of the metallizations, and also the losses in the dielectric substrate. It can be defined by the expression 2.8 [46]:

$$\eta_{tot} = \eta_{ray} * (1 - S11^2) \tag{2.8}$$

Knowing the gain and directivity of an antenna, one can deduce the efficiency of the antenna under test using the following relationship 2.9:

$$G(\theta, \phi) = \eta_{tot} * D(\theta, \phi) \tag{2.9}$$

A radiated efficiency of 50% is a typically acceptable value for miniature antennas.

2.2.6 Radiation Pattern

The radiation pattern is characterized by the power radiated by the antenna in all directions in the far-field space around it. This parameter depends on the overall structure of the antenna and is not controllable by the designer. It helps identify the areas in space and the directions around the antenna where radiation is strong or weak. Two typical forms of radiation patterns can be distinguished [46]:

Omnidirectional Radiation: Characterized by the ability to radiate equally in all directions within a plane, as shown in Figure 2.2.

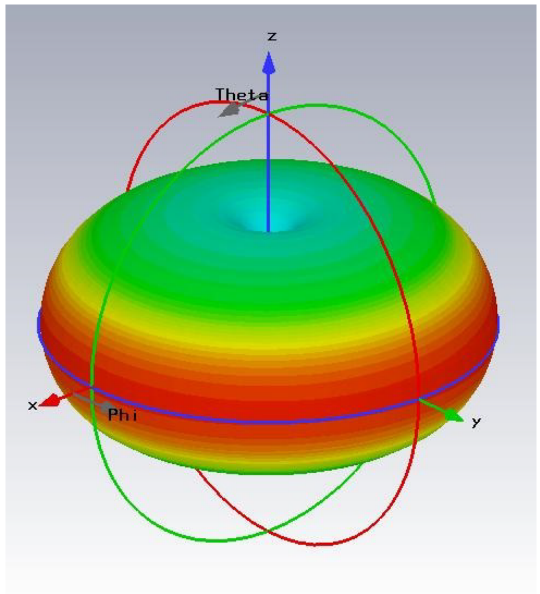


Figure 2.2: Omnidirectional Radiation.

Directive Radiation: An antenna that concentrates the energy it radiates in a preferred direction in space, as depicted in Figure 2.3.

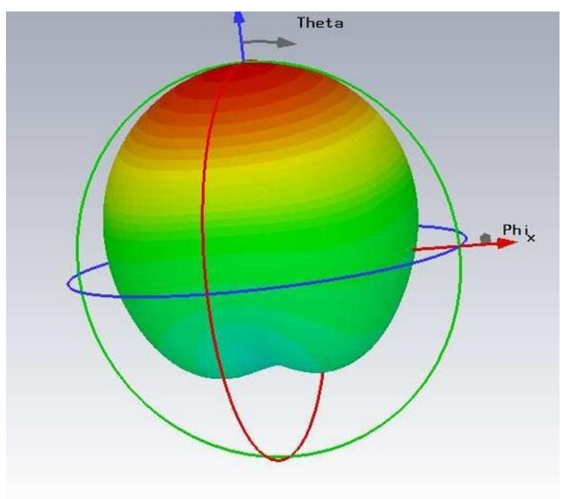


Figure 2.3: Directive Radiation.

2.2.7 Bandwidth

The bandwidth of an antenna refers to the frequency range where the transfer of energy from the feed to the antenna (or from the antenna to the receiver) is at its maximum. It typically corresponds to the frequency range over which 90% of the incident power is transmitted, which corresponds to the reflection coefficient S11 = -10dB, provided that the radiation pattern does not change within this range as shown in figure 2.4 and calculated by the following relationship 2.10 [47] .

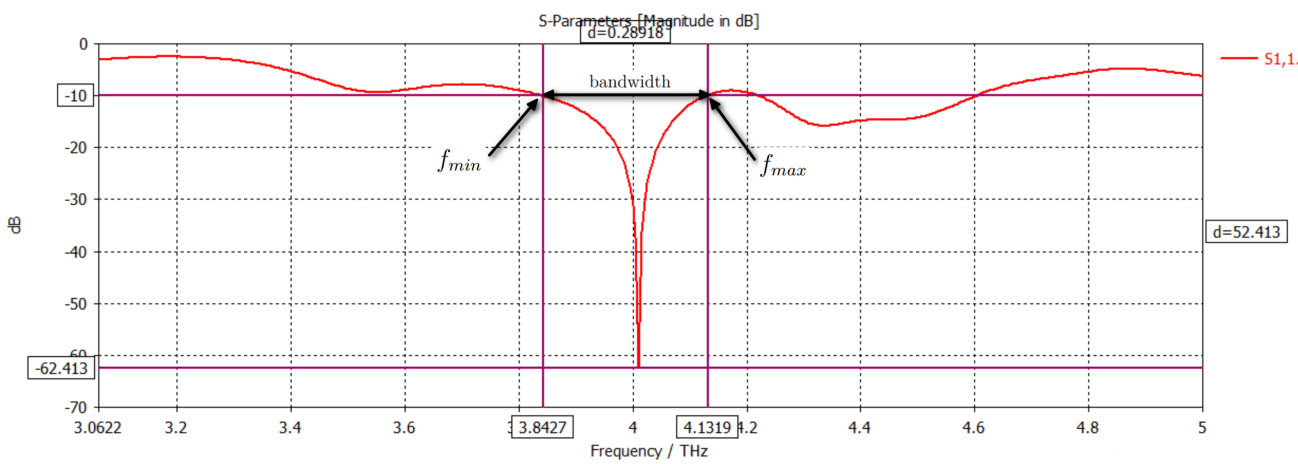


Figure 2.4: Bandwidth and Reflection Coefficient.

$$B = \Delta f = f_{max} - f_{min} \tag{2.10}$$

We also define the fractional bandwidth using expression 2.11:

$$B_f = \frac{B}{f_c} \tag{2.11}$$

f_c:Being the center frequency, calculated using the following relationship 2.12:

$$f_c = \frac{f_{max} + f_{min}}{2} \tag{2.12}$$

f_{max} and f_{min}represent, respectively, the high and low frequencies of the antenna's operating band. The fractional bandwidth is sometimes expressed as a percentage relative to the centre frequency using expression 2.13:

$$\%B_f = 100 * \frac{\Delta f}{f_c} \tag{2.13}$$

An antenna can be considered 'wideband' when it covers 5% of the bandwidth or even an octave, depending on the criteria one chooses to apply.

2.3 Historical background of optical terahertz antenna

The optical band research was started in the 19th century. But it was not studied as a separate field due to the lack of an ideal THz source capable of providing a few milliwatts of tunable power over a wide THz frequency range. It was not until the mid-twentieth century that scientists began to develop terahertz studies of millimeter waves [48]. In $April22, 1928$ Edward Hutchinson Synge described to Albert Einstein a letter demonstrating a microscopic method in which a field scattered by a fine particle can be used as a light source as shown in the figure 2.5 [49].

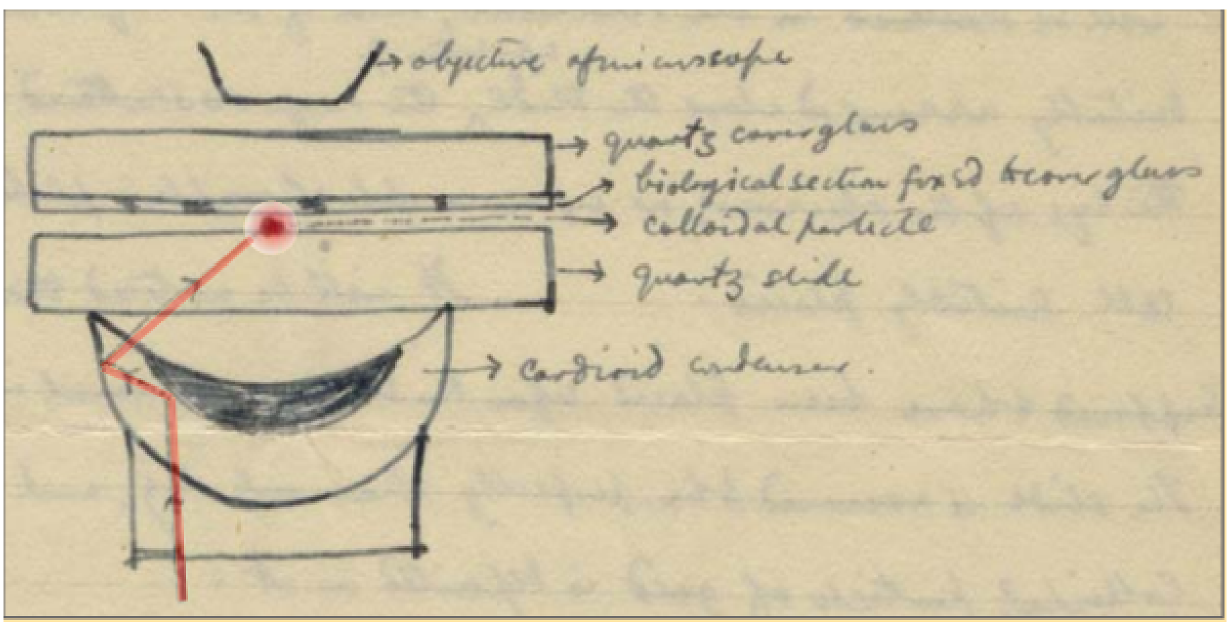


Figure 2.5: The letter of Edward Hutchinson to Albert Einstein [49].

In the $1980's$ a terahertz radiation source appeared which allowed the use of THz waves in practical systems . In the early $1980's$Auston invented the technology of THz radiation sources with femtosecond laser linked to photo-conductive antennas [50], and gave his name to this type of antenna. As shown in figure 2.6 .

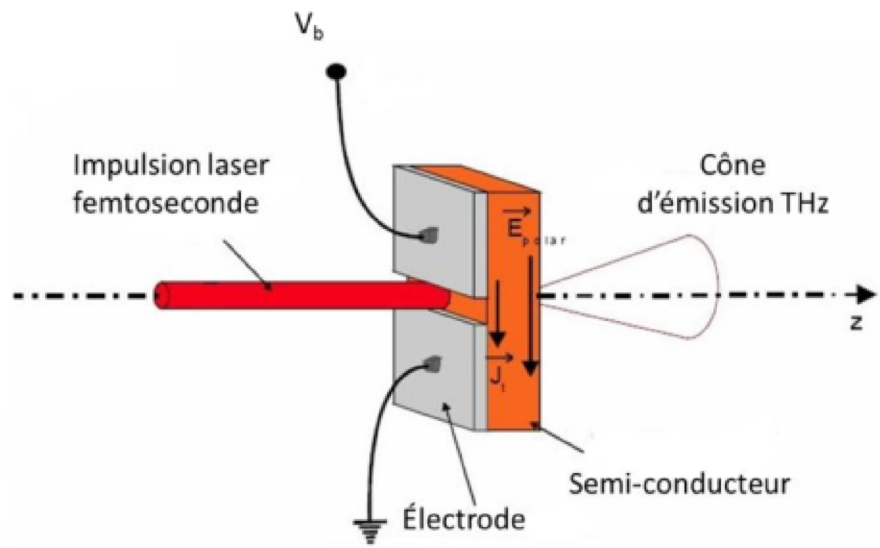


Figure 2.6: Photo-conductive antennas [51].

Since the beginning of the 21st century, wireless communication technology has developed very rapidly, and the demand for information and the development of communication devices have made the data rate requirements of communication increasingly stringent [52, 53].
The technological development of the 21st century that born high data rate of gigabits per second, and the development of communication devices have imposed requirements to the data transmission rates leads to problems of spectrum congestion that push many companies will use MIMO technique to increase the system capacity and spectral efficiency by multiplexing.

With the development of 5G network [54], the data transmission speed of each user will exceed that of GPS doc the data traffic of base stations will be increased significantly as well. In this case, traditional communication systems using millimeter wave and microwave links will not be able to handle these huge data streams. Then the terahertz band can provide a much higher communication capacity than microwaves because the terahertz frequency range is about 1000 times higher than traditional mobile communications. Thus, using the far infrared range to build ultra-fast wireless communication is a promising solution to solve the problem of high-speed data transmission. In addition the terahertz band has a wide bandwidth and higher throughput that cannot be expected with the millimeter spectrum. Therefore, the establishment of the terahertz communication system has attracted the attention of all countries in the world and many studies have been conducted. Optical terahertz antennas were also rapidly developed as an important part of the THz communication system.

The first terahertz band telecommunication system was successfully established in 2004 at the frequency 0.12 THz, and the realization of a terahertz antenna was made in 2013 at the frequency 0.3 THz [55] . In 2004 in Japan Nippon Telegraph and Telephone Company (NTT) introduced two cases of antenna configuration in short and long distance with Gaussian lens based optical antennas to improve the gain to more than 50 dBi [56], furthermore in 2012 they are improving a telecommunication system of frequency 0.3 THz and optimizing the transmission rate to more than 100 Gbps [57].

Previous research on optical antennas in the last few years has focused on improving the gain of the antenna by different methods using dielectric lens, use of more powerful materials etc., increasing the bandwidth, facilitating the manufacture of terahertz sources, and searching for algorithms that allow increasing the efficiency of communication.

2.4 The need of Nano antenna for THz domain

The terahertz antennas provide various unique advantages that make them indispensable in particular circumstances Here are a few reasons why terahertz antennas are preferred over alternative approaches for specific fields:

1. Optical waves operate in a specific frequency range that enables them to penetrate deep in biological tissue without damaging it. This means that they can be used for non-invasive medical imaging applications [58], contrary to lasers which may necessitate direct skin contact or more invasive procedures [59].

2. Terahertz antennas can be used to provide high spatial resolution, enabling the identi-

fication and imaging of minute details in biological structures. This is extremely beneficial in fields like RADAR, medical imaging, and the detection of material faults [60].

3. The optical terahertz waves are very sensitive to the chemistry of materials. They can be used to investigate the composition of substances, detect subtle variations in samples and identify specific compounds. This chemical detection capacity is invaluable in applications such as pharmaceuticals analysis [61], the detection of toxic substances and the identification of biological compounds [62].

4. The terahertz waves are considered to be safe for medical applications [63]. Contrary to some lasers, optical waves have no major thermal properties and therefore do not present any substantial risk to health when used in compliance with all safety requirements [64].

It is important to never forget that any technique has positive effects and limitations, so the ideal method is determined by the application's specific needs. Other treatments, such as lasers,X-rays, or ultrasound, may be more appropriate in some situations.

2.5 Challenge of THz antenna

2.5.1 Fabrication of terahertz antenna

2.5.1.1 Size of terahertz antenna

The dimensions of optical terahertz antenna structures are of the order of far-infrared wavelength, which is generally of the order of 3 mm to 30 μm wavelength [65]. These modest dimensions are determined by the frequency of the antenna's resonance. The figure 2.7 shows the size of the antenna in the frequency range from 0.5 to 3.5 THz, if the antenna frequency is changed to a higher frequency in the optical spectrum, the antenna size becomes very smaller.

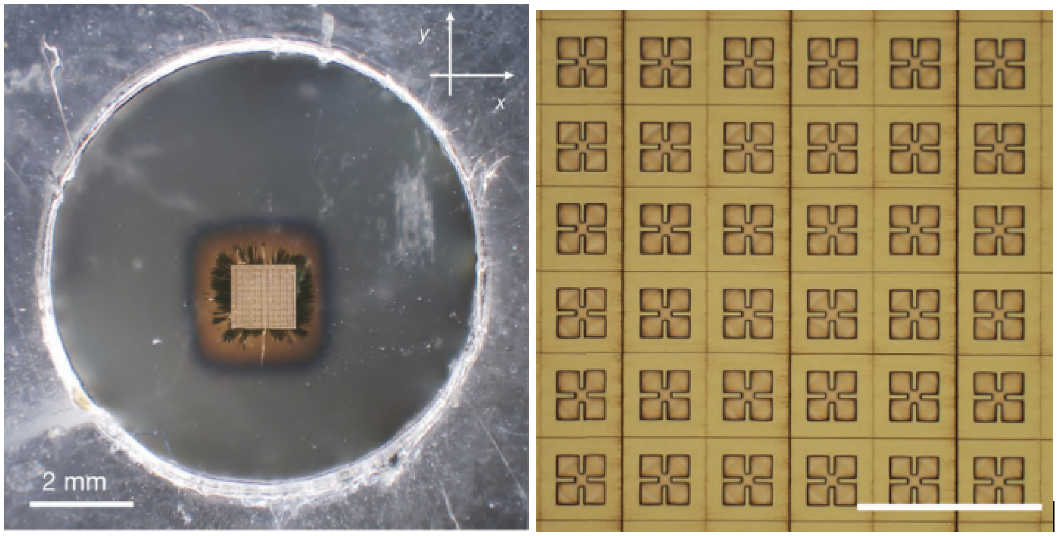


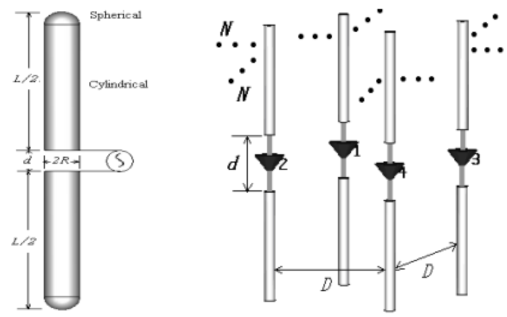
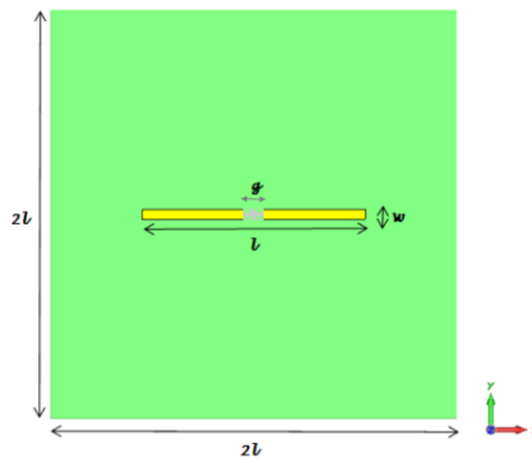
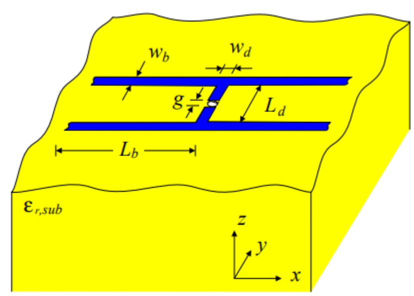
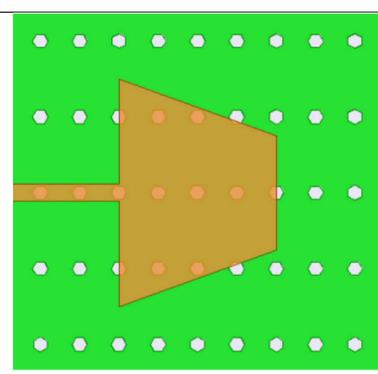
Figure 2.7: A terahertz antenna[66].

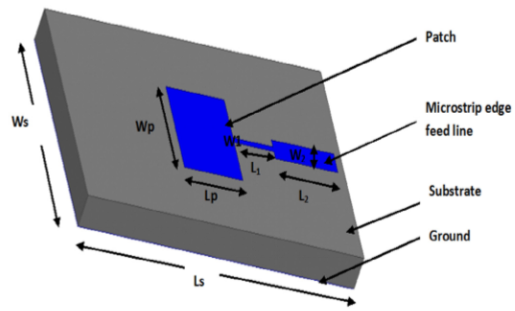
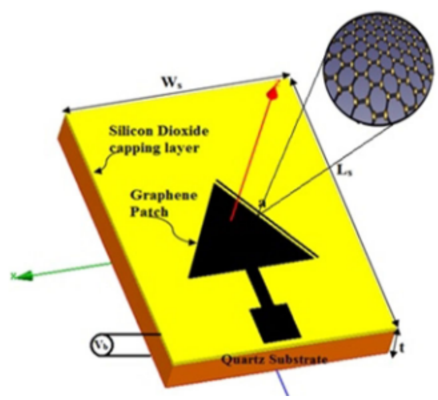
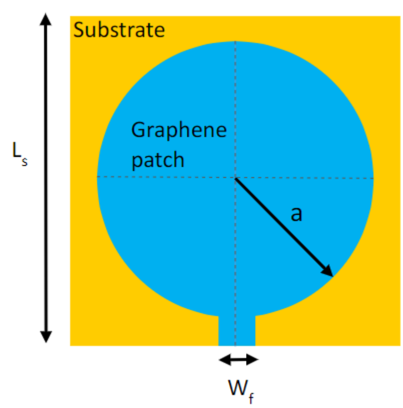
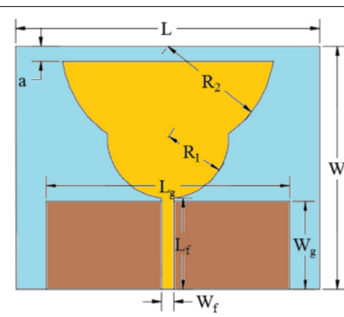
2.5.1.2 Shape

1. **Geometry:** The specific shape of the Nano-structure has a significant impact on its plasmonic properties. Common shapes include spheres, rods, triangles, cubes, and more complex geometries. Different shapes have different plasmonic resonances and field enhancement capabilities.

2. **Symmetry:** Symmetry in the shape of the nano-structure can lead to enhanced performance characteristics. For example, symmetric nano-antennas often exhibit more predictable and efficient light-matter interactions.

In the table 2.1 below, we present researches work on Nano antennas with various shapes:

References	Frequency band (THz)	Nano antenna design
[67]	9.3-10.2	
[68]	1	
[69]	1	
[70]	0.88–1.62	

References	Frequency band (THz)	Nano antenna design
[71]	2.67–2.92	
[72]	2.6	
[73]	2	
[74]	1.12	

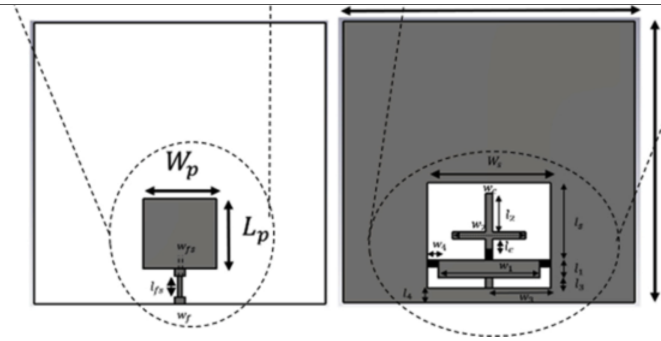
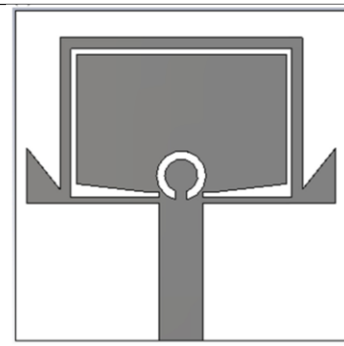
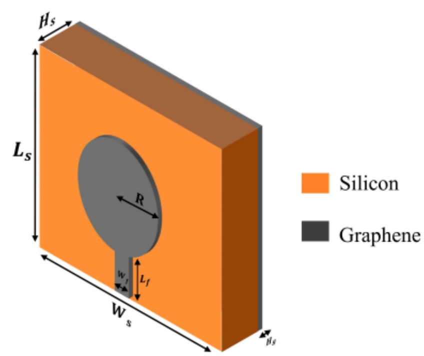
References	Frequency band (THz)	Nano antenna design
[75]	2.8 -4.2	
[76]	5.963	
[77]	2 and 5	

Table 2.1: Researches work on Nano antennas with various shapes.

2.5.1.3 Fabrication

Due to their nano dimensions, the precise manufacture of optical antenna structures can be technically difficult. Traditional manufacturing techniques may not provide the resolution necessary to produce these structures with precision. Therefore require a high degree of dimensional accuracy for optimum operation, in suite require a high level of dimensional accuracy for optimum operation. Deviation from specified dimensions can lead to performance degradation, such as energy losses, incorrect radiation angles or reduced bandwidth . It is essential, for this reason, to control the dimensions of the structures with high precision when manufacturing terahertz antennas [78]. The fabrication process for a micro-meter antenna for terahertz applications is composed of several steps [79]:

- **Choosing the appropriate substrate material:** This step has to consider the properties of the substrate material as well the properties of the substrate material such as the required thermal resistance, mechanical stability, electrical conductivity, and the dimensions of the chosen substrate.
- **Preparation of the substrate material:** The substrate material must be thoroughly cleaned to remove all kinds of impurities, dust and other particles.
- **Thin film deposition:** A thin film made by chemical vapor deposition is deposited on the substrate to be bonded to the patch .
- **Preparation of patch material**
- **patch deposition:** The material of the patch must be deposited on the substrate by dry transfer or by wet transfer.

2.5.1.4 Integration

The integration of nano optical terahertz antennas into a micro-meter circuit, as shown in the figure 2.8, presents a several difficulties and challenges [65]. Firstly,terahertz transmissions are sensitive to attenuation and interference, which can complicate the interaction and transfer of signals from the antenna to electronic circuits or sensing equipment.System performance can be affected by electromagnetic interference,energy losses,and dispersion effects.

Therefore, careful design of feed circuits, wave guides or lenses is often required to optimize coupling and minimize losses. Impedance matching between the optical terahertz antenna and associated electronic circuits is crucial to maximize power transfer and ensure optimum transmission efficiency. However, due to the specific characteristics of the terahertz band, impedance matching can be more complex than at lower frequencies. Innovative impedance matching techniques, such as matching networks and filter design techniques, may be required to overcome these challenges [80].

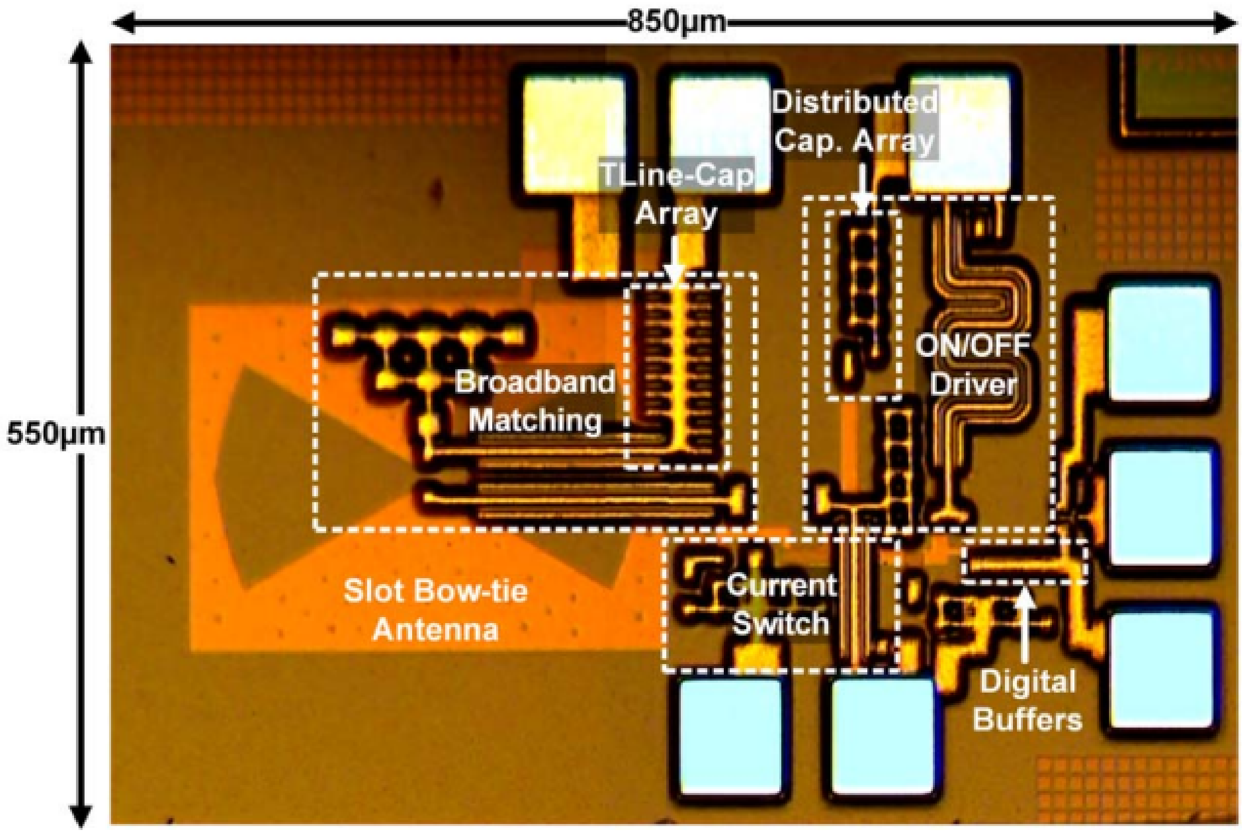


Figure 2.8: Micro-graph of the chip with terahertz antenna [81].

2.5.1.5 Measurement

The challenge of measuring nano terahertz antennas lies principally in the particular characteristics of this optical frequency range [82]. The following describes some of the particular challenges involved in measuring terahertz antennas:

Signal sources and detectors: Terahertz signal detectors and sources are less frequent and more expensive than those used in traditional radio wavelength frequencies.

Antenna characterization: Terahertz antennas have small dimensions, often of the order of the terahertz wavelength (a few tens of micrometers to a few millimeters). Precise manufacturing and characterization of antennas at these scales are technological challenges, which can make measuring terahertz antennas complex.

Equipment availability : The specialized equipment necessary for terahertz measurements needed for terahertz measurements schow in figure 2.9, such as terahertz generator and detectors, can be limited in terms of commercial availability and cost. This can make terahertz measurements difficult to access for laboratories or researchers with limited resources.

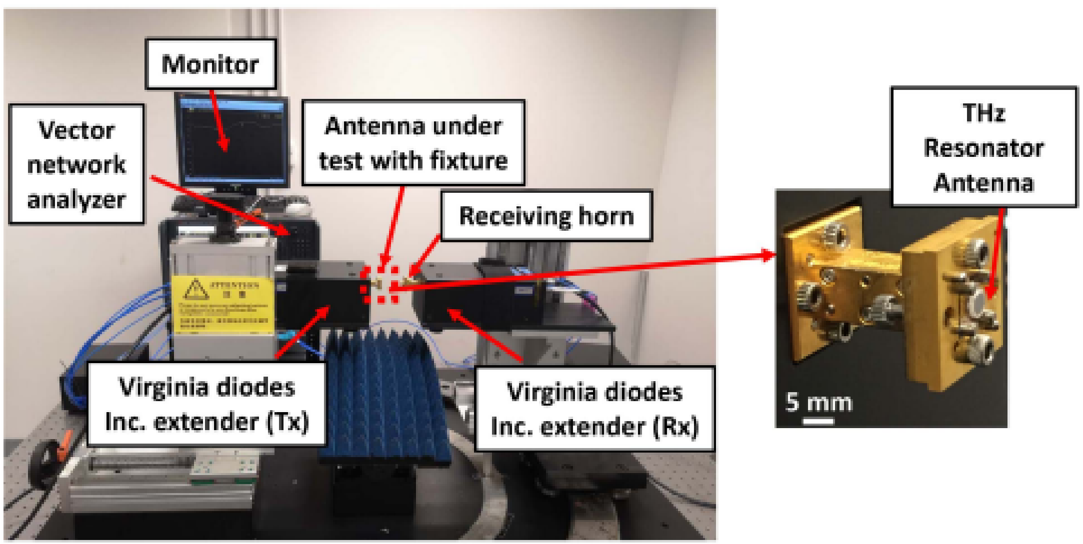


Figure 2.9: THz antenna measurement system [83].

2.5.2 Propagation

Terahertz signal transmission presents several unique challenges due to the unique characteristics of this frequency range. Here are some current propagation challenges associated with terahertz antennas.

- The interaction with the atmosphere considerably attenuates terahertz vibrations. The terahertz signals are strongly absorbed by water and oxygen molecules, resulting in considerable power loss over very short distances. This limits the range of terahertz communications and can complicate the transmission of terahertz signals in certain atmospheric conditions. This attenuation can lead to significant signal losses and reduce the overall gain of the terahertz antenna [84].

- Terahertz waves are deformed and dispersed when they travel through the air and contact objects or surfaces. This can result in variations of the spatial profile of the terahertz signal as well as in time domain distortions, making it difficult to discern the precise direction of arrival of information or to establish a stable communication link [85].
- Terahertz signals propagate along multiple routes, resulting in differences in the arrival times of the reflected signals. This multi-route interference can lead to temporal spreading of the signal, reducing the coherence and quality of the received signal [86].

These terahertz propagation challenges can limit the range, antenna gain, spatial resolution and quality of terahertz signals in terahertz antenna applications. propagation conditions.To address these issues, researchers are developing a variety of techniques and technologies, including as antenna arrays, enhanced focusing techniques, adaptive signal processing, and precise modeling of propagation circumstances.

2.5.3 Choosing the appropriate materials for Nano optical antennas in terahertz band

The choice of materials for Nano terahertz antennas should be guided by the specific application requirements and design goals. To make informed choices, researchers frequently employ experimentation and simulation methods to assess and enhance material performance within the THz frequency domain. These assessments consider critical factors such as permittivity, losses, and dispersion properties [87].

2.5.3.1 Plasmonic Materials

Materials with plasmonic properties can establish robust interactions with THz waves by virtue of surface plasmon resonances. Metals like gold (Au), silver (Ag), and Graphene find frequent application in plasmonic THz antennas. The deliberate manipulation of the metal's shape and dimensions allows for the fine-tuning of plasmonic resonances to achieve desired THz frequencies.Some of the materials commonly used in THz applications include:

1. **High mobility semiconductors:** Due to their capacity to operate efficiently at high terahertz frequencies, high mobility semiconductors such as gallium arsenide (GaAs), indium phosphide (InP), Teflon (PTFE), quartz, and silicon are often employed for terahertz applications. These materials can transmit THz frequencies due to their high electrical conductivity, low electron density, and low resistance [88].

2. **Graphene material:** Due to their amazing mechanical, electrical, and optical characteristics, graphene is an attractive material. It is regarded as the material meter in communication systems operating at extremely high frequencies (terahertz band) [0.1- 10] THz between the optical and microwave bands. As the main disadvantage of Nano systems is the limited mobility of electrons in metallic structures such as copper, graphene has a high ability to sustain surface plasmon polaritons (SPP) [89].

   Graphene is one of the minor electric charge conducting materials existing in the world due to its high electron mobility (2×105 cm^2/VS), high room temperature conductivity with a resistance of 31$\omega/sq$and a conductivity of 160 S/m [90]. Graphene material characteristics The Graphene characteristics are:

   - **Surface Plasmon's:**Copper is a renowned choice of material for crafting antennas intended for radio frequency (RF) and microwave applications. The design of metal antennas has undergone thorough exploration within the RF and microwave frequency spectrums, leading to the development of systematic antenna design techniques. Nevertheless, when considering copper-based antennas operating in the terahertz (THz) band, their design diverges significantly from that of conventional microwave metal antennas. Traditional microwave metal antennas are energized using various types of feed lines, such as microstrip, coaxial cable, and coplanar wave guide (CPW). On the other hand, terahertz (THz) antennas are alimented using fiber optics or air and requires bias voltage. Plasmonics can be likened to electronics in its reliance on plasmons, which are quantum phenomena in physics that characterize the collective excitation of unbound electrons within materials. Due to the characteristics of the dielectric-metal boundary between the medium and the particles, plasmonic nano-particles possess an electron density that allows them to interact with electromagnetic (EM) radiation having wavelengths longer than the size of the particle. Nevertheless, at the junction between a metal and a dielectric material, there are specific conditions that facilitate the precise matching of the electron wave, enabling it to oscillate and interact with light effectively [91].

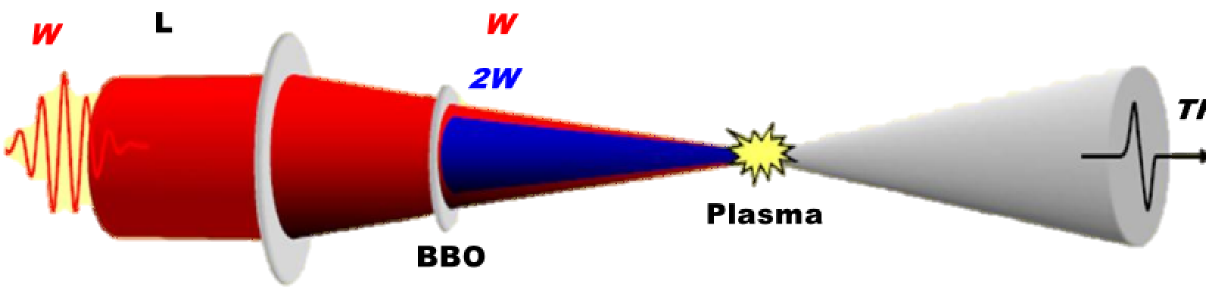


Figure 2.10: The phenomenon in terahertz materiel.

This phenomenon is commonly known as surface plasmons (SPs) or surface plasmon polaritons (SPPs). It originates at the metal surface and travels along the interface between the metal and the dielectric material. These phenomena can manifest in various ways, ranging from electron density waves freely propagating across metal surfaces to localized electron oscillations occurring on metal nanoparticles. Their distinctive characteristics enable a wide range of applications, such as nano-scale manipulation, the detection of biological analytes at the single-molecule level, and the enhancement of molecular resonances.

- **Graphene conductivity:** The conductivity of graphene in the terahertz band has three important properties:
  - A negative real permittivity , the existence of plasmon and infrared which can create plasma nano-antennas with lower loss and higher binding [92] .
  - The possibility to adjust the conductivity of graphene this technique is used to create optical modulators [93].
  - The ability to generate a non-reciprocal magneto-static field in order to produce non-reciprocal devices such as insulators [94].
- **Relaxation time and Chemical potential:** Graphene offers ideal conditions for the propagation of surface plasmon polaritons (SPPs), which are electromagnetic waves guided along the interface between a metal and a dielectric, typically generated by incident high-frequency radiation. In fact, a standalone graphene layer can support transverse magnetic modes. Certainly, within graphene, the edges of the graphene patch serve as mirrors, and graphene itself functions as a resonator for surface plasmon polariton (SPP) modes.

  The minimum essential relaxation time consistently falls within the few hundred femto-seconds range, and it diminishes as the chemical potential (symbolized by μ_c) increases. This decrease is attributed to the greater availability of charge carriers with an elevated chemical potential, leading to an increase in conductivity. To achieve a distinct antenna response, it is imperative for graphene to possess both adequately high relaxation times and chemical potentials.

  The researchers also studied the dependence of the minimum relaxation time on the chemical potential and were able to find a figure of merit γ for the functionality of graphene-based antenna devices using expression 2.14 [95]:

$$(\gamma) = \mu_c * T_r^2 \tag{2.14}$$

3. **Gold material:**Gold is the most famous material in the world because of its excellent characteristics, stainless metal and high electrical conductivity of45.2Ö10^6 S/m with an energy close to the energies of the free states of the conduction band, strongly influence

the optical properties because of the complex set of d-bands located very close to the Fermi level (some eV) [96].

Here are some key characteristics of gold for THz transmission [96, 97] :

- **High Electrical Conductivity:** Gold demonstrates remarkably high electrical conductivity within the THz frequency range. This attribute plays a crucial role in facilitating the efficient propagation of THz waves, making it especially valuable in the construction and optimization of THz wave guides and antennas.
- **Low Absorption:** Gold exhibits comparatively minimal absorption within the THz frequency spectrum, particularly when contrasted with metals such as copper. This characteristic offers distinct advantages in scenarios where minimizing signal attenuation is of paramount importance, notably in THz imaging and communication applications.
- **Good Reflectivity:** Gold's high reflectivity within the THz spectrum can be harnessed for the creation of mirrors and other reflective components, serving as a valuable asset in the development of THz optical systems and imaging technologies.
- **Bio-compatible Nature**: Gold's bio-compatibility and non-toxicity render it well-suited for THz applications in fields like biology and medicine. Its safe usage in THz spectroscopy and imaging of biological specimens ensures minimal harm.
- **Utilization of Surface Plasmon Resonance:** The THz range sees gold nano particles and thin films capable of exhibiting surface plasmon resonance, a feature skillfully employed in THz sensing and imaging applications. This characteristic enhances detector sensitivity, offering substantial benefits.
- **Simplified Fabrication:** Gold can be readily deposited as thin films or precisely patterned into intricate shapes through conventional micro-fabrication methods. This practicality simplifies the process of crafting THz devices.
- **Robust Chemical Stability:** Gold's chemical stability safeguards it against corrosion and tarnishing, bolstering its longevity and consistent performance in THz devices over extended periods.

- **Temperature-Resilient Properties:**Gold maintains its inherent properties across a broad temperature range, a pivotal attribute for applications susceptible to temperature fluctuations. This stability ensures reliability in diverse THz scenarios.

4. **Silver material:** The electrical conductivity of silver is exceptionally high, making it one of the most conductive metals known. At room temperature (around 20°C or 68°F). Due to its high conductivity, silver is extensively used in various electrical applications, including wiring, electronics, and circuitry, where efficient transmission of electricity is crucial [98]. Here are some key characteristics of Silver for THz transmission [99, 100]:

   - **Conductivity**: Silver possesses high electrical conductivity, even in the terahertz frequency range. This property allows silver to efficiently transmit THz waves without significant loss, making it suitable for THz transmission applications.
   - **Reflectivity**: Silver exhibits high reflectivity in the THz band. While this property can be advantageous for certain applications, such as THz mirrors or reflectors, it may also lead to signal loss in transmission scenarios if not properly managed.
   - **Surface Roughness**: The surface roughness of silver can affect THz transmission properties. Smooth surfaces are generally preferred for minimizing scattering losses and maintaining transmission efficiency.
   - **Dielectric Properties**: Silver's dielectric properties, including its permittivity and loss tangent, can impact THz transmission. Understanding these properties is crucial for designing and optimizing THz devices and systems involving silver components.

2.5.3.2 Substrates

The careful selection of a suitable substrate material is of paramount importance in the context of terahertz transmission. This is because the distinctive characteristics and challenges inherent to this frequency range make the choice of substrate material a pivotal factor that can substantially influence the effectiveness and functionality of terahertz communication systems. In making this selection, several key factors warrant consideration [101]:

1. **The dielectric constant:** Also known as relative permittivity, plays a significant role in terahertz wave behavior, which shares similarities with both microwaves and optical waves. The choice of substrate material's dielectric constant influences how waves propagate and their phase velocity in the terahertz range. To mitigate signal attenuation, it is common practice to opt for low-loss dielectric materials possessing an appropriate dielectric constant suited for terahertz frequencies.

2. **Minimizing Absorption:** Terahertz (THz) signals are particularly prone to being absorbed by materials, particularly at specific frequencies. To mitigate signal losses, opt for a substrate material with minimal absorption in the THz spectrum. Suitable choices encompass materials such as quartz, sapphire, or specific polymers acknowledged for their low THz absorption properties.

3. **Dielectric Loss :** Assess the dielectric loss tangent ($\tan \gamma$) of the substrate material, aiming for lower values to reduce signal attenuation. Materials such as polyethylene, polypropylene, and polytetrafluoroethylene (PTFE) are known for their low dielectric losses in the THz frequency range and are thus advantageous choices.

2.5.3.3 Compatibility with Fabrication Techniques

Consider the suitability of the selected substrate material with respect to the fabrication methods intended for use in creating antenna or circuit components. Recognize that various materials may demand specific procedures or treatments during the manufacturing process.

2.5.3.4 Frequency Range

Confirm that the substrate material's characteristics align with the precise terahertz (THz) frequency range you plan to operate in, as material properties can exhibit variations at different THz frequencies.

2.5.3.5 Hybrid Structures

Some nano terahertz antennas employ hybrid structures that combine different materials to achieve specific properties. For example, a plasmonic nano structure on a dielectric substrate can offer improved performance. Combining materials with complementary characteristics can enhance the overall antenna performance.

2.5.3.6 Thermal Properties

Materials with plasmonic properties can establish robust interactions with THz waves by virtue of surface plasmon resonances. Metals like gold (Au), and silver (Ag),find frequent application in plasmonic THz antennas. The deliberate manipulation of the metal's shape and dimensions allows for the fine-tuning of plasmonic resonances to achieve desired THz frequencies [87].

2.5.4 Terahertz source

Due to the absence of an ideal THz source capable of delivering power of a few milliwatts over a wide THz frequency range [102], optical antennas have used light at visible, infrared and near-infrared wavelengths as shown in figure 2.11 . These technologies generate the far-infrared range, thanks to slides such as quantum cascade lasers [56, 57] , laser diodes [55] , optical fiber or various devices based on nonlinear optics [103]. This technique suffers from important challenges:

- Optical antennas require a significant quantity of optical energy to function correctly. The power source must be powerful enough to generate this energy [104].
- Optical antennas are frequently created from materials with special optical characteristics, such as plasmonic metals or semiconductors, which may have unique optical properties. The power source must be compatible with these materials and antenna structures, while avoiding unwanted interference or disruption [105].
- The terahertz antennas are generally designed at the nano-scale, which means that power sources need to be small and easy to integrate into the system as shown in the figure 2.11 [106]. This can be a technological challenge, as it can be difficult to miniaturize energy sources without compromising their efficiency or power.

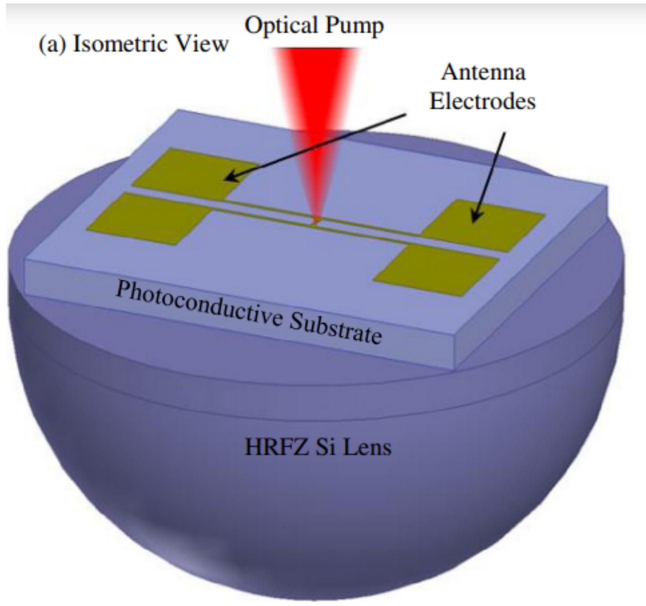


Figure 2.11: Terahertz source [51].

2.6 THz antenna classification

Plasmonic materials are widely used in terahertz antenna design due to their unique optical characteristics at this frequency range. For improved terahertz antenna efficiency, Gold and graphene are the best materials to use for nano-antennas as they exhibit high electron mobility and plasma effects. Selection of the plasmonic material will depend on the specific requirements of the terahertz antenna, the required performance, the domain of application and the type of antenna used.The terahertz antennas can be classified into different categories according to their design.

2.6.1 Metal antenna

The development of the terahertz antenna began in 1928 by Edward Hutchinson Synge who first proposed the use of metallic nanoparticles to limit the optical field [49]. In 1985 John Wessel showed that these nanoparticles behave like a metallic antenna [103], he also showed that we can limit the diffraction in the resolution of optical devices and predict its resolution down to 1 nm if using a single plasmon particle; these nano-antennas are called mono-pole antennas in the current literature. The horns are conceded to be metallic antennas as shown in the figure 2.12 operating in the optical band this type of antenna have many advantages including a high gain of 20 to 30 dBi, and efficiency of 97% to 98% [107] .

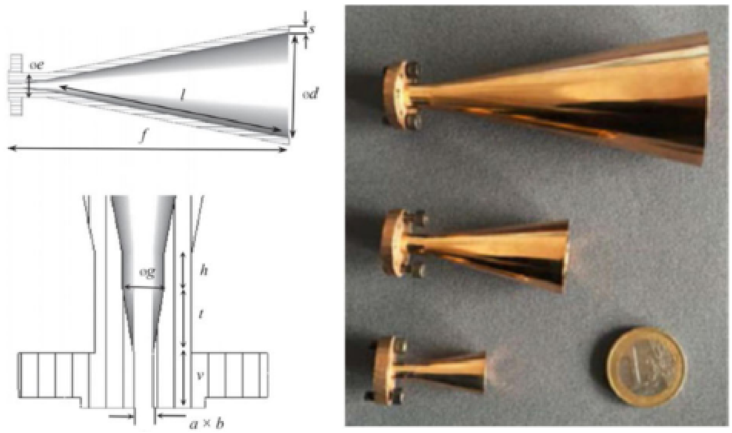


Figure 2.12: Terahertz horn antenna [108].

Given the terahertz band the size of the horn antenna becomes very small, which makes the processing of the antenna at the end very difficult and the realization very complex with a production cost becoming very high, Optical waves therefore impose a number of technological constraints for these antennas, both in terms of manufacture and use. Due to these difficulties to reduce the manufacturing cost, the production complexity and increase the radiation performance of the antenna, a simple horn antenna was used. Another simple dipole antenna has been designed to ease the complexity of the horn antenna [109]. It features low manufacturing requirements and generally uses frequency bands above 0.6 THz.A major drawback of terahertz dipoles is their low radiation efficiency figure 2.13.

The Yagi antenna, also referred the Yagi-Uda antenna, is a type of directional antenna widely used in terahertz wireless communications because it offers increased directivity, higher gain, better interference rejection, longer range, low sensitivity to multipath interference and greater frequency selectivity than the dipole and the horn antenna [111] as show in figure 2.14.

The metal used in these types of antennas is gold because this optical band requires a material with high electron mobility.Nano-antennas made from conventional materials such as copper would make communication between low-power nano-machines practically impossible.

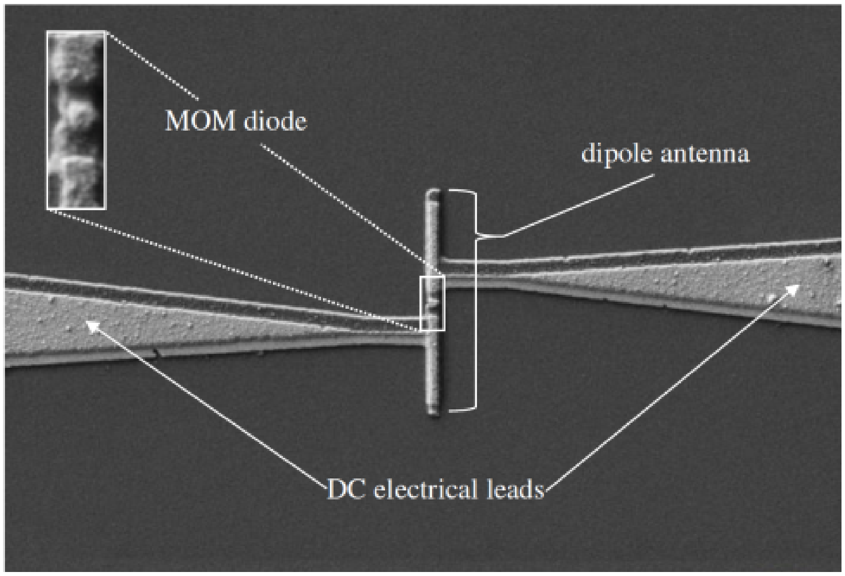


Figure 2.13: Dipole antenna [110].

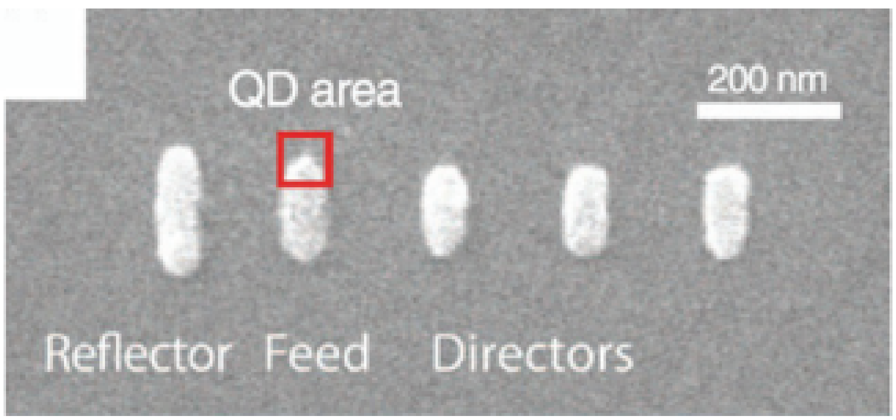


Figure 2.14: Yagi-Uda antenna [112].

2.6.2 Dielectric antenna

Dielectric antennas are antennas based on semiconductor materials combining a radiating element and a dielectric substrate, these antennas have the advantages of a simple process, easy integration with low manufacturing cost. In recent years several works have appeared on the design of nano antennas with optical response that are suitable for weak sensors, dualn antennas [113, 114], butterfly antennas [115, 116], and periodic sinusoidal antennas [117].

Why are researchers interested in dielectric nano-antennas? Firstly, dielectric materials are characterized by a particularly low power loss in the optical range. Second, there is a frequency range in which a dielectric material with a high dielectric constant exhibits both electrical and magnetic resonance. Thanks to this, it is possible to create the Huygens element with a single particle. However, the disadvantage of dielectric nano-antennas is the combination with the dielectric substrate which is responsible for the surface wave effect generated when the frequency tends towards the THz band and causes a high energy dissipation [55].

2.6.2.1 Substrate Gold antenna

Gold (Au) provides potential advantages in certain domains such as optical applications, plasmonics and biomedical applications, generally used as the main material in terahertz antennas waves has the frequency optical spectrum base due to its electrical properties at these frequencies [118].

The first gold-based antennas in the submilimeter band are bow-tie antennas, named after their characteristic bow-tie-like shape figure 2.15. Gold bow-tie antennas in the terahertz band offer several advantages: wide bandwidth, high directivity and low losses, but the main difficulty with this band is that gold bow-tie antennas are more difficult to manufacture and require a complex manufacturing technique that demands precision and concentration in the event of a small offset, the antenna loses its radiation characteristics.

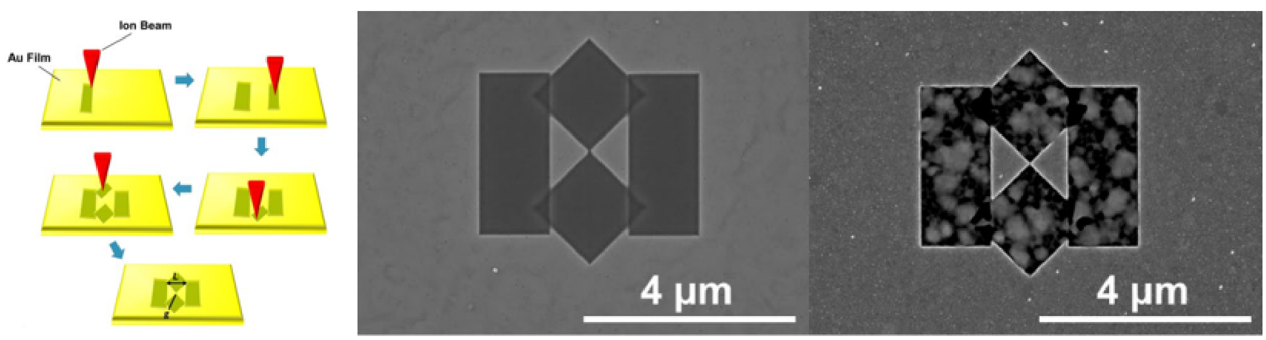


Figure 2.15: Butterfly gold antenna [119].

Other type of antenna with simple shape schow in figure 2.16 has been proposed for facilitating fabrication, this type of antenna suffers from poor radiation characteristics it's for this reson an antenna network has been introduced for increased performance of proposed antenna and facilitate the fabrication.

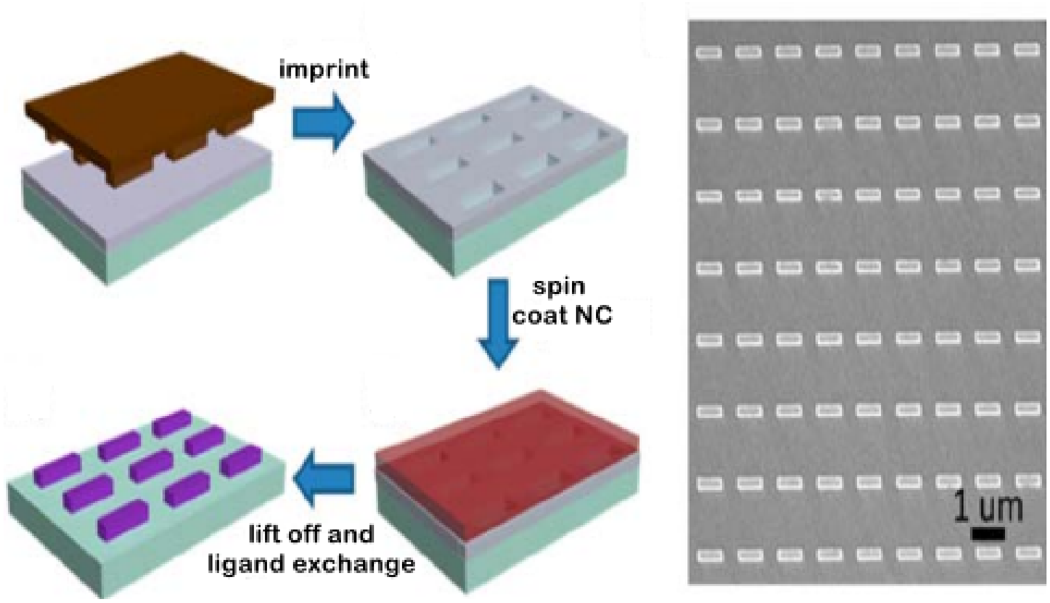


Figure 2.16: Rectangular gold antenna [120].

However, the choice of material for an antenna will depend on the specific requirements of the application, the desired performance and manufacturing constraints.

2.6.2.2 Substrate graphene antenna

A graphene antenna is a high-frequency antenna made of graphene, a two-dimensional carbon crystal one atom in thickness, which can generate an electrical signal wave, enabling antennas one micron long and 10 to 11 nanometers wide to perform the function of much larger antennas.

Graphene-based antennas are a promising area of research that explores the use of graphene to further enhance far-infrared antenna performance and meet high-gain, wide-bandwidth requirements [121].

one of the major challenges in the use of graphene-based antennas is your manufacture for this reason the antenna network has been used to improve performance and make the antenna realizable figure 2.17 and figure 2.18.

Researchers are interested in integrating innovative high-conductivity materials such as graphene to achieve significant improvements in antenna performance, opening up new possibilities for wireless communication applications.

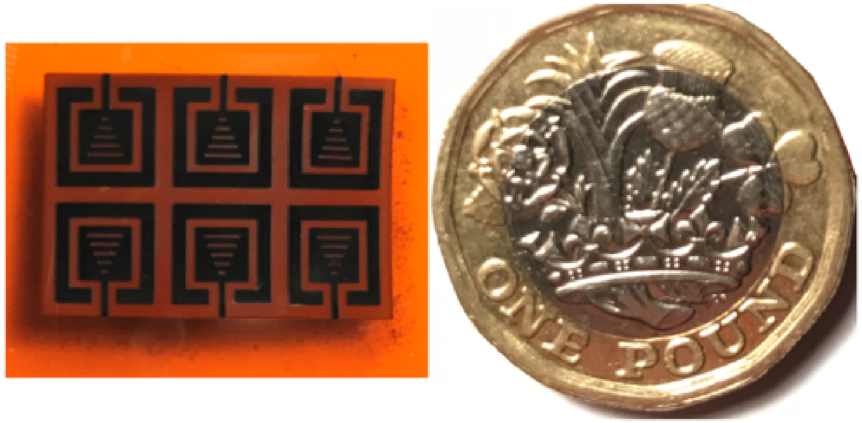


Figure 2.17: Graphene terahertz antenna [122].

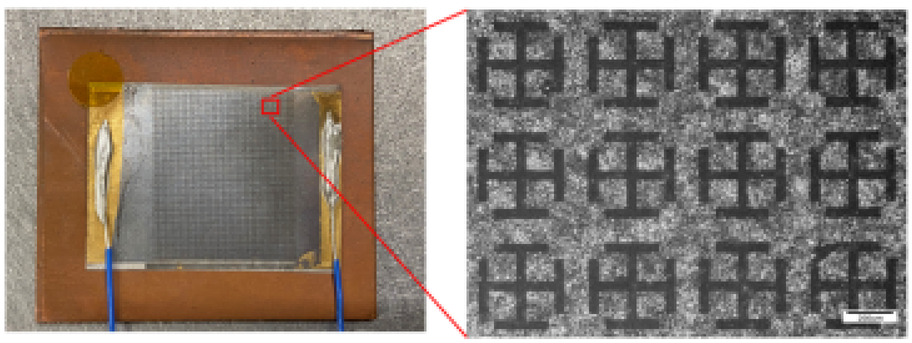


Figure 2.18: Graphene antenna [123].

2.6.2.3 Properties Comparison between gold and graphene antenna

Here's a comparison of the main properties of gold and graphite in the context of antennas:

- **Electrical Conductivity:** The Gold material has a higher electrical conductivity than graphene, making it more effective for applications requiring high radiation efficiency [124].

- **Operating frequency:** Graphene is a particularly promising material for optical applications due to the fact that it can operate at considerably higher frequencies than characteristic metals such gold and copper. In fact, graphene, graphene can operate at frequencies in the terahertz range [125].

- **Fabrication:** Gold is easy to produce and include into traditional electronic circuits, while graphene antenna production necessitates more complex nano fabrication processes [126].

- **Transparency:** Graphene is more transparent than gold, making it more suitable for optical applications [127].
- **Weight and flexibility:** Graphene is more suited for mobile and embedded applications than gold due to it is lighter and more flexible [124].
- **Heat Resistance:** Graphene is more heat resistant than gold, allowing it to operate at higher temperatures [128].
- **Cost:** The cost of graphene is relatively high compared with that of gold, which can limit its use in certain applications [129].

Gold antennas are frequently employed in terahertz applications that demand excellent radiation efficiency with fast frequency response, whereas graphene antennas are more suited to mobile or integrated applications [55].

The table 2.2 provides an extensive comparison between gold and graphene concerning their application as terahertz antennas.

Gold antenna	**Graphene antenna**
A bandwidth limit < 1 THz	High bandwidth$>$ 1 THz
Acceptable gain$<$ 5.5 dBi	Higher gain $>$5 dBi
Low cost	High cost
Better interference resistance	acceptable interference resistance
terahertz low frequencies 0.1 THz to 6 THz	higher frequencies more then 5 THz

Table 2.2: Comparison of gold and graphene antenna.

2.7 Conclusion

This chapter gives an overview of the state of the art of optical antennas and the various challenges they face. Nano antennas offer significant advantages for applications in the terahertz band. Their ability to concentrate electromagnetic energy into subwavelength volumes, tunability, and compatibility with hybrid structures make them highly promising for terahertz technology. With further advancements in fabrication techniques and material engineering, nano optical antennas are expected to play a crucial role in the development of advanced terahertz devices and systems.

Chapter 3

Wireless applications THz antenna

3.1 Introduction

A terahertz wireless antenna operates in the terahertz frequency band, offering a promising frontier for high-speed wireless communication. Terahertz frequencies provide a substantial increase in bandwidth compared to conventional microwave communication, enabling faster data transmission rates.

In this chapter, we designed nano optical antennas for wireless communications in terahertz band [0.1-10] THz using graphene radiating element with polymer,Dielectric and High-Frequency Laminate substrates because of their flexibility, light weight and low cost to increase performances of antennas.

3.2 Terahertz antenna characteristics in wireless application

Terahertz antenna characteristics in wireless applications refer to the specific properties and features of antennas designed to operate in the terahertz frequency range for wireless communication purposes.Wireless terahertz (THz) transmission is typically situated within the terahertz frequency spectrum, covering a broad range from roughly 100 gigahertz (GHz) to multiple terahertz (THz). This spectrum encompasses frequencies ranging from 100 GHz to 10 THz. The precise frequencies employed in wireless terahertz communication can differ based on the specific application and technological considerations.

Terahertz-band communication will be crucial in satisfying the requirements for ultra-high data rates in future wireless communication systems. To achieve these extremely high data rates, antennas with high gain (greater than 5 dBi) and wide bandwidth (up to 100 GHz) are required.

3.3 Nano optical antenna design

To design Nano optical antennas in wireless terahertz band, the choice of radiant element and substrate materials is crucial. In the following section, we briefly describe the choice of materials used in the design of the optical antennas proposed in our thesis:

3.3.1 Radiating element material choice for wireless terahertz transmission

Terahertz (THz) transmission emanates from the distinctive characteristics and promising applications found within the terahertz frequency range. This range occupies the intermediate space between the microwave and infrared segments of the electromagnetic spectrum. The radiating element of optical antenna must be with very high electron mobility and conductivity at room temperature. The researchers have identified Graphene as the best material to use in wireless communications due to several unique properties that make it stand out in this specific frequency range.

3.3.1.1 Graphene conductivity

Due to its remarkable mechanical, electrical, and optical characteristics, graphene is a promising material. It is considered as the material meter in communication systems operating at very high frequencies (terahertz band)[0.1- 10]THz, Between the optical and microwave bands [130]. Graphene has a high capacity for surface plasmon polaritons (SPP) because the major drawback of Nano systems is the low mobility of electrons in metallic structures such as copper [131].In general, the SPP wavelength is expressed as a function of frequency,As a result, the SPP wavelength in the terahertz frequency region is of the order of a few micrometers,corresponds to the size of the nanometer antenna and the comparatively short wavelength.in effect the propagation length of a graphene based antenna is less than the wavelength [132].In the realm of effective index, the SPP dispersion of Grapnene relation may be represented as 3.1 [133]:

$$\sqrt{\eta^2-\eta_{eff}^2}+\eta^2\sqrt{\eta^2-\eta_{eff}^2}+\frac{4\pi}{c}\sigma\sqrt{1-\eta_{eff}^2}\sqrt{\eta^2-\eta_{eff}^2}=0 \tag{3.1}$$

Where σ is the conductivity of Graphene and c is the speed of light ,η is the refractive index ,and η_{eff} the complex effective index can be expressed with the following equation 3.2:

$$\eta_{eff}=\sqrt{1-4\frac{\mu_0}{\epsilon_0}\frac{1}{\sigma^2}} \tag{3.2}$$

The dispersion relation can also be expressed in terms of K_{spp} as shown by the equation 3.3 and 3.4 [134]:

$$\frac{1}{\sqrt{K_{spp}^2 - \frac{w^2}{c^2}}} + \frac{\epsilon}{\sqrt{K_{spp}^2 - \frac{w^2}{c^2}\epsilon}} = -j\frac{\sigma}{w\epsilon_0} \tag{3.3}$$

Where ϵ_r is the dielectric constant of the substrate material and effective index K_{spp}:

$$K_{spp} = \epsilon_0 \frac{1+\epsilon_r}{2}\frac{2iw}{\sigma} \tag{3.4}$$

Graphene is a material of two-dimensional monolayer structure in which carbon atoms are provided in the form of infinitely honeycomb. Graphene conductivity can be given of the Kubo formula 3.5, 3.6, 3.7 and 3.8 [135, 131]:

$$\sigma_{inter} = \frac{e^2}{4h}H(\frac{w}{2}) + 4\frac{wj}{\pi}\int_0^\infty \frac{H(w) - H(\frac{w}{2})}{w^2 - 4\epsilon^2}\delta\epsilon \tag{3.5}$$

$$H(\epsilon) = \frac{\sinh(\frac{h\epsilon}{KT})}{\cosh(\frac{\mu_c}{KT})\cosh(\frac{h\epsilon}{KT})} \tag{3.6}$$

$$\sigma_{intra} = \frac{2kTq^2j}{h(T^{-1}hj + wh)} 2\ln\cosh\frac{\mu}{2TK} \tag{3.7}$$

$$\sigma_s = \sigma_{intra} + \sigma_{inter} \tag{3.8}$$

σ_s:surface conductivity consists of two terms , σ_{intra} and intraband conductivity and σ_{inter} interband conductivity .

At terahertz frequencies we have room temperature, and generally $hw << 2\mu_c$ in this case we have either in the ohmic domain or in the plasmonic domain, and inter-band(σ_{intra}) transitions can be neglected.

Moreover, the condition $\mu_c >> kBT$ is generally very small, allowing a low temperature approximation. Thus, the final approximate formula is 3.9:

$$\sigma_s = \frac{2kTq^2j}{h(T^{-1}hj + wh)} 2\ln\cosh\frac{\mu}{2TK} \tag{3.9}$$

3.3.1.2 Graphene modeling

CST Microwave Studio, a computer simulation software, offers Graphene as a material option specifically designed for antenna applications. The relaxation time and chemical potential as well as the total conductivity are changed due to chemical doping or electrostatic polarization,which results in the modification of the resonance characteristics of Graphene using equation 3.9 we presented with Matlab the simulation result of graphene conductivity properties.Figure 3.1 represents the real and imaginary part of Graphene conductivity for $\mu_c = 0$ eV and $\tau = 0.1$ ps at T=300 K. Figure 3.2 represents Graphene conductivity variation with respect to chemical potential (μ_c) for $\tau = 0.1$ ps at T = 300 K and figure 3.3 represents Graphene conductivity curve variation with respect to relaxation time (τ) for $\mu_c = 0$ eV at T = 300 K. The antenna operates in the terahertz frequency range using surface-plasmon polariton wave propagation in graphene. Simulation results demonstrate the conductivity of Graphene and structured has the potential to be used as a tunable terahertz antenna .

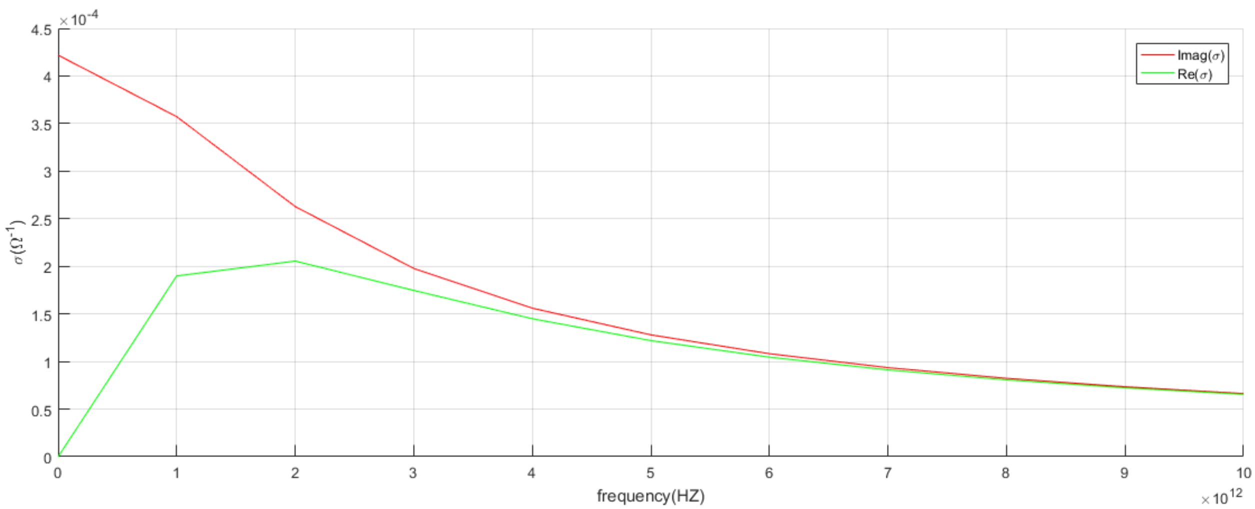


Figure 3.1: Graphene conductivity curve with properties $\mu_c = 0$ eV and $\tau = 0.1$ps at T=300 K.

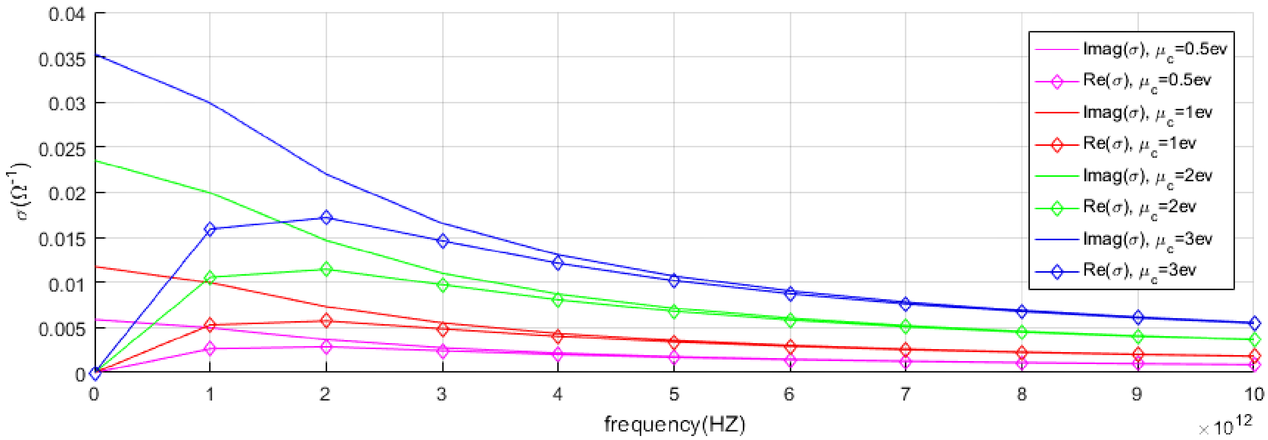


Figure 3.2: Graphene conductivity curve variation with respect to chemical potential(μ_c) for $\tau = 0.1$ps at T=300 K.

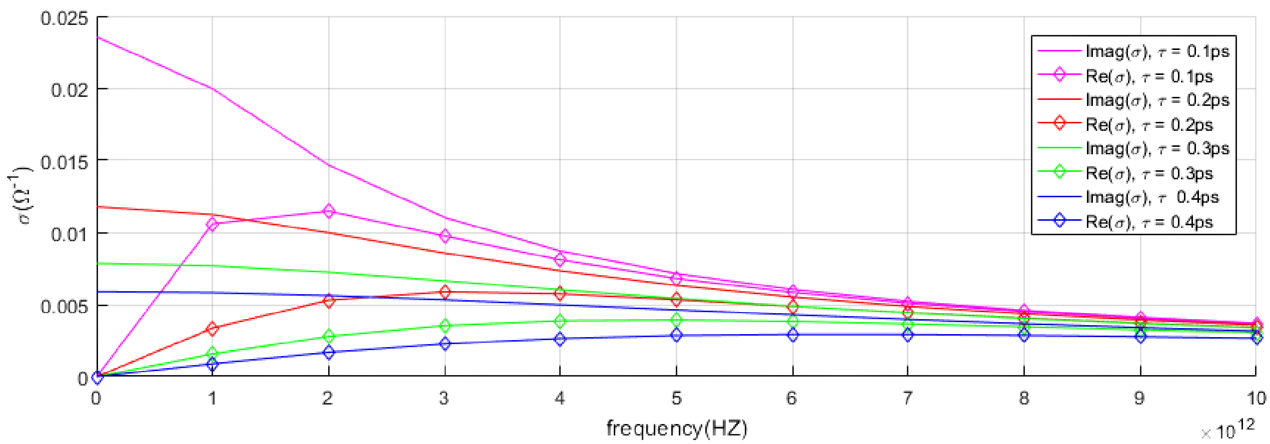


Figure 3.3: Graphene conductivity curve variation with respect to relaxation time (τ) for $\mu_c = 0$ eV at T = 300 K.

3.3.2 Substrates material choice for wireless terahertz transmission

Choosing the right substrate material for wireless terahertz band applications is a crucial decision since it has a substantial impact on the performance of terahertz devices and antennas. When selecting a substrate material, it's essential to consider various factors, including the target operating frequency, mechanical demands, thermal properties, and compatibility with other components or technologies [136]. Here are some common types of substrates used with graphene antennas: Dielectric Substrates (Quartz, Sapphire, Silicon,Arlon AD250C), Polymer Substrates(Polyimide, Polyethylene (PE) or Polypropylene (PP)...), Photonic Crystal Substrates, Metamaterial Substrates, Semiconductor Substrates, Graphene Substrates and finally High-Frequency Laminate (Composite) [137, 138].

Typically, engineers rely on simulations and experiments to fine-tune the substrate selection for a specific graphene antenna design, aiming to attain optimal performance aligned with the intended application. In this thesis work, we opted for polymer and High-Frequency Laminate (Composite) subsrates because of their flexibility, light weight and low cost, making them suitable for flexible, conformal graphene antennas [138].

3.4 Circular Graphene Optical antenna design

We designed using CST software a nano terahertz circular patch antenna using graphene as conducting material (figure 3.4) with the following characteristics: chemical potential μ_c=2 eV, room temperature T =300 K,relaxation time $\tau = 1$ ps and thickness 0.6nm. A microstrip line with an impedance of 50 Ω feeds the antenna. PTFE ($\epsilon_r = 2.1$), Polyimide ($\epsilon_r = 3.5$), Roger RO3003($\epsilon_r = 3$),Arlan AD250C($\epsilon_r = 2.5$), and Roger RO4003($\epsilon_r = 3.4$) were employed as substrates. The dimensions of the antenna are computed using the calculations below 3.10, 3.11, 3.12, 3.13 and 3.14 [139] :

$$F = \frac{(8.791 * 10^9)}{f_r\sqrt{\epsilon_r}} \tag{3.10}$$

$$a = \frac{F}{\sqrt{1 + \frac{2h}{\pi\epsilon_r F}[ln(\frac{\pi F}{2h}) + 1.7726]}} \tag{3.11}$$

$$ae = a\sqrt{1 + \frac{2h}{\pi\epsilon a}\ln(\frac{\pi a}{2h}) + 1.7726} \tag{3.12}$$

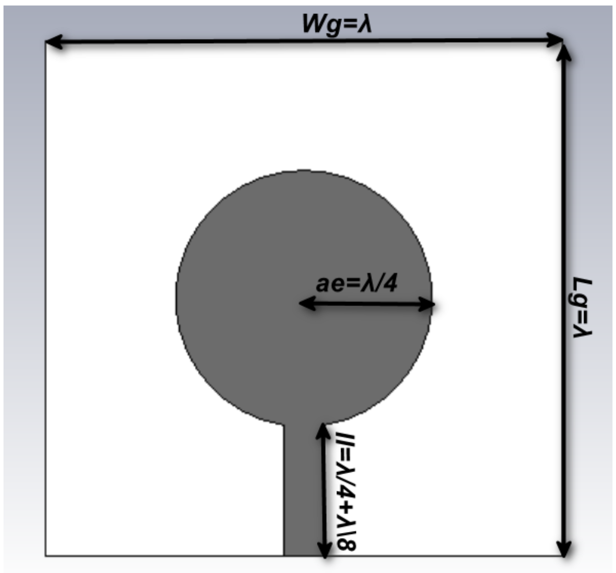
$$Lg = ll + 2ae + 6h \tag{3.13}$$

$$Wg = 2ae + 6h \tag{3.14}$$

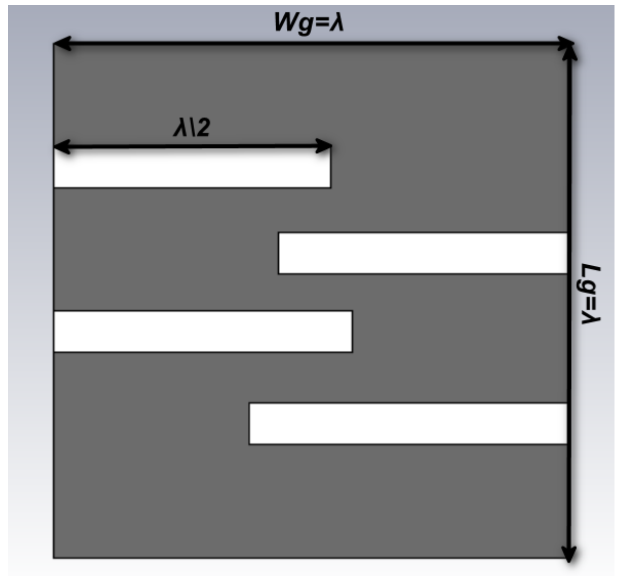
ae: Radius of the crescent patch.

Lg: Length of both substrate and ground plane.

Wg: Width of both substrate and ground plane.



(a)



(b)

Figure 3.4: (a) Front view of the Circular Proposed Graphene patch antenna with DGS ; (b) rear view of the Circular Proposed Graphene patch antenna with DGS .

3.4.1 Circular patch antenna with different materials as substrate

Figure 3.5 shows the simulation results of the Graphene circular printed antenna with two type of substrates:

Polymer : PTFE ($\epsilon_r = 2.1$), Polyimide ($\epsilon_r = 3.5$).

High-frequency laminates : Roger RO3003($\epsilon_r = 3$), Roger RO4003($\epsilon_r = 3.4$).

Dielectric substrate : Arlon AD250C($\epsilon_r = 2.5$).

DGS is inserted in the ground plane to increase the bandwidth of the circular patch antenna, all the results are summarized in Table 3.1:

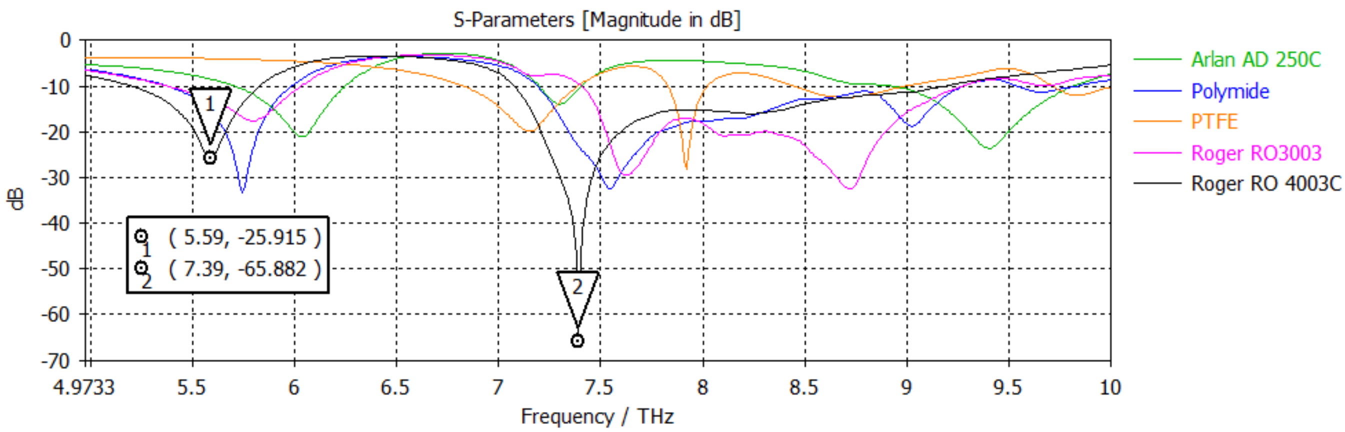


Figure 3.5: Reflection coefficient parameter S11 of circular graphene antenna for different substrates material.

Substrat	Frequencies (THz)	S11(dB)	Gain (dBi)	BP(GHz)
PTFE	7.15	-19.91	3.34	573.8
	7.92	-28.23	3.964	232
	8.69	-12.5	2.265	573.84
Polyimide	5.74	-33.403	2.11	298.18
	7.55	-32.391	2.8	2118.1
Arlan AD250C	6.4	-21.082	3.932	548.2
	7.31	-13.857	3.789	206.67
	9.41	-23.57	5.07	0.852
Roger RO3003	5.82	-17.36	2.269	729.62
	8.63	-32.5	4.51	1869.2
Roger RO4003C	5.6	-25.559	2.1	675.11
	7.39	-65.88	2.759	2016.9

Table 3.1: Results comparison substrate for circular Graphene antenna.

As shown in Table 3.1, the change in substrates material from polymer to High-frequency laminates change antenna performances with greater changes in antenna return loss, gain and bandwidth. Rogers RO4003C substrate produces superior performance and the circular antenna operate around the desired resonant frequencies of 5.6 THz with -25.559 dB and 7.39 THz with -65.88 respectively. The bandwidth achieved is 675.11 GHz and 2016.9 GHz respectively. Regarding antenna gain, we obtained values around 2 dBi as shown in figure 3.6, so This antenna can be used for applications that do not require high gain, such as spectroscopy and imaging.

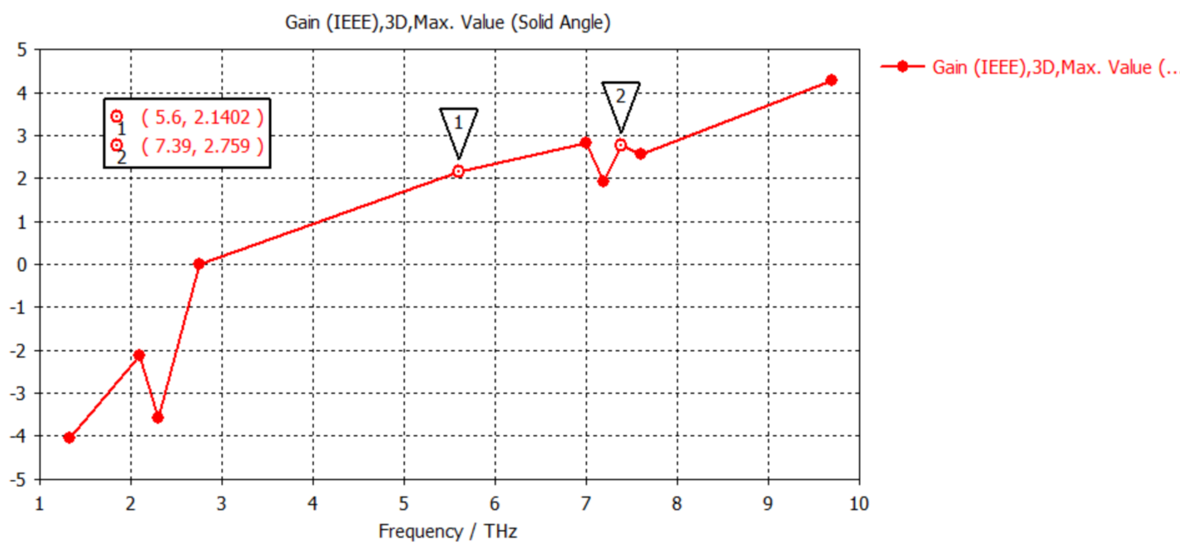
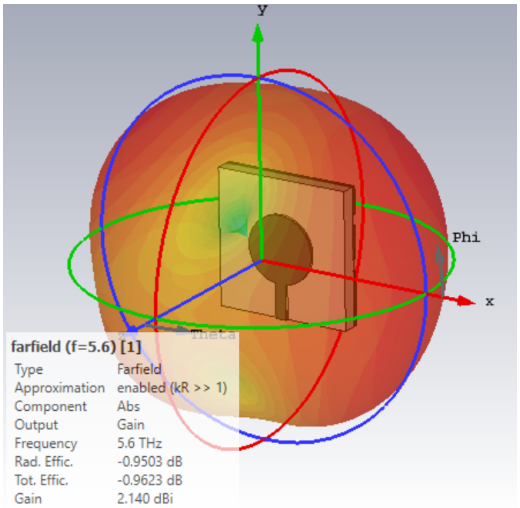
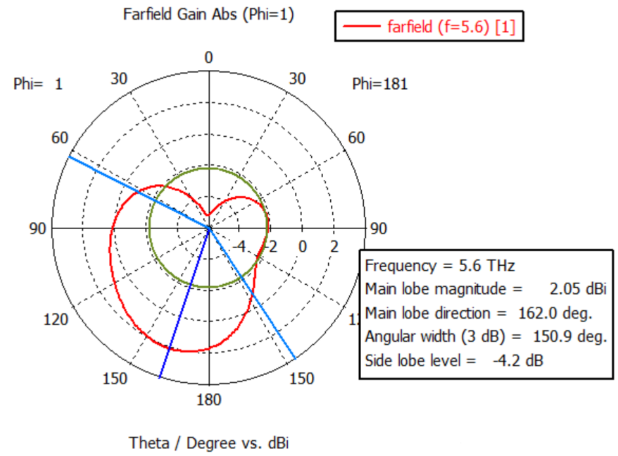


Figure 3.6: Gain of circular antenna with Roger RO4003C substrate.

Figures 3.7 and 3.8 presents the radiation pattern of circular patch antenna, the angular widths are 150deg and 115deg for 5.6 THz and 7.39 THz respectively.

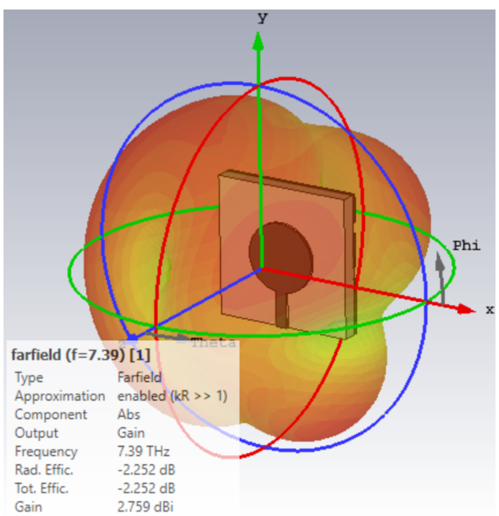


(a)

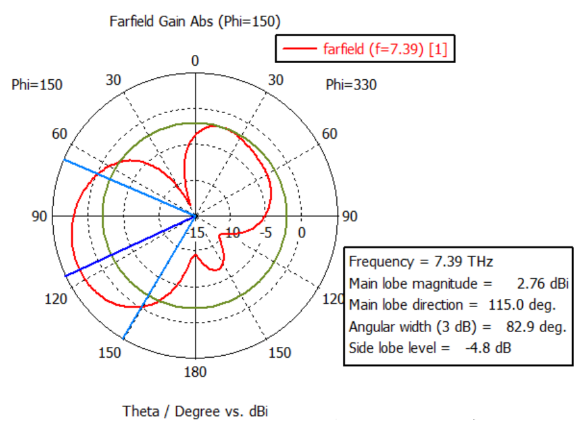


(b)

Figure 3.7: (a) 3D radiation pattern of circular antenna with Roger RO4003C substrate at 5.6 THz frequency ; (b) polar radiation pattern of circular antenna with Roger RO4003C substrate at 5.6 THz frequency .



(a)



(b)

Figure 3.8: (a) 3D radiation pattern of circular antenna with Roger RO4003C substrate at 7.39 THz frequency ; (b) polar radiation pattern of circular antenna with Roger RO4003C substrate at 7.39 THz frequency .

3.4.2 Circular Antenna optimisation with Chemical potential variation

To optimize the performances of the circular graphene patch antenna such as the gain and bandwidth, we changed the values of the chemical potentiel which dictates the presence of carriers (either electrons or holes) within graphene, and these carriers, in turn, influence both the electrical conductivity and the electromagnetic characteristics of the graphene antenna. We used Rogers RO 4003C substrate, which has good radiation characteristics, and we changed the chemical potential of graphene material in figure 3.9 and figure 3.10 to get more performances. All the results are resumed in in Table 3.2.

As demonstrated in Table 3.2, we achieved a high gain of 6.62 dBi at 6.95 THz, 5 dBi at 4.69 THz and 3.43 dBi at 3.26 THz. The bandwidth obtained is very large: 653.45 GHz, 2472.9 GHz and 2120.5 GHz for 3.26 THz, 4.69 THz and 6.95 THz respectively, so we can use this antenna for wireless applications that need high gain an bandwidth with minimum losses like sensing, communication and security.

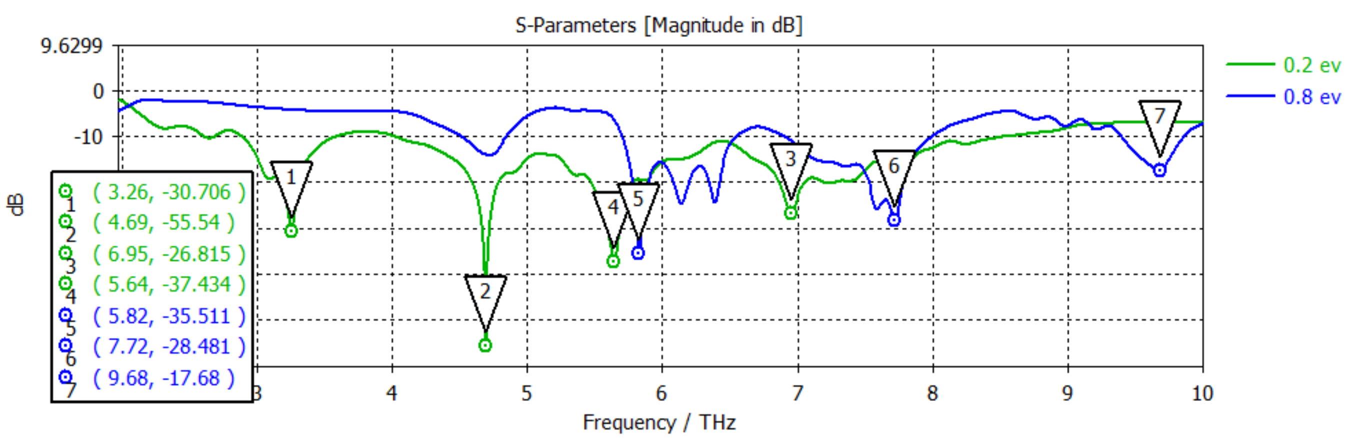


Figure 3.9: S11 Parameter with chemical potential values of 0.2 eV and 0.8 eV of circular graphene antenna.

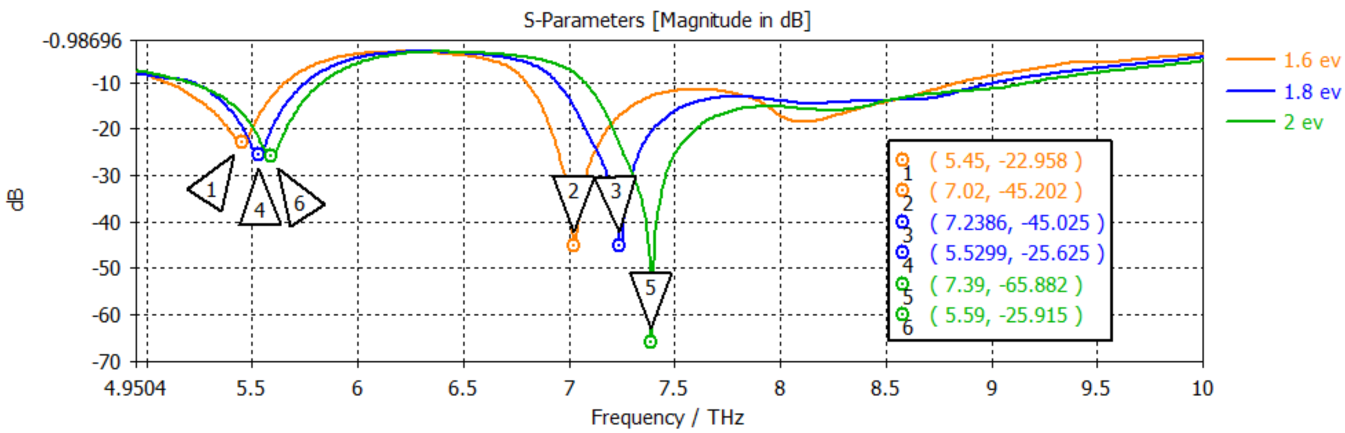


Figure 3.10: S11 Parameter with chemical potential values of 1.6 eV, 1.8 eV and 2 eV of circular graphene antenna.

Chemical Potential (eV)	Frequency (THz)	S11(dB)	VSWR	Gain (dBi)	Bp(GHZ)
2	5.6	−25.559	1.1117	2.1	675.11
	7.39	−65.88	1.0016	2.759	2016.9
1.6	7.02	−22.958	1.011	2.628	563.52
	5.45	−45.202	1.1532	1.726	2084.9
1.8	5.53	−21.573	1.665	2.03	536.5
	7.24	−45.629	1.105	2.86	2084.9
0.8	5.82	−35.51	1.0342	0.196	849.8
	7.72	−28.48	1.0783	1.734	1120.4
	9.68	−17.68	1.3005	1.66	492.97
0.2	3.26	−30.706	1.0603	3.437	653.46
	4.69	−55.54	1.0034	5.008	2472.9
	6.95	−26.812	1.0956	6.62	2120.5

Table 3.2: Simulations Results of Chemical potential variation for proposed circular graphene antenna.

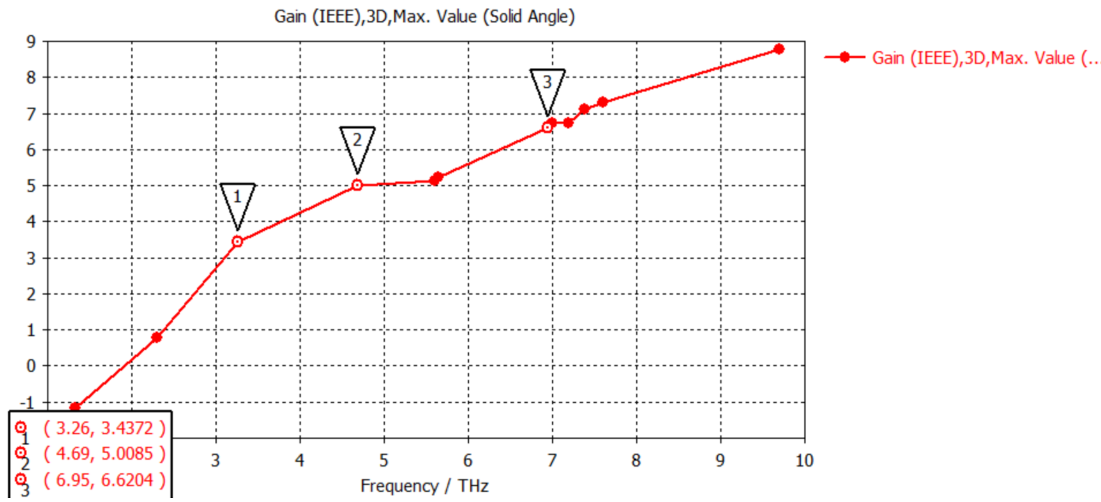
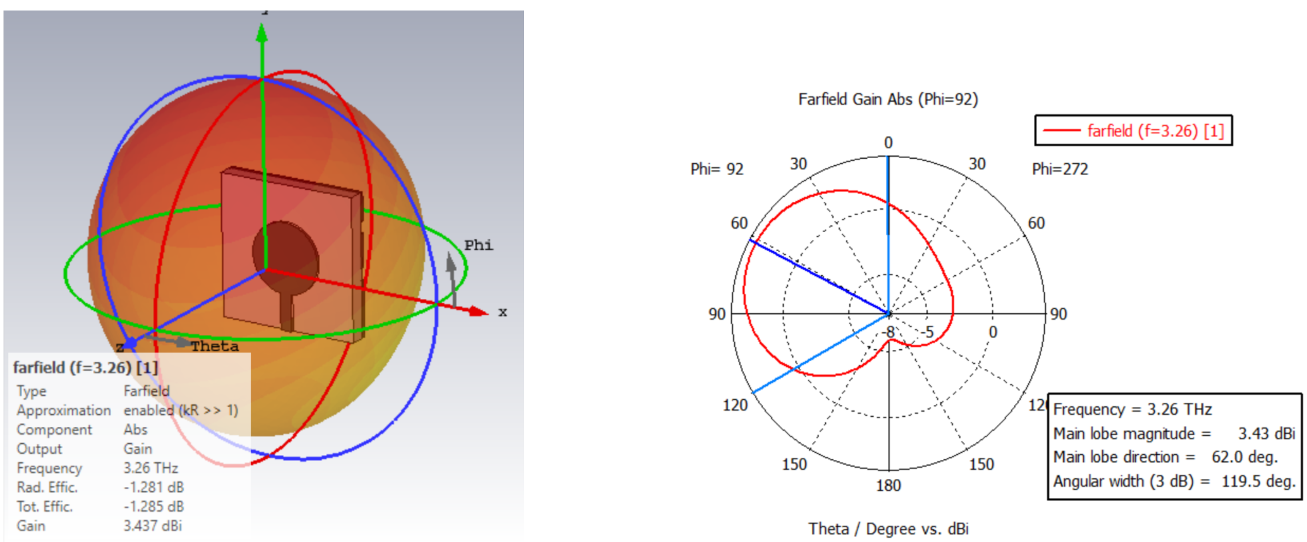
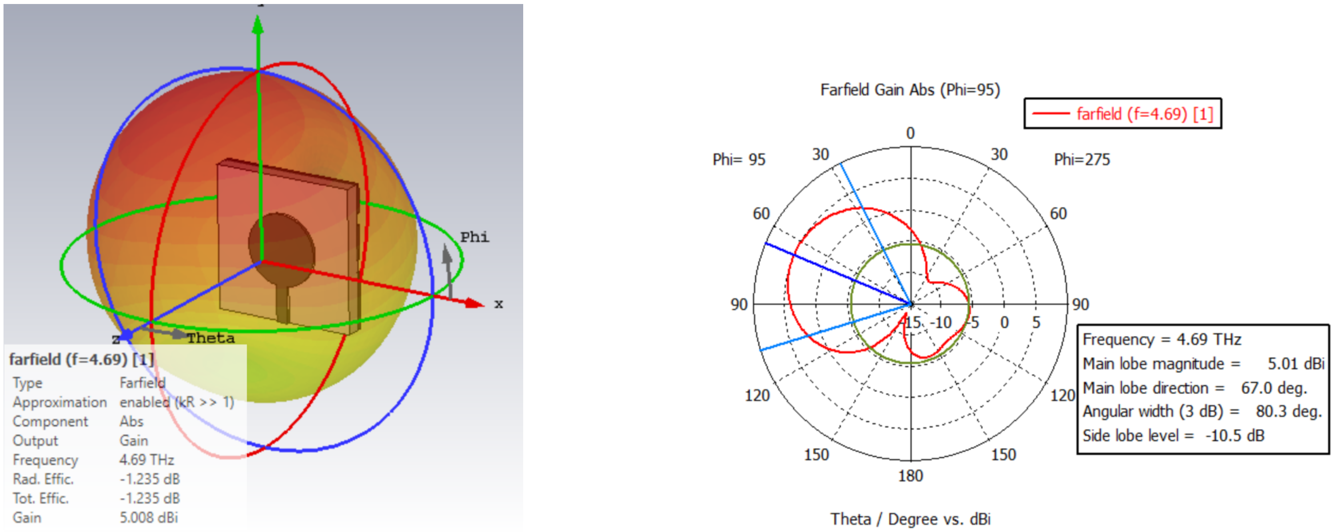


Figure 3.11: Gain of terahertz antenna with chemical potential 0.2 ev.



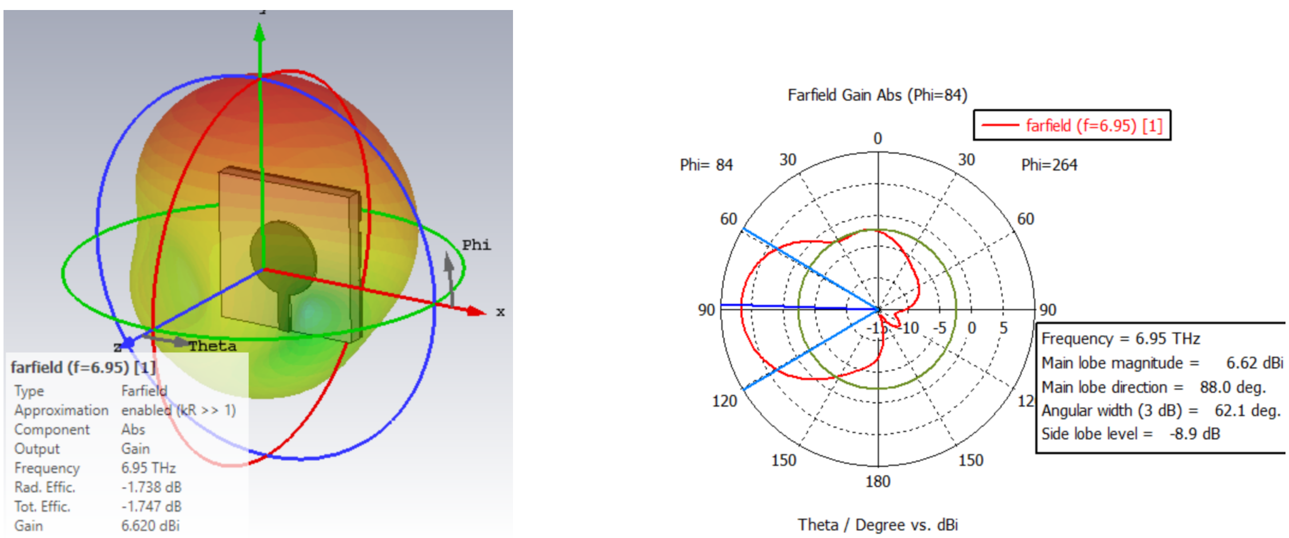
(a) (b)

Figure 3.12: (a) 3D radiation pattern of the antenna at 0.2 ev for 3.26 THz ; (b) Polar radiation pattern of the antenna at 0.2 ev for 3.26 THz.



(a) (b)

Figure 3.13: (a) 3D radiation pattern of the antenna at 0.2 ev for 4.69 THz ; (b) polar radiation pattern of the antenna at 0.2 ev for 4.69 THz.



(a) (b)

Figure 3.14: (a) 3D radiation pattern of the antenna at 0.2 ev for 6.95 THz ; (b) Polar radiation pattern of the antenna at 0.2 ev for 6.95 THz.

Figure 3.12, 3.13, 3.14 presents the 3D and polar radiation pattern of Graphene circular patch antenna with 0.2 eV of chemical potential. The main lobe value is 62 deg for 3.26 THz, 67 deg for 4.69 THz and 88 deg for 6.95 THz respectively. The antenna radiations is directional which is very satisfactory for sensing, security and communication applications in terahertz band.

3.5 Crescent Graphene patch antenna design

Using the CST software, we designed a small crescent terahertz microstrip antenna (Figure 3.15) fed by microstrip line with a 50 ω impedance. We used graphene material for radiating element with the following properties: Temperature 300 k, chemical Potential (μ_c=2ev) , relaxation Time($\tau =$ 1ps)and thickness 60 nm. The patch antenna dimensions are calculated from the equations (3.10) (3.11) (3.12) (3.13) (3.14).

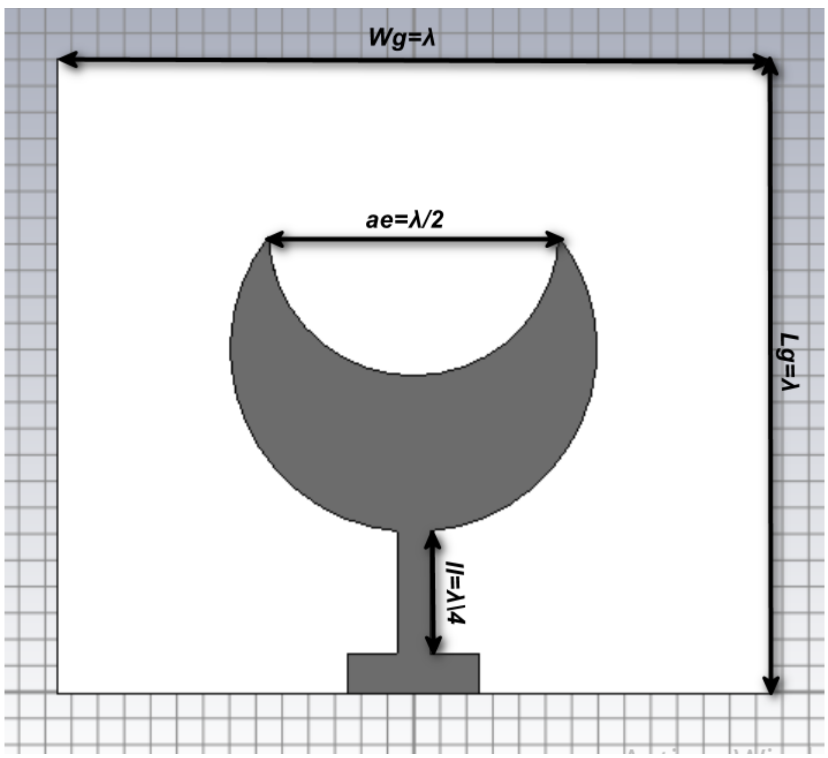


Figure 3.15: The Crescent Graphene patch antenna design.

3.5.1 Crescent patch antenna with different materials as substrate

In this section, we simulated in figure 3.16 the crescent patch antenna using various substrates such as PTFE(ϵ_r= 2.1), polymide (ϵ_r = 3.5), Roger RO3003 (ϵ_r = 3) , Roger RO4003C (ϵ_r = 3.4) and Arlan AD250C (ϵ_r = 2.5) to evaluate the performance of the nano crescent patch antenna.

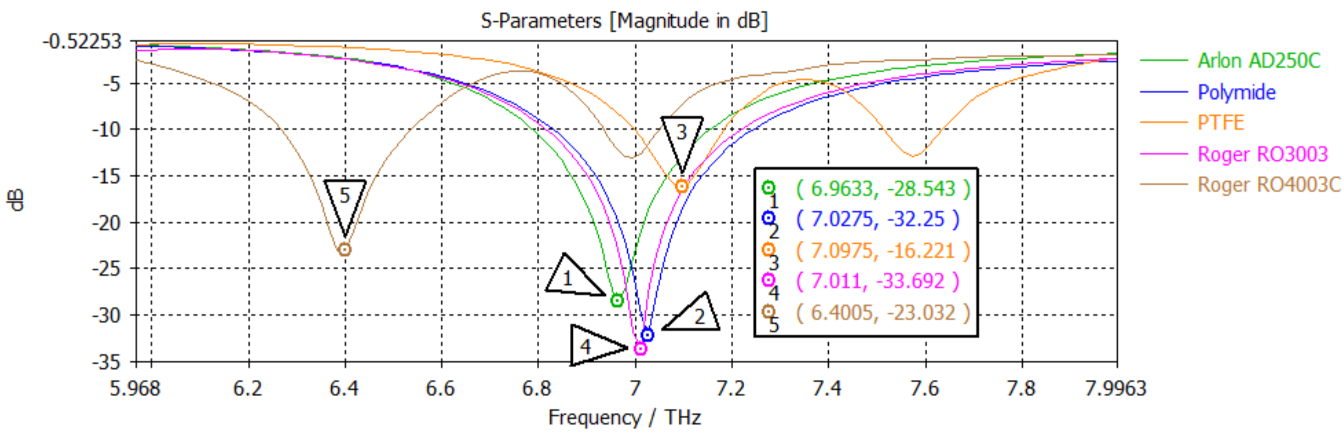


Figure 3.16: Reflection coefficient parameter S11 of crescent Graphene antenna for different type of substrate material.

The figure 3.17 show the stands for Voltage Standing Wave Ratio(VSWR) of crescent graphene antenna for different type of substrate material.

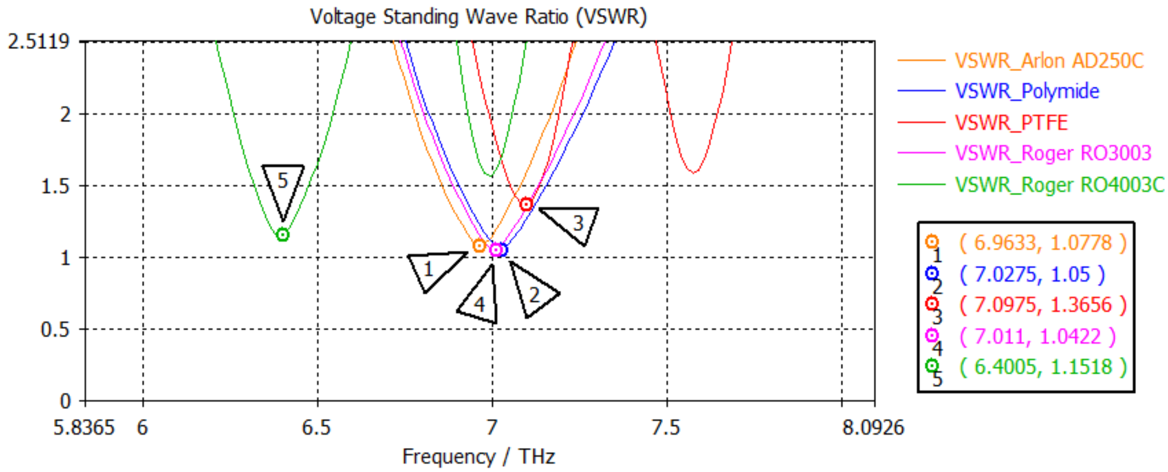


Figure 3.17: VSWR parameter of crescent graphene antenna for different type of substrate material.

Table 3.3 summarizes the simulation result of reflection coefficient:

The substrate	Frequency (THz)	S11(dB)	Gain (dBi)	VSWR	BP(GHZ)
Arlan AD250C (ϵ_r=2.5)	6.9615	-28.592	5.24	1.07	350.63
RO3003(ϵ_r =3)	7.011	-33.692	4.803	1.04	441.77
Polymide (ϵ_r =3.5)	7.0275	-32.25	4.568	1.05	418.99
Teflon (ϵ_r =2.1)	7.0935	-16.323	4.417	1.36	168.52
RO4003C(ϵ_r =3.4)	6.9945	-13.152	2.287	1.57	124.11

Table 3.3: Results comparison substrate for Crescent graphene antenna.

Table 3.3 demonstrates that Arlan AD250C is the best material substrate, producing high gain of 5.24 dBi at 6.9615 THz as shown in figure 3.18. The return loss of the crescent antenna is -28.592 dB and the bandwidth is 350.63 GHz.

Figure 3.18 and 3.19 shows the radiation pattern of the crescent patch antenna at 6.96 THz :

The angular wide obtained is 69.7 deg with a main lobe magnitude of 5.24 dBi, so the radiation pattern is directional and the antenna can be used for wireless applications.

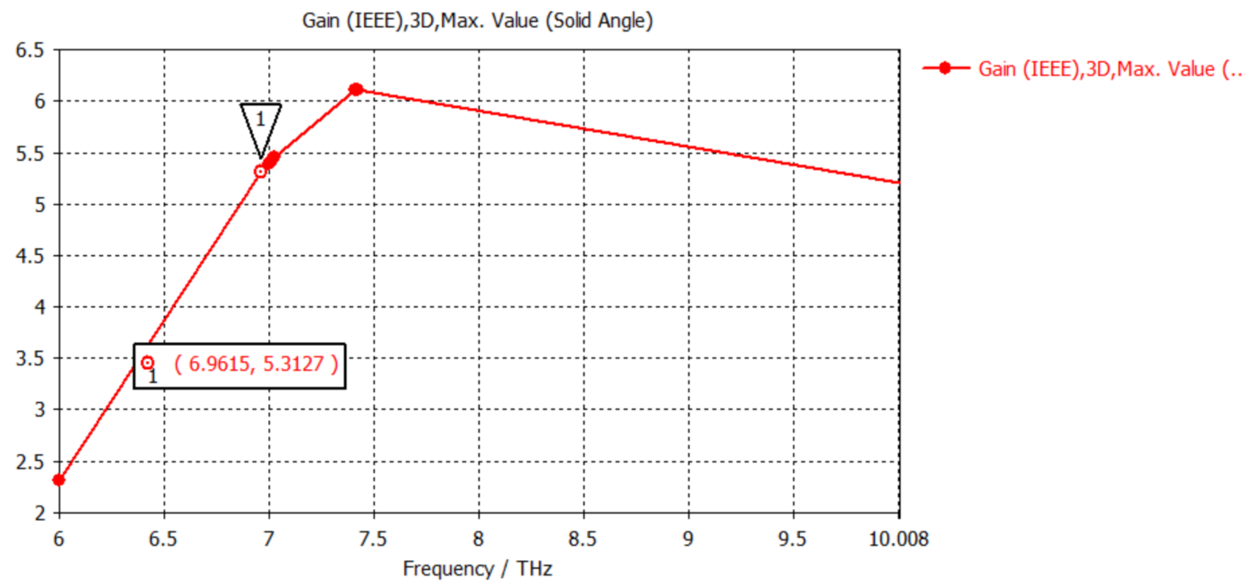
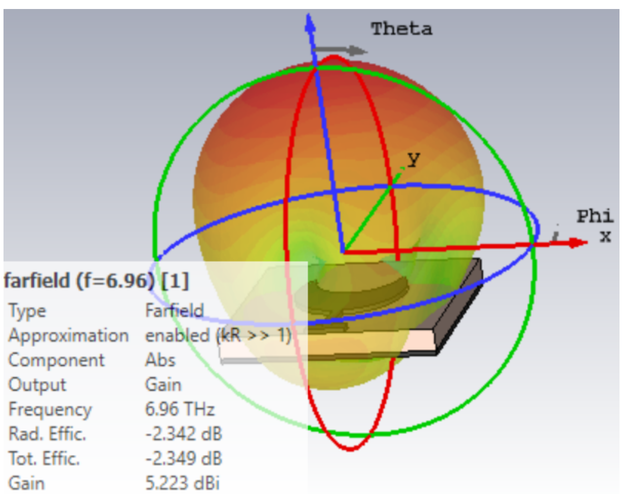
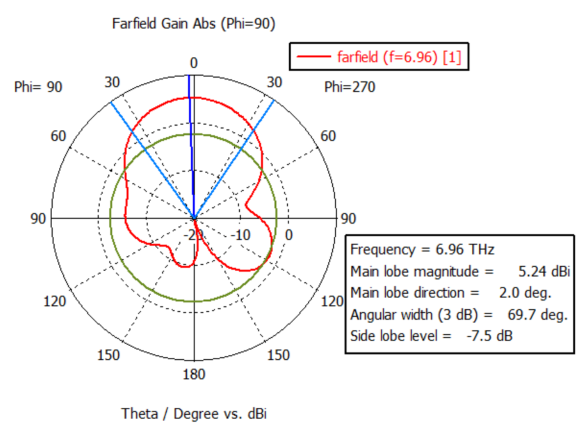


Figure 3.18: Gain of the cresent antenna with Arlan AD250C substrate.



(a)



(b)

Figure 3.19: (a) 3D radiation pattern of the crescent antenna with Arlan AD250C substrate ; (b) polar radiation pattern of the crescent antenna with Arlan AD250C substrate.

3.5.2 Crescent Antenna optimisation with Chemical potential variation

Crescent patch antenna is designed to be used for integrating into compact devices for wireless data transfer at terahertz frequencies, so the bandwidth and the gain must be with high values. In this section, We used Arlan AD250C substrate (ϵ_r=2.5) which is the best material chosen and we changed in chemical potential value to get more performances. The simulation results of return loss S11 are given in figure 3.20.

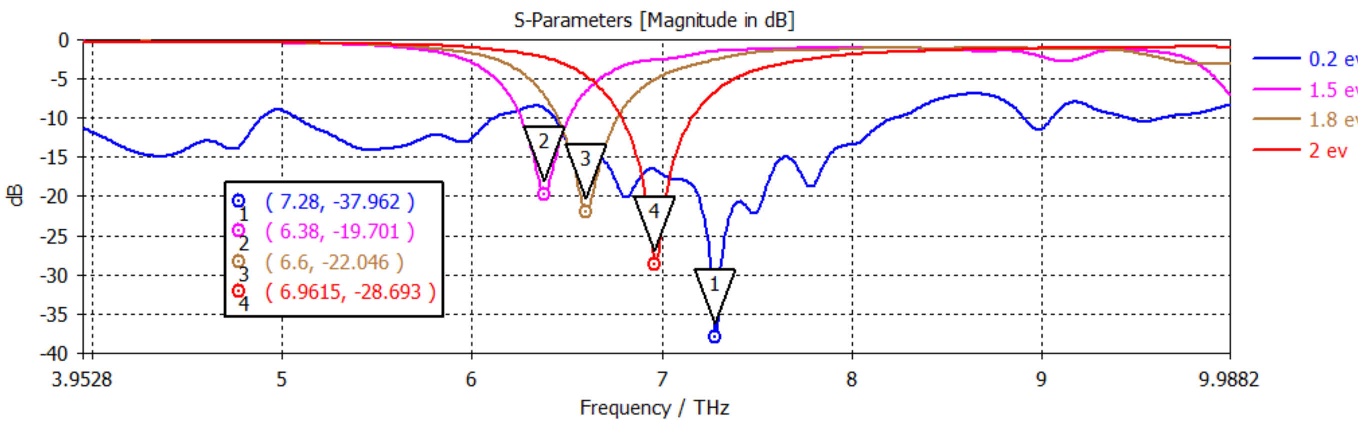


Figure 3.20: Return loss S11 with 0.2 eV, 1.5 eV,1.75 eV and 3ev of chemical potential for proposed Crescent graphene antenna.

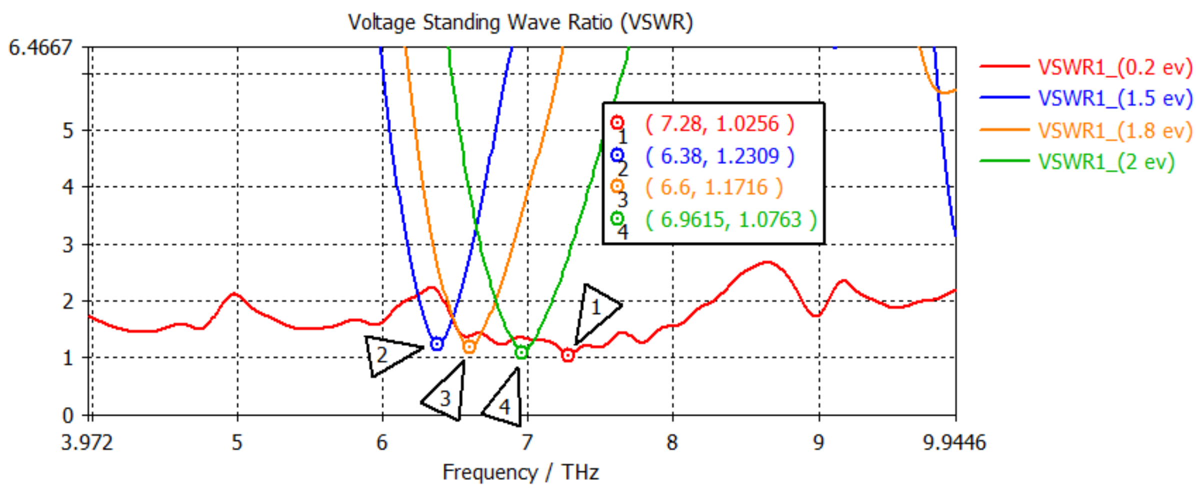


Figure 3.21: VSWR with 0.2 eV, 1.5 eV,1.75 eV and 3ev of chemical potential of the Crescent graphene antenna.

ChemPotential(ev)	Frequency (THz)	S11(dB)	Gain (dBi)	BP(GHZ)
2	6.9615	-28.592	5.24	350.63
1,8	6.6	-22.046	4.55	322.18
1.5	6.38	-19.701	4,573	252.29
0.2	7.28	-37.962	7.134	1767.3

Table 3.4: Simulations Results of Chemical potential variation of the Crescent graphene antenna

As shown in Figure 3.20, 0.2 ev of chemical potential gives better gain of 7.13 dBi (figure 3.22) , high bandwidth of 1.769 THz and VSWR less then 2 (figure 3.21) with means that all the energy is transmitted without reflection. The return loss of the crescent patch antenna is -37.962 dB at 7.28 THz of frequency. Table 3.4 summarizes all the results obtained with variation of chemical potential:

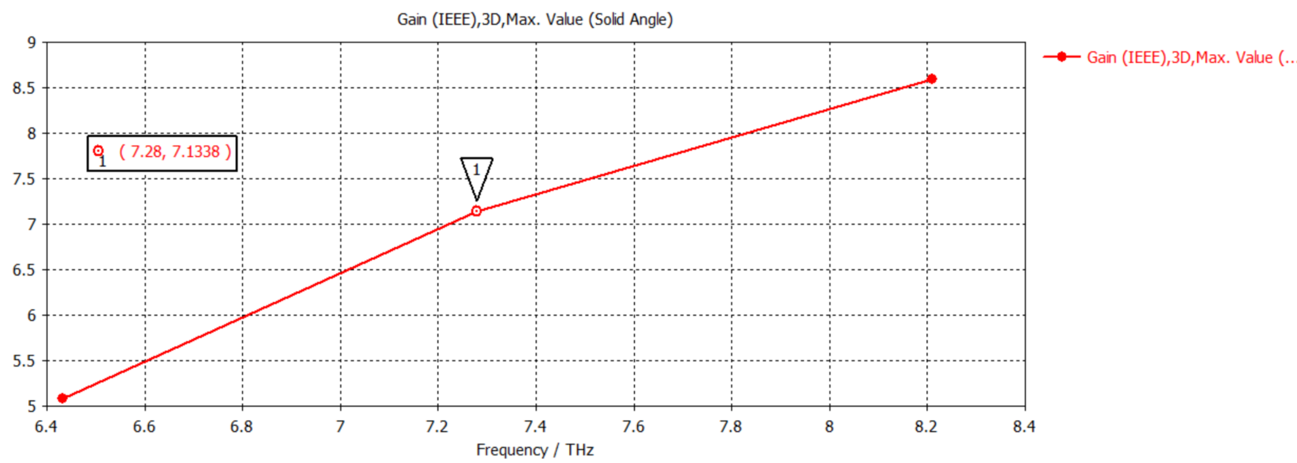
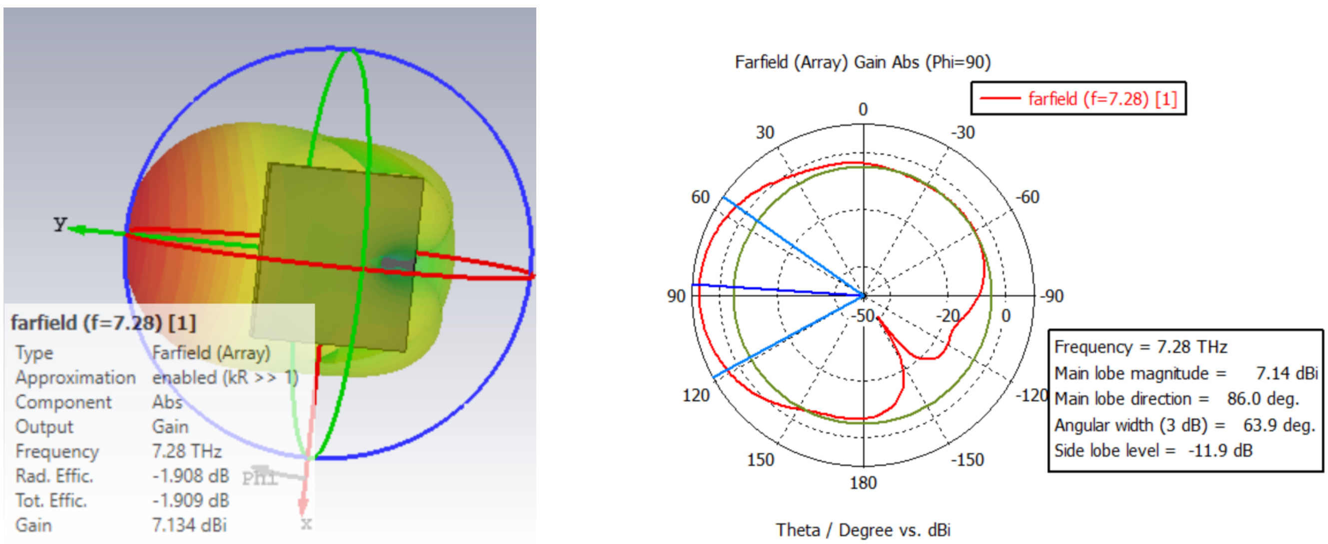


Figure 3.22: Gain of crescent antenna at 0.2 ev of Chemical potential.



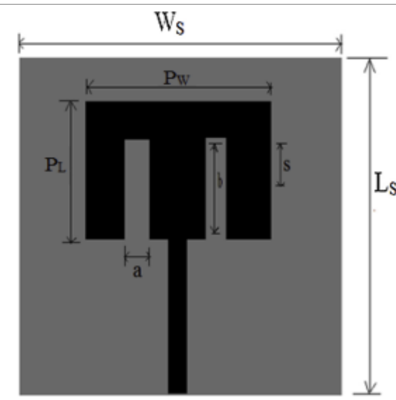
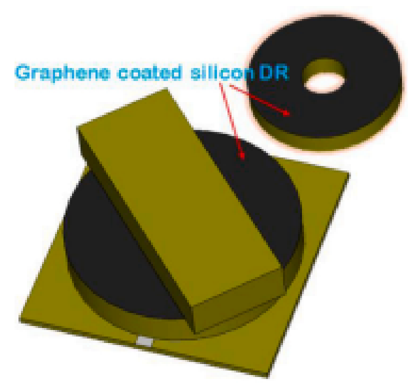
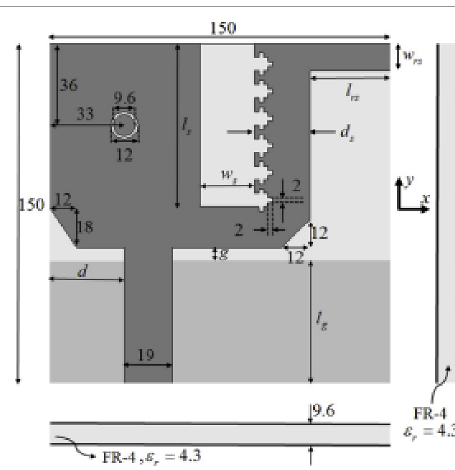
(a) (b)

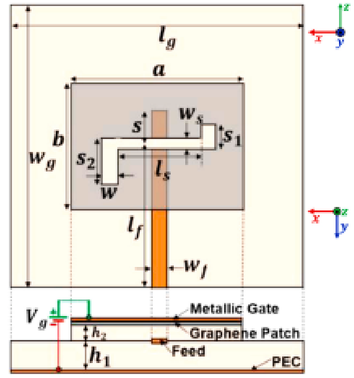
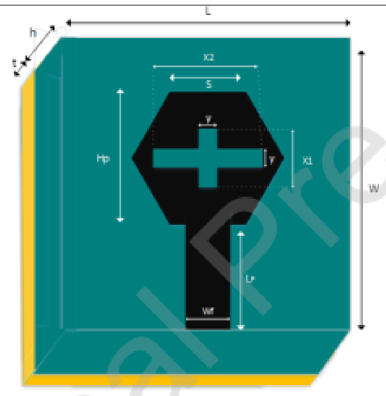
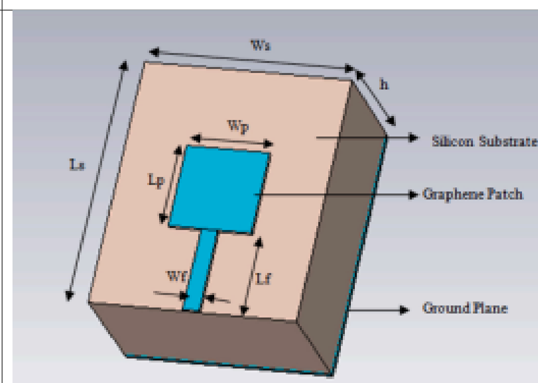
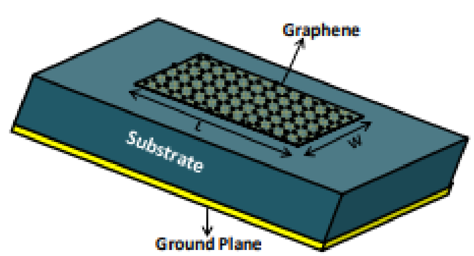
Figure 3.23: (a) 3D radiation pattern of the crescent antenna with 0.2 ev of chemical potential ; (b) polar radiation pattern of the crescent antenna with 0.2 ev of chemical potential.

As shown in figure 3.23, the radiation pattern is directional with an angular wide of 63.9 deg at 3dB.

3.6 Comparison of proposed work with previous literature

To evaluate the quality of our research, we compared in Table 3.5 our simulation results with other previous and recent literature's:

Referance	Frequencies (THz)	S11(dB)	BP(GHz)	Gain (dBi)	Antenna design
[140]	2.05	-22	500	5.02	
[141]	4.104	-40	130	3.8	
[142]	0.434-1.684	-39	1250	5.72	

Referance	Frequencies (THz)	S11(dB)	BP(GHz)	Gain (dBi)	Antenna design
[143]	1	-18	100	4.31	
[144]	2.14 5.41	-24.65 -25.86	658	4.71 6.61	
[95]	2.58 4.41	-33.7 -10.56	Not mentioned	2.58 1.22	
[145]	3.5	-30	245	Not mentioned	

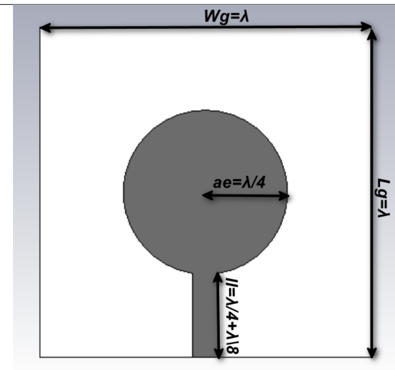
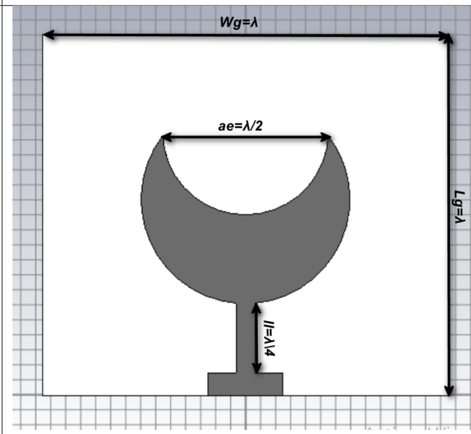
Referance	Frequencies (THz)	S11(dB)	BP(GHz)	Gain (dBi)	Antenna design
Circular Graphene antenna with DGS	3.26 4.69 6.95	-30.706 -55.54 -26.812	653.46 2472.9 2120.5	3.437 5.008 6.62	
Crescent Graphene antenna	7.28	-37.962	1767.3	7.134	

Table 3.5: Comparison of proposed work with previous literature.

The authors in [141] and [95] have used graphene-based patch antennas with a circular shape to improve radiance. In addition, the antennas proposed in [142],[140],[143] and [145] have used rectangular antennas which widen the bandwidth, while [144] propose an hexagonal antenna with high gain and small bandwidth. In our work, we have obtained a very good performances with circular and crescent antenna. The gain exceeds 6 dBi and the bandwidth is between 1 and 2 THz.The results are very satisfying for terahertz wireless transmission such as spectroscopy and immaging, security and sensing and finally for communication. if we compared our works, with circular patch antenna, we have used DGS in the ground plane and we changed in chemical potential value to increase the gain and the bandwidth for using in majority of applications in wireless terahertz band. The second antenna with crescent shape gives more performances with his simple structure and the antenna can be used for communication application in which we need high gain and bandwidth.

3.7 Antenna fabrication

The fabrication and characterisation of a graphene patch terahertz antenna is a complex process, needing a very high degree of competence in this sector, hence consulting with professionals in this field or professional assistance for patch antenna production and characterization is strongly advised.

Once the antenna design has been optimized, the antenna can be fabricated and characterized as follows [146, 147]:

- **Preparation The substrate material:** To eliminate all kinds of impurities, dust and other contaminants.The material must be be properly cleaned.
- **Thin film deposition:** A thin film made by chemical vapor deposition is deposited on the substrate to be bonded to the graphene.
- **Preparation of graphene:**Graphene may be produced by a variety of processes, such chemical vapor deposition (CVD), epitaxial growth, and mechanical exfoliation. Chemical Vapor Deposition (CVD) involves developing a thin layer of graphene on a metal substrate in a high-temperature furnace by adding a hydrocarbon gas, such as methane or ethylene, in a high-temperature furnace. Then, the carbon atoms in the gas are deposited on the metal substrate, creating a graphene layer.
- **Graphene deposition:** Graphene must be put on the substrate by dry or wet transfer.
- **Patch antenna fabrication:** Standard photolithography procedures such as spin coating, mask alignment, and etching are used.
- **Patch antenna characterization:** In this stage, we can use a network analyzer, far-field radiation pattern measurement, and impedance measurement to characterize the proposed patch antenna.

3.8 Conclusion

The design of nano crescent and circular terahertz antennas shows great potential for a multitude of applications spanning diverse fields. These antennas mark a notable progression within the realm of terahertz technology, unlocking new and unparalleled possibilities in sectors including communication, imaging, spectroscopy, and sensing. While these nano terahertz antenna design offers significant promise, it is not without its challenges in both production and deployment. Their fabrication and implementation demand highly accurate manufacturing processes to attain the desired nanostructures. Additionally, signal propagation within the terahertz range can be susceptible to interference from atmospheric absorption and scattering, further complicating their practical use.

Chapter 4

WBAN THz antenna

4.1 Introduction

Wireless Body Area Networks (WBANs) represent specialized wireless networks tailored for human body-centric applications. They employ wearable or implantable devices to track and gather diverse physiological data, including metrics like heart rate, body temperature, blood pressure, and muscle activity. An emerging frontier in WBAN research and innovation revolves around harnessing terahertz (THz) technology to explore diverse applications.Among the highly auspicious applications of terahertz technology within WBANs, medical imaging stands out prominently. Terahertz waves possess the unique capability to permeate a wide range of substances, encompassing attire and biological tissues, while remaining completely non-ionizing and harmless to the human body. This property makes them ideal for non-invasive imaging techniques.THz spectroscopy is another important application of terahertz technology in WBANs, it encompasses the examination of how THz waves interact with substances, with the aim of discerning both the chemical composition and physical characteristics of these materials. THz waves exhibit distinctive absorption spectra, which serve as a valuable tool for distinguishing and identifying various molecules and materials.

In this chapter, we designed two nano optical antennas for WBAN applications. The first rectangular antenna has been designed to operates at 0.74 THz, 1.148 THz, and 1.734 THz frequencies for medical imaging . The second circular antenna has been designed to radiates at the frequency 3.93 THz for spectroscopy applications. To improve more the radiation characteristics performances of the antennas, we combined different types of substrates materials with Gold radiating element.

4.2 Terahertz Nano patch antenna design for WBAN applications

The process of crafting antennas for Wireless Body Area Network (WBAN) applications demands careful deliberation to guarantee dependable and effective communication within the unique context of the human body, so we tacked account some key aspect like: frequency range, size and form factor, bio compatibility, radiation pattern and bandwidth. The human body has a significant impact on the performance of WBAN antennas. The presence of the body can detune the antenna, alter its radiation pattern, and introduce signal attenuation. Antenna designs should account for these effects to ensure reliable performance in realistic usage scenarios [148].

In all cases, the use of antennas in medical technology requires a reliable communications network with sufficient bandwidth above 50GHz to transmit medical data in real time without interfering with other wireless networks, such as Wi-Fi figure 4.1. Minimal power consumption to prolong the life of medical device batteries, gain of no more than 6 dBi and greater than 2 dBi as it is primarily intended for short-distance communication, small size of around 1 mm for easy integration into the human body, resistance to interference caused by the human body [149, 150].

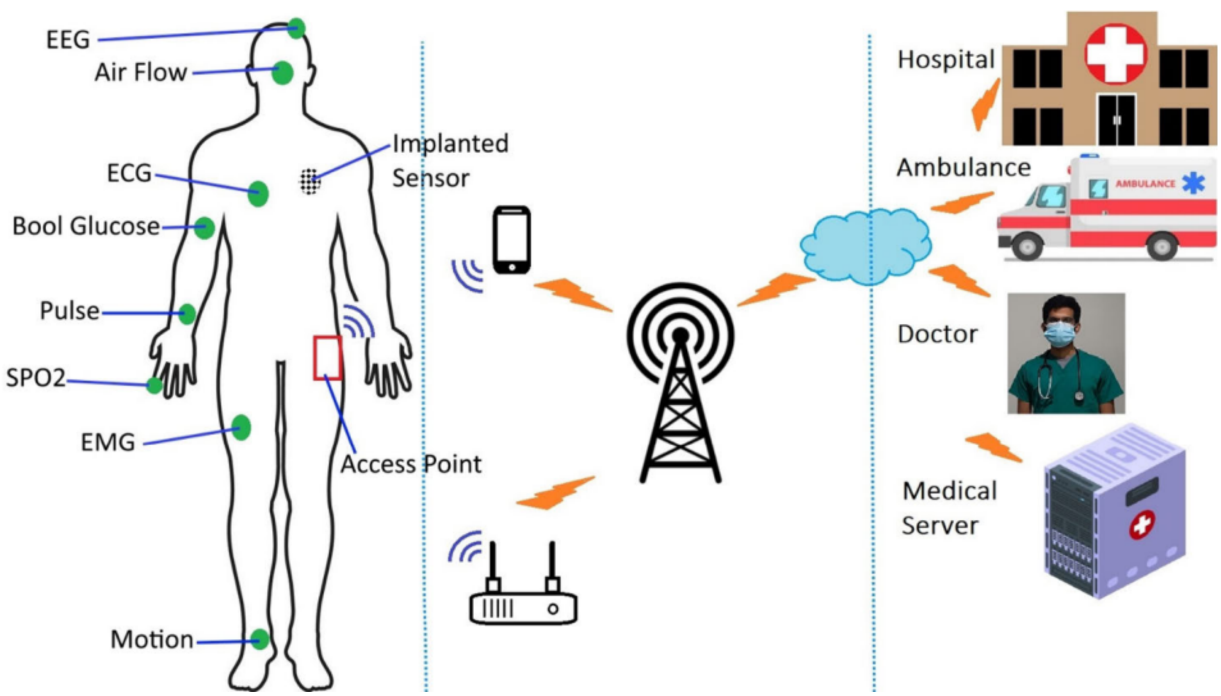


Figure 4.1: Wireless Body Area Networks application [151].

4.3 Material chosen for WBAN applications in terhertz band

For successful WBAN applications within the THz range, it is crucial to select materials that have been tailored for THz applications, minimizing their absorption of THz frequencies. These materials are engineered to reduce signal loss. Researchers in the realm of THz for WBAN frequently employ such specialized materials to guarantee superior outcomes in medical contexts.

The contribution of this work is to design nano terahertz optical antenna combining gold material radiating element for its favorable important characteristics [152] such as high conductivity and low absorption with thin substrates thickness such as: Alumina (ϵ_r=9.9), Rogers R04003C (ϵ_r=3.5), RT Duriod 5880 (ϵ_r=2.2), RT Duriod 3210(ϵ_r=10.8),Silicon (ϵ_r=2.1) to minimize signal loss and reduce the overall size and weight of the optical antenna in the system [153].

The first antenna resonate from 2 THz to 4 THz and it can be used for spectroscopy applications in terahertz band [154]. The second antenna resonate from 0.5 THz to 2 THz and it can be used for medical imaging application in terahertz band [155].

4.4 Nano circular antenna design for spectroscopy applications

In this section, we designed a circular nano patch antenna in figure 4.2 for spectroscopy applications for [2- 4] THz band. In biological and biomedical THz spectroscopy applications, the antenna is designed to optimize the interaction between THz radiation and the biological samples while ensuring minimal disturbance to the samples. It satisfied the following specifications:

- Radiant element shape: Circular.
- Power supply: Microstrip line suitable for 50 Ω.

- Substrate Silicon: $\epsilon_r = 11.9$; h=5.4μm.
- Radiating element material : Gold ; t=3.205 μm.

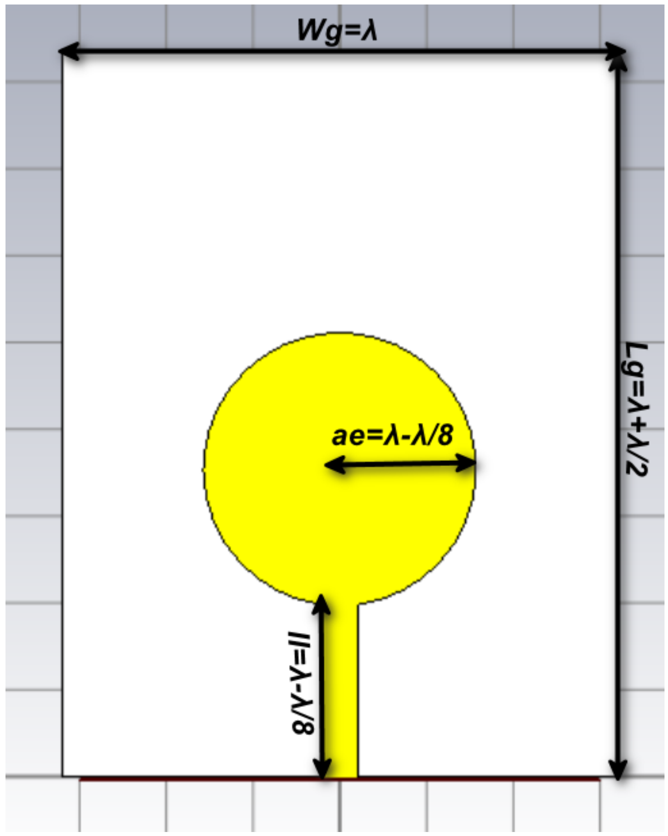


Figure 4.2: Nano circular patch antenna.

The formulae given in the previous chapter (3.10) (3.11) (3.12) (3.13) (3.14) are used for calculating the antenna's parameters.

4.4.1 Simulation result of circular antenna

The simulation results of return loss parameter (S11) for the Gold antenna with Silicon substrate ($\epsilon_r = 11.9$) are shown in Figure 4.3 . We can see that the circular antenna have an amazing return loss of -54.964dB with a bandwidth 309.72 GHz at the desired frequency of 3.93 THz . The Voltage Standing Wave Ratio (VSWR) of proposed antenna as shown in Figure 4.4 is less than 2 means that all electromagnetic energy is transmitted through the antenna without being reflected . We can see also in figure 4.5, The radiation from the rear lobes, the gain is very low, so we can say that the proposed antenna is very suitable to use in spectroscopy applications.

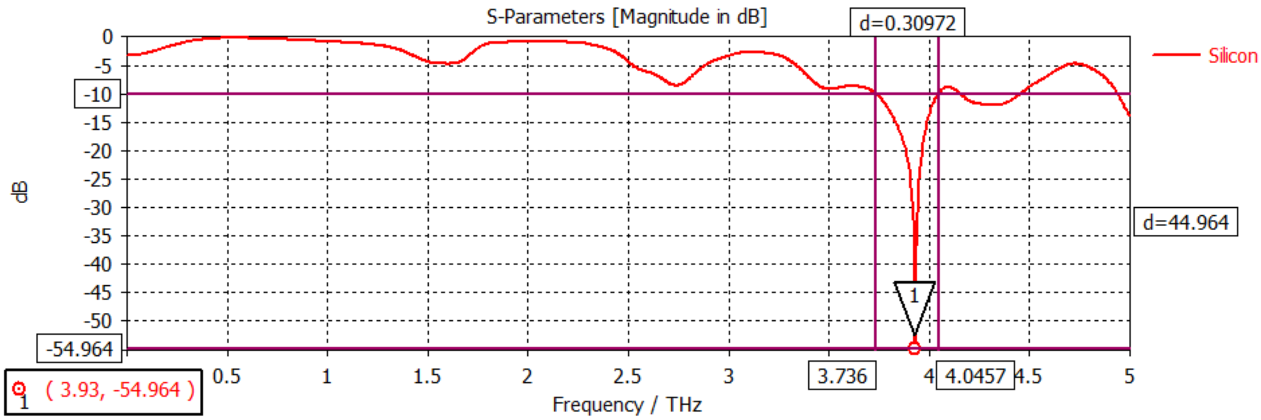


Figure 4.3: Reflection coefficient parameter ofcircular antenna with Silicon substrate.

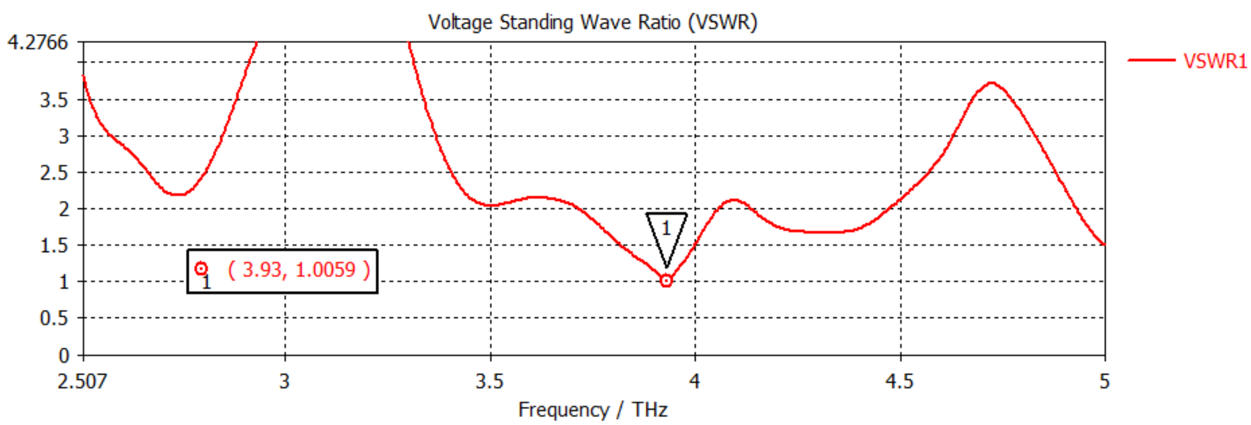
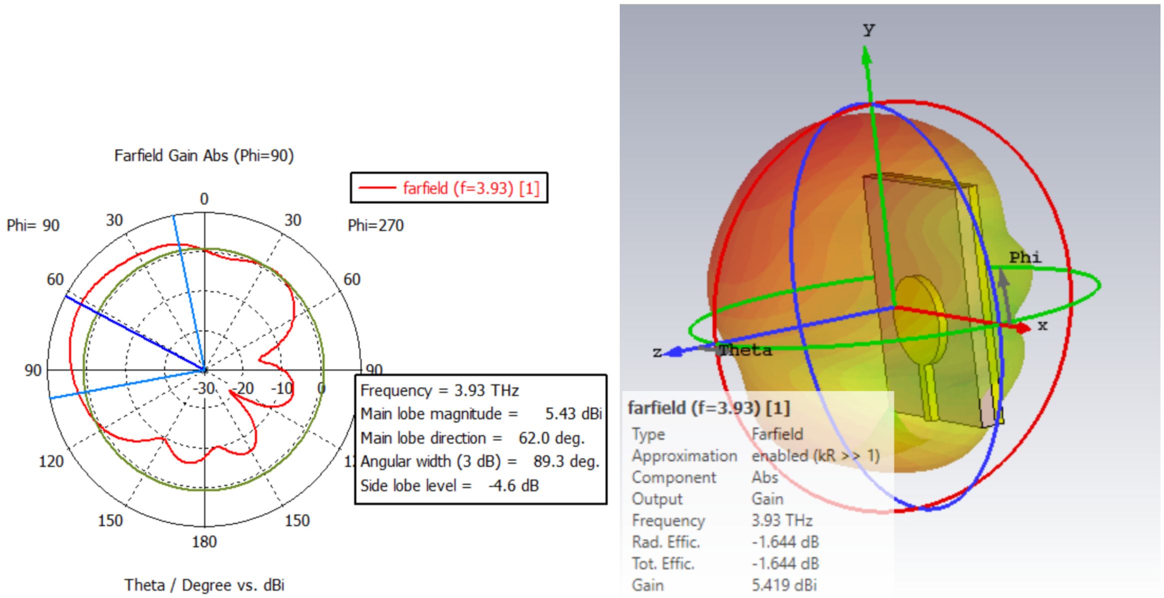


Figure 4.4: VSWR ofcircular antenna with Silicon substrate.



(a) (b)

Figure 4.5: Radiation pattern of circular antenna with Silicon substrate (a) Polar radiation pattern ; (b) 3D radiation pattern.

4.4.2 Simulation result of circular antenna with different type of substrates material

The substrate used for a patch antenna is very important as it affects the antenna's performances. Opting for a high dielectric substrate when conducting THz spectroscopy in the 2-3 THz frequency range can exert a substantial influence on the spectroscopic procedure. It affects the confinement of the electromagnetic field, interactions with the sample, resolution capabilities, signal fidelity, and the overall efficacy of the spectroscopic arrangement. In this section, we simulated the circular gold antenna with high dielectric substrates as : Alumina (ϵ_r = 9.9),RT Duriod 3210(ϵ_r=10.8) and with low dielectric substrates as RT Duriod 5880 (ϵ_r=2.2), RT Duriod 4003C (ϵ_r=3.5) for analyzing radiation characteristics.

Figures 4.6, 4.7 and 4.8 shows all the simulation results obtained:

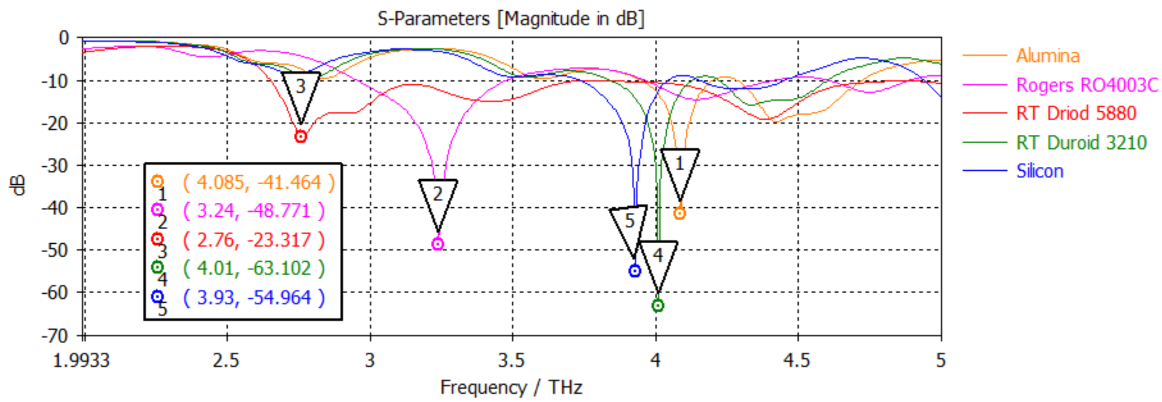


Figure 4.6: Reflection coefficient parameter of circular antenna for each substrate substrates.

As shown in the figure 4.6, several frequencies are obtained by changing the substrate material such as 3.24 THz, 2.76 THz ,4.085 THz,3.93THz and 4.01 THz with the use of Rogers RO4003C, RT Duriod 5880,Alumina, Silicon and RT Duriod 5880 respectively. The return loss obtained for each one of them is:-48.771 dB, -23.317 dB,-41.464 dB,-54.964 dB and -63.102 dB respectively.

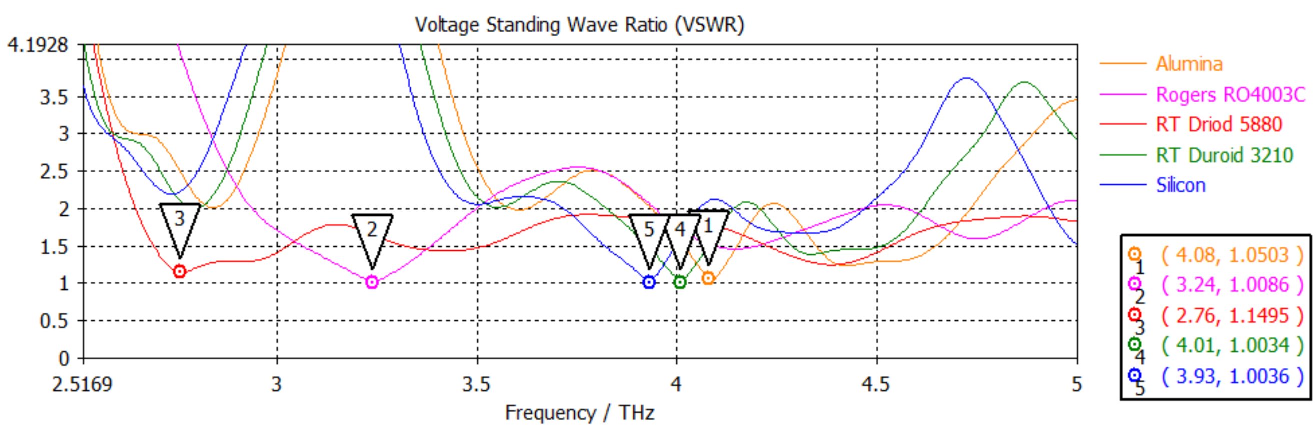


Figure 4.7: VSWR of the circular antenna.

As shown in figure 4.7, the VSWR (Voltage Standing Wave Ratio) in all frequencies obtained with different substrates is less than 2 which indicates that no part of the energy is reflected.

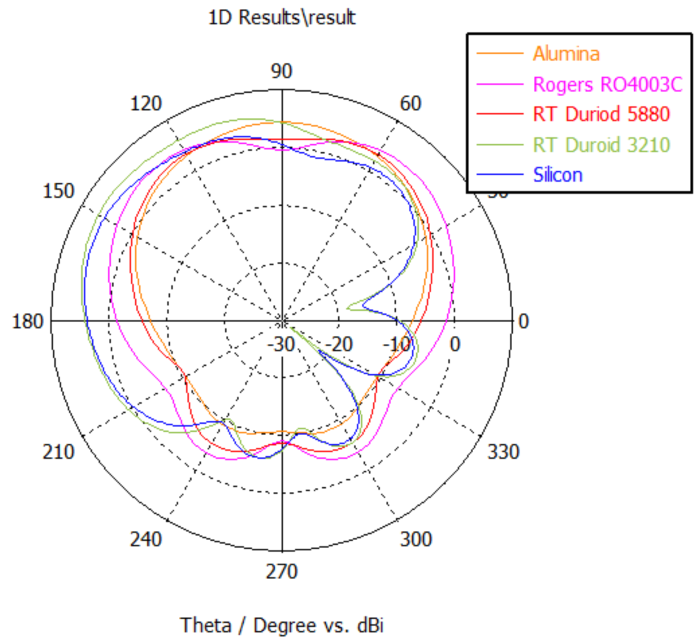


Figure 4.8: Polar radiation pattern of circular antenna for each substrate.

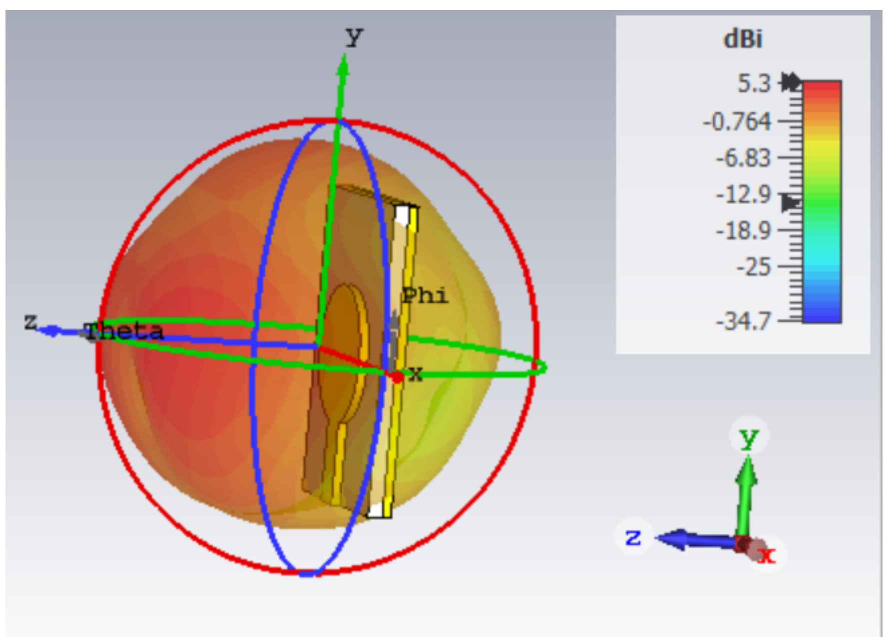


Figure 4.9: 3D radiation pattern of circular antenna for each substrate.

As we can see in figures 4.8 and 4.9, The radiation from the back lobes is very low with the chosen substrates, so we can say that the antenna is directional for spectroscopy applications.

Table 4.1 resume all simulation results obtained with each substrate material , we can result that the use of high dielectric substrate material gives amazing performances in term of high gain and excellent reflection coefficient. For example, RT Duroid 3210 and Silicon achieved -63.10 and -54.96 of return loss with 5 dBi of gain respectively. On the other hand, the use of low dielectric substrate material gives amazing performances in term of bandwidth, for example, the use of Roger 5880 achieved a very large band of 1166.7 GHz, so The choice of substrate depends on the spectroscopy application to be used.

Furthermore, the simulation results demonstrate that antennas crafted with etched substrates exhibit characteristics conducive to medical applications. This conclusion arises from the observation that these antennas showcase SAR parameters below 1.6 W/kg, meeting safety standards.

Antenna parameters	Proposed antenna				
substrates	Silicon(ϵ_r=11.9)	RT Duroid 3210(ϵ_r=10.8)	Alumina (ϵ_r=9.9)	Roger 4003C(ϵ_r=3.55)	Roger 5880 (ϵ_r=2.2)
a(µm)	15.66	16.198	16.7	24.77	30.36
fr (THz)	3.93	4.01	4.085	3.24	2.76
S11(dB)	-54.96	-63.10	-41.32	-48.77	-23.317
Gain (dBi)	5.40	5.06	5.25	4.346	4.504
Directivity	7.574	6.637	6.719	5.294	7.229
Bp (GHZ)	305.91	280.59	280.59	559.07	1166.7

Table 4.1: The simulation result of circular antenna with different type of substrates material.

4.5 Nano rectangular antenna design for medical applications

In this section, we designed in figure 4.10 a rectangular nano patch antenna for [0.5- 2] THz band that can efficiently generate and receive THz radiation for medical imaging applications [156]. It satisfied the following specifications:

- Operating frequency: 0.74 THz, 1.148 THz, and 1.734 THz.
- Radiant element shape: Rectangular.

- Power supply: Microstrip line suitable for 50 Ω.
- Substrate Roger RO4003C : ϵ_r= 3,55 ; h = 15 μm .
- Patch material : Gold ; t=8μm

The dimensions of the proposed antenna are determined in relation to the frequency [45] of the specified application using the following formulae 4.1, 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 [157, 158]:

$$w = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} \tag{4.1}$$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}(1+12\frac{h}{w})^{-0.5} \tag{4.2}$$

$$\frac{\delta L}{h} = 0.412\frac{(\epsilon_{eff}+0.3)(\frac{w}{h}+0.264)}{(\epsilon_{eff}-0.258)(\frac{w}{h}+0.8)} \tag{4.3}$$

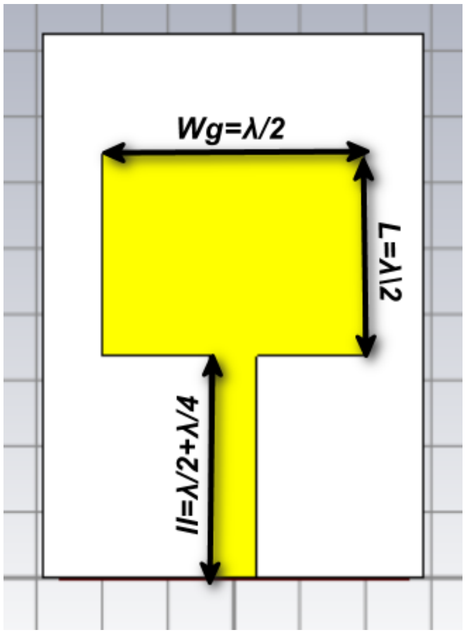
$$L = 0.412\frac{c}{2F_r\sqrt{\epsilon_{eff}}} - 2\delta L \tag{4.4}$$

$$L_{eff} = L - 2\delta L \tag{4.5}$$

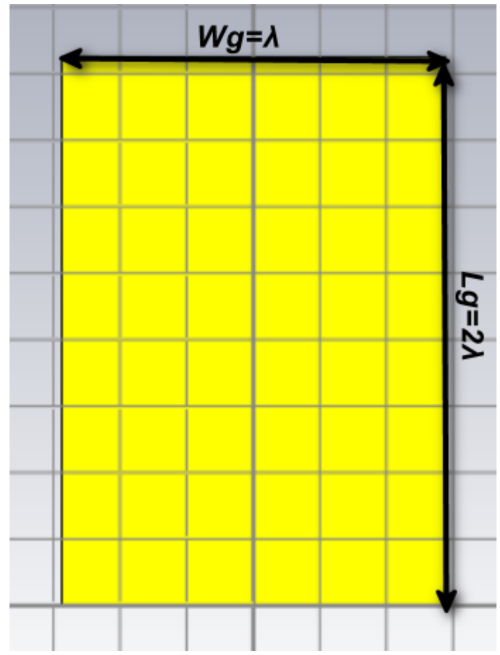
$$Lg = ll + 2L + 6h \tag{4.6}$$

$$Wg = 2L + 6h \tag{4.7}$$

Where h:substrate thickness ,fr : the resonant frequency,ϵ_r :dielectric constant ,ll:the length of the line,Lg: length of both substrate and ground plane,and Wg: width of both substrate and ground plane.



(a)

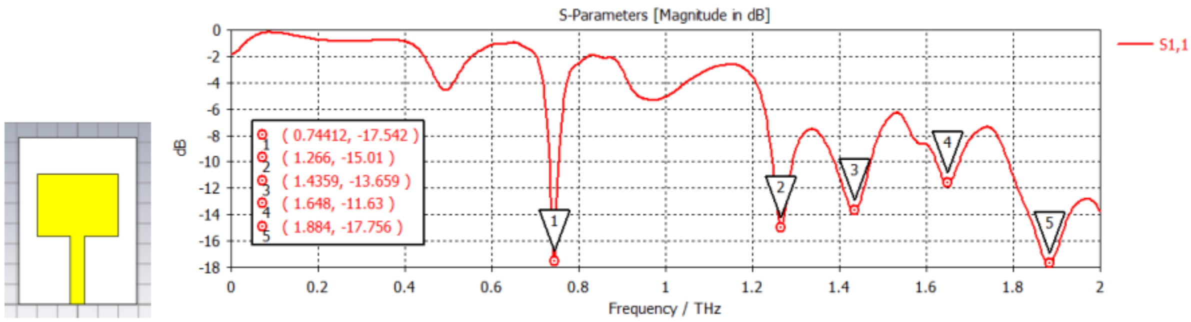


(b)

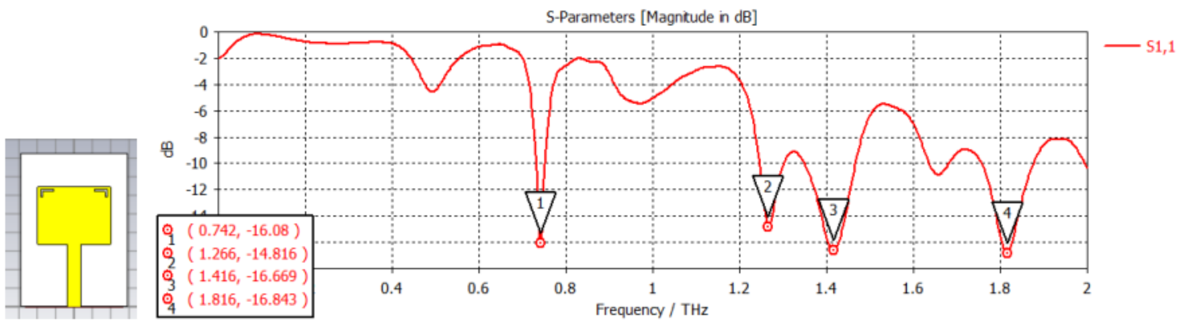
Figure 4.10: (a) Front view of the rectangular proposed patch antenna ; (b) rear view of the rectangular patch antenna.

4.5.1 Simulation and results of the rectangular patch antenna

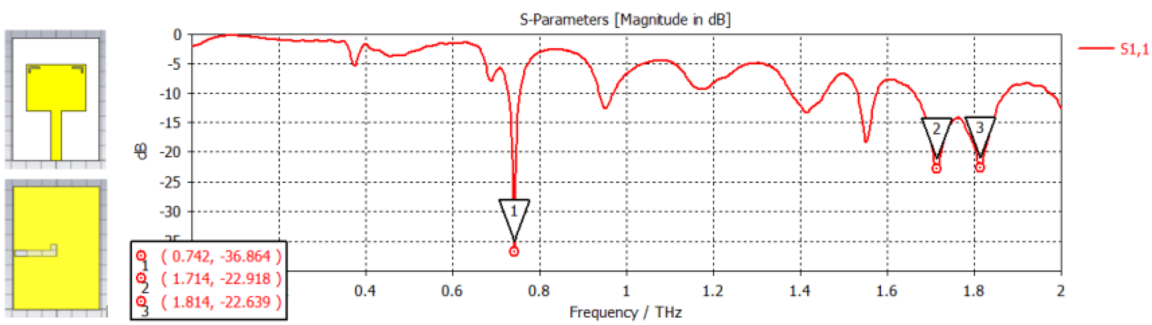
We presented in figures 4.11 and 4.12 the return loss and the VSWR of the rectangular Gold patch antenna:



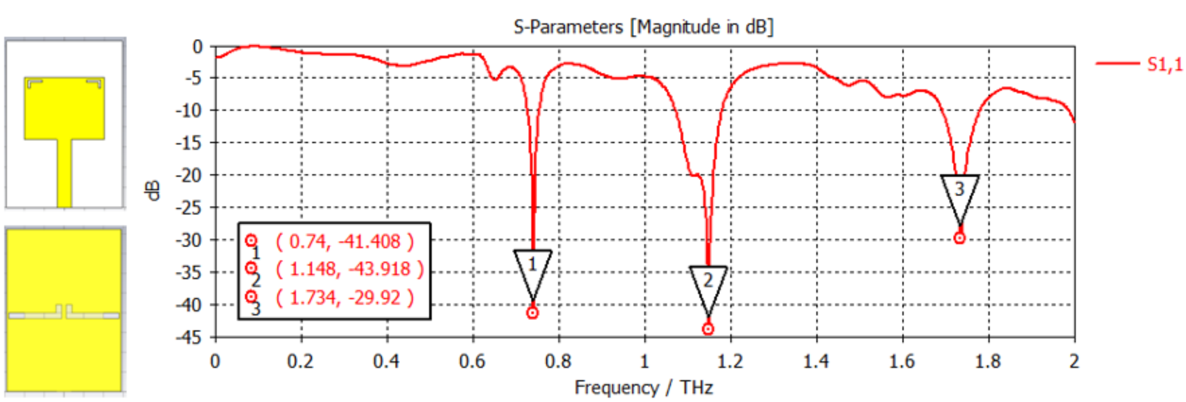
(a)



(b)



(c)



(d)

Figure 4.11: Reflection coefficient S11 of antenna matching mechanism.

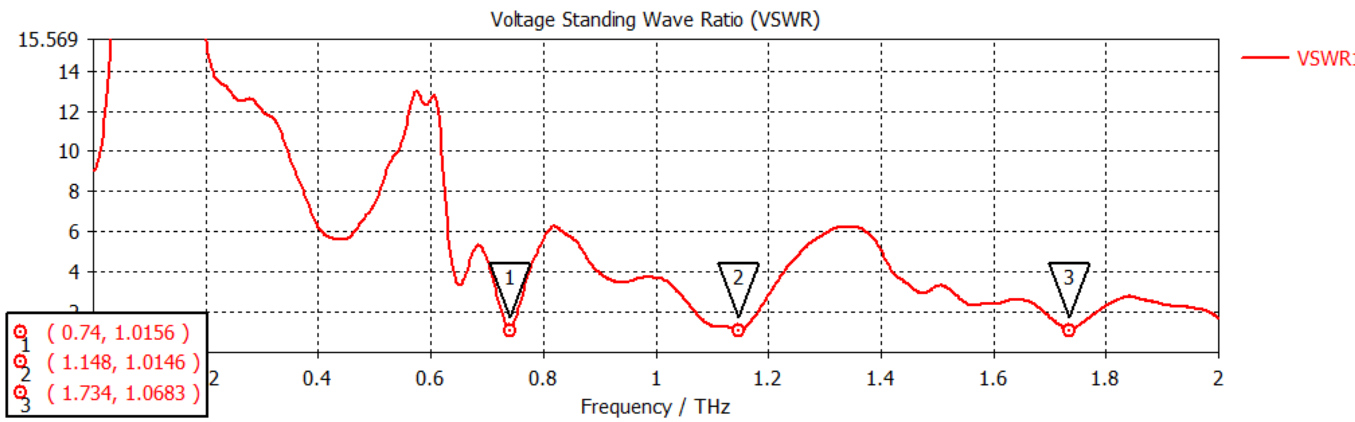


Figure 4.12: VSWR of proposed rectangular gold antenna.

As shown in Figure 4.11, the simulation results of the antenna gives in initial states: several peaks that have lower return loss. To reach peaks in the medical imaging terahertz band, we created two slots in the patch and two slots in the ground plane. Three frequencies of 0.74 THz, 1.148 THz, and 1.734 THz, which have excellent reflection coefficients of –41.408 dB, –43.918 dB, and –29.92 dB, respectively, The bandwidths obtained are 27.4 GHz, 108.9 GHz, and 89.76 GHz for the frequencies respectively. Figure 4.12 shows that the voltage standing wave ratio (VSWR) in all frequencies obtained with RO4003C substrate ($\epsilon_r = 3.55$) is less than 2 which is very satisfactory.

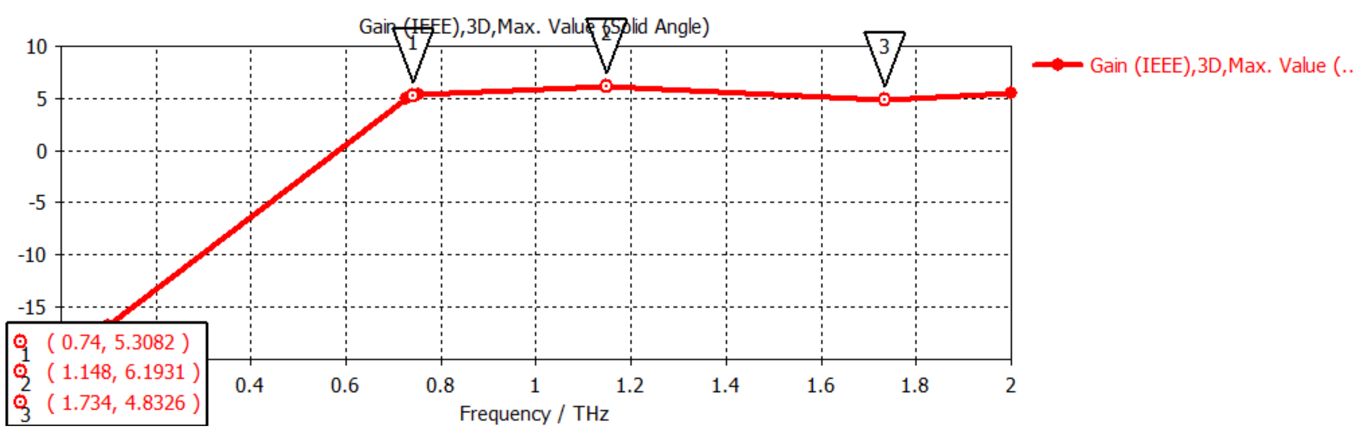
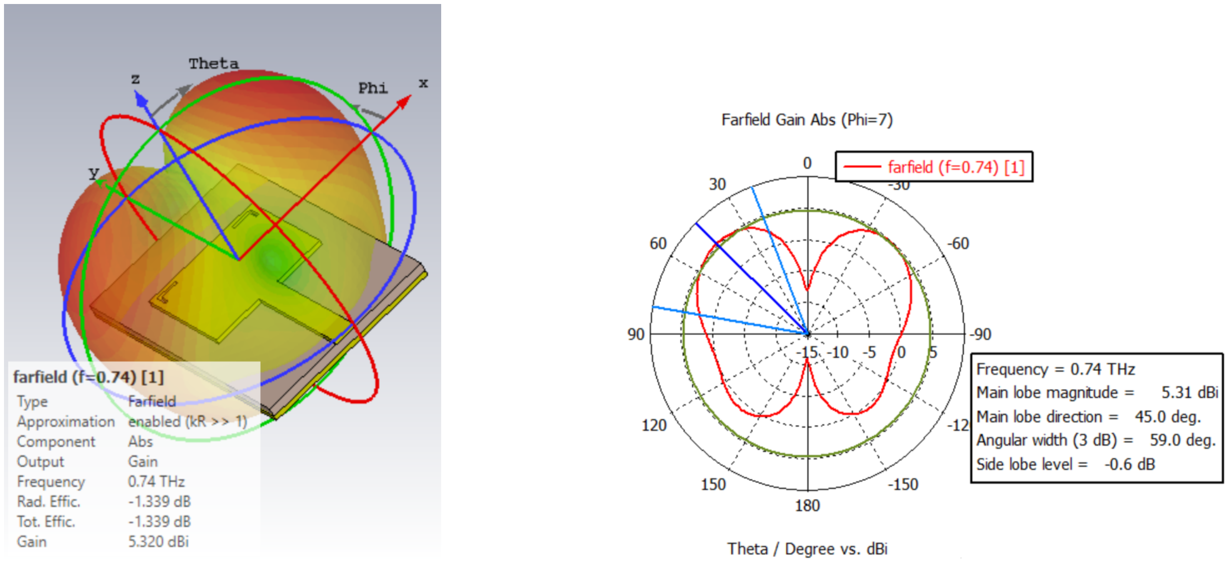


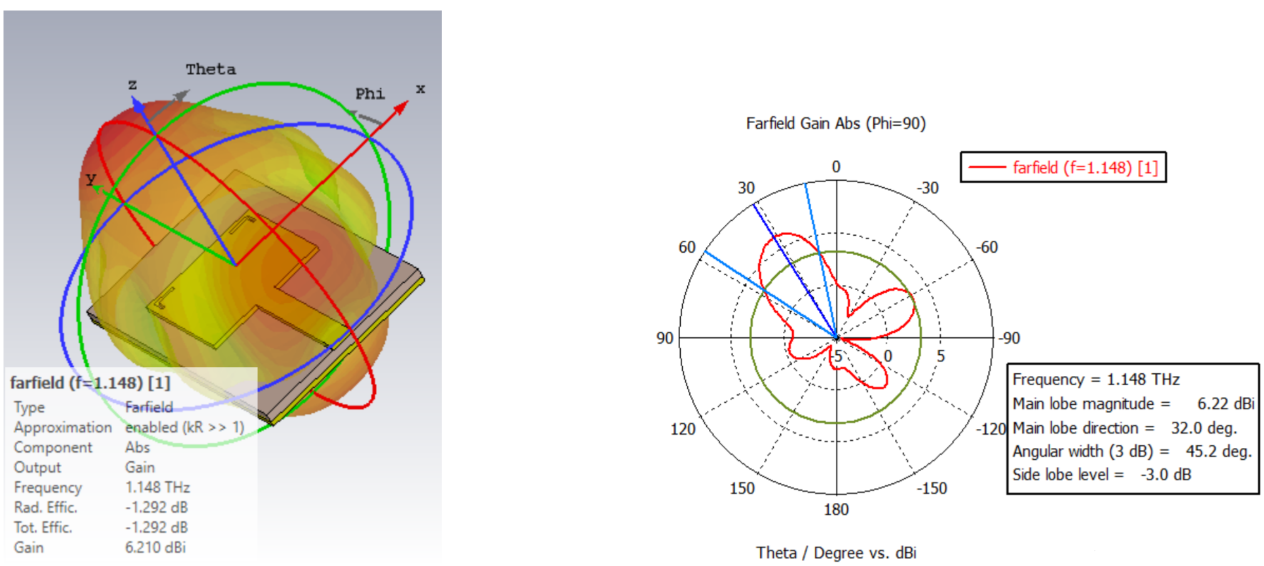
Figure 4.13: Gain of rectangular gold antenna.

As shown in Figure 4.13 The proposed antenna has an excellent gain of 5.32 dBi, 6.21 dBi, and 4.851 dBi at THz at frequencies obtained respectively.



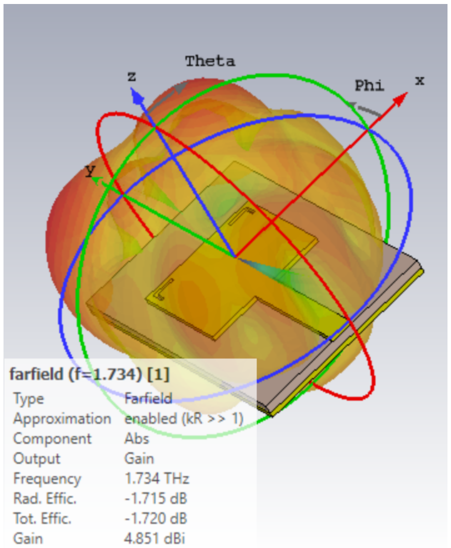
(a) (b)

Figure 4.14: (a)3D radiation pattern of rectangular gold antenna in frequency 0.74 THz ; (b) Polar radiation pattern of rectangular gold antenna in frequency 0.74 THz.

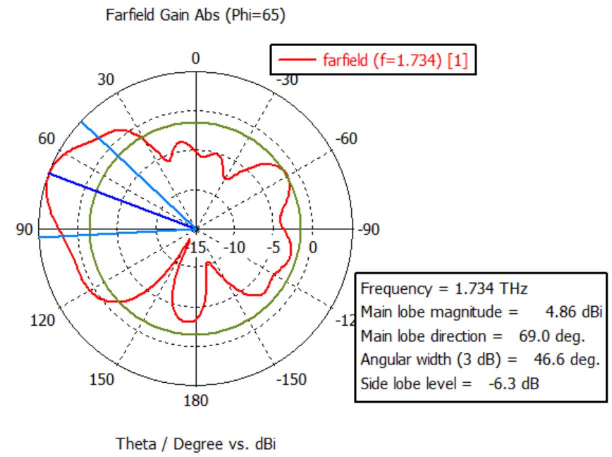


(a) (b)

Figure 4.15: (a)3D radiation pattern of rectangular gold antenna in frequency 1.148 THz ; (b) Polar radiation pattern of rectangular gold antenna in frequency 1.148 THz.



(a)

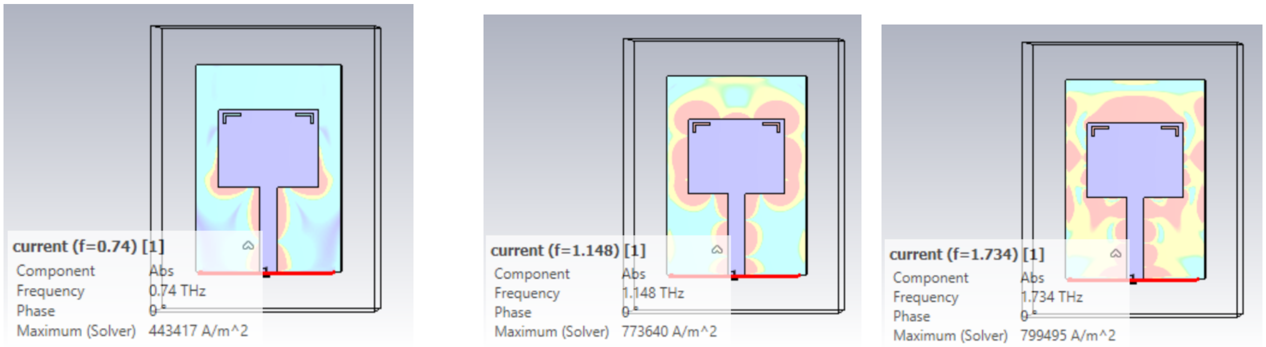


(b)

Figure 4.16: (a)3D radiation pattern of rectangular gold antenna in frequency 1.734 THz ; (b) Polar radiation pattern of rectangular gold antenna in frequency 1.734 THz.

In figures 4.14, 4.15, 4.16, the angular widths at 0.74 THz, 1.14 THz and 1.73 THz are 59 deg, 45.2 deg and 46.6 deg respectively and the radiation pattern from the back lobes is low compared to the front lobe. The antenna is directional and is suitable to use for medical imaging applications.

Figure 4.17 represents the current density of our proposed antenna at all deferent frequencies 0.74 THz, 1.148 THz, and 1.734 THz.



(a) (b) (c)

Figure 4.17: Current density of rectangular gold antenna : (a) in frequency 0.74 THz ; (b) in frequency 1.148 THz ; (c) in frequency 1.734 THz.

4.6 Comparison of proposed work with previous literature

In this section, we presented a comparison of the Two nano Gold patch antenna for WBAN application with other references.

The table 4.2 summarizes all the simulation results with the various current WBAN terahertz antenna works. If we compare the rectangular nano antenna with the different references [159] [162] [164] and [165] we will see that our proposed antenna has a wide dimension (some micrometers) but that has an excellent characteristic of return loss, gain and directivity with three frequencies that allow us to use each frequency in a different medical applications.

In order to compare the second circular nano antenna to the references [160] and [161] we will observe that our proposed antenna has a small dimension with excellent radiation characteristics as the gain that exceeds 5 dBi, a reflection coefficient more than -54 dB, and a directivity more than 6 dB. Finally compared to the reference [163] the size of our antenna is a little larger but it has better radiation characteristics.

	Substrate material	Frequency (THz)	Size (μm)	S11(dB)	Gain (dBi)	Directivity (dB)
[159]	RT Duriod 6010(ϵ_r = 10.2)	0.852	200×200×50	–20	2.5	2.6
[160]	RT Duriod 6010(ϵ_r = 10.2)	2.270	100×100×10	–22.39	4.8	3
	Silicon(ϵ_r=11.9)	3.254		–42.67	5.3	3.1
[161]	Glass(ϵ_r=6)	2.150	250×400×5	–15	4.97	Not mentioned
[162]	FR-4(ϵ_r = 4.3)	1.684	150 ×150×9.6	-39	5.72	Not mentioned
[163]	FR-4(ϵ_r = 4.3)	3.734	60×50×0.52666	-52.97	2.13	4
[164]	Polyimide(ϵ_r = 4.3)	0.445–0.714	300×300×45	-26.4	5.4	5.7
[165]	Quartz (ϵ_r = 3.78)	1.02	180×212×10	-28.76	1.44	9.58
proposed rectangular gold antenna	Roger RO4003C (ϵ_r = 3.55)	0.740	288.9×412.06×15	–41.408	5.32	6.659
		1.148		–43.918	6.21	7.502
		1.734		–29.92	4.851	6.566
proposed circular gold antenna	Silicon(ϵ_r=11.9)	3.930	63.72 ×83.47×5.4	-54.96	5.4	7.574
	Duroid 3210(ϵ_r=10.8)	4.010	81.95×110.85×5.4	-63.1	5.06	6.637
	Alumina (ϵ_r=9.9)	4.085	65×85×5.4	-41.32	5.25	6.719
	Roger 4003C(ϵ_r=3.55)	3.24	81×110×5.4	-48.77	4.346	5.294
	Roger 5880 (ϵ_r=2.2)	2.76	81×110×5.4	-23.317	4.504	7.229

Table 4.2: Comparison of our results with others work researches.

4.7 Conclusion

Nano optical terahertz antennas have been designed in this chapter for medical imaging and spectroscopy, taking account several factors like size, bandwidth, radiation pattern and high-conductivity materials to achieved a good performances.

The combination of high conductive radiating element and thin laminate substrates improve significantly radiation characteristics performances of the terahertz optical antennas.

General conclusion

Thesis objective

The objective of this thesis is to propose and design nano optical antennas with small size, high performance and efficient antenna structures for Wireless communication and Medical applications.

Work in progress

The occupation of the microwave spectrum is a significant concern due to the immense potential it holds for various applications. The terahertz spectrum, positioned between microwaves and infrared, offers a wide array of applications. The ability to operate within the terahertz frequency range provides distinct advantages, including high bandwidth, high resolution, deep imaging capability, low power consumption, compact size, and safety in terms of health impact. The primary objective of this thesis was to investigate the novel nano optical terahertz antenna technology across different types of applications. Nano-optical antennas in the terahertz band have shown great potential in various fields, including wireless communication, medical imaging, and spectroscopy.

Our contribution is This thesis was the combination of Graphene material with thin substrates for wireless applications and Gold material with thin substrates for medical imaging and spectroscopy applications. One of the key advantages of using graphene-based antennas is their exceptional electrical and optical properties. It exhibits remarkable conductivity, high carrier mobility, and broadband absorption characteristics, making it an ideal candidate for terahertz applications. By integrating graphene into the design of nano-optical antennas, it is possible to enhance their performance in terms of efficiency, bandwidth, and radiation pattern control. Furthermore, the use of thin epesser substrates in conjunction with graphene-based antennas offers additional benefits. Thin epesser substrates are dielectric materials that provide mechanical support and insulation for the antenna structure. By theirs using, the overall size and weight of the antenna can be significantly reduced while maintaining its functionality. This is particularly advantageous for wireless applications where compactness and portability are crucial. The terahertz frequency range offers higher bandwidth and faster data transfer capabilities compared to traditional microwave frequencies. In the context of medical imaging and spectroscopy applications, gold-based nano-optical antennas have demonstrated promising results. Terahertz radiation is non-ionizing and can penetrate biological tissues with minimal harm, making it suitable for medical imaging and diagnostics. the use of thin epesser substrates in gold-based nano-optical antennas provides mechanical stability and compatibility with biological systems. This is particularly relevant for medical applications where the antennas need to be biocompatible and non-toxic. The combination of gold and thin epesser substrates offers a versatile platform for various medical imaging techniques, such as photoacoustic imaging and optical coherence tomography, as well as spectroscopic analysis of biological samples. In conclusion, nano-optical antennas in the terahertz band, including graphene-based antennas with thin epesser substrates for wireless applications and gold-based nano-optical antennas with thin epesser substrates for medical and spectroscopy applications, hold immense potential for advancing technology in multiple domains. The unique properties of graphene and gold nanoparticles, coupled with the advantages of using thin epesser substrates, enable the development of high-performance, compact, and versatile devices. Further research and development in this field are expected to unlock even more opportunities for innovation and practical applications.

Prospects and future work

1- Research in The future of wireless communication could lead to the development of terahertz-based wireless networks capable of handling the growing demand for data-intensive applications, such as augmented reality, virtual reality, and the Internet of Things (IoT).

2- The outlook is one of improved access to healthcare and enhanced patient monitoring, especially in underserved or remote areas.

3- The miniaturization of terahertz antennas and their integration into various devices and systems is an exciting prospect. As these antennas become smaller and more energy-efficient, they can be seamlessly incorporated into smartphones, wearable devices, and even autonomous vehicles. This integration outlook promises improved capabilities for sensing, communication, and navigation.

4-The future of nano-optical antennas in the terahertz band will likely involve increased collaboration between researchers from different fields. Engineers, physicists, chemists, and medical professionals may work together to explore new applications and possibilities. This interdisciplinary outlook underscores the importance of diverse perspectives in driving innovation.

5- Advancements in fabrication technologies continue to play a critical role in improving the efficiency and performance of these antennas for various applications, So We try to manufacture our proposed antennas with precision and collaboration across multiple disciplines, including materials science, nanotechnology, and electromagnetic engineering, to achieve successful results.

Bibliography

[1] Jeremy Blond. *Détecteur térahertz hautes performances pour l'imagerie passive.* PhD thesis, Université Grenoble Alpes [2020-....], 2021.

[2] Kévin Froberger. *Caractérisation et modélisation de composants terahertz.* PhD thesis, Université de Lille, 2019.

[3] Ian F Akyildiz, Josep Miquel Jornet, and Chong Han. Terahertz band: Next frontier for wireless communications. *Physical communication*, 12:16–32, 2014.

[4] Abdoalbaset Abohmra. *Terahertz antenna design for future wireless communication.* PhD thesis, University of Glasgow, 2022.

[5] Kossaila Medrar. *antennes intégrées haute directivité aux fréquences millimétriques et térahertz.* PhD thesis, Université Grenoble Alpes, 2020.

[6] Lucie Juery. *Communication térahertz sans fil à haut débit avec un transistor à haute mobilité électronique comme détecteur.* PhD thesis, Université Montpellier II-Sciences et Techniques du Languedoc, 2014.

[7] Idriss Abdoulkader Ibrahim. *Nano-antennes optiques pour l'inspection des structures photoniques.* PhD thesis, Université de Franche-Comté, 2010.

[8] Xi-Cheng Zhang, Jingzhou Xu, et al. *Introduction to THz wave photonics*, volume 29. Springer, 2010.

[9] Louis-Philip Béliveau. *Développement de l'imagerie à un pixel aux fréquences électromagnétiques térahertz (THz) avec l'utilisation d'un modulateur de type microsystème électromécaniques (MEMS)*. PhD thesis, École de technologie supérieure, 2022.

[10] Seishiro Ishii, Syuji Sayama, and Toshihisa Kamei. Measurement of rain attenuation in terahertz wave range. 2011.

[11] Vitaly Petrov, Thomas Kurner, and Iwao Hosako. Ieee 802.15. 3d: First standardization efforts for sub-terahertz band communications toward 6g. *IEEE Communications Magazine*, 58(11):28–33, 2020.

[12] Joonas Kokkoniemi, Janne Lehtomäki, and Markku Juntti. Simple molecular absorption loss model for 200–450 gigahertz frequency band. In *2019 European Conference on Networks and Communications (EuCNC)*, pages 219–223. IEEE, 2019.

[13] Hong Cui, XianBin Zhang, JunFei Su, YueXing Yang, Qiong Fang, and XuYan Wei. Vibration–rotation absorption spectrum of water vapor molecular in frequency selector at 0.5–2.5 thz range. *Optik*, 126(23):3533–3537, 2015.

[14] Chao Li, Ya Zhang, and Kazuhiko Hirakawa. Terahertz detectors using microelectromechanical system resonators. *Sensors*, 23(13):5938, 2023.

[15] Zaka Ullah, Gunawan Witjaksono, Illani Nawi, Nelson Tansu, Muhammad Irfan Khattak, and Muhammad Junaid. A review on the development of tunable graphene nanoantennas for terahertz optoelectronic and plasmonic applications. *Sensors*, 20(5):1401, 2020.

[16] Mario Bareiß. *Nanodiodes and Nanoantennas Fabricated by Transfer Technology*. PhD thesis, Technische Universität München, 2012.

[17] Ekta Sharma, Reena Rathi, Jaya Misharwal, Bhavya Sinhmar, Suman Kumari, Jasvir Dalal, and Anand Kumar. Evolution in lithography techniques: Microlithography to nanolithography. *Nanomaterials*, 12(16):2754, 2022.

[18] Haofan Yi, Danping He, P Takis Mathiopoulos, Bo Ai, Juan Moreno Garcia-Loygorri, Jianwu Dou, and Zhangdui Zhong. Ray tracing meets terahertz: Challenges and opportunities. *IEEE Communications Magazine*, 2022.

[19] Neha Arora, Sindhu Hak Gupta, and Basant Kumar. Analyzing and optimizing cooperative communication for in vivo wban. *Wireless Personal Communications*, 122(1):429–450, 2022.

[20] Sara Bretin. *Communications sans fil aux fréquences terahertz: applications à la vidéo haute définition temps réel*. PhD thesis, Université de Lille, 2019.

[21] Torsten Löffler, T Bauer, KJ Siebert, Hartmut G Roskos, A Fitzgerald, and S Czasch. Terahertz dark-field imaging of biomedical tissue. *Optics express*, 9(12):616–621, 2001.

[22] Annalisa D'Arco, Marta Di Fabrizio, Valerio Dolci, Massimo Petrarca, and Stefano Lupi. Thz pulsed imaging in biomedical applications. *Condensed Matter*, 5(2):25, 2020.

[23] Kodo Kawase, Yuichi Ogawa, Yuuki Watanabe, and Hiroyuki Inoue. Non-destructive terahertz imaging of illicit drugs using spectral fingerprints. *Optics express*, 11(20):2549–2554, 2003.

[24] YC Shen, PF Taday, DA Newnham, and M Pepper. Chemical mapping using reflection terahertz pulsed imaging. *Semiconductor science and technology*, 20(7):S254, 2005.

[25] B Fischer, M Hoffmann, H Helm, G Modjesch, and P Uhd Jepsen. Chemical recognition in terahertz time-domain spectroscopy and imaging. *Semiconductor Science and Technology*, 20(7):S246, 2005.

[26] Hui Feng, Deyue An, Hao Tu, Weihua Bu, Wenjing Wang, Yuehao Zhang, Huakun Zhang, Xiangxin Meng, Wei Wei, Bingxi Gao, et al. A passive video-rate terahertz human body imager with real-time calibration for security applications. *Applied Physics B*, 126(8):143, 2020.

[27] Alexei Semenov, Heiko Richter, Ute Böttger, and Heinz-Wilhelm Hübers. Imaging terahertz radar for security applications. volume 6949, pages 7–17. SPIE, 2008.

[28] Erik Öjefors, Neda Baktash, Yan Zhao, Richard Al Hadi, Hani Sherry, and Ullrich R Pfeiffer. Terahertz imaging detectors in a 65-nm cmos soi technology. In *2010 Proceedings of ESSCIRC*, pages 486–489. IEEE, 2010.

[29] Albert Redo-Sanchez, Barmak Heshmat, Alireza Aghasi, Salman Naqvi, Mingjie Zhang, Justin Romberg, and Ramesh Raskar. Terahertz time-gated spectral imaging for content extraction through layered structures. *Nature communications*, 7(1):12665, 2016.

[30] C Seco-Martorell, Víctor López-Domínguez, Gianluca Arauz-Garofalo, A Redo-Sanchez, J Palacios, and J Tejada. Goya's artwork imaging with terahertz waves. *Optics express*, 21(15):17800–17805, 2013.

[31] R. U. Sm and S. M. Gestion. *Orientations technologiques des services actifs dans la gamme de fréquences 275-3000 GHz*. PhD thesis, 2015.

[32] Hadeel Elayan, Osama Amin, Raed M Shubair, and Mohamed-Slim Alouini. Terahertz communication: The opportunities of wireless technology beyond 5g. In *2018 International Conference on Advanced Communication Technologies and Networking (CommNet)*, pages 1–5. IEEE, 2018.

[33] Ian F Akyildiz, Josep Miquel Jornet, and Chong Han. Terahertz band: Next frontier for wireless communications. *Physical communication*, 12:16–32, 2014.

[34] Yongzhi Wu and Chong Han. Interference and coverage analysis for indoor terahertz wireless local area networks. In *2019 IEEE Globecom Workshops (GC Wkshps)*, pages 1–6. IEEE, 2019.

[35] Ian F Akyildiz, Josep Miquel Jornet, and Chong Han. Terahertz band: Next frontier for wireless communications. *Physical communication*, 12:16–32, 2014.

[36] Qingling Liu, Shahid Sarfraz, and Shubin Wang. An overview of key technologies and challenges of 6g. In *Machine Learning for Cyber Security: Third International Conference, ML4CS 2020, Guangzhou, China, October 8–10, 2020, Proceedings, Part II 3*, pages 315–326. Springer, 2020.

[37] Changhwan Yi, Dongkyo Kim, Sourabh Solanki, Jae-Hong Kwon, Moonil Kim, Sanggeun Jeon, Young-Chai Ko, and Inkyu Lee. Thz wireless systems design for personal area networks applications. In *2020 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 529–531. IEEE, 2020.

[38] Syed Agha Hassnain Mohsan, Muhammad Asghar Khan, and Hussain Amjad. Hybrid fso/rf networks: A review of practical constraints, applications and challenges. *Optical Switching and Networking*, 47:100697, 2023.

[39] Michele Gallo, Luciano Mescia, Onofrio Losito, Michele Bozzetti, and Francesco Prudenzano. Design of optical antenna for solar energy collection. *Energy*, 39(1):27–32, 2012.

[40] NA Eltresy, HA Malhat, SH Zainud-Deen, and KH Awadalla. Dual-polarized nanoantenna solar energy collector. In *2016 33rd National Radio Science Conference (NRSC)*, pages 390–397. IEEE, 2016.

[41] Salah Obayya, Nihal Fayez Fahmy Areed, Mohamed Farhat O Hameed, and Mohamed Hussein Abdelrazik. Optical nano-antennas for energy harvesting. In *Innovative Materials and Systems for Energy Harvesting Applications*, pages 26–62. IGI Global, 2015.

[42] Dale K Kotter, Steven D Novack, WD Slafer, and PJ Pinhero. Theory and manufacturing processes of solar nanoantenna electromagnetic collectors. 2010.

[43] Hedi Ragad. *Etude et conception de nouvelles topologies d'antennes à résonateur diélectrique dans les bandes UHF et SHF*. PhD thesis, UNIVERSITE DE NANTES; UNIVERSITE DE TUNIS EL MANAR, Tunisie, 2013.

[44] Mickaël Jeangeorges. *Conception d'antennes miniatures intégrées pour solutions RF SiP*. PhD thesis, Université Nice Sophia Antipolis, 2010.

[45] BENDAHMANE Zhor. Contribution à la conception,optimisation et réalisation d'antennes miniatures reconfigurables. 2022.

[46] Constantine A Balanis. *Antenna theory: analysis and design*. John wiley & sons, 2016.

[47] Constantine A Balanis. *Modern antenna handbook*. John Wiley & Sons, 2011.

[48] Pavel Shumyatsky and Robert R Alfano. Terahertz sources. *Journal of biomedical optics*, 16(3):033001–033001, 2011.

[49] Lukas Novotny. From near-field optics to optical antennas. *Phys. Today*, 64(7):47–52, 2011.

[50] Nathan M Burford and Magda O El-Shenawee. Review of terahertz photoconductive antenna technology. *Optical Engineering*, 56(1):010901–010901, 2017.

[51] Nathan M Burford and Magda O El-Shenawee. Review of terahertz photoconductive antenna technology. *Optical Engineering*, 56(1):010901–010901, 2017.

[52] Thomas Kleine-Ostmann and Tadao Nagatsuma. A review on terahertz communications research. *Journal of Infrared, Millimeter, and Terahertz Waves*, 32:143–171, 2011.

[53] IEEE. Ieee standard for high data rate wireless multi-media networks—amendment 2: 100 gb/s wireless switched point-to-point physical layer, 2017.

[54] Vitaly Petrov, Alexander Pyattaev, Dmitri Moltchanov, and Yevgeni Koucheryavy. Terahertz band communications: Applications, research challenges, and standardization activities. In *2016 8th international congress on ultra modern telecommunications and control systems and workshops (ICUMT)*, pages 183–190. IEEE, 2016.

[55] Yejun He, Yaling Chen, Long Zhang, Sai-Wai Wong, and Zhi Ning Chen. An overview of terahertz antennas. *China Communications*, 17(7):124–165, 2020.

[56] T Nagatsuma, A Hirata, Y Sato, R Yamaguchi, H Takahashi, T Kosugi, M Tokumitsu, H Sugahara, T Furuta, and H Ito. Sub-terahertz wireless communications technologies. In *2005 18th International Conference on Applied Electromagnetics and Communications*, pages 1–4. IEEE, 2005.

[57] H-J Song, K Ajito, Y Muramoto, A Wakatsuki, T Nagatsuma, and N Kukutsu. 24 gbit/s data transmission in 300 ghz band for future terahertz communications. *Electronics Letters*, 48(15):953–954, 2012.

[58] Mohammadreza Omidali, Ali Mardanshahi, Mariella Särestöniemi, Zuomin Zhao, and Teemu Myllylä. Acousto- optics: Recent studies and medical applications. *Biosensors*, 13(2):186, 2023.

[59] Seung Hoon Woo, Phil-Sang Chung, and Sang Joon Lee. Safe use of medical lasers. *Medical Lasers; Engineering, Basic Research, and Clinical Application*, 10(2):68–75, 2021.

[60] Isha Malhotra, Kumud Ranjan Jha, and Ghanshyam Singh. Terahertz antenna technology for imaging applications: A technical review. *International Journal of Microwave and Wireless Technologies*, 10(3):271–290, 2018.

[61] Shuting Fan, Yuezhi He, Benjamin S Ung, and Emma Pickwell-MacPherson. The growth of biomedical terahertz research. *Journal of Physics D: Applied Physics*, 47(37):374009, 2014.

[62] Alfonsina Ramundo Orlando and Gian Piero Gallerano. Terahertz radiation effects and biological applications. *Journal of Infrared, Millimeter, and Terahertz Waves*, 30:1308–1318, 2009.

[63] Qiushuo Sun, Yuezhi He, Kai Liu, Shuting Fan, Edward PJ Parrott, and Emma Pickwell-MacPherson. Recent advances in terahertz technology for biomedical applications. *Quantitative imaging in medicine and surgery*, 7(3):345, 2017.

[64] Penny J Smalley. Laser safety: Risks, hazards, and control measures. *Laser therapy*, 20(2):95–106, 2011.

[65] Rocco D'Antuono and John W Bowen. Towards super-resolved terahertz microscopy for cellular imaging. *Journal of Microscopy*, 288(3):207–217, 2022.

[66] Andrea Ottomaniello, Paolo Vezio, Omar Tricinci, Frank M Den Hoed, Paul Dean, Alessandro Tredicucci, and Virgilio Mattoli. Highly conformable terahertz metasurface absorbers via two-photon polymerization on polymeric ultra-thin films. *Nanophotonics*, 12(8):1557–1570, 2023.

[67] Qun Wu, Yue Wang, Shao-qing Zhang, and Lei-lei Zhuang. Terahertz generation in the carbon nanotube antenna. In *2008 Asia-Pacific Microwave Conference*, pages 1–4. IEEE, 2008.

[68] Catur Apriono and Eko Tjipto Rahardjo. Radiation characteristics of a planar strip dipole antenna and a slot dipole antenna for thz applications. *Makara Journal of Technology*, 17(3):138–144, 2013.

[69] Truong Khang Nguyen and Ikmo Park. Effects of antenna design parameters on the characteristics of a terahertz coplanar stripline dipole antenna. *Progress in Electromagnetics Research M*, 28:129–143, 2013.

[70] Amandeep Singh and Surinder Singh. A trapezoidal microstrip patch antenna on photonic crystal substrate for high speed thz applications. *Photonics and Nanostructures-Fundamentals and applications*, 14:52–62, 2015.

[71] Rajni Bala and Anupma Marwaha. Investigation of graphene based miniaturized terahertz antenna for novel substrate materials. *Engineering Science and Technology, an International Journal*, 19(1):531–537, 2016.

[72] Rajni Bala and Anupma Marwaha. Development of computational model for tunable characteristics of graphene based triangular patch antenna in thz regime. *Journal of Computational Electronics*, 15:222–227, 2016.

[73] Mojtaba Dashti and J David Carey. Graphene microstrip patch ultrawide band antennas for thz communications. *Advanced Functional Materials*, 28(11):1705925, 2018.

[74] Mohammad Faridani and Mehdi Khatir. Wideband hemispherical dielectric lens antenna with stabile radiation pattern for advanced wideband terahertz communications. *Optik*, 168:355–359, 2018.

[75] Khatereh Moradi, Ali Pourziad, and Saeid Nikmehr. A frequency reconfigurable microstrip antenna based on graphene in terahertz regime. *Optik*, 228:166201, 2021.

[76] Vishal Das and Sanyog Rawat. Modified rectangular planar antenna with stubs and defected ground structure for thz applications. *Optik*, 242:167292, 2021.

[77] Mohammad Mashayekhi, Pooria Kabiri, Amir Saman Nooramin, and Mohammad Soleimani. A reconfigurable graphene patch antenna inverse design at terahertz frequencies. *Scientific Reports*, 13(1):8369, 2023.

[78] Rocco D'Antuono and John W Bowen. Towards super-resolved terahertz microscopy for cellular imaging. *Journal of Microscopy*, 288(3):207–217, 2022.

[79] Josélyne Nshimirimana. Caractéristiques d'antennes térahertz photoconductrices de type micro-ruban coplanaire. *Diss. Université de Sherbrooke*, 2016.

[80] Kaushik Sengupta, Tadao Nagatsuma, and Daniel M Mittleman. Terahertz integrated electronic and hybrid electronic–photonic systems. *Nature Electronics*, 1(12):622–635, 2018.

[81] M Mahdi Assefzadeh and Aydin Babakhani. Broadband oscillator-free thz pulse generation and radiation based on direct digital-to-impulse architecture. *IEEE Journal of Solid-State Circuits*, 52(11):2905–2919, 2017.

[82] M Rashid Karim, Xiaodong Yang, and Muhammad Farhan Shafique. On chip antenna measurement: A survey of challenges and recent trends. *IEEE Access*, 6:20320–20333, 2018.

[83] Shu-Yan Zhu, Yuan-Long Li, Kwai-Man Luk, and Stella W Pang. Compact high-gain si-imprinted thz antenna for ultrahigh speed wireless communications. *IEEE Transactions on Antennas and Propagation*, 68(8):5945–5954, 2020.

[84] Milda Tamosiunaite, Stasys Tamosiunas, Mindaugas Zilinskas, and Gintaras Valusis. Atmospheric attenuation of the terahertz wireless networks. *Broadband Communications Networks-Recent Advances and Lessons from Practice*, pages 143–156, 2017.

[85] David M Slocum, Thomas M Goyette, Elizabeth J Slingerland, Robert H Giles, and William E Nixon. Terahertz atmospheric attenuation and continuum effects. In *Terahertz Physics, Devices, and Systems VII: Advanced Applications in Industry and Defense*, volume 8716, pages 24–37. SPIE, 2013.

[86] Mingming Pan. *Terahertz wave-guided reflectometry system*. PhD thesis, Université de Bordeaux, 2020.

[87] Hamed Abdolmaleki, Preben Kidmose, and Shweta Agarwala. Droplet-based techniques for printing of functional inks for flexible physical sensors. *Advanced Materials*, 33(20):2006792, 2021.

[88] Robert E Miles, X-C Zhang, Heribert Eisele, and Arunas Krotkus. *Terahertz frequency detection and identification of materials and objects*. Springer Science & Business Media, 2007.

[89] Mehdi Hasan, Sara Arezoomandan, Hugo Condori, and Berardi Sensale-Rodriguez. Graphene terahertz devices for communications applications. *Nano Communication Networks*, 10:68–78, 2016.

[90] Kirill I Bolotin, KJ Sikes, Zhifang Jiang, M Klima, G Fudenberg, James Hone, Phaly Kim, and Horst L Stormer. Ultrahigh electron mobility in suspended graphene. *Solid state communications*, 146(9-10):351–355, 2008.

[91] Heinz Faether. Surface plasmons. *Smooth and Rough Sur [aces and on Gratings (Springer Tracts in Modem Physics*, 111:642–646, 1988.

[92] Svetlana V Boriskina, Thomas Alan Cooper, Lingping Zeng, George Ni, Jonathan K Tong, Yoichiro Tsurimaki, Yi Huang, Laureen Meroueh, Gerald Mahan, and Gang Chen. Losses in plasmonics: from mitigating energy dissipation to embracing loss-enabled functionalities. *Advances in Optics and Photonics*, 9(4):775–827, 2017.

[93] Chao Xu, Yichang Jin, Longzhi Yang, Jianyi Yang, and Xiaoqing Jiang. Characteristics of electro-refractive modulating based on graphene-oxide-silicon waveguide. *Optics express*, 20(20):22398–22405, 2012.

[94] Nima Chamanara, Dimitrios Sounas, and Christophe Caloz. Non-reciprocal magneto-plasmon graphene coupler. *Optics express*, 21(9):11248–11256, 2013.

[95] G Jemima Nissiyah and M Ganesh Madhan. Graphene based microstrip antenna for triple and quad band operation at terahertz frequencies. *Optik*, 231:166360, 2021.

[96] Jung-Chul Thomas Eun. *Handbook of engineering practice of materials and corrosion*. Springer Nature, 2020.

[97] Laura Fabris. Gold nanostars in biology and medicine: understanding physico-chemical properties to broaden applicability. *The Journal of Physical Chemistry C*, 124(49):26540–26553, 2020.

[98] Gururaj V Naik, Vladimir M Shalaev, and Alexandra Boltasseva. Alternative plasmonic materials: beyond gold and silver. *Advanced Materials*, 25(24):3264–3294, 2013.

[99] Aleksandr S Baburin, Alexander M Merzlikin, Alexander V Baryshev, Ilya A Ryzhikov, Yuri V Panfilov, and Ilya A Rodionov. Silver-based plasmonics: golden material platform and application challenges. *Optical Materials Express*, 9(2):611–642, 2019.

[100] VG Kravets, R Jalil, Y-J Kim, D Ansell, DE Aznakayeva, B Thackray, L Britnell, BD Belle, F Withers, IP Radko, et al. Graphene-protected copper and silver plasmonics. *Scientific reports*, 4(1):5517, 2014.

[101] Rajour Tanyi Ako, Aditi Upadhyay, Withawat Withayachumnankul, Madhu Bhaskaran, and Sharath Sriram. Dielectrics for terahertz metasurfaces: Material selection and fabrication techniques. *Advanced Optical Materials*, 8(3):1900750, 2020.

[102] MJ Fice, E Rouvalis, L Ponnampalam, CC Renaud, and AJ Seeds. Telecommunications technology-based terahertz sources. *Electronics Letters*, 46(26):28–31, 2010.

[103] John Wessel. Surface-enhanced optical microscopy. *JOSA B*, 2(9):1538–1541, 1985.

[104] Palash Bharadwaj, Bradley Deutsch, and Lukas Novotny. Optical antennas. *Advances in Optics and Photonics*, 1(3):438–483, 2009.

[105] Jin Z Zhang and Cecilia Noguez. Plasmonic optical properties and applications of metal nanostructures. *Plasmonics*, 3:127–150, 2008.

[106] Kalindi S Shinde, Shweta N Shah, and Piyush N Patel. A review on opportunities and challenges of nano antenna for terahertz communications. In *2019 5th International Conference On Computing, Communication, Control And Automation (ICCUBEA)*, pages 1–6. IEEE, 2019.

[107] Gabriel M Rebeiz. Millimeter-wave and terahertz integrated circuit antennas. *Proceedings of the IEEE*, 80(11):1748–1770, 1992.

[108] Rui Xu, Steven Gao, Benito Sanz Izquierdo, Chao Gu, Patrick Reynaert, Alexander Standaert, Gregory J Gibbons, Wolfgang Bösch, Michael Ernst Gadringer, and Dong Li. A review of broadband low-cost and high-gain low-terahertz antennas for wireless communications applications. *Ieee Access*, 8:57615–57629, 2020.

[109] Alexandre Beck, Tahsin Akalin, Guillaume Ducournau, Emilien Peytavit, and Jean-François Lampin. Terahertz photomixers based on ultra-wideband horn antennas. *Comptes Rendus Physique*, 11(7-8):472–479, 2010.

[110] Mohamed H Mubarak, Othman Sidek, Mohamed R Abdel-Rahman, Mohd Tafir Mustaffa, Ahmad Shukri Mustapa Kamal, and Saad M Mukras. Nano-antenna coupled infrared detector design. *Sensors*, 18(11):3714, 2018.

[111] Kyungho Han, Truong Khang Nguyen, Ikmo Park, and Haewook Han. Terahertz yagi-uda antenna for high input resistance. *Journal of Infrared, Millimeter, and Terahertz Waves*, 31:441–454, 2010.

[112] Nikolai Berkovitch, Pavel Ginzburg, and Michel Orenstein. Nano-plasmonic antennas in the near infrared regime. *Journal of Physics: Condensed Matter*, 24(7):073202, 2012.

[113] Truong Khang Nguyen, Won Tae Kim, Bong Joo Kang, Hyeon Sang Bark, Kangho Kim, Jaejin Lee, Ikmo Park, Tae-In Jeon, and Fabian Rotermund. Photoconductive dipole antennas for efficient terahertz receiver. *Optics Communications*, 383:50–56, 2017.

[114] K. Ranjan Jha I. Malhotra and G. Singh. Analysis of highly directive photoconductive dipole antenna at terahertz frequency for sensing and imaging applications. *Optics Communications*, 397:129–139, 2017.

[115] Yi Shi, Xiaodong Zhang, Qinxi Qiu, Yinrui Gao, and Zhiming Huang. Design of terahertz detection antenna with fractal butterfly structure. *IEEE Access*, 9:113823–113831, 2021.

[116] Jitao Zhang, Mingguang Tuo, Min Liang, Wei-Ren Ng, Michael E Gehm, Hao Xin, et al. Terahertz radiation of a butterfly-shaped photoconductive antenna. , 48(4):402001–0402001, 2019.

[117] Palash Bharadwaj, Bradley Deutsch, and Lukas Novotny. Optical antennas. *Advances in Optics and Photonics*, 1(3):438–483, 2009.

[118] Wendao Xu, Lijuan Xie, Jianfei Zhu, Xia Xu, Zunzhong Ye, Chen Wang, Yungui Ma, and Yibin Ying. Gold nanoparticle-based terahertz metamaterial sensors: mechanisms and applications. *Acs Photonics*, 3(12):2308–2314, 2016.

[119] Sasan V Grayli, Saeid Kamal, and Gary Leach. High-performance, single-crystal gold bowtie nano-antennas via epitaxial electroless deposition. 2021.

[120] Sanjay Kumar, S Tanwar, and SK Sharma. Nanoantenna–a review on present and future perspective. *Int. J. Sci. Eng. Technol*, 4(1):240–7, 2016.

[121] Holger F Hofmann, Terukazu Kosako, and Yutaka Kadoya. Design parameters for a nano-optical yagi–uda antenna. *New journal of physics*, 9(7):217, 2007.

[122] Mohammad Alibakhshikenari, Bal S Virdee, Shahram Salekzamankhani, Sonia Aïssa, Chan H See, Navneet Soin, Sam J Fishlock, Ayman A Althuwayb, Raed Abd-Alhameed, Isabelle Huynen, et al. High-isolation antenna array using siw and realized with a graphene layer for sub-terahertz wireless applications. *Scientific Reports*, 11(1):1–14, 2021.

[123] Andrew D Squires, Xiang Gao, Jia Du, Zhaojun Han, Dong Han Seo, James S Cooper, Adrian T Murdock, Simon KH Lam, Ting Zhang, and Tim van der Laan. Electrically tuneable terahertz metasurface enabled by a graphene/gold bilayer structure. *Communications Materials*, 3(1):56, 2022.

[124] Yong Ju Yun, Chil Seong Ah, Won G Hong, Hae Jin Kim, Jong-Ho Shin, and Yongseok Jun. Highly conductive and environmentally stable gold/graphene yarns for flexible and wearable electronics. *Nanoscale*, 9(32):11439–11445, 2017.

[125] Philippe Tassin, Thomas Koschny, Maria Kafesaki, and Costas M Soukoulis. A comparison of graphene, superconductors and metals as conductors for metamaterials and plasmonics. *Nature Photonics*, 6(4):259–264, 2012.

[126] Nana Zhang, Haixia Qiu, Yu Liu, Wei Wang, Yi Li, Xiaodong Wang, and Jianping Gao. Fabrication of gold nanoparticle/graphene oxide nanocomposites and their excellent catalytic performance. *Journal of Materials Chemistry*, 21(30):11080–11083, 2011.

[127] Philippe Tassin, Thomas Koschny, Maria Kafesaki, and Costas M Soukoulis. A comparison of graphene, superconductors and metals as conductors for metamaterials and plasmonics. *Nature Photonics*, 6(4):259–264, 2012.

[128] Ravi S Sundaram, Mathias Steiner, Hsin-Ying Chiu, Michael Engel, Ageeth A Bol, Ralph Krupke, Marko Burghard, Klaus Kern, and Phaedon Avouris. The graphene–gold interface and its implications for nanoelectronics. *Nano letters*, 11(9):3833–3837, 2011.

[129] Wencai Ren and Hui-Ming Cheng. The global growth of graphene. *Nature nanotechnology*, 9(10):726–730, 2014.

[130] Mojtaba Dashti and J David Carey. Graphene microstrip patch ultrawide band antennas for thz communications. *Advanced Functional Materials*, 28(11):1705925, 2018.

[131] Md Abdul Kaium Khan, Towqir Ahmed Shaem, and Mohammad Abdul Alim. Graphene patch antennas with different substrate shapes and materials. *Optik*, 202:163700, 2020.

[132] Ignacio Llatser, Christian Kremers, Albert Cabellos-Aparicio, Josep Miquel Jornet, Eduard Alarcón, and Dmitry N Chigrin. Graphene-based nano-patch antenna for terahertz radiation. *Photonics and Nanostructures-Fundamentals and Applications*, 10(4):353–358, 2012.

[133] Md Abdul Kaium Khan, Md Ibrahim Ullah, and Mohammad Abdul Alim. High-gain and ultrawide-band graphene patch antenna with photonic crystal covering 96.48% of the terahertz band. *Optik*, 227:166056, 2021.

[134] Md Abdul Kaium Khan, Md Ibrahim Ullah, Rifat Kabir, and Mohammad Abdul Alim. High-performance graphene patch antenna with superstrate cover for terahertz band application. *Plasmonics*, 15:1719–1727, 2020.

[135] Abdoalbaset Abohmra, Fizzah Jilani, Hasan Abbas, Muhammad Ali Imran, and Qammer H Abbasi. Terahertz antenna based on graphene for wearable applications. In *2019 IEEE MTT-S International Wireless Symposium (IWS)*, pages 1–3. IEEE, 2019.

[136] Selvakumar George and Nandalal Vijayakumar. Investigations of substrate and patch materials for sub-terahertz wireless applications scenario. *Journal of Electronic Materials*, 51(9):5065–5073, 2022.

[137] Reefat Inum, Md Masud Rana, and Kamrun Nahar Shushama. Performance analysis of graphene based nano dipole antenna on stacked substrate. In *2016 2nd International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE)*, pages 1–4. IEEE, 2016.

[138] Diego Correas-Serrano and J Sebastian Gomez-Diaz. Graphene-based antennas for terahertz systems: A review. *arXiv preprint arXiv:1704.00371*, 2017.

[139] R Kiruthika and T Shanmuganantham. Comparison of different shapes in microstrip patch antenna for x-band applications. In *2016 International Conference on Emerging Technological Trends (ICETT)*, pages 1–6. IEEE, 2016.

[140] M Shalini et al. A compact antenna structure for circular polarized terahertz radiation. *Optik*, 231:166393, 2021.

[141] Richa Gupta, Gaurav Varshney, and RS Yaduvanshi. Tunable terahertz circularly polarized dielectric resonator antenna. *Optik*, 239:166800, 2021.

[142] Hossein Davoudabadifarahani and Behbod Ghalamkari. High efficiency miniaturized microstrip patch antenna for wideband terahertz communications applications. *Optik*, 194:163118, 2019.

[143] Gaurav Varshney, Sunandita Debnath, and Ajay Kumar Sharma. Tunable circularly polarized graphene antenna for thz applications. *Optik*, 223:165412, 2020.

[144] Nasrin Shoghi Badr and Gholamreza Moradi. Graphene-based microstrip-fed hexagonal shape dual band antenna. *Optik*, 202:163608, 2020.

[145] Sasmita Dash and Amalendu Patnaik. Impact of silicon-based substrates on graphene thz antenna. *Physica E: Low-dimensional Systems and Nanostructures*, 126:114479, 2021.

[146] Jayendra Kumar, Banani Basu, Fazal Ahmed Talukdar, and Arnab Nandi. Multimode-inspired low cross-polarization multiband antenna fabricated using graphene-based conductive ink. *IEEE Antennas and Wireless Propagation Letters*, 17(10):1861–1865, 2018.

[147] Mitra Akbari, M Waqas A Khan, Masoumeh Hasani, Toni Björninen, Lauri Sydänheimo, and Leena Ukkonen. Fabrication and characterization of graphene antenna for low-cost and environmentally friendly rfid tags. *IEEE Antennas and Wireless Propagation Letters*, 15:1569–1572, 2015.

[148] Taznoon Khajawal, Qudsia Rubani, Asmita Rajawat, and Sindhu Hak Gupta. Performance analysis and optimization of band gap of terahertz antenna for wban applications. *Optik*, 243:167387, 2021.

[149] Md Mohiuddin Soliman, Muhammad EH Chowdhury, Amith Khandakar, Mohammad Tariqul Islam, Yazan Qiblawey, Farayi Musharavati, and Erfan Zal Nezhad. Review on medical implantable antenna technology and imminent research challenges. *Sensors*, 21(9):3163, 2021.

[150] Baneen Alarkaees and Muhammad Ilyas. Design of antennas with small dimensions for medical implant applications in the millimeter-range. *Journal of Positive School Psychology*, pages 5380–5387, 2022.

[151] DMG Preethichandra, Lasitha Piyathilaka, Umer Izhar, Rohan Samarasinghe, and Liyanage C De Silva. Wireless body area networks and their applications–a review. *IEEE Access*, 2023.

[152] Suling Shen, Xudong Liu, Yaochun Shen, Junle Qu, Emma Pickwell-MacPherson, Xunbin Wei, and Yiwen Sun. Recent advances in the development of materials for terahertz metamaterial sensing. *Advanced Optical Materials*, 10(1):2101008, 2022.

[153] Md Sohel Rana and Md Mostafizur Rahman. Design and performance evaluation of a hash-shape slotted microstrip antenna for future high-speed 5g wireless communication technology. In *2022 6th International Conference on Trends in Electronics and Informatics (ICOEI)*, pages 668–671. IEEE, 2022.

[154] Edward Philip John Parrott, Yiwen Sun, and Emma Pickwell-MacPherson. Terahertz spectroscopy: Its future role in medical diagnoses. *Journal of Molecular Structure*, 1006(1-3):66–76, 2011.

[155] Milad Mirzaee, Amir Mirbeik-Sabzevari, and Negar Tavassolian. 15–40 ghz and 40–110 ghz double-ridge open-ended waveguide antennas for ultra-wideband medical imaging applications. *IEEE Open Journal of Antennas and Propagation*, 2:599–612, 2021.

[156] Debabrata Samanta, MP Karthikeyan, Daksh Agarwal, Arindam Biswas, Aritra Acharyya, and Amit Banerjee. Trends in terahertz biomedical applications. *Generation, Detection and Processing of Terahertz Signals*, pages 285–299, 2022.

[157] Houda Werfelli, Khaoula Tayari, Mondher Chaoui, Mongi Lahiani, and Hamadi Ghariani. Design of rectangular microstrip patch antenna. In *2016 2nd International Conference on Advanced Technologies for Signal and Image Processing (ATSIP)*, pages 798–803. IEEE, 2016.

[158] Mohamed Karim Azizi, Mohamed Amin Ksiksi, Hosni Ajlani, and Ali Gharsallah. Terahertz graphene-based reconfigurable patch antenna. *Progress In Electromagnetics Research Letters*, 71:69–76, 2017.

[159] Qudsia Rubani, Sindhu Hak Gupta, Shuchismita Pani, and Arun Kumar. Design and analysis of a terahertz antenna for wireless body area networks. *Optik*, 179:684–690, 2019.

[160] Qudsia Rubani, Sindhu Hak Gupta, and Arun Kumar. Design and analysis of circular patch antenna for wban at terahertz frequency. *Optik*, 185:529–536, 2019.

[161] S Anand, D Sriram Kumar, Ren Jang Wu, and Murthy Chavali. Analysis and design of optically transparent antenna on photonic band gap structures. *Optik*, 125(12):2835–2839, 2014.

[162] Hossein Davoudabadifarahani and Behbod Ghalamkari. High efficiency miniaturized microstrip patch antenna for wideband terahertz communications applications. *Optik*, 194:163118, 2019.

[163] Tanvir Hossain, Masud Parvez, Abu Zafar Md Imran, Mohammed Jashim Uddin, Abdul Gafur, and Syed Zahidur Rashid. Terahertz antenna for biomedical application. In *2022 International Conference on Innovations in Science, Engineering and Technology (ICISET)*, pages 42–45. IEEE, 2022.

[164] Ch Murali Krishna, Sudipta Das, Anveshkumar Nella, Soufian Lakrit, and Boddapati Taraka Phani Madhav. A micro-sized rhombus-shaped thz antenna for high-speed short-range wireless communication applications. *Plasmonics*, 16(6):2167–2177, 2021.

[165] Amalraj Taksala Devapriya and Savarimuthu Robinson. Investigation on metamaterial antenna for terahertz applications. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 18:377–389, 2019.