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Substrate Effects on the Plasmonic Resonance of Graphene Nano-Antenna

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Abstract. In this manuscript, a pentagon shaped plasmonic graphene nano patch antenna is designed and investigated on silicon dioxide, silicon nitride and zinc oxide substrates. The optical characteristics of the graphene such as conductivity and permittivity are analyzed at various values of chemical potential using Kubo conductivity model. The plasmonic resonance of the proposed nano-antenna is analyzed through the graphene chemical potential varied in the span from 0.0 eV to 2.0 eV. It is observed that the proposed pentagon shaped graphene nano patch antenna shows good plasmonic resonance characteristics at 29.8750 THz with the reflection coefficient of -27.4153 dB, 91.5650 THz with -27.5179 dB and 853.7350 THz with -40.3267 dB on silicon dioxide, zinc oxide and silicon nitride substrates respectively. These optimum characteristics are observed at the chemical potential values 2.00 eV and 0.50 eV for the proposed graphene nano patch antenna.

Keywords. Kubo, Lorentz, Graphene, Chemical potential, Nano patch antenna, Silicon dioxide, Zinc oxide and Silicon nitride

1. Introduction

A recent development in the field of plasmonics and nanotechnology has enabled the design of nano-antenna structures for the photonic applications [1]. The limitations in the optical waveguides and couplers used at the nano scale are overcome with the help of nano-antennas [2-3]. The nano-antenna is a structure which is radiating at the terahertz frequency, and it contains a plasmonic metal conductor on a dielectric substrate. The optical properties of plasmonic metals play a phenomenal role in determining resonance characteristics of nano-antenna [4]. At terahertz frequencies, plasmonic materials exhibit complex permittivity values that vary with operating frequencies. Among other plasmonic metals, gold and silver are considered in nano-antennas design due to their chemical stability [5]. In recent years, graphene material caught attention of the nano-antenna design community due its tunable conductivity [6].

Graphene is a monolayer of graphite which has exceptional optical and electrical properties [7-8]. One vital property of the graphene is its variable carrier concentration. This is attained by altering the chemical potential of graphene through electrostatic

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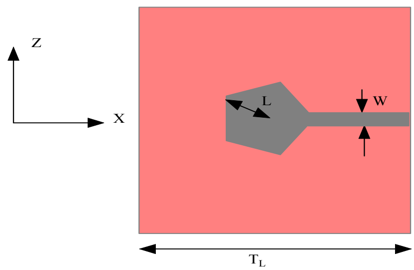
biasing. This results in tunable plasmonic resonance characteristics which makes graphene material suitable for the nano-antenna design. Another important parameter in the design of graphene nano-antenna is use of proper substrate material to enhance the characteristics of the graphene nano-antenna. A preliminary work on the graphene optical antenna has been reported by Jornet *et. al* [9]. The graphene nano-antenna on a silicon based and quartz substrates is reported by numerous research groups like dash *et. al.* [10], Ignacio *et. al* [5]., S *at. al*. [11], Bala *et. al.* [12], Gruhler *et. al.* [7], Singh *et. al* [13]. They have investigated the tunable property of the graphene as well as plasmonic wave propagation in the graphene nano-antenna in micrometer and millimeter range. In this regard plasmonic resonance characteristic of graphene optical antenna is investigated on zinc oxide dielectric and it is compared with that of silicon-based substrates.

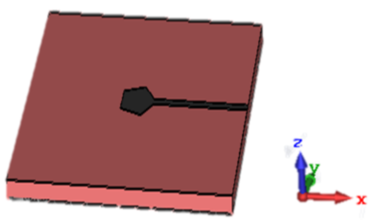
In this manuscript pentagon shaped graphene optical antenna is designed and investigated on zinc oxide, silicon dioxide and silicon nitride substrates. In this study optical properties of the graphene are analyzed using Kubo conductivity formula and parametric analysis is conducted using the chemical potential. The comparative study of plasmonic resonance characteristics of the graphene nano-antenna is performed on the three mentioned substrates.

2. Pentagon Shaped Graphene Nano-antenna Structure Design

The two- and three-dimensional structure of the proposed pentagon shaped graphene antenna is depicted in the figure 1 (a) and (b). Design parameters considered in the structure are the radius of the pentagon L, width of the microstrip feed line W, the thickness of the pentagon patch T_p, length of the square shaped substrate T_L and thickness of the substrate T_s. The modelling of the proposed pentagon shaped patch antenna is attained by means of Finite Integration Technique (FIT) on CST Microwave studio platform. The optimization of the design parameters is executed through CST and the design specifications selected for the pentagon shaped antenna is listed in Table 1. The graphene used in the simulation has a thickness of 10 nm, relaxation period of 0.1 psec, chemical potential μ_c = 0.10 eV-2 eV at 300° K. The waveguide port of 50 Ω is used to excite the proposed pentagon shaped nano patch antenna.



(a)



(b)

Figure 1. Graphene antenna view (a) 2 Dimensional (b) 3 Dimensional

Table 1. Pentagon shaped nano patch antenna design specifications

Design parameter	Value (nm)
L	60
W	10
Tp	3
TL	700
Ts	36

3. Graphene Conductivity Tuning

The optical property of the graphene plays a vital role in the resonance behavior of graphene nano patch. The complex conductivity of graphene is demonstrated though the use of Kubo formula at the terahertz frequency. The equation (1)-(3) exhibit Kubo conductivity model, which shows that the conductivity is a function of Boltzman constant k_B , reduced Planks constant *ħ= h / 2π*, chemical potential μ_c, frequency ω and scattering rate Γ_s at the temperature T_c . The model includes inter as wells as intra band conductivities.

$$\sigma(\omega, \mu_c, \Gamma_s, T_c\ ) = \sigma_{intrab}(\omega, \mu_c, \Gamma_s, T_c) + \sigma_{interb}(\omega, \mu_c, \Gamma_s, T_c) \tag{1}$$

$$\sigma_{intrab}(\omega, \mu_c, \Gamma_s, T_c) = \frac{-ie^2 k_B T_c}{\pi\hbar^2(\omega - i2\Gamma_s)}\left(\frac{\mu_c}{k_B T T_c} + 2\ ln\left(e^{\frac{\mu_c}{k_B T_c}} + 1\right)\right) \tag{2}$$

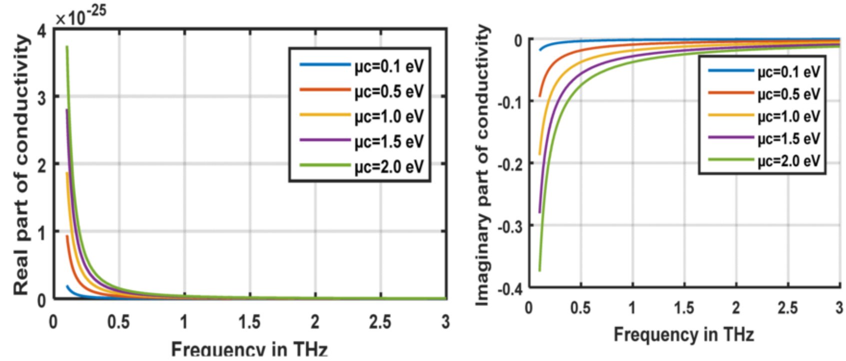
The inter band conductivity of the graphene is approximated at a low temperature value in the range $k_B T_c << |\mu_c|$, $\hbar\omega$ which is given in equation (3).

$$\sigma_{interb}(\omega, \mu_c, \Gamma_s, 0) = \frac{-ie^2}{4\pi\hbar^2}\, ln\left(\frac{2|\mu_c| - (\omega - i2\Gamma_s)\hbar}{2|\mu_c| + (\omega - i2\Gamma_s)\hbar}\right) \tag{3}$$

The conductivity of the graphene is easily tuned with the help of its chemical potential through electrostatic biasing or doping. The real and imaginary part of the $\sigma(\omega, \mu_c, \Gamma_s, T_c\ )$ for μ_c in the span from 0.10 eV to 2 eV insteps of 0.5 eV are depicted in the figure 2 (a) and (b). It is observed from figure 2 (a) that the σ of the graphene increases with the increase in μ_c. The permittivity $\epsilon(\omega)$ of graphene material is derived from the conductivity model which is shown in equation (4). The ϵ_R and imaginary part of $\epsilon(\omega)$ of graphene is portrayed in figure 3 (a) and (b). The graphene must exhibit negative real permittivity for the occurrence of plasmonic resonance in graphene antenna. It is found from the figure 3 (b) that graphene material will support plasmonic resonance. The losses occurring in graphene antenna is described by the imaginary part of the conductivity. Further it is observed that optical properties of the graphene are stable after 3 THz frequency.

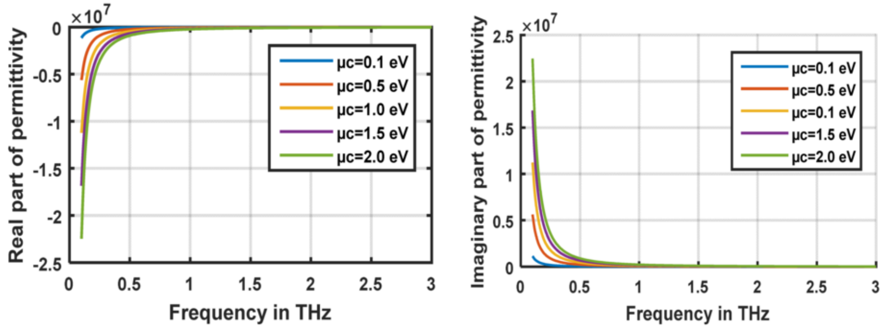
Conductivity model:

$$\epsilon(\omega) = \epsilon_R - j\ \sigma(\omega)/\omega\epsilon_0 \tag{4}$$



(a) (b)

Figure 2. $\sigma(\omega, \mu_c, \Gamma_s, T_c)$ of graphene (a) Real (b) Imaginary



(a) (b)

Figure 3. $\epsilon(\omega)$ of graphene (a) Real (b) Imaginary

4. Results and Discussion

The analysis of graphene-based pentagon shaped nano-antenna on the three dielectrics is presented in this section. The parametric analysis of the proposed pentagon patch antenna is performed through the design parameter μ_c which is the graphene chemical potential.

4.1 Pentagon Graphene Nano Patch on Silicon Dioxide Substrate

The figure 4 (a) depicts S_{11} parameters of the pentagon shaped graphene patch for the values of μ_c in the span 0.0 eV to 2.0 eV on Silicon Dioxide (SiO_2) substrate. It is found that reflection coefficient of the proposed nano pentagon patch becomes more negative as the chemical potential of the graphene increases. The resonance frequency of the proposed SiO_2-graphene nano patch antenna 29.8750 THz with -25.8952 dB, -25.4444 dB, -26.13 dB, -26.7365 dB, -26.9214 dB and -27.4153 dB at the chemical potential 0.00 eV, 0.10 eV, 0.50 eV, 1.00 eV, 1.50 eV and 2.00 eV respectively. Further it is observed that although graphene and silicon dioxide combination show reflection coefficient below -10 dB at several frequencies these frequencies are not suitable for optical wireless communication. The optical wireless communication reflection coefficient must be below -20 dB for the confinement and localization of the energy. The variation of the peak resonance frequency of SiO_2-graphene nano patch with μ_c of is depicted in figure 4(b) and it is listed in Table 2.

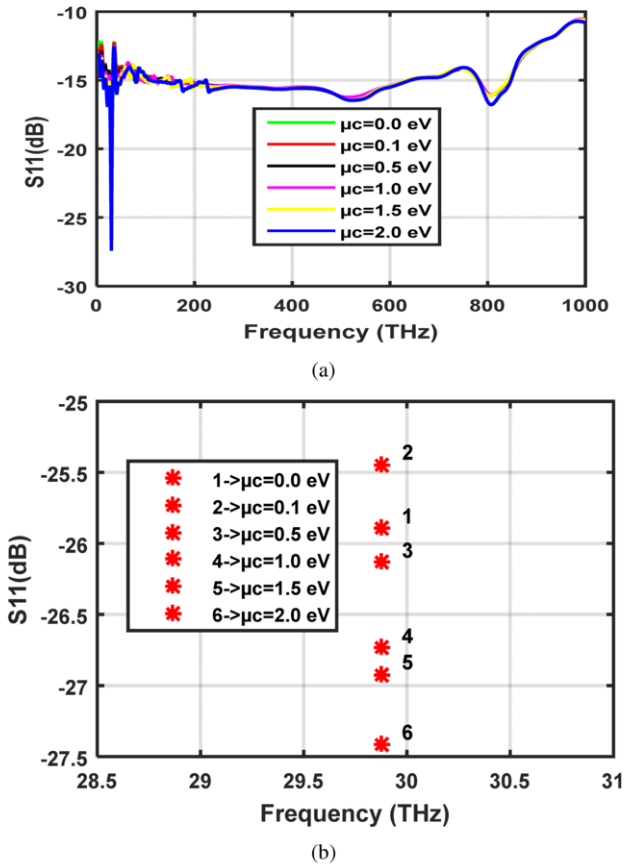


Figure 4. Plasmonic resonance of the pentagon graphene-SiO_2 nano patch (a) Reflection coefficient (b) Resonance frequency

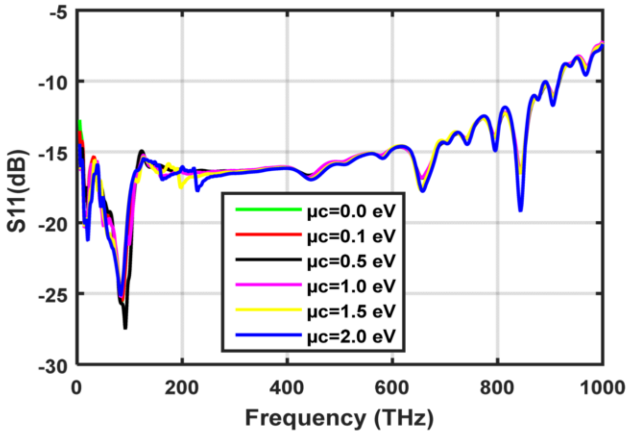
Table 2. Plasmonic resonance of the pentagon graphene-SiO_2 nano patch

Chemical potential μc (eV)	Resonance frequency (THz)	Reflection coefficient (dB)
0.0	29.8750	-25.8952
0.1	29.8750	-25.4444
0.5	29.8750	-26.13
1.0	29.8750	-26.7365
1.5	29.8750	-26.9214
2.0	29.8750	-27.4153

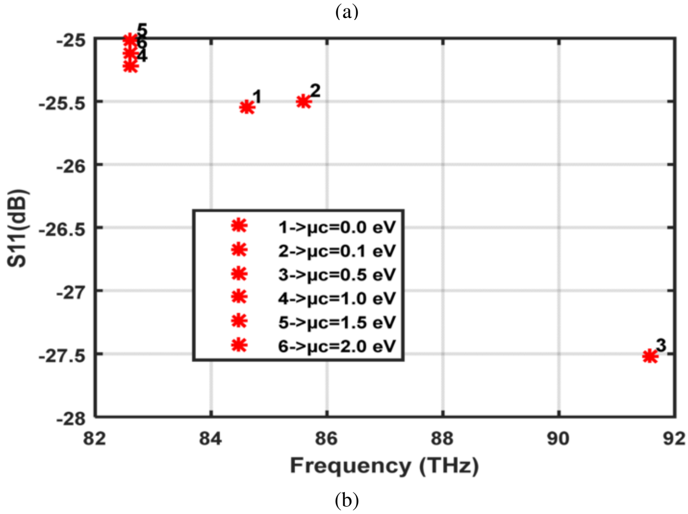
4.2 Pentagon Graphene Nano Patch on Zinc Oxide Substrate

The S_{11} characteristic of the proposed pentagon shaped graphene patch antenna on the Zinc Oxide (ZnO) substrate is shown in figure 5 (a). Resonating frequency of ZnO-graphene nanostructure is 84.6000 THz with -25.5476 dB, 85.5950 THz with -25.4992 dB and 91.5650 THz with -27.5179 dB at the chemical potential 0.00 eV, 0.10 eV and

0.50 eV respectively. The resonating frequency is 82.6100 THz with the reflection coefficient values -25.2206 dB, -25.0190 dB and -25.1150 dB at the chemical potential 1.00 eV, 1.50 eV and 2.00 eV as shown in the Table 3. The variation of the resonance frequency of the graphene-ZnO nano patch with μ_c of the graphene is depicted in figure 5 (b). It is observed that the resonating frequency of the graphene nanostructure increases with the increase in μ_c up to 0.50 eV and above 1 eV it shows the stable characteristics. This behavior is because of the graphene and zinc oxide combined structure.



(a)



(b)

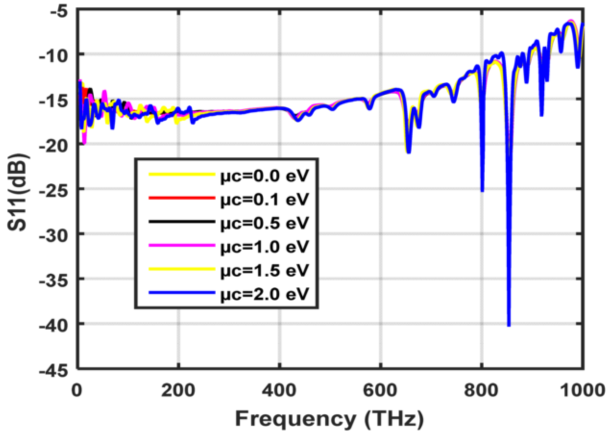
Figure 5. Plasmonic resonance of the pentagon graphene-ZnO nano patch (a) Reflection coefficient (b) Resonance frequency

Table 3. Plasmonic resonance of the pentagon graphene-ZnO nano patch

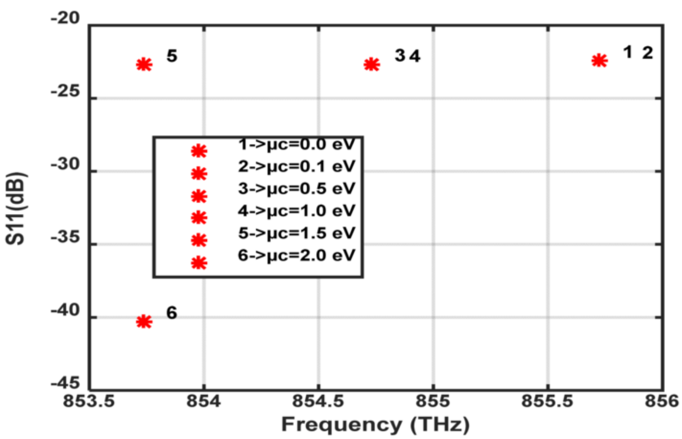
Chemical potential μc (eV)	Resonance frequency (THz)	Reflection coefficient (dB)
0.0	84.6000	-25.5476
0.1	85.5950	-25.4992
0.5	91.5650	-27.5179
1.0	82.6100	-25.2206
1.5	82.6100	-25.0190
2.0	82.6100	-25.1150

4.3 Pentagon Graphene Nano Patch on Silicon Nitride Substrate

The figure 6(a) depicts the plasmonic resonance of proposed pentagon shaped graphene antenna on silicon nitride substrate. It is observed that graphene-Si_3N_4 nanostructure is radiating at 855.7250 THz with S_{11} coefficient of -22.4579 dB and -22.4563 dB respectively at the chemical potential 0.00 eV and 0.10eV respectively. The resonance frequency is 854.7300 THz with S_{11} coefficient of -22.6880 dB and -22.7326 dB at the chemical potential 0.50 eV and 1.00 eV respectively. At the chemical potential 1.50 eV and 2.00 eV the resonance frequency is 853.7350 THz with the reflection coefficient of -22.7175 dB and -40.3267 dB respectively. The graphene nano particles with silicon nitride show good plasmonic resonance as the combination produces good conductivity in the proposed nano-antenna. The variation in the resonating frequency of the graphene-Si_3N_4 nanostructure shown in the figure 6 (b) and it is tabulated in Table 4.



(a)



(b)

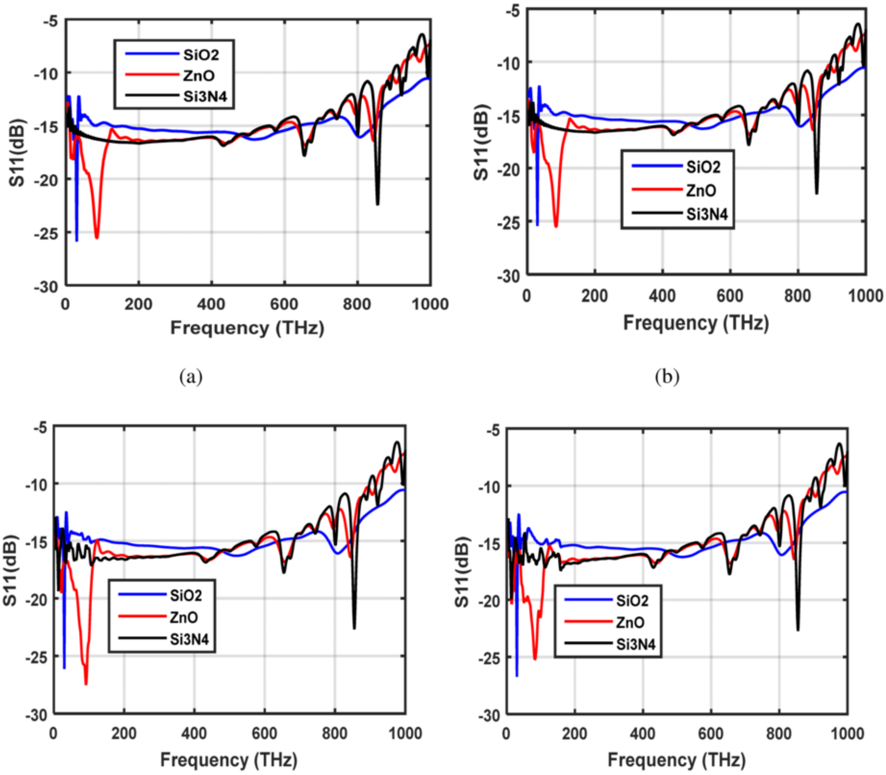
Figure 6. Plasmonic resonance of the pentagon graphene-Si_3N_4 nano patch (a) Reflection coefficient (b) Resonance frequency

Table 4. Plasmonic resonance of the pentagon graphene-Si_3N_4 nano patch

Chemical potential μc (eV)	Resonance frequency (THz)	Reflection coefficient (dB)
0.0	855.7250	-22.4579
0.1	855.7250	-22.4563
0.5	854.7300	-22.6880
1.0	854.7300	-22.7326
1.5	853.7350	-22.7175
2.0	853.7350	-40.3267

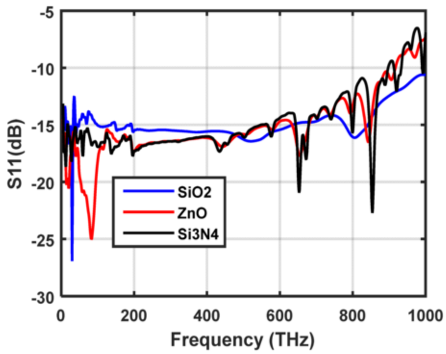
4.4 Impact of Substrate materials on Pentagon Graphene Nano Patch

The figure 7 (a) to (f) show the plasmonic resonance properties of the graphene pentagon antenna on zinc oxide, silicon dioxide and silicon nitride substrates at the chemical potential 0.00 eV, 0.10 eV, 0.50 eV, 1.00 eV, 1.50 eV and 2.00 eV. It observed that graphene-SiO_2 and graphene-ZnO nanostructures show good plasmonic resonance characteristics at low terahertz frequencies. The graphene-Si_3N_4 nanostructures shows good show good plasmonic resonance characteristics at high terahertz frequencies. The optimum characteristics are observed at 29.8750 THz with -27.4153 dB, 91.5650 THz with -27.5179 dB and 853.7350 THz with -40.3267 dB on silicon dioxide, zinc oxide and silicon nitride respectively. These characteristics are observed at the chemical potential values 2.00 eV, 0.50 eV and 2.00 eV respectively for the graphene-SiO_2, graphene-ZnO and graphene-Si_3N_4 nanostructures.

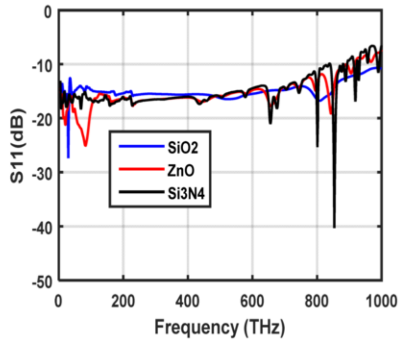


(a) (b)

(c) (d)



(e)



(f)

Figure 7. Plasmonic resonance of pentagon graphene antenna on SiO_2, ZnO and Si_3N_4 substrates for μc (a) 0.00 eV (b) 0.10 eV (c) 0.50 eV (d) 1.00 eV (e) 1.50 eV (f) 2.00 eV

5. Conclusion

The proposed pentagon shaped graphene nano patch antenna is designed and investigated on the zinc oxide, silicon dioxide and silicon nitride substrates using chemical potential of the graphene. The optical properties of the graphene such as conductivity and permittivity are analyzed using Kubo conductivity model at the terahertz frequency. It is found that the proposed graphene antenna has good plasmonic resonance characteristics at 29.8750 THz with the reflection coefficient -27.4153 dB, 91.5650 THz with -27.5179 dB and 853.7350 THz with -40.3267 dB on silicon dioxide, zinc oxide and silicon nitride substrates respectively. Further it is found that the reflection coefficient of the graphene plasmonic antenna improves with the increase in the chemical potential of the graphene.

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