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Graphene-Based Reconfigurable Intelligent Metasurface Structure for THz Communications

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Abstract—**In this paper, a graphene based reconfigurable intelligent metasurface structure is proposed for terahertz (THz) communication applications. The proposed structure consists of multilayer unit cells with a graphene radiating patch. By using different values of biasing voltages, the chemical potential (μ_c) of the graphene is changed which leads to have different reflected phases. Based on this property we are able to create different reflected phase distributions within the full structure metasurface array which can be controlled by coding pattern in processing units. The proposed unit cell can provide an acceptable reflection characteristic around 4.35 THz. In addition, by changing the biasing voltage, four states are generated which can transmit 1-bit and 2-bits data. The proposed metasurface structure has small size and high flexibility in controlling radiation patterns. The simulated results such as reflected phase distributions and reconfigurable radiation patterns show the effectiveness of the proposed design for THz communication.**

Index Terms— graphene based terahertz (THz) metasurface, reconfigurable intelligent metasurface (RIM), multi-bit coding pattern, space-time coding, THz communication.

I. INTRODUCTION

In recent years there have been a lot of researches on the using of reconfigurable metasurface structure at terahertz frequency range [1-2]. Metasurface structure as a 2D structure of metamaterials has been used extensively in the range of terahertz imaging and communication applications [3-4]. Metasurface has found a variety of applications in areas, such as space-time coding, holographic imaging, biosensors [3-6].

Graphene has been successfully used in reconfigurable metasurface structure for manipulation of terahertz waves due to its surface conductivity characteristics. Because of the boundary conditions in graphene, its radiation characteristics make it extremely sensitive to external excitation [7-8]. Conventionally, using external bias like voltage splitter which is controlled by FPGA, we can tune the AC conductivity of graphene [9]. Based on this mono-atomic specification, graphene can be modelled as a complex surface conductivity tensor [10]. Due to the fact that reprogrammable structures can be created for THz communication using graphene based metasurface, and regarding to their potential characteristics, such as their flexible structure, small dimensions structures can be realized with a variety of materials such as silicon, quartz and gold, with the ability to simultaneously control the size and phase of the reflected waves [11-12].

In this paper, a new reconfigurable metasurface structure based on graphene is proposed for THz communication. By using different biasing voltage values, the μ_c of the graphene is changed which leads to have different reflected phases. Based on this property in full structure mertasurface array we are able to create different reflected phase distributions which can be controlled by coding pattern in processing unit. The proposed unit cell can provide an acceptable reflection characteristic around 4.35 THz. In addition, by changing the biasing voltage the proposed structure is designed for two modes: First, by 1-bit structures for beam steering applications and second, by 2-bit structures for space-time modulation. The simulation results show good performance of the proposed scheme for both applications.

The rest of the paper is organized as follows. In Section II we describe the scheme of the proposed metasurface structure. In Section III, first we demonstrate parametric sweep analysis of unit cell parameters, the we detail the full structure radiation characteristics in two modes of time-space coding and beam-steering mode.

II. GRAPHENE-BASED RECAONFIGURABLE INTELLIGENT METASURFACE STRUCTURE

The schematic of the reconfigurable intelligent metasurface with space-time coding capability in THz communication application is shown in Fig. 1. As illustrated in Fig. 1, the multi-bit coding pattern and wavefront modulation is generated in processing unit. After creating the required voltage in field programmable gate array (FPGA), the reconfigurable metasurface will be created by these voltages. In this point of view, manipulating of the radiation patterns is preformed, by using FPGA and digitally drive the RIM layout based on required voltage which is determined in multi-bit coding sequences generation [13].

In this study, for the proposed unit cell structure a multilayer structure is proposed as shown in Fig. 2. In the proposed structure for having complete reflection of the wave to the upper surface, there is a thin layer of gold in the bottom layer and then a thick layer of quartz. These layers help to avoid energy transmission and to have a reflective digital. In order to apply voltage to graphene an auxiliary floating-gate panel including alumina and silicon are patched to monolayer of graphene as shown in Fig. 2. In addition, the periodicity of Wu= 25 μm is considered in full array structure for the distance between unit cells.
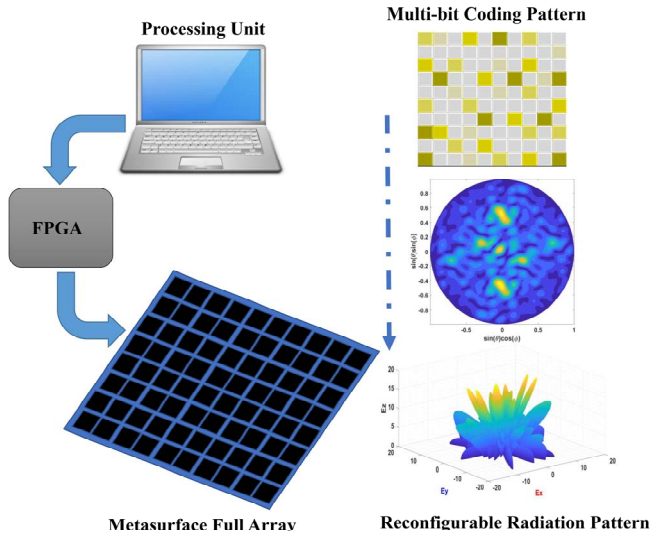
Fig. 1. Schematic of reconfigurable inteligent metasurface including array of multi-layer unit-cells, field programmable gate array (FPGA) and a processing unit.
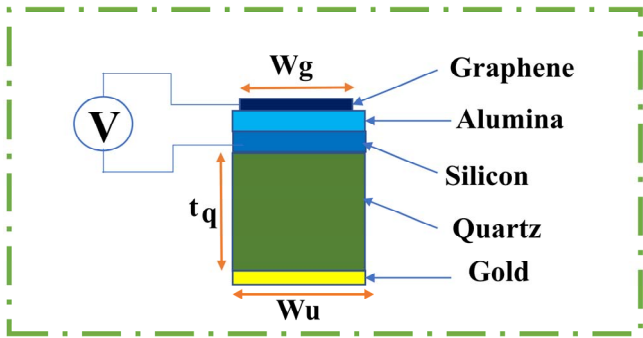

Fig. 2. The configuration of the proposed multi-layer graphene based unit cell including folating biasing point and voltage source.

In order to modify the surface conductivity of the graphene mono-layer, the biasing voltage source is applied to the floating gate, as shown in Fig. 2. The graphene monolayers theoretically based on the Kubo formula are represented by a surface impedance boundary $Z_S = 1/\sigma_s(\omega)$, where $\sigma_s(\omega)$ demonstrates the frequency-dependent complex conductivity of the graphene with interbond and intraband transition contributions [11]. In addition, for the 2-bit metasurface four operational status can be generated by using a proper external biasing circuit. In this study, the 2-bit phase modulation is generated by changing the μ_c in single-layer graphene-based meta-atom.

III. RESULTS AND DISCUSSIONS

A. Unit-Cell Design and Configurations

After detremining the multi-layer configuration, a parametric sweep analysis of the proposed structure is performed to obtain optimal dimensions for space-time coding in THz communication paradigm. The main objective is finding the final configuration and its dimension which create the best design of unit cell which can generate four states with 90º phase differences for 2-bits communication

framework. The multi-layer unit cell is simulated by CST simulator [14] which for the boundary condition in x- and y-directions unit cell and in z direction open-add space are selected. The "adaptive mesh refinement" method is selected for meshing. Fig. 3 shows the reflected phase changes for different values of graphene monolayer width (Wg). In addition, the reflected phase variations for different thicknesses of the quartz substrate are also shown in Fig. 4. In all these cases, the chemical potential of graphene is zero. The expectation is having the 90º phase at a frequency of 4.35 THz. The optimal value for these two parameters can be extracted from these figures, which is 23 µm for the width of the radiating square and 28 µm for the thickness of the quartz substrate.
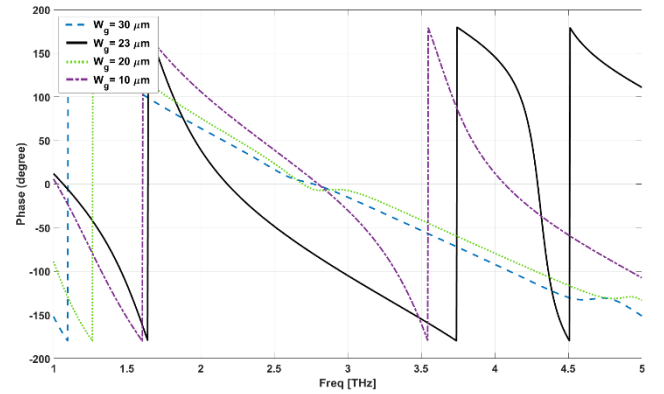

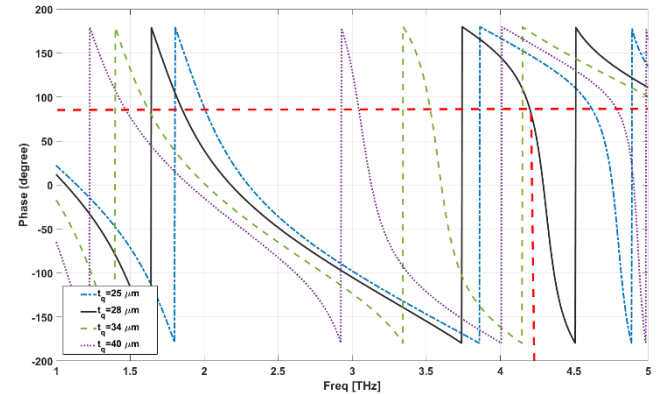Fig. 3. Simulated reflected phase results for the proposed unit cell for different values of radiating square width (W_g).

Fig. 4. Simulated reflected phase results for the proposed unit cell for different values of quartz's thickness (t_q).

Regarding to the parametric sweep results, the working frequency is set to 4.35THz. In order to demonstrate the 2-bit property of the proposed design, Fig. 5 shows the reflection characteristics of the proposed structure with different chemical potentials for graphene. As illustrated in Fig. 5 (a) and (b), the optimal design is able to generate four different phases (-90º, 0º, 90º, 180º) at 4.35 THz, which proves its ability to transfer 2-bit data. There is a slight drop in amplitudes of different states which is less than half of the incident power and is acceptable for reflection mode. These amplitudes can be enhanced by considering more parameters in parametric sweep analysis such as thickness of the gold layer, distance of the exciting port and etc. [11-12].
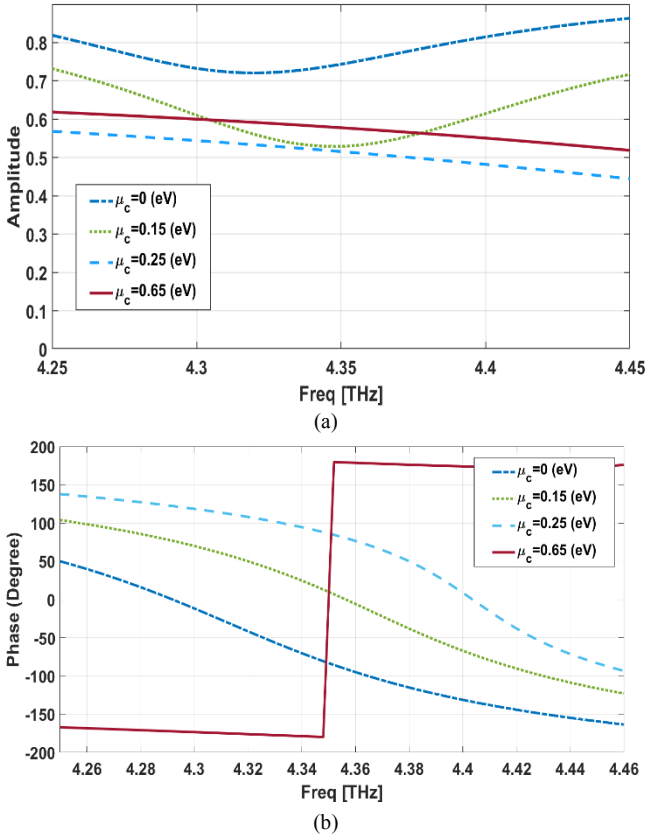
Fig. 5. Simulated (a) reflection coefficients and (b) reflected phase results for the proposed unit cell for different values of chemical potential μ_c.

B. Full Structure of Metasurface Array Construction

In this section, by creating a full-array structure of 16×16 of the proposed unit-cells, which includes 4×4 sub-array structures as a gradient coding sequence, the radiation patterns are controlled and steered by reconfigurable metasurfaces. First, a phase distribution calculation algorithm is provided in MATALB to demonstrate 2D and 3D radiation patterns of each coding matrix. Then, the full structure metasurface array is simulated using CST simulator to demonstrate the radiation characteristics of the proposed full structures. In this simulation, the metasurface is located in the X-Y plane, and two wave ports are used as an THz-EM sources.

B.1. Space-Time Coding for THz Communication

First by using 1-bit unit cells two different coding matrices are generated based on sub-matrix decomposition as shown in equiations (1) and (2). For these two examples of single-bit structures, Fig. 6 shows the 2D and 3D radiation pattern results. As shown in Fig. 6 (a), having 1-bit reconfigurable metasurface with one-dimensional change in the code sequence, it is possible to create a multi-beam radiation pattern in one dimension of space. In Fig. 6 (b), we used a variable code sequence in two dimensions, which resulted in the creation of multi-beam radiation pattern in two dimensions of space. It can be concluded that this structure has the ability to space-time coding.

$$\varphi_0 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}; \quad \varphi_1 = \begin{bmatrix} \pi & \pi & \pi & \pi \\ \pi & \pi & \pi & \pi \\ \pi & \pi & \pi & \pi \\ \pi & \pi & \pi & \pi \end{bmatrix} \quad (1)$$

$$\psi_1 = \begin{bmatrix} [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_1] & [\varphi_1] & [\varphi_1] & [\varphi_1] \\ [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_1] & [\varphi_1] & [\varphi_1] & [\varphi_1] \end{bmatrix}; \quad \psi_2 = \begin{bmatrix} [\varphi_0] & [\varphi_1] & [\varphi_0] & [\varphi_1] \\ [\varphi_1] & [\varphi_0] & [\varphi_1] & [\varphi_0] \\ [\varphi_0] & [\varphi_1] & [\varphi_0] & [\varphi_1] \\ [\varphi_1] & [\varphi_0] & [\varphi_1] & [\varphi_0] \end{bmatrix} \quad (2)$$
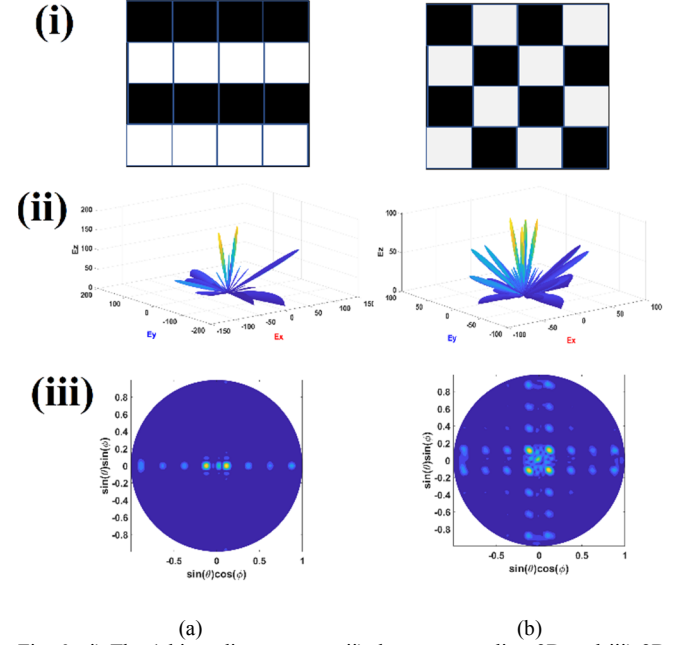

Fig. 6. i) The 1-bit coding patterns, ii) the corresponding 3D and iii) 2D scattering patterns changing in (a) one-dimension and (b) two-dimensions of coding sequence space (each square is 4×4 uint-cell sub-array).

B.2. Beam- Steering of Radiation Pattern

For more advanced purposes such as tracking and beam steering, the convolution technique is required to apply in coding sequence [15]. In this case, the gradient coding sequence is placed inside 4×4 sub-arrays. By creating these gradient changes inside the subarrays, we are able to create a single main beam as a directional pattern and rotating this main beam to the desired direction by using a 2-bit metasurface for beam-steering applications. Fig. 7 shows two examples of these code matrix with their 2D and 3D scattering patterns. As shown in Fig. 7, by creating gradient metasurface inside the 4×4 subarrays, a scattering pattern with a main beam can be generated which is suitable for beam steering applications. It also changes the direction of main beam by changing the phase arrangement inside each sub-array. Equations (3) and (4) show the coding pattern of the gradient coding subarray with a horizontal coding sequence at first raw is "$0\ \pi/2\ \pi\ -\pi/2$" which indicates '0 1 2 3' logics and in the second raw is "$\pi\ -\pi/2\ 0\ \pi/2$" which indicates '0 1 2 3' logics '2 3 0 1'. In the matrix form we applied φ_0 and φ_2 inside full structure matrix as follow:

$$\varphi_0 = \begin{bmatrix} 0 & \pi/2 & \pi & -\pi/2 \\ 0 & \pi/2 & \pi & -\pi/2 \\ 0 & \pi/2 & \pi & -\pi/2 \\ 0 & \pi/2 & \pi & -\pi/2 \end{bmatrix}; \quad \varphi_2 = \begin{bmatrix} \pi & -\pi/2 & 0 & \pi/2 \\ \pi & -\pi/2 & 0 & \pi/2 \\ \pi & -\pi/2 & 0 & \pi/2 \\ \pi & -\pi/2 & 0 & \pi/2 \end{bmatrix} \quad (3)$$

$$\psi_1 = \begin{bmatrix} [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \end{bmatrix} \psi_2 = \begin{bmatrix} [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_2] & [\varphi_2] & [\varphi_2] & [\varphi_2] \\ [\varphi_0] & [\varphi_0] & [\varphi_0] & [\varphi_0] \\ [\varphi_2] & [\varphi_2] & [\varphi_2] & [\varphi_2] \end{bmatrix} \quad (4)$$
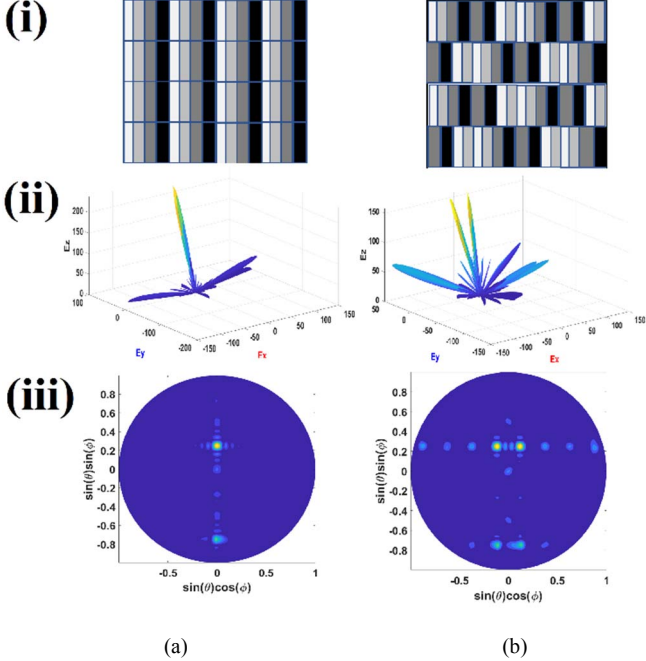

(a)   (b)

Fig. 7. i) The 2-bit coding matrix, ii) the corresponding 3D and iii) 2D scattering patterns changing in (a) one-dimension, and (b) two-dimensions of coding sequence space (each square is 4×4 uint-cell sub-array).

At the end of this section, the results from CST have been demonstrated based on the coding matrix and the results obtained in the previous part. The simulated radiation patterns are shown in Fig. 8 for the four coding modes at 4.35 THz. Almost all modes produce the expected patterns. The only difference between the simulation and the numerical results is in the zero-degree beam, which is more intense for two of the simulated results, which can be due to the involvement of various parameters in the simulation model such as the size of the radiation box or the power sent from the excitation port which can be solved by including these factors by tuning precisely in both MATLAB and CST environments.
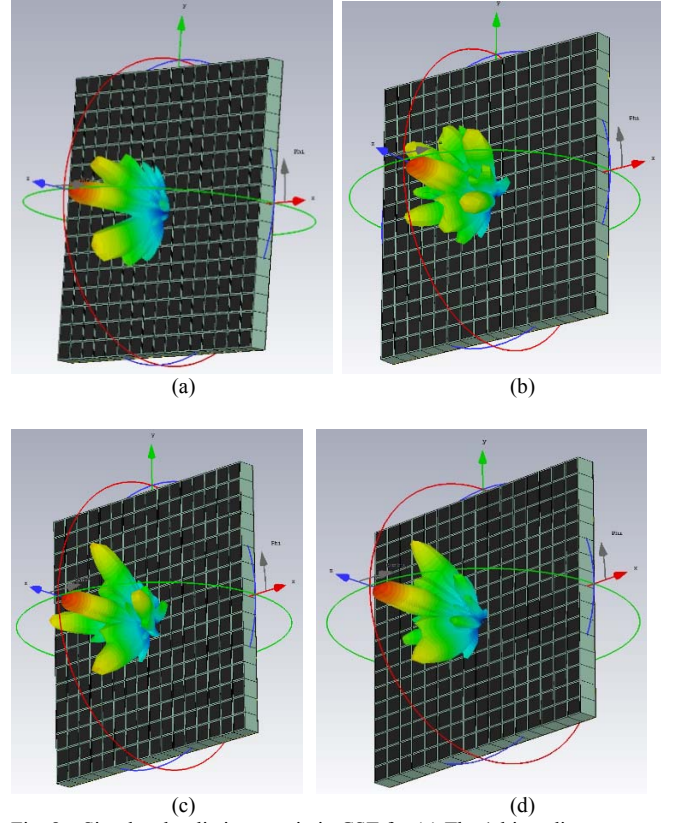

(a)   (b)

(c)   (d)

Fig. 8. Simulated radiation matrix in CST for (a) The 1-bit coding patterns changing in one-dimension , (b) The 1-bit coding patterns changing in two-dimensions, (c) The 2-bits coding patterns changing in one-dimension, and (d) The 2-bits coding patterns changing in two-dimensions

IV. CONCLUSION

In this paper, a new design of 2-bit graphene-based reconfigurable intelligent metasurface is presented for THz communication applications. A multilayer structure is used for the proposed unit cell configuration which includes a floating point using a thin layer of alumina and silicon between graphene and quartz substrate. In order to create reconfigurable structure by applying different voltage to this point the chemical potential of the graphene is changed. A parametric sweep analysis is performed to reach the optimal dimension. In addition, based on changing of the chemical potential four different phase states are obtained for 2-bit communications. By creating full-array structures using 16×16 elements of the proposed unit-cells, which includes 4×4 subarrays as a gradient coding sequence, the radial pattern is manipulated for time-space coding and beam-steering applications.

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