A Review of Design and Analysis For Various Shaped Antenna in Terahertz and Sub-terahertz Applications

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Abstract: Recent years have seen massive advances in communication technology. The continuously incrementing demands of high bandwidth, data rates and spectrum efficiencies have fostered the exploitation of terahertz (THz) and sub-terahertz (S-THz) communications, opening broad opportunities in the development of THz and S-THz antennas. This paper presents a brief review of antennas in THz and S-THz frequency bands. It describes the scope of THz spectrum in wireless communication and explains the unique radiation characteristics of the THz spectrum. The paper also enumerates the crucial benefits of implementing THz band in communication systems. Furthermore, this work reviews several antenna designs and their performances and even explores antennas of different shapes employed in numerous studies for THz and S-THz applications. This article gives a brief comparative survey of various shaped antenna designs for THz/S-THz band operations and analyzes the key findings of reviewed works and investigates the further developments needed in antenna designs, their structures and performance parameters for introducing, developing and optimizing antennas appropriate for diverse THz/S-THz applications.

Keywords: Antennas, Terahertz radiation characteristics, Terahertz applications, Sub-terahertz applications

1. Introduction

With the increase in services and users of wireless communication day-by-day, the demand for utilizing Terahertz (THz) and Sub-terahertz (S-THz) spectrum in the foreseeable future is growing specifically for preventing congestion and traffic in microwave and radio frequency spectrum. From the past certain decades, the vast demands of communication systems with high spectral efficacies, huge data rates, efficient information transmission/reception and robust fading mitigation along wideband in highly mobile situations have enhanced briskly. For satisfying these necessities, wireless communication experts in both industry and universities started working at frequencies greater than microwave region but lower than infrared range. Majority of this frequency band is covered by the THz and S-THz spectrum. This band provides 100 Gbps data rate that is indispensable for new generation communication operations [1]. The THz and S-THz band is roughly defined as a section of the electromagnetic spectrum extending from 0.1 THz to 10 THz, occupying a mega regime of spectrum between the microwave and infrared bands. This band shows rich potentials in imaging, communication, screening and sensing applications [2], [3], [4], [5]. Due to these notable and profitable features of this band, antenna engineers have come up with various antenna designs for THz systems. These antennas have been designed using diverse geometrical shapes as shown in Figure 1. The basic intention behind exploiting such shapes in antenna structures is to achieve miniaturization, low loss and excellent performance. This survey explores such various shaped antenna structures reported in existing research studies for providing knowledge regarding their suitability for THz and S-THz applications.

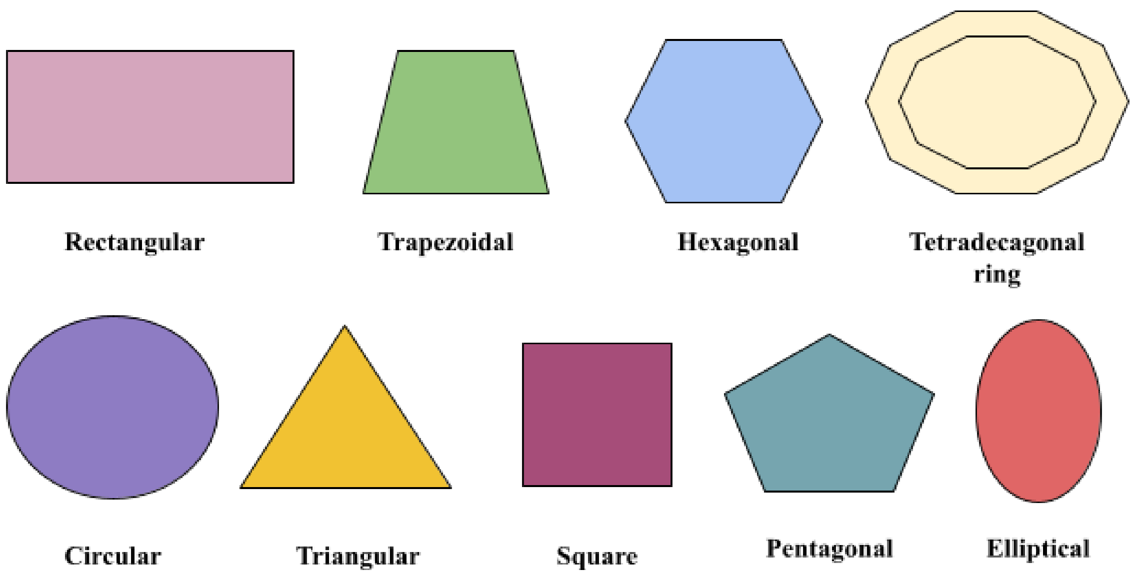

Figure 1. Popularly used geometrical shapes for antenna designs

1.1 Paper Organization

Section 1 explains the scope of diverse antennas in terahertz and sub-terahertz applications. Section 2 describes the importance of terahertz spectrum in wireless communication and discusses the THz radiation characteristics and advantages of THz spectrum in communication systems. Section 3 reviews the various antenna designs. Section 4 explores the different shaped antenna designs employed in existing studies. Section 5 gives a comparative analysis of various shaped antenna designs employed for terahertz and sub-terahertz applications. Section 6 provides the vital findings of this review.

1.2 Contributions of this Review

This research article intends to study the diverse antennas operating in terahertz and sub-terahertz frequency ranges, their advantages and applications. The important contributions of this research include investigation and analysis of antenna designs of various shapes employed for terahertz and sub-terahertz applications.

2. Significance of Terahertz Band

In past certain years, the wireless communication arena has undergone phenomenal developments because of the rise in clamors for huge data rates and high spectral efficacy. The key challenge for the scientific community has been upgrading the communication bandwidth for meeting the 40-100 Gbps data rates for indoor and 100 Gbps data rates for outdoor applications [6]. The possible solution can be boosting the communication system’s bandwidth. But the communication system is inherited with low bandwidth. Moreover, in many situations, the bandwidth of the device is just 10% of its working/operating frequency. In such scenarios, enhancing the working frequency to a level that even with low-bandwidth, the systems may grab a high data rate can help greatly. Recently, 90 GHz and 60 GHz [7], [8], [9] wireless systems have been introduced for satisfying the high bandwidth demand, although these systems are still inadequate for fulfilling the future demands. Therefore, to overcome these weakpoints, research focus is shifted towards the THz band that is sandwiched between far-infrared and microwave frequency region of the spectrum as portrayed in Figure 2. Interestingly, owing to its position between the two well explored bands of spectrum, it is feasible to employ photonic and electronic routes to clear the path in THz spectrum.

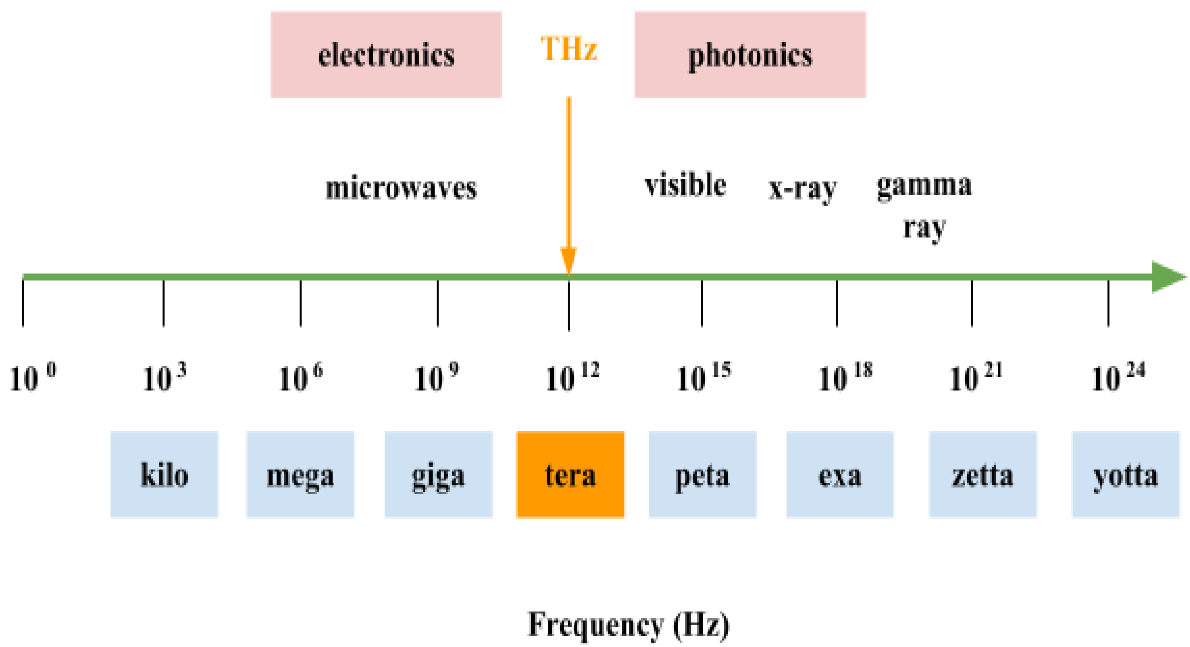

Figure 2. The position of THz band [10]

2.1 THz Radiation Properties

The unique radiation properties of THz spectrum makes it more appropriate and preferable over existing frequency bands for modern communication systems [10]. Some of these radiation characteristics include:

- Penetration: The THz signal exhibits good penetration as it can pass through various thin materials with diverse attenuation levels.
- Intensity: The adjustment of the signal is simpler in the THz region of spectrum when compared to microwave region.
- Scattering: As scattering is inversely proportional to wavelength, in the THz band, the scattering is less due to longer wavelength.
- Non-ionization: THz signal exhibits least ionization effects and is less harmful due to low power ranges.

- Spectroscopy: Several gaseous and solid materials exhibit THz signature in the range of 0.5-3 THz and thus can be utilized for the detection.
- Resolution: In THz band, the resolution is high when compared to the microwave region of spectrum because of the fact that the image resolution increases with the decrease in the wavelength.

2.2 Advantages of THz band

The THz wave has numerous advantages when compared to infrared and microwave communication [10]. The diverse advantages of THz band of spectrum in the wireless communication system are

- Wide bandwidth: The microwave band is almost entirely preoccupied by distinct services. Moreover, its bandwidth is also limited. Thus, instead of microwave band THz can provide a wider bandwidth.
- Secure: THz band of spectrum is comparatively safe, specifically in the spread spectrum communication.
- Low diffraction: The THz signal has less diffraction than that of millimeter wave and microwave thus making it advantageous in the point-to-point line of sight link.
- Less scintillation effect: In the infrared link, the time variant refractive index of the atmospheric path enhances the scintillation effect whereas this can be alleviated in the THz link.
- Low attenuation: THz exhibits low signal attenuation than infrared in specific atmospheric situations like fog.
- High data rate: The THz signal can provide higher data rate than infrared and microwave signals owing to its advanced features.

3. Literature Survey

In [11], dual-polarized microstrip patch antenna (MPA) was proposed for THz applications. This antenna comprised a graphene patch fed via orthogonally oriented dual ports. The dual ports provided horizontal and vertical polarized THz radiations. The MPA was designed to operate in a 3.98 THz frequency. This dual-polarized MPA provided 90% efficiency, 9.6 dB peak gain and -36 dB maximum return loss (RL). In [12], a graphene-dependent MPA design operating at 0.72 THz frequency and having $120\times120\times45\mu m^3$ overall dimension was presented. It was fabricated on a substrate Arlon 1000 with 10.2 relative permittivity (ϵ_r) and 0.0023 tangent loss (TL). The antenna operated from 0.53-0.84 THz frequency and provided a good radiation pattern, an impedance bandwidth of 37.50 %, maximum directivity and RL of 6.60 dB and 59.87 dB. In [13], design of MPA based on photonic crystal was presented for THz applications. The MPA was placed on a polyimide substrate having $800\mu m\times600\mu m\times191.29\mu m$ dimension with patch, ground plane and feeding line thickness of $7\mu m$. This antenna offered 36.25 GHz bandwidth, 8.62 dBi directivity, 7.94 dB gain, RL of -44.71 dB and -10 dB impedance with working frequency ranging from 0.6152 to 0.6514 THz, making it appropriate for material characterization and explosive detection applications. In [14], dual-band fractal antenna was presented for THz communication applications. T-shaped parasitic loads were utilized for providing dual-band properties and a multi-layered graphene load was employed for enhancing the RL value via varying top layer’s surface impedance and antenna gain. The RO-5880 was employed as substrate with $60\times60\mu m^2$ patch size. The antenna was made to operate at 1 to 1.48 THz frequency. The optimum gain of 7.64 dBi was obtained at 1.47 THz frequency thus making it reliable for THz imaging and nanosatellite applications.

In [15], ultra-wideband antenna design was presented for THz applications. In proposed antenna structure, higher degree transverse magnetic modes reverberating at closeby frequencies were excited for attaining ultra-wideband response. This antenna provided 100% of impedance bandwidth covering the THz lower band. In [16], electromagnetic radiations of circular, three-segmented and planar antenna arrays were analyzed. Beam steering potentials of every array were studied. Radiation patterns of these arrays were analysed in THz band. Findings revealed that circular arrays showed improved beam scanning potential while three-segmented arrays showed better directivity. In [17], a photoconductive pulsed-THz antenna design was provided for spectroscopy operations. This antenna showed broadband characteristics in 0.3 to 2 THz. In [18], helix antenna design using MEMS technology was presented for THz system operations. The antenna comprised metallic helix and utilized coplanar waveguide (CPW) for feeding. The proposed helix based MEMS antenna design showed smooth gain outputs, broadband input match and consistent radiation patterns along with easy integration, low cost, compact and simple structure. In [19], graphene control based Yagi antenna was proposed for THz applications. This design employed silicon substrate of 1μm thickness. The antenna had 160μm$\times$$220\mu$m size. It showed improved gain, Q-factor and bandwidth characteristics. Utilization of graphene pins in the substrate enhanced theYagi antenna's gain and bandwidth. In [20], a circularly polarized, high gain THz lens antenna was proposed. It achieved 13.3% gain bandwidth and 18.8% axial ratio bandwidth. In [21], a Yagi-Uda THz antenna design was provided. This antenna achieved greater input resistance through full-wavelength dipoles than available THz antennas. It achieved improved THz output power. Utilization of GaAs substrate for antenna design mitigated impedance mismatch issues linked with the substrate's dielectric constant.

4. Various Shaped Antennas

In [22], a jasmine flower shaped THz antenna fed using CPW was designed for THz pattern diversity applications. It comprised a radiator of jasmine flower shaped etched in a circular ring. The working frequency of the antenna element ranged from 0.65 to 100 THz. The diversity configuration and antenna element's overall footprint was 110μm$\times$$185.5\mu$m and 110μm$\times$$78.5\mu$m. It exhibited contorted omnidirectional radiation patterns and acceptable multiple input multiple output (MIMO) performance parameter values. In [23], an on-chip circular shaped antenna implemented on dual-layered polyimide substrate with 500 μm thickness was presented for S-THz applications. In proposed design, the concentric dielectric-rings etched in the ground plane, implemented on top-layer suppressed the surface waves, minimized the substrate losses which led to improved radiation characteristics and bandwidth. This antenna exhibited 0.350-0.385 THz bandwidth, 8.15 dBi mean radiation gain and 65.71% efficiency. In [24], a circular shaped patch antenna was designed for THz band application. The proposed antenna comprised a thin layered substrate mounted on the ground plane with circular patch positioned on the substrate and a superstrate mounted on the patch. A thin layered Teflon superstrate was employed for antenna performance upgradation and patch protection against environmental treacheries. The antenna operated around 7 THz frequency and provided high gain and better radiation efficacy.

In [25], a trapezoidal shaped MPA was devised for THz system applications. The coupling between antenna and source was provided through a microstrip line and workability of MPA was enhanced through embedding photonic crystals in the substrate. The proposed trapezoidal shaped MPA showed enormous improvements in gain, VSWR and RL. It showed good radiation characteristics and exhibited a broad bandwidth of 1.2-1.62 THz. Moreover, within the principal band, it offered four resonant frequencies of 1.56 THz, 1.43 THz, 1.28 THz and 0.96 THz and RL of -33.60 dB, -34.28 dB, -27.23 dB and -15.70 dB. In [26], a horn shaped antenna was proposed for strengthening imaging and spot focussing systems performance at THz frequencies. This design aimed at enhancing the focussing and radiation performance. A horn-waveguide-horn pattern of design was exploited for attaining combined advantages of less cross polarization, thin spot focussing and plane-wave patterns. The antenna was designed to work at 0.9 to 1 THz frequency level. The comparison of horn shaped and lens corrected horn antenna indicated that horn shaped antenna showed good spot focussing performance. In [27], a tetradecagonal ring microstrip antenna was presented for superwideband MIMO applications. It comprised a tetradecagonal radiator with a partly-circular ground plane. The footprints of pattern diversity and spatial diversity configurations were $800\mu m \times 1220\mu m$ and $800\mu m \times 1170\mu m$. Both these configurations showed superwideband bandwidth and miniaturized dimensions. Moreover, in these configurations, an isolation > -30 dB was obtained at optimum frequencies without utilizing any isolation methods.

In [28], a graphene-based reconfigurable V-shaped antenna functioning at 0.95 THz frequency was proposed. The antenna design was implemented depending on two modes of radiation patterns namely directional and quasi-isotropic patterns. The design proposed presented miniaturization and pattern reconfigurability benefits. This antenna achieved less than 8 dB gain variation in quasi-isotropic mode and 5.3 dB optimal gain in directional mode. In [29], a simplex Z-shaped circular polarized double band THz antenna was presented for communication in THz range. For this design, circular polarization was obtained through rotating the radiating component by 45^0 along the horizontal surface. The Rogers RT6006 substrate with $127\mu m$ thickness and $6.15\epsilon_r$ was employed for antenna design and total antenna dimension was $850\times770\times197\mu m^3$. This antenna design offered simple structure, easy fabrication and wide bandwidth. It exhibited 0.38 to 0.49 THz and 0.575 to 0.59 THz bandwidth and 5.8 dBi maximum gain. In [30], a graphene-based hexagonal shaped microstrip-fed double band antenna was analyzed. The antenna comprised a microstrip feed with a plus shaped slot and a hexagonal shaped patch. This antenna was designed on a substrate with $40\mu m$ thickness and $2.2\epsilon_r$. It operated with reasonable radiation properties with RL of < -10 dB at 5.41 THz and 2.41 THz frequencies. It provided 5.61 dB gain at 5.41 THz and 4.71 dB gain at 2.41 THz frequencies.

In [31], a fractal hexagonal antenna design was proposed. It operated at 0.2-11.5 THz frequency range. The techniques of backed plane loading, defected uneven ground plane and fractal geometry were employed for attaining superwideband performance. It exhibited a contorted omnidirectional pattern of radiation and 10.82 dB peak gain. In [32], the performance of a triangular shaped graphene patch antenna was studied. In the antenna design, photonic crystals were implanted in the substrate for enhancing antenna's radiation characteristics. The antenna's resonant frequency was tunable through varying surface conductivity and chemical potential using electrostatic external bias voltage. It achieved better impedance matching, 6.58 dB directivity, -24.05 dB RL and 4.65 dB gain. In [33], an elliptical shaped antenna was designed for THz frequencies. This antenna was fabricated on a polyamide substrate with 0.004 TL and 4.3 ϵ_r. It comprised a semi-rectangular shaped ground plane and microstrip feedline. The radiator, ground plane and feedline had $7\mu m$ thickness. The diverse consequences of ground length, substrate thickness and feedline width variations on antenna behaviors were analyzed. The proposed elliptical antenna displayed omnidirectional radiation form, 12 dB peak gain and 5 THz impedance bandwidth. In [34], parametric performances of hexagonal, circular and pentagonal shaped antennas were investigated in the THz range. Evaluation of output responses of these antennas indicated that pentagonal and hexagonal shaped antennas yielded higher resonant frequency ranges and showed improved performances than circular shaped ones.

In [35], inverted K-shaped design was proposed for THz frequencies. The squared shaped patch was modified into inverted K-shaped design through inplanting triangular holes in the patch. The antenna had 600×600 μm^2 dimension and utilized polyimide substrate and microstrip line for feeding. It covered 0.46 to 8.84 THz bandwidth and showed 22.1 dB gain at 8.8 THz. Due to its broad bandwidth, high gain and simple structure it could be exploited for different THz communication applications. In [36], fractal loaded, microstrip-fed circular shaped antenna was designed. It utilized polyamide substrate with 0.004 LR and 4.3ϵ_r. The fractal geometry was embedded with circular radiating patch for attaining antenna operation over the complete 0.1-10 THz spectrum. A reasonably consistent radiation pattern along with an acceptable gain value was achieved over the complete operation band. It showed least physical dimension and greatest impedance bandwidth than earlier reported THz antenna structures. In [37], performance of circular shaped graphene patch antenna employing distinct substrate components in THz region was explored. The substrate components like silicon nitride, silicon dioxide, quartz and polyimide were employed and antenna performance was examined based on VSWR, RL and gain. Proposed antenna with polyimide substrate components showed excellent gain performance and with quartz substrate showed maximum RL. In [38], slot antenna with dual-fan-shaped design was realized for THz band applications. This antenna was circularly polarized and fed using WR1.9 waveguide. The estimated axial ratios of this antenna were less than 1.5 dB in 490-500 GHz range. This antenna attained 12.5 dBi gain.

In [39], a circular shaped antenna design was provided for THz band operations. This design utilized FR-4 substrate and had 120μm×80μm size. The circular radiator, tapered feedline and partial ground were used for acquiring impedance bandwidth of 10 dB. This antenna showed 14.18 dB peak gain at 22.75 THz range. Moreover, it presented an omnidirectional pattern of radiation and compact size making it fit for THz systems. In [40], design of an elliptical ring shaped superwideband antenna was described. Antenna had a semi-rectangular shaped ground plane and a microstrip feedline. The overall antenna volume was 800μm×600μm×81.29μm. It used polyamide substrate with 0.004 TL and 4.3ϵ_r. It achieved superwideband properties through asymmetric feeding, semi ground plane and fractal geometry methods and showed 9.5 dB gain. In [41], five rectangular shaped THz microstrip antennas were designed. Antennas were fabricated on the polyimide substrate with 0.0027 TL and 3.5ϵ_r. They showed better radiation properties at 0.65 THz. Utilization of improved photonic crystal design resulted in improvements of 15.1%, 50.41% and 279% in radiation efficacy, gain and RL. In [42], circular shaped compact antenna design was provided. This design utilized RT/Duroid and silicon substrate having 10.2ϵ_r and 11.9ϵ_r and 100μm×100μm×10μm dimensions. This antenna offered better link quality at THz frequency.

In [43], dual bow-tie shaped slot antenna was proposed for THz and mmWave applications. It showed increased impedance bandwidth qualities. In [44], a deoxyribonucleic acid (DNA) shaped design of antenna was provided for S-THz and THz applications. This antenna was designed with a single coiled patch and four fractal coils inserted in a shape of DNA. Antenna's bandwidth was enhanced through altering full ground to semi ground. This antenna exhibited double-band characteristics in S-THz and THz range and attained 9.03 dBi gain. In [45], a multiband slotted pentagonal THz patch antenna was described for multiple THz applications. The proposed THz antenna was developed from a rectangular shaped antenna through altering the shape of ground plane and radiating patch. A polyimide substrate was employed for antenna design having 21.5μm thickness and 3.5ϵ_r. It covered bandwidth which resonated at 10.785 THz, 9.43 THz, 8.87 THz, 7.02 THz, 4.85 THz and 3.00 THz frequencies with reflection coefficient < - 10 dB. It achieved better gain and radiation efficacy than earlier documented THz antennas. In [46], a rectangular shaped double-band patch antenna was proposed at THz frequency. This antenna was designed on a dual-layered substrate with TL of 0.003 and ϵ_r of 3.2 (for layer1) and TL of 0.0035 and ϵ_r of 6 (for layer2). The thickness of each layer was 25μm. It employed microstrip line for feeding. This antenna showed considerable improvements in radiation efficiency, directivity and gain when compared to similar existing antennas.

5. Comparative Study

Table 1. Comparison of various shaped antennas

References	**Objectives**	**Operating Frequency**	**Applications**	**Antenna Shape**	**Antenna Type**	**Results Obtained**	**Future Directions**
Shalini, M., & Madhan, M. G. (2019)	To design a miniaturized wideband MPA for THz applications.	0.72 THz	Medical imaging, chemical detection material characterization, cancer cell detection, explosive detection, homeland defense	Rectangular	Patch antenna	Exhibited 37.50% impedance bandwidth, 1.007 VSWR, maxim RL of -59.87 dB and 6.60 dB maximum directivity.	Antenna's efficiency must be determined.
Singhal, S. (2021)	To design an antenna for THz pattern diversity applications.	0.65 to 100 THz	THz communication	Jasmine flower	Patch antenna	Provided reasonable values of MIMO performance parameters.	Antenna performance in other THz operatingfrequency ranges should be evaluated.
Khan, M. A. K., Ullah, M. I., Kabir, R., & Alim, M. A. (2020)	To devise an antenna of high performance for THz applications.	7 THz	THz communication	Circular	Patch antenna	Provided 7.286 dB gain, 7.392 dB gain for glass, 97.21% efficiency and 7.408 dB directivity.	Further improvement in antenna gain is required.
Singh, A.,	To design a	0.8-1.62	Imaging	Trapezoidal	Patch	Exhibited	Radiation

& Singh, S. (2015)	MPA for high speed THz applications.	THz	and scanning systems, radar communication		antenna	1.2 to 1.62 THz bandwidth, 57.96% impedance bandwidth, -42.5 dB minimum RL and 10.5 dB gain	efficiency should be determined.
Shahid, S., & Gentili, G. G. (2016, November)	To improve imaging and spot focussing systems performance at THz frequencies.	0.9-1 THz	THz Imaging, material characterization	Horn shaped	Horn antenna	Produced good spot focusing at 0.09, 0.08, 0.15 and 0.16 mm than lens corrected horn.	Antenna gain, radiation patterns, efficiency and diverse other performance parameters must be examined.
Singhal, S. (2020)	To propose an antenna for THz MIMO applications.	0.3 to 15.1 THz	Imaging, sensing biohazards, explosives, weapon screening, short and long distance communication	Ring (tetradecagonal) shaped	Monopole antenna	Exhibited 14.8 THz impedance bandwidth.	Other performance characteristics of antenna should be determined.
Chashmi, M. J., Rezaei, P., & Kiani, N. (2019)	To devise a reconfigurable graphene dipole antenna for THz band application.	0.95 THz	THz communication	V-shaped	Dipole antenna	Offered 5.3 dB gain in directional mode and less than 8 dB gain variation in quasi-isotropic mode.	Antenna gains in other operational modes must be identified.
Ullah, S., Ruan, C., & Haq, T. U. (2019, September)	To propose microstrip antenna for short-range wireless communication.	0.19 to 0.24 THz and 0.38 to 0.49 THz	THz communication	Z-shaped	Monopole antenna	Achieved 5.8 dBi maximum gain.	Antenna performance for long-range communication must be

							evaluated.
Badr, N. S., & Moradi, G. (2020)	To analyze dual-band graphene-based microstrip-fed antenna for THz applications.	5.41THz and 2.14 THz	THz communication	Hexagonal	Patch antenna	Provided 1.024 THz bandwidth and 5.61 dB gain.	More antenna parameters should be determined for further design optimization.
Singhal, S. (2020)	To propose a superwideband antenna for THz applications.	0.2-11.5 THz	Imaging of concealed object and skin, sensing explosives, sensing biohazards, weapon screeningand communication applications	Hexagonal	Monopole antenna	Achieved 10.82 dB peak gain.	Further upgradation in antenna efficacy is required.
Bala, R., & Marwaha, A. (2015, December)	To analyze the performance of graphene based patch antenna with photonic crystal substrate.	1-3 THz	Wireless applications	Triangular	Patch antenna	Achieved good impedance matching with 5.6% bandwidth.	Further optimization is needed in antenna performance.
Singhal, S. (2019)	To propose an elliptical antenna for THz applications.	0.46 to 5.46 THz	Screening biohazards, weapons and explosives, imaging skin, water contents and concealed objects, wireless communication and sensing	Elliptical	Patch antenna	Provided 5 THz impedance bandwidth and 12 dB gain.	Other parametric performances like directivity, efficiency, etc. must be analyzed.

Anusha, N., Sujatha, M., Srikanth, V., Kumar, R. S., & Varma, T. J. V. (2017, April)	To investigate the parametric performances of THz antenna with diverse configurations.	5-10 THz	Imaging and sensing, security, communication, remote detection, energy conservation and electronic devices.	Pentagonal, circular and hexagonal	Patch antenna	Showed reduction in loss response and improved bandwidth.	Radiation efficiency, directivity, gain parameters should be determined.
Keshwala, U., Rawat, S., & Ray, K. (2020)	To devise an antenna for THz applications.	8.8 THz	Wireless body area networks (WBAN)	Inverted K-shaped	Patch antenna	Achieved 22.1 dB gain and 92% maximum efficiency.	Radiation performance must be further optimized.
Das, S., Mitra, D., & Chaudhuri, S. R. B.	To propose fractal loaded patch antenna in THz range for superwideband operation.	0.1-10 THz	Sensing, communication, screening and imaging applications	Circular	Patch antenna	Provided 12.89 dB peak gain.	Antenna efficacy, directivity parameters should be analyzed.
Azam, S., Khan, M. A. K., Shaem, T. A., & Khan, A. Z. (2017, September)	To proposed graphene-based THz antenna.	6.8 to 7.2 THz	THz communication.	Circular	Patch antenna	Achieved 16.7 dB gain.	Radiation efficiency must be maximized.
Zhao, P., Liu, Y., Lu, H., Wu, Y., & Lv, X. (2017)	To study circularly-polarized, waveguide-fed THz slot antenna performance.	-	THz detection and imaging systems.	Dual-Fan-shaped	Slot antenna	Provided 12.5 dBi gain.	More performance variables should be analyzed.
Singhal, S. (2019)	To propose a THz fractal antenna.	0.3-9.3 THz	Communication, imaging, screening and sensing applications	Elliptical ring	Monopole antenna	Provided 9.5 dB peak gain.	Further increase in gain is required.

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Hocini, A., Temmar, M. N., Khedrouche, D., & Zamani, M. (2019)	To design a THz patch antenna	0.5-0.8 THz	THz communication.	Rectangular	Patch antenna	Offered 90.84% radiation efficacy and 9.19 dB gain.	Antenna performance must be further upgraded.
Rubani, Q., Gupta, S. H., & Kumar, A. (2019)	To propose an antenna for THz range application.	-	WBAN	Circular	Patch antenna	Achieved 4.8 dB gain and 5.3 dB gain, 3dB directivity and 3.1 dB directivity for RT duroid and silicon substrate.	Antenna efficiency must be determined.
Alazemi, A. J., Yang, H. H., & Rebeiz, G. M. (2016)	To devise a slot antenna for THz band applications.	0.1 THz to 0.3 THz and 0.2 THz to 0.6 THz.	Imaging systems and radio astronomy.	Dual bow-tie shaped	Slot antenna	Provided Gaussian coupling efficacy of 78-97%.	Other parametric performance investigation is required.
Keshwala, U., Rawat, S., & Ray, K. (2021)	To design an antenna for S-THz and THz applications.	0.22 THz to 0.32 THz and 1.38 THz to 2.89 THz.	Wireless communication	DNA shaped	Patch antenna	Exhibited 9.03 dBi maximum gain.	Antenna efficiency, directivity and other performance factors should be determined.
Singh, M., & Singh, S. (2021)	To devise a multiband antenna for multiple THz applications.	3 THz to 10.785 THz.	Medical imaging, arms and explosive detection, indoor communications, industrial inspections and pharmaceutical analysis.	Pentagonal	Patch antenna	Provided 13.92 dB maximum gain and 85.77% radiation efficacy.	Further upgradation in antenna performance is needed.
Jha, K. R.,	To propose	800 GHz	Surveillanc	Rectangular	Patch	Showed	Antenna

& Singh, G. (2010)	a THz antenna for monitoring applications.	and 600 GHz.	e system		antenna	79.9% radiation efficiency, 10 dBi directivity and 9.8 dB gain.	design should be optimized for attaining better resolution, bandwidth and speed.
Chashmi, M. J., Rezaei, P., & Kiani, N. (2020)	To design a graphene-based antenna with commutable circular polarization for THz applications.	0.45 THz	THz wireless communication	Y-shaped	Patch antenna	Exhibited RL > 12 dB and axial ratio < 2.15 dB.	Antenna efficacy should be enhanced.
Bhardwaj, S., & Volakis, J. L. (2018)	To develop hexagonal waveguide based horn antennas for Sub-mm/THz band.	90 to 140 GHz	THz wireless communication	Horn shaped	Horn antenna	Provided 37% bandwidth for 3 dB axial ratio and 18 dBi midband gain.	Efficiency and other antenna parameters must be evaluated.

The antenna types such as helix antenna, Yagi-Uda antenna, lens antenna, dipole antenna, horn antenna, slot antenna, monopole antenna and patch antenna reviewed in Sections 3, 4 and 5 are represented in Table 2 and depicted in Figure 3. Among the reviewed antenna types, patch antenna is used in 21 papers, monopole antenna in 4 papers, Yagi-Uda, horn and slot antennas in 2 papers and helix, dipole and lens antenna in 1 paper.

Table 2. Summarized list of antenna types

Antenna Types	**References**
Lens antenna	[20]
Dipole antenna	[28]
Helix antenna	[18]
Horn antenna	[26], [48]
Yagi-Uda antenna	[19], [21]
Slot antenna	[38], [43]

Monopole antenna	[27], [29], [31], [40]
Patch antenna	[11], [12], [13], [14], [22], [23], [24], [25], [30], [32], [33], [34], [35], [36], [37], [41], [42], [44], [45], [46], [47]

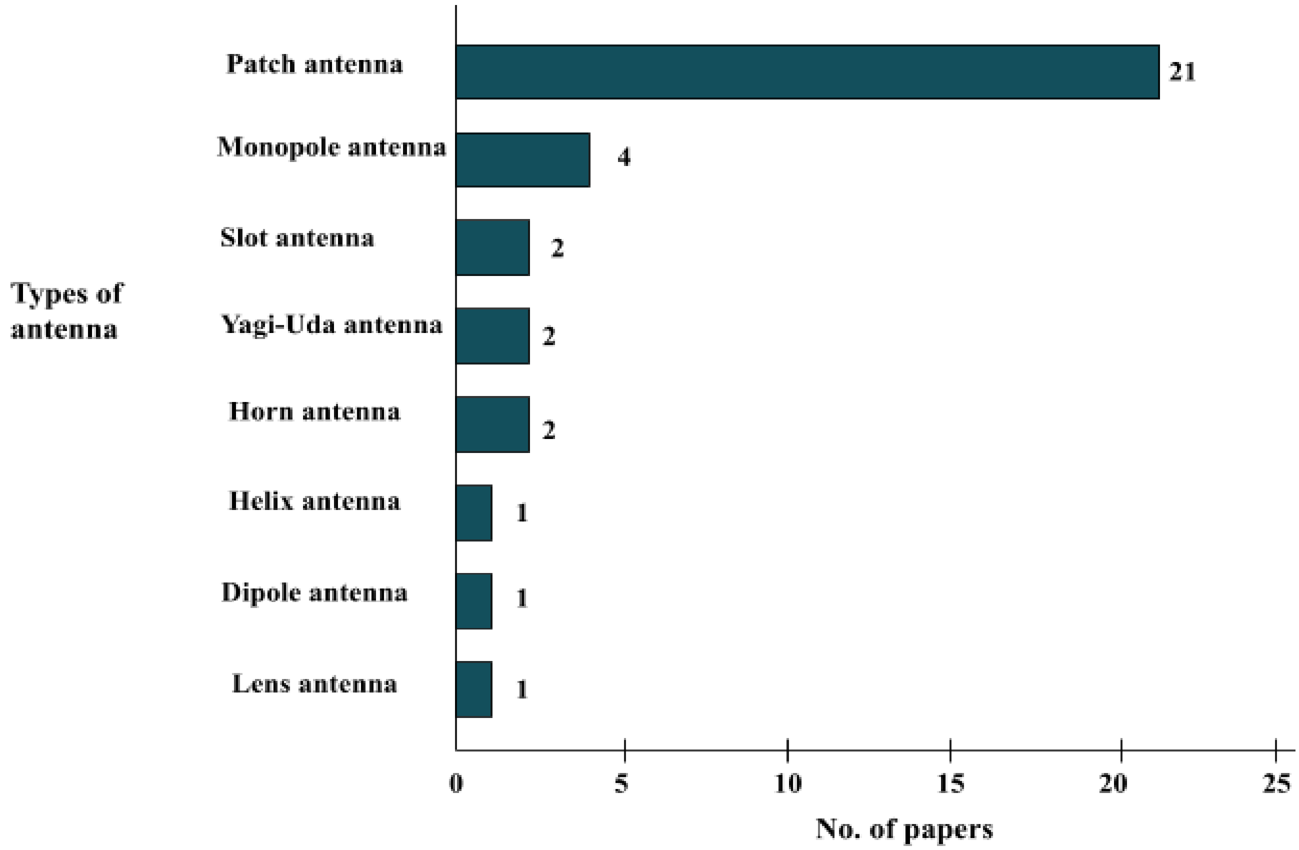

Figure 3. Antenna types used in literary works

The commonly exploited various shaped antenna designs such as triangular, trapezoidal, tetradecagonal, horn, rectangular, elliptical, pentagonal, hexagonal, circular and others (jasmine shaped, v-shaped, z-shaped, inverted k-shaped, dual-fan shaped, dual-bow-tie shaped, DNA-shaped and y-shaped) reviewed in Sections 4 and 5 are represented in Table 3 and depicted in Figure 4. Among the reviewed antenna designs, circular shaped antenna designs are used in 7 papers, hexagonal shaped designs in 3 papers, pentagonal-, elliptical-, rectangular- and horn-shaped designs in 2 papers, tetradecagonal-, trapezoidal-, and triangular-shaped designs in 1 paper and other designs in 8 papers.

Table 3. Summarized list of various shaped antennas

Various Shaped Antennas	**References**
Triangular	[32]

Trapezoidal	[25]
Tetradecagonal	[27]
Horn	[26], [48]
Rectangular	[41], [46]
Elliptical	[33], [40]
Pentagonal	[34], [45]
Hexagonal	[30], [31], [34]
Circular	[23], [24], [34], [36], [37], [39], [42]
Others	[22], [28], [29], [35], [38], [43], [44], [47]

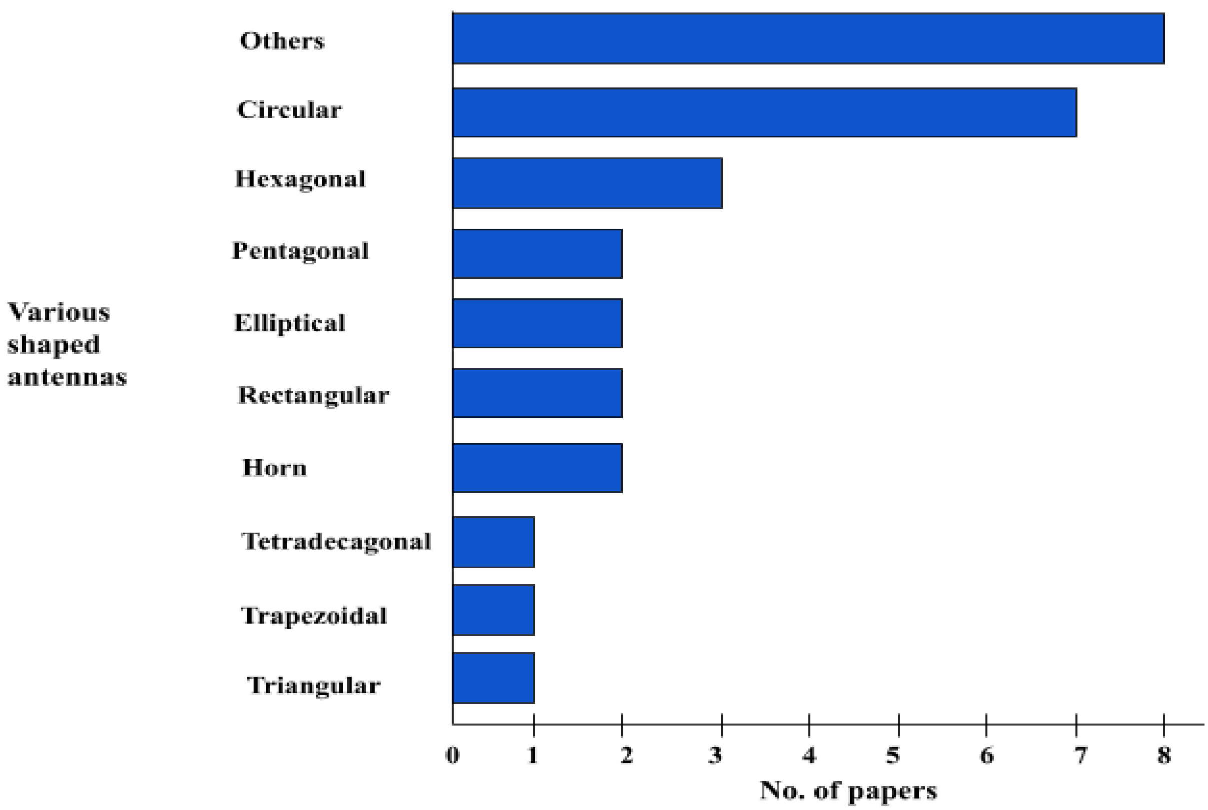

Figure 4. Various shaped antennas exploited in literary works

6. Conclusion

This review work presented a general idea of antennas designed for THz and S-THz operations. It provided the scope of THz band in the communication field and discussed its advantages. The vital THz radiation characteristics like resolution, non-ionization, intensity, spectroscopy, penetration and scattering were described. In the paper, several existing THz antenna designs were investigated and their parametric performances were studied. The antennas designed with diverse shapes and configurations for supporting THz/S-THz applications were reviewed and the findings and technical gaps of these studies were tabulated. Though these various shaped antennas achieved good performances at THz/S-THz frequencies, they are inadequate for meeting the explicit requirements of new THz and S-THz systems. Therefore their design and performances must be further optimized and improved antenna designs should be introduced for obtaining still greater performance outcomes suitable enough for supporting freshly emerging applications.

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