Terahertz Antennas: A Review of Historical Development and Future Design Challenges

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Abstract:
Communication technology has advanced greatly recently. Terahertz (THz) and sub-terahertz (S-THz) communications have grown due to increasing bandwidth, data rates, and spectrum efficiency, creating several prospects for antenna development. This study discusses THz and S-THz antennas. It discusses wireless communication and THz spectrum radiation properties. The report also lists the key benefits of the THz band in communication systems. This study also examines several antenna designs and their performance in THz and S-THz applications. This article provides a brief comparative survey of various shaped antenna designs for THz/S-THz band operations, analyses the key findings of reviewed works, and examines the further developments needed in antenna designs, structures, and performance parameters for introducing, developing, and optimizing antennas for diverse THz/S-THz applications.

Keywords: Fractal Antenna, Terahertz applications, Sub-terahertz applications, Terahertz radiation characteristics.

1. INTRODUCTION

Data traffic also known as the explosion of data traffic has entered a new stage of rapid development [1], as a result of the growing popularity of wireless devices. At this time, a significant number of apps are making the transition one step at a time. from PCs to wireless devices such as mobile phones, which are comfortable to carry and can be operated in real time. However, this situation also leads to a rapid increase in data traffic and a scarcity of bandwidth resources. In the next ten to fifteen years, according to the statistics, the data rate on the market is projected to approach gigabits per second (Gbps) or even terabits per second (Tbps) [2, 3]. In the present day, the data rate for THz communication has reached Gbps, but the data rate for Tbps communication is only in the beginning stages of development [4]. [5] provided an overview of current developments in data rates of up to terabits per second (Gbps) based on the THz band and predicted that terabits per second (Tpbs) might be attained by polarisation multiplexing. The development of a new frequency band [6], which would consist of a THz electromagnetic wave in the "blank area" between microwaves and infrared light, is therefore a workable approach for increasing the data transmission rate. The frequency band of 275 to 450 GHz has been utilised for both fixed and land mobile services during the 2019 ITU World Radiocommunication Conference (WRC-19). Terahertz electromagnetic waves have a wavelength that ranges from 0.03 to 3 millimetres and are typically classified as existing within the frequency region of 0.1–10 THz [7] (1 THz = 1012 Hz). The frequency range of the THz wave, as specified by the IEEE standard, is between 0.3 and 10 THz. As shown in Fig. 1., the THz wave can be placed between the microwave and infrared light spectrums. The THz wave has many positive qualities, including the following:

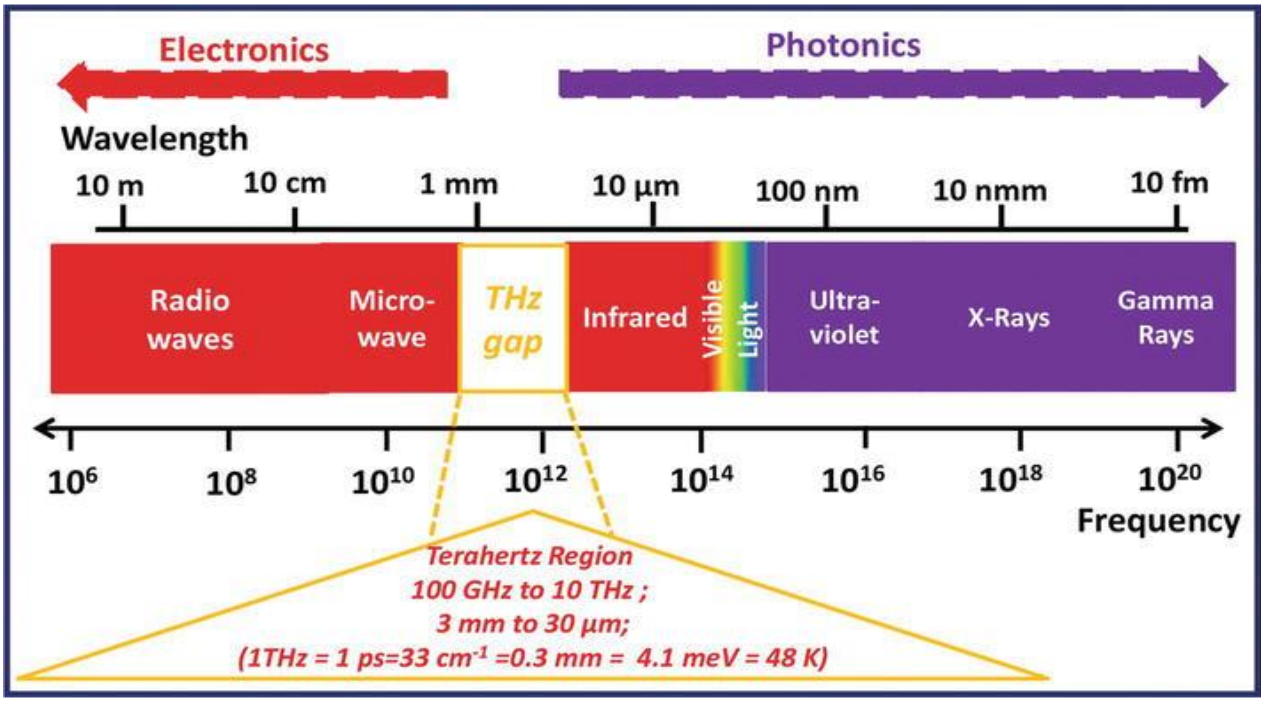

Fig. 1. The position of the THz wave in the electromagnetic spectrum.

- **Low damage:** The amount of energy carried by a single photon in a THz wave is considerably less than that of an X-ray; it is only approximately one part per million. As a result, the use of THz waves in the biomedical area, such as scanning the body for skin cancer, can be of assistance in the treatment of the condition, despite the fact that THz waves do not cause any harm to the organisms [8].

- **High spectral resolution:** The THz band dominates the spectra of the vast majority of big molecules. When it comes to the detection of potentially hazardous items such as viruses, explosives, firearms, chemicals, and so on, conducting an analysis of the spectrum of THz radiation is of utmost importance [9].

- **Visualization:** Due to the fact that THz waves have such short wavelengths, they are able to pass through some non-metallic and non-polar materials. It is possible to scan the THz waves and make them opaque to visible opaque objects, which can result in images with a greater definition [10]. As a consequence of this, the THz wave is utilised in a variety of sensing applications, including the full-body scanners found in airports.

- **Wide bandwidth:** The THz wave is considered to be the electromagnetic wave with the highest frequency band in the field of electronics. Utilising THz waves as the signal carrier for transmission via antennas has the potential to significantly enhance the rate of information transfer, potentially achieving Tbps speeds.

Paper Organization

The first section delineates the extent of varied antennas in terahertz and sub-terahertz applications. Section 2 examines the various antenna configurations utilised in prior research. Section 3 presents a comparative examination of diverse antenna configurations utilised in terahertz and sub-terahertz applications. Section 4 presents the crucial outcomes of the present analysis. Section 5 presents the future scope and challenges in the terahertz antenna domain.

2. LITERATURE SURVEY

This paper [11] presents millimetre-wave and terahertz double bow-tie slot antennas on a synthesized elliptical silicon lens. Two different antennas are designed to cover 0.1–0.3 and 0.2– 0.6 THz, respectively. The double bow-tie slot antenna results in a wide impedance bandwidth and 78–97% Gaussian coupling efficiency over a 3:1 frequency range. A wideband coplanar-waveguide low-pass filter is designed using slow-wave techniques, and the measured filter response shows an S2 1 < −25 dB over a 3:1 frequency range. Absolute gain measurements done at 100–300 GHz and 200– 600 GHz confirm the wideband operation of this design.

[12] The study presented a design for an MPA that relies on graphene and operates at a frequency of 0.72 THz. The overall dimensions of the MPA are 120×120×45μm3. The fabrication process involved the use of a substrate Arlon 1000, which possesses a relative permittivity (ϵr) of 10.2 and a tangent loss (TL) of 0.0023. The antenna was found to operate within the frequency range of 0.53-0.84 THz and exhibited favourable radiation characteristics, an impedance bandwidth of 37.50%, as well as maximum directivity and return loss values of 6.60 dB and 59.87 dB,respectively.

[13] This paper presents the construction of a butterfly antenna utilising independent fractal unit groups, resulting in a simplified manufacturing process and reduced cost. The antenna exhibits a frequency range of 0.1-10 THz and an impedance bandwidth of 85%, with resonance occurring at 4.9 THz. The return loss is measured to be as low as -33.59 dB, and the maximum gain is 16.95 dB. The antenna featuring 3 to 4 fractal unit groups exhibits optimal performance within the frequency range of 6.2-6.4 THz. The fractal butterfly antenna under consideration exhibits a promising potential to enhance the operational efficiency of terahertz detectors, thereby enabling the exploration of detection mechanisms in elevated frequency spectra.

[14] The present study examines the design methodologies employed in the development of a 340 GHz on-chip 3-D antenna. Initially, a substrate integrated waveguide (SIW) cavity backed on-chip antenna with high-gain and high-radiation efficiency is formulated through the utilisation of a conventional 0.13-m SiGeBiCMOS technology. Subsequently, the proposed on-chip antenna is augmented with a low-permittivity supporter and a dielectric resonator (DR) that are vertically aligned, thereby creating a 3-D Yagi-like antenna that serves to amplify the gain and radiation efficiency.

[15] The current study showcases the development, production, and evaluation of a monopole antenna and a patch antenna array with multi-membrane support and polymer-cavity backing. The antennas operate within the 135-GHz frequency range and were characterised through on-wafer testing. The fabrication of the designs was carried out on a two-layer membrane of benzocyclobutene (BCB) material, which was obtained through micromachining of low resistivity silicon. The process involves the extraction of silicon material from beneath the monopole antenna, resulting in the creation of a cavity that is enclosed by metal and subsequently filled with polymer. The utilisation of a polymer-filled cavity in lieu of a traditional air cavity is of significant importance in practical applications, as it provides enhanced support to the membrane. The enhanced dielectric permittivity of the BCB-polymer mixed region, compared to the BCB-air mixed region, allows for the potential development of more condensed antenna array designs. The monopole antenna under consideration exhibits an impedance

bandwidth ranging from 124 to 136 GHz for |S11| values less than -10 dB. At 131 GHz, the antenna achieves a maximum measured gain of 6.74 dBi. On the other hand, the 2×1 patch antenna array demonstrates a measured impedance bandwidth ranging from 126.5 to 138 GHz for |S11| values less than -10 dB. At 130 GHz, the antenna array achieves a maximum measured gain of 8.66 dBi.

[16] The current study showcases the development, production, and analysis of a broad-spectrum cavity-backed aperture-coupled patch antenna and a 16-unit antenna array on multilayer PCB, specifically intended for employment in D-band scenarios. The investigation of line losses at the D-band involves the design and testing of both microstrip line and grounded coplanar waveguide (GCPW) transmission lines. The test structures are produced utilizing printed circuit board technology, which involves the semi-additive processing (mSAP) of conductors on a substrate that is composed of multiple layers. The experimental findings demonstrate that the microstrip line and coplanar waveguide exhibit an insertion loss of 1.9 dB/cm and 1.8 dB/cm, respectively, when measured at a frequency of 150 GHz. At a frequency of 143 GHz, the maximum gains recorded for a single antenna and a 16-element array were 7 dBi and 14 dBi, respectively. The bandwidth of the antenna input matching has been measured to be 20 GHz.

[17]The need for compact high-gain antennas is significant in the realm of high-speed terahertz (THz) wireless systems, particularly for space-limited applications like high-speed interlinking within high-density wireless communication base stations. The present study introduces a folded reflect array (FRA) antenna operating at a frequency of 400 GHz, which exhibits notable characteristics such as high gain, high aperture efficiency, and a compact profile.

[18] The present study showcases the implementation of a multi-beam lens antenna operating in the D-band frequency range, utilizing 3D printing technology. This study presents the first instance of an all-metal Luneburg lens being extended to the terahertz band. Additionally, it showcases the potential for the application of 3D-printed antennas in communication and radar systems. In contrast to the conventional D-band antenna, our antenna's structure is characterized by its simplicity, consisting solely of a Luneburg lens and a waveguide feeder array. A prototype of an antenna is produced using the technique of projection micro-stereolithography 3D printing in combination with magnetron metal sputtering for the purpose of validation. This technology exhibits several benefits, including cost-effectiveness, exceptional accuracy, and streamlined processing capabilities. The prototype's measured outcomes demonstrate that the reflection coefficients fall below -10dB in the frequency range of 110GHz to 170GHz, and its bandwidth is 42.8%. Furthermore, the centre frequency yields a gain exceeding 20dBi, and the multiple beams scan loss measures less than 1.6dB within the range of -45° to +45°, which is consistent with the outcomes of the simulation.

[19] The present paper presents an experimental investigation of the breakdown mechanism of the photoconductive antenna (PCA) made of low-temperature-grown gallium arsenide (LT-GaAs) at low temperatures. The Terahertz (THz) Principal Component Analysis (PCA) is a significant apparatus utilised for the generation of THz waves. The study has investigated various trigger positions and bias voltages in response to the typical breakdown scenarios of LT-GaAs PCAs. The analysis of the breakdown mechanism has revealed that the likelihood of PCA breakdown is higher when the trigger position is located on the edge of the antenna electrode. This is due to the fact that the electric field at the edge of the electrode is approximately three times stronger than that at the centre of the electrode. Additionally, research has demonstrated that the breakdown of the LT-GaAs PCA was primarily attributed to the thermal effect. The calculation of PCA lifetime has been performed utilising the present waveform and thermal effect analysis.

[20] The present study aims to examine the correlation between the efficiency of THz wave emission, noise, and stability, and the material properties of low-temperature (LT) GaAs and semi-insulating GaAs antennas that are fabricated with identical structures. Additionally, the study seeks to compare the emission power, signal-to-noise ratio, and stability of the two types of antennas under identical experimental conditions. The LT-GaAs antenna has been found to possess high THz wave emission efficiency, low noise, and high stability based on both theoretical analysis and experimental results. These characteristics are attributed to the short carrier lifetime and high resistivity of the antenna. This information can be utilised as guidance for the production of high-performance photoconductive antennas.

[21] The present study introduces a fully-recessed, ultra-wideband (UWB) antenna with band-notching and compact design, which exhibits pattern diversity. The proposed antenna is intended for vehicle-to-X communications. The antenna comprises a central radiator with multiple ports that is entirely embedded within a ground structure shaped like a bowl and featuring a top that is flush. The multi-port central radiator is composed of several components, including a circular plate situated at the top, four split-quarter conical monopoles, four strips that are oriented both vertically and horizontally, a metallic cylinder at the centre, and a bottom cylinder. In addition, a multi-port central radiator is equipped with four F-shaped monopoles to generate two narrow notched bands. The form factor of the integrated antenna is 0.23λ3L, wherein λL denotes the free space wavelength at the minimum operational frequency. The antenna that was suggested underwent fabrication and characterization, resulting in a measured S11<−10 dB band that spanned from 1.7 to 6 GHz. Additionally, two stopbands were observed at approximately 2.5 and 5.15 GHz for all four ports. Additionally, the recorded mutual coupling demonstrates a value less than -15 dB, whereas the envelope correlation coefficients (ECCs) exhibit values lower than 0.1 among distinct input ports. The simultaneous excitation of all four ports enables the support of a vertically-polarized (VP) omni-directional pattern. Conversely, individual excitation of the four ports allows for the realisation of four directional patterns that point towards different directions in the azimuthal plane. The antenna that has been presented exhibits potential as a viable option for employment in communication systems that utilise multiple-input multiple-output technology across a diverse range of platforms. A study was conducted wherein a helix antenna was designed utilising MEMS technology for the purpose of THz system operations.

In [22] The metallic helix constituted the antenna and was fed through coplanar waveguide (CPW). The helix-based design for MEMS antennas exhibits several desirable characteristics, including consistent radiation patterns, broadband input match, and smooth gain outputs. Additionally, this design is characterised by its ease of integration, low cost, compactness, and simplicity of structure.

A Yagi antenna for THz applications was proposed in [23], utilising graphene control. The utilised design incorporated a silicon substrate with a thickness of 1μm. The dimensions of the antenna were 160μm×220μm. The results indicated enhanced gain, Q-factor, and bandwidth properties. The implementation of graphene pins within the substrate resulted in an increase in both the gain and bandwidth of the Yagi antenna.

A proposal was put forth in [24] for a high gain THz lens antenna that is circularly polarised. A gain bandwidth of 13.3% and an axial ratio bandwidth of 18.8% were attained.
The authors [25] presented a design for a Yagi-Uda antenna operating in the terahertz frequency range. The input resistance of this antenna was enhanced by utilising full-wavelength dipoles, surpassing the input resistance of currently available THz antennas. It attained enhanced output power in the THz range. The utilisation of a Gallium Arsenide (GaAs) substrate in antenna design has been found to

effectively address impedance mismatch issues that are associated with the substrate's dielectric constant.

Terahertz Antennas of diverse shapes

In [26] The proposed study presents a dual-polarized dual-band antenna that utilises a straightforward bifunctional meta surface (MS). Prior research frequently necessitates diverse components for the creation of MSs, and the majority of single-functional MSs are devised to govern a solitary inherent characteristic of electromagnetic radiation. In contrast, the proposed manuscript employs a singular element type to achieve dual functionalities. The utilisation of the MS in the lower frequency band induces excitation of the TM leaky-wave mode, which, in conjunction with the slot mode, results in a substantial bandwidth of 25.8%. At higher frequency bands, the MS operates as a frequency selective surface, thereby augmenting the antenna gain by 6 dB and reducing the separation distance between the MS and the patch antenna to 0.1 wavelength. Dual bands and dual polarisations are achieved by constructing the antenna using a combination of stub-loaded slots and a rectangular patch that share a common ground and diamond-shaped microstrip. Initially, the MS antenna is subjected to a simulation process, followed by its subsequent fabrication and measurement. The antenna under consideration exhibits operational frequencies of 2.12-2.75 GHz (25.8% bandwidth, 0.63 GHz) for Port 1 and 5.69-5.91 GHz (3.8% bandwidth, 0.22 GHz) for Port 2. The maximum boresight gains are observed to be 7.9 dBi at 2.7 GHz and 11.7 dBi at 5.75 GHz.

[27] The present study explores the efficacy of a newly designed waveguide-fed antipodal exponential tapered slot antenna (AETSA) for the purpose of achieving circular polarisation over a wide frequency range. The AETSA under consideration is supplied with double-ridge waveguide and equipped with antipodal exponential tapered slots. A comprehensive analysis of the wideband axial ratio (AR) performance is presented. The AETSA exhibits a right-hand circularly polarised AR of less than 3 dB in a bandwidth of 94.5%, ranging from 12.4 to 34.6 GHz, thereby demonstrating its potential for utilisation in a broad range of applications. The recorded Voltage Standing Wave Ratio (VSWR) falls below 2.1 within the designated frequency range. The gain exhibits a range of 8.3 to 18.3 dBi. The AETSA exhibits compatibility with wideband circular polarisation applications in the millimetre-wave and terahertz frequency ranges.

A circular antenna design was presented for operations in the THz band in [28]. The design employed FR-4 substrate and possessed dimensions of $120\mu m \times 80\mu m$. The utilisation of a circular radiator, tapered feedline, and partial ground was employed to achieve a 10 dB impedance bandwidth. The antenna exhibited a peak gain of 14.18 dB within the 22.75 THz range. Furthermore, the device exhibited a radiation pattern that was omnidirectional and possessed a compact form factor, rendering it suitable for employment in THz systems.

The authors [29] presented the methodology for designing a super wideband antenna with an elliptical ring shape. The antenna exhibited a ground plane with a semi-rectangular shape and a microstrip feedline. The dimensions of the antenna in question were 800 micrometres by 600 micrometres by 81.29 micrometres. The substrate employed in the study was composed of polyamide and possessed a thickness of 0.004 TL and a relative permittivity of $4.3\epsilon r$. The super wideband properties were attained by utilising asymmetric feeding, semi ground plane, and fractal geometry techniques, resulting in a gain of 9.5 db. A set of five THz microstrip antennas, each possessing a rectangular shape, were designed as described in [30]. Antennas were manufactured utilising a polyimide substrate possessing a thickness of 0.0027 TL and a relative permittivity of $3.5\epsilon r$. Superior radiation characteristics were exhibited at a frequency of 0.65 THz. The implementation of enhanced photonic crystal configuration yielded enhancements of 15.1%, 50.41%, and 279% in radiation efficiency, gain, and RL, respectively.

The authors [31] presents a design for a compact antenna with a circular shape. The present study employed RT/Duroid and silicon substrate materials with respective dielectric constants of 10.2ϵr and 11.9ϵr, and dimensions of 100μm×100μm×10μm. The antenna demonstrated improved link quality when operating at terahertz frequencies.

The authors [32] introduced a dual bow-tie shaped slot antenna designed for utilisation in THz and mm Wave applications. The results indicated an augmentation in the impedance bandwidth characteristics. A study conducted in [33] presented an antenna design for S-THz and THz applications that was modelled after the structure of deoxyribonucleic acid (DNA). The antenna was devised utilising a solitary coiled patch and four fractal coils that were arranged in the configuration of a DNA structure. The bandwidth of the antenna was increased by modifying the ground from a full ground to a semi ground configuration. The antenna demonstrated dual-band properties within the S-THz and THz frequency ranges and achieved a gain of 9.03 dBi. A proposal was put forth in [34] for a V-shaped antenna that operates at a frequency of 0.95 THz, utilising graphene as its primary material. The implementation of the antenna design was based on two distinct modes of radiation patterns, namely directional and quasi-isotropic patterns. The proposed design offers advantages in terms of miniaturisation and reconfigurability of patterns. The antenna demonstrated a gain variation of less than 8 dB in quasi-isotropic mode and an optimal gain of 5.3 dB in directional mode.

Table 1. Comparison of various shaped antennas

Reference No.	**Objectives**	**Applications**	**Antenna Shape**	**Dimension**	**Operating Frequency**	**Results Obtained**	**Future Directions**
26	Dual-polarized dual-band antenna that utilises a straightforward bifunctional meta surface (MS).	Medical imaging, chemical detection material characterization, cancer cell detection, explosive detection, homeland defense	Rectangular		2.12-2.75 GHz	The maximum boresight gains are observed to be 7.9 dBi at 2.7 GHz and 11.7 dBi at 5.75 GHz.[	More antenna parameters should be determined for further design optimization.
27	Achieving circular polarisation over a wide frequency range.	Broad range of wireless applications	Waveguide-fed antipodal exponential tapered slot		0.3 to 15.1 THz	The AETSA exhibits a right-hand circularly polarised AR of less than 3 dB in a bandwidth of 94.5%, ranging from 12.4 to	Antenna gains in other operational modes must be identified.

			antenna (AETSA)			34.6 GHz. The recorded Voltage Standing Wave Ratio (VSWR) falls below 2.1 within the designated frequency range. The gain exhibits a range of 8.3 to 18.3 dBi.	
28	To propose an antenna for THz range application.	Wireless applications	Circular	120μm× 80μm	0.72 THz	The antenna exhibited a peak gain of 14.18 dB within the 22.75 THz range.	Other parametric performances like directivity, efficiency, etc. must be analyzed.
29	Designing a superwideband antenna	THz communication	Semi-rectangular shape	800 micrometres by 600 micrometres by 81.29 micrometres.		A gain of 9.5 dB achieved	Further upgradation on antenna efficacy is required.
30	Design a Terahertz antenna having high gain and bandwidth	THz communication	Rectangular shape			The antenna demonstrated improved link quality when operating at terahertz frequencies. yielded enhancements of 15.1%, 50.41%, and 279% in radiation efficiency, gain,	Other parametric performances like directivity, efficiency, etc. must be analyzed.

						and RL, respectively	
31	Design for a compact antenna with a circular shape	Sensing, communication, screening and imaging applications	Circular shape	$100\mu m\times 100\mu m\times 10\mu m$	Terahertz frequencies.	Improve Gain and bandwidth both.	Radiation efficiency must be maximized.
32	Designing a antenna working at terahertz frequencies	Communication, imaging, screening and sensing applications	Dual bow-tie shaped slot antenna		terahertz frequencies.	The results indicated an augmentation in the impedance bandwidth	More performance variables should be analyzed.
33	Antenna design for S-THz and THz applications that was modelled after the structure of deoxyribonucleic acid (DNA).	THz wireless communication	DNA Structure		90 to 140 GHz	The results indicated an increased bandwidth and achieved a gain of 9.03 dBi.	Efficiency and other antenna parameters must be evaluated.
34	To design a graphene-based antenna with commutable circular polarization for THz applications.	THz wireless communication	V Shaped		0.45 THz	Exhibited RL > 12 dB and axial ratio < 2.15 dB.	Antenna efficacy should be enhanced.

3. CONCLUSION

This literature review provides a comprehensive overview of antennas specifically designed for THz and S-THz frequency ranges. The text expounded upon the potential applications of the THz band within the realm of communication and elaborated on its associated benefits. The salient features of

THz radiation, such as resolution, non-ionizing nature, intensity, spectroscopy, penetration, and scattering, were delineated. The study conducted an investigation into various pre-existing designs of THz antennas, with a focus on analysing their parametric performances. A comprehensive analysis was conducted on antennas that have been specifically developed to facilitate THz/S-THz applications, taking into account their varied shapes and configurations. The results of these investigations, as well as the technical limitations that have been identified, were systematically documented. While these antennas of varying shapes have demonstrated satisfactory performance at THz/S-THz frequencies, they are insufficient for fulfilling the specific demands of emerging THz and S-THz systems. Hence, it is imperative to optimise the design and performance of existing antennas and introduce novel antenna designs to achieve superior performance outcomes that are capable of supporting emerging applications.

Future scope and Challenges in the Terahertz antenna

Some challenges in terahertz antennas to overcome issues like It does not support long-range communication due to scattering and absorption by clouds, dust, rain, etc. It has a lower penetration depth than microwave radiation. Moreover, it has limited penetration through clouds and fog. THz waves cannot penetrate liquid water or metal. It is difficult to detect terahertz frequencies as black body radiation at room temperatures is very strong at these frequencies. Sources, detectors, and modulators are not available at affordable prices, which hinders its commercial availability as a communication system. So, there are lots of opportunities in this field.

Acknowledgement

Nil

4. REFERENCES

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