Designing and Simulating of Tunable Microstrip Patch Antenna for 5G Communications Utilising Graphene Material

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Abstract—The patch antennas are considered one of the widespread antennas that are extensively utilized due to their capability to combine and unite with various devices, and their manufacturing cost is low, in addition to their low weight. On the other hand, in contrast to these advantages, these antennas are tainted by their narrow bandwidth and low efficiency, in addition to their weak gain. The use of high frequencies such as 60-GHz for indoor uses and the future of the next generation of wireless communications allows users to obtain a high data transfer speed of up to many gigabits per second but at the expense of losses in this frequency band, which must be rationed as much as possible through the antenna design. In this article, a Microstrip Patch (MP) antenna with the rectangular patch shape will be simulating and improved for 60-GHz applications based on graphene material. This material has amazing and unique characteristics one of which is the variable surface impedance which can be tuned via practised DC voltage on the material layer. This property allows constructing the tunable antennas that are considered as a good solution to eliminate the narrow bandwidth of the MP antennas. The introduced antenna structure comprises of fully copper radiated patch inside it two graphene slots are inserted, a substrate with 2.2 relative permittivity and 0.1 mm thickness, and a fully copper ground plane. The suggested antennas design is done by using the finite integration that is offered by the CST software. The obtained gain results for the simulated antenna is diverse among 6.19-4.6dBi for both states of the surface impedance (i.e. low graphene surface impedance and high graphene surface impedance).

Index Terms—5G, CST, MP antenna, graphene, tunable antenna, 60-GHz

I. Introduction

The wireless communication technology has been evolved swiftly to satisfy the need for the high data rate capacities in electronic appliances. The Fifth-generation (5G) technology employs the higher frequencies to provide the comprehensive information capacities required to support the many gigabits/second data rates and handle the infinite information broadcasts adopting the most advanced mobile technology [1], [2].

Over the last three decades, telecommunications has grown at an exponential rate. In today's world, the quantity of data used by the ordinary person is growing gradually. When studying the progression of wireless communications, this growth is more noticeable. As a result, the demand for faster data rates has risen, prompting researchers to look for ways to develop data rates [3].

The currently utilised piece of the electromagnetic spectrum for wireless communications such as on the cellular, Wi-Fi, Bluetooth, and so on is approximately about 0.5-6GHz, which is a little piece of the spectrum and extremely congested because of the large amount of the applications that operated in such band. Moreover, with the numerous advancements in spectral efficiency, this is a border factor [4].

Inventors and researchers have been investigating other parts of the frequency spectrum that could be practised to improve the wireless technologies for an extended time. One of these bands is the licence-free 60GHz band. The aforementioned band was previously only employed for the short-range requirements of point-to-point radio links such as the satellite-to-satellite communications and personal applications. Now it is employed at the home to a number of short-range high-throughput wireless technologies such as the Wireless HD and the Wireless Gigabit Alliance (WiGig) [5], [6].

According to the countries rules, this licence-free band has a bandwidth of approximately about 9GHz. The 60 GHz band in North America ranges at 57-64 GHz and differs from the other countries. The antenna that is suitable for these requirements must have a reasonable bandwidth and cover the whole WiGig band and the future of the next generation. Short-range requirements function as point-to-point radio links, which necessitate a high degree of directivity and gain [7].

The antennas that have been designed with a steelyard of price and performance can achieve a vaster development. The antenna is one of the most important segments of a wireless communications system in terms of performance and combination. Rain attenuation is unusual at the 60GHz band, and the power losses are meaningful. Further importantly, there is a peak in oxygen intake at this precise frequency. At the millimeter-wave frequencies, Fig. 1 depicts atmospheric attenuation. As a result, such frequencies is used for indoor requirements [8].

One of the most famous types of antennas is the Microstrip Patch (MP) antennas that offered a low

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fabrication cost, lightweight, and low profile as opposed that these antennas characterized by the narrow bandwidth [9].

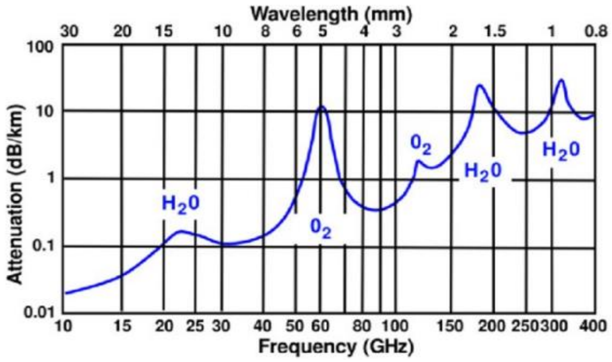

Fig. 1. The mean of atmospheric attenuation for the millimeter-waves.

Many manners were introduced to enhance the bandwidth such as metamaterials, array configuration, and frequency selective surfaces, and tunable antennas. The tunable or reconfigurable antennas are made up from a traditional patch coupled with it an extension by means of the PIN diode, varactors, or tunable materials like the graphene [10].

The graphene can be defined as an individual layer of the carbon atoms. In innocent terms, the graphene is a one-atom-thick layer of carbon atoms systematised in the form of a hexagonal lattice, as shown in Fig. 2 [11].

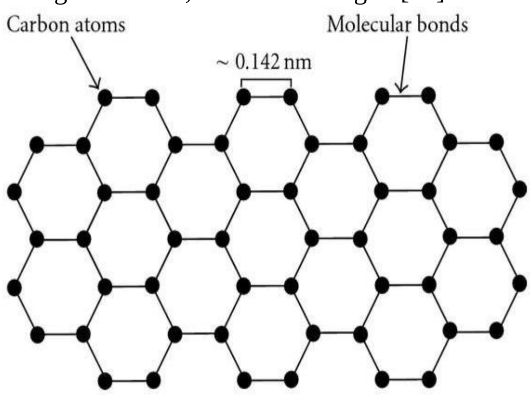

Fig. 2. The structure of the graphene material layer.

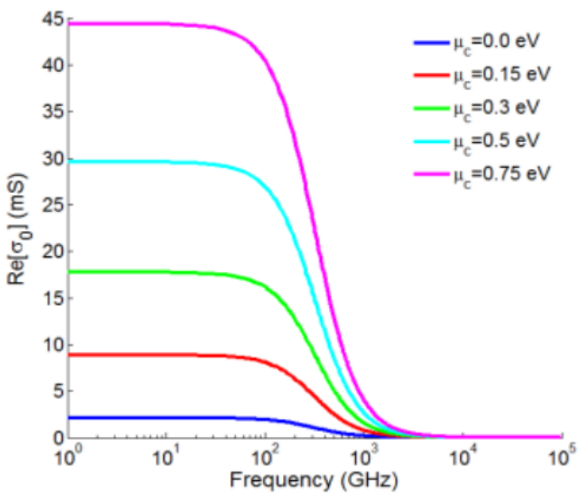

Fig. 3. Real-part surface conductivity of graphene versus frequency.

The graphene owns many properties the most excited one is the reconfigurable surface conductivity that is dependent on the applied DC voltage. The conductivity of the graphene is split into two major parts, the first one is termed as the intra-band and the latter termed as inter-band conductivity. The intra-band contributes its effect on the total graphene conductivity at the frequencies around the 5-THz band and it fluctuates or diminishes at the frequencies above the mentioned range. Whereas, the inter-band conductivity contributes its effect on the total conductivity in the frequencies above the 5-THz, as demonstrated in Fig. 3 and Fig. 4 [12], [13].

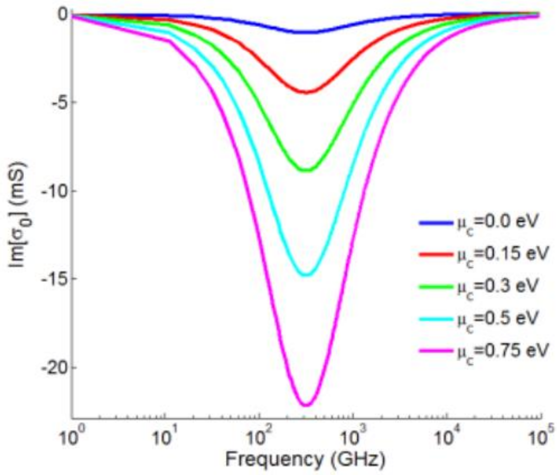

Fig. 4. Imaginary-part surface conductivity of graphene versus frequency.

The reconfigurable graphene conductivity allows the designers to construct the microwave attenuators, filters, and tunable appliances in the electronic science. Besides the variety of the other utilisation, the graphene can be utilised to implement the tunable antennas which are helping to minimise the difficulties of the narrow bandwidth of the MP antennas. In order to tune the graphene material conductivity that is utilised in the reconfigurable MP antenna, a DC voltage must be applied to the graphene layer, as illustrated in Fig. 5 [14].

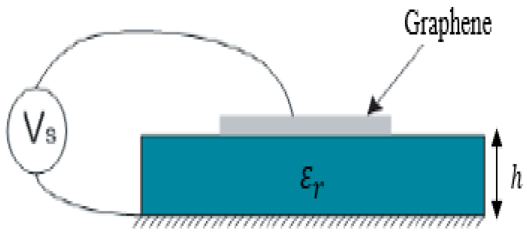

Fig. 5. Graphene-based reconfigurable MP antenna.

In this article, a tunable graphene-based rectangular MP antenna will be simulated and improved for the WiGig (i.e. 60GHz) and the 5G applications by using the powerful Computer Simulation Technology (CST) software. The simulated antenna contains a copper patch with a pair of the graphene material slots, a substrate with a 2.2 dielectric constant and 0.1mm thickness, a fully copper ground plane, and is fed by an inset line feeding technique.

II. Rectangular MP Antenna

The MP antennas (or utterly "patch" antenna) are a kind of the antenna which is more useful and used because they can be printed immediately onto a substrate. In addition, they offer the benefit of being easily fabricated making them cost-effective. Their small profile design, which is often square or rectangular, permits them to be installed on flat surfaces [15]. The general structure of the rectangular MP antenna contains a copper radiated patch, insulating material often called substrate, ground plane, and feed line, as shown in Fig. 6.

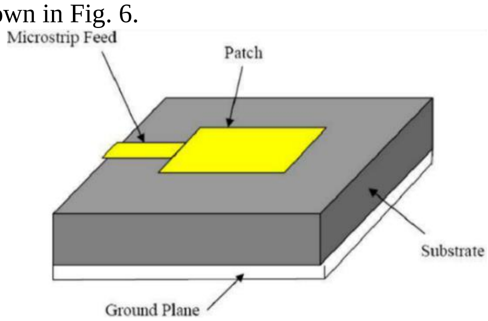

Fig. 6. Structure of the rectangular MP antenna

III. MP Antenna Design and Simulation Procedure

In this work, special simulation software was used called "Antenna Magus" that helps in designing the antenna completely without the need to use mathematical equations. This program can provide the antenna structure only by entering three basic parameters, which are the operating frequency (f_r), the thickness of the dielectric substrate (h), and the dielectric constant of the substrate (ε_r). Then the antenna structure is exported to the CST software for antenna testing and optimization to enhance its performance. In order to test the validity and accuracy of the antenna dimensions obtained from the program, the following set of equations were used, which confirmed the validity of the dimensions [16], [17]:

$$W_p = \frac{c_o}{2f_r\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

$$\varepsilon_{r.eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{\frac{-1}{2}} \tag{2}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left[\frac{W_p}{h}+0.264\right]}{(\varepsilon_{r.eff}-0.258)\left[\frac{W}{h}+0.8\right]} \tag{3}$$

$$L_{.eff}=\frac{c}{2f_r\sqrt{\varepsilon_{r.eff}}} \tag{4}$$

$$L_p = L_{.eff} - 2\Delta L \tag{5}$$

$$W_{sub} = 6h + Wp \tag{6}$$

$$L_{sub} = 6h + Lp, \tag{7}$$

where W_p is the width of the radiating patch, $\varepsilon_{r.eff}$ is the effective relative permittivity, ΔL is the length expansion, $L_{.eff}$ is the effective length of the radiating patch, L_p is the length of the radiating patch, W_{sub} is the width of the substrate, L_{sub} is the length of the substrate, and c_o is the light speed in the free space.

In order to facilitate the fabrication process, obtain the best return loss (S_{11}) value beyond the 60-GHz, and improve the gain the optimization process is applied by trial and error procedure on the antenna dimensions. Table I and Fig. 7, respectively, illustrates the dimensions of the rectangular MP antenna and the exported rectangular MP antenna in the CST software.

Table I: Rectangular MP Antenna Dimensions

Description	Value (mm)	Optimized (mm)
Patch Width (W_p)	1.975	2.01
Patch Length (L_p)	1.630	1.623
Substrate Width (W_{sub})	2.575	4.02
Substrate Length (L_{sub})	2.23	3.246
Feed Width (W_f)	0.30810174	0.303
Feed Length (L_f)	1.82632978	1.82
Feed-Patch-Spacing (g)	0.04201480	0.05
Feed inset (f)	0.56641348	0.49

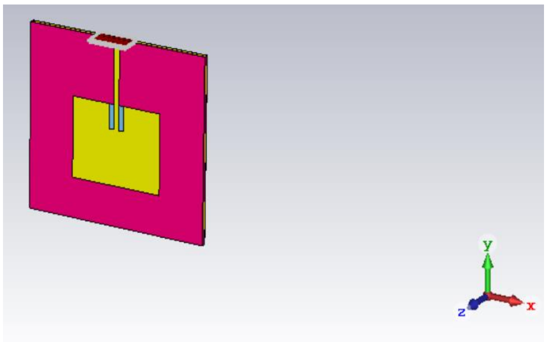

Fig. 7. Simulated rectangular MP antenna with ε_r=2.2 and h=0.1mm in CST.

IV. Graphene-Based MP Antenna Design

In this section, the design and simulation process for the graphene-based MP antenna will be presented and discussed. In order to construct the graphene-based reconfigurable MP antenna, five major steps must be considered, which are summarised as follows:

- Design the MP antenna with operating frequency of 60 GHz.
- Checking the current distribution on the patch.
- Calculating the graphene strips impedance.
- Implant the strips of the graphene in the position with the good current distribution.
- Starting the simulation via CST software.

In this work, the variable surface impedance of the graphene material will be employed to construct the proposed tunable antenna. The surface impedance of the graphene material is linked with the applied DC voltage on the material sheet. Whereas once the applied voltage rises the surface impedance drops and vice versa. (These slots work as a voltage controlled switch to change the current distribution over the patch [18]). Where in the low graphene surface impedance (i.e. high applied DC voltage (ON state)) the current is able to pass through the slot while in the high graphene surface impedance (i.e. low applied DC voltage (OFF state)) the current is not able to pass through the slot. In the ON state, the antenna is operating with its actual length while in the OFF state the antenna appeared to be operated smaller than its actual length because the current is not able to pass through the slots. To select the proper location for the slots of the graphene material a current distribution monitor is created by the CST, as shown in Fig. 8.

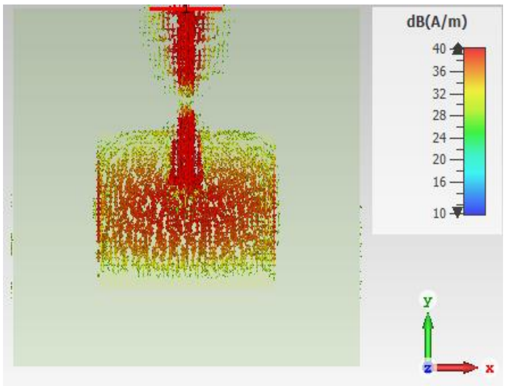

Fig. 8. Current distribution on the patch of the antenna.

To simulate the graphene material in the CST software the surface impedance should be calculated by using the following equations [18], [19]:

$$\sigma = \sigma_{intra} + \sigma_{inter} \tag{8}$$

$$\sigma_{s,intra} = -j\frac{q_e^2 k_B}{\pi\hbar^2(w - j2\Gamma)} \left[\frac{\mu_C}{k_B T} + 2ln\left(e^{-\mu_c/(k_B T)} + 1\right)\right] \tag{9}$$

$$\sigma_{inter}(\omega, \mu_c, \gamma, T) = \frac{-je^2}{4\pi h} \ln\left(\frac{2|\mu_c| - (\omega - j2\gamma)h}{2|\mu_c| + (\omega - j2\gamma)h}\right) \tag{10}$$

$$n = \frac{\varepsilon_o \varepsilon_r V_b}{dq} \tag{11}$$

$$\mu_c = \hbar v_f \sqrt{n\pi} \tag{12}$$

$$Zs = \frac{1}{\sigma_s} \tag{13}$$

where ω is the frequency in radian, k_B is the Boltzmann constant, T is the room temperature (K), Γ is the scattering losses coefficient for the graphene, $\hbar$ is the reduced Plank constant, q_e is the electron charge, μ_c is the graphene chemical potential, n is the charge carrier density, V_b is the applied DC on the graphene, v_f is the Fermi velocity, and Zs is the graphene surface impedance. After study the current distribution and calculating the graphene impedance by the previously mentioned equations, two graphene strips are inserted into the selected slots to construct the proposed tunable MP antenna, as presented in Fig. 9.

Fig. 9. Proposed tunable MP antenna.

In order to check the validity of the graphene material surface impedance, a current monitor is creating in the CST for the both ON and OFF states. As mentioned previously once the graphene surface impedance is low the current will pass through the strips while when the graphene surface impedance high only the leakage current is present, as shown in Figs. 10 and 11.

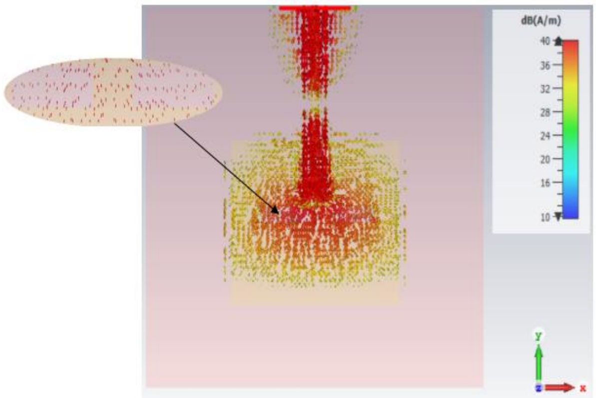

Fig. 10. Current distribution at low graphene surface impedance (ON state).

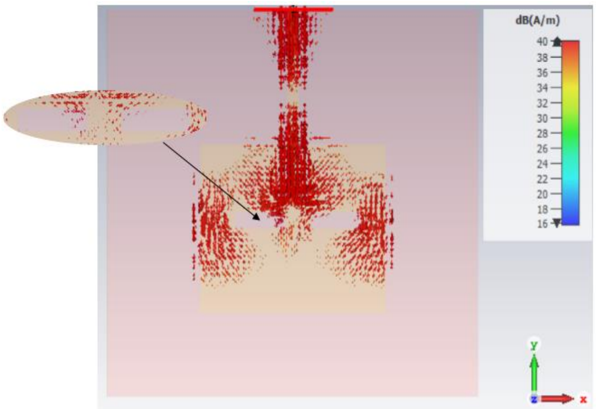

Fig. 11. Current distribution at low graphene surface impedance (ON state).

V. Simulation Results

This part of the article illustrates the results that are obtained for the proposed MP antenna like gain, return loss

(S_{11}), and bandwidth after completed the simulation process within the CST antennas simulation software environment.

A. Return Loss

The antenna Return Loss (S_{11}) is a term that designates the relationship of received antenna power at its input that are reflected as a ratio against that the received power. In the antenna design, this amount is significant to be minimum as possible to ensure the antenna operation properly [20]. The simulation results of the S_{11} for the proposed tunable rectangular MP antenna from CST software in the low graphene surface impedance case (i.e. ON state) is about -31.88dB at the 60GHz, while the S_{11} for the high graphene surface impedance case (i.e. OFF state) is about -16.25dB at 52.73GHz, as presented in Fig. 12 and Fig. 13, respectively.

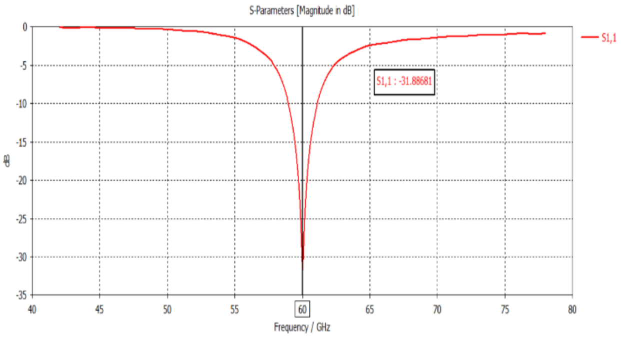

Fig. 12. The S_{11} for the ON state ($fr = 60GHz$).

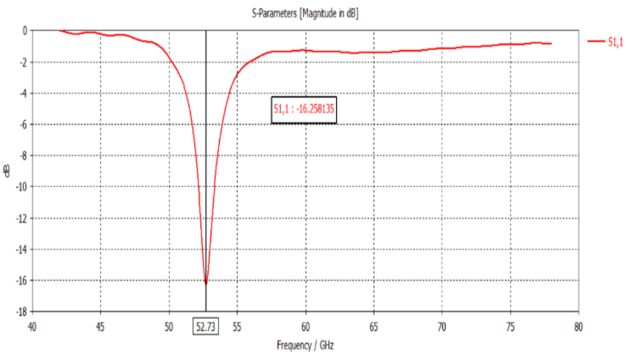

Fig. 13. The S_{11} for the OFF state ($fr = 52.73GHz$).

B. Bandwidth Results

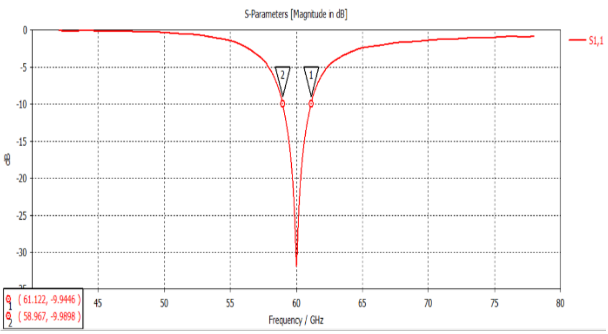

Fig. 14. The bandwidth results for the ON state ($fr = 60GHz$).

The bandwidth of the antenna is the range over which the antenna is operated properly [21]. The MP antenna bearing from the narrow bandwidth and tuning problems, the proposed tunable MP antenna is useful to minimise the mentioned issue. The bandwidth of the proposed antenna is estimated from the S_{11} pattern. The bandwidth of the proposed tunable MP antenna is found to be 2.155GHz for the ON state and 1.173GHz for the OFF state, as shown in Fig. 14 and Fig. 15, respectively.

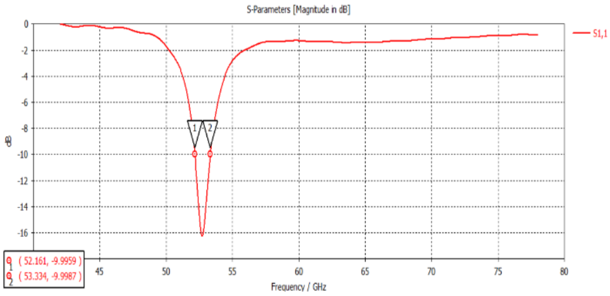

Fig. 15. The bandwidth results for the OFF state ($fr = 52.73GHz$).

C. Antenna Gain

The gain of the antenna is a measure for the greatest effectiveness with which the antenna can radiate the power surrendered to it through the transmitter towards a target. In general, the MP antennas are a needy gain because they are influenced by the substrate height and dielectric constant [22], [23]. The determined gain for the proposed tunable MP antenna is close to 6.19dBi for the ON state and 4.6dBi for the OFF state, as presented in Fig. 16 and Fig. 17, respectively.

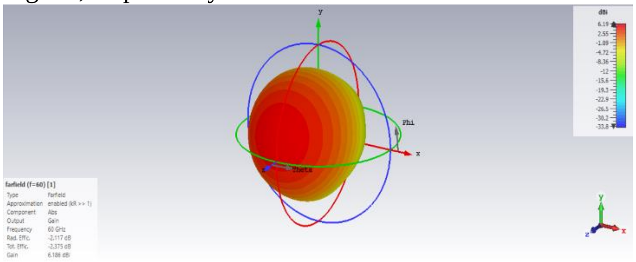

Fig. 16. The gain results for the ON state ($fr = 60GHz$).

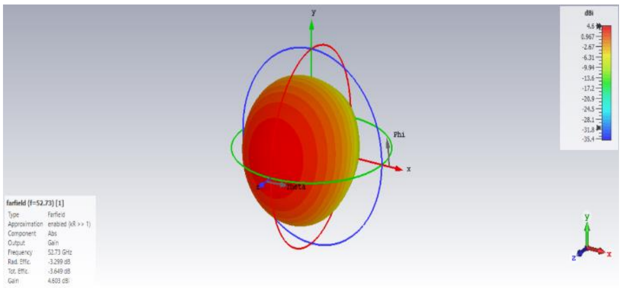

Fig. 17. The gain results for the OFF state ($fr = 52.73GHz$).

VI. Conclusion

In this paper, a rectangular MP antenna has been simulated and improved for the 5G communication and indoor applications. The suggested tunable MP antenna exploit the variable surface impedance to arrange and controlling the distribution of the current over the antenna contributing shifting in the antenna operating frequency.

The simulated antenna was made up from a copper patch etched inside it a pair of graphene flakes that controlling the current arrangement resulting in a tuning in the operating frequency of the antenna. The simulated antenna have been designed and evaluated by practising the finite integration that is offered by the CST software. The realised gain results for the simulated antenna were in the range of 6.19dBi for the ON state and 4.6dBi for the OFF state. Whereas the bandwidth results were in the range of 2.155GHz for the ON state and 1.173GHz for the OFF state in the frequencies of 52.16-61.122 GHz.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

We, as scientific research teamwork, together with proposed the idea of the proposed work as a reconfigurable MP antenna based on graphene utilised for fifth-generation mobile communications applications. The first author laid the cornerstone for the primary antenna design, and the second author has suggested and done the modelling for the graphene strips through the mathematical equations mentioned previously in Section (IV) as well as the utilise of the MATLAB software. Finally, the last author made the optimisation process in the CST simulation, compiled the research, typeset it and sent it to the journal. All cooperative authors have been confirmed the last copy of this paper.

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