



Design of a Compound Reconfigurable Terahertz Antenna Based on Graphene

Zhao Jin¹ · Yu Rong¹ · JingDong Yu¹ · Fei Wu¹

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Abstract

In this paper, a terahertz dipole antenna with compound reconfigurability is designed, which possesses the capability of controlling frequency, radiation pattern, and polarization state. A capacitive load loop (CLL) made of graphene–metal composite material is applied around a pair of mutually orthogonal graphene-based dipole antennas. By controlling the bias voltage, the surface conductivity of graphene is adjusted, enabling compound reconfigurability. The graphene strips on the CLL provide a high degree of freedom for the radiation characteristics of the antenna. By adjusting the combination of chemical potentials of graphene, the operating frequency of the antenna can be reconfigured within the range of 1.40 to 1.84 THz. Moreover, it is possible to control the antenna to achieve directional radiation with four beams (0°, 90°, 180°, 270°) in the XOY plane at 1.75 THz, and ranging from 1.68 to 1.81 THz, it can be reconfigured to achieve controllable RHCL or LHCL.

Keywords Compound reconfiguration · Terahertz · Dipole antenna · Graphene

Introduction

On one hand, with the increasing demand for advanced wireless communication networks in the application of the 6th generation mobile communication (6G), the existing spectrum utilization is becoming more congested and is gradually unable to meet the rapid development of military and civilian technologies. Developing new frequency bands has become a feasible solution to alleviate this issue [1]. The terahertz spectrum ranges from 0.1 to 10 THz, which is a transition band from electronics to photonics. It possesses characteristics such as high-speed data transmission, large channel capacity, improved security, and anti-interference capability. Utilizing terahertz for constructing ultra-high-speed wireless communication systems has emerged as a promising solution to address the challenges of high data rates [2, 3]. On the other hand, the next-generation communication systems often require enhanced capabilities to adapt to the surrounding environment and enable spatial reuse, among other functionalities. However, traditional antennas have limited performance and cannot effectively cope with

the variability of the environment. Reconfigurable antennas, on the other hand, enable multiple performance characteristics without altering the antenna structure, allowing antennas to meet the diverse requirements of the system [4].

Traditionally, the implementation of reconfigurable antennas involves the integration of adjustable devices such as diodes [5, 6] or MEMS [7]. However, in the terahertz frequency range, these devices are not effectively able to achieve the desired design objectives. Graphene, as a novel carbon-based tunable material, is a two-dimensional crystal composed of carbon atoms arranged in a honeycomb lattice structure within a plane [8]. It exhibits a wide range of tunability spanning from microwave and millimeter wave to terahertz frequency ranges. Furthermore, graphene material can be controlled through various means such as electrical or temperature control [9], making it an ideal choice for developing reconfigurable terahertz devices and antennas.

Reconfigurable antennas are typically categorized into frequency–reconfigurable, polarization–reconfigurable, and radiation pattern–reconfigurable antennas. In Ref [10], a graphene-based tunable terahertz frequency-selective surface is designed and a radome based on this FSS is constructed to propose a terahertz antenna that enables full-angle beam scanning, where the graphene is endowed with digital coding capability by varying the bias voltage. In Ref [11], a semi bow tie antenna surrounded by a circular arrangement of parasitic

✉ Yu Rong
2021224135@chd.edu.cn

¹ School of Information Engineering, Chang'an University, Xi'an 710064, China

graphene patches is proposed. By utilizing perfect electric conductor (PEC) and graphene (with chemical potentials set to 0 or 1 eV) as the ground plane, the parasitic elements can exhibit different reflection or redirection effects in three states. This enables a wide scanning angle range from 0° to 180° . In Ref [12], by adding two “L”-shaped and one rectangular graphene strip on a circular microstrip antenna, the electrical length of the radiating element can be altered. This enables the control of resonant frequency and radiation direction of the circular antenna by varying the chemical potential states of the graphene. In Ref [13], based on the Yagi-Uda antenna, a graphene plasmonic nanoantenna operating in the terahertz frequency range is proposed, utilizing SiO_2 substrate. By controlling the graphene state, it can switch between transmission and reflection, allowing the antenna to achieve directional radiation with four beams ($0^\circ, \pm 90^\circ, 180^\circ$) and controllable resonant frequencies. Although the aforementioned work has achieved a certain degree of reconfigurability, terahertz antennas with simultaneous reconfigurability in terms of frequency, radiation pattern, and polarization still require further research and innovation.

The paper proposes a compound reconfigurable terahertz antenna. Firstly, a graphene-based THz dipole antenna is designed, and the influence of chemical potential on its resonance frequency, radiation direction, and gain is analyzed. Then, a compound reconfigurable THz antenna is introduced by incorporating a CLL. By controlling the variation of the chemical potential in graphene within the antenna, the frequency, radiation pattern, and polarization characteristics can be reconfigured.

Graphene-based Terahertz Dipole Antenna

Graphene, a nanomaterial, has gained significant attention due to its unique property of tunable surface conductivity through the application of a bias voltage. It has been extensively studied, especially in the terahertz frequency range. This material has opened up many possibilities in the field of reconfigurable terahertz device design. The conductivity of graphene can be characterized using the Drude model [14]:

$$\sigma_s = \sigma_{\text{intra}}(\omega, \mu_c, \Gamma, T) + \sigma_{\text{inter}}(\omega, \mu_c, \Gamma, T) \quad (1)$$

$$\sigma_{\text{intra}}(\omega, \mu_c, \Gamma, T) = -j \frac{e^2 k_B T}{\pi \hbar^2 (\omega - j2\Gamma)} \left(\frac{\mu_c}{k_B T} + 2 \ln \left(e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right) \quad (2)$$

$$\sigma_{\text{inter}}(\omega, \mu_c, \Gamma, T) = -j \frac{e^2}{4\pi \hbar} \ln \left(\frac{2|\mu_c| - (\omega - j2\Gamma)\hbar}{2|\mu_c| + (\omega - j2\Gamma)\hbar} \right) \quad (3)$$

where σ_{intra} is the intraband conductivity, σ_{inter} is the interband conductivity, ω is the angular frequency of the electromagnetic wave, μ_c is the chemical potential of graphene,

$\Gamma = 2/\tau$ represents the scattering rate of graphene, where τ is the relaxation time, T is the temperature, e is the elementary charge, and $\hbar = h/2\pi$ is the reduced Planck's constant, where h is the Planck's constant. In this work, the operating frequency is less than 5 THz, and at room temperature, the intraband conductivity σ_{intra} is much larger than the interband conductivity σ_{inter} , and it can be approximated to zero, so the surface conductivity of graphene can only be expressed in terms of the inband conductivity. Under the setting of relaxation time $\tau = 1$ ps and $T = 300$ K, the variation curve of conductivity with chemical potential and frequency is calculated by MATLAB software as shown in Fig. 1. The real part of surface conductivity decreases with increasing frequency, while the imaginary part of surface conductivity decreases when the frequency is from 0 to 0.3 THz, and increases when it is greater than 0.3 THz. And in the low-frequency part of the terahertz, the chemical potential leads to a more dispersed change in conductivity. The variation in graphene surface conductivity is achieved by adjusting the chemical potential. In fact, the magnitude of the chemical potential depends on the density of free charge carriers, which can be controlled by changing parameters such as gate voltage, electric field intensity, magnetic field, or chemical doping. The relationship between graphene's chemical potential μ_c and the applied bias voltage V_g can be expressed as follows [15]:

$$\mu_c \approx \hbar v_f \sqrt{\frac{\pi \epsilon_0 \epsilon_r V_g}{et}} \quad (4)$$

Here, v_f is the Fermi velocity of graphene, ϵ_r is the relative permittivity of the substrate, and t is the thickness of the substrate.

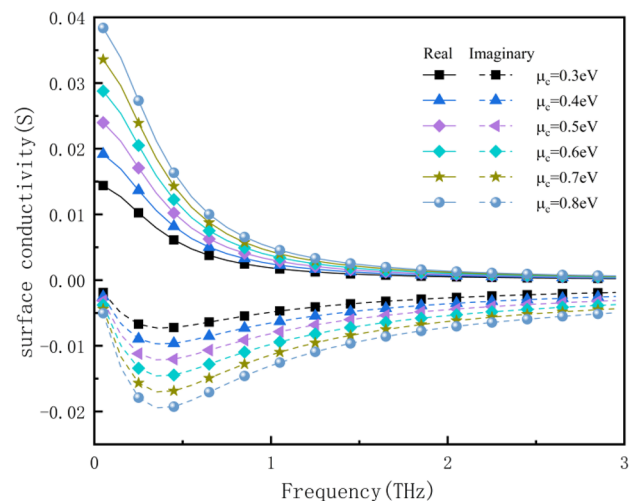


Fig. 1 The variation of the conductivity of graphene with frequency at different chemical potentials

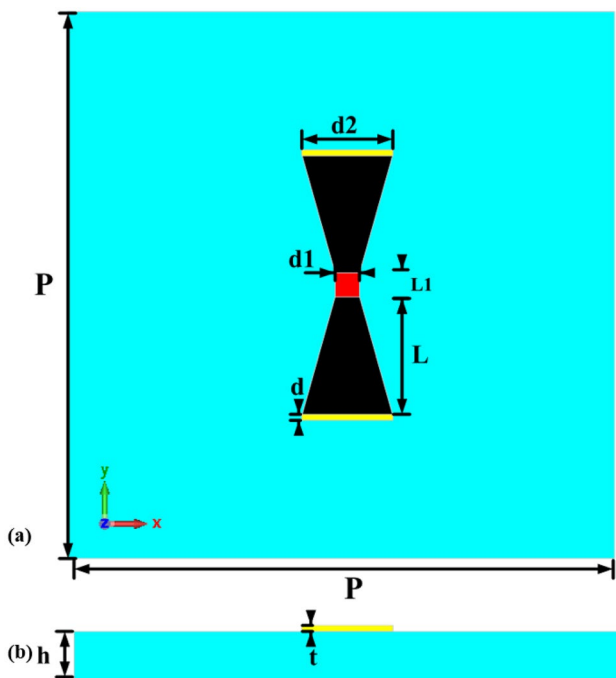


Fig. 2 The structure of the graphene-based dipole antenna. **a** Top view, **b** side view

Figure 2 in the paper shows the geometry of the proposed graphene-based terahertz dipole antenna. The dipole oscillator consists of a trapezoidal patch of graphene with metal strips made of gold that are attached to the ends of the oscillator. The proposed dipole antenna is placed on a SiO₂ dielectric substrate with a dielectric constant of 3.5 and a thickness of *h* and is fed by a 50 Ω source. In addition, the antenna parameters of the proposed design are presented in Table 1. The proposed antenna was simulated, optimized, and validated using CST Studio Suite 3D electromagnetic simulator.

The frequency tunability of graphene-based dipole antennas can be achieved by adjusting the chemical potential of graphene. In a graphene-based dipole antenna, when electromagnetic waves interact with graphene, surface plasmon oscillations are excited. By adjusting the chemical potential of graphene, the carrier concentration in graphene can be controlled, thereby altering its conductivity properties and consequently changing the resonance frequency of

the antenna. Increasing the chemical potential of graphene results in an upward shift of the Fermi level, leading to an increase in the number of electron-filled states and a decrease in the number of empty states. This causes the resonance frequency of the dipole antenna to tune towards higher frequencies. Conversely, decreasing the chemical potential of graphene leads to a downward shift of the Fermi level, reducing the number of electron-filled states and increasing the number of empty states. This results in the resonance frequency of the dipole antenna tuning towards lower frequencies. Figure 3 presents several sets of key characteristics of the dipole antenna under different chemical potentials. When the chemical potential of graphene increases, the resonant frequency of the antenna also increases, allowing the antenna to effectively radiate and receive signals in a higher frequency range. By controlling the chemical potential of the graphene resonators within the range of 0.4 to 0.8 eV, the resonant frequency gradually shifts from 1.42 to 1.91 THz. Moreover, it is observed that the radiation patterns in different frequency bands exhibit omnidirectional radiation in the YOZ plane and bidirectional radiation in the XOZ plane. The peak gain changes from 1.68 to 1.8 dBi.

Compound Reconfigurable Terahertz Antenna (CRTA)

The antenna structure proposed in this section is based on the dipole antenna described in “Graphene-based Terahertz Dipole Antenna.” In order to achieve simultaneous control over frequency, radiation pattern, and polarization characteristics, a compound reconfigurable terahertz antenna is designed. The antenna consists of a pair of orthogonal graphene-based dipole antennas as driving elements, and four CLLs with semi-circular graphene–metal strips are introduced around them, as shown in Fig. 4. The specific antenna parameters are shown in Table 1. By controlling the variation of chemical potential on the graphene in the CLL, the current distribution and magnitude on them can be adjusted, thereby affecting the different radiation modes of the proposed antenna. For the convenience of analysis, we use μ_{c1} to μ_{c12} to represent the magnitudes of chemical potential on different graphene strips in the CLL, and use μ_{c-d-1} and μ_{c-d-2} to represent the magnitudes of chemical potential on the two pairs of orthogonal graphene-based dipole oscillators.

The Frequency Reconfigurability of the Antenna

Similar to the analysis process described in “Graphene-based Terahertz Dipole Antenna” regarding the frequency reconfigurability mechanism of graphene-based dipole antennas, the capacitive load loop is integrated around the orthogonal dipole antenna, and simulations are conducted

Table 1 The optimized parameters of the proposed antenna (unit: μm)

Parameters	Value	Parameters	Value	Parameters	Value
P	65	L1	4	g2	1.5
d	0.5	h	1.6	g3	8
d1	3	t	0.5	X1	10
d2	8	R	15	X2	4
L	5	g1	1		

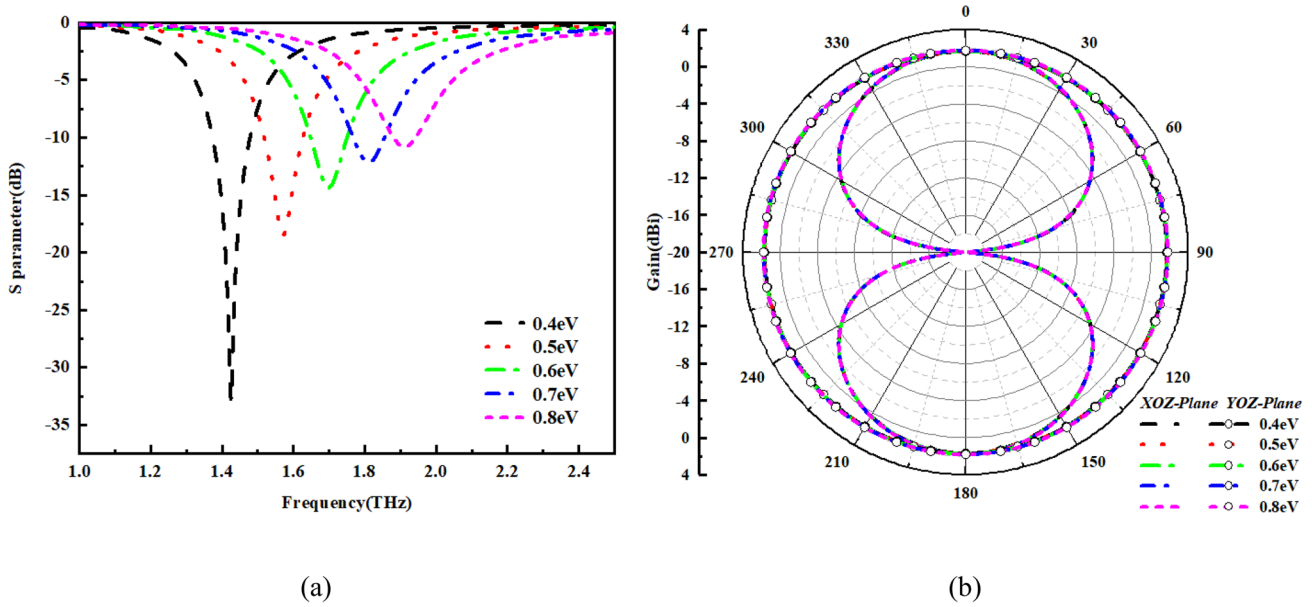


Fig. 3 The key characteristics of graphene-based dipole antenna: **a** S-parameters, **b** radiation pattern

to observe the variations of key parameters. The frequency reconfigurability capability of the proposed antenna is presented in Table 2.

As shown in Fig. 5, when the chemical potential of the graphene oscillator, μ_{c-d-1} , varies from 0.4 to 0.8eV, the resonant frequency increases from 1.40 to 1.84THz. Additionally, it can be observed that the radiation pattern exhibits omnidirectional radiation in the YOZ plane and bidirectional

radiation in the XOZ plane. This maintains nearly the same polarization and radiation pattern within different frequency ranges. Furthermore, across different frequency bands, the peak gain of the radiation increases overall from 2.165 to 2.727dBi, demonstrating better signal gain compared to the antenna structure described in the “[Graphene-based Terahertz Dipole Antenna](#).” When driving dipole-2, the radiation direction is orthogonal to that of driving dipole-1 and the analysis for other aspects is similar to the previous discussion.

The Radiation Pattern Reconfigurability of the Antenna

The radiation pattern of the antenna can be controlled by loading CLLs, primarily through the manipulation of current distribution and interaction effects. On one hand, adjusting the chemical potential of the graphene strips on the CLLs allow for control of the current distribution, thereby changing the radiation intensity of different parts of the antenna.

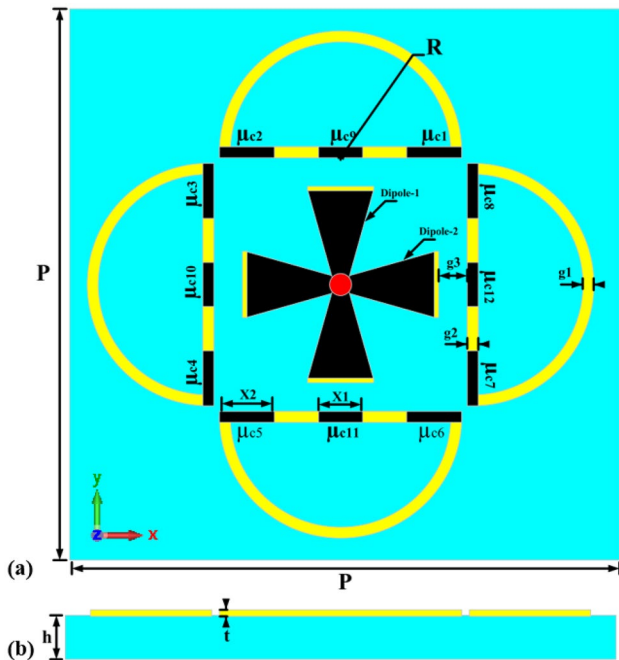


Fig. 4 Structure of the CRTA. **a** Top view. **b** Side view

Table 2 Frequency reconfigurability of CRTA

Antenna	Chemical potential (eV)			Resonant frequency (THz)	Peak gain (dBi)
	μ_{c-d-1}	μ_{c-d-2}	Others		
Antenna-F ₁	0.4	0	0	1.40	2.165
Antenna-F ₂	0.5	0	0	1.54	2.167
Antenna-F ₃	0.6	0	0	1.65	2.346
Antenna-F ₄	0.7	0	0	1.75	2.503
Antenna-F ₅	0.8	0	0	1.84	2.727

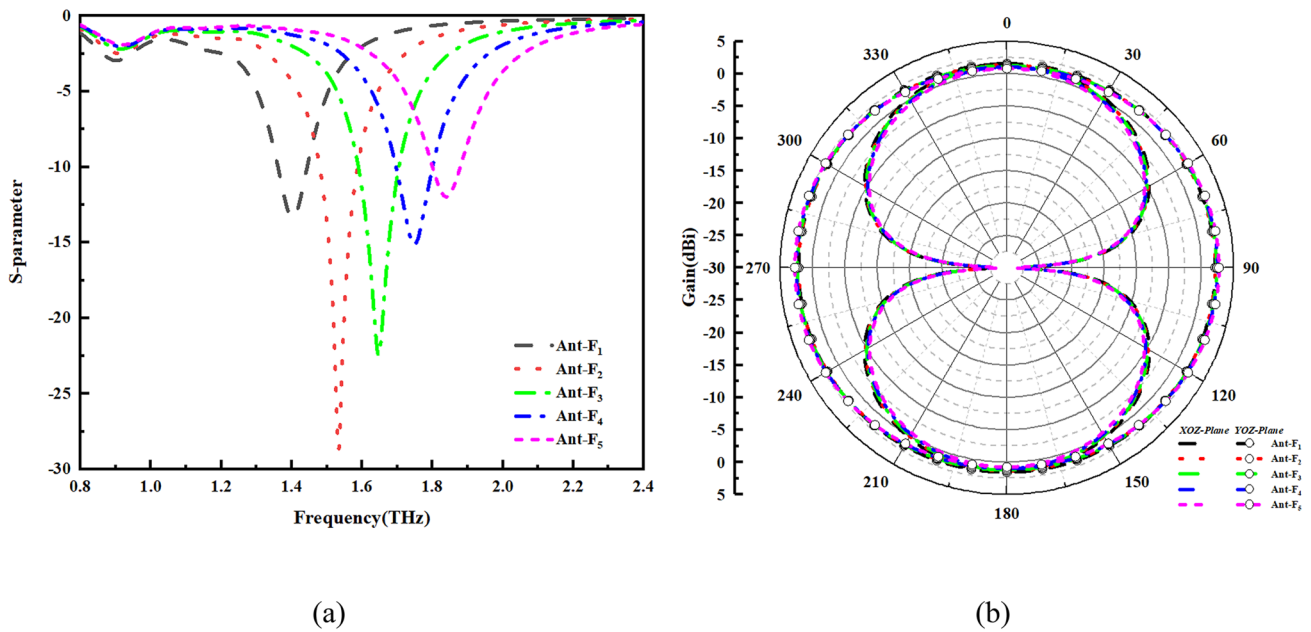


Fig. 5 The key characteristics of the frequency reconfigurable terahertz antenna. **a** S-parameter. **b** Radiation pattern

On the other hand, there exists an interaction effect between the CLLs and the orthogonal dipole antenna. This interaction can act as a director in the radiation direction of the antenna. As shown in Table 3, the directional pattern reconstruction capability of the antenna is presented.

By adjusting the graphene chemical potential, the three-dimensional radiation pattern of the designed antenna was observed within the operating frequency range of 1.75 THz, as shown in Fig. 6a, b. The antenna can achieve four different beam directions with similar radiation characteristics. If dipole-2 is used as the driving element and the chemical potentials of graphene strips μ_{c1} and μ_{c2} are set to 3eV, the radiation patterns on the XOY plane and YOZ plane were observed. The results indicate that the antenna exhibits end-fire radiation patterns towards the 270° direction, as shown in Fig. 6c, d. Based on the same operation, by adjusting the respective driving dipole and the chemical potentials of graphene strips, three other different beam radiation directions can be controlled. Furthermore, simulation results show that the peak gain of the antenna is approximately

3.84dBi, with a front-to-back ratio of about 6.12dB. This tunable radiation direction provides the antenna with flexibility and adaptability in different application scenarios, allowing it to radiate energy in a directed manner according to specific requirements.

The polarization Reconfigurability of the Antenna

Designing asymmetric antenna structures or excitation methods provides an effective approach for polarization control of the antenna. In this paper, by loading a capacitive resonant loop and adjusting the graphene strips to specific states, it effectively introduces asymmetric radiating elements to the antenna. This asymmetry results in the rotation of the polarization state of the electromagnetic wave. By adjusting the structure of the capacitive resonant loop to generate a 90° phase difference and equal amplitudes at the resonant frequency, circular polarization can be achieved. Table 4 demonstrates the polarization reconfigurability capability of the antenna.

Table 3 Radiation pattern reconfigurability of CRTA

Antenna	Chemical potential (eV)											Radiation direction	Resonant frequency (THz)	Peak gain (dBi)
	μ_{c-d-1}	μ_{c-d-2}	μ_{c1}	μ_{c2}	μ_{c3}	μ_{c4}	μ_{c5}	μ_{c6}	μ_{c7}	μ_{c8}	Others			
Antenna-R ₁	0	0.7	3	3	0	0	0	0	0	0	0	270°	1.75	3.84
Antenna-R ₂	0.7	0	0	0	3	3	0	0	0	0	0	0°		
Antenna-R ₃	0	0.7	0	0	0	0	3	3	0	0	0	90°		
Antenna-R ₄	0.7	0	0	0	0	0	0	0	3	3	0	180°		

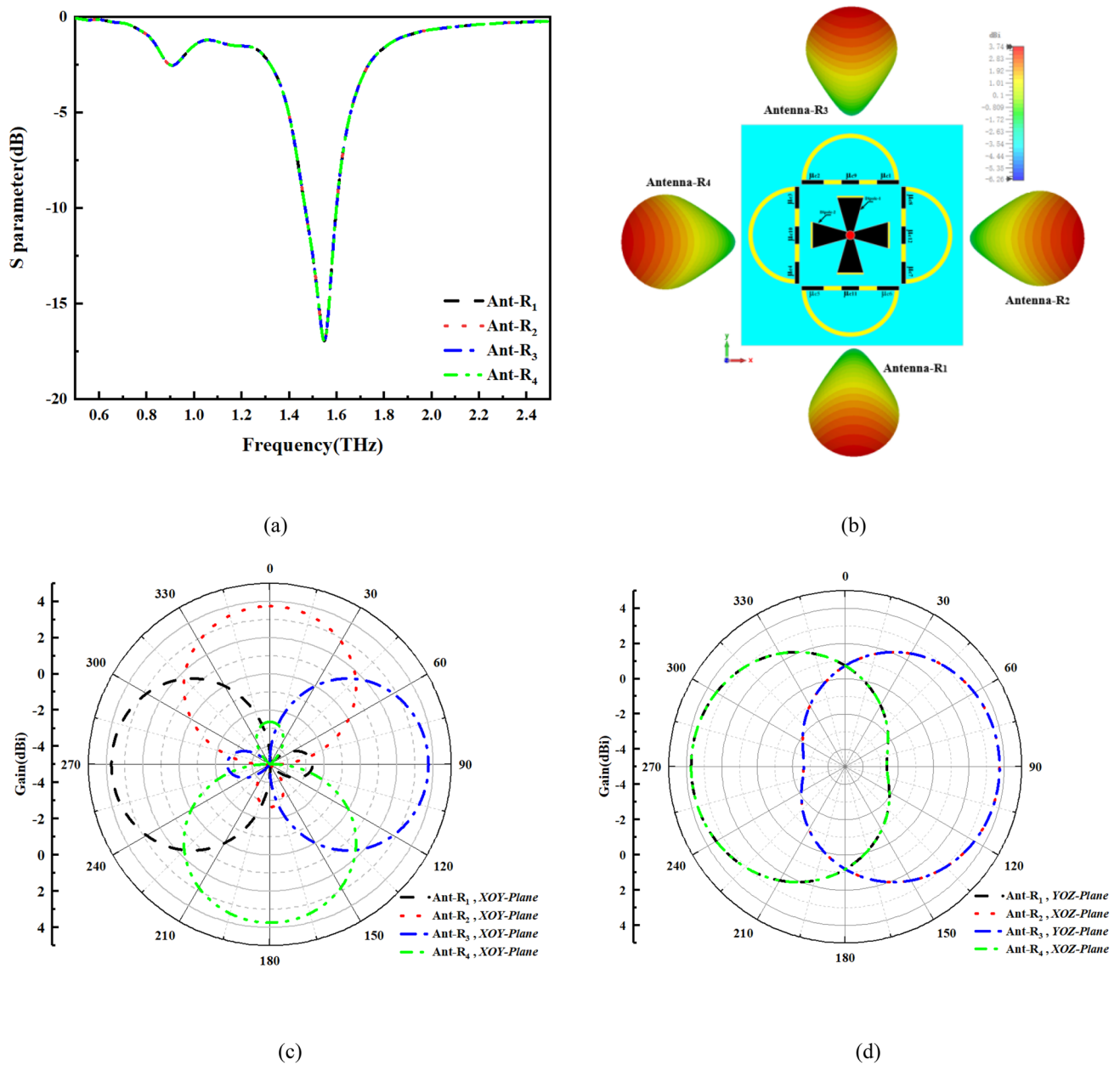


Fig. 6 The key characteristics of the radiation pattern–reconfigurable terahertz antenna. **a** *S*-parameters. **b** 3D radiation pattern. **c** Radiation pattern in the XOY plane. **d** Radiation patterns in the YOZ and XOZ planes

Table 4 Polarization reconfigurability of CRTA

Antenna	Chemical potential (eV)									Resonant frequency (THz)	Polarized state	Axial ratio(dB)
	μ_{c-d-1}	μ_{c-d-2}	μ_{c3}	μ_{c4}	μ_{c7}	μ_{c8}	μ_{c10}	μ_{c12}	Others			
Antenna-P ₁	0.7	0	0.7	0	0.7	0	0.7	0.7	0	1.73	RHCP	1.64
Antenna-P ₂	0.7	0	0	0.7	0	0.7	0.7	0.7	0	1.77	LHCP	1.66
Antenna-P ₃	0.65	0	0	0.65	0	0.65	0.65	0.65	0	1.68	LHCP	1.92
Antenna-P ₄	0.75	0	0	0.75	0	0.75	0.75	0.75	0	1.77	LHCP	1.08
Antenna-P ₅	0.8	0	0	0.8	0	0.8	0.8	0.8	0	1.81	LHCP	1.61

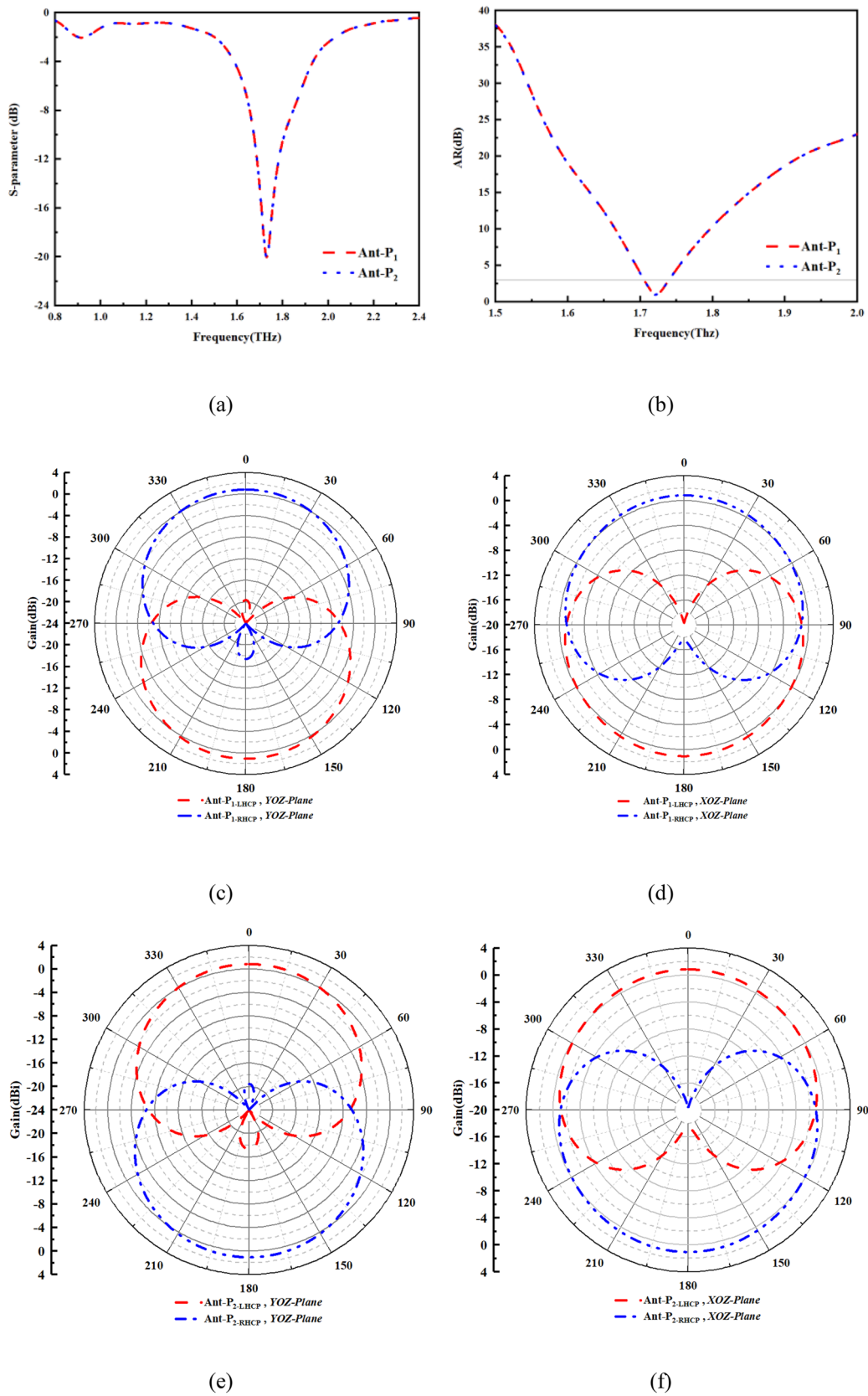


Fig. 7 The key characteristics of the polarization-reconfigurable terahertz antenna. **a** S-parameters. **b** Axial ratio. **c, e** Radiation pattern in the YOZ plane. **d, f** Radiation patterns in the XOZ planes

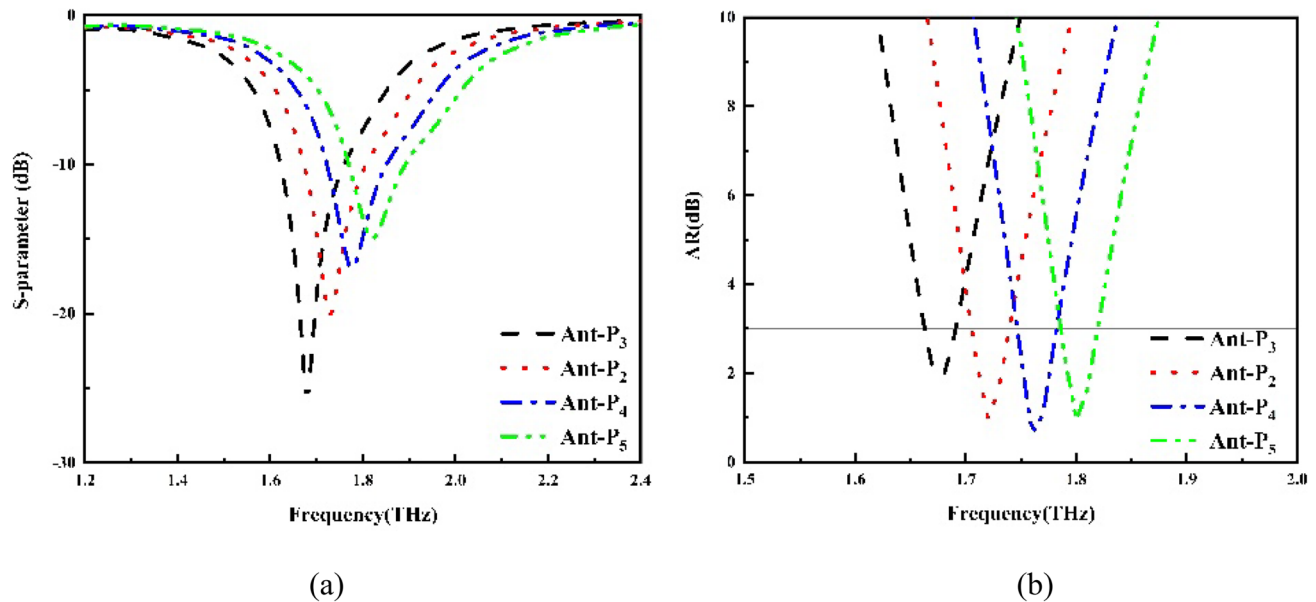


Fig. 8 The polarization characteristics of the polarization-reconfigurable terahertz antenna vary with frequency. **a** *S*-parameters. **b** Axial ratio

When the dipole dipole-1 is used as the driving element and the chemical potentials of graphene strips μ_{c3} , μ_{c7} , μ_{c10} , and μ_{c12} are set to 0.7eV, the resonant frequency and axial ratio are simulated and shown in Fig. 7a, b. At the central frequency of 1.73THz, the axial ratio is 1.64dB, indicating good circular polarization performance. Furthermore, observing the radiation patterns in the YOZ plane and XOZ plane at 1.73THz, it is evident that the antenna operates in RHCP as shown in Fig. 7c, d. Similarly, by adjusting the chemical potentials of graphene strips μ_{c4} , μ_{c8} , μ_{c10} , and μ_{c12} to 0.7eV, the antenna achieves LHCP at the central frequency due to the structural symmetry. Furthermore, analyzing the circular polarization characteristics with respect to frequency, by adjusting the chemical potential of graphene strips and dipole resonators within the range of 0.65 to 0.8eV, as the chemical potential increases, the surface conductivity of graphene increases. Consequently, the resonant frequency of the antenna shifts towards higher frequencies, while maintaining an axial ratio below 3dB at the corresponding resonance frequencies, indicating favorable polarization characteristics, as shown in Fig. 8. When driving dipole-2, the discussion results are similar to the analysis mentioned above. A detailed repetition of the analysis will not be provided here.

Conclusion

This paper proposes a compound reconfigurable terahertz dipole antenna with tunable frequency, radiation pattern, and polarization characteristics. By adjusting the chemical

potential of the graphene-based dipole antenna oscillators, it can be reconfigured to operate within the frequency range of 1.40 to 1.84 THz while maintaining a nearly constant radiation pattern. Additionally, by utilizing CLLs as a radiating element and controlling the chemical potential states of the graphene strips on the CLL, interaction between the CLL and the dipole antenna is achieved. This interaction allows the antenna to achieve four beam directions (0° , 90° , 180° , and 270°) in the XOY plane at 1.5 THz, with a peak gain of 3.84 dBi. At 1.73 THz, different types of RHCP and left-hand circular polarization LHCP can be realized, with an axial ratio of approximately 1.64 dB at the resonance frequency. Furthermore, the relationship between polarization characteristics and different frequencies was investigated. The proposed antenna allows for circular polarization radiation by adjusting the chemical potential of graphene within the range of 1.68 to 1.81 THz. This work provides a simple method for the design of compound reconfigurable terahertz antennas, enabling nano-scale wireless communication and sensing devices for various application scenarios. It is expected to play a significant role in future terahertz communication systems.

Author Contribution Jin Zhao was responsible for the review of manuscripts, supervision, and leadership of experiments; Rong Yu was responsible for the research method design, experimental exploration, and the first draft writing; Yu Jingdong was responsible for the review of the first draft and the discussion of research methods; Wu Fei was responsible for the review of the first draft and the discussion of research methods.

Availability of Data and Materials No data sets were available for this research.

Declarations

Consent to Participate All authors agreed to participate in the study.

Consent to Publication The publication of this manuscript has been approved by all authors.

Competing Interests The authors declare no competing interests.

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