Optical nano patch antenna for terahertz applications with graphene

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Nano optical crescent patch antenna for Terahertz applications using Graphene is designed in this paper. The antenna is designed at 7.28 THZ with several substrates material as PTFE ($\epsilon r = 2.1$), polymide ($\epsilon r = 3.5$), RO3003 ($\epsilon r = 3$), RO4003 ($\epsilon r = 3.4$) and Arlon AD ($\epsilon r = 2.5$). Graphene is the material patch used with different properties such as chemical potential $\mu c = 0.2$ eV, relaxation time $\tau = 1$ ps and thickness of 60 nm to achieve a high gain and bandwidth. We obtained a very good performance of crescent antenna at 7.28 THZ with -37.962 dB, 7.124 dBi, 1.767 THZ of return loss, gain and bandwidth respectively which is very satisfactory for terahertz transmission between [0.1-10] THZ.

Keywords: Optical antenna; Graphene properties; return loss; radiation pattern; substrate; terahertz band; optical transmission.

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1. Introduction

Graphene has become a highly researched and used material due to its impressive properties. Scientific interest in this materiel has grown considerably since its first isolation in 2004 and continues to do so, it has many outstanding properties including electronic, optical, electrical thermal and mechanical [1].

Graphene has very high electron mobility (2×10^5 cm^2/Vs) [2], making it the most highly conductive material at room temperature, witch a conductivity of 160 S/m and a sheet resistance of 31 ohm/sq that make it a potential to overcome some draw band in new technologies, especially at band, making it able to support plasmon polariton waves which makes it of great interest to use for microstrip antenna applications. Terahertz band is located between infrared wave and microwave [3], it has a lower energies so that it is non ionizing and do not damage the samples.

The terahertz wavelength is much smaller than that of millimeter wave microwaves [4]. Therefore it has broadband advantages which carry hope to increase data transmission rate. However, it faces many challenges: As the resonance frequency is higher, the antenna size is smaller, in this case the radiation efficiency is considerably reduced and the macro-molecular absorption increases strongly. The second challenge is the lack of suitable substrate materials for this band, the substrate materials for the millimeter band cannot be used at the resonant frequency of the THz microstrip antennas and the manufacture of the terahertz antenna requires microscopic equipment for realization. These challenges arise from the fact that the THz frequency is higher than the millimeter wave frequency and the size of the corresponding antenna is much smaller than that of the millimeter wave antennas [5].

Several works have been conducted in the terahertz band including Graphene properties such as that of Moulfi *et al*., where design a circular terahertz antenna based on Graphene and use the DGS technique to extend the bandwidth, performing a parametric study on Graphene [6], Khan *et al*., designed a circular terahertz patch antenna and made one with different shapes of substrate and materials [2]. Abohmra *et al*., made a study on the characteristics of Graphene at terahertz band in a rectangular antenna for Wearable application [7]. Fakharian proposed a graphene-based multi-functional terahertz antenna [8]. Badr and Moradi proposed a new shape of the hexagonal antenna dual band the 2.14 THz and 5.41 THZ frequencies [9]. Nissiyah and Madhan did a search on Graphene based patch antenna for triple and quad band act at terahertz frequencies [10].

In this paper, we designed an optical nano crescent patch antenna for terahertz transmission using Graphene material for patch and ground plan with $t = 0.6$ μm properties. Several material substrate such as PTFE ($\epsilon r = 2.1$), polymide ($\epsilon r = 3.5$), RO3003 ($\epsilon r = 3$), RO4003 (ϵr = 3.4) and arlon AD ($\epsilon r = 2.5$) have been integrated to get a good performance of the antenna. The substrates used are based on graphene and have unique electrical and optical properties. They are very heat resistant, very flexible and inexpensive. These substrates are obtained by mixing graphene with a solution of the used substrate, namely PTFE, polymide, RO3003, RO4003 and Arlon, after which this solution is deposited on the substrates to dry it. In this way, their electrical and thermal properties are improved for use in the terahertz band [11].

The change in Graphene properties, especially in chemical potential achieve a high gain and bandwidth, which is very satisfying for terahertz transmission.

2. Crescent antenna design

We designed a nano crescent microstrip antenna using the CST software. It is fed by microstrip line with 50 ohm of impedance. Graphene is the materiel used for the radiation element called the patch and for the ground plan (Fig. 1). We used different type of materiel substrate as PTFE ($\epsilon r = 2.1$), polymide ($\epsilon r = 3.5$), RO3003 ($\epsilon r = 3$), RO4003 ($\epsilon r = 3.4$) and arlon AD ($\epsilon r = 2.5$) with thickness $h = 2.798$ μm.

The fabrication of a micrometer-thick substrate requires a complex manufacturing process. Here are some general steps for the fabrication of such a substrate: The process of fabricating a micrometer graphene-based substrate for terahertz applications is complex and relies on several steps [12–14]:

Choosing the appropriate substrate material: This step takes into account the properties of the substrate material as well as the properties of the substrate itself: thermal resistance, mechanical stability and electrical conductivity required.

Preparation of the substrate material: The material must be thoroughly cleaned to remove all kinds of impurities, dust and other contaminants.

Thin film deposition: A thin film made by chemical vapor deposition is deposited on the substrate to be bonded to the graphene.

Preparation of graphene: Graphene can be prepared using several techniques such as: chemical vapor deposition (CVD), epitaxial growth, or mechanical exfoliation.

Graphene deposition: Graphene must be deposited on the substrate by dry transfer or by wet transfer. It should be noted that the fabrication phase of graphene thin film substrates is very sensitive and an expert in the field of manufacturing should be consulted.

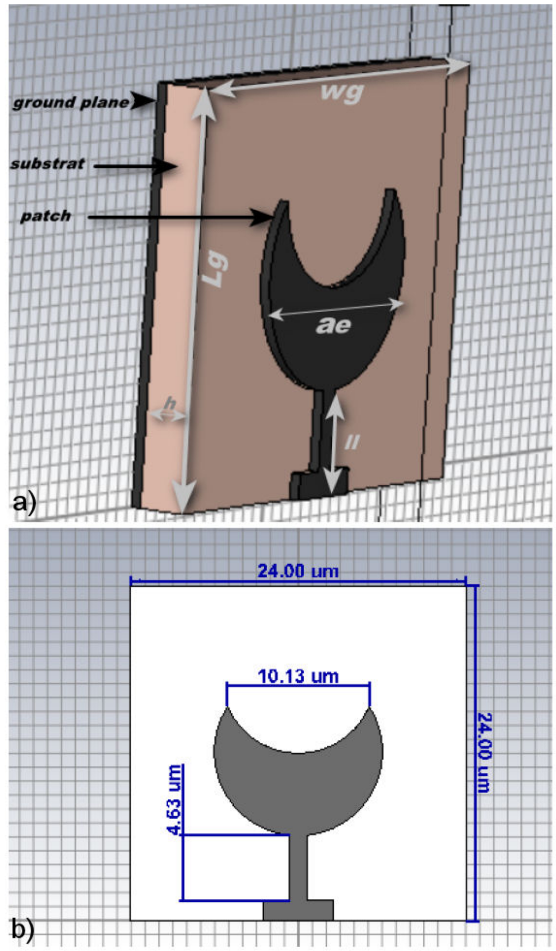

FIGURE 1. The Crescent Proposed Graphene patch antenna, a) antenna design, b) antenna dimensions.

The patch antenna dimensions are calculated from the equations below [15]:

$$ae = a\sqrt{1 + \frac{2h}{\pi \epsilon a} \ln\left(\frac{\pi a}{2h}\right) + 1.7726}, \quad (1)$$

where

$$a = \frac{F}{\sqrt{1 + \frac{2h}{\pi \epsilon_r F}[\ln\left(\frac{\pi F}{2h}\right) + 1.7726]}}, \quad (2)$$

and

$$F = \frac{(8.791 * 10^9)}{fr\sqrt{\epsilon r}}, \quad (3)$$

$$ll = L - 2\delta L, \quad (4)$$

where

$$\frac{\delta L}{h} = 0.412\frac{(\epsilon_{\text{eff}} + 0.3)(\frac{w}{h} + 0.264)}{(\epsilon_{\text{eff}} - 0.258)(\frac{w}{h} + 0.8)}, \quad (5)$$

$$Lg = ll + 2ae + 6h, \quad (6)$$

$$Wg = 2ae + 6h, \quad (7)$$

with ae the radius of the crescent patch; Lg the length of both substrate and ground plane; Wg the width of both substrate and ground plane; h the substrate thickness; fr the resonant frequency; ϵ_r the dielectric constant; and ll the length of the line.

Graphene is a two-dimensional material consisting of a single layer of carbon atoms in the form of a honeycomb lattice. The graphene layer is made by a technique called chemical vapor deposition (CVD). It consists in depositing a thin layer of graphene on a substrate by means of a chemical reaction. To produce high quality graphene with desired properties, it is necessary to carefully control the chemical potential by adjusting the temperature, gas pressure and other factors in the CVD process [4,5].

3. Dispersion relation of graphene

Graphene is considered as an excellent material because of its surface plasmon polarization propagation (SPP) [17].

The SPP wavelength is generally represented as a function of frequency, so in the terahertz frequency range the SPP wavelength is of the order of a few micrometers, corresponding to the size of the nanometer antenna and the wavelength is relatively small. In effect the propagation length of a graphene based antenna is less than the wavelength [18].

The SPP dispersion of Graphene relation in the field of effective index can be presented as [19]

$$\sqrt{\eta^2-\eta_{\text{eff}}^2}+\eta^2\sqrt{\eta^2-\eta_{\text{eff}}^2} + \frac{4\pi}{c}\sigma\sqrt{1-\eta_{\text{eff}}^2}\sqrt{\eta^2-\eta_{\text{eff}}^2}=0, \tag{8}$$

where η is the refractive index, σ is the conductivity of Graphene and c is the speed of light, and η_{eff} the complex effective index

$$\eta_{\text{eff}}=\sqrt{1-4\frac{\mu_0}{\epsilon_0}\frac{1}{\sigma^2}}. \tag{9}$$

The dispersion relation can be also presented in terms of k_{spp} as [17]

$$\frac{1}{\sqrt{K_{\text{spp}}^2-\frac{w^2}{c^2}}}+\frac{\epsilon}{\sqrt{K_{\text{spp}}^2-\frac{w^2}{c^2}\epsilon}}=-j\frac{\sigma}{w\epsilon o}, \tag{10}$$

where r is the dielectric constant of the substrate material and the effective index K_{spp} (surface plasmons wave vector) varies with the dielectric material metal interface and ω is the angular frequency of the waves: ($\omega=kc$)

$$K_{\text{spp}}=\epsilon_0\frac{1+\epsilon r}{2}\frac{2iw}{\sigma}. \tag{11}$$

4. Graphene conductivity

Graphene has two-dimensional single layer design in which carbon atoms are provided in the form of infinite honeycombs. Graphene conductivity formula is given by the Kubo formula [8]:

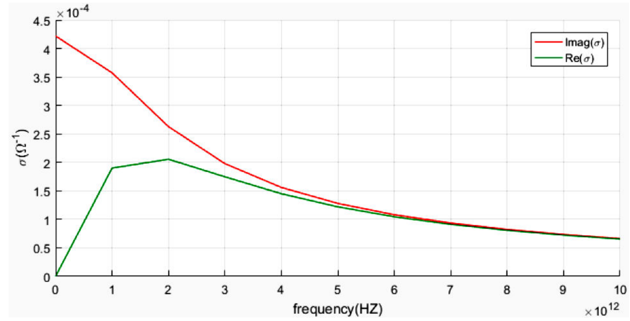

FIGURE 2. Graphene conductivity curve with properties μc= 0 eV and $\tau=0.1$ ps at $T=300$ K [1].

$$\sigma\text{inter}=\frac{e^2}{4h}H\left(\frac{w}{2}\right) + 4\frac{wj}{\pi}\int_0^\infty\frac{H(w)-H(\frac{w}{2})}{w^2-4\epsilon^2}\delta\epsilon, \tag{12}$$

$$H(\epsilon)=\frac{\sinh\left(\frac{h\epsilon}{KT}\right)}{\cosh\left(\frac{\mu c}{KT}\right)}\cosh\left(\frac{h\epsilon}{KT}\right), \tag{13}$$

$$\sigma\text{intra}=\frac{2kTq^2j}{h(T^-1hj+wh)}2\ln\left(\cosh\frac{\mu}{2TK}\right), \tag{14}$$

$$\sigma s=\sigma\text{intra}+\sigma\text{inter}, \tag{15}$$

where σs the surface conductivity, consists of two terms σinter: the interband conductivity and σintra:the intraband conductivity.

At terahertz frequencies we have room temperature, and generally $hw \ll 2\,\mu c$ in this case we have either in the ohmic domain or in the plasmonic domain, and inter-band (σintra) transitions can be neglected.

Moreover, the condition $\mu c \gg kBT$ is generally very small, allowing a low temperature approximation. Thus, the final approximate formula is

$$\sigma s=\frac{2kTq^2j}{h(T^-1hj+wh)}2\text{in}\cosh\frac{\mu}{2TK}. \tag{16}$$

The chemical potential and the relaxation time of Graphene as well as the total conductivity are changed due to chemical doping or electrostatic polarization, which results in the modification of the resonance characteristics of Graphene. Figure 2 represents the real and imaginary part of Graphene conductivity for μc = 0 eV and $\tau=0.1$ ps at $T=300$ K. Figure 3 represents Graphene conductivity variation with respect to chemical potential (μc) for $\tau=0.1$ ps at $T=300$ K and Fig. 4 represents Graphene conductivity curve variation with respect to relaxation time (τ) for $\mu c=0$ eV at $T=300$ K. The antenna uses surface-plasmon polariton wave propagation in Graphene at the terahertz frequency

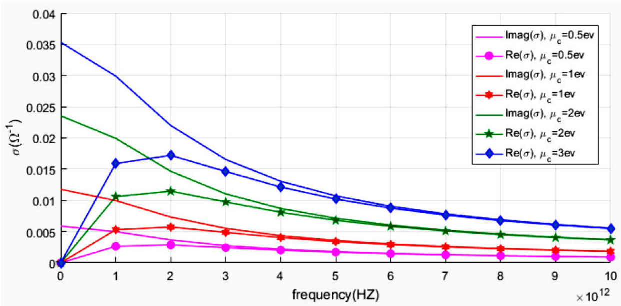

FIGURE 3. Graphene conductivity curve variation with respect to chemical potential (μc) for $\tau = 0.1$ ps at $T = 300$ K [1].

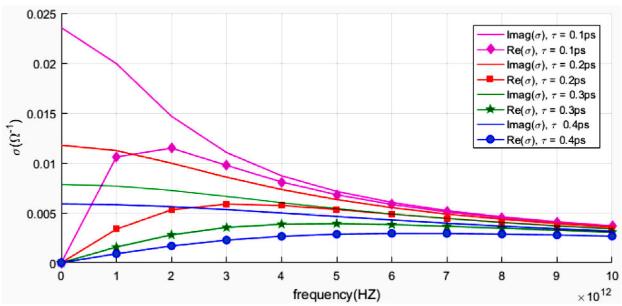

FIGURE 4. Graphene conductivity curve variation with respect to relaxation time (τ) for $\mu c = 0$ eV at $T = 300$ K [1].

band. Simulation results demonstrate the conductivity of Graphene and structured has the potential to be used as a tunable terahertz antenna.

5. Choice of substrate

In this part we simulated the crescent patch antenna with several type of substrates as PTFE ($\epsilon r = 2.1$), polymide ($\epsilon r = 3.5$), RO3003 ($\epsilon r = 3$), RO4003 ($\epsilon r = 3.4$) and Arlon AD ($\epsilon r = 2.5$) to evaluate performance crescent patch antenna. The antenna parameters are calculated using Eqs. (1-7); we used Graphene material for the patch and ground plane with the following characteristics: temperature $T = 300$ K, chemical potential $\mu c = 2$ eV, relaxation time $\tau = 1$ ps and thickness of 60 nm.

A graphene layer with a chemical potential of 2 eV is ensured for a thickness of 60 nm using a technique called “adsorption doping”, which consists in intentionally introducing impurities into the graphene layer to adjust its electrical properties. The doping concentration required to reach a chemical potential of 2 eV depends on the specific type of dopant used, the temperature and the duration of the doping process. Experimental optimization is very necessary to reach the desired doping concentration. Once the desired doping concentration is reached, the graphene layer can be characterized using techniques such as Raman spectroscopy to confirm the existence of the desired electronic properties [6,7].

Figure 5 summarizes the simulation results of reflection coefficient and Fig. 7 represent the polar radiation pattern of crescent antenna with different types of substrate.

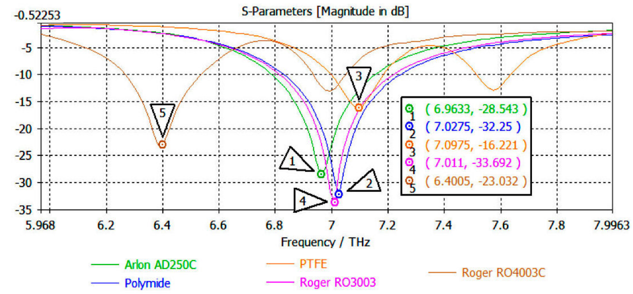

FIGURE 5. Reflection coefficient parameter $S11$.

As shown in Fig. 5, we obtained a very good return loss of -28.592 dB at 6.9615 Thz frequency and 350.63 GHZ of bandwidth, by using Arlan AD 250 C material substrate.

There are several applications in the terahertz band and especially the 7 THZ frequency such as:

- **Medical imaging:** The 7 THZ band is used for imaging applications such as security control and medical imaging. Terahertz waves pass through clothing and skin.
- **Spectroscopy:** The 7 THz band is useful for spectroscopy applications. These applications could be used in fields such as materials science, chemistry and biology.
- **Wireless communication:** The 7 THz band offers the possibility of broadband wireless communication for applications such as virtual reality, high-definition video streaming, and ultra-fast data transfer.

The frequency of 7 THz corresponds to a wavelength of 42.8 micrometers, which is in the far infrared region of the optical band. This frequency is generated using high power laser sources, which are capable of producing very short optical pulses with high repetition rates. Two infrared diode lasers with neighboring wavelengths are used and combined in a tellurium crystal to produce an electromagnetic wave with a wavelength of 42.8 micrometers.

The detection of the frequency of 7 THz presents a great technical challenge since it is located in the region of terahertz waves. The photoconductive detection is the most com-

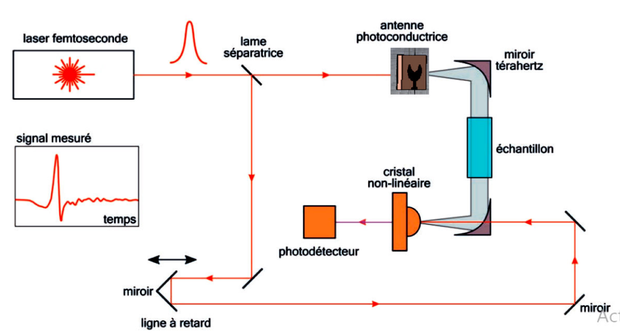

FIGURE 6. The detection of the frequency of 7 THz with proposed antenna [22].

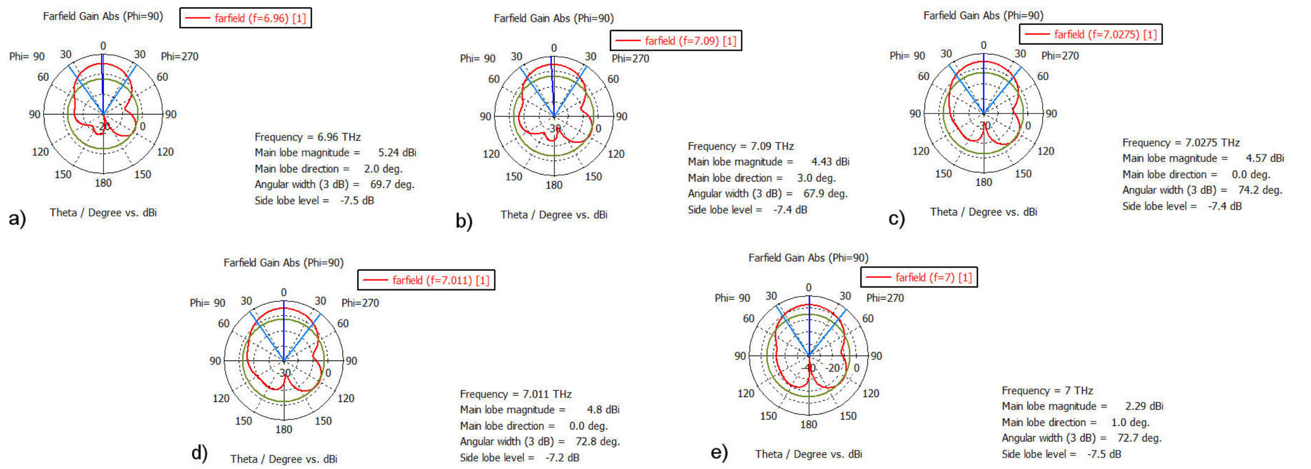

FIGURE 7. Polar gain with a) arlan AD 250C ($\epsilon r = 2.5$) b) teflon ($\epsilon r = 2.1$) c) polymide ($\epsilon r = 3.5$) d) RO3003 ($\epsilon r = 3$) e) RO4003 ($\epsilon r = 3.4$).

TABLE I. Results comparison.

The substrat	Frequency [THZ]	$S11$ (dB)	Gain (dBi)	VSWR	BP (GHZ)
Arlan AD 250C ($\epsilon r = 2.5$)	6.9615	-28.592	5.24	1.07	350.63
Teflon ($\epsilon r = 2.1$)	7.0935	-16.323	4.417	1.36	168.52
Polymide ($\epsilon r = 3.5$)	7.0275	-32.25	4.568	1.05	418.99
RO3003 ($\epsilon r = 3$)	7.011	-33.692	4.803	1.04	441.77
RO4003C ($\epsilon r = 3.4$)	6.9945	-13.152	2.287	1.57	124.11

mon technique for the detection of these waves, it consists in using a photoconductive material like gallium arsenide (GaAs) which is sensitive to terahertz frequencies. When a terahertz wave beam is directed onto the material, it generates electrons and holes that can be detected using an electrode connected to the material. The displacement of the mirror allows to adjust the delay while allowing to measure the phase and the amplitude of the signal [8, 9].

Figure 7 shows the 3D polar radiation pattern of crescent antenna at all frequencies obtained with the use of several material substrates. The radiation pattern obtained is unidirectional. Table I resumes all simulations results obtained with severals substrate materials and Graphene properties mentioned above.

6. Graphene chemical potential variation

The objective of our work is to design a graphene-based patch antenna for the terahertz band with the best characteristics. According to our results, all the substrates used show good performance in terms of $S11$, gain and bandwidth. The Arlan substrate shows a higher gain of 5.28 dB, hence we will use it to further improve the performance of the designed patch antenna in the terahertz band. We simulated in Fig. 8 the return loss of the proposed antenna and we varied the value of the chemical potential for gain and bandwidth enhancement.

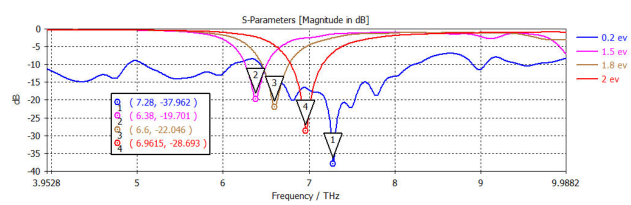

FIGURE 8. Return loss $S11$ with 0.2 eV, 1.5 eV, 1.75 eV and 3 eV of chemical potential.

As shown in Fig. 8, a high bandwidth of 1.767 THz is obtained with -37.962 dB of return loss and with 0.2 eV of chemical potential.

The polar radiation of Fig. 8 b)-d) is almost omnidirectional for 1.5, 1.8, 2 eV of chemical potential values. The best performances are obtained with 0.2 eV in wich the polar radiation pattern is omnidirectional with angular wide of 63.2 deg and gain of 7.13 dBi.

TABLE II. Simulations Results.

Chem-Potential (eV)	Fr (THZ)	$S11$ (DB)	GAIN (dBi)	BP (GHZ)
2	6.9615	-28.592	5.24	350.63
1.8	6.6	-22.046	4.55	322.18
1.5	6.38	-19.701	4,573	252.29
0.2	7.28	-37.962	7.134	1767.3

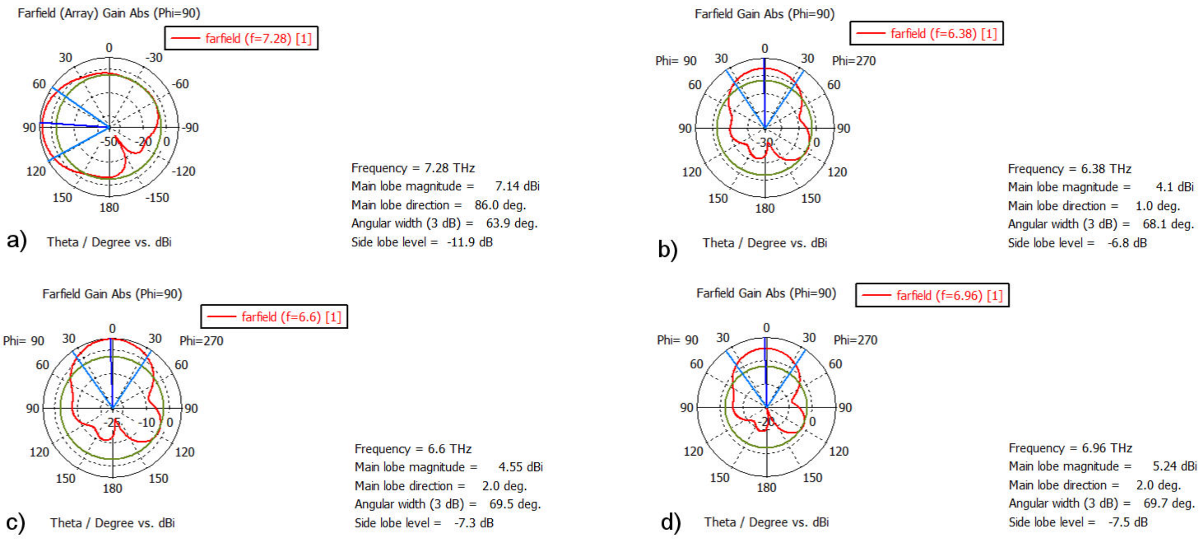

FIGURE 9. 3D Gain a) with chemical potential 0.2 eV, b) with chemical potential 1.5 eV, c) with chemical potential 1.8 eV, d) with chemical potential 2 eV.

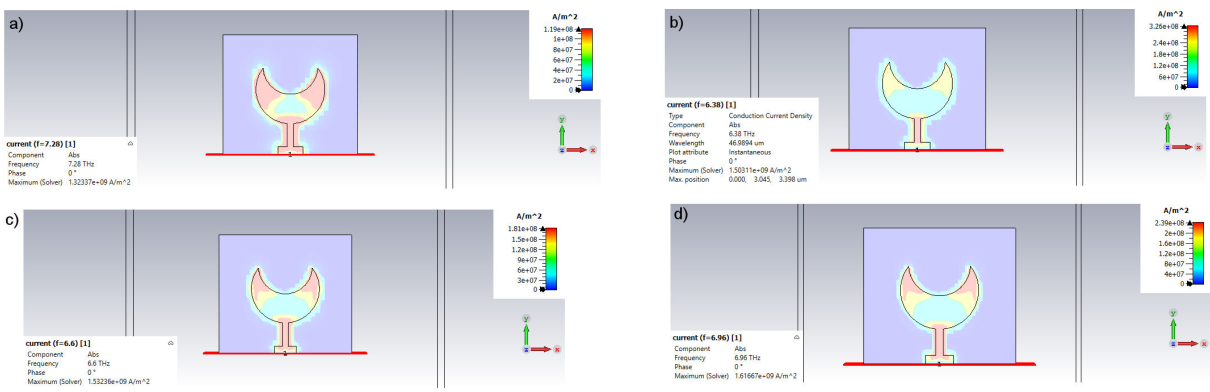

FIGURE 10. Current density a) with chemical potential 0.2 eV, b) with chemical potential 1.5 eV, c) with chemical potential 1.8 eV (d)with chemical potential 2 eV.

TABLE III. Comparison of proposed work with previous research.

	Fr (THZ)	$S11$ (DB)	GAIN (dBi)
Proposed antenna	7.28	-37.962	7.134
[6]	3.26	-30.706	3.437
	4.69	-55.54	5.008
	5.64	-37.434	5.233
	6.95	-26.812	6.62
[24]	$0.434 - 1.684$	-39	5.72
[25]	4.104	-40	3.8
[26]	2.9	-28.39	6.48

Obtained a high gain of 7.13 dB with 0.2 eV which is very satisfactory in terahertz transmission.

Figure 10 shows the current density of the proposed crescent antenna for 0.2, 1.5, 1.8 and 2 eV of Graphene chemical potential. The majority of the current density is concentrated in the left and right ends of the patch antenna.

To value our work, we compared in Table III the simulations results obtained with other previous and recent literature.

As shows in Table III, the proposed crescent patch antenna gives a high gain of 7.13 dBi and bandwidth of 1.769 Thz compared to all references cited.

7. Antenna fabrication

Fabrication and characterization of a graphene based patch antenna is a complex process, requiring a very high level of expertise in this field hence consultation with experts in this field or professional assistance for fabrication and characterization of the patch antenna is highly recommended.

Once the design of the antenna is optimized, the proposed patch antenna can be fabricated and characterized as follows [27, 28]:

Preparation of the substrate material: The material must be thoroughly cleaned to remove all kinds of impurities, dust and other contaminants.

Thin film deposition: A thin film made by chemical vapor deposition is deposited on the substrate to be bonded to the graphene.

The chemical Vapor Deposition (CVD) involves growing a thin layer of graphene on a metal substrate by adding a hydrocarbon gas, such as methane or ethylene, in a high-temperature furnace. Then, the carbon atoms in the gas are deposited on the metal substrate, creating a graphene layer.

Graphene deposition: Graphene must be deposited on the substrate by dry transfer or by wet transfer.

Patch antenna fabrication: it consists on using standard photolithography techniques such as spin coating, mask alignment and etching.

Patch antenna characterization: in this step, we can use network analyzer, far-field radiation pattern measurement, and impedance measurement for proposed patch antenna characterization.

Preparation of graphene: Graphene material can be prepared using several techniques such as: chemical vapor deposition (CVD), epitaxial growth, or mechanical exfoliation.

8. Conclusion

The Terahertz band is envionned for serveral application such as WBAN, 6G, 5G, teledetection etc.

In this paper a high gain and bandwidth optical crescent antenna has been designed to be used in Terahertz applications from 0.1 to 10 THz . The nano patch antenna is analysed and simulated using Graphene for the patch and several material substrates such as PTFE($\epsilon r = 2.1$), Polymide ($\epsilon r = 3.5$), RO3003 ($\epsilon r = 3$), RO4003 ($\epsilon r = 3.4$) and Arlon AD ($\epsilon r = 2.5$). We obtained a very good performance with a Graphene chemical potential of 0.2 eV and Arlon AD ($\epsilon r = 2.5$) material substrate. The results obtained are very satisfactory and the proposed crescent antenna can be used in several terahertz band applications.

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