A Tunable Linear to Right-Handed Circularly Polarized THz Antenna Based on Graphene Switch

Mohammad M. Fakharian[1], Mohammad Alibakhshikenari[2], and Mariana Dalarsson[3]

[1]Faculty of Engineering, University of Garmsar, Garmsar, Iran

[2]Department of Signal Theory and Communications, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain

[3]School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, SE 100-44 Stockholm, Sweden

fakharian@fmgarmsar.ac.ir, mohammad.alibakhshikenari@uc3m.es, mardal@kth.se

***Abstract*— We propose a linear to right-handed circularly polarized tunable terahertz antenna. Polarization-switchable graphene is used to enable tunable polarization conversion and circular polarization. Polyimide is used as a substrate material for designing THz components due to its low absorption. By adjusting the graphene chemical potential to be between 0 eV to 0.8 eV, the polarization state in the 0.55 THz band can be obtained without changing the physical geometry. The proposed antenna has a significant potential for use in tunable terahertz devices and related applications.**

Keywords—Terahertz, antenna, tunable, polarization converter, graphene.

I. INTRODUCTION

The electromagnetic radiation in frequency range 0.1–10 terahertz (THz) is known as the THz band of the electromagnetic spectrum [1]. Wave manipulation in the THz band is a technology of great significance for research and applications of wireless communication, space exploration and other related fields [2–3]. In recent years, manipulating the polarization state of terahertz waves has also become an important research area in high resolution imaging, terahertz communication, remote sensing and other mid-infrared applications [4–5]. On the other hand, as one of the key THz devices, a polarized tunable antenna can effectively reduce signal loss caused by polarization mismatch and multipath effects, which has attracted increasing attention in recent years. Traditional antennas' polarization transformation methods include birefringent materials, crystals, optical gratings [6], controlling the on-off of a PIN diode [7], and rotating converters to achieve different polarization states [8], which have limitations such as high loss, large volume, and requirements to change the physical structure. Recently, polarization conversion using graphene switches in terahertz band has become a new research hotspot [9].

Graphene is a two-dimensional material built up by carbon atoms in a honeycomb lattice [10]. The Fermi energy levels of graphene can be altered by using chemical doping or electrostatic gating [11]. Such procedures change the electrical conductivity of graphene, which makes graphene a promising candidate for the design of tunable devices. Therefore, graphene has been widely used in micro-nano devices including sensors, absorbers, and antennas [9]. One idea is to combine the antenna with graphene switches to expand the polarization conversion functionality, in order to enable tunable linear polarization and circular polarization characteristics at the same working frequency band.

In this work, a tunable linear to right-handed circularly polarized THz antenna is designed and studied. Graphene is employed as a switch to achieve a reconstruction of the polarization state. Polyimide is selected as a suitable dielectric substrate for broadband THz components due to its low absorption. By adjusting the chemical potential of graphene between 0 eV and 0.8 eV, the working states of the circularly polarized antenna and linearly polarized antenna can be switched for operating frequencies around 1 THz (0.7–0.75 THz) without changing the physical geometry of the antenna. This combination can easily create a multistate THz antenna that can be used for the design of circularly polarized antennas.

II. CONDUCTIVITY MODEL OF GRAPHENE

The conductivity of graphene is provided by Kubo's equation [12], which is determined by both intra-band and inter-band transitions.

$$\sigma_S = \sigma_{\text{intra}} + \sigma_{\text{inter}} \tag{1}$$

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

$$\sigma_{\text{inter}} = \frac{-je^2}{4\pi\hbar}\ln\left(\frac{2|E_F| - (\omega - j\,2\Gamma)\hbar}{2|E_F| + (\omega - j\,2\Gamma)\hbar}\right) \tag{3}$$

In these equations, k_B is Boltzmann's constant, e is the electron charge, E_F is the Fermi energy, $\omega = 2\pi f$ is the angular frequency, and $\hbar = h/(2\pi)$ is the reduced Planck's constant. In the simulations, T is the environmental temperature, which is fixed at 300 K, G = $1/2\tau$ is the phenomenological scattering rate, where τ = 1 ps is the electron-phonon relaxation time. The main advantage of graphene is that its surface conductivity can be tuned by changing the Fermi energy. By applying a transverse electric field through a bias gated structure, E_F can be adjusted over a wide range of energies (between ±1.0 eV), so the conductivity of graphene can be controlled by a DC bias voltage. An approximate closed-form expression relating the Fermi energy E_F to the bias voltage V_g is given by Ref [13].

$$E_F \approx \hbar v_f \sqrt{\frac{\pi \varepsilon_r \varepsilon_0 V_g}{e t_S}} \tag{4}$$

In Equation (4), v_f is the Fermi velocity, which is fixed at 1.1×10^6 m/s, V_g is the bias voltage, which can be artificially controlled, ε_0 and ε_r are the permittivity of the vacuum and dielectric, respectively, and t_s is the thickness of the insulating spacer. In summary, Equations (1)–(4) provide an effective solution of the equations that dynamically control the polarization state of the terahertz wave by the bias voltage. Actually, by loading the graphene units as a switch on the antenna configuration, the working modes of the designed graphene-based antenna can be tuned by the adjustable surface conductivity of the graphene.

III. STRUCTUREOF THE PROPOSED THZ ANTENNA

The configuration of the designed THz antenna is shown in Figure 1, which is printed on a polyimide substrate with relative permittivity 3.5, thickness 6.25µm, tangential loss factor 0.008. It consists of a circular radiating patch as a driven element in the center of the substrate and two parasitic elements around it. In order to increase the capacitive load, the distance between the parasitic elements and the driven element is reduced, and thus the overall radius of the antenna is reduced. The parasitic elements are connected to the driven element through graphene switches. Metal layers in the two sides of graphene can be used to provide a tunable graphene complex conductivity through the electrostatic field effect and produce varying chemical potential on the graphene stubs by applying a gate bias voltage. The modified geometrical parameters of the antenna are shown in Table I. The spectra and the results in the present paper are obtained by using the commercial 3D software CST Microwave Studio, based on the Finite Integration Technique.

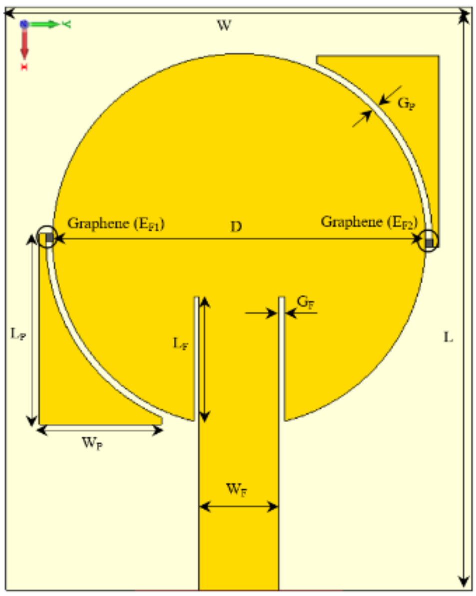


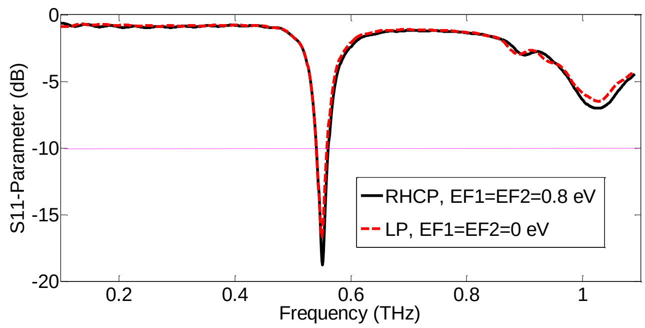
Fig. 1. Structure of the proposed THz antenna.

TABLE I. THE DETAIL PARAMETERS OF THE PROPOSED ANTENNA.

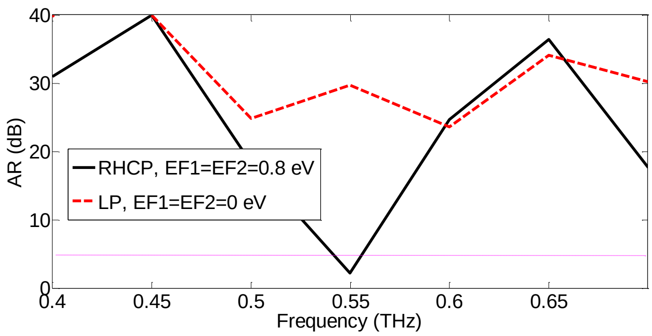
Parameters	Dimension (µm)	Parameters	Dimension (µm)
W	220	W_F	37
L	273	L_F	65
D	175	G_F	3.2
W_P	57.3	G_P	3.5
L_P	89.5	-	-

IV. NUMERICAL RESULTS AND DISCUSSIONS

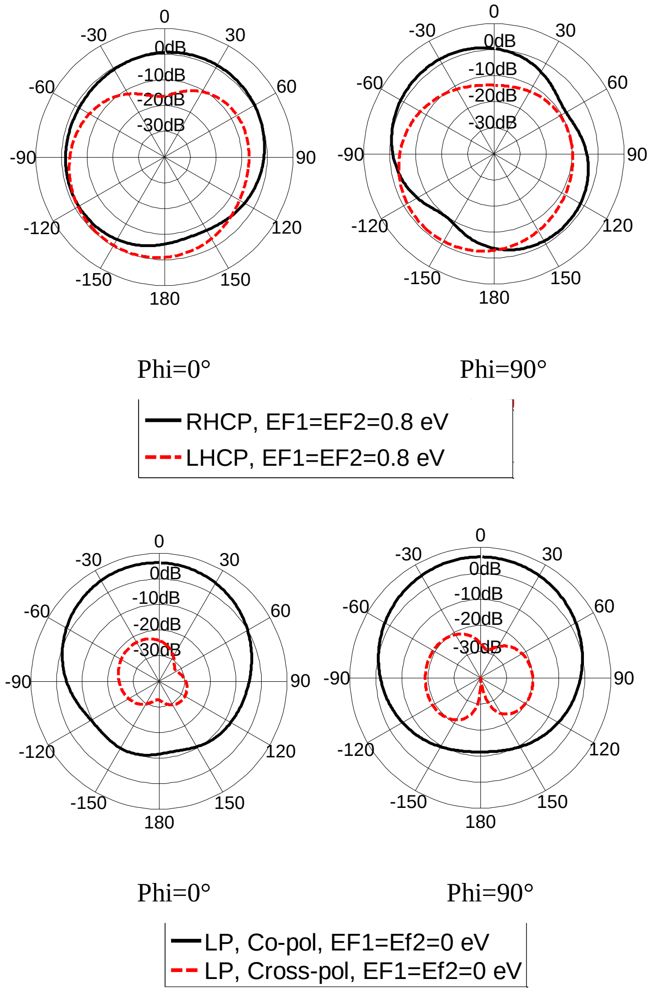
The purpose of the proposed design is to control the polarization of a linearly polarized incident wave. The designed structure can convert the polarization from linear to right-hand circular polarization. This feature can be shown by examining the axial ratio (AR) of the wave passing through the structure. AR is the ratio of the cross-polarized wave to the co-polarized wave, so for a perfect circular polarization conversion, the AR should be equal to one. A 3-dB point can be considered as the reference point for polarization conversion. The performance of the proposed antenna has been studied in the range of 0.1– 1.1 THz with the reflection coefficient ($|S_{11}|$), AR, and radiation pattern responses, as shown in Fig. 2. The chemical potential of graphene switches varies from 0 to 0.8 eV and the corresponding characterizes for the linear and polarization agilities are illustrated in Fig. 2(b). For RHCP, impedance bandwidth fully covers the corresponding 3-dB AR bandwidth at the center frequency of 0.55 THz. The minor polarization Z <0 is the LHCP and the major is the RHCP for Z >0 for the proposed antenna. Moreover, the antenna can be operated as a multi-characterized antenna with different radiation patterns at the same operating frequency, as verified in [7]. It is however not studied in this work. The gain attained by the proposed antenna is more than 0 dB with an efficiency of 40% at different modes.



(a)



(b)



(c)

Fig. 2. (a) $|S_{11}|$, (b) AR, and (c) radiation patterns of the THz antenna at different chemical potentials, left- and right-sides represent Phi=0° and 90°.

V. Conclusion

In summary, a linear to right-handed circularly polarized tunable THz antenna is designed and studied. The employment of graphene switches enables tunable polarization conversion and circular polarization. By electrically shifting the Fermi energy of two graphene switches, the polarization state of the band can be changed without changing the physical geometry. The proposed design has a simple geometry, and gives a strong conversion from linearly to circularly polarized waves at around of 0.55 THz and it can be adjusted to any desired frequency range.

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