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Antenna Design and Simulation Analysis for GaN HEMT Terahertz Receivers

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Abstract: *This project focuses on the design and simulation of antennas for GaN HEMT terahertz receivers. Three types of antennas (two-port asymmetric antenna, 3D butterfly antenna, and fractal butterfly antenna) were designed, and their S-parameter models were analyzed using CST STUDIO SUITE. The models were imported into AWR to simulate the AC response at approximately 4 THz, thereby identifying the fractal butterfly structure as the most effective antenna. Simulation results include S-parameter analysis, verification of the Voltage Standing Wave Ratio (VSWR), and power attenuation measurements. The fractal butterfly antenna achieves optimal performance in directivity, isolation, and near-field enhancement, thereby meeting the requirements of engineering-grade terahertz receivers.*

Keywords: *Terahertz antenna; Fractal butterfly structure; S-parameters; VSWR; Responsivity; GaN HEMT*

1. Introduction

Terahertz receivers are critical components for next-generation high-speed wireless communication systems with data rates exceeding 10 Gb/s[1]. While much research has focused on terahertz or sub-terahertz frequency bands, relatively little research has examined devices operating in the several- to tens-terahertz range, mainly due to the stringent manufacturing requirements for terahertz antennas in this band. Dipole antennas fabricated by physical vapor deposition (PVD) face limitations in manufacturing multilayer and precisely three-dimensional complex structures, and mass-produced semiconductor processes cannot meet the precision requirements for frequencies in the tens of terahertz range[2]. A study on terahertz antennas shows that an optimization method for butterfly antennas at 4 THz can maximize antenna gain; thus, this paper selects 4 THz as the target frequency.

Self-mixing technology has grown rapidly in recent years, and electron ballistic transport contributes to the nonlinear properties of nanoscale plasmonic waves, enabling HEMT FET channels to respond to frequencies significantly higher than the device's cutoff frequency. HEMTs can be used for both resonant and non-resonant terahertz detection, with performance tunable by gate voltage, making suitable antenna design essential to enhance terahertz wave detection efficiency.

The Friis transmission formula is commonly used to calculate transmit and receive power in a transmission system:

$$P_R=\frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}$$

Where G_T is transmit antenna gain, G_R is receive antenna gain, P_T is transmit power, P_R is receive power, λ is signal wavelength, and R is the distance between transmit and receive antennas[3]. Reducing receive-antenna loss increases received signal power; therefore, the main objective of the receive-antenna system is to improve the received power level and detector responsivity while maintaining satisfactory speed and noise levels.

2. Receiver Antenna Design

2.1. Two Port Antenna Structure

Conventional terahertz antennas typically use dipole antennas; this paper employs a two-terminal

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system composed of two dipole antennas. Terahertz waves enter through the HEMT gate, pass through the source, and exit through the drain, with the design aiming to concentrate antenna energy into the source plate to enhance resonance with the 2DEG electron cloud cavity[4]. The antenna design focuses on reducing input return loss and output feedback coefficient to retain more energy in the device for induced current generation and higher responsivity.

The measurement circuit uses terahertz wave input through the device source electrode, transmitted to the gate electrode via the antenna's S-parameter model. Gate bias voltage affects 2DEG depth and concentration (higher bias enhances terahertz response), and the self-mixing effect of asymmetric antenna structures can enhance HEMT-induced DC, so this paper adopts and optimizes a dual-port antenna structure.

2.2. Asymmetric Antenna Design

A simple dipole antenna has a length of approximately 1/4 wavelength (calculated as the speed of light divided by frequency), with a gap determined by dividing the half-wavelength antenna length by an empirical value (usually equal to antenna length). The dual-port system consists of two dipole antennas: Port 1 (source-drain) and Port 2 (gate-drain)(Fig. 1).

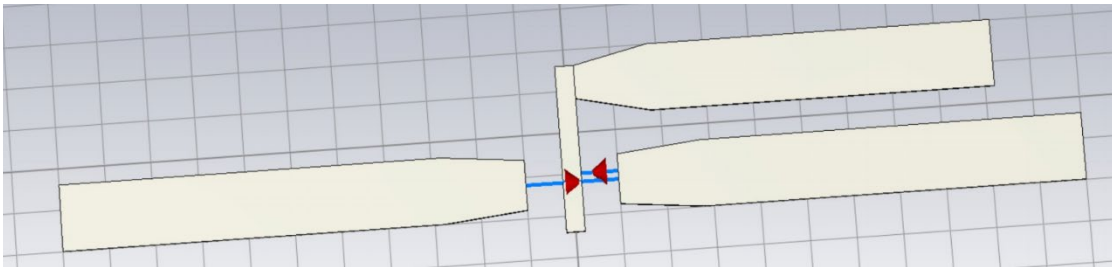

Fig. 1 Asymmetric antenna structure

At 4 THz, the gate section of the asymmetric antenna is approximately 47 microns long, with source and drain antennas set to 50 microns (accounting for input loss), resulting in an antenna spacing of approximately 200 nanometers. However, the 2D asymmetric structure causes a gap between Port 1 and Port 2 in the HEMT, resulting in losses in the transmission coefficients (S12, S21).

2.3. Butterfly Structure 3D Antenna Design

To mitigate transmission losses, the 2D structure is optimized into a 3D double-layer butterfly antenna, with HEMT electrodes on different layers[5]. The 3D structure enables gate-source resonance, yielding better performance than asymmetric antennas while retaining z-axis resonant structure to improve responsivity. The reverse-hedged butterfly structure improves input-output signal isolation (shown in the far-field image in Fig. 2), ensuring input energy retention.

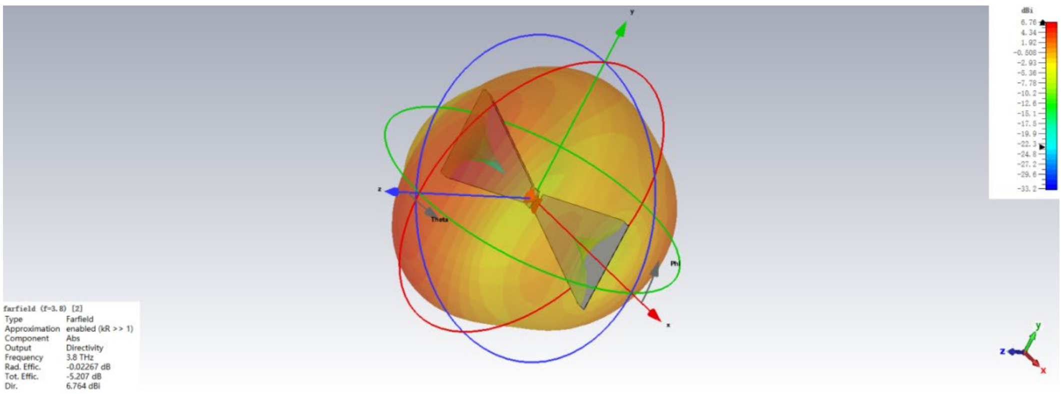

Fig. 2 Farfield image of detection terahertz wave by butterfly antenna at 3.8 Thz

2.4. Fractal Butterfly Structure 3D Antenna Optimization

The 3D butterfly structure is further optimized by integrating fractal antenna characteristics—achieved by overlapping profiles, removing excess parts, and optimizing local parameters. The fractal

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butterfly antenna features a simple structure, stable broadband performance, and substantial local near-field enhancement, with its resonant frequency tunable via adjustments to arm length, opening angle, and feed gap width[6].

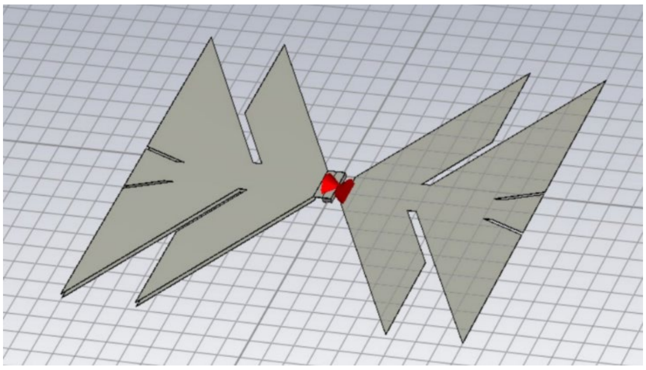

Fig. 3 Fractal butterfly antenna structure

Increasing fractal elements requires adjusting overall size via fractal spacing, which affects antenna performance[7]. This paper selects the optimal-performing antenna structure for reproduction and parameter optimization; the final structure (Fig. 3) meets terahertz-band miniaturization requirements, with higher gain and stronger effective electric-field coupling at the feed gap (as evidenced by normalized electric-field distribution simulations at 3.8 THz).

3. Simulation Results and Analysis

Antennas of different structures were tested and optimized at the same frequency to compare performance via S-parameters, VSWR, and power attenuation analysis:

3.1. Asymmetric Antenna Simulation Results

Manufacturing process limitations (55 nm/180 nm process) require setting the antenna gap to 200 nm (four times the resolution), leading to poor directivity, isolation, and transmission characteristics (signal energy cannot effectively enter or remain in the device[8]). However, return loss (S11) and transmission factor (S22) are approximately 15 dB as shown in figure 4, making it marginally suitable for engineering applications.

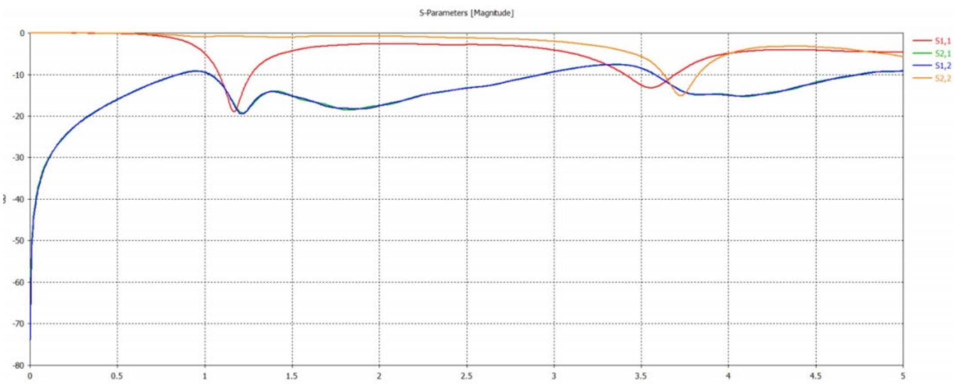

Fig. 4 S-parameters of asymmetric antenna working under 4 Thz

3.2. Butterfly Antenna

Butterfly antennas exhibit better directivity and isolation than asymmetric antennas, with lower return loss and transmission coefficients: S11 = -18.09 dB, S22 = -11.98 dB, S21 = S12 = -1.99 dB. At 0.5 W input power, power attenuation at the target frequency is ≤3 dB, and VSWR at the target frequency is approximately 1.2 (meeting the engineering-grade requirement of VSWR < 2 for good impedance matching) as shown in figure 5~7.

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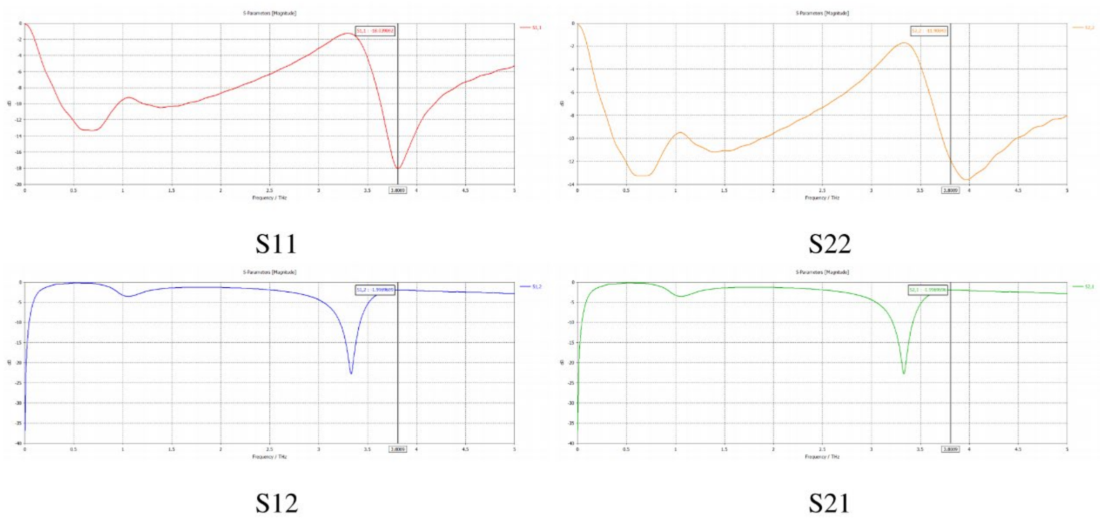

Fig. 5 S-parameter result of butterfly structure antenna

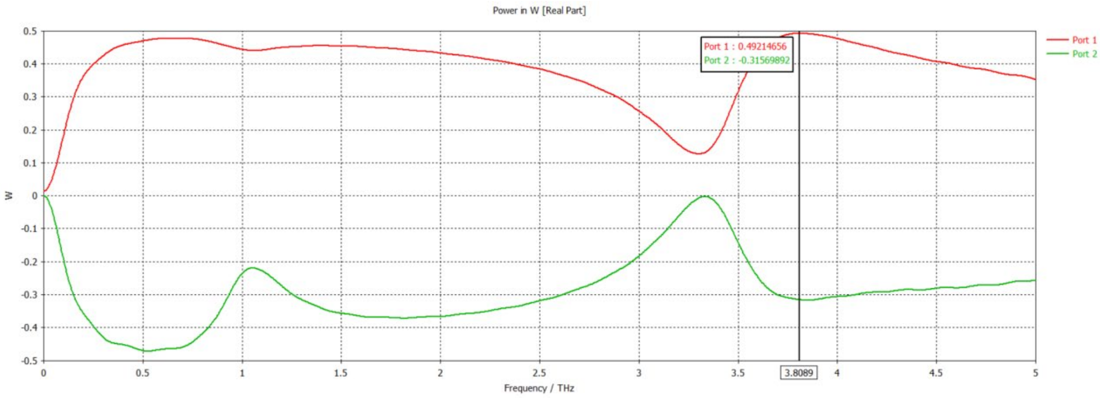

Fig. 6 Power attenuation of butterfly structure antenna

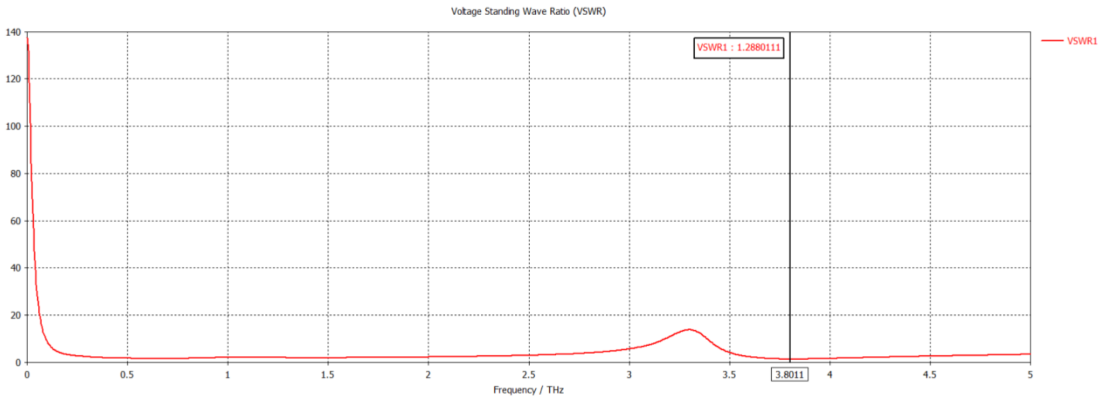

Fig. 7 VSWR of butterfly structure antenna

3.3. Fractal Butterfly Antenna

The fractal butterfly antenna outperforms conventional butterfly antennas: S11 = -18.65 dB, S22 = -16.58 dB, S12 = S21 = -1.89 dB, power attenuation ≤3 dB, and VSWR ≈1.12 at 3.9 THz. When applied to an ideal HEMT model, the responsivity is significantly higher than that of asymmetric antennas, making it suitable for practical terahertz antenna prototyping at 3.9 THz as shown in figure 8~10.

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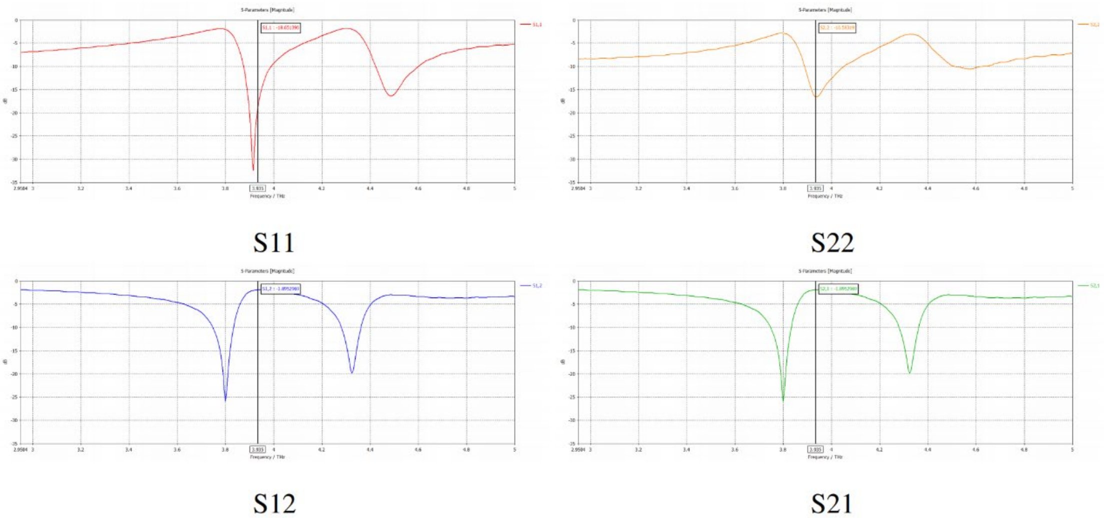

Fig. 8 S-parameter result of fractal butterfly structure antenna

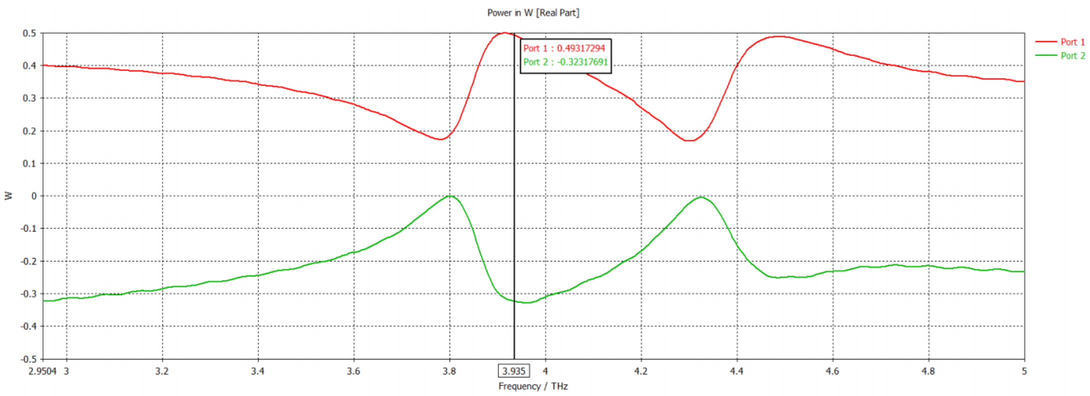

Fig. 9 Power attenuation of fractal butterfly structure antenna

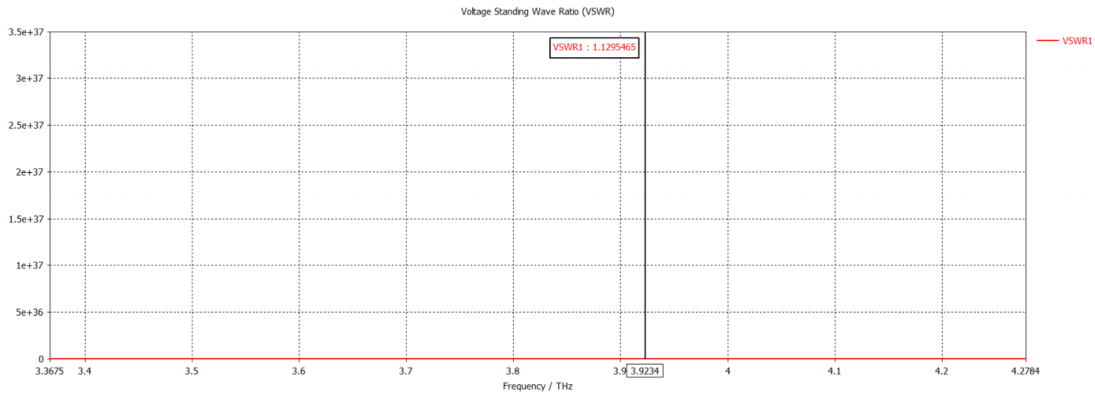

Fig. 10 VSWR of fractal butterfly structure antenna

4. Conclusions

This project successfully designed three types of antennas for GaN HEMT terahertz receivers and conducted comprehensive simulation analyses. The fractal butterfly antenna was identified as the most effective, with superior S-parameters (-18.65 dB for S11, -16.58 dB for S22), low VSWR (1.12 at 3.9 THz), and minimal power attenuation (<3 dB). It meets engineering-grade application requirements with a compact structure[8], substantial near-field enhancement, and stable broadband performance, thereby addressing manufacturing challenges for 4 THz-band terahertz antennas.

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