Graphene based nano-antenna for wireless communication systems at terahertz band

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Article Info

Article history:

Received May 22, 2024
Revised Oct 28, 2024
Accepted Nov 19, 2024

Keywords:

Chemical potential
Graphene
Nanoantenna
Terahertz
Wireless communication

ABSTRACT

The need for nano-antennas with decreased size and the capacity to operate at mid-infrared frequencies to enable adequate coverage of signal is being investigated. In this paper, we present graphene-based nano-antenna and analysed at the resonating frequency 33 THz using gallium arsenide material as a substrate having dielectric constant 11.35 and a loss tangent of 5.6×10-4 for terahertz (THz) frequency. The height of substrate is optimized to 108 nm and in-plane dimension being 1,700×1,400 nm. Graphene was used as a rectangular patch with dimension 850×450×5 nm and ground having chemical potential=1.4 eV, and relaxation time=1 ps, to achieve high gain and bandwidth. Impact of slot width variation on the antenna parameters have been reported in terms of reflection coefficient (S11), voltage standing wave ratio (VSWR), radiation pattern and gain. Reported beam width being 90.4° for both electric and magnetic planes. Proposed antenna achieved a return loss of -18.38 dB, VSWR less than 2, indicating good match with load, highest gain of 8.8 dBi and bandwidth of 500 GHz at the target resonance frequency making it suitable for 5G/6G mm wave wireless communication.

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1. INTRODUCTION

In comparison to traditional antennas, optical nanoantennas are less prevalent, owing to the compact size. Development in nanoscience, nanotechnology and the device development technologies have enabled the realisation of structures as small as nanometers, paving the door for new and better optical nanoantenna designs [1]. Terahertz (THz) technology requires very compact radiating element with increased transmission speed. Graphene has the potential of miniaturization and low power loss due to its extraordinary electrical properties. Here, we propose nano-antenna based on graphene for nano-devices supporting wireless communication, with all good electromagnetic radiation feature and electrical behaviour at THz frequency. A nanoantenna, is a device made of nano particles of metals that functions in the optical spectrum. Other than the properties of traditional antenna, nanoantennas have a larger bandwidth than standard antennas. The concept of converting oscillating currents into electromagnetic radiation and vice versa, is utilised to create light antennas [2], [3], to improve interaction of matter and light even at the nanoscale [4]. The THz spectrum in electromagnetic waves is the most suitable approach for data transmission. THz are a section of the electromagnetic spectrum that includes both the electronics part as well as the photonic part, with prominent quantum nature of light. THz vibrations do not ionise and can pass through conventional garment fabrics. They are significantly easier to collimate and focus, with much reduced dispersion. However, for high frequencies in the THz region, many basic antenna theory principles must be altered [5]-[9]. Certainly, optical wireless technologies have resulted in higher signal quality, faster data rates, and more advanced transceiver technology.

THz technology necessitates the miniaturisation of communication equipment in order to increase transmission speed [10], [11]. At THz frequency, the oscillations are caused by surface plasmon polaritons (SPP). Metals, like gold, can create SPP, but only at much higher frequencies. The metallic nanostructures resonate at extremely high THz frequencies, resulting in substantial electrical power losses. Other issue is that such devices come with a complicated mechanism of tuning for regulating resonance frequency [12]. To address these restrictions, graphene has lately acquired popularity because of its favourable optical characteristics. Fakharian [13] showed that graphene-based antenna bearing multi-functional characteristic approach is possible at THz frequencies using radiating graphene dipole and variable capacitively loaded loops. The main benefit of graphene is its adjustable conductivity, which makes it attractive in plasmonic applications [14]. Kabir *et al.* [15] provided and in-depth analysis on nanoantenna with special emphasis on its variants and characteristics and have discussed the application capability of the EM mode for nanoantenna. Abbasi *et al.* [16] prepared nano communication network that may be integrated with the present communication circuit. They modelled and examined nanoantennas and observed that upon excitation of graphene with electromagnetic waves, electrons perform back and forth oscillations at low frequencies, a phenomenon known as SPP, which is investigated and evaluated. Merlo *et al.* [17] have reported a wireless communication system at nano dimension, which radiates in the visible wavelength band using in-plane transmission. Radiation in plasmonic antenna happens in stepwise transition from surface plasmon to photon and vice versa. Colmiais *et al.* [18] have reported the current manufacturing issues with the graphene oscillators, mixers, and multipliers, and have provided a global overview on graphene-based device applications in the radiofrequency domain. Naghdehforushha and Moradi [19] produced a graphene-based plasmonic patch antenna capable of adjustable THz band communications. A one-dimensional photonic crystal (PC) cover is employed to increase antenna gain [20]. Yousif and Samra [21] investigated the performance of optical nanoantennas and concluded that polarisation parallel to the axis of antenna improves antenna efficiency. Iovine *et al.* [22] investigated the electrical and magnetic properties of graphene nanoparticles, consisting square/circular rings enclosed within a dielectric material and observed that altering the geometrical structure of the nanoparticles results in a greater bandwidth. Tamagnone and Perruisseau-Carrier [23] studied a graphene dipole antenna driven by a photo-mixer at THz frequencies and reported striking tuning characteristics of the graphene antenna. Different shapes of nano optical antennas like hexagonal, trapezoidal have been studied and their optimum good results have been reported using graphene-based surface plasmonics [24]-[26].

This article examines a graphene-based nanoantenna working in the THz band utilising 3D high frequency structure simulator software (HFSS). Gallium Arsenide is used as substrate because of its unique electrical and optical features, such as improved heat resistance, greater flexibility, and low cost, to provide superior antenna performance. A parametric study was conducted to determine how substrate thickness, permittivity (ϵ), and graphene layer diameters affect antenna impedances and radiation properties. The findings were compared to a standard metallic antenna, and it was discovered that the suggested model provides good radiation and impedance properties while reducing size significantly. Hence, the suggested antenna model is appropriate for use in wireless nano communicating systems.

Remaining paper is organized in sections. Section 2 discusses the theoretical design methodology of the suggested antenna and discusses the software design and simulation using 3D electromagnetic solver HFSS. We discuss results in section 3 and present the comparison outcome with other published works. Finally, we report conclusion and scope for future work in section 4.

2. METHOD

The selection of an appropriate conductive material for the antenna's patch and ground has a significant impact on its performance. In order to improve performance of antenna and reduce electric power loss, materials used must have low electrical surface resistance. At frequencies above infrared, practically all metals carry current near the surface of the wire, known as skin effect, reducing the effective cross-sectional area and increasing resistance. Graphene and carbon nanotubes do not exhibit skin effect at higher frequencies.

Substrate material having less dielectric loss, lower thermal expansion coefficient and thermal conduction coefficient [27], [28] is always an excellent choice for the microstrip patch antenna. In ordert to reduce the size of antenna, the relative permittivity of the substrate must be high. On the other hand, increasing antenna efficiency requires a larger antenna size, resulting in a trade-off between efficiency and antenna design size. The relative permittivity and thickness of dielectric material influence the efficiency and bandwidth of antenna. Because of the materials' fairly narrow permittivity range, thickness may create significant differences. As a result, it plays an important role in the design of antenna as it controls the input impedance, bandwidth, and resonance frequency. A thin substrate with low dielectric constant upto 2 provides a narrow antenna route, whereas a thick substrate with low dielectric constant results in a big antenna patch [29]. The resonance length of an antenna is determined from the expression:

$$L = \frac{\lambda}{2} = \frac{c}{f \times \sqrt{\epsilon_{eff}}} \quad (1)$$

where λ is the wavelength of electromagnetic waves, c is the speed of light, f is the operating frequency of the dipole antenna, and $\sqrt{\epsilon_{eff}}$ is the relative permittivity. A free space standing graphene sheet supporting transverse magnetic (TM) plasmon mode is calculated as (2) and (3):

$$k_{spp} = k_0\sqrt{1 - (\frac{2}{n\sigma})^2} \quad (2)$$

$$Z_c = \frac{k_{spp}}{\omega\epsilon_0\epsilon_{eff}} \quad (3)$$

k_{spp} is the surface plasmons wave vector and Z_c is the characteristics impedance of the graphene. A free-standing graphene sheet supports TM SPP waves with an effective mode index expressed in (4). The coupling of incoming electromagnetic radiation to the relevant SPP modes causes resonances in the graphene-based nano-patch antenna. The resonance condition is defined by (5):

$$n_{eff}(w) = \sqrt{1 - 4\frac{\mu_0}{\varepsilon_0\sigma(w)^2}} \quad (4)$$

$$m\frac{\lambda}{2n_{eff}} = L + 2\delta L \quad (5)$$

where m is an integer, λ is the wavelength of the incident radiation, L is the antenna length and δL is a measure of the field penetration outside the graphene-based nano-patch antenna. This equation determines a set of m resonance frequencies w_m corresponding to m modes of the resonator. We explore graphene-based nano-patch antennas that are only a few nanometers in size and can be incorporated into a nanosystem. Because the effective mode index n_{eff} in graphene is on the order of 10^2, according to this model, the initial resonance frequency of our proposed antenna is in the THz range, about two orders of magnitude lower than what would be predicted from an ordinary metal antenna.

The whole design approach, analysis, and simulations are carried out using HFSS (Figure 1). To design using the programme, three design parameters, such as resonance frequency, substrate dielectric constant, and substrate height, must be selected. It is supplied via a microstrip line with an impedance of 50 ohm. Graphene is utilised for the radiation element patch and the ground plane. The slotted nano patch antenna is made of a rectangular graphene patch of dimension 850×450×5 nm. It is mounted on a gallium arsenide substrate having relative permittivity of 11.35 and power loss tangent of 5.6×10^{-4} for high frequency. Chemical potential of graphene is μ_c=1.4 eV and temperature T=300 K. The substrate has dimension 1,700×1,400×108 nm. Substrate gallium arsenide has thermal conductivity of 0.46 Wcm^{-1} °C at room temperature and diffusivity value of 0.31 cm^2s^{-1}, along with the heat capacity of 0.327 J/g-K, which make it a suitable candidate for as substrate material.

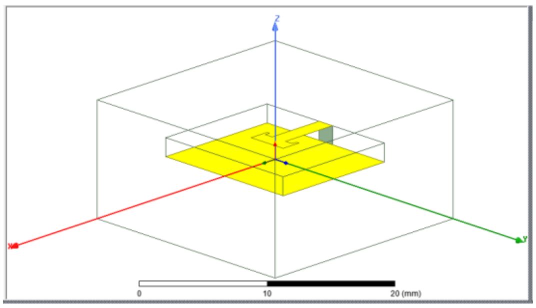
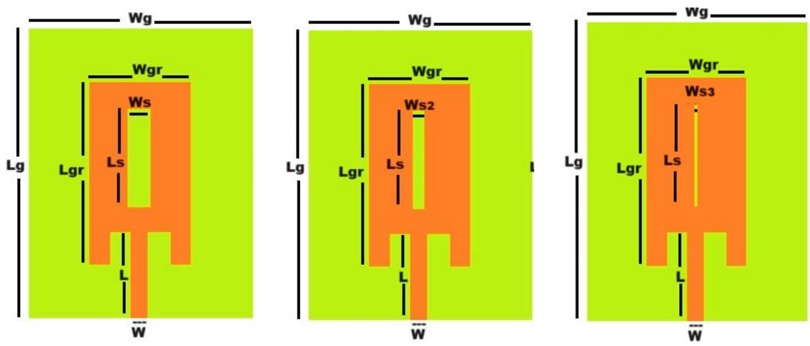


Figure 1. HFSS antenna design

We investigated the topology of several slot areas on a graphene patch of the same size. Many academics are working on slot design to improve antenna performance. The beauty of this research is that varied result parameters are recorded for different slot areas while other design factors such as ground, patch, substrate feed, and port dimensions remained constant. The antenna design has a rectangular slot on a patch with dimensions of 373×82 nm^2. The ground plane has planar dimensions of 1700×1400 nm. The slot was optimised to increase the gain. A transmission line of length 148 nm and width 5 nm was used to excite the antenna for electromagnetic radiation fields, and the resulting characteristics such as reflection coefficient (S11), voltage standing wave ratio (VSWR), gain, and 2D radiation pattern were computed. After collecting the result parameters at 82 nm slot width and 373 nm length, the parameters are compared to 41 nm and 13 nm slot widths, without affecting other dimensions. The appropriate impedance matching was employed to deliver energy to the patch at 33 THz via a microstrip line of length (L) 148 nm and width (W) 5 nm. Geometric configuration of the antenna is shown in Figure 2, where designs with three different slot width are shown. Figure 2(a) represents design with slot width 82 nm. Figures 2(b) and (c) are designs with slot widths 41 nm and 13 nm respectively, keeping the slot length unchanged at 373 nm. The different slot locations are selectable by varying merely the slot width. Dimensions of antenna parameters are mentioned in Table 1.



(a) (b) (c)

Figure 2. Geometric configuration and dimension of proposed antenna: (a) slot width 82 nm, (b) slot width 41 nm, and (c) slot width 13 nm

Table 1. Antenna parameters dimension

Parameter	Symbol	Dimension (nm)
Planar area of ground	$L_g \times W_g$	1,700×1,400
Planar area of graphene patch	$L_{gr} \times W_{gr}$	850×450
Planar area of feedline	$L \times W$	148×5
Length of slot	L_s	373
Width of slot	W_s, W_{s2}, W_{s3}	82, 41, 13

3. RESULTS AND DISCUSSION

This section is on the discussion of results due to simulation. The planned structure is studied using 3D electromagnetic solver HFSS using a time domain solution and the method of moments. This study looked into the effect of different slot areas keeping other design factors such as ground, patch, substrate feed, and port dimensions unchanged. While previous studies investigated the impact of slots on the antenna parameters, they did not explicitly address its influence while keeping other paramenters unchanged. Figure 3(a) displays the fluctuation of the return loss (S11) with frequency for the suggested graphene nano patch antenna. S11 helps determine the mismatch from the transmission line in terms of power reflection. The graphene is modelled with a chemical potential of 1.4 eV and a relaxation duration of 0.1 pico second at 300 K. The reported antenna resonates at 33.8 THz with a return loss of -19.23 dB, an excellent S11 characteristic, making it appropriate for THz optical communications. It has a frequency bandwidth of 3.2 THz (32.3-35.5=3.2 THz) and a percentage bandwidth of 10%. Changing the slot area on the patch at the same resonance frequency had nearly identical results, as shown in Figures 3(b) and (c), with return loss values of -18.76 dB and -18.38 dB, respectively. Figure 3(d) shows the return loss variation with frequency at the three different slot width. This indicates that reflected signals will not affect the transmitted signal. Furthermore, the insertion loss will be close to zero because the return loss is less than -10 dB.

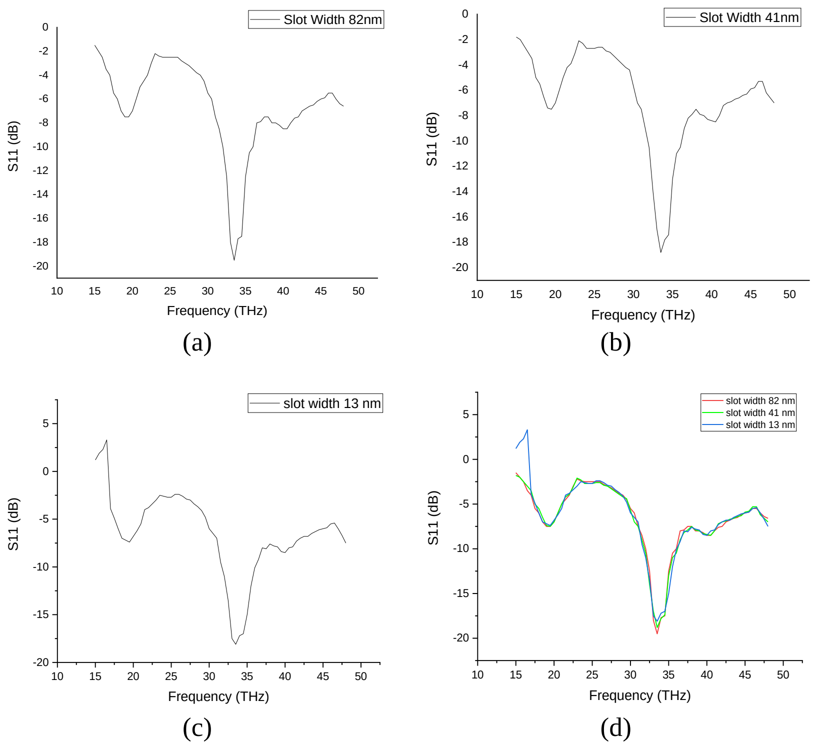


Figure 3. Return loss vs frequency at slot width: (a) 82 nm, (b) 41 nm, (c) 13 nm, and (d) all together

A lower VSWR value allows for better antenna matching and more power delivery to the load. The VSWR values attained for the suggested antenna with slit widths of 82 nm, 41 nm, and 13 nm, illustrated in Figures 4(a) to (c) are 1.65, 1.4, and 1.1, respectively, with a bandwidth of around 500 GHz. VSWR values were suitably achieved below the theoretical limit of 2. Figure 4(d) shows the variation of VSWR with frequency at the three different slot width.

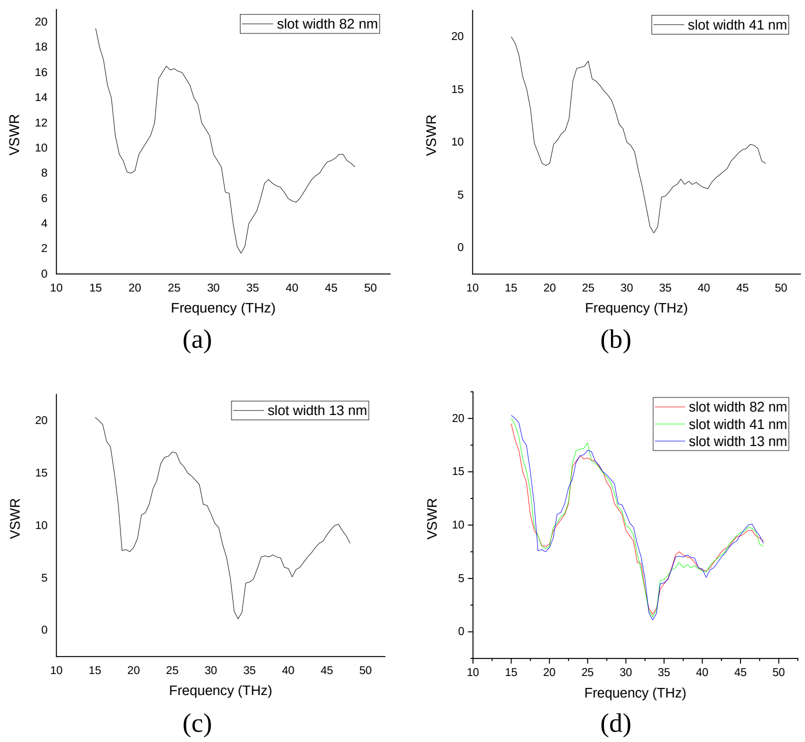
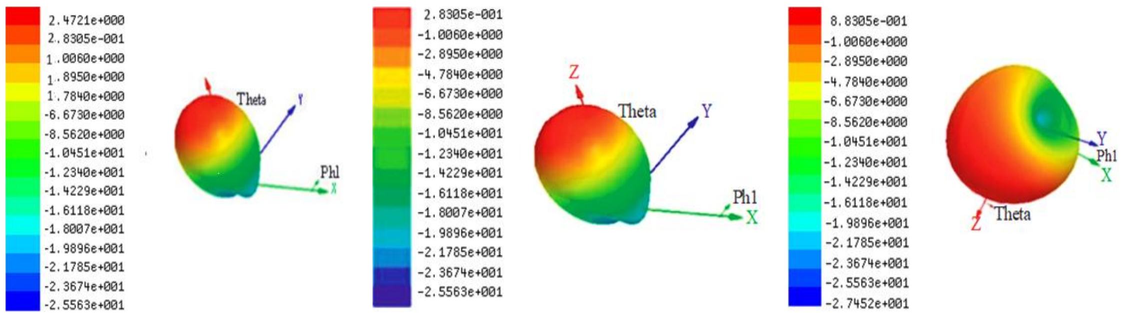


Figure 4. VSWR vs frequency at slot width: (a) 82 nm, (b) 41 nm, (c) 13 nm, and (d) all together

Antenna gain is the amount of power delivered by an antenna in the direction of peak radiation. High gain antennas come with more range in one direction, and require aiming with high precision. Low gain antennas respond to signals from a wider range of directions, but have a shorter range. Figure 5 shows the plot of antenna gain against the operational range of frequencies. For the different slot width of 82 nm, 41 nm, and 13 nm, as shown in Figures 5(a) to (c) respectively, the proposed antenna has realised gain of 2.4 dB, 2.8 dB and 8.8 dB.



(a) (b) (c)

Figure 5. Antenna gain for slot width: (a) 82 nm, (b) 41 nm, and (c) 13 nm

Figure 6 displays the polar plots of the antenna's E plane (left) and H plane (right) patterns for slot width 82 nm. Beam width value of 90.4° is realized in the E and H plane. Figure 7 expresses the polar plots of the E plane (left) and H planes (right) with slot width 41 nm. It is noted that the E and H planes have no side lobes. The half power beam widths for the E and H planes are 88.2° and 94.8°, respectively. Beam width of the H field is greater than that of the E plane. Figure 8 depicts radiation patterns for the E plane (left) and H planes (right) with slot widths of 13 nm. The beam width of the E plane is 89.9°, whereas that of the H plane is 55.1°. The beam width of the E and H planes is lowered in comparison to the slot widths of 82 nm and 41 nm, respectively. The revised construction demonstrated improved antenna gain. The H plane has many subsidiary lobes.

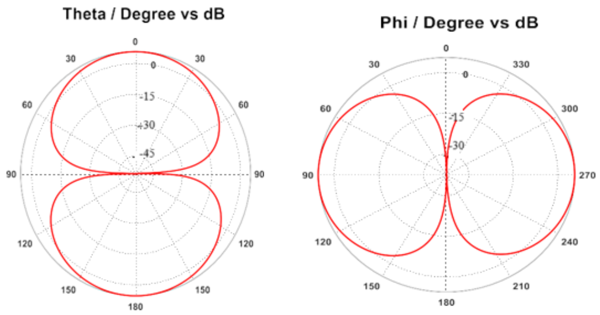


Figure 6. Polar plots of the E and H plane for slot width 82 nm

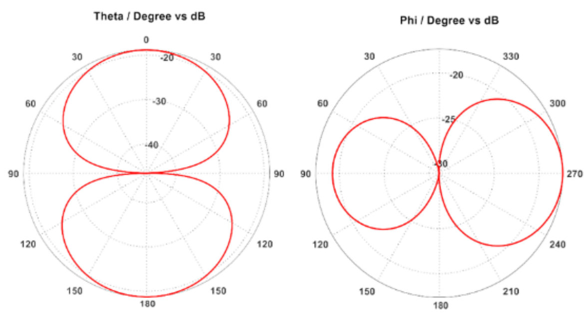


Figure 7. Polar plots of the E and H plane for slot width 41nm

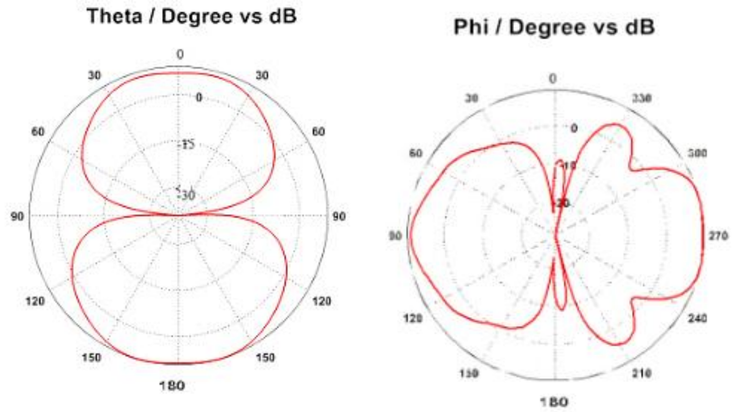


Figure 8. Polar plots of the E and H plane for slot width 13 nm

The propsed method in this study tended to have an inordinately higher portion of gain, directivity and efficiency. Results of the present work is compared with some of the latest published works on the parameters like the resonating frequency, substrate material used and its chemical potential (μ), return loss (S11), gain and bandwidth, and expressed in Table 2. The proposed antenna resonates at higher frequency compared to those proposed by Kiani *et al.* [29], Moulfi *et al.* [30], Nasr and Sagha [25], except that of Kavitha *et al.* [24]. which has a higher resonance frequency of 54 THz, in addition to 25 THz. Gain realised by the antenna is at par with gain value reported in other works. Our observations indicate that higher gain is not associated with poor performance in other prominent parameters of antenna. Obviously, the proposed antenna comes with several advantageous features, like good return loss and bandwidth, compact size, easy to construct, a low-profile, strong omnidirectional radiation, and a reasonably good gain, and is more resilient.

Table 2. Result comparison

References	Substrate	f (THz)	μ (eV)	S11 (dB)	Gain (dBi)	Bandwidth (THz)
Kiani *et al.* [29]	Silicon dioxide	0.6	0.6	<-10	-	0.1
Moulfi *et al.* [30]	PTFE, polmide, RO3003, RO4003, and arlon	7.2	2	-37.96	7.1	1.76
Nasr and Saghai [25]	Gallium arsenide	0.7	0.2	<-10	6.8	0.5
Kavitha *et al.* [24]	Silicon	25, 54	2	-39.88, -21.45	5.15, 10.8	6, 13
This work	Gallium arsenide	33	1.4	-18.89	8.8	0.5

4. CONCLUSION

Graphene-based nano-antennas are intended to allow nano communication systems to send and receive data, resulting in a new era of wireless communication enabled with the use of graphene. This work provides a basic model for a nano-patch antenna using graphene patch, as well as simulation results obtained with Ansoft HFSS software. The results demonstrated the applicability of a nano-patch antenna for resonance in the THz region, which is compatible with the theoretical model. Our study showed that the antenna resonant frequency was dependent on the patch made up of graphene and the size of the dielectric substrate. The radiation pattern of antenna resembled the pattern of traditional equivalent antenna employing copper metal as patch. These findings will be valuable to future designers working for nanoantennas for wireless communication using graphene as patch material. However, in future, additional and in-depth research may be required to confirm its tolerance and sensitivity, particularly regarding ambient temperature variation, physical stress and impact of impurity on the efficiency of antenna.

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