Graphene based Nano Patch Antenna Performance Analysis with Various Dielectric Substrate Materials and Implanted Photonic Band Gap Structure

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Abstract- Micro strip patch antenna is a significant device in terahertz frequency (0.1THz -10 THz) regime on account of its adaptability for miniaturization and conformability. Selection of appropriate dielectric material enhances the overall performance characteristics of graphene-based nano patch antenna. The dielectric constant of the substrate material can alter the transport properties of the Graphene and hence has an impact on the resonant properties of the patch antenna. In this paper, the performance of Graphene-based rectangular patch antenna designed at the resonant frequency of 750 GHz employing different dielectric substrate materials, namely Rogers 3003, polyimide, silica, RT/ Duroid 6006 and aluminum oxide. Microstrip line edge feeding used in the design and radiation characteristics such as return loss, Voltage standing wave ratio (VSWR), Gain and also absorption cross sections of the materials are evaluated. The simulations are carried out using HFSS software. It is found out that, Rogers's 3003 dielectric substrate material offers improved gain compared to materials under consideration. The work is further extended to improve gain of Rogers RO 3003 by implanting small photonic band gaps (PBG) in the substrate. PBG structures reduce the surface wave losses hence improvement in the gain. An additional Gain of 1.55 dB is observed with PBG implantations. The influence of height of dielectric substrate and PBG radius on the gain also investigated as a part of work.

Keywords- Terahertz regime, Novel substrate material, Graphene nano patch antenna, photonic band gap, Return loss, Absorption cross section.

I. INTRODUCTION

The Terahertz (THz) frequency band is coarsely defined as a portion of the electromagnetic spectrum which covers from 0.1-10 THz, which represents the free-space wavelength from 3 millimeters (mm) to 30 micrometers (μm) [1]. The recent advances in technology seek attention in the THz system. The applications of Terahertz spectrum ranging from explosive and concealed weapon detection, medical diagnosis, security, testing, time-domain spectroscopy, nondestructive testing, and quality regulate to next-generation wireless communication systems [2-6]. THz communication band preferred for protected communication to short-distance and immediate higher data transfer (multi-Mb/s to Gb/s). Bandwidth offered by THz wireless communications is large, hence the data rates of 40-100 Gbps for the indoor and 100 Gb/s for outdoor communication can be obtained rather than microwave systems [7]. The next generation wireless communication system needs greater broadband antenna in a high mobility environment with lower transmitting power. The microstrip patch antenna is a significant device in terahertz frequency (0.1THz -10 THz) regime on account of its adaptability for miniaturization, advantages of conformal to planar as well as non-planar surfaces [8]. The standard patch antenna is composed of the copper material as patch conductor has disadvantages of narrow bandwidth, lower gain, and minimal power handling capability caused by skin effect at terahertz frequency. Graphene possesses outstanding mechanical, electronic and optical properties [9]. It attains the carrier mobility of 2, 00,000 cm^2/v-s at room temperature and a young modulus of 1.5 TPa, makes the graphene suitable for high-frequency applications [10]. Choice of appropriate dielectric material to attain desired antenna performance is an essential task for the designer. In general low dielectric permittivity materials are preferred because the electromagnetic energy storage is less within these materials. A significant fact that, as the value of dielectric constant increases, the surface wave losses are enhanced, and the radiation efficiency is degraded even in the terahertz regime [11]. In general, the antenna performance measured interims of return loss, VSWR, gain, directivity, impedance bandwidth, radiation efficiency and absorption cross-section, etc. The microstrip line feeding technique is most widely used to match the impedance of rectangular patch with source impedance. The optimized width of the feed line minimizes the mismatch losses. The prime advantage of using microstrip feeding technique at terahertz antenna is comfortable with fabrication over other feeding techniques [12].

In this paper graphene based rectangular patch is designed, which is often the most recommended shape due to numerous benefits such as low-profile, compact, economical and occupying small area for metallization. The modeling of the antenna is performed using the commercial ANSYS and high frequency simulation (HFSS) software based on finite element method (FEM).This work mainly focuses on designing of graphene-based rectangular nano patch antenna and compares its performance with various dielectric substrate materials in the band of 720GHz-780GHz frequency range. Further PBG structures are introduced on the substrate to improve gain. Also the effect of thickness of the dielectric substrate and PBG radius on the performance of the antenna is also observed. This paper is organized into following sections, section II novel dielectric substrate materials. Section III discusses the graphene-based patch antenna, section IV deals the PBG substrate and section V investigates the results and discussion. Conclusions are made in section VI.

II. NOVEL DIELECTRIC SUBSTRATE MATERIALS

The selection of appropriate dielectric substrate material is significant for graphene nano patch antenna, the dielectric constant and thickness of the substrate dramatically influences the resonant frequency and impedance properties of the patch antenna. The charge carrier density of the graphene varies with the dielectric constant of the substrate material used [13]. Thus it has control on the carrier mobility and thereby contributing tunable properties of graphene patch. As material science advances, the new dielectric materials are also emerging It has been noticed from the literature that there is a chance to investigate different dielectric substrate materials like Rogers 3003, Polyimide, Rogers RT/Duroid 6006, silica, Al_2O_3 to have further improvement in graphene patch antenna performance. Among these, Rogers 3003 offers stable dielectric constant versus temperature and frequency. It has outstanding mechanical properties versus temperature, low dielectric constant and loss tangent enables its usage in microstrip patch antennas [14]. It is an ideal material for microstrip patch antennas, bandpass filter. Its potential applications are in many areas, such as automotive global positioning satellite, wireless communications, direct broadcast satellites, cellular and pager telecommunications [18], [19]. Polyimide has outstanding mechanical properties and high heat, corona and chemical resistance properties. Polyimide generally compounded with graphite or glass fiber. It has various applications in displays, high-temperature fuel cells, medical tubing, electronics industry for flexible cables and different military roles [15]. RT/Duroid 6006 substrate has good mechanical, thermal stability and ease of fabrication. It has almost isotropic electrical Properties and less moisture absorption [16]. Aluminum is a chemical composite commonly referred to as alumina. It has an excellent sequence of graphene as it increases the dielectric's wear resistance and decreases friction [17]. Due to its excellent features, Al2O3 has given rise to the abundance of potential applications in many fields such as ultra-high speed transistors, high voltage insulators, high-temperature electrical insulators and instrumentation parts for thermal property for test machines thermometry sensors, electronic substrates, and Gas laser tubes. Silica is one of the most versatile oxide materials in the earth crust. It can be present in a variety of crystalline forms. It frequently occurs as a non-crystalline (glass) oxidation product on the surface of silicon or silicon compounds. It has low dielectric constant, low dissipation factor and close to zero thermal expansion coefficient. The dielectric properties are constant over gigahertz frequencies. The mechanical, thermal and electrical properties of various dielectric materials under consideration are tabulated in Table 1.

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III. GRAPHENE BASED NANO PATCH ANTENNA

The primary source of electromagnetic radiation is the fringing fields in microstrip antenna. The excited electric fields at the edge of the patch undergo fringing. The dielectric substrate having smaller values of dielectric permittivity is preferred because it enhances the fringing fields. The length of the rectangular patch antenna must be slightly less than λ/2 when it operated in the fundamental TM_{10} mode. A λ is the medium dielectric wavelength and is equal to $\lambda_0/(\sqrt{\varepsilon_{reff}})$, and λ0 is the free space wavelength. The TM_{10} mode shows that the field changes one λ/2 cycle along the length and there is no change in the width of patch antenna [20]. The thickness of the dielectric substrate (h should be less than the free space wavelength (0.03λ0≤ h ≤0.05λ0) [21]. Patch antenna and ground planes are separated by thin dielectric substrate material under consideration. Microstrip line with quarter wavelength transmission line feeding is used to match the impedance of microstrip feed with the patch. Antenna impedance can be matched to the microstrip feed line by tuning width of quarter wave and feed line. Copper (CU), and gold (AU) materials can be used as patch antenna but they exhibit skin effect at THz frequency hence its efficiency is effected, where as in Graphene materials it is not observed [22]. In this work Graphene rectangular patch is integrated on different dielectric substrate (having equal thickness "h") materials under consideration is as shown in Fig1.

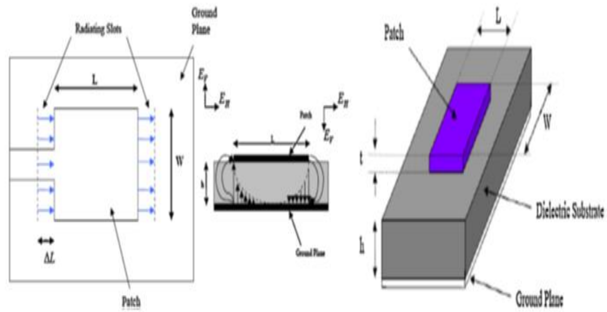
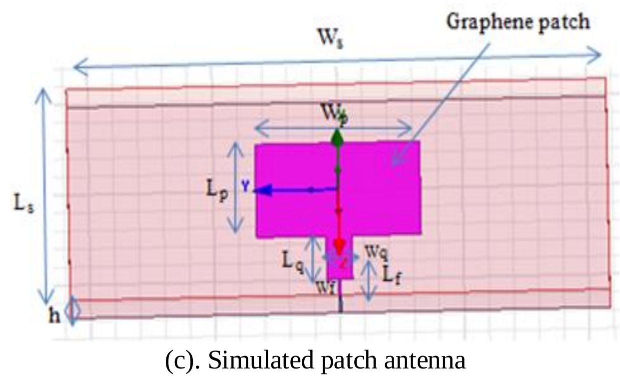


Fig.1: Top and side views of the antenna (b). Schematic view of the microstrip patch antenna



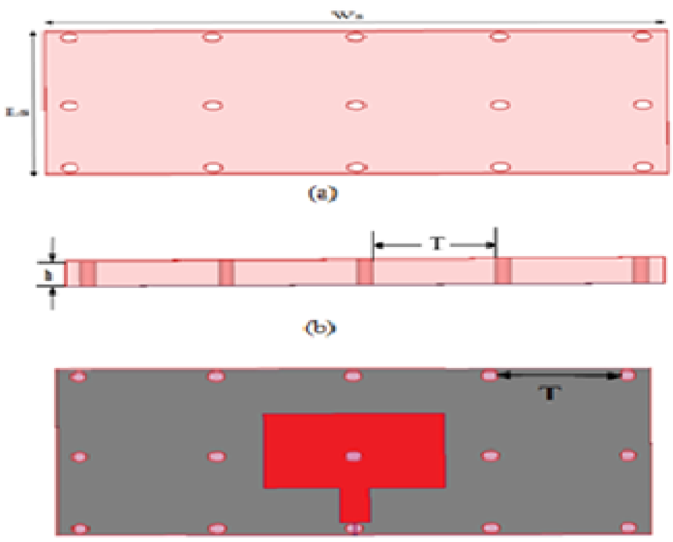
(c). Simulated patch antenna

IV. PBG SUBSTRATE IMPLANTATION

Antenna performsnce is effected by surface wave accumulation in the dielectric material. These surface wave losses are reduced by implanting photonic band gaps (PBG) on the substrate [23]. The introduction of air cavity periodic cylindrical unit cells into the substrate volume leads to the structure of PBG dielectric substrate [24]. These air cavities are primarily used to degrade the accumulation of fields in the dielectric substrate, hence reduces the effective dielectric constant of the substrate material, and so fringing fields are enhanced. When the hole radius is narrow, the field is tightly coupled and radiation from the patch is less, as the hole radius increases, the radiation of electromagnetic energy also increases and hence gain is improved. Further increase the whole radius reduces the gain, due to reduction in electromagnetic coupling [11]. Fig.2(a) shows dielectric substrate layer after implantation of photonic band gaps. The photonic crystals 'T' in the substrate layer should approximately be half of the guide wavelength of microstrip patch according to the Bragg reflect condition. [26].

TABLE I. PROPERTIES OF VARIOUS SUBSTRATE MATERIAL

	SI/metric	Rogers 3003	Polyimide	RT/Duroid 6006	Al_2O_3	Silica
Mechanical properties						
Density	Gm/cc	2.1	1.42	2.7	3.69	2.2
Elastic modulus	Gpa	0.9	2.5	1	300	-
Poisson's ratio	-	0.6	3.4	0.6	0.21	-
Thermal properties						
Thermal conductivity	$W/m.^0K$	0.5	0.16	0.5	18	1.5
Coefficient of thermal expansion	$10^{-6}/ ^0K$	13	40	34	8.1	4.5
Specific heat	$J/Kg.^0K$	900	1090	970	800	745
Electrical properties						
Dielectric constant	-	3.0	3.5	6.15	9.1	4.0
Dissipation factor	-	0.0013	0.008	0.0019	0.0007	-



(c)

Fig.2: PBG implanted substrate b. Vertical cross –Section view c. Proposed antenna on a periodic substrate

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} \qquad (1)$$

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{reff}}} \qquad (2)$$

$$T = \lambda_{g/2} \qquad (3)$$

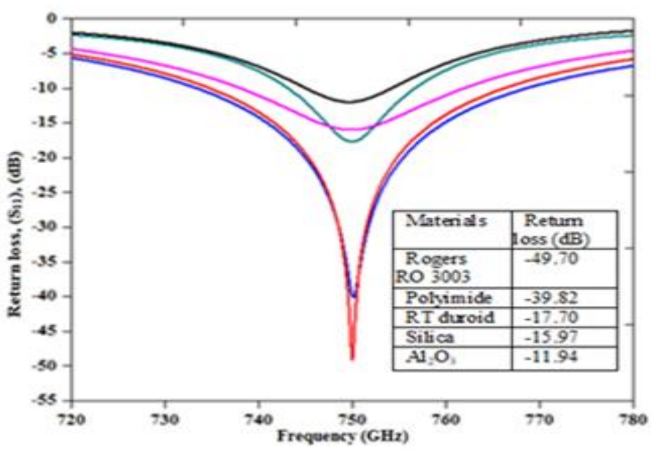
Where λg Guide wavelength, c is the velocity of light, f is the resonant frequency. The equations 1 to 3 are used for calculation of air cavities [25].

V. RESULTA AND DISCUSSION

Graphene-based nano patch antenna for different dielectric substrate materials is designed in the frequency band of 720GHz-780GHz. The parameters of patch antenna and their dimensions at resonant frequency f_r= 750 GHz are tabulated in table2. Planar feeding considered for this design. Various antenna performance parameters like return loss, VSWR, gain, and absorption cross section are analyzed and plotted using substrate material like RO3003, Polyimide, Silica, RT/Duroid, Aluminum oxide and are shown from fig 3 (a) to (d). Fig 4 shows the 2D and 3D radiation patterns of the graphene patch antenna. Further, photonic band gaps (PBG) are implanted to improve the gain of the THz patch antenna. The analytical value of air cylinders radius of 2µm is implanted on a dielectric substrate. The photonic crystal period 'T' is chosen as 100µm instead of calculated air gap distance between the centers is 141.4 µm, in order to accommodate the photonic crystal structure in the substrate material adequately. Gain variations on hole radius is observed in the range of 2-15 µm for uniform structure. It is noticed from the fig 6 (a) that there is a right shift in resonant frequency. It is also observed from (b) & Figure7. (a) that the resonant frequency of the antenna is decreased by increasing the thickness of the dielectric substrate from 20μm to 25 μm and decreases in the gain.

TABLE II. DESIGN SPECIFICATIONS PATCH ANTENNA

Parameter	Symbol	Equation	Calculated at resonant frequency
Resonant frequency	f_r	$f_r = \frac{c}{2(L+2\Delta L)\sqrt{\varepsilon_{eff}}}$	750GHz
Width of the patch	(W_p)	$W_p = \frac{c}{2fr}\sqrt{(\frac{2}{\varepsilon_r + 1})}$	134.6 μm
Length of the patch	(L_p)	$L_p = \left(\frac{c}{2fr\sqrt{\varepsilon_{eff}}}\right) - 2\Delta L$	94.24 μm
Extension Length	ΔL	$\Delta L = 0.412h \frac{(\varepsilon eff+0.3)((\frac{W}{h})+0.264}{(\varepsilon eff-0.258)((\frac{W}{h})+0.8)}$	3.32 μm
Effective dielectric constant	ε_{eff}	$\varepsilon eff = \left(\frac{\varepsilon_r+1}{2}\right) + \left(\frac{\varepsilon_r-1}{2}\right)\left[\sqrt{1} + \frac{W}{12h}\right]$ for $\frac{w}{h}$ >1	2.80
Dielectric constant	ε_r	-	3
Loss tangent	Tanδ	-	0.0013
Height of substrate	(h)	$0.003\lambda_0 \leq h \leq 0.05\lambda_0$	20 μm
Width of substrate	(W_s)	$W_s = 6\times h$ +Wp	440 μm
Length of substrate	(L_s)	$L_s = 6\times h$ +Lp	210 μm
Width of quarter wave transformer	(W_q)	$\lambda_0/20$	21 μm
Length of quarter wave transformer	(L_q)	$\lambda_0/10$	43.02 μm
Width of feed line	(W_f)	$W_f = h\ (\frac{377}{50\sqrt{\varepsilon r}}-2)$	2 μm
Length of feed line	(L_f)	$\lambda_0/25$	15.17 μm



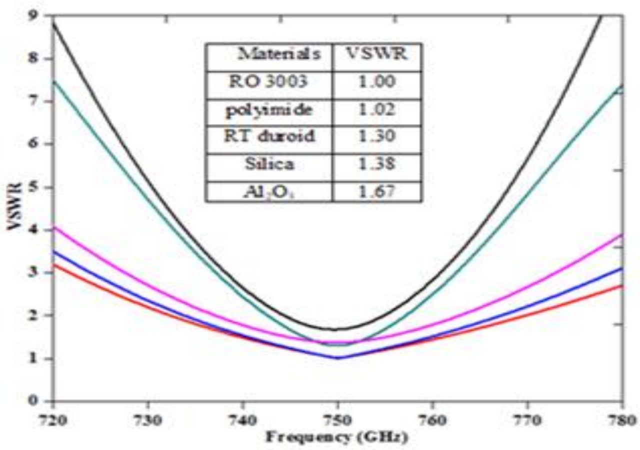
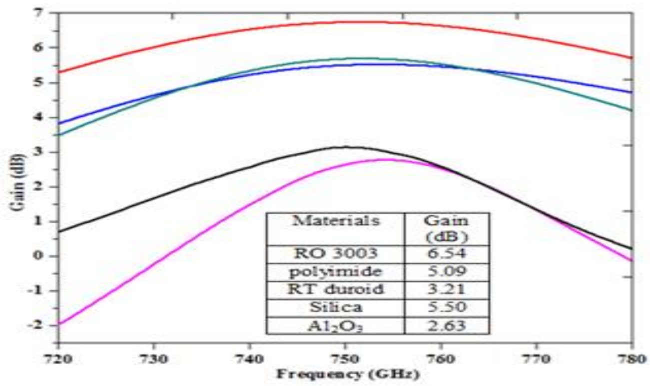
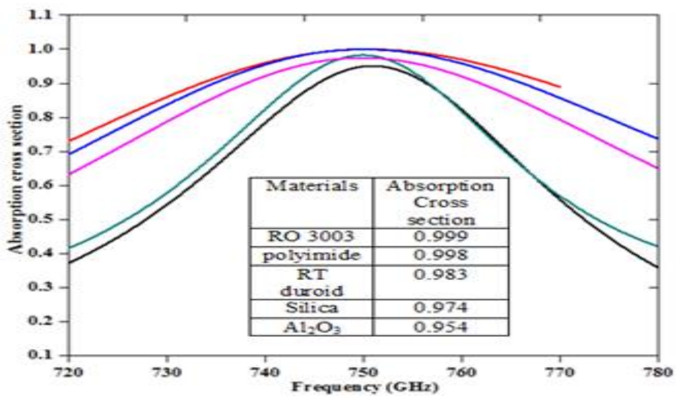


Fig.3:Return loss graphs for various substrate materials Rogers 3003 (Red line), Polyimide (Blue line, RT duroid (Cyan), Silica (Magenta), Al_2O_3 (Black)

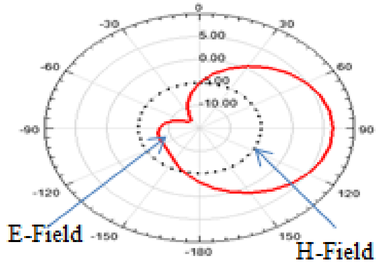
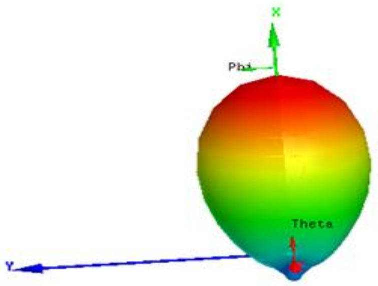
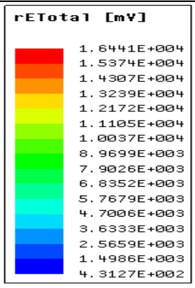
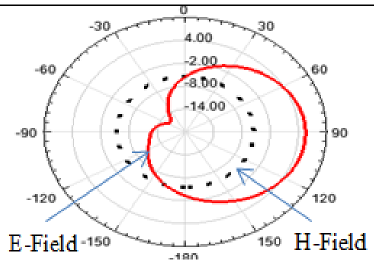
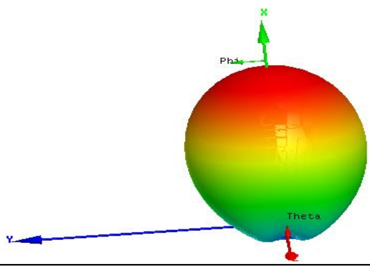
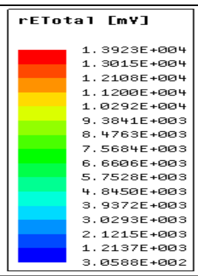
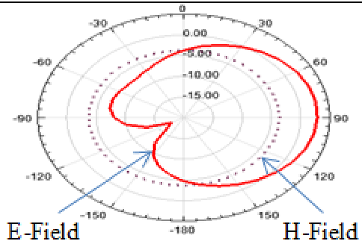
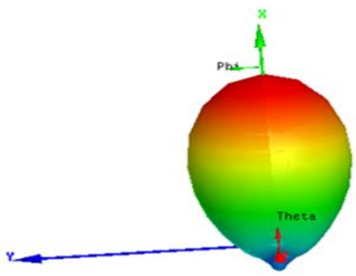
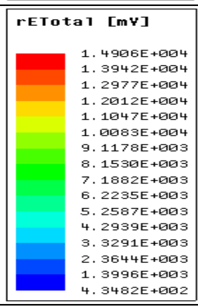
(b) VSWR graphs for various substrate materials Rogers 3003 (Red line), Polyimide (Blue line), RT duroid (Cyan), Silica (Magenta), Al_2O_3 (Black)



(c) Gain graphs for various substrate materials Rogers 3003 (Red line), Polyimide (Blue line), RT duroid (Cyan), Silica (Magenta), Al_2O_3 (Black).



(d) Absorption cross section (μm^2) of graphene tunable at resonant frequencies

Substrate material	2D Radiaton pattern	3D Radiation patterns	
Rogers 3003			
Polymide.			
Silica.			

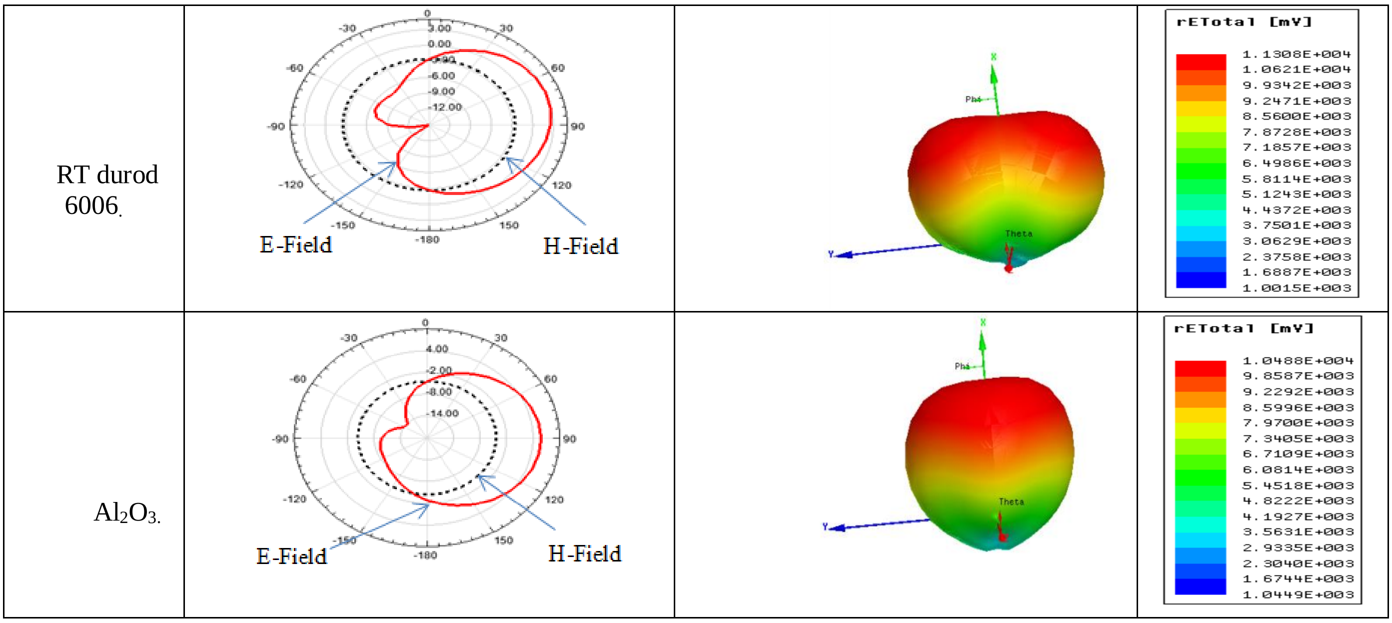


Fig4. 2D and 3D Radiation patterns for various substrate materials

TABLE III. PERFORMANCE PARAMETERS OF DIFFERENT SUBSTRATE MATERIALS

Dielectric substrate parameters		Resonant frequency (GHz)	Return loss (dB)	VSWR	Gain (dB)
Material	Dielectric constant				
Rogers 3003	$\varepsilon_r = 3$	750GHz	-49.70	1.00	6.54
Polyimide	$\varepsilon_r = 3.5$	750GHz	-39.82	1.02	5.09
Silica	$\varepsilon_r = 4$	750GHz	-15.97	1.38	5.50
Rogers RT/Duroid	$\varepsilon_r = 6.15$	750GHz	-17.70	1.30	3.21
Al_2O_3	$\varepsilon_r = 9.1$	750GHz	-11.94	1.67	2.63

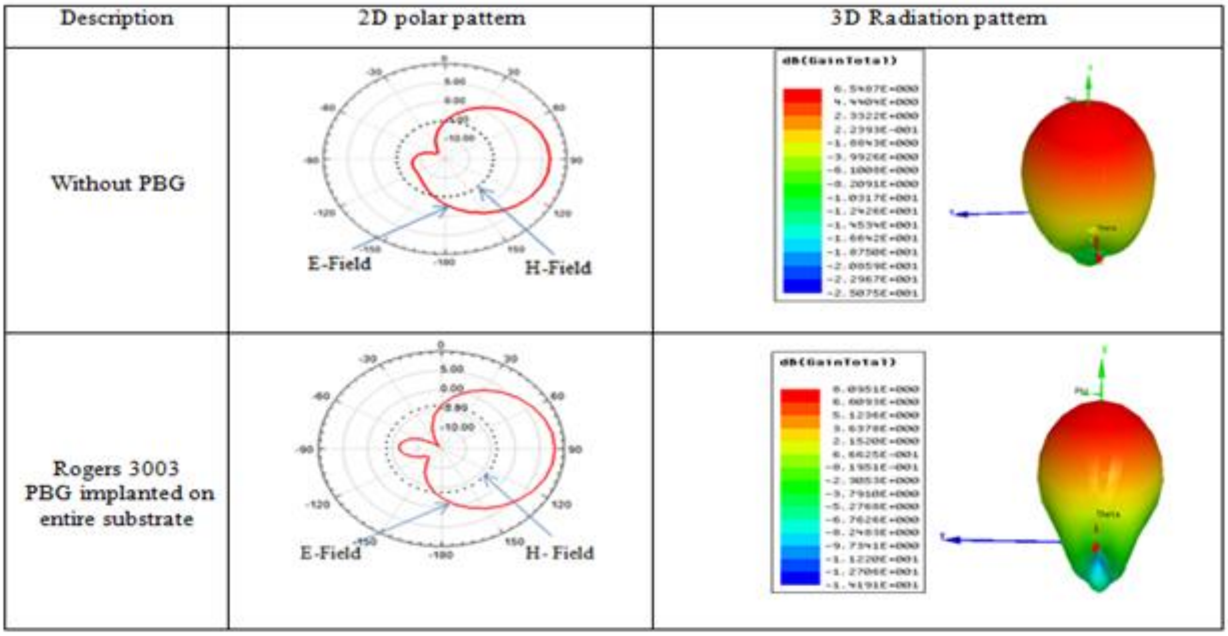


Fig.5: 2D and 3D radiation patterns for Rogers 3003 with PBG (at 10μm) and without PBG

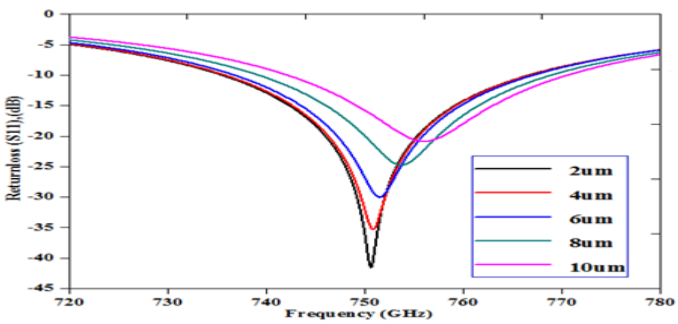
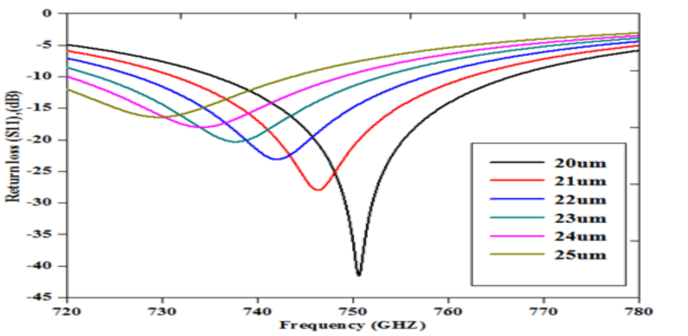


Fig.6: (a) Effect of hole radius on return loss



(b) Effect of substrate thickness on return loss

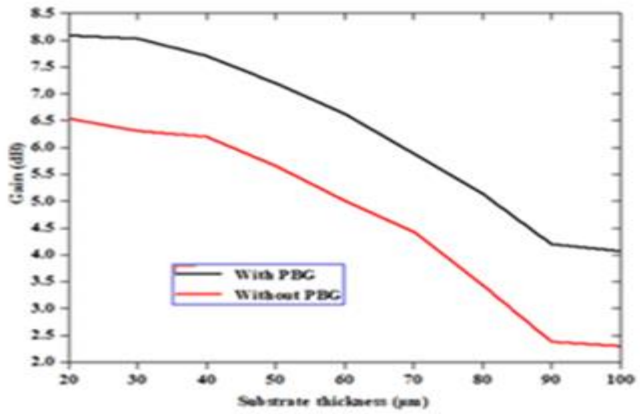
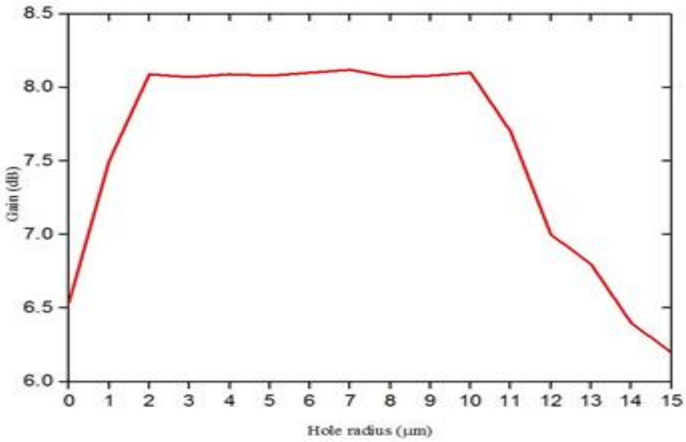


Fig.7: (a) Effect of substrate thickness on antenna gain



(b) Effect of hole radius on antenna gain

VI. CONCLUSION

In this paper, the performance of Graphene rectangular microstrip patch antenna in terahertz regime (operating band of 720 - 780GHz) is investigated with different substrate materials. The materials considered in this work are Rogers 3003, polyimide, silica, RT/ Duroid 6006 and aluminum oxide. The finite element method (FEM) based HFSS simulator used for graphene patch antenna analysis. Absorption cross-section at centre frequency is more than 80% is observed for all dielectric materials considered in this work. Graphene exhibits higher absorption cross section compare to other materials considered. Among all materials Rogers's 3003 material has better performance in terms of gain (6.54 dB), return loss (-49.70 dB) and VSWR. Using PBG structures additional gain of 1.55 dB is achieved in Rogers 3003.

The gain of the antenna is enhanced with hole radius from 0µm to 10 µm, further increase in the hole radius has opposite effect on gain. It observed from the results that increase in the substrate thickness reduces the gain. Therefore it can be concluded that Rogers 3003 is the appropriate dielectric substrate material for the graphene-based nano patch antenna to achieve higher gain in terahertz applications. Further the work can be extended for fabrication using nano lithography techniques and metamaterials can be used to enhance the antenna performance.

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