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# Design of Terahertz Detection Antenna With Fractal Butterfly Structure

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**ABSTRACT** Terahertz (THz) technology can be widely used in radar, remote sensing, homeland security and counter-terrorism, high-secret data communication and transmission, atmospheric and environmental monitoring, real-time biological information extraction, and medical diagnosis. It is the frontier of current research. However, most of highly sensitive THz detectors work in a relatively narrow frequency range. It attracts great attention to design a high-gain terahertz antenna which operates in a wide spectrum range. In this paper we propose a new structure of fractal butterfly antenna with high gain which can be used for broadband THz detection. This fractal butterfly antenna is constructed by independent fractal unit groups on butterfly antenna, which simplifies the antenna manufacturing process and reduces the manufacturing cost. The antenna can operate in the 0.1-10 THz frequency band, with impedance bandwidth of 85% resonated at 4.9 THz, return loss of as small as  $-33.59$  dB, and maximum gain of 16.95 dB. Among the antenna with 3 to 4 fractal unit groups, the best operation band of the antenna is 6.2-6.4 THz. The proposed fractal butterfly antenna can effectively improve the performance of terahertz detectors, and provide the possibility for detection research in higher frequency bands.

**INDEX TERMS** Terahertz technology, terahertz antennas, terahertz detector, terahertz patch antenna, resonant frequency.

## I. INTRODUCTION

Terahertz wave refers to electromagnetic wave with a frequency range of 0.1 to 10.0 THz and a corresponding wavelength of  $30 \mu\text{m}$  to 3 mm. It locates between the millimeter wave band and the infrared wave band in the electromagnetic spectrum. The low frequency part intersects with the millimeter wave, and the high frequency part intersections with infrared wave which makes terahertz technology is a frontier technology in electronics and photonics [1]. Terahertz wave has many excellent characteristics, such as low damage, high spectral resolution, and visualization. Due to its low power level and low ionizing effect on biological tissue, terahertz is not harmful to the organism, making it widely used in the medical field prospect. The resolution of the image increases as the wavelength decreases, and the resolution in the terahertz band is better than that in the

microwave region. Because of its short wavelength, terahertz wave can penetrate non-metal or non-polar materials and image objects behind them. Terahertz can pass through opaque objects, which can provide higher-definition imaging capability [2]. Moreover, the terahertz wave has the advantages of millimeter wave and the far-infrared wave at the same time. Compared with millimeter wave, the usable frequency band is wider, the beam direction is stronger, and the confidentiality and anti-interference performance are better. Compared with far-infrared wave, terahertz wave has higher efficiency and stronger penetrating power [3]. Based on the unique characteristics of terahertz wave, terahertz technology has broad application prospects in the fields of astrophysics, biomedicine, non-destructive testing, confidential communications, explosive detection, human security, fire monitoring and national defense security [4]–[9].

The terahertz science is in a transitional stage from macro-physics to microscopic quantum theory [10]. In the last 20 years, terahertz technology has enjoyed a real renaissance

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with great interest in applications in space science, molecular spectroscopy, medical imaging, and plasma diagnostics [11]. For these and future applications in terahertz communications and surveillance, efficient transmission (reception) of terahertz signals in free space is essential and requires appropriate antenna design [12].

Terahertz antenna is an indispensable part of detecting terahertz wave, and the performance of the terahertz antenna directly affects the quality of the entire detection system. Among the parameters of the antenna, the working bandwidth and gain of the antenna have big influence on the responsiveness of the terahertz detector [13]. At present, there are still many shortcomings in the research of terahertz antenna. Because the terahertz antenna works in the high frequency band, the size of the antenna is greatly reduced compared with regular antenna such as microwave antenna. Most of the terahertz antennas have relatively high energy loss and low manufacturing accuracy compared with microwave antenna. Therefore, improving the performance of the terahertz detector is a big challenge. In many ways to improve the performance of detector, coupling more energy is a proper solution. At present, many types of research on terahertz detectors have adopted various forms of antennas to enhance the coupling of antennas to terahertz wave [14]–[17], such as terahertz photoconductive antennas [14], terahertz active phased arrays antenna [15] and MLFMM algorithm terahertz lens antenna [16], etc. Among them, the floating antenna based on GaN field effect transistor improves the performance of the detector, but its manufacturing requirement is demanding. The asymmetrical geometric structure means that the impedance at resonance becomes higher, which causes the noise of the antenna to become larger and reduces the efficiency of the antenna [17]. Another high-gain lens antenna, which relies on the main light source being placed behind the collimated lens to increase the antenna directionality. However, as the extension length increases, the compactivity of the antenna is hard to satisfy, and it is difficult to integrate various main light sources into the lens, which increases the production cost of the antenna [17]. A high-gain coaxial control antenna was proposed in ref. [18]. However, the large range of relative dielectric constants of lens materials and the directivity of feed elements indicate that the antenna needs to increase the extension length to meet the specific directivity requirements.

Rajawat *et al.* proposed a terahertz microstrip patch antenna with return loss of  $-52.46$  dB, maximum gain of  $11.97$  dB, and operating frequency of  $0.23$  THz. But its disadvantage of the antenna is relatively large size, low gain and low operating frequency [19]. Ren *et al.* presented a bowtie antenna fed by a coplanar strip line for terahertz applications. The proposed antenna can cover  $1$ – $10$  THz range with averaged  $2.2$  dB higher gain of the dipole antenna [20]. Bansal *et al.* performed simulations on a variety of antennas and proved that the planar slot butterfly antenna was the best choice for wide-band applications. They also designed a graphene-based band-gap butterfly terahertz antenna with

a radiation efficiency of  $71\%$ , directivity of  $18.194$  dB and gain of  $17.529$  dB at a resonant frequency of  $11.1$  THz [21]. Thakur *et al.* designed a novel photonic bandgap substrate microstrip patch antenna for cancer detection that resonated at  $0.198$  THz with a reflection coefficient of  $-68.53$  dB and a gain of  $3.43$  dBi. The voltage standing wave ratio is  $1.0007$  [22]. Kazemi *et al.* proposed a dual-frequency characteristic terahertz antenna based on Koch fractal in which meta-material load were applied to the special structure of the fractal to obtain the dual-frequency characteristics. The maximum gain of the antenna was  $7.5$  dBi [23]. From the above studies, the antennas developed by former researchers also have some deficiencies, such as low working frequency, narrow band-width, high cost and low efficiency.

The butterfly antenna is one of the commonly used antennas for terahertz detectors. Compared with other terahertz antennas, the butterfly antenna has a simple structure and a stronger energy coupling ability [20], [21]. The structure of a butterfly antenna is similar to a dipole antenna, so it can be fed by an optical hybrid [24]. But the butterfly antenna is larger in size than other terahertz antennas, and the current flows in a single way when coupling energy. As the surface excitation current is small, most of the energy is reflected when the antenna is coupled. In order to solve this problem, this study fuses the structure and characteristics of the fractal antenna to the butterfly antenna. Because the fractal geometry has self-similarity ability and space self-filling ability [23], it can be successfully applied to antenna design for achieving multi-frequency operation and the effect of size reduction.

Most of the currently used terahertz antennas are modified by millimeter wave antennas, and lack of original designs for terahertz antennas. Therefore, in order to improve the performance of the terahertz detection system, an important task is to optimize the structural design of the terahertz antenna. This article proposes a brand-new antenna structure in view of the existing problems of the terahertz antenna at present. The design concept of the antenna is to perform fractal processing on the conventional butterfly antenna, which improves the gain and working bandwidth of the antenna while ensuring the advantages of the butterfly antenna. The advantage is that the antenna proposed in this article can work from  $0.1$  THz to  $10$  THz, and it can expand or contract the size of the antenna according to the wavelength of different frequency bands. Meanwhile, this design can meet the antenna size requirements of different application frequency bands and reduce the design cost of the antenna.

In brief, antenna plays an important role in detection and wireless communication. The performance of terahertz system is directly determined by the performance of antenna [25]. Previous researchers have designed many terahertz antennas. Their proposed antennas are either larger in size or narrower in bandwidth. Therefore, further studies of antenna structure are needed to meet the requirement of broadband and high gain in terahertz band.

In this article, the absorption efficiency of the fractal butterfly antenna is  $0.958$  according the simulation result. At the

resonant frequency of 4.9 THz, the impedance bandwidth and return loss are 85% and  $-33.59$  dB, respectively. The maximum gain can reach 16.95 dB. Higher gain and absorption of the antenna improves detector performance.

This paper is structured as follows: Section II describes details of the fractal butterfly antenna design. Section III illustrates the effects of different parameters on the performance of the fractal butterfly antenna. The simulation results of the fractal butterfly antenna are discussed in Section IV.

## II. DESIGN METHODOLOGY

### A. REVIEW OF ANTENNA DESIGN

The antenna structure proposed in our study is very innovative in the existing antenna structure design methods. At the beginning, we proposed an initial structure. In the initial structure, the conventional butterfly antenna and the fractal antenna were combined, and the nested structure of the fractal antenna was used to improve the shortcomings of the large-area oneness of the conventional butterfly antenna. In detail, when a large amount of current converges to a relatively small area due to the reception of large area of electromagnetic wave, the current density will be excessive and it will reduce the efficiency of energy coupling and lead to the rapid loss of absorbed energy. The relationship between the self-similarity of the fractal antenna nested structure and the multi-frequency characteristics of the fractal antenna can be used to improve those shortcomings of the butterfly antenna. The fractal method reduces the mutual coupling between the antennas formed by the array, and the electric field and current distribution on the surface of the antenna can be more concentrated, thus the antenna has higher gain and directionality. The nested fractal structure has good multi-frequency characteristics, which can increase the current flow area, so that the antenna can better accept and couple the energy. In our research, Koch fractal unit was applied to the common butterfly antenna. The transverse length of fractal butterfly antenna was the same as the length of ordinary butterfly antenna, and the spacing between the fractal unit was a set of variable parameters that could be adjusted according to the antenna size requirement in different bands, which improved the flexibility of antenna used in different bands and made it possible to have widespread applications. We preferred graphene as the substrate for the antenna. Because of the high electron mobility of graphene, terahertz antennas using graphene has better gain and greater peak return loss and are able to dynamically modify the operating frequency [26]. Graphene carrier mobility can easily reach  $1500 \text{ cm}^2/(\text{V}\cdot\text{s})$  and even up to  $25000 \text{ cm}^2/(\text{V}\cdot\text{s})$  under special conditions such as low temperature. The conductivity of graphene can reach  $1.12 \times 10^6 \text{ S/m}$  [27]. The use of graphene as an antenna material is shown in Figure 1.

The terahertz band requires antennas with a high directionality coefficient, wide bandwidth and high gain. Among them, the directional coefficient shows the antenna concentrated coupling energy characteristics; gain determines the input power concentrated coupling level of antenna. The

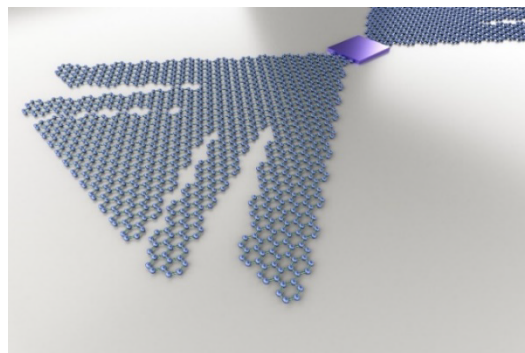


FIGURE 1. Schematic of fractal butterfly antenna material.

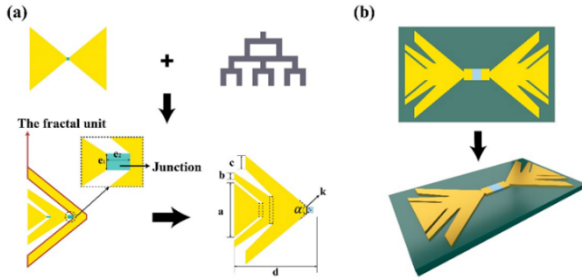
usage of high gain antenna can increase the effective coupling power under the condition of constant input power. Terahertz antennas are very different from conventional microwave antennas in feed, measurement equipment and antenna angle. Terahertz antennas are usually based on laser excitation through air or optical fiber, while conventional antennas such as RF/microwave antennas are excited by various similar feed lines, such as coaxial cables, microstrip, and CPW [28].

The antenna performance will be analyzed by the following parameters: Antenna Efficiency, which indicates the conversion efficiency of the antenna in energy; Voltage Standing Wave Ratio (VSWR), which is used to indicate whether the antenna and the radio wave transmitter match; Return Loss, which is one of the parameters to measure the quality of the antenna feed system; Scattering Loss ( $S(p1,p1)$ ),  $S(p1,p1)$  is the reflection coefficient of port 2 matching port 1, which is usually used to indicate the return loss characteristics, the larger the value of  $S(p1,p1)$ , the larger the energy reflected back from the antenna itself, so that the efficiency of the antenna is worse.

This paper proposes a fractal butterfly antenna which not only has high gain and wide bandwidth, but most importantly, the structure of the antenna is scalable and universal. It simplifies the design cost of the antenna.

### B. ANTENNA DESIGN

The fractal butterfly antenna proposed in our study adds the structural characteristics of the fractal antenna to the butterfly antenna. The mutual combination of the two antenna structures is meaningful in the field of antenna structure design. In order to determine the antenna geometry to achieve the desired resonant frequency, we used a method of overlapping the two antennas in silhouette and cutting off the excess, then optimizing and integrating the local parameters one by one. The characteristics of the proposed fractal butterfly antenna include simple structure, stable wideband performance and strong local near-field enhancement. The resonant frequency of the fractal butterfly antenna can be tuned by appropriately modifying and scaling the butterfly geometry, such as arm length, opening angle, and feed clearance width, as shown in Figure 2(a). The two variables  $e_1$  and  $e_2$  in Figure 2(a) are the key factors to control the antenna size. The quadrilateral



**FIGURE 2.** Antenna structure schematic ( $e_1$  and  $e_2$  in (a) are the patch junctions that articulate the fractal modules. These two variables control the antenna length and the size of the opening angle, which determine the size of the gap between the fractal units. Antenna model structure is shown in (b)).

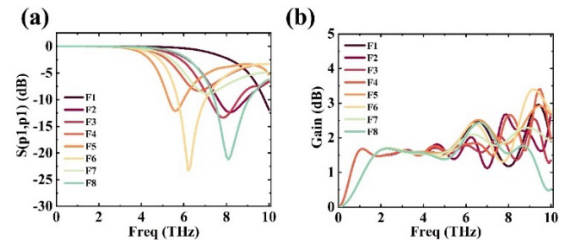
**TABLE 1.** Comparison of optimized results of each band.

Frequency Range (THz)	Value of $e_1$ and $e_2$ ( $\mu m$ )	Resonance Point (GHz)	Max Gain (dB)	VSWR	Return Loss of $S(p1,p1)$ (dB)
0.1-1	(16,5)	0.6	3.68	1.005	-27.17
1-2	(16,6)	1.7	4.96	1.006	-21.37
2-4	(8,2)	3.3	3.88	1.009	-26.81
4-6	(2,1)	4.9	19.87	1.003	-33.59
6-8	(1,0.5)	7.4	8.96	1.011	-23.38
8-10	(2.4,0.6)	8.6	9.04	1.002	-28.65

formed by  $e_1$  and  $e_2$  is used to articulate the fractal units,  $e_1$  can control the gap between every two fractal units of the fractal structure, and  $e_2$  can control the opening angle of the whole fractal butterfly antenna. That is, when the structural size of the fractal butterfly antenna is determined, the overall size of the antenna can be determined by modifying the variables  $e_1$  and  $e_2$  to meet the required working frequency band. This special structure feature allows the fractal butterfly antenna to operate in a wide frequency range of 0.1-10 THz and can be flexibly used in different frequency bands. It improves the application scope and universality of antennas, simplifies the processing of antennas, and reduces the design cost.

For the scalability of fractal butterfly antenna, we divided 0.1 THz to 10 THz into 6 small bands (0.1-1 THz; 1-2 THz; 2-4 THz; 4-6 THz; 6-8 THz; 8-10 THz). The optimal values of  $e_1$  and  $e_2$  in each band were optimized, and the resonance points and maximum gain of the fractal butterfly antenna in the six bands were calculated. A comparison of each band simulated data is shown in Table 1.

As can be seen from Table 1, for different band requirements, the fractal butterfly antenna only needs to adjust the values of  $e_1$  and  $e_2$  to control the antenna opening angle and arm length, and then achieve the best antenna size in the band. It also proves that in the range of 0.1-10 THz band, the fractal butterfly antenna size can be adjusted according to the size requirements of antennas in different frequency bands to achieve the best antenna coupling efficiency. The scalability of the fractal butterfly antenna allows it to be



**FIGURE 3.** Comparison of  $S(p1,p1)$  (a) and Gain (b) for 8 groups of tested antenna structures.

flexibly applied to multiple frequency bands, and reduces the design cost of the antenna.

For the number of fractal units used, we increased it from 1 to 8 and conducted simulations for each of them, and the results were analyzed. As shown in Figure 3(a), it is a comparison of the Scattering Loss of 8 groups of antennas. It can be seen from Figure 3(a) that as the number of fractal units increases, the resonance point of the antenna is approaching the central frequency point. However, we find that when the fractal unit of the antenna in a certain range of size increases to a certain number, the resonance point will start to move away from the central frequency point. It indicates that the number of fractal units used also affects the performance of fractal butterfly antenna. And as the number of fractal units increases, the size of the antenna also increases, which in turn affects the selection of the operating band of the antenna. It means that for different operating bands there will be a corresponding number of fractal units, not the more the better. As shown in Figure 3(b), it is the Gain curve corresponding to 8 groups of antennas. It can be seen that the first half of gain relative to the entire band changes a little. Increasing the number of fractal units mainly affect the second half of gain. It is probably due to the higher frequency in the second half of the band, and the antenna size is becoming smaller in size by the wavelength increases. Smaller size will affect the coupling efficiency of the antenna for large area of terahertz wave, but due to the increase in the number of fractal units, the required current flows through a longer path, and the energy that can be coupled per unit of time will increase. For the closer to 10 THz part of the curve, fluctuation amplitude is bigger, which is likely to be caused by the antenna impedance matching problem. It requires subsequent work to continually study in depth. The combination of multiple fractal units can be in various forms, which is a major challenge for the next work to be studied. Specific research directions can be referred to antenna structures that are relatively mature, such as log-periodic antennas and spiral antennas. Both antennas have involved the gap problem and period variation law of antenna.

After analyzing the simulated data of 8 groups of antennas, we found that when the number of fractal units was 3-4, the antenna appeared to have a trend of wide-band. As shown in Figure 4(a), it is the Return Loss of the antenna when the number of fractal units is 3 or 4. When the fractal unit is 3 pairs, the antenna resonates at 6.2-6.3 THz with Return Loss

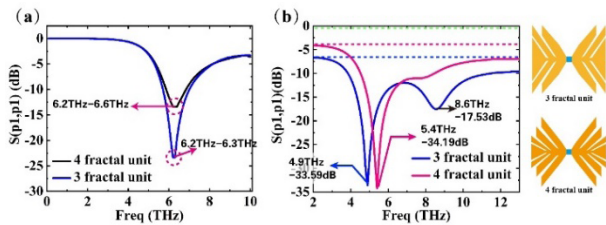


FIGURE 4. Return loss of 3 pairs fractal unit and 4 pairs fractal unit antennas.

of  $-23.33$  dB. And when the fractal unit is 4 pairs, the antenna resonates at 6.2-6.4 THz with  $-13.37$  dB Return Loss. This indicates that the fractal butterfly antenna structure proposed in this research may become a wide-band antenna. For these two antennas, a comparison of the Return Loss obtained by parameter optimization is shown in Figure 4(b). As can be seen from the Figure 4(b), the antenna with 3 fractal units resonates near the center frequency of 4.9 THz after parameter optimization, the maximum Return Loss reaches  $-33.59$  dB, and two peaks appeared. The antenna with 4 fractal units resonates near the center frequency of 5.4 THz, the maximum Return Loss reaches  $-34.19$  dB, and there are also two peaks appeared. But the second peak amplitude is very small. In general, the overall  $S(p_1, p_1)$  values of the two antennas in the simulated frequency range have been reduced compared to those before the parameter optimization, which indicates that the antennas have better performance in a relatively wide bandwidth.

The increase in the number of fractal units requires overall sizing by modulating the  $\epsilon_1$  and  $\epsilon_2$  values of the previous fractal unit. These details change can affect the performance of the antenna. The relationship between the number of fractal units and the range of the operating band, and the relationship between the number of fractal units and the parameters of  $\epsilon_1$  and  $\epsilon_2$  are still under study. The main work of this experiment is to find out how to tune the better antenna structure parameters in the determined operating frequency band. The antenna structure proposed in this study has more extension possibilities, and the field involved will also be possible to expand from detection to RF communication. It also offers an alternative antenna structure option for more researchers. In general, the proposed antenna structure has considerable scope for exploitation.

Figure 2(b) shows the structure of fractal butterfly antenna. The geometric structure combines the geometric features of conventional butterfly antenna and fractal antenna. Based on the conventional butterfly antenna structure, two groups of separate wings were constructed, which were designed to change the path of the current, so that the current path for reaching half-wavelength at a specific frequency was reduced, and it was increasing the efficiency of the coupling to terahertz wave. In the near field ( $d < \lambda/2\pi$ ), the double-sided arm structure of the antenna subtype element is a channel similar to a semicircular ring. This is similar to the multi-loop nested structure, equivalent to a large current

TABLE 2. Geometric parameters of the final antenna structure.

Antenna	Parameters					
Fractal Butterfly Antenna	$a(\mu m)$	$b(\mu m)$	$c(\mu m)$	$d(\mu m)$	$k(\mu m)$	$\alpha(^{\circ})$
	8	3	6	7	0.5	60

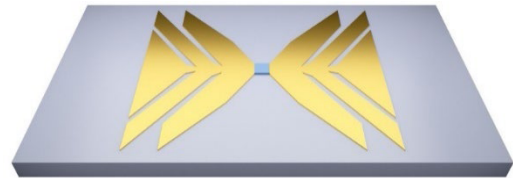


FIGURE 5. Optimized final antenna structure.

low voltage radiator. This structure mainly produces a low impedance magnetic field. Depending on the shape of the antenna, plane waves can actually be generated in the near field if the antenna impedance is well matched. The antenna with this special structure can use the arms on both sides to enhance the field strength in near field and accelerate the dipole oscillation. The constantly changing charge accumulates in the continuous bending of the fractal structure, causing the fluctuating voltage signal generated in the center of the antenna to fluctuate. When the frequency of the output voltage signal is the same as that of the received electromagnetic wave, the oscillating dipoles within the antenna are all uniformly incorporated into the central receiver. For our research, the parameters were optimized for the resonant frequency of 4.9 THz. In the last optimized design, the antenna size and performance can be adjusted by changing the length of the two groups of wings, the opening angle between the wings and the width of the wings to achieve the requirement of the detector's detection sensitivity of terahertz wave. The final optimized sizes are shown in Table 2.

In the process of parameter optimization, the arm length of the fractal butterfly antenna was reduced with the aim of achieving that the center resonant frequency could be in the terahertz range. By modifying the geometry of the antenna, the gain was improved compared to the previous one. The fractal unit of this fractal butterfly antenna was resized based on the initial sizes, so that it could achieve the expected results. In addition to the structure of the antenna itself, which affects the performance of the detector, the height of the substrate also affects the effectiveness of the antenna, thus, the performance of the detector. The height of the substrate has an effect on the absorption cross section, and the maximum value of the absorption cross section needs to be obtained by varying the substrate height of the fractal butterfly antenna [29]. After determining the optimal substrate height, each size variable of the fractal butterfly antenna was optimized to obtain the final antenna size as shown in Table 2. The final obtained antenna structure is shown in Figure 5.

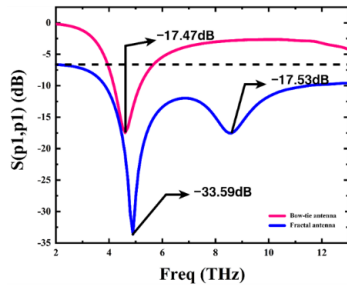


FIGURE 6. Scattering loss comparison of ordinary butterfly antenna and fractal butterfly antenna.

C. SIMULATION RESULTS

1) ONE ELEMENT

The scattering loss of ordinary butterfly antenna and fractal butterfly antenna is shown in Figure 6 by ANSYS HFSS simulation. It can be seen that the resonant frequency of the fractal butterfly antenna is higher than that of the ordinary butterfly antenna, and the Scattering Loss of the center resonant frequency is reduced from  $-17.47$  dB to  $-33.59$  dB. The antenna after fractal has two peaks, and the overall Scattering Loss value is reduced. Therefore, it is concluded that the Scattering Loss of the fractal butterfly antenna is lower than that of the ordinary butterfly antenna, which indicates that the fractal effect is good and the overall performance of the antenna has been improved after fractalization. It means that if both antennas operate at the same frequency, the size of this antenna can be eventually reduced due to the fractal technique, which will be very useful to solve the problem of antenna miniaturization. And it makes the antenna have a wide-band performance, which is very beneficial for the antenna to work on the detector.

An important parameter to measure the antenna performance is the absorption efficiency of the antenna  $\eta_{EM}$ , which is defined as the ratio of the energy absorbed by the antenna to the energy of the incident wave, and in antenna modeling, it can be expressed in another way as:

$$\eta_{EM} = P_{ab}/P_{in} = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (1)$$

where  $P_{ab}$  is the absorbed energy by the antenna,  $P_{in}$  is the incident power,  $|S_{11}|$  is the reflection coefficient of the incident wave,  $|S_{21}|$  is the transmission coefficient, because the fractal butterfly antenna has only one port as the receiving antenna, so the value of  $|S_{21}|$  is set to 0 here.

In the antenna simulation software ANSYS HFSS, the absorption efficiency of the antenna can also be obtained by building a 3D antenna model simulation as shown in Figure 7(a).

According to the simulation results, the smaller the simulation parameters, the smaller the reflection coefficient  $|S_{11}|$ . And according to (1), the larger the absorption efficiency of the antenna  $\eta_{EM}$ , the better the performance of the antenna. The fractal butterfly antenna proposed in this paper has an absorption rate of 0.945, which indicates that the proposed antenna can effectively improve the response rate of the detector.

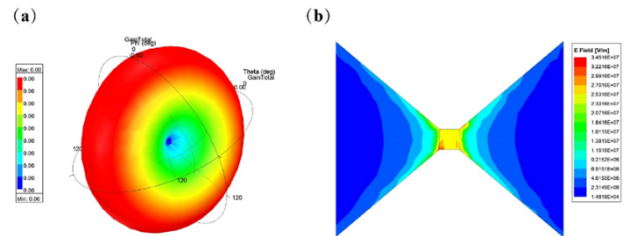


FIGURE 7. (a) 3D simulation of fractal butterfly antenna energy absorption efficiency; (b) Electric field energy distribution of fractal antenna.

The proposed fractal butterfly antenna can meet the requirement of miniaturization of antenna size in terahertz band and achieve relatively high gain. As shown in Figure 6, it can be seen that the efficiency of the antenna increases after performing fractal processing on the butterfly antenna. In addition, the improved performance of the proposed antenna is demonstrated in terms of VSWR, Directivity, and Input Impedance. The  $S(p1,p1)$  value of ordinary butterfly antenna is as low as  $-17.47$  dB, while in the range of 0.1 THz to 10 THz, meanwhile, the fractal butterfly antenna has a lower  $S(p1,p1)$  value of  $-33.59$  dB at a resonant frequency of 4.9 THz. As shown in Figure 7 (b), the simulated normalized electric field distribution of the fractal butterfly antenna at 4.9 THz frequency with strong near-field enhancement in the feed gap, which indicates that the electric field energy is well coupled to the center of the device.

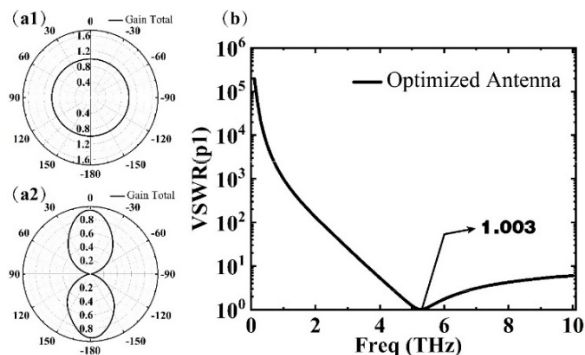
2) SIMULATION RESULT ANALYSIS

As previously noted, in our research the performance characteristics of the antenna are studied in terms of  $S(p1,p1)$ , VSWR, and Input Impedance. The reflection coefficient or return loss of the antenna is the ratio of the incident power to the reflected power, measured in decibels. It is expressed by  $S(p1,p1)$  (dB). For the effective antenna,  $S(p1,p1)$  should be less than  $-10$  dB [30]. At the resonance point of 4.9 THz, the return loss of the antenna reaches  $-33.59$  dB, and the impedance bandwidth of  $-10$  dB reaches 85%. The return loss within its resonant frequency point is much less than  $-10$  dB, which means that the fractal butterfly antenna maintains good antenna impedance performance in the impedance bandwidth. Figure 8(a) shows the directions of H-plane (a1) and E-plane (a2), and Figure 8(b) shows the simulated VSWR after fractal butterfly antenna optimization.

Ideally, the VSWR should be equal to 1, indicating that the antenna receives 100% power and zero reflection [31]. The VSWR value of fractal butterfly antenna proposed in this simulation is 1.003. The results show that the VSWR of the antenna is reduced by fractalizing the common butterfly antenna. In summary, the performance characteristics of the proposed fractal butterfly antenna are improved in all aspects compared to the common butterfly antenna.

III. DATA COMPARISON AND ANALYSIS

Terahertz detectors can be divided into photodetectors and photothermal detectors [32], in which photodetectors are used



**FIGURE 8.** Fractal butterfly antenna E plane (a1) and H (a2) plane directions; (b) VSWR of fractal butterfly antenna.

to sense incident terahertz wave by using the electrons in the device. But these detectors can only detect the terahertz band below 2 THz due to the limitation of the cutoff frequency of the detector device, leaving a large number of terahertz blank bands that cannot be fully used. In order to break the limit of detection frequency and make full use of the frequency of terahertz band, a grid antenna that can operate at room temperature and detect the incident terahertz radiation by detecting the temperature change caused by terahertz wave [33] has been proposed in the reference [34]. The proposed grid antenna in reference [34] is formed by extending the grid of an NMOS tube, and the length of the antenna is one-fourth of the desired incident terahertz wave wavelength. The two grids of NMOS tubes are used as antenna arms to form a pair of dipole antennas. This antenna can be designed to the required size according to the incident terahertz wave wavelength, to achieve the filtering function of specific terahertz wave, and the antenna is simple to make in the manufacturing. But the antenna’s own performance is easily interfered by materials. The antenna proposed in the reference [35] is innovative in structure, the proposed antenna is designed based on rectangular radiating patch with rectangular slot, T-slot, double T-slot and double E-slot antennas using TSMC 40 nm CMOS process. By changing the slotted structure and position, we can gradually reduce the size of antenna and optimize the performance. However, the slotting will reduce the coupling efficiency of the antenna, and the tuning of this antenna is very difficult. In the reference [36], a wide-band, efficient and re-configurable antenna simultaneously with double rectangular rings for THz communications has been presented. In this proposed antenna topology, the width of the rings and the distance between them are used to achieve impedance matching and optimal efficiency. In [4] demonstrates a polyimide based optical rectangular patch antenna capable of operating at THz frequencies. The effects of variation in the substrate width on the return loss and percentage bandwidth has also been observed. And it has been concluded that with increase in the substrate width, the minimum return loss and impedance bandwidth of antenna decreases significantly. After comparing the existing terahertz antenna models, the antenna proposed in this article

**TABLE 3.** Comparison of multiple antenna performance parameters.

Types of Antenna/Performance	Max Gain (dB)	Bandwidth (THz)	Impedance Bandwidth (%)	Return Loss (dB)
[34]	15.328	0.1-1	32.00	-15.34
[35]	2.450	1-3	26.00	-24.00
[36]	5.220	0.1-1	5.85	-81.18
[4]	3.870	0.1-3	37.50	-59.97
Fractal Butterfly Antenna	16.950	0.1-10	34.40	-33.59

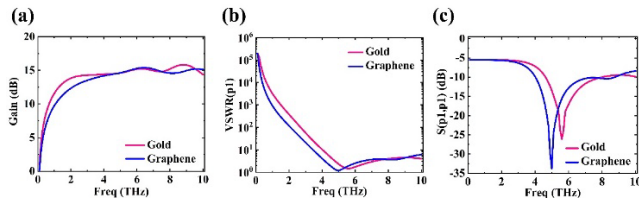
has better performance characteristics, smaller size, and very impedance bandwidth. The proposed structure has been compared with previously reported terahertz antenna structure, which is tabulated in Table 3. The parameter considered for this comparison is the antenna dimension, return loss and percentage bandwidth.

Table 3 is a comparison of performance parameters for the above three antennas and fractal butterfly antenna. It can be seen from Table 3, that the fractal butterfly antenna not only has better performance compared with the grid antenna and slotted antenna, but also circumvents the shortcomings of the grid antenna and slotted antenna in both material and structure. Although the antenna proposed in reference [34] has the highest absorption and the antenna proposed in reference [35] has the highest gain, they have a narrower bandwidth compared to our proposed antenna. It can be concluded that the proposed antenna has a wider impedance bandwidth than the existing antenna. Though Li *et al.* [34] proposed antenna that has smaller in size, and Ying *et al.* [35] proposed antenna that has minimal return loss, they have narrow band-width compare to the proposed antenna. The impedance bandwidth of the proposed antenna is 85% at 4.9 THz resonant frequency, which is comparatively higher than the previous works. This large bandwidth in the terahertz regime makes it a good candidate for rapid detection of room temperature in the future. In order to study the effect of material properties on antenna performance, two different materials, gold and graphene, are used to simulate the proposed fractal butterfly antenna. And the performance of our fractal butterfly antenna which using graphene material is also compared with other two antennas which proposed in reference [29] and [37]. The comparison results are shown in Table 4, where gold and graphene 1 are the simulated results of the fractal butterfly antenna, and graphene 2 and 3 are the antenna performance parameters of references [29] and [37]. Figure 9 shows the simulated results (Gain, VSWR, S(p1,p1)) of the fractal butterfly antenna using gold and graphene as materials, respectively.

Through the above comparison, the performance of the fractal butterfly antenna is better than the other two antennas under the same material, which proves that the fractal structure improves the performance of the common butterfly antenna and optimizes the shortage of the antenna in the structure. The antenna with graphene material has better performance than the antenna with gold material. However, for

**TABLE 4. Comparison of multiple antenna made by different materials.**

Antenna Materials	Antenna Performance Parameters			
	Max Gain (dB)	Return Loss (dB)	Efficiency (%)	Substrate Height ( $\mu\text{m}$ )
Gold	15.40	-15.59	93.00	2.0
Graphene 1	16.95	-33.59	94.50	2.0
Graphene 2 in reference [29]	2.80	-27.00	92.00	37.5
Graphene 3 in reference [37]	3.55	-36.10	82.05	75.0



**FIGURE 9. (a) Gain; (b) VSWR; (c) S(p1,p1) comparison of gold and graphene.**

the proposed fractal butterfly antenna, the simulated results of antenna made by graphene do not differ much from antenna made by gold, which indicates that the antenna structure proposed in this paper can weaken the difference of antenna performance caused by material. The structure of the antenna can be applied to most materials, providing more possibilities for material selection of terahertz detectors. In other words, the fractal butterfly antenna proposed in this article has a universal applied capability, and it can work under different material selection and maintain good antenna performance. This could reduce the production cost of the antenna. After comparing the existing terahertz antenna models, the proposed antenna in this paper has better performance characteristics, smaller size, and larger impedance bandwidth.

**IV. CONCLUSION**

We have proposed a new structure of high gain, wide bandwidth and miniaturized fractal butterfly antenna operated in the frequency band of 0.1~10 THz. It can be flexibly adjusted by its own size according to the applied frequency band range, which makes it operate in different frequency bands and reduces the process design cost of the antenna. The advantage of the special structural fractal butterfly makes it possible to achieve good antenna performance parameters by its own structural adjustment according to the applied frequency band. The designed fractal butterfly antenna resonates at a frequency of 4.9 THz with minimum return loss of -33.59 dB, maximum gain of 16.95 dB, antenna efficiency of 96%, and VSWR of 1.003. Compared with the ordinary butterfly antenna, the fractal processing of the butterfly antenna combines the multi-frequency characteristics of the fractal antenna to further enhance the overall directionality of the antenna while meeting the high gain. The proposed fractal butterfly antenna improves the performance of the butterfly antenna and increases the gain of the terahertz antenna. It can

be used in various applications such as medical imaging, tumor and cancer cell detection, explosive detection, chemical detection, and homeland defense systems. The antenna we proposed has enhanced gain in performance, reduced size in structure and can be flexibly spliced according to design requirements. And due to the structural characteristics of the antenna itself, the performance impact caused by the material characteristics can be greatly reduced, and it can be used in a variety of materials. This provides more choice for the use of antenna materials with great development possibilities. Therefore, the designed antenna not only reduces the cost of design, but also saves a lot of resources in process production and production materials. But terahertz source technology is still in development. There is no one or a set of terahertz source with such a wide-band (0.1-13 THz) in the world. Meanwhile, the terahertz antenna manufacturing process needs improvement. With fast developing terahertz technology, the experimental results of proposed antenna can be obtained in the future.

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