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Performance Analysis of Graphene Plasmonic Nanoantenna using Different Substrate at Terahertz Band

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ABSTRACT

Owing to the support of surface plasmon polaritons (SPP) in graphene, the graphene plasmonic nanoantenna resonates at THz frequency regime. SPP waves propagate in the graphene-substrate interface and have a significant role in the performance of graphene plasmonic nanoantenna. With the aim of finding a suitable substrate for graphene plasmonic nanoantenna, this paper presents a comparative performance analysis of graphene nanoantenna using different substrates like glass, polyamide, quartz, and gallium arsenide. Antennas are analyzed in terms of the reflection coefficient, impedance bandwidth, radiation pattern, half-power beamwidth, front to back ratio and directivity. It is found that the low reflection coefficient, maximum bandwidth, lower back lobe radiation, high front to back ratio and high directivity of the graphene plasmonic nanoantenna is obtained when gallium arsenide used as a substrate.

Keywords: Graphene, Surface plasmon polaritons, Nanoantenna, Different substrates, Terahertz

1. INTRODUCTION

Terahertz (THz) regime is the most promising regions of the electromagnetic spectrum for a growing range of application in numerous fields applications including spectroscopy, astronomy, atmospheric research, high-speed communication, military and defense, safety monitoring and quality control, biomedical, THz imaging, and sensing, etc. [1-9]. The THz band in the electromagnetic spectrum lies from 0.1 THz to 10 THz. Wireless communications is one of the most promising applications in THz band [11]. The demand for THz antennas has been increased because of tremendous advancements in THz wireless communications. THz antennas enable miniaturization of the antenna (size reduces to um), higher bandwidth and higher bit rate. The design of the conventional metallic nanoantenna at THz frequency faces many difficulties. The skin depth and conductivity of conventional copper metal are decreases at THz frequency, which leads to high propagation losses and degradation of radiation efficiency of the conventional metallic nanoantenna. Therefore, the use of the metallic nanoantenna at THz band is very challenging.

On the other hand, owing to its two-dimensional nature and honeycomb lattice structure of carbon atom, graphene has excellent unique electrical, mechanical and optical properties [12-15]. Graphene possesses high carrier mobility (2×10^5 $cm^2V^{-1}s^{-1}$), high thermal conductivity (5000 W/mK), high mechanical strength (1.5 TPa), maximum surface area to volume ratio and outstanding biocompatibility. Due to its unique properties, graphene has attracted numerous applications such as ultrahigh-speed transistors [16], transparent solar cells [17], metamaterials [18], and graphene plasmonics [19]. Moreover, owing to the support of surface plasmon polaritons (SPP) at THz frequency range [20], graphene has become the most promising plasmonic material for THz miniaturized antenna [21-30]. Due to slow-wave property, the graphene nanoantenna (GNA) enables high miniaturization and high directivity compared to conventional metal antenna [23]. Furthermore, the surface conductivity of graphene can be controlled by means of electrostatic bias or chemical doping, which in turn tunes the properties of GNA [23]. Different types of antenna concepts such as dipole antenna, patch antenna, bowtie antenna, Yagi-Uda antenna, leaky-wave antenna, MIMO antenna, reflectarray antenna, *etc*. have been implemented using graphene [23- 30]. However, the selection of suitable substrate material is a main important task in the design of graphene antennas. In order to find a suitable substrate for GNA, this paper presents a comparative performance analysis of GNA using different substrates like gallium arsenide (GaAs), glass, quartz, and polyamide.

2. MATERIAL AND METHOD

2.1. Graphene EM Properties

Graphene has surface conductivity σ (ω, μ_c, Γ, T) that depends on frequency ω, chemical potential μ_c, scattering rate Γ, and temperature T. The conductivity of graphene consists two terms and has been expressed by the Kubo formula [31], $\sigma=\sigma_{intra}+\sigma_{inter}$, where σ_{intra} is due to the intraband contributions and σ_{inter} is due to the interband contributions. The interband term is negligible and the intraband term is dominant for the frequency below $\hbar\omega$, where $\hbar$ is the reduced Planck constant. The intraband term is the dominant term in THz regimes. Intraband conductivity σ_{intra} can be expressed as [31].

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$$\sigma_s = \frac{-je^2\kappa_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left[\frac{\mu_c}{\kappa_B T} + 2\ln\left(e^{-\mu_c/\kappa_B T} + 1\right)\right] \qquad (1)$$

where Γ is the scattering rate, e is the electron charge, $\hbar$ is the reduced Planck's constant and k_B is the Boltzmann's constant.

In this work, graphene is modeled as a resistive sheet using conductivity eqn (1). In order to find the best substrate for GNA, the graphene sheet is placed over different substrates such as glass, polyamide, quartz, and gallium arsenide. Owing to its unique plasmonic properties at THz, SPPs wave propagate at the graphene-substrate interface [32]. SPP properties have impact on surface conductivity. Graphene conductivity can be calculated from SPP dispersion relation as [33]

$$\sigma_s(\omega) = -i\omega\varepsilon_0\left(\frac{\varepsilon_0 + \varepsilon_s \coth(K_{SPP}h)}{K_{SPP}}\right) \qquad (2)$$

where $\sigma_s(\omega)$ is the graphene surface conductivity, K_{SPP} is the SPP wave vector, h is the thickness of the substrate, ε_s is the relative permittivity of the substrate, and ε_0 is the absolute permittivity of free-space. Substrate material has a great impact on SPP propagation of graphene, which in turn, impacts on the performance of graphene antenna. The dispersion relation allows the derivation of the resonant frequency of GNA, using the resonance condition

$$L = m\frac{\lambda_{SPP}}{2} = m\frac{\pi}{K_{SPP}} \qquad (3)$$

where L is the length of GNA, m is an integer, which determines the order of the resonance and λ_{spp} is the SPP wavelength. The SPP wavelength is almost two-three orders of magnitude shorter than the free-space electromagnetic radiation wavelength [34].

2.2 Graphene Nanoantenna Design

The schematic of the GNA is shown in Fig. 1. The proposed antenna consists of a rectangular graphene sheet of width (W_g) = 9 µm and length (L_g) = 11 µm. The ground plane is attached to the back of the substrate with the dimensions of 28×18 µm^2. Different substrate material such as gallium arsenide, glass, polyamide and quartz of the same width (W_s) = 18 µm, length (L_s) = 28 µm, and height (h) = 1.4 µm are selected. In this work, we assume T =300 K, τ = 1 ps, and μ_c= 0.5 eV.

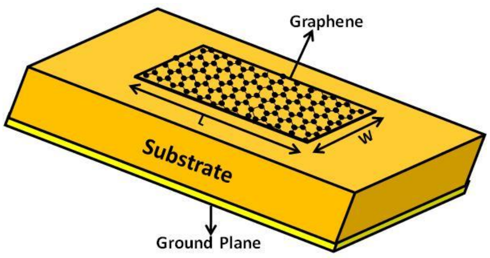

Fig.1. Schematic of graphene nanoantenna over the substrate

To study the impacts of the substrates on the performance of antenna, the GNA over different substrate have been simulated using the finite element method (FEM) based Ansys high-frequency structure simulator (HFSS) software. It has been observed that the substrate impacts on plasmonic dispersion relation, which in turn affects the resonant frequency and radiation properties of GNA.

3. RESULT AND DISCUSSION

3.1. Effect of substrate on S11 parameter and bandwidth of GNA

The substrate influences on the magnitude of the resonance of GNA. The simulated S_{11} parameter of GNA for different substrates is shown in Fig.2. It is found that the GNA resonates at 2.18 THz, 2.70 THz, 2.94 THz, and 3.10 THz for glass, polyamide, quartz and GaAs substrates respectively. A Reflection coefficient of -22 dB, -27dB, -30 dB and -31 dB obtained from glass, polyamide, quartz and GaAs substrates respectively. From the results, it can be noticed that the maximum -10 dB bandwidth of 256 GHz is obtained when GaAs is used as a substrate for the proposed GNA structure, whereas 156 GHz, 189 GHz and 210 GHz of bandwidth obtained if substrate glass, polyamide, and quartz used respectively.

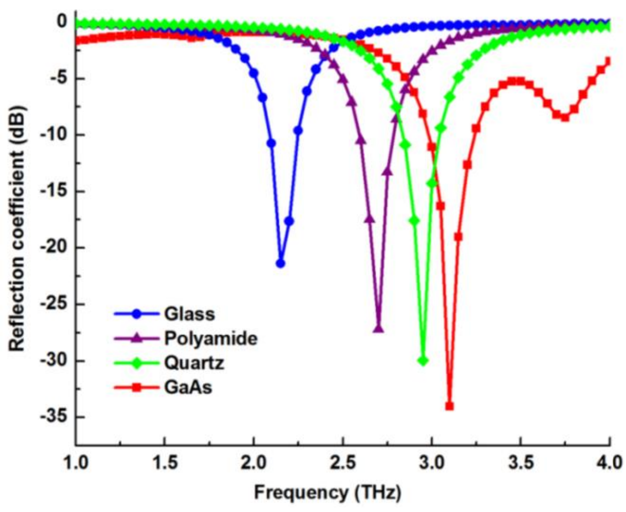

Fig.2. S_{11} parameter of GNA for different substrate

3.2. Effect of substrate on the radiation pattern of GNA

The simulated normalized radiation pattern of GNA for different substrates is shown in Fig.3. From the result, it can be seen that the radiation patterns of GNA are broadside pattern for all cases. Furthermore, it can be noticed that GNA provides lower back lobe radiation with a high front to back ratio of 21 dB when GaAs is used as a substrate, whereas front to back ratio of 15 dB, 14 dB and 14 dB obtained for glass,

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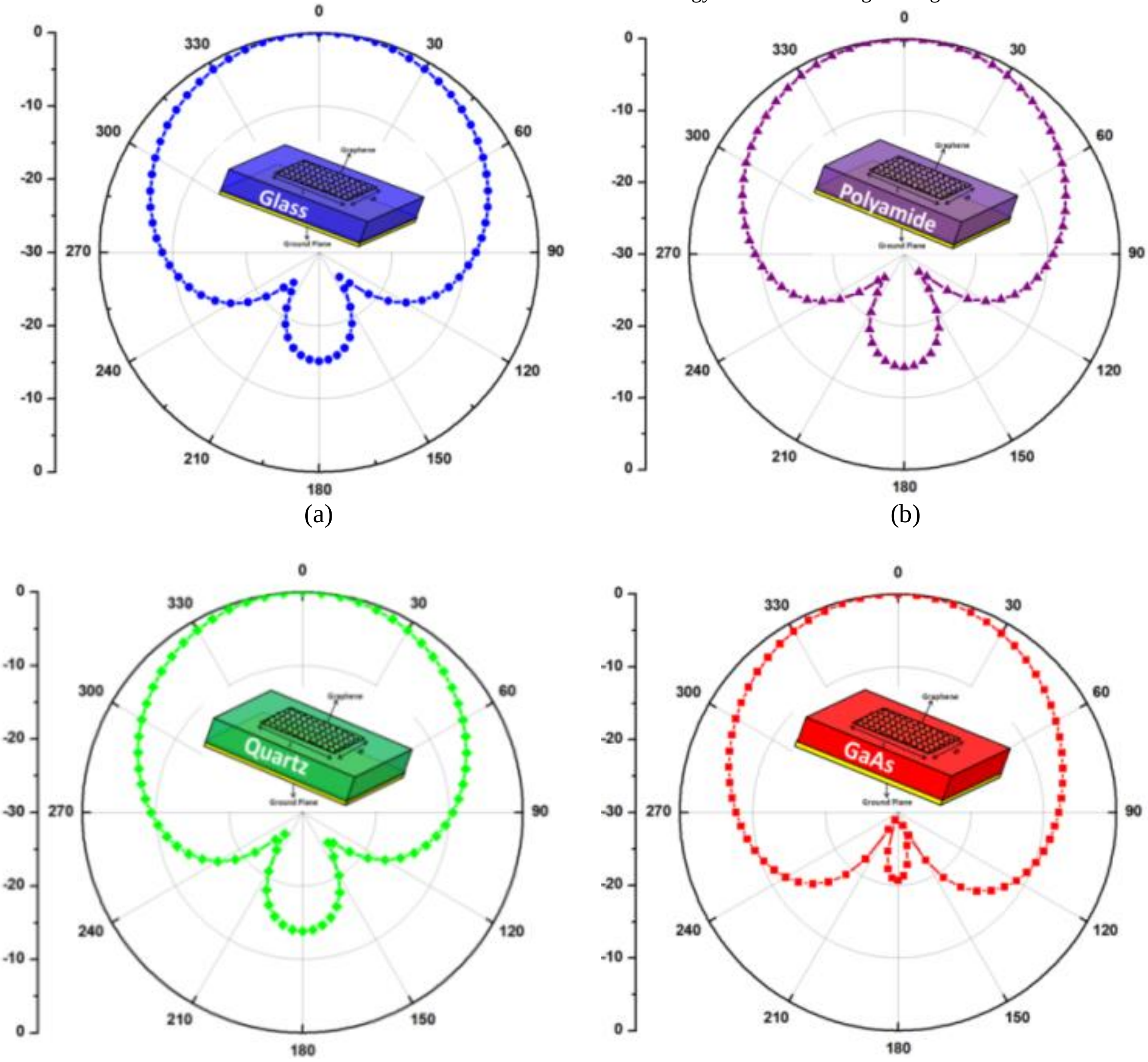

Fig.3. The normalized radiation pattern of GNA for different substrates. (a) Glass (b) Polyamide (c) Quartz and (d) GaAs.

polyamide, and quartz substrate respectively. Fig.4 shows the directivity of GNA for different substrates. From the simulation result, it has been found that maximum directivity of 3.66 dBi and 3.25 dBi obtained for GNA when quartz and GaAs substrates selected respectively. The directivity of GNA for glass and polyamide substrates is 1.38 dBi and 2.99 dBi respectively. Fig. 5 shows half-power beamwidth (HPBW) of GNA for different substrates. Maximum HPBW of 101^0 is obtained for GNA over glass substrates. For acquiring more beamwidth, the glass substrate is suitable for GNA. HPBW of GNA for polyamide, quartz, and GaAs substrate are 93^0, 93^0 and 92^0 respectively. The performances of GNA for different substrates are summarized in Table.1.

Table I: Performance of GNA for different substrate

Substrate	Glass	Polyamide	Quartz	GaAs
Resonant frequency (THz)	2.18	2.7	2.94	3.10
Reflection coefficient(dB)	-22	-27	-30	-31
Bandwidth (GHz)	156	189	210	256
Directivity (dBi)	1.38	2.99	3.66	3.25
HPBW (Degree)	101	93	93	92
F/B ratio (dB)	15	14	14	21

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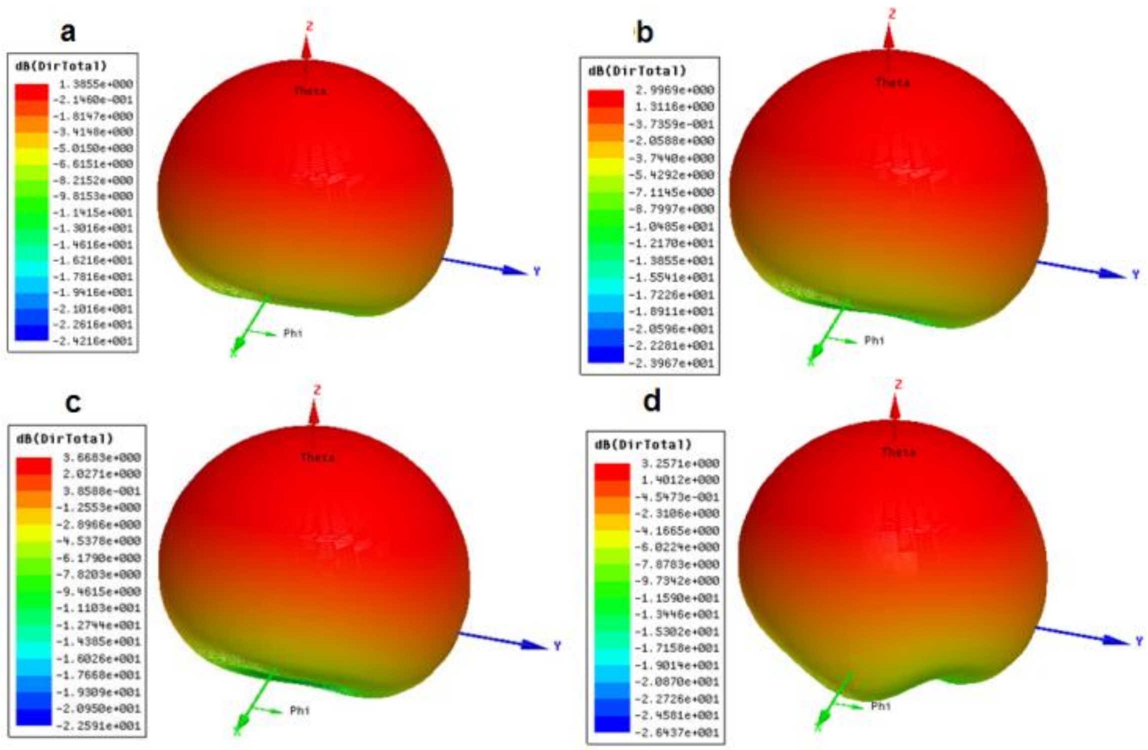

Fig.4. Directivity and far-field pattern of GNA for different substrates. (a) Glass, (b) Polyamide, (c) Quartz and (d) GaAs.

4. CONCLUSION

This work numerically investigated the performance of graphene nanoantenna over different substrates such as glass, polyamide, quartz, and GaAs. GNAs are analyzed in terms of reflection coefficient, impedance bandwidth, radiation pattern, half-power beamwidth, front to back ratio and directivity. It has been found that GaAs is a suitable substrate candidate for graphene nanoantenna as compared to other substrates. graphene nanoantenna over GaAs provides low reflection coefficient, maximum bandwidth, high front to back ratio and high directivity compared to other substrate materials glass, polyamide, and quartz.

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