The Comparative Analysis of Graphene Nano-based and Copper Nano-based Patched Antenna using HFSS

A R Atser 1, J M Mom 2 and G A Igwue 3

Department of Electrical and Electronics Engineering, Federal University of Agriculture, Makurdi, Benue State, Nigeria.

e-mail: atserakpennongun@gmail.com

Abstract: Patch material plays a significant role in controlling the performance and resonating frequency of patch based antennas. In this work, we compared graphene and copper nano-based patch antennas in terms of return loss, bandwidth, gain, directivity and voltage standing wave ratio (VSWR). The simulation is carried out using high frequency structure simulator HFSS. The substrate material used is Silicon dioxide. The antenna is designed to operate in the THz frequency band of (1-15THz) with the fundamental frequency of 5.5THz. The result shows that, the classical metallic antennas with copper material resonant at lower frequency of 3THz while graphene resonant at the higher frequency of 7THz, this is due to high electrons mobility in graphene than in copper. Graphene based patch antenna achieves maximum return loss of -24.4555dB with the corresponding VSWR of 1.0413. The maximum gain of 7.1943dB is achieved with a bandwidth of 522.3GHz; this shows better antenna performance than copper except the bandwidth. The contemporary copper antenna attains return loss of -14.7028dB with the corresponding VSWR of 3.2336. The gain of 4.6219dB is achieved with a bandwidth of 1188.5GHz. With this result, it can be seen that graphene is a suitable choice and can replace copper patch material for patch antennas for wireless applications in terahertz frequency band.

Keywords: graphene, terahertz frequency, bandwidth, patch antenna

1. Introduction

Graphene is a single-layer, two-dimensional material recently discovered as nano-material. It has a very good mechanical and optical properties that distinguishes it from other materials such as copper and Aluminum [1]. Graphene can conduct electricity million times more that copper [2]. Graphene’s strength is almost 100 times more than steel [3]. It has ability to expand up to twenty percent of its original size and length. To this end, it can be used to make curved display screens, and it is known to conduct heat more than diamond [4]. Antennas made of copper material cannot work effectively on high frequencies such as terahertz frequency due to high losses on the surface of the copper material. This phenomenon can be resolved with graphene. The high frequency structure simulator HFSS will be used as a simulator tool for evaluating the performances of both materials for wireless applications.

2. Modelling of complex surface properties of graphene

Graphene is a single-layer, two dimensional material made of carbon atoms packed in a structure known as hexagonal. It can be modeled using Kubo formula [5].
The surface conductivity $\sigma(\omega)$ consist of intraband and interband contribution.

$$\sigma(\omega) = \sigma_{\text{intra}}(\omega) + \sigma_{\text{inter}}(\omega)$$

(1)

$$\sigma_{\text{intra}}(\omega, \mu_c, \Gamma, T) = \frac{q_e^2 K_B T}{\hbar (\omega - j \Gamma)} \left( \frac{\mu_c}{K_B T} + 2 \ln \left( e^{\frac{-\mu_c}{K_B T}} + 1 \right) \right)$$

(2)

And an interband contribution

$$\sigma_{\text{inter}}(\omega, \mu_c, \tau, T) = \frac{q_e^2}{4\hbar \pi} \left[ \frac{2|\mu_c| - (\omega + j \tau^{-1})}{2|\mu_c| + (\omega + j \tau^{-1})} \right]$$

(3)

where $j$ is the imaginary unit, $q_e$ the electron charge, $\hbar$ the reduced Plank constant, $KB$ the Boltzmann’s constant, $T$ the temperature, $\mu_c$ the chemical potential, and $\omega$ the operating angular frequency. Scattering rate $\Gamma = 1/2\tau$ represents its loss mechanism and $\tau$ the relaxation time. The value of $\tau$ in previous literature ranges between $10^{-11}$ and $10^{-14}$ [6]. In this work, the utilized $\tau$ is $3\times10^{-12}$ [5][7].

The interband and intraband surface conductivity are evaluated using equ (2) and (3). Intraband represents total conductivity value from the frequency range below 5THz, while interband has no effect on the total surface conductivity within the band value. Fig 1(a) and 1(b) represents the surface conductivity at different values of graphene chemical potential. It depends on the carrier density, which can be controlled using three parameters which include gate voltage, electric bias field or chemical doping. By increasing chemical potential will leads to corresponding increase in graphene surface conductivity. This however, cause antenna to resonate at higher frequencies. The shifting of antenna resonance, as a result of change in chemical potential enhances flexibility for the design of tunable antennas within the terahertz frequency band. By electrically changing gate voltage ($V_g$) on the layer of graphene, changes the value of the chemical potential [8][9].

$$V_g = \left[ \frac{q_e \mu_c^2 \hbar}{\pi \hbar v_f \zeta 0 \rho} \right]$$

(4)

Figure 1. Conductivity of graphene, (a) intra, inter and total conductivity at 0 eV chemical potential, (b) Real and imaginary graphene conductivity for different chemical potentials [9].
where $\varepsilon_r$ presents relative permittivity of the substrate and $h$ is the substrate thickness. The electromagnetic scattered field can be calculated from the graphene structure which is related to the coupling between the graphene conductivity model and Maxwell’s equations.

The modelling challenge of graphene is as a result of its thin layer structure and finite mesh cell size in space numerical calculation. Graphene is modelled based on equivalent surface impedance $Z_s = 1/\sigma$, where $\sigma$ is frequency dependent surface conductivity computed using Equations (2) and (3). Different values of chemical potentials then result in different graphene models [9].

The patch dimension, resonant frequency and Fermi energy contribute to the wave propagation velocity of the graphene material. Based on this, graphene resonant frequency can be calculated using the formula [10]

$$f_0 = \frac{v_f}{2L} \quad (5)$$

Where $v_f$ = wave propagation velocity; while, $L$ = patch length of graphene

Graphene’s ability to support surface plasmon polaritons (SPP) has placed it above other materials for used as future material for antenna design and implementation at terahertz frequency ranging from (0.1 to 10THz). A typical nano-patch antenna consists of a conducting patch and a conducting ground plane separated by a substrate material [11][12].

![Fig 2 graphene based patch Antenna](image)

Table 1: Design parameters for graphene based-nano patch antenna.

| Design parameters     | Measurement |
|-----------------------|-------------|
| Length of the Patch ($L_1$) | 22µm        |
| Width of the Patch ($W_1$)  | 30µm        |
| Height of Substrate ($h$)   | 7.0µm       |
| Length of Substrate ($L$)   | 100µm       |
| Width of Substrate ($W$)    | 63µm        |
| Length of feed line ($L_2$) | 21µm        |
| Width of feed line ($W_2$)  | 6.0µm       |
| Thickness of the patch ($K_1$) | 0.690nm     |
3. Results and Discussion

The comparison between graphene nano-based patch antenna and its copper counterpart in terahertz frequency

Figure 3a shows the value of where return loss is minimum for graphene. It has a return loss of -24.4555dB with the resonant frequency of 7THz which is greater than the working frequency of 5.5THz. The simulated result shows that graphene achieved the bandwidth of 522.3GHz.

Figure 3b shows the value of where return loss is minimum for copper. The classical metallic antenna made with copper material resonant at lower frequency of 3THz. It has a return loss of -14.7028dB. The simulated result shows that copper achieved the bandwidth of 1188.5GHz.
Figure 3. Return loss (in dB) curve for (a) Graphene (b) Copper based patch Antenna

Figure 4a and b show the value where voltage standing wave ratio (VSWR) is minimum for both graphene and copper based nano patch. The graphene based nano patch has VSWR of 1.0413, which is within the acceptable figure of VSWR ≤ 2 while copper has VSWR of 3.2336, which is outside the acceptable figure of VSWR ≤ 2.
Figure 4. VSWR curve for (a) Graphene (b) Copper based patch Antenna

Figure 5a and b show 2D radiation pattern for the antenna gain for Graphene and the contemporary copper antenna in azimuth plane.

Figure 5. 2D polar plot of gain (dB) in azimuth plane $\phi = 0^\circ$ (red) and $\phi = 90^\circ$ (purple) for (a) Graphene (b) Copper based patch Antenna

Figure 6a and b show 3D radiation pattern for the antenna gain. Graphene achieved the maximum gain of 7.1943dB while the contemporary copper antenna has the gain of 4.6219dB.
Figure 6. 3D radiation pattern for (a) Graphene (b) Copper based patch Antenna

Figure 7a and b show 3D radiation pattern for the antenna directivity for Graphene and copper based nano antenna with the maximum value of 7.2067 and 7.9384 respectively.

Figure 7. 3D radiation patterns for (a) Graphene (b) Copper based nano patch Antenna

Conclusion
In this research work, a comparative analysis of graphene based nano patch antenna with copper based nano patch has been presented. The simulation is carried out using high frequency structure simulator HFSS. The antenna is designed to operate in the THz frequency band of (1-15THz) with the fundamental frequency of 5.5THz. Silicon dioxide was used as the substrate. The results show that, the classical metallic antennas with copper material resonant at lower frequency of 3THz while graphene resonant at the higher frequency of 7THz. Graphene based patch antenna achieves maximum return loss of -24.4555dB with the corresponding VSWR of 1.0413. The maximum gain of 7.1943dB is achieved with a bandwidth of 522.3GHz. The contemporary copper antenna attains return loss of -14.7028dB with the corresponding VSWR of 3.2336. The gain of 4.6219dB is achieved with a bandwidth of 1188.5GHz. The higher the VSWR, the greater is the mismatch. The minimum possible value of VSWR is unity and this corresponds to a perfect match. The return losses (RL), obtained from fig (3a) and (3b), indicate the amount of power that is transferred to the load or the amount of power reflected back. This result shows drawback of copper patch antenna as it encounters higher losses due to reflected power observed from the high value of VSWR. The acceptable figure for VSWR is between 1 and 2. However, copper patch antenna achieved better bandwidth at the expense of higher power loss due to copper losses on the surface. This result agreed with (Azizi et al, 2017)[13]. From their work they achieved return loss of -29dB at the operating frequency of 0.7THz for graphene which is almost twice the value obtained with the copper patch. Graphene achieved the gain of 7.16dB while that of copper is 5.73dB

The result shows that graphene based nano patch antenna performs better than copper based nano patch antenna as presented. The strong gain and high return loss obtain in graphene is as a result of high mobility of electrons in graphene materials. In conclusion, graphene can replace copper patch in patch antennas as a solution to terahertz frequency regime.

References

[1] Randir S, Kumar D and Tripathi C.C 2015 Graphene: potential material for nanoelectronics application” India Journal of pure and applied physics vol. 53, August 2015, pp 501-513
[2] Moser J, Barreiro A and Bachtold A 2007 Appl. Phys Lett, 91(2007) 163513
[3] Geim, A. K and Novoselov K. S 2007 Nature mater, 6 (2007) 183
[4] Balandin A A, Ghosh S, Bao W, Calizo I, Teveldebrhan D, Miao F and Lau C N 2008 Nano Lett, 8(2008) 902
[5] Hanson G W, 2008 Dyadic Green’s functions for an anisotropic, non-local model of biased graphene,” Journal of Applied Physics, Vol 103, issue 6, pp 064302, 2008.
[6] Llatser I, C. Kremers, D. N. Chigrin, J. M. Jornet, M. C. Lemme, A. Cabellos-Aparicio 2012 Radiation characteristics of tunable graphenennas in the terahertz band,” Radioengineering, Vol. 21,946–953, 2012.
[7] Gusynin, V. P., Sharapov S. G and Carbotte J. P 2006 Magneto-optical conductivity in graphene,” Journal of Physics: Condensed Matter, Vol. 19, 026222, 2006.
[8] Radwan, A. H, Amico M. D and Gentili G 2014 Reconfigurable THz Yagi antenna based on hybrid graphene-metal layout,” 2014 Loughborough Antennas and Propagation Conference (LAPC), 671–675, 2014.
[9] Gatte, M., Soh, P. J., Rahim, H., Ahmad, R. & Abdul Malek, M. Fareq. 2016, ‘The performance improvement of thz antenna via modeling and characterization of doped graphene’, Progress in Electromagnetics Research (PIER), vol. 49, pp. 21-31.
[10] Skulason H S, Nguyen H V, Guermoune A, Szkopek T 2011, 110 GHz measurement of large-area graphene integrated in low-loss microwave structures. Applied Physics Letter. 2011; 99(153504).
[11] Balanis C A 1997 “Antenna Theory Analysis and Design,” *John-Wiley and Sons Publications*, 2nd edition, ISBN No. 978-81-265-1393-2, 1997.

[12] Rajni B, and Anupma M 2015 Comparative investigation of Graphene Nano Patch Antenna for different Substrate Materials in Terahertz Region’International Journal of Science Research and Technology Volume 1 Issue 1, pp 9-16, 15th September 2015

[13] Mohamed K. A, Mohamed A. K, Hosni A, and Ali G 2017 Terahertz Graphene-Based Reconfigurable Patch Antenna; *Progress In Electromagnetics Research Letters, Vol. 71*, 69–76, 2017