URSI - RCRS 2022, IIT (Indore), India, 1 - 4 December, 2022

Graphene based Turnstile Antenna for Terahertz (6G) Applications

Amit Sharma(1), Dinesh K. Vishwakarma* (2)
(1) PDPM IIITDMJ, Jabalpur, India, 482005
(2) PDPM IIITDMJ, Jabalpur, India, 482005

1. Abstract

The work presented in this paper addresses the design & detailed analysis of a novel, graphene based, crossed-dipole (turnstile) patch antenna. This narrowband antenna is constructed to resonate at 1THz targeting under research 6G communication band, with added features such as circular polarization, frequency tunability, miniaturized structure etc. The antenna provides bi-directional radiation with sophisticated performance such as 69.79% radiation efficiency, 69.78% total efficiency, approx. 0.5dBi gain.

2. Keywords

Turnstile, Graphene, Terahertz Antenna, 6G Communication, Circular Polarization

3. Introduction

The ability of graphene, to support the generation and the propagation of transverse magnetic surface plasmon polariton (TM SPP) waves which are very highly dense EM waves, along with its other superior material properties, such as very high values of electron mobility (upto 2,00,000cm^2/V.s), current density (around 109 A/cm), tensile strength, thermal and electrical conductivity than copper or silver, at terahertz frequency, with an added feature of tunable complex surface conductivity [1], makes it very appropriate, to be used as an effective patch element for terahertz planar antennas. There have been several investigations of turnstile antenna in literature, to achieve circular polarization using turnstile mode at microwave frequencies, though very limited work is done for the same at terahertz frequency, that too using graphene [2].

The significance of circularly polarized patch antennas, in satellite communication-based applications for their inherent ability of eliminating errors due to multipath propagation from ground station to satellite receivers & vice versa, gains researchers' attention every now and then [4]. Apart from this, effect of Faraday rotation in the ionosphere due to earth's magnetic field, on signals transmitted by linearly polarized antennas is severe, while it doesn't affect signals from circularly polarized antennas [5]. Such communications, from terrestrial base stations to satellites, demand for ultrafast data transmission, for which high gain antennas are used, though the effect of atmospheric absorption hinders the application of terahertz antennas for this purpose. Hence, inter-satellite communication, at space, at terahertz speed, is very much possible using graphene terahertz antennas. Apart from this, an important area in which application of terahertz antennas has become the demand of the hour, is upcoming 6G communication, which targets lower terahertz band from 0.1 THz to 10 THz [6]. Hence, graphene, having features such as very high conductivity (thermal as well as electrical), very high tensile strength, and very high current density at terahertz band, as compared to copper at terahertz, shows the convenience of using it, for the design of terahertz antenna [7].

There are several works present in literature, based on graphene terahertz antenna. As in [8], authors have explained the basic understanding of graphene plasmonic nanoantenna and its analysis, though they haven't tried to design a circularly polarized antenna. In [9], a transmission line fed dual band graphene patch antenna has been designed, and analyzed, along with it, authors have studied the tunability and frequency reconfigurability of graphene, by varying its chemical potential. The authors in [10], have performed a very detailed analysis on the factors affecting the performance of graphene terahertz antenna. In [11], authors have provided very detailed and elaborated discussion on the applicability of 6G communication services and possible ways to realize it.

This work presents the design of a graphene turnstile (cross-dipole) antenna at the resonant frequency of 1 THz, along with analysis of graphene's frequency tunability with respect to S_{11} vs. frequency plot, turnstile mode analysis, as well as study of electric field distribution of the antenna with associated gain as well as axial ratio variation plots. The antenna, simulated using CST microwave studio, provides circular polarization at resonant frequency with 30% 3-dB axial ratio bandwidth, antenna gain is 0.454dBi, radiation efficiency is 69.79%, while total efficiency is 69.78%. name.

4. Antenna Design and Results

The uniqueness of graphene at terahertz, can be clearly understood by studying the energy band diagram of graphene, in which the valence band and conduction band meet at a single point, called the Dirac point, where a free electron exists, which, due to very weak forces at the Dirac point, contains very high mobility. The position of this electron can be changed from Dirac point to either of the valence band and the conduction band, by changing the doping level of graphene or by applying some specific chemical potential to the graphene sheet using dc gating pads [7]. This makes the conductivity of graphene tunable at terahertz.

The conductivity of graphene, denoted by σ_{gr} is divided into 2 parts, which are the intra-band conductivity (σ_{gIntra}), dominant for 0.1TH to 5THz and inter-band conductivity (σ_{gInter}), dominant for 5THz to 10THz. The controlling parameters of graphene's conductivity are the applied chemical potential (μ_c), the scattering rate (Γ), the frequency (ω) and temperature (T) [8].

$$\sigma_{gr} = \sigma_{gIntra} + \sigma_{gInter} \tag{1}$$

$$\sigma_{gIntra}(\omega, \mu c, \Gamma, T) = -\mathrm{j}\left(\frac{q^2 k_B T}{\pi \hbar^2 (\omega - j2\Gamma)}\right)\left[\frac{\mu_c}{k_B T} + 2\ln\left[e^{\left(\frac{\mu_c}{k_B T}\right)} + 1\right]\right] \tag{2}$$

$$\sigma_{gInter}(\omega, \mu c, \Gamma, T) = \mathrm{j}\left(\frac{q^2}{4\pi\hbar}\right)\ln\left(\frac{2|\mu_c| - (\omega + j\tau^{-1})\hbar}{2|\mu_c| + (\omega + j\tau^{-1})\hbar}\right) \tag{3}$$

Here, q is charge of electron, k_B is Boltzmann's constant, ħ is reduced plank's constant, and ω is frequency in radians. The value of graphene's chemical potential mainly depends upon the applied gate voltage, which indirectly controls the carrier concentration in it. The scattering rate (Γ), in equation (2) & (3), is inversely proportional to the relaxation time of electron, which is directly proportional to the electron mobility [8].

The architecture of the turnstile antenna, also known as the crossed dipole antenna, consists of two orthogonally placed dipole antennas with the feeds having phase difference of a quadrature. The antenna is made up of 2 graphene dipole patches ($L = \lambda_{spp}/2$), fed with 90° phase difference, over silica (ε_r=3.8, h=1µm), epoxy resin (ε_r=4, h1=2µm) dual substrate. The chemical potential (μ_c), of this single atom thick sheet of carbon, (graphene), is taken as 3eV, while relaxation time (τ) is 1ps, providing scattering rate ($\Gamma = 1/2\tau$) as 0.5, at room temperature 300k, providing complex intra-band (f< 5THz) surface conductivity of graphene (given by eqn.1), using MATLAB, as (0.0087 – 0.0548j), here, the imaginary part of surface conductivity is negative, which verifies the generation and propagation of TM SPP waves, at graphene-air interface [3]. SPP wavelength, λ_{spp} is calculated to be 192um, which gives dipole length $(\lambda_{spp})/2$ as 96um including 10um feed gap.

The simulated antenna is shown in figure.1, where the crossed dipole structure of graphene is placed over 140x140 um^2, silica/epoxy resin dual substrate. The exact length of each arm of the antenna is taken as 42.75um, as per parametric analysis, while the width of the arm is taken as 8um.

The associated performance of the antenna is studied using the S_{11} vs. frequency plot, for different values of graphene chemical potential, show in figure.2. As can be observed from the plot, at the value of 0eV chemical potential of graphene, its surface conductivity is negligibly small, providing poor S_{11} vs. frequency response, while as we increase the chemical potential to 2eV, the graphene patch starts behaving like a good conductor, while at the chemical potential of 3eV, the antenna resonates at 1THz, with S_{11} of -39dB, which further shifts to 1.05THz and 1.1THz for graphene chemical potentials of 4eV and 6eV respectively, demonstrating the frequency tunability of graphene.

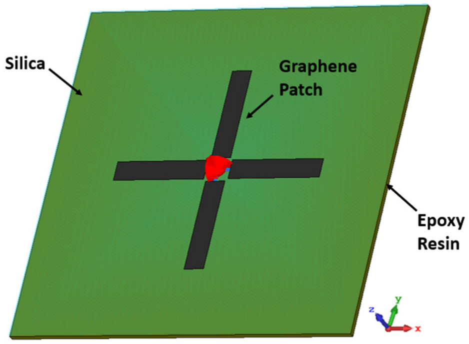


Figure 1. Graphene THz Turnstile Antenna at 1THz

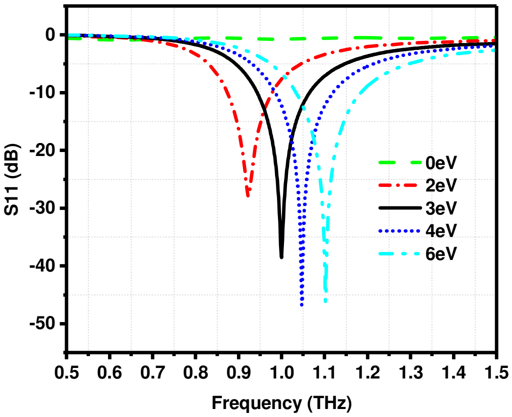
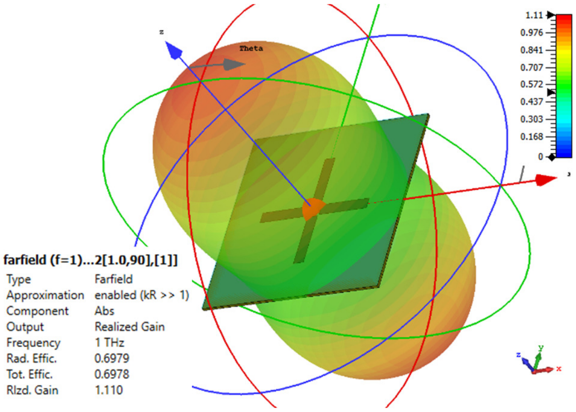


Figure 2. S_{11} variation with respect to frequency, for graphene chemical potential (μ_c) = 0eV, 2eV, 3eV, 4eV and 6eV, respectively.

The analysis of the 3D gain radiation pattern of the antenna in linear scale, shown in figure.3, verifies the directive dual sided response due to the absence of ground plane, with 2dBi directivity, having strong radiation at the direction, normal to the plane of the patch.



farfield (f=1)...2[1.0,90],[1]]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	1 THz
Rad. Effic.	0.6979
Tot. Effic.	0.6978
Rlzd. Gain	1.110

Figure 3. 3D gain radiation pattern of the antenna at the chemical potential of 3eV.

The variation of antenna gain (dBi) as well as axial ratio (dB) with respect to frequency (THz) is shown in figure.4. It can be observed from the figure that the antenna, due to phase quadrature feeding in crossed dipole structure, provides below 3dB axial ratio around the resonant frequency of 1THz as per the expectation from the structure, while the absence of ground plane verifies small gain as well as directivity.

The 2D polar plot shown in figure.5 verifies that the shape of the antenna radiation pattern is maintained with respect to the change in graphene chemical potential, though the antenna gain is maximum at 3eV, while it is minimum at 6eV.

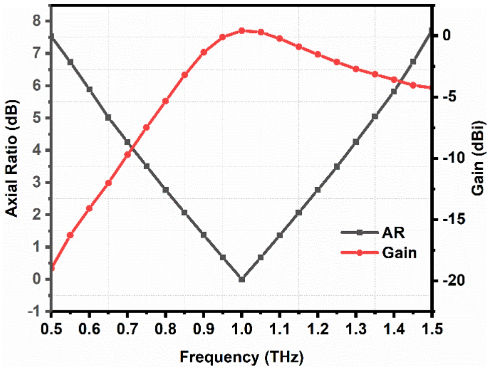


Figure 4. Axial ratio and gain plot with respect to frequency variation for μ_c= 3eV.

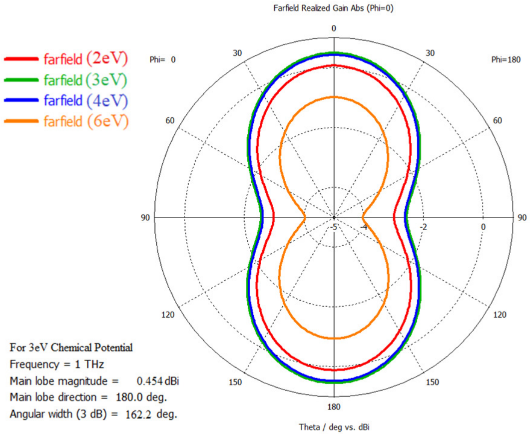


Figure 5. 2D polar plot of antenna gain (dBi) with respect to theta variation for different chemical potentials at Phi=0°.

The variation in the electric field distribution throughout the antenna structure with change in angle theta, is presented in figure.6. It can be concluded that the for θ=0°, dipole-1 (along x-axis) of the turnstile antenna dominates in the contribution for radiation, while at θ=90°, dipole-2 (along y-axis) mainly contributes for the radiation, and the cycle goes like this, verifying the left-hand circular polarization (LHCP) nature of the antenna, as the dipole-1 is fed with phase quadrature (+90°), with respect to dipole-2. Similarly, to achieve right-hand circular polarization (RHCP), one should feed the dipole-2, at +90°, with respect to dipole-1.

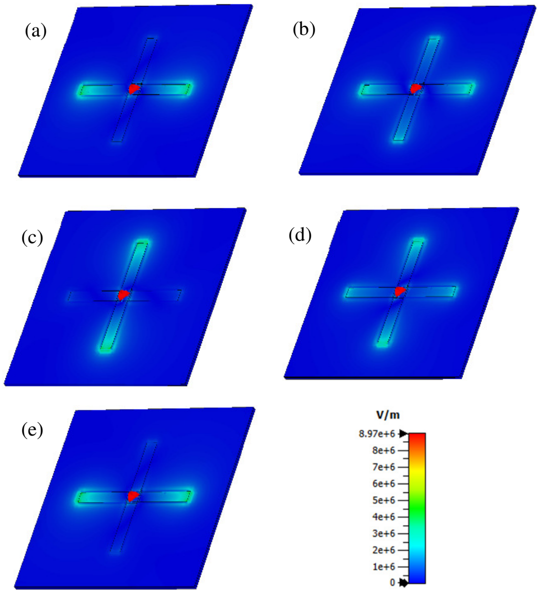


Figure 6. E-field variation of the antenna for (a) θ=0°, (b) θ=45°, (c) θ=90°, (d) θ=135°, and (e) θ=180°.

The direction of the main-lobe of the antenna can be converted to broadside, instead of current bi-directional nature. Similarly, the radiation pattern as well as the gain, directivity response of the antenna could be improved by adding the ground plane at the base of the antenna structure, though this process isn't followed here, as one of the objectives of this work was to analyze the effect of keeping the basic design of the crossed-dipole antenna, same as of a typical microwave frequency dipole antenna.

The antenna performance can be further improved by converting this patch antenna to a lens antenna, which can be fed by femtosecond laser using photo-mixer at one end, while the terahertz radiation can be achieved on the other side, having lens structure, to improve directivity as well as gain of it.

5. Conclusion

The novel graphene turnstile THz antenna presented in this work, is thoroughly analyzed, suggesting its appropriateness in the field of 6G communication, while further investigation of this antenna using arrays (1D and 2D) to achieve better gain response, can be considered as future work.

5. References

1. G. W. Hanson, “Dyadic Green’s functions and guided surface waves for a surface conductivity model of graphene”, Journal of Applied Physics, 103, p. 064302, 2008.

2. Y. Luo et al., "Graphene-Based Multi-Beam Reconfigurable THz Antennas," in IEEE Access, vol. 7, pp. 30802- 30808, 2019.

3. A. Sharma, P. Tiwari and D. K. Vishwakarma "Frequency re-configurable metal-graphene hybrid MIMO patch antenna for terahertz communication" Frequenz, vol. no. 2022.

4. M. Kulkarni, Microwave and Radar Engineering, 4th ed., Umesh Publications, 2010.

5. I. F. Akyildiz, J. M. Jornet, and C. Han, “Terahertz band: Next frontier for wireless communications,” Physical Communication, Elsevier, Vol. 12, Pages 16-32, 2014.

6. G. C. Ghivela and J. Sengupta, “The Promise of Graphene: A Survey of Microwave Devices Based on Graphene,” IEEE Microwave Magazine, vol. 21, no. 2, pp. 48-65, Feb. 2020.

7. M. Fuhrer, C. Lau, and A. MacDonald, “Graphene: Materially Better Carbon,” MRS Bulletin, 35(4), 289-295, 2010.

8. S. Dash, A. Patnaik, and B. K. Kaushik, “Performance enhancement of graphene plasmonic nanoantennas for THz communication,” IET Microw. Antennas Propag., 13: 71-75, 2019.

9. S. Mrunalini, and A. Manoharan, “Dual-Band Reconfigurable Graphene based Patch antenna in Terahertz band for WNoC Applications,” IET Microwaves, Antennas & Propagation, 2017.

10. S. Rakheja, P. Sengupta and S. M. Shakiah, "Design and Circuit Modeling of Graphene Plasmonic Nanoantennas," in IEEE Access, vol. 8, pp. 129562-129575, 2020.

11. I. F. Akyildiz, A. Kak and S. Nie, "6G and Beyond: The Future of Wireless Communications Systems," in IEEE Access, vol. 8, pp. 133995-134030, 2020.