IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 18, 2019, accepted March 1, 2019, date of publication March 6, 2019, date of current version March 25, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2903135

Graphene-Based Multi-Beam Reconfigurable THz Antennas

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This work was supported in part by the National Natural Science Foundation of China under Grant 61774021, Grant 6181101299, and Grant 61674020, in part by the Fundamental Research Funds for the Central Universities under Grant 2018XKJC05, in part by the Beijing University of Posts and Telecommunications (BUPT) Excellent Ph.D. Students Foundation under Grant CX2019315, and in part by the Fund of State Key Laboratory of Information Photonics and Optical Communications (BUPT), China, under Grant IPOC2017ZT02 and Grant IPOC2017ZZ01.

ABSTRACT Several configurations of multi-beam reconfigurable THz antennas based on graphene have been investigated. Two modulation mechanisms of graphene-based THz antenna are introduced, one is the reflector-transmission window model, and the other is the reflector-director model (Yagi-Uda antenna). The main parameters, such as main beam direction, resonance frequency, peak gain, and the front-to-back ratio of the proposed antenna can be controlled by adjusting the chemical potentials of the graphene in the antenna. Moreover, this paper provides an easy way to obtain complex graphene-based multi-beam antennas, showing strong potential in the design of other complex graphene-based systems, enabling nanoscale wireless communications and sensing devices for different applications.

INDEX TERMS Graphene, multi-beam, reconfigurable, THz antenna.

I. INTRODUCTION

The frequency range of terahertz (THz) wave is about 0.1-10 THz at submillimeter wave band. THz wave has been widely used in environmental monitoring, object imaging and broadband communication due to its unique penetrability, high image analyticity [1]–[3]. Antenna is a key element for THz transmission. However, in THz spectrum, traditional metal is no longer applicable due to the strong skin effect, which would result in the large loss of the antenna [4]. Graphene is emerging as a promising 2D material for electronic and photonic applications. Owing to the high conductivity and its inherent tunability, as well as little skin effect, graphene is particularly attractive for reconfigurable THz antennas [2]. Up to date, graphene-based reconfigurable THz antennas have been widely investigated [6]–[13]. Particularly, Yagi-Uda antenna is a potential structure to design reconfigurable multi-beam THz antennas [7], [8]. However, the design process of graphene-based Yagi-Uda antenna is always complexed. As reported in [7], the author designed a two-beam and a four-beam reconfigurable Yagi-Uda antenna with graphene switches. The structures of these two antennas are quite different, which may cause more difficulties for the design process. In this case, it is meaningful to provide a simple way to design graphene-based multi-beam reconfigurable antenna with complex structure.

In this work, several configurations of multi-beam reconfigurable THz antennas based on graphene have been investigated. Firstly, a graphene-based THz dipole antenna has been designed, and we analyze the effect of chemical potential on the resonance frequency and gain. Then, four kinds of THz antennas with two or six radiation patterns dependent on two modulation models are introduced, one is reflector-transmission window model, and the other is reflector-director model (Yagi-Uda antenna). The main parameters, such as main beam direction, resonance frequency, peak gain, and front-to-back ratio of the proposed antenna, can be controlled by adjusting the chemical potentials of the graphene in the antenna. Moreover, comparing to the reflector-director model, the reflector-transmission window model is more

The associate editor coordinating the review of this manuscript and approving it for publication was Kwok L. Chung.

applicable for the design of reconfigurable graphene-based antenna with complex structure, showing a strong potential for nanoscale wireless communications and sensing applications.

II. THE DESIGN OF A GRAPHENE-BASED THz DIPOLE ANTENNA

It is known that the surface conductivity plays an important role in the antenna performance. The surface conductivity of a single layer graphene is given by Kubo's formulas [14], [15]. According to our previous work, the strong dependence of the conductivity on the chemical potential offers a possible way to adjust the working status of the graphene-based antenna [16]. Particularly, several random special chemical potentials of 0 eV, 3 eV, 6 eV and 10 eV are adopted in this work. In addition, the establishment of the graphene conductivity model and the design of the antenna structures in this work are basing on the Full-Wave Electromagnetic Simulator.

Plane dipole antenna has been widely adopted as a feed source into complex antenna structures owning to its advantages of low profile, light weight, easy fabrication, and nearly omnidirectional radiation pattern [6], [7], [17]–[19]. In this work, four kinds of multi-beam antennas are composed by the dipole antenna and different parasitic elements.

Fig. 1 (a) shows the geometry of the proposed graphene-based dipole antenna. The antenna has a simple structure that consists of a graphene dipole radiator (fed by a 50 Ω source) and a hexagonal polyimide substrate with a relative permittivity of 3.5, a dielectric loss tangent of 0.008, and a thickness of 1μm. And the yellow area of all antennas in this paper is metal. Detailed dimensional parameters of all antennas in this work are summarized in Table 1. Fig. 1 (b) presents the |S11| parameters of the current dipole antenna

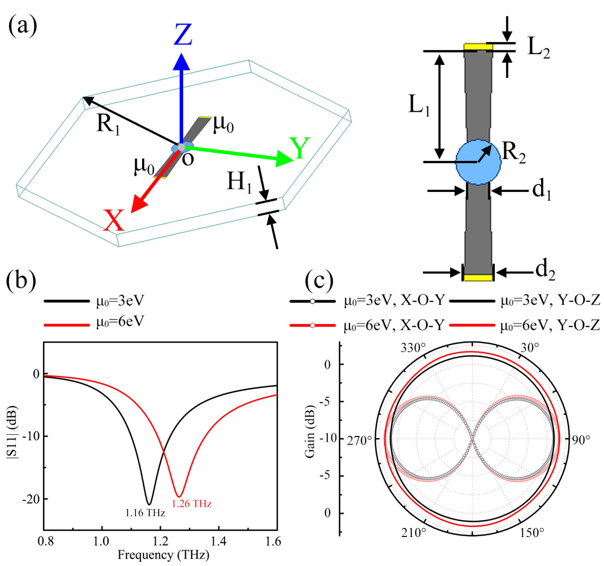

FIGURE 1. (a) The geometry of the proposed graphene-based dipole antenna, (b) The |S11| parameters of the current dipole antenna, (c) The radiation patterns of the dipole antenna.

TABLE 1. Dimensional parameters of the proposed antenna (μm).

Parameter	Value	Parameter	Value
R_1	120	L_6	2
R_2	8	L_7	15
H_1	1	d_1	8
H_2	0.1	d_2	10
L_1	40	d_3	42
L_2	2	d_4	10
L_3	90	d_5	50
L_4	2	d_6	4
L_5	80		

with different chemical potentials (μ_0 = 3 eV or 6 eV). As we can see, the resonance frequencies increase with the chemical potential, and a wide frequency range varies from about 1.16 to 1.26 THz is obtained, which means that the operation frequency of the proposed graphene-based dipole antenna can be dynamically controlled by the chemical potential μ_0. Similar regularities have been reported in other works [4], [13], [20]. In addition, the peak gains of the antenna are obviously increased from 0.94 dB to 1.72 dB when the chemical potential μ_0 varies from 3 eV to 6 eV, as shown in Fig. 1 (c).

III. TWO-BEAM RECONFIGURABLE THz ANTENNA BASED ON THE REFLECTOR-TRANSMISSION WINDOW MODEL

By introducing parasitic elements into to the dipole antenna, the radiation pattern of the dipole antenna could be affected. This is a potential method to design multi-beam antennas [7]. In this section, two graphene parasitic elements are added to the dipole antenna, and the new antenna can realize two different beams.

Fig. 2 (a) presents the geometry of the proposed two-beam reconfigurable antenna (Antenna 1). As shown in Fig. 2 (b), the antenna presents two working modes, and achieves two radiation directions. When μ_1 = 0 eV, μ_2 = 3 eV, and μ_3 = 6 eV, the corresponding parasitic elements left and right in Fig. 2 (a) behave as a transmission window and a reflector in mode 1, respectively. Similarly, when μ_1 = 6 eV, μ_2 = 3 eV, and μ_3 = 0 eV, the corresponding parasitic elements left and right in Fig. 2 (a) behave as a reflector and a transmission window in mode 2, respectively. This is due to the fact that the conductivity of graphene could be tuned by chemical potential, making the parasitic elements switch between two operation states (reflector and transmission window). Based on this property, the two-beam reconfigurable THz antenna is proposed. Correspondingly, the current distributions of the proposed Antenna 1 in mode 1 and mode 2 have been presented in Fig. 2 (c).

Furthermore, the effect of different chemical potential combinations on the antenna performance has been investigated. Fig. 3 (a) shows the |S11| parameters of the proposed Antenna 1 with different chemical potential combinations. It is clearly that the operation frequency is almost mainly

TABLE 2. Detailed changes of the Antenna 1 parameters under different chemical potential combinations.

Potential	Frequency	Bandwidth	Peak gain	Front-to-back ratio
Mode 1, $\mu 1=0$ eV, $\mu 2=3$ eV, $\mu 3=6$ eV	1.137 THz	8.2%	4.5 dB	7.3 dB
Mode 2, $\mu 1=6$ eV, $\mu 2=3$ eV, $\mu 3=0$ eV	1.136 THz	8.3%	4.5 dB	7.6 dB
Mode 1, $\mu 1=0$ eV, $\mu 2=6$ eV, $\mu 3=6$ eV	1.214 THz	12.5%	4.9 dB	10.5 dB
Mode 2, $\mu 1=6$ eV, $\mu 2=6$ eV, $\mu 3=0$ eV	1.212 THz	12.7%	4.8 dB	10.3 dB
Mode 1, $\mu 1=0$ eV, $\mu 2=6$ eV, $\mu 3=10$ eV	1.220 THz	10.2%	5.6 dB	9.3 dB
Mode 2, $\mu 1=10$ eV, $\mu 2=6$ eV, $\mu 3=0$ eV	1.216 THz	10.2%	5.6 dB	10.0 dB

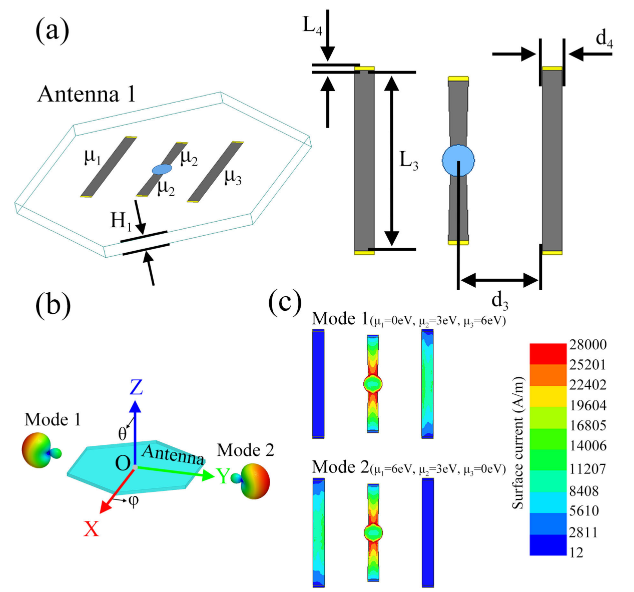

FIGURE 2. (a) The geometry of the two-beam reconfigurable antenna based on the reflector-transmission window model (Antenna 1), (b) Two working modes of the Antenna 1, (c) The current distributions of the proposed Antenna 1.

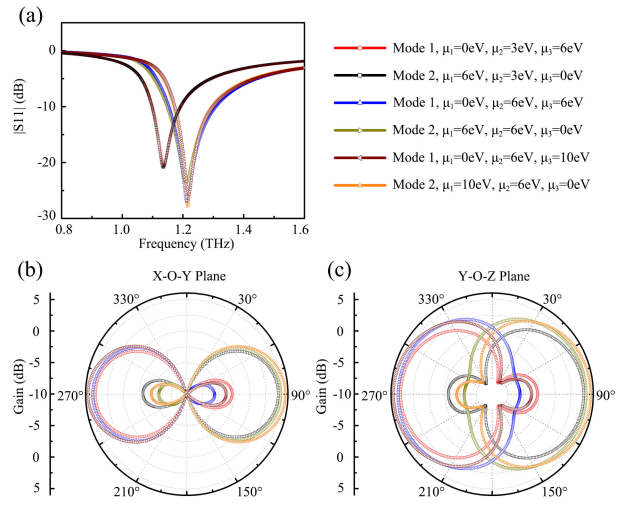

FIGURE 3. (a) The |S11| parameters of the proposed Antenna 1 with different chemical potential combinations, (b) The radiation patterns of the Antenna 1 in X-O-Y Plane, (c) The radiation patterns of the Antenna 1 in Y-O-Z Plane.

affected by μ_2, which means that the variety of chemical potential in the parasitic elements has little interference with the main frequency of the proposed antenna. Moreover, adopting a larger chemical potential in the dipole radiator could make the antenna working at a higher frequency. Fig. 3 (b) and (c) shows the radiation patterns at X-O-Y Plane and Y-O-Z Plane of the Antenna 1 with different chemical potential combinations. We can see that peak gain of the antenna can be enhanced by increasing μ_2 and μ_3. When $\mu_1 = 10$ eV, $\mu_2 = 6$ eV, and $\mu_3 = 0$ eV, the peak gain of the antenna is 5.6 dB with a front-to-back ratio of 10.0 dB. Detailed changes of the Antenna 1 parameters under different chemical potential combinations are listed in Table 2. It can be observed that operation frequency of Antenna 1 is mainly dependent on the chemical potential of graphene dipole radiator, while the gain can be affected by the chemical potentials of graphene dipole radiator and parasitic elements at the same time.

IV. SIX-BEAM RECONFIGURABLE THz ANTENNA BASED ON THE REFLECTOR-TRANSMISSION WINDOW MODEL

Furthermore, to expand the beam scanning range of the proposed Antenna 1, a simple centrosymmetric structure (Antenna 2) has been designed, as shown in Fig. 4 (a). And the geometric parameters of Antenna 2 are the same as that of Antenna 1. Moreover, an additional polyimide insulating

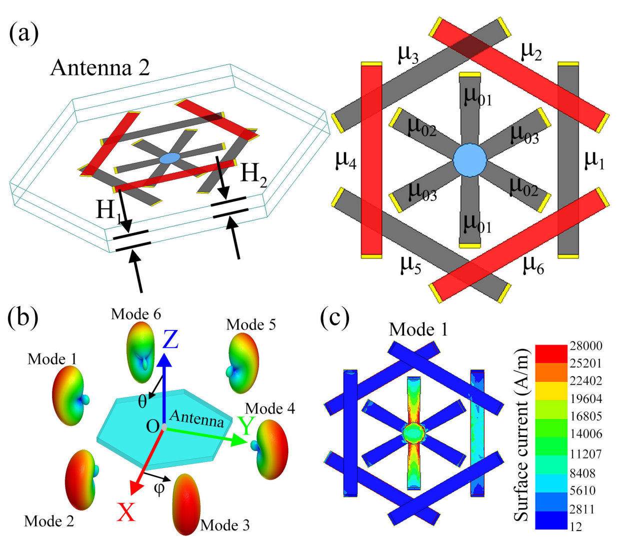

FIGURE 4. (a) The geometry of the six-beam reconfigurable antenna based on the reflector-transmission window model (Antenna 2), (b) Six working modes of the Antenna 2, (c) The current distribution of the proposed Antenna 2 in mode 1.

layer with a thickness of $H_2 = 0.1$ μm is adopted to avoid overlap between adjacent parasitic elements. In Fig. 4 (b), the Antenna 2 presents six working modes, and achieves six radiation directions. That means the Antenna 2 can realize the 360° omnidirectional beam scanning in free space. Fig. 4 (c) presents the current distribution of the proposed Antenna 2 in mode 1. As we can see that the Antenna 1 and 2 have the same reconfigurable mechanism. That is, high-chemical potential parasitic element acts as reflector, while low-chemical potential parasitic element acts as transmission window.

The main parameters of the Antenna 2 with a special chemical potential combination are plotted in Fig. 5 (a) to (c). The resonance frequency is about 1.21 THz with a −10 dB impedance bandwidth of about 10.6%, and the peak gain is about 5.5 dB with a 10.2 dB front-to-back ratio. And these performance indexes are close to the Antenna 1 with an identical chemical potential combination, which means that the reflector-transmission window model is applicable for the design of reconfigurable graphene-based antenna with complex structure. In other words, the similar antennas with more beams can be realized by this simple design method.

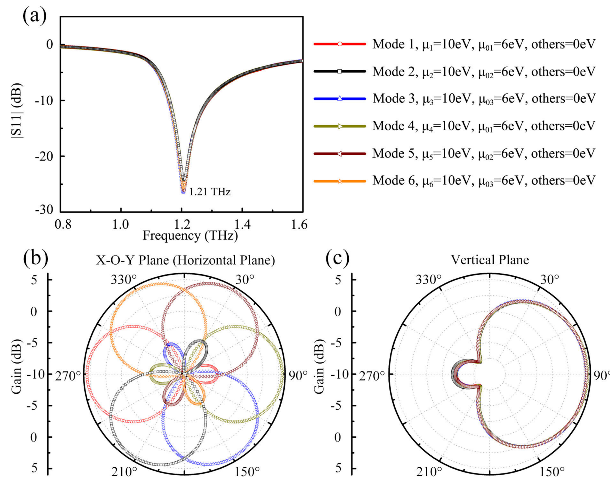

FIGURE 5. (a) The |S11| parameters of the proposed Antenna 2 for six modes, (b) The radiation patterns of the Antenna 2 in X-O-Y Plane, (c) The radiation patterns of the Antenna 2 in Vertical Plane.

V. TWO-BEAM RECONFIGURABLE THz ANTENNA BASED ON THE REFLECTOR-DIRECTOR MODEL

To prove that the above model is superior to the reflector-director model (Yagi-Uda antenna) when designing complex antenna structures, two corresponding antennas are presented in the following two sections, as contrasts. Here, a two-beam reconfigurable antenna based on the reflector-director model (Antenna 3) has been demonstrated. Fig. 6 (a) presents the geometry of the Antenna 3, which consists of the dipole radiator mentioned above and two metal parasitic elements embedded with graphene units. The basic modulation principle of Antenna 3 is Yagi-Uda antenna. That is, by switching the state of graphene embedded in the metal parasitic elements,

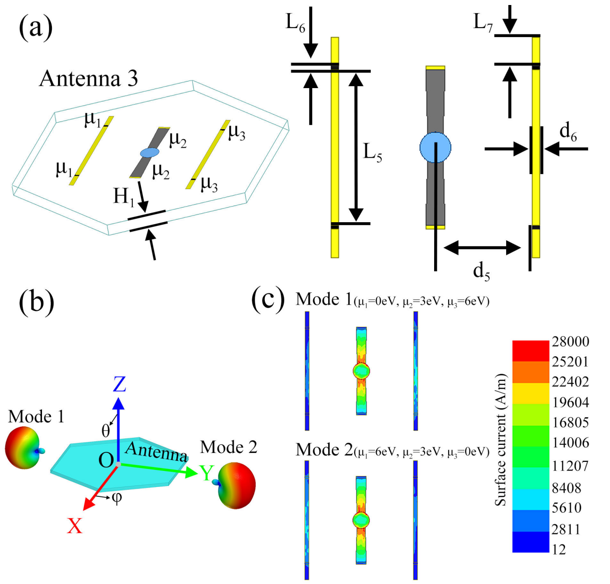

FIGURE 6. (a) The geometry of the two-beam reconfigurable antenna based on the reflector-director model (Antenna 3), (b) Two working modes of the Antenna 3, (c) The current distributions of the proposed Antenna 3.

forcing the parasitic elements to act as reflectors or directors and thus changing the main beam direction of the antenna.

In Fig. 6 (b), the Antenna 3 presents two working modes, and achieves two radiation directions. When $\mu_1 = 0$ eV, $\mu_2 = 3$ eV, and $\mu_3 = 6$ eV, the corresponding metal parasitic elements left and right in Fig. 6 (a) behave as a director and a reflector in mode 1, respectively. Similarly, when $\mu_1 = 6$ eV, $\mu_2 = 3$ eV, and $\mu_3 = 0$ eV, the corresponding parasitic elements left and right in Fig. 6 (a) behave as a reflector and a director in mode 2, respectively. This is due to the fact that the conductivity of graphene could be tuned by chemical potential, making the parasitic elements switch between two operation states (reflector and director). Based on this property, a two-beam reconfigurable THz Antenna 3 is proposed. Correspondingly, the current distributions of the proposed Antenna 3 in mode 1 and mode 2 have been presented in Fig. 6 (c). As we can see, metal parasitic element integrated with high-chemical potential graphene acts as reflector, while metal parasitic element integrated with low-chemical potential graphene acts as director.

Similarly, the effect of different chemical potential combinations on the Antenna 3 is also investigated, and the phenomenon is the same as that of Antenna 1. That means the operation frequency and peak gain of Antenna 3 can be affected by the chemical potential of graphene dipole radiator, and the gain can be further improved by increasing the chemical potential of the graphene embedded in the reflector, as shown in Fig. 7 (a) to (c). When $\mu_1 = 10$ eV, $\mu_2 = 6$ eV, and $\mu_3 = 0$ eV, the resonance frequency of Antenna 3 is about 1.243 THz with a −10 dB impedance bandwidth of about 10.5%, and the peak gain is about 6.5 dB with a 12.1 dB front-to-back ratio. Detailed changes of the Antenna 3 parameters

TABLE 3. Detailed changes of the Antenna 3 parameters under different chemical potential combinations.

Potential	Frequency	Bandwidth	Peak gain	Front-to-back ratio
Mode 1, μ1=0 eV, μ2=3 eV, μ3=6 eV	1.139 THz	10.9%	5.7 dB	17.9 dB
Mode 2, μ1=6 eV, μ2=3 eV, μ3=0 eV	1.139 THz	10.9%	5.7 dB	17.5 dB
Mode 1, μ1=0 eV, μ2=6 eV, μ3=6 eV	1.245 THz	10.4%	6.4 dB	12.2 dB
Mode 2, μ1=6 eV, μ2=6 eV, μ3=0 eV	1.243 THz	10.5%	6.4 dB	12.2 dB
Mode 1, μ1=0 eV, μ2=6 eV, μ3=10 eV	1.244 THz	10.5%	6.5 dB	12.1 dB
Mode 2, μ1=10 eV, μ2=6 eV, μ3=0 eV	1.243 THz	10.5%	6.5 dB	12.1 dB

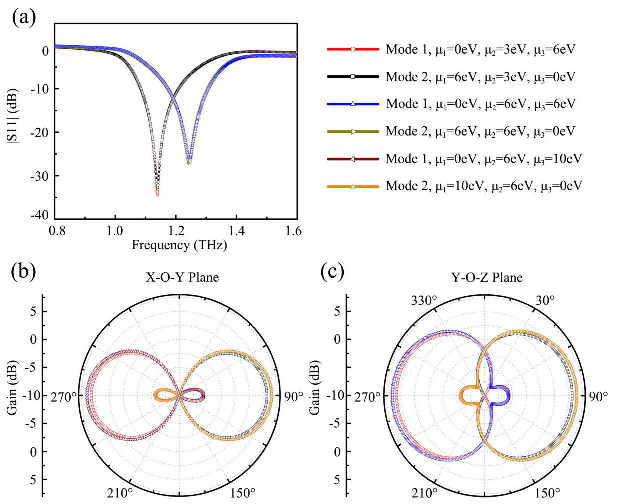

FIGURE 7. (a) The |S11| parameters of the proposed Antenna 3 with different chemical potential combinations, (b) The radiation patterns of the Antenna 3 in X-O-Y Plane, (c) The radiation patterns of the Antenna 3 in Y-O-Z Plane.

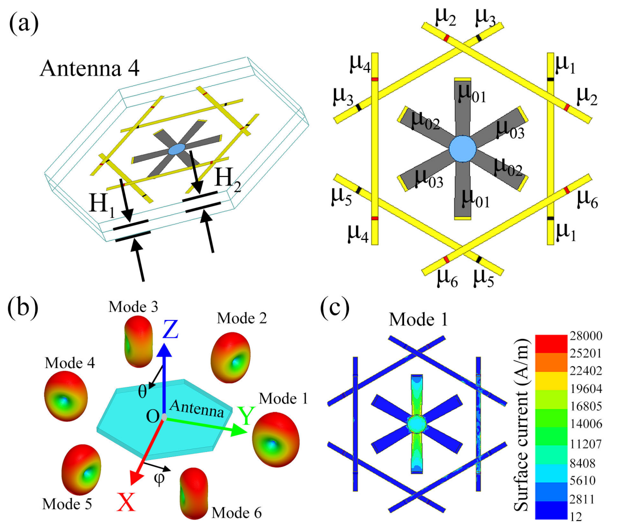

FIGURE 8. (a) The geometry of the six-beam reconfigurable antenna based on the reflector-director model (Antenna 4), (b) Six working modes of the Antenna 4, (c) The current distribution of the proposed Antenna 4 in mode 1.

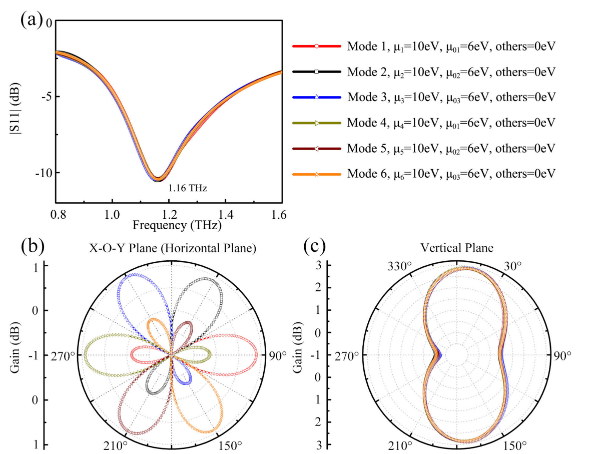

FIGURE 9. (a) The |S11| parameters of the proposed Antenna 4 for six modes, (b) The radiation patterns of the Antenna 4 in X-O-Y Plane, (c) The radiation patterns of the Antenna 4 in Vertical Plane.

under different chemical potential combinations are listed in Table 3.

VI. SIX-BEAM RECONFIGURABLE THz ANTENNA BASED ON THE REFLECTOR-DIRECTOR MODEL

As mentioned above, a six-beam reconfigurable antenna can be achieved through simple rotation transformation of the two-beam reconfigurable antenna based on the reflector-transmission window model. So, in this section, a simple centrosymmetric six-beam reconfigurable antenna (Antenna 4) based on the Antenna 3 has also been designed, as shown in Fig. 8 (a). Fig. 8 (b) presents six working modes of the Antenna 4. Fig. 8 (c) shows the current distribution of the proposed Antenna 4 in mode 1. Unlike Antenna 3, the beam of Antenna 4 in the X-O-Y Plane points to the metal parasitic element integrated with high-chemical potential graphene. In other words, it seems that the metal parasitic element integrated with high-chemical potential graphene can be regarded as a director. So, the previous regular patterns are no longer applicable in here.

In addition, the main parameters of the Antenna 4 with a special chemical potential combination are plotted in Fig. 9 (a) to (c). Comparing with the two-beam Antenna 3, the performance of Antenna 4 is greatly weakened. Moreover, the main beam direction of Antenna 4 is no longer in the X-O-Y Plane, while in the normal direction of the antenna. Hence, designing multi-beam reconfigurable antenna by simple rotation transformation of the two-beam reconfigurable antenna is not feasible in here. Further optimizing is necessary for Antenna 4, which will bring a lot of trouble to antenna design.

In the six-beam reconfigurable antenna based on the reflector-transmission window model, the graphene parasitic elements can be switched between the good conductors or insulators through tuning the chemical potential. And there is little interference between each graphene parasitic element. So, this six-beam antenna obtained by simple rotation transformation can still maintain a stable performance. However, in the six-beam reconfigurable antenna based on the reflector-director model (Yagi-Uda antenna), the interference between the metal parasitic elements could not be ignored. Hence, the reflector-transmission window model is more applicable for the design of reconfigurable graphene-based antenna with more complex structure.

VII. CONCLUSION

Several configurations of multi-beam reconfigurable THz antennas based on graphene have been investigated. Two modulation mechanisms of graphene-based THz antenna are introduced. The main parameters, such as main beam direction, resonance frequency, peak gain, and front-to-back ratio of the proposed antenna, can be controlled by adjusting the chemical potentials of the graphene in the antenna. Excellent unidirectional symmetrical radiation patterns with the front-to-back ratio of 10 dB are achieved by choosing the applicable chemical potentials for the proposed two-beam reconfigurable THz antenna based on the reflector-transmission window model, and the peak gain is about 5.6 dB and the −10 dB impedance bandwidth is about 10.2%. Particularly, a six-beam reconfigurable antenna can be achieved through simple rotation transformation of the two-beam reconfigurable antenna based on the reflector-transmission window model. The new six-beam antenna still maintains a high performance. This work provides a simple way to design complex graphene-based multi-beam reconfigurable antennas. This design scheme may be also applicable to other complex graphene-based systems, enabling nanoscale wireless communications and sensing devices for different applications.

ACKNOWLEDGMENT

(Yanbin Luo and Qingsheng Zeng contributed equally to this work.)

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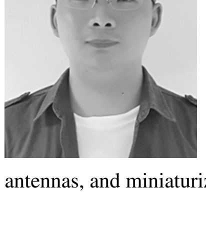

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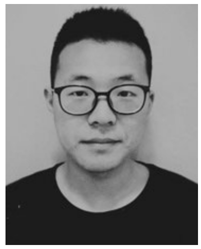

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