

Advancing Terahertz Connectivity of Innovative Design of a Directional Cross-Dipole Antenna with Conformal Graphene-Based Reconfigurable Intelligent Surface

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In contemporary systems, there is a growing emphasis on harnessing tunable terahertz (THz) waves to advance wireless communication swiftly. Furthermore, reconfigurable intelligent surfaces (RISs) have noticeably enhanced the performance of THz components and devices that enabling them to control electromagnetic waves effectively. Within the domain of wireless systems operating within the THz frequency range, a demand has arisen for adjustable directional antennas. This paper presents a novel approach that suggests a solution involving a customizable directional antenna design which utilizing a cross-dipole configuration with a central graphene-based dipole element. The electrical conductivity of these dipole elements can be adjusted independently by applying a bias voltage via the graphene's chemical potential. The concept of employing a graphene-based Reconfigurable Intelligent Surface (RIS) to actively manipulate Terahertz (THz) waves. By carefully engineering the reflection characteristics of the individual unit cells, the overall system performance can be enhanced. The proposed conformal RIS design comprises a repetitive arrangement of rectangular graphene meta-atoms positioned on a silicon substrate grounded with metal. The paper also provides a model featuring an equivalent circuit for the RIS design and its solution. Furthermore, an implementation of tunable surfaces featuring the conformal graphene-based RIS. It is developed to be placed beneath the cross-dipole antenna at an appropriate distance. This setup enables the control of radiated patterns through a reconfigurable process that involves changing the states of the meta-atoms to achieve specific codes with corresponding patterns. The antenna can achieve various gains that ranging from 8.3 to 9.3 dBi. The results of this study demonstrate the promising potential of the proposed antenna structure for efficient and intelligent THz wireless communications.

Keywords: Terahertz; Cross-dipole antenna; Reconfigurable intelligent surfaces (RIS); Conformal; Graphene

1 Introduction

The Terahertz band or THz covers frequencies ranging from 0.1 to 10 THz and occupies the portion of the electromagnetic spectrum that falls between the microwave and infrared (IR) frequency bands¹. THz wireless communications offer several advantages including high data rates and ample bandwidth². They have various potential applications in fields like medical imaging, spectroscopy, security, and pharmaceuticals. However, THz bands suffer from high propagation losses in wireless systems due to molecular absorption³. Consequently, the design of directional THz antennas is of paramount importance as they can help offset these propagation losses. In recent times, a multitude of THz antenna designs have been introduced in research articles⁴. Some of these designs employ traditional metals like copper which

are unsuitable for the THz band due to their limited skin depth and reduced conductivity⁵. Even, a significant gap in the field of terahertz (THz) connectivity by tackling the challenge of enhancing directional signal transmission and improving the efficiency of wireless communications at high frequencies. The innovative design of a directional cross-dipole antenna combined with a conformal graphene-based reconfigurable intelligent surface (RIS) introduces a novel solution to the limitations of conventional antennas, such as signal attenuation and limited beam-steering capabilities in the THz range. By leveraging graphene's tunable properties, the proposed antenna-RIS system enables dynamic reconfiguration, allowing for improved beam directionality and adaptability to varying communication environments. This approach not only enhances connectivity but also contributes to overcoming obstacles related to power loss, signal interference, and limited range, making it

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highly relevant to the advancement of terahertz wireless communication networks. On the other hand, graphene a nanomaterial known for its unique electromagnetic properties and its ability to support surface plasmon polaritons in the THz regime⁶. It is frequently used in most THz antenna designs. Graphene possesses exceptional electronic, mechanical, optical, and thermal characteristics, making it a highly promising material for THz antenna technology⁷. It surpasses conventional metal antennas and carbon nanotube (CNT) antennas in this frequency range. Moreover, graphene can dynamically adjust its surface conductivity by modifying its chemical potential over a wide range. As a result, there has been significant interest in the development of graphene-based reconfigurable antennas operating in the THz band with numerous proposals in this direction⁸⁻⁹.

A cross-dipole antenna that often referred to as a crossed dipole antenna. It is indeed a well-known and widely used antenna configuration. It consists of two dipole antennas oriented at right angles to each other¹⁰. This design is primarily used in applications that require enhanced directivity of radiation patterns and polarization diversity¹¹. It is envisaged that the directional cross-dipole antenna will play a pivotal role in transmitting and receiving THz communication systems¹²⁻¹⁴. Furthermore, by harnessing the tunable conductivity of graphene in the THz range. A dynamically adjustable cross-dipole antenna can be crafted. This antenna boasts dynamic radiation patterns and the ability to reconfigure its operating frequencies. In contrast to previous endeavors, like the graphene-based Yagi-Uda antenna concept and the graphene-based V-shaped dipole antenna¹⁵. The cross-dipole antenna presents a novel and uncomplicated approach to designing a graphene antenna with a reconfigurable bandwidth and beam in the THz spectrum¹⁶. A reconfigurable intelligent surface (RIS) is a type of meta surface capable of manipulating electromagnetic waves that including THz waves by controlling the characteristics of its constituent elements¹⁷⁻¹⁹. In a similar vein, a graphene-based meta surface/RIS offers dynamic tunability and reconfigurability that rendering it ideal for various applications, particularly in the realm of antennas where it can effectively control radiation patterns. The potential of RIS technology is also promising for 6G communication systems as it can significantly enhance wireless network capacity and coverage²⁰. In the design of RIS-assisted communication systems, one of the most crucial

parameters is the reflection coefficient of each unit cell. By having either global or local control over the complex coefficients, a range of related applications and adjustable functionalities such as absorbers, anomalous reflectors, polarizers, *etc.*, can be achieved²¹⁻²². In this paper, we propose the integration of a conformal graphene-based RIS into a cross-dipole THz antenna to enhance the antenna's performance. This integration allows for dynamic control over the antenna's radiation properties, including beam focusing, directivity, and frequency reconfigurability²³. Graphene-based RISs can manipulate electromagnetic waves due to their unique electronic properties, which can be modified by applying an external bias voltage. In practical terms, the RIS elements can be controlled by adjusting chemical potential changes in various directional pattern modes, enabling the design of a directional antenna on the same structure²⁴⁻²⁷. On the other hand, conformal RIS technology in THz antenna systems holds considerable potential for a range of applications, particularly in the context of 6G communication systems. These applications include enhanced physical-layer security, non-line-of-sight (NLOS) transmission, beam steering and focusing, improved energy efficiency, and enhanced communication links²⁸⁻³². These promising applications position conformal graphene-based RIS as an appealing technology for advancing THz antenna systems and enabling new capabilities in next-generation communication systems such as 6G³³⁻³⁵. Overall, the integration of graphene-based RIS into THz antenna systems holds tremendous promise for unlocking new capabilities in 6G communication networks. From enabling ultrafast data transmission and low-latency connectivity to enhancing security and supporting massive device connectivity, graphene-enabled THz communication technologies are poised to reshape the future of wireless communication³⁶⁻³⁹.

Therefore, the novel aspects of this antenna design lie in its integration of a directional cross-dipole structure with a conformal graphene-based reconfigurable intelligent surface (RIS), which sets it apart from existing solutions. Unlike traditional antennas, this design utilizes the unique tunable properties of graphene, allowing the surface to dynamically reconfigure and adapt to changing communication environments. This provides enhanced beam-steering capabilities, improved signal directionality, and greater flexibility in managing terahertz frequency propagation. Additionally, the

conformal nature of the RIS makes it suitable for various surfaces and environments, offering more versatility in deployment compared to rigid antenna structures. The synergy between the cross-dipole antenna and the graphene-based RIS also addresses common challenges in terahertz communications, such as signal attenuation and power efficiency, making it a groundbreaking solution for high-frequency wireless networks.

2 Graphene Modeling

Two-dimensional nanomaterial graphene is an infinitesimal thin monolayer of carbon atoms arranged in a hexagonal lattice. To investigate the graphene-based THz structures. It is necessary to model the graphene conductivity at THz bands. The conductivity of graphene can be characterized using the Kubo's formula. It consists of two main terms due to the interbond conductivity (σ_{intra}) and intraband conductivity (σ_{inter}) contributions. Therefore, the equation for σ_{intra} can be demonstrated using Eq. 1 expressed as follows⁴⁰:

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

The symbol \hbar represents reduced Planck's constant. The Boltzmann constant is denoted as K_B . The charge of an electron is represented by e . μ_c refers to the chemical potential which holds considerable importance in determining the characteristics of interest. One crucial aspect of μ_c is its dependency on the bias voltage. Consequently, when the voltage is adjusted, the electric field undergoes proportional changes. This results in the modulation of the direct current (dc) bias voltage. Similarly, the term σ_{inter} can be expressed using the following Eq. 2⁴¹.

$$\sigma_{inter} = -\frac{J e^2 (\omega - j\Gamma)}{\pi \hbar} \int_0^\infty \left(\frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega - j\Gamma)^2 - 4 \left(\frac{\varepsilon}{\hbar}\right)^2} \right) d\varepsilon \dots (2)$$

Further, simplified σ_{inter} is calculated in Eq. 3. The total conductivity is the sum of σ_{intra} and σ_{inter} and it is expressed in equation⁴².

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

Total conductivity =

$$\sigma_{intra} + \sigma_{inter} = -j \frac{e^2 K_B T}{\pi \hbar^2 (\omega - j2\Gamma)} \left[\frac{\mu_c}{K_B T} + 2 \ln \right] - \frac{j e^2}{4\pi \hbar} \ln \left(\frac{2|\mu_c| - (\omega - j\Gamma)\hbar}{2|\mu_c| + (\omega - j\Gamma)\hbar} \right) \dots (4)$$

Here, Graphene was specifically chosen for the reconfigurable intelligent surface (RIS) in this design due to its exceptional electrical, mechanical, and tunable properties, which are crucial for enhancing the antenna's performance in terahertz (THz) communication. Graphene offers high electron mobility and conductivity, making it ideal for efficiently handling high-frequency signals with minimal loss. Its tunability through electrical biasing enables dynamic reconfiguration of the RIS, allowing for real-time control of the surface's reflective and refractive properties, which improves beam-steering and signal directionality. Additionally, graphene's conformal nature allows it to be integrated into flexible surfaces, making the design adaptable to different environments. These properties significantly enhance the overall performance of the antenna by reducing signal attenuation, improving energy efficiency, and providing better control over the THz wave propagation, making graphene a key factor in the advancement of reconfigurable intelligent surfaces for terahertz connectivity.

3 THz Graphene Cross-Dipole Antenna Design

First as illustrated in Fig. 1(a) cross-dipole-like antenna made of single-layer graphene is built in this study in order to provide a multi-function characterized by good radiation efficiency and miniaturization. Over a circular-shaped SiO₂ substrate with a thickness of 3 μm and a relative permittivity of 3.8. The suggested graphene-based antenna is positioned. It is conceivable that a terahertz photo mixer serving as a photoconductive source excites the cross-dipole antenna in its center gap of length. Additionally, four 0.2 μm -thick metal layers are applied to each of the cross-dipole antenna's four sides in order to create distinct chemical potentials on the graphene stubs and offer tunable graphene complex conductivity via the electrostatic field effect. The THz antenna's dimensions are adjusted for an operating frequency of about 1.2 THz. The side view is shown in Fig. 1(b). Fig. 2(a) illustrates the impact of changing the chemical potentials on the frequency response of the graphene-based antenna. By utilizing the graphene's chemical potential, a bias voltage may be applied to each antenna element separately to

modify its surface conductivity. The chemical potential (μ_c) values of the antenna are adjusted within the range of 0.3 to 0.5 eV in this investigation. According to the results shown in Fig. 2(a), the antenna's resonant frequency increases from 1.08 to 1.38 THz when the chemical potential value increases. Reconfigurability is made possible by this dynamic regulation of the chemical potential which makes the suggested design a

viable technique for THz antennas. Furthermore, we may vary the bidirectional radiation pattern as demonstrated in Fig. 2(b) by dynamically adjusting the chemical potential which causes the antenna's peak gain to fluctuate from 1.5 to 1.72 dBi. Fig. 1 The configuration of the cross-dipole antenna, which is based on graphene, includes a feeding point indicated by a red dot and powered by an optical pump source.

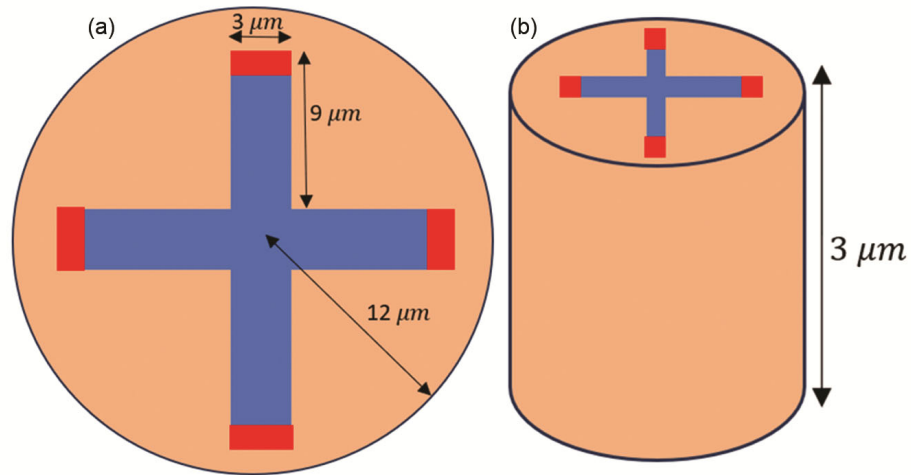


Fig. 1 — Geometry of proposed antenna (a) top view, and (b) side view

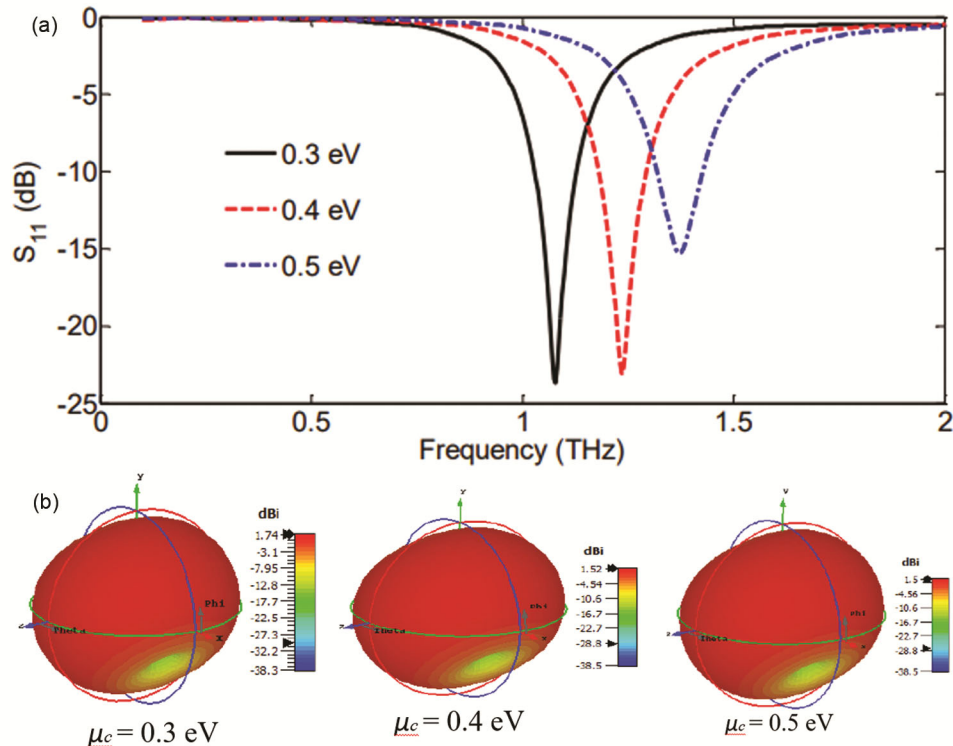


Fig. 2 (a) — S_{11} parameter (b) radiation patterns of the proposed graphene-based cross-dipole antenna for different cross-dipole arm chemical potential values

The radiation pattern of the Directional Cross-Dipole THz Antenna, augmented by a Conformal Graphene-Based Reconfigurable Intelligent Surface (RIS), exhibits exceptional directional characteristics in the terahertz frequency range. The cross-dipole configuration ensures precise control over polarization, contributing to the antenna's directionality. The integrated graphene-based RIS adds a layer of sophistication by offering dynamic tuning capabilities. This conformal intelligent surface enables real-time adjustments to the electrical properties, optimizing the antenna's performance. The radiation pattern showcases a focused beam with enhanced directivity, reducing undesired side lobes. The synergy between the cross-dipole structure and the reconfigurable graphene-based surface empowers the antenna to adapt to varying frequency requirements, making it versatile for applications demanding precise and customizable THz radiation patterns. The innovation presented in this design holds promise for advanced communication, imaging, and sensing systems in the terahertz domain.

4 THz Graphene Conformal RIS Design

A smart and simple conformal RIS using graphene meta-atoms at the THz band is proposed in this section. The RIS is composed of a two-dimensional periodic array of meta-atoms. It has the ability to independently modify the phase and amplitude of the incident THz electromagnetic signal in a fully customizable mode. The dimensions of the conformal RIS and the graphene properties are selected for the over-reflection of the THz waves in the desired directions. The EM solver CST Microwave Studio was used to simulate the proposed graphene-based unit cell and RIS design. The simulation was performed in the frequency domain using a tetrahedral mesh with a Floquet port to excite a plane wave impinging on the structure. The proposed conformal graphene-based RIS design and its unit cell are depicted in Fig. 3 (a). The design features a graphene meta-atom positioned above a metallic grounded SiO₂ substrate. To ensure proper grounding, a perfect electrical conductor (PEC) with a thickness of 1 μm is employed as the ground plane. The proposed model represents Graphene as a thin conductive sheet with a thickness of 1 nm. The reconfigurability of the Graphene RIS is achieved by applying an external gate voltage V_g which can be control by the chemical potential in ranging from $\mu_c = 0.3$ to 0.5 eV. The operational frequency of the graphene model is

studied in a wide range of 1.1 to 1.4 THz as shown in Fig. 3(b)

5 THz Antenna with Conformal RIS Structure

In this section, we investigate the implementation of a smart and reconfigurable layer of conformal RIS meta-atoms with a graphene-based cross dipole-like antenna structure. This layer is situated beneath the antenna as seen in Fig. 4 This study examines how the conformal RIS behaves in relation to the antenna structure's performance. In particular, we study how the reconfigurability of the conformal RIS affects the operating frequency and radiation pattern. Pattern reconfiguration to produce directed, high gain, and programmable radiation patterns over a broad range is one of the conformal RIS's primary functions. This property can be achieved by changing the state of meta-atoms of graphene from various states ("0" and "1") that constitute the conformal RIS as shown in Fig. 4. It is possible to manipulate the different states of graphene meta-atoms using external control methods such as a field programmable gate array (FPGA) and dynamic control of the bias voltage on the graphene chemical potential $\mu_c = [0.3, 0.5]$ eV. The proposed conformal programmable RIS states that the desired

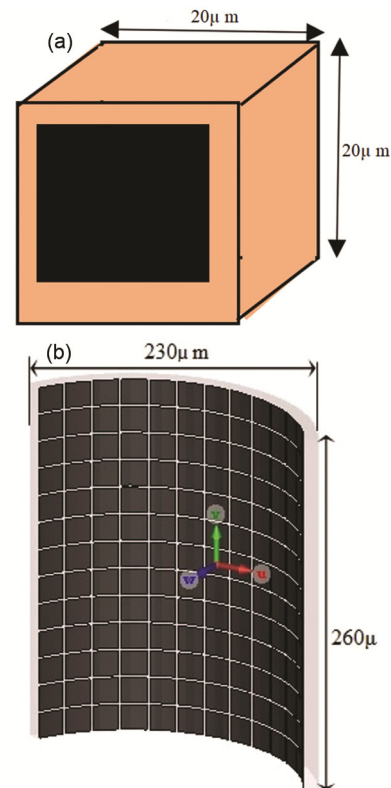


Fig. 3 — Design of the RIS based on conformal graphene; (a) unitcell and (b) 3D view of RIS

directed radiation pattern can be obtained by varying the meta-surface code in a number of different forms. The appropriate conformal RIS arrangement is shown in Fig. 5 which is based on the findings of a parametric study. This is clearly shown in the picture which shows how the various configurations affect the directivity and gain (which range from 8.33 dBi to 9.35 dBi). Furthermore, the cross-dipole antenna's graphene chemical potential may be changed to alter the structure's agility frequency. As previously indicated, this causes the operating frequency to shift to higher values as the chemical potential increases. A THz antenna with a conformal RIS structure can be a sophisticated solution for enhancing the performance of THz communication systems that particularly in terms of beam forming, signal steering, and signal-to-noise ratio improvement.

The surface current on the RIS is investigated in order to evaluate the effect of RIS bias graphene elements on the radiation pattern operation. The findings are shown in Fig. 5. Due to the biased graphene elements' high conductivity and resemblance to conductive properties in the THz frequency region.

The elements in Configurations "1" and "3" have a significantly higher surface current than the other graphene stubs. This suggests that biasing graphene elements can have a significant effect on the behavior of the RIS in terms of surface currents and radiation patterns. The analysis of surface current on the Reconfigurable Intelligent Surface (RIS) is pivotal for understanding the impact of RIS bias on its performance. Surface currents, induced by the biasing mechanism, play a crucial role in determining the interaction between the electromagnetic waves and the intelligent surface. By investigating these currents, researchers gain insights into how the bias voltage influences the reflection, absorption, and transmission characteristics of the RIS. The effect of RIS bias on surface current offers valuable information for optimizing the reconfigurability of the intelligent surface. Changes in bias voltage can dynamically alter the electrical properties of the graphene-based RIS that allowing for real-time adjustments to the reflected and transmitted waves. This investigation is particularly significant in the context of terahertz applications where precise control over electromagnetic interactions is essential. Understanding the nuances of surface currents under varying bias conditions provides a foundation for enhancing the overall performance of the RIS-equipped system. Researchers can leverage this knowledge to design intelligent surfaces that efficiently manipulate terahertz waves, enabling

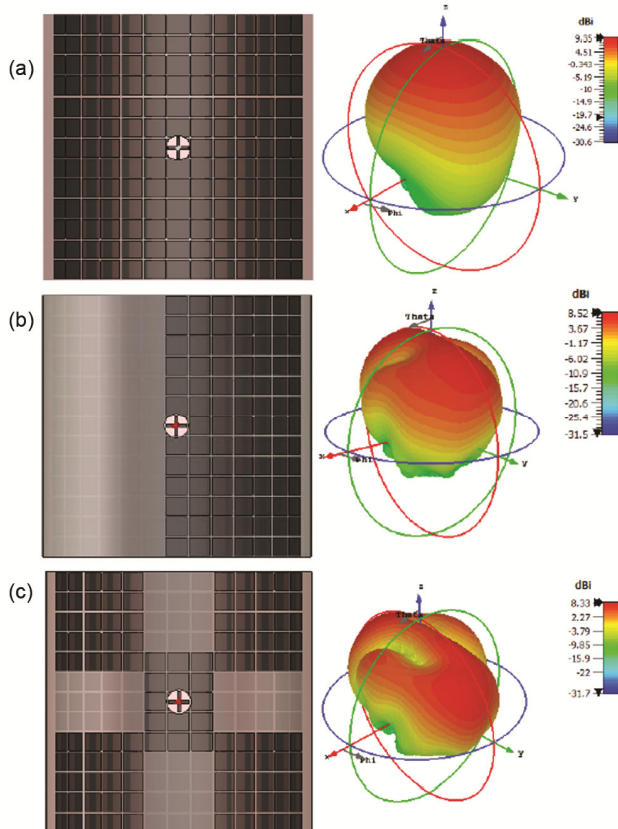


Fig. 4 — The proposed antenna with different configurations of the conformal RIS meta-atoms

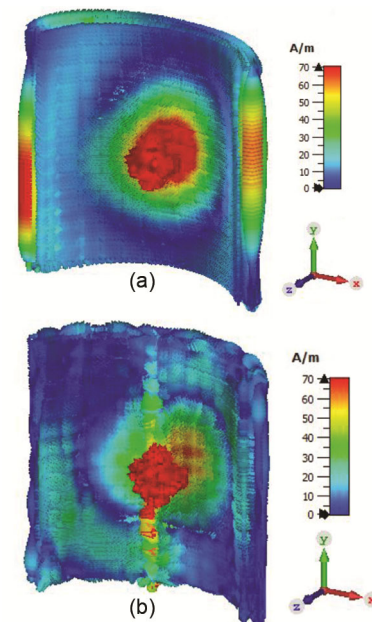


Fig. 5 — Surface current on the RIS when the elements of the Configuration "1" and "3" are activated

applications such as beam steering, signal modulation, and adaptive communication systems. Ultimately, the study of surface current in response to RIS bias contributes to the ongoing development of reconfigurable intelligent surfaces with advanced functionalities in the terahertz frequency range.

6 Conclusion

This work proposes a graphene-based directional cross-dipole antenna for THz wireless communication system with a straightforward and graphene-based conformal RIS. A model of an equivalent circuit and a closed-form solution for the RIS structure are shown. Underneath the antenna, the graphene meta-atom-based RIS layer is used to modify the radiation pattern and gain. The suggested THz antenna based on graphene is thought to be a strong contender for numerous applications. The suggested antenna design's excellent performance qualifies it for use in upcoming 6G communication networks as well as high-speed, short-distance indoor communication applications like Internet of Things. Therefore, there is a lot of room for this suggested design to be implemented in THz applications.

Data Availability

The manuscript contains the information and materials needed to support the study. The corresponding author will provide raw data files on request.

Competing interests

The authors declare no competing interest.

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