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Multi-band and Ultra-wideband inner Slotted Blade Terahertz Antenna Design and optimization

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Abstract With the increasing expansion of the Internet of Things (IoT), the Internet of Vehicles (IoV), and the application of mass connectivity technologies, there is a mounting demand for ultra-high-rate, ultra-broadband communications, and low-latency communications. However, the transmission technology of existing antennas cannot satisfy this support well. The terahertz antenna with high bandwidth and high directional characteristics can better fulfil the communication needs of ultra-wideband, high speed, large-scale connection and low latency. Although the existing literature has already done a lot of research work on terahertz antenna design, there are still the disadvantages of complex structure, high fabrication difficulty and high price, as well as the disadvantages of a single operating frequency band and inferior directionality. In this paper, we design a multi-band, ultra-wideband rectangular internal slotted terahertz antenna. The antenna has the characteristics of simple structure, small size (16mm×8mm), simple fabrication (metal film coating) and cheap material (copper). In this paper, the simulation is performed at the operating frequency of 100GHz, and the results show that the antenna has the characteristics of multi-band, ultra-wideband, high gain and good directionality near the operating frequency. Simultaneously, this paper simulates the optimization of slot width.

Keywords: Machine Internet, Internet of Things, Ultra-Massive connectivity, THz Antenna, High Grain.

1. Introduction

With the expansion of fifth and sixth generation mobile communications and IoT technology applications such as wearable electronics that are lightweight, durable, and easy to integrate with clothing, medicine, research, aerospace, and defence [1]. There is an increasing demand for ultra-high rate and ultra-high communication [2], especially in short-range, ultra-broadband communication, and ultra-high speed wireless communication, such as fixed point-to-point (P2P) communication in server rooms or supercomputers [3]. Such as a high volume of wire connections in a server room or supercomputer. Another instance is Wi-Fi and base stations where antennas transmit large amounts of data at ultra-high speeds over short distances. In order to meet the requirements of communication systems such as higher data rates and higher reliability, the use of higher frequencies for information transmission is a preferable solution [4]. Terahertz bands are playing an important role in accommodating ultra-high rate and ultra-high communication. Tera Hertz (THz) refers to frequencies between 100 GHz and 10,000 GHz, where the 0.1 to 0.3 THz is sub-terahertz and the 0.3 to 10 THz is terahertz [5]. Terahertz technology has well-defined applications in health monitoring systems, Internet of Nano-Things (IoNT), ultra-high-speed on-chip communications, environmental pollution monitoring, military, entertainment technology, augmented reality, directional communication links, satellite communications, and heterogeneous networks [6, 7]. Such as mobile broadband reliable low-latency communications, large-scale ultra-reliable low-latency communications, human-centred services, multi-purpose and energy services [8]. These new 6G use cases need to support higher data rates or capacity (1 terabit per second), higher convergence, lower latency (1 microsecond), higher reliability (10-9), lower energy and cost, massive connectivity, global connectivity, batteryfree Internet of Things (IoT) devices, and intelligence connected to machine learning [2, 9]. However, terahertz technology confronted great challenges in wireless mobile communication systems, the main trouble is that terahertz waves encounter high path loss and molecular absorption during propagation. This high propagation loss indicates that wireless communication systems in the terahertz band are only capable of achieving shorter distances. In addition, transceivers should be able to operate in higher bandwidths in the terahertz bands, so the development of a terahertz band antenna that supports higher bandwidths and high directional characteristics is a very important work.

2. Status of terahertz antenna research

The application of terahertz antennas in wireless mobile communications has become a focus of recent research [10]. Currently, the research on terahertz antennas is mainly focused on the design and measurement of terahertz antennas. For example, graphene-based rectangular microstrip line antennas, K-patch antennas, and plant shape antennas, which have relatively wide operating bandwidths, operating frequencies of 0.33-10 THz, and gains of 12-22.1 dB [2]. However, the work bandwidth and gain of these antenna structures are only the performance that can be achieved by the description in the literature, and the actual results are not in any information support. In the literature [11], the authors design a log-periodic dipole array antenna with an operating bandwidth of 30 THz and a peak gain of 16.02 dBi. the antenna is structured with a double-layer superposition, which increases the complexity of the design. Some recent work related to terahertz-band antennas has achieved a minimum high-gain antenna of 18 dbi or more for 6G wireless communication systems. However, the radiation efficiency and fractional bandwidth of these studies are low or unknown, and the FBW of ultra-wideband antennas is above 50%. In literature [12], the authors employed a transparent thin film patch antenna made of Ta4C3 compound having several atomic layer thicknesses, which operated up to 800 GHz with a wide impedance bandwidth and good radiation performance. In the literature [13], the authors achieved a new method of antenna operating frequency from GHz to THz by reducing the size of the patch antenna to the micron level. The method achieves a change in the operating frequency from the original 5.5 GHz to 5.5 THz and the bandwidth from the original 1.1 GHz to 1.1 THz. However, the authors do not state whether all patch antennas have such characteristics, and the universality of their conclusions needs to be further verified. Furthermore, none of these studies included ultra-wideband and multi-band antennas. There are also very few studies on dual, tri-band and multi-band antennas for terahertz bands. Nevertheless, their dual, tri-band or multi-band antennas are multi-narrowband rather than multi-ultra-wideband or they do not mention the performance of their antennas in terms of radiation and total efficiency, polarisation and FBW and their gain is also below 18 dBi. On the other hand, an analysis of the performance of the latest work related to terahertz band antennas shows that these antenna types are only microstrip/patch antennas (single/array), with maximum gains of 25 and 22.1 dB for single patch antennas. Since 6G technology for the higher gain directional antennas (18-40 dBi) is required to overcome the high path loss in the terahertz band and this antenna may not be achievable 6G antenna specifications, the directivity or bandwidth of the above mentioned terahertz band antenna studies will still need to be further enhanced for the upcoming 6G wireless communication systems. In terms of terahertz antenna design, the authors in the literature [15] comprehensively describe a review article on terahertz antenna design by using deep learning or machine learning, which fully explains the advantages of deep learning or machine learning. However, the authors only listed the deep learning or machine learning's powerful data analysis, processing and computational capabilities, while no schemes and methods that can be practically operated are given for the design of the antenna or how to design it. Therefore, there is still a necessity to develop a new multiband and ultra-wideband antenna with very high directionality (or omnidirectional, very high gain) in the THz band for 6G wireless communication systems. The work performed and the innovations in this paper are mainly contained in the following:

(1) Design of a novel terahertz band antenna which conforms to the specification of 6G wireless communication system.
(2) Simulation and analysis of S(1,1), Z(1,1), directivity and polarisation direction characteristic curves of the designed antenna.
(3) Optimisation of antenna slot width is Simulated.

3. Terahertz antenna design and simulation

In the terahertz band, the propagation path loss is higher and the electromagnetic wave is propagated over a shorter distance. In general, antennas with small sizes tend to have lower bandwidths, while larger sizes, have higher costs. In addition, the bandwidth and gain of the antenna also have a great correlation, that is, the ultra-wideband antenna has lower directivity, while the narrowband antenna does have better directivity and gain. So it is very difficult for antenna design to meet the requirements of many aspects in parallel. However, because of the very short wavelength of the terahertz band, the aperture size of the antenna can be increased to improve the directional gain of the antenna. Therefore, there are high requirements on the directionality of terahertz antenna propagation, and its design should give full consideration to wireless mobile application scenarios and meet the application requirements of ultra-wideband, small size and low cost. At the same time, the material and shape of the antenna also affect its manufacturing cost, because the traditional antenna can not be adapted to the terahertz frequency band, so in order to meet the demand for terahertz antennas for wireless mobile applications, the manufacturing cost of the terahertz antenna should be reduced to a minimum. In regard to the material, graphene is the more ideal material, but there is less data related to its antenna research in terahertz band. While metal antennas can effectively reduce the cost and manufacturing complexity, used to make antennas, copper is becoming the best choice for antenna fabrication. In the terahertz frequency range, the skin depth and conductivity of copper metal decreases, which reduces the radiation efficiency of the antenna element. In the sub-terahertz frequency range, e.g., at a resonance frequency of 6.45 terahertz, resistance plays a dominant role in contributing to the copper surface impedance, which makes the design of antennas made of copper difficult. The design of such terahertz band antennas using copper materials is a challenging task due to metal surface losses. Furthermore, the energy consumption of antennas is also a focus of close attention in wireless communication systems. Reducing the transmission energy consumption of antennas can reduce the cost for operators and improve the standby time for user terminals, increasing the user experience and highlighting the green communication. Terahertz antenna can play an important role in energy saving and consumption reduction because of its small size and only serves in short distance communication [14].

3.1 Terahertz Antenna Structure

The terahertz antenna structure designed in this paper is a metal coated rectangular internal slot structure and the material used is metallic copper. Where the length parameter is “a“ mm and width is ”b” mm. The slotting method is a centre-symmetric way, the slotting width is “w” mm is 2 times the wavelength of the operating frequency, and the slotting interval is “l” mm, the antenna structure is shown in Fig. 1, and parameters are set as in Table 1.

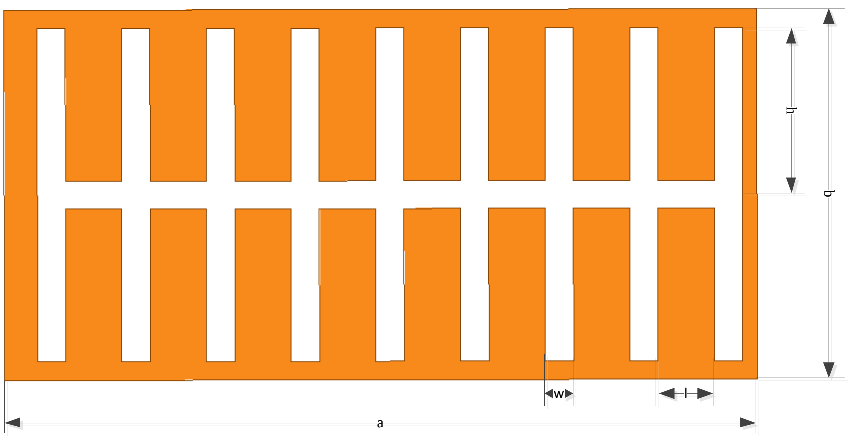


Figure 1: Internal slotted terahertz antenna structure

Table 1: Antenna parameter setting

Antenna length (a)/mm	Antenna width (b)/mm	Slot height (h)/mm	Slot width (w)/mm	Slot interval (l)/mm	Material
16	8	**3.85**	**0.6**	**1.8**	Copper

3.2 Simulation analysis

The paper utilizes the HFSS15 software platform for the design and simulation of the antenna, with an operating frequency of 100GHz and a design simulation bandwidth of 30GHz, i.e. 90GHz to 120GHz, with a maximum number of solutions of 200 and an error tolerance of 0.5%. The S(1,1) feature curve of the antenna can be illustrated in Fig. 2, i.e., the S(1,1) feature at point “m1’ decreases rapidly from 1.6300 dB to -13.4977 dB at point “m2”, with a gain decrease of 15.1277 dB and an over-bandwidth of 2.5 GHz. As shown the simulation results, there is a 15 GHz bandwidth from simulation 90 GHz to 105 GHz on the left side of the m1 point. Its S(1,1) value decreases from 1.1600dB at point m1 to about -1dB at 100GHz.To the right of point m2, the S(1,1) feature of the antenna starts to increase, and if it increases by 3dB from the m4 point of 109.5857GHz by -5.2736dB to the frequency of about m3 point at 117.5GHz, there is a 120GHz from the m4 point to the simulation in this paper with a bandwidth of about 10.4GHz bandwidth. This is a conclusion which shows that the present antenna structure satisfies the multi-band and ultra-wideband features.

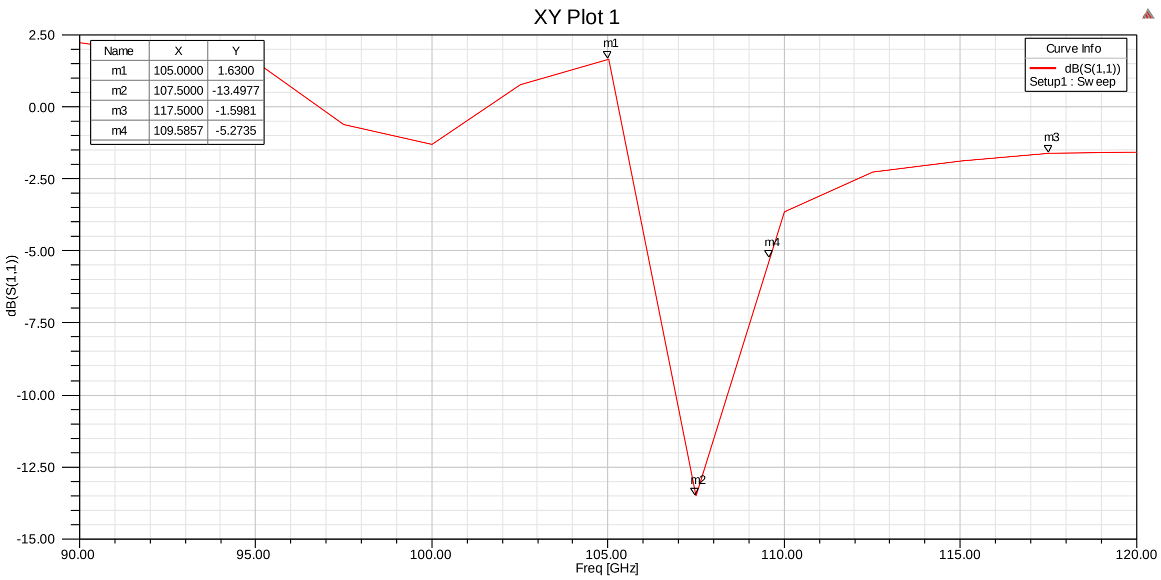


Figure 2. Antenna S(1,1) feature curve

Next, this paper simulates the amplitude-frequency properties on Z(1, 1), as shown in Fig. 3. The red and blue curves in Fig. 3 represent the real and imaginary curve feature of Z(1, 1), respectively. From Fig. 3, it can be seen that the Z(1, 1) characteristic re, im curve produces an abrupt change at 105 GHz (points m1 and m2). Similarly, at points m3 and m4, the reZ(1,1) and imZ(1,1) curves again produce mutation and gradually level off after m7,m8. The characteristic curves of the structure exhibit properties corresponding to those in Fig. 2. Simulations show that the structure has stable properties.

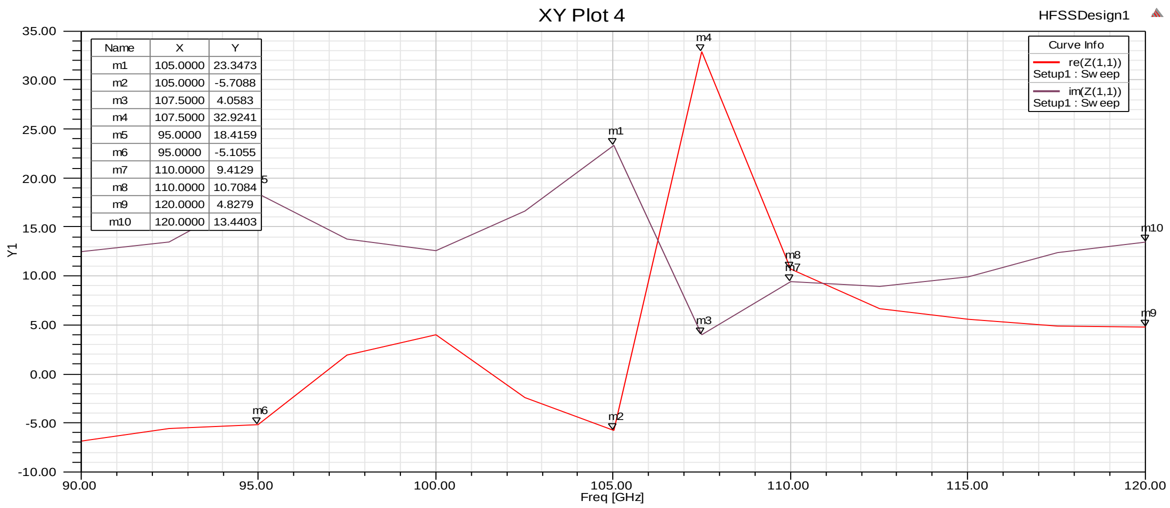
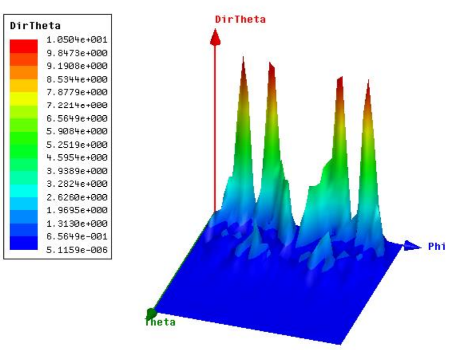
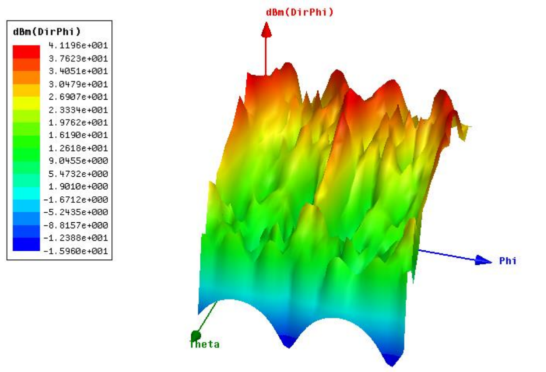


Figure 3. Z(1,1) feature curve of the antenna

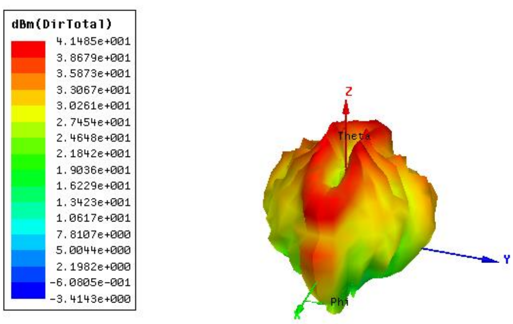
Meanwhile, the radiation polarisation directional plots of the antenna are simulated as shown in Figs. 4(a), 4(b) and 4(c), which are azimuthal angle theta, directional angle Phi, and the total directional gain, respectively. The 2 peak gains at azimuth angle theta (5 degrees to 15 degrees, 40 to 55 degrees) and direction angle Phi (0 to 90 degrees) is shown in Fig. 4 (a) and (b). The figure also indicates that the antenna structure in this paper has symmetrical properties for its polarisation direction radiation. Simulation results demonstrate that the antenna structure has excellent directionality.



(*a*)



（*b*）



（*c*）

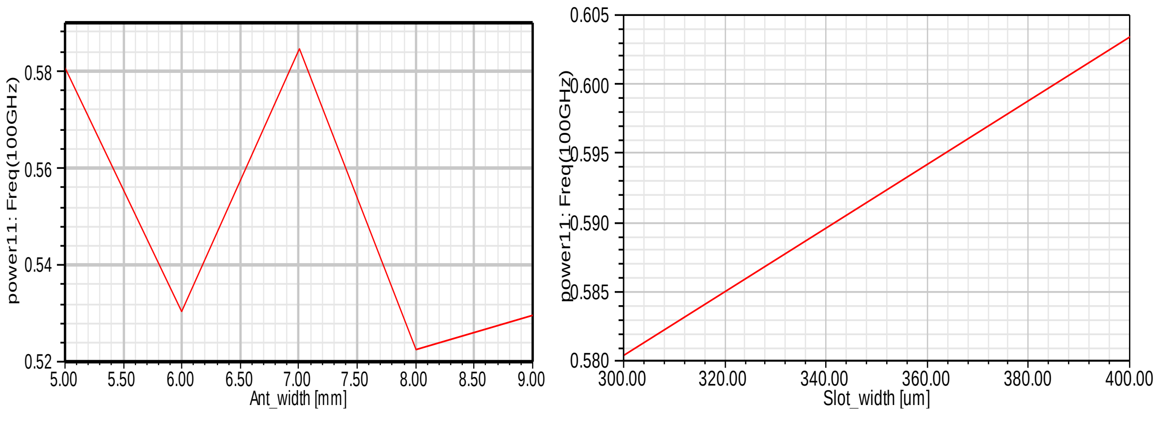
Figure 4. 3D polarization orientation of the antenna

Finally, in order to further understand the effect of slot width on the S(1,1) performance of the antenna to further optimise the antenna to lay a reference, this paper simulates the relationship between the length and width of the antenna as well as the width of the slot, and the results are shown in Table 2.

Table 2: S(1,1) properties of the antenna for different parameters

Ant_long	Ant_width	Slot_width	power11: Freq(100GHz)/ （dB）
16mm	5mm	0.3mm	0.580444
16mm	6mm	0.3mm	0.530361
16mm	7mm	0.3mm	0.584518
16mm	8mm	0.3mm	0.522612
16mm	9mm	0.3mm	0.529938
16mm	5mm	0.4mm	0.603373
16mm	6mm	0.4mm	0.564155

From Table 2, it can be observed that the S(1,1) radiated power of the antenna will also change when the antenna length is 16 mm, the width is between 5 mm and 9 mm, and the slot width is 0.3 mm or 0.4 mm, respectively, and the operating frequency is at 100 GHz. The result from Table 2 is that when the length of the antenna is 16mm and width is 5mm, and the slot width is 0.4, the antenna's S(1,1) power is the maximum, and is 0.6033. This is the comparison with the simulation in this paper which is the length of 16mm, width of 8mm, and slot width of 0.6mm, which indicates that the antenna's structure in this paper can be further optimized. Fig. 5(a), it can be noticed that the width of the antenna has a still larger effect on power of S(1,1), where it has a larger power gain of 0.58 dB and 0.582 dB at widths of 5 mm and 7 mm, respectively. here the same conclusions as in Table 2 are basically consistent. In addition, if we only observe from the width of the slot, as in Fig. 5(b), i.e., the S(1,1) radiated power of the antenna is simply linear when the width of the slot increases between 0.3 mm and 0.4 mm. More simulations observe that this conclusion only applies to a certain extent. For an antenna length of 16mm and a width of 8mm, the optimization of the slot width results in 0.64601mm, the difference between this conclusion and the slot width of 0.6mm in the paper is 0.04601mm.In view of the time-consuming nature of the simulation, this conclusion is not further verified in this paper.



(*a*) （*b*）

Figure 5. Optimisation of simulation parameters

4. CONCLUSION

The paper has designed a multi-frequency, ultra-wideband terahertz antenna, which is structured with a blade-internal slot structure. The antenna is characterised by simple structure and easy fabrication. By simulating the S(1,1), Z(1,1) and polarisation direction of the antenna, the results show that the structure has two operating bands near the excitation frequency of 105 GHz from 90 GHz to 105 GHz and from 109 GHz to 120 GHz, with the two bands spaced at 2.5 GHz.In addition, in order to further explore the factors affecting the antenna's structural characteristics, the paper also analyses the antenna's length, width and slot width on the performance of the antenna, and the relationship between them is basically clarified. In conclusion, the terahertz antenna designed in this paper is simple in structure, easy to fabricate and has high operating bandwidth as well as good directional characteristics, which has the value of further research and exploration needs.

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

Data Sharing Agreement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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