Investigations of Substrate and Patch Materials for Sub-Terahertz Wireless Applications Scenario

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Abstract

The appropriate choice of patch and substrate materials has great significance in the performance of the terahertz (THz) microstrip patch antenna. The resonant frequency is dependent on various factors such as dimensions of the patch, substrate thickness, and permittivity. In this work, initially, a microstrip antenna with a silicon substrate was analyzed for different patch materials such as copper, graphene, and gold with a central operating frequency of 300 GHz. The result reveals that the graphene patch has a maximum bandwidth of 1.49 GHz and ideal radiation efficiency. Then, adopting graphene as a patch material, the performance of the antenna is analyzed on the basis of return loss, voltage standing wave ratio (VSWR), radiation efficiency, bandwidth, and gain with different substrate materials such as quartz, silicon, silicon dioxide, and silicon nitrate. The results show that quartz has an optimal performance by generating higher bandwidth and radiation efficiency when compared to other chosen substrate materials.

Keywords Graphene · microstrip patch antenna · THz · quartz · silicon · silicon dioxide

Introduction

The sixth-generation (6G) communications systems demand higher speed, broader bandwidth, and lower latency than the fifth-generation (5G) networks. One of the 6G Internet targets is to enable communication with ultra-speed data transfer. To achieve this target, a wideband spectrum and efficient systems compatible with such a spectrum are required. Recent research proclaims that utilizing the terahertz (THz) band of the electromagnetic spectrum caters to a wide bandwidth in wireless systems.[1] To define the THz band, it is required to recall the structure of the electromagnetic spectrum, which is shown in Fig. 1.[3] The THz band has a frequency range between 0.1 THz and 10 THz. Tera is a scale of 10^{12} units. The characteristics of the THz band are listed in Table I.[2]

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Since the THz band lies between the microwave and infrared region, it inherits the advantage of electronics as well as photonics. Applications of the THz band include wireless cognition, imaging, sensing, and spectroscopy. To utilize such an efficient THz wave, challenges such as material selection, THz signal generation, transceiver design, and biological effects must be seriously considered. This paper mainly focuses on the analysis of different materials for microstrip patch antenna under the THz regime. Copper is an excellent material for low-frequency antenna fabrication. However, at high frequencies, skin depth and conductivity decrease, which makes for poor radiation efficiency. The disadvantages of using conventional copper antennas are their weight and losses.[4] Hence, material selection for antenna design in the THz range is the foremost task.[5] To conquer such constraints, this paper suggests different patch and substrate materials. The impact of material on antenna performance is also investigated. Graphene has recently stimulated the interest of many researchers for its unique characteristics. Graphene is a two-dimensional ductile material. The electrical and optical properties of graphene can be amended by deformation and strain.[6] For low noise and rapid communication, a graphene-based patch antenna with complementary metal-oxide semiconductor compatibility is a promising solution.[7] The chemical potential of graphene-based patch
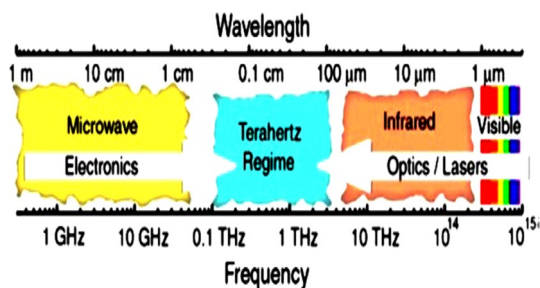
Fig. 1 Position of THz band in the electromagnetic spectrum.

Table I Characteristics of THz band

Characteristics	Range
Frequency	100 GHz–10 THz
Wavelength	3 mm–300 m
Duration	1 ps
Energy	4.1 meV
Temperature	48 °K
Ionization	Non-ionizing

antennas may be changed for electromagnetic applications to get desirable and controllable features.[8] Gomez-Diaz et al.[9] analyzed the properties of a graphene antenna at different frequencies with divergent chemical potentials and inferred that at terahertz frequency the behavior of graphene is not affected by losses and enhances radiation efficiency by 60% compared to graphene at microwave frequency. Azizi et al. used graphene as a patch material and obtained a return loss of − 29 dB and gain of 7.16 dB for a microstrip antenna. They also conclude that graphene is a reconfigurable material that permits change of the resonant frequency and radiation pattern of an antenna.[2]

To select suitable material for effective THz antennas with 1 THz resonant frequency, Dash et al.[5] designed a simple dipole antenna with different patch materials such as copper, graphene, and carbon nanotubes and realized that graphene has excellent electromagnetic performance. Hence, literature study shows that graphene is the most suitable patch material for a THz antenna for its great optical, mechanical, and electrical properties.[10] In this proposed work, gold and copper were also analyzed along with graphene, and their performance was compared.

Similar to patch material selection, choosing good dielectric substrate material is also vital for graphene patch antennas because the impedance, carrier mobility and resonant frequency of an antenna are strongly affected by the dielectric constant and thickness of substrate material. Hence, selection of good dielectric substrate material is vital for graphene patch antennas. Recent research is being carried out on various materials such as silicon, polyamide,[11,12] quartz, silicon
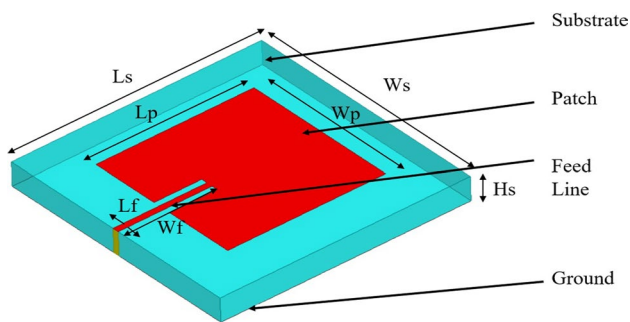
dioxide, and duroid,[13] which can be used as a substrate for a graphene-based antenna.[14,15] Graphene grown by chemical vapour deposition (CVD) on boron nitride shows improvement in breakdown power density, carrier mobility and resistivity when compared with CVD graphene on silicon dioxide.[16] Rajni et al.[17] analysed various substrate materials such as boron nitride, silica, silicon nitrate and aluminium oxide for a graphene patch antenna operating in the frequency range of 2.67–2.92 THz. The results reveal that silicon nitride has maximum bandwidth and better radiation efficiency. Tamagnone et al. used glass as the substrate material which has low permittivity and is electrically small in size. For glass substrate, due to intrinsic dissipation losses, the radiation efficiency is low even though the patch is perfectly matched to the photomixer.[18] Anand et al.[14] used polymide material as a substrate for a graphene nanoribbon (GNR) patch antenna at 0.75 THz. The performance results show a gain of 5.09 and directivity of 5.71 dB. Khan et al. investigated a graphene patch antenna with different substrate geometries. Among all the combinations, a circular patch with a triangular-shaped Roger 400C substrate gives better performance with a gain of 5.15 dB, return loss of -48.85 dB, voltage standing wave ratio (VSWR) of 1.007 and staggered bandwidth of 677 GHz.[19] Llatser et al.[20] used silicon and silicon dioxide as substrates for analyzing the scattering behavior of terahertz radiation on a graphene-based nano-patch antenna and inferred that modifying the substrate material or adding an external electrostatic bias can be used to tune the antenna resonant frequency. Kushwaha et al.[21] compared various photonic crystal materials such as polyamide, FR4, quartz, arlon, and air cavity. The simulation results found that the air cavity photonic band gap (PBG) structure is more efficient than other materials. Thus, several substrate materials for a graphene patch antenna were studied, and many were found to be well suited for the intended application and circumstances. In this proposed work, substrate materials such as quartz, silicon, silicon dioxide, and silicon nitride were analysed, and their performance was compared with conventional material.

The organization of the paper is structured as follows: 'Materials and Methods' describes the analysis different patch materials of the THz antenna. 'Patch Materials' compares different substrate materials for the graphene patch THz antenna. 'Simulation Results' illustrates the various testing methods for the proposed THz antenna, and 'Conclusion' concludes the article.

Materials and Methods

Patch Materials

The microstrip patch antenna is designed here as shown in Fig. 2. It consists of a $252.4 \times 252.4\ \mu m^2$ patch and a ground

Fig. 2 Top view of the microstrip patch antenna.

Table II Dimensions of the Antenna Parameters

Design parameters	Measurement (in mm)
Length of the patch (Lp)	0.25
Width of the patch (Wp)	0.25
Height of the patch (Hp)	0.001
Length of the substrate (Ls)	0.4
Width of the substrate (Ws)	0.4
Height of the substrate (Hs)	0.04
Length of the feed (Lf)	0.2
Width of the feed (Wf)	0.01
Height of the feed (Hf)	0.001

plane which is separated by a single layer of 400×400 μm^2 silicon substrate. The patch is usually made of a thin copper foil and a thickness of 0.001 mm is plated with corrosion-resistant metals. The proposed work compared three types of materials plated on the patch such as copper, gold, and graphene, as they exhibited high values of radiation efficiency. Numerous types of patches can be designed, but the proposed work implements the most commonly used microstrip patch antenna model. The substrate is generally used to provide mechanical support and proper spacing between the patch and the ground plane. The substrate utilized here is silicon. As silicon is a cost-efficient material and has a high dielectric constant (ε_r) of 11.9, the size of the antenna can be reduced to obtain an efficient antenna. The antenna is fed with a microstrip line for better impedance matching. The influence of thickness, dimensions, and patch material on the performance of the microstrip patch antenna has been examined numerous times and the results are attained. The patch antenna is designed and simulated using the Ansys High-Frequency Structure Simulator (HFSS) software tool for different patch materials. The dimensions of the microstrip patch antenna design are as shown in Table II.

Simulation Results

The antenna has been designed and simulated using Ansys HFSS for a central operating frequency of 300 GHz. On completion of the design of the proposed antenna, we acquired the simulation results including return loss (S_{1_1}), VSWR, two-dimensional (2D) radiation pattern and three-dimensional (3D) polar plot.

Return Loss

Return loss (in dB) is the difference between the power directed towards the antenna and the power reflected from the antenna. In Fig. 3, the return loss of the proposed microstrip patch antenna at 300 GHz frequency for different patch materials, copper (red line), graphene (green line), and gold (blue line) are plotted. Here, copper provides a return loss of − 26.22 dB at a resonant frequency of 300.34 GHz. Graphene provides a return loss of − 20.62 dB at a resonant frequency of 299.91 GHz and gold provides a return loss of − 20.03 dB at a resonant frequency of 300.58 GHz. In, Ref. 2 graphene and copper are used as a patch material and obtained a return loss of − 29 dB and − 15 dB, respectively. In proposed work, the return loss of copper is comparatively higher than the other two materials.
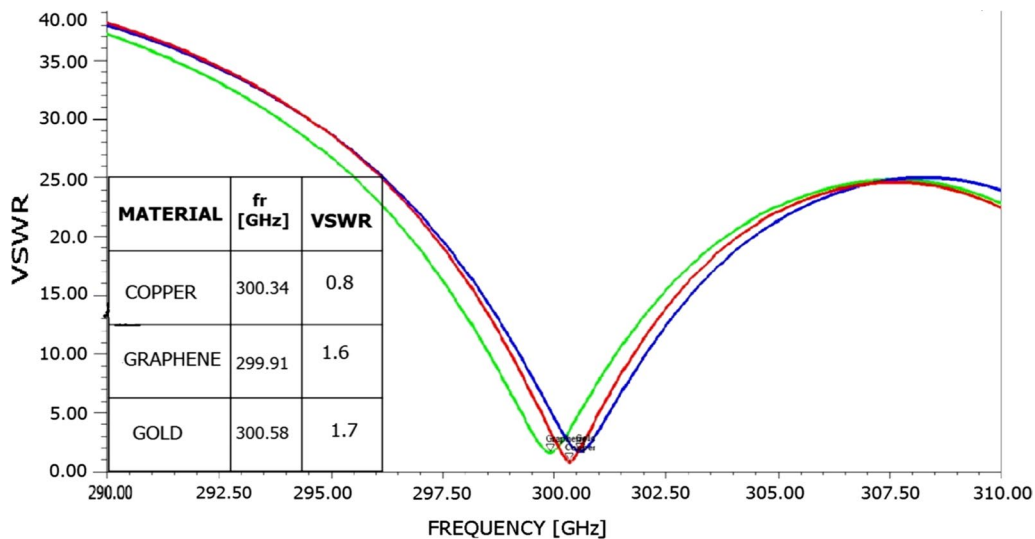
VSWR

The voltage standing wave ratio (VSWR) is a metric that describes how efficiently radio-frequency power is delivered from a power source to a load through a transmission line. A VSWR value under 2 is considered a suitable value for most antenna applications. In Fig. 4, the VSWR plot of the patch antenna at 300 GHz frequency for copper, graphene, and gold patch materials are plotted. The proposed design obtained a VSWR with a minimum value of copper providing 0.8 at a resonant frequency of 300.34 and a maximum value of gold providing 1.7 at a resonant frequency of 300.58 GHz.

Radiation Pattern

The direction of electromagnetic waves radiating out from the antenna is referred to as the radiation pattern. For the results, the proposed design has set the solution frequency to 300 GHz for the maximum number of 10 adaptive solutions with a maximum delta of 0.01. The phi = 0° and theta = 90° degree radiation patterns of the design are displayed as they represent the maximum number of electric fields and magnetic field of the antenna, respectively. In Figs. 5 and 6, the 2D radiation pattern of the E-plane and H-plane for three
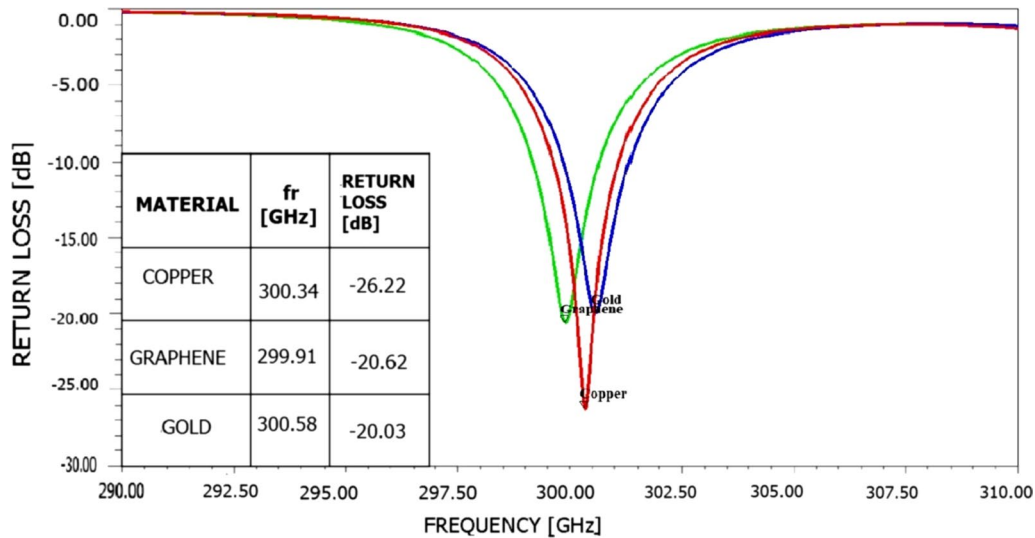
Fig. 3 Return loss (in dB) of different patch materials at 300 GHz (Color figure online).

Fig. 4 VSWR of the microstrip patch antenna for copper, graphene and gold patch materials.

different patch materials (i.e., copper, gold, and graphene) are shown, respectively.

Gain

In simple terms, the gain is the product of the antenna's directivity and electrical efficiency. It is a value that denotes the maximum efficient power radiated to the target by the transmitter, in a given direction. In Ref. 2, 7.16 dB and 5.7 dB of gain are obtained for graphene and copper patch material. The gain of an antenna can be calculated using Eq. 1.

$$G = \eta * D \qquad (1)$$

where η = the efficiency, D = the directivity. Figure 7 shows the gain of a designed microstrip patch antenna. In Ref. 2, 7.16 dB and 5.7 dB of gain are obtained for graphene and copper patch material.

In Table III, a few simulation parameters of the microstrip patch antenna with three different patch materials to trace more efficient patch materials are compared. For the proposed antenna design, the impedance bandwidth achieved is in the range of 1.47–1.49 GHz at different resonant frequencies. The patch antenna on the graphene substrate achieves the maximum bandwidth of 1.49 GHz.
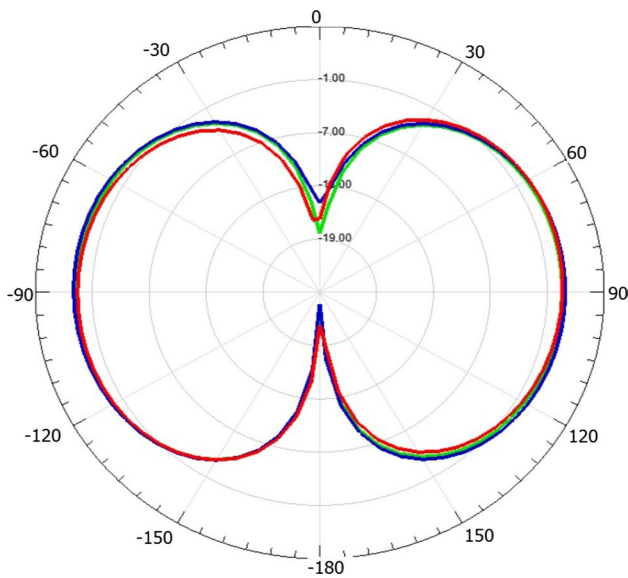
Fig. 5 Radiation pattern of E-Plane corresponding to the electric field (at 0°) of the microstrip patch antenna.
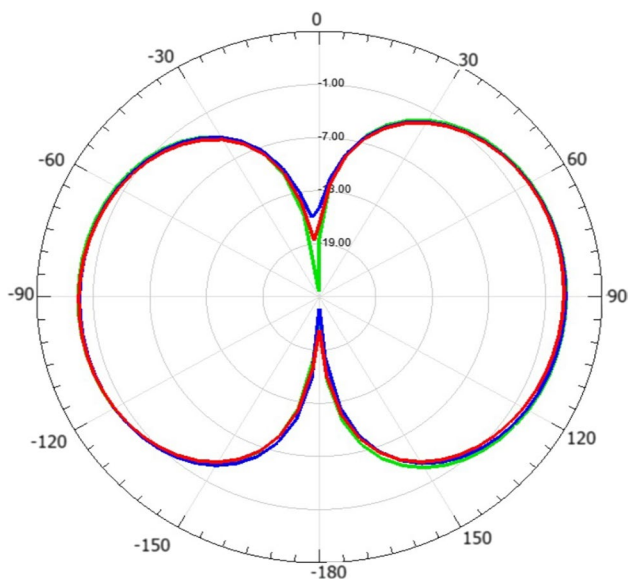
Fig. 6 Radiation pattern of H-Plane corresponding to the magnetic field (at 90°) of the microstrip patch antenna.

All the patch materials showcased good radiation efficiencies with none of them below 98.3% and exceptionally gold with 100%.

THz Antenna Design for Different Substrate Materials

Substrate Materials

The design specifications of an antenna are similar to the previous one (as in Fig.2), except for the material of the substrate and the dimensions of the patch. Since the length and width of the patch depend upon the dielectric constant (ε_r) of the substrate material, there is a slight modification in the dimensions of the patch, whereas the material of the patch remains to be the same for all variations of the substrate. Graphene is the most appropriate material as a patch in all aspects, as it shows comparatively improved radiation efficiency, bandwidth, and VSWR and is also cost-efficient (Refer to Table III). Because of its exceptional electromagnetic characteristics, the usage of graphene as a conducting material for the antenna is projected to have a high bandwidth and radiation efficiency.[7] With graphene as the patch material, a set of newly advanced substrate materials are implied: quartz, silicon (Si), silicon dioxide (SiO_2), and silicon nitrate (Si_3N_3).

Simulation Results

The designed antenna is simulated for an operating frequency of 300 GHz. The simulation results include different parameters such as gain, return loss (S_{11}), VSWR, and a 2D radiation pattern for the designed graphene patch antenna. The return loss is determined for the proposed design with various substrate materials, and it should be less than − 10 dB for proper impedance matching.

Return Loss

The simulated findings show the return loss values for the different substrate materials at respective resonant mode frequencies as shown in Fig. 8, i.e. − 15.18 dB for quartz at 301.00 GHz (green line), − 20.62 for silicon at 299.91 GHz (red line), − 12.26 dB for silicon dioxide at 299.20 GHz (orange line) and − 10.61 dB for silicon nitrate at 300.64 GHz (blue Line). In Ref. 17, silicon nitride, aluminum oxide and boron nitride substrate materials have return losses of − 26.71 dB , − 20.7 dB and − 12.19 dB, respectively. Comparatively, in the proposed design, silicon has a better return loss value of − 20.62 dB. As mentioned above, the return loss must be below − 10 dB to obtain the desired impedance matching, which is achieved in all the employed substrate materials.
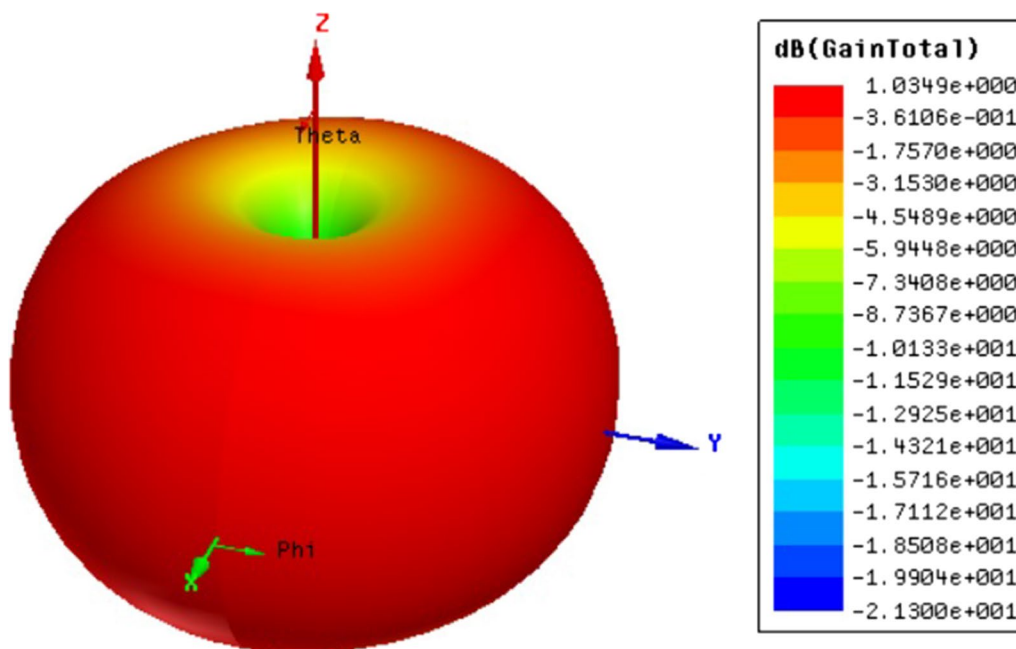
Fig. 7 3D polar plot displaying the gain (in dB) of the microstrip patch antenna.

Table III Performance comparison of micro-strip patch antenna with various patch materials

Simulation parameters	Copper	Graphene	Gold
Dielectric constant (ε_r)	6	6.9	6.9
Resonating frequency (GHz)	300.34	299.91	300.58
Return loss (dB)	− 26.22	− 20.62	− 20.03
VSWR	0.8	1.6	1.7
Radiation efficiency	98.3%	99.4%	100%
− 10 dB bandwidth (GHz)	1.47	1.49	1.48

VSWR

The voltage standing wave ratio measures the amount of mismatch between an antenna and the feed line that connects to it. In Ref. 17, silicon nitride, aluminum oxide, and boron nitride substrate materials have VSWR of 1.1, 1.2, and 1.7, respectively. The VSWR values for the proposed substrate materials are plotted in Fig. 9. Quartz substrate has a VSWR value of 3.0. Silicon substrate has a value of
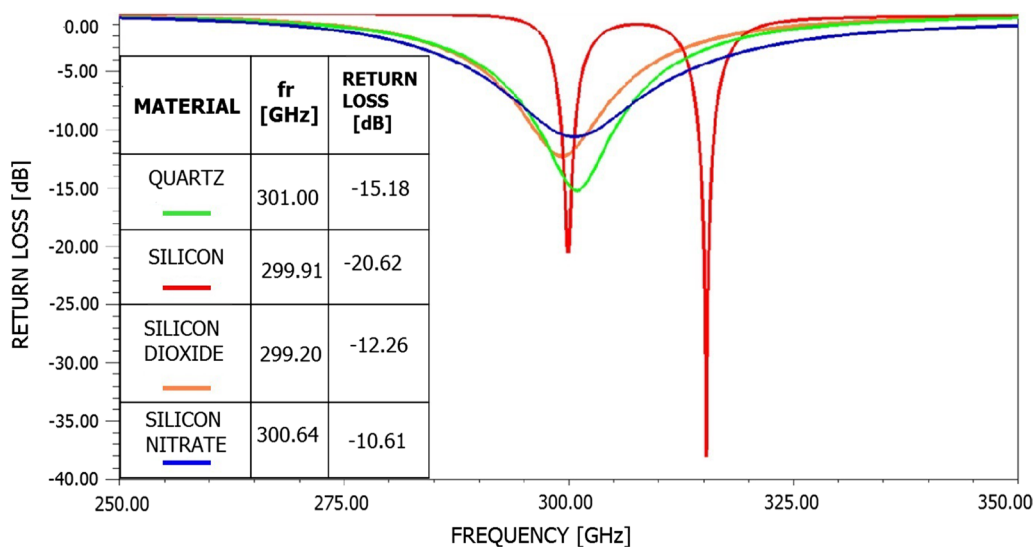

MATERIAL	fr [GHz]	RETURN LOSS [dB]
QUARTZ	301.00	-15.18
SILICON	299.91	-20.62
SILICON DIOXIDE	299.20	-12.26
SILICON NITRATE	300.64	-10.61

Fig. 8 Return loss (in dB) of different substrate materials at 300 GHz.

1.6. Silicon dioxide substrate has a value of 4.3, and silicon nitrate substrate has a value of 5.2.

Directivity

Directivity is another important antenna parameter which measures the power density of the antenna in its direction of maximum radiation. The substrate materials of the proposed antenna pose high directivity values, with silicon dioxide having the highest gain of 4.13, quartz with 4.09, followed by silicon nitrate with 3.73, and the smallest value is for silicon with 1.32 as directivity.

Radiation Pattern

The radiation pattern of an antenna gives an image of the value and direction of its radiation. It has a standard radiation distribution on its surface by which the antenna emits and receives the electromagnetic waves. The radiation pattern is plotted to provide a view of the radiation from the antenna. The radiation pattern of the graphene patch antenna at phi = 0° (E-plane) and theta = 90° (H-plane) is plotted in Figs. 10 and 11, respectively. It shows the distribution of power radiation around the antenna in a direction represented by the phi and theta angles at 300 GHz (Table IV).
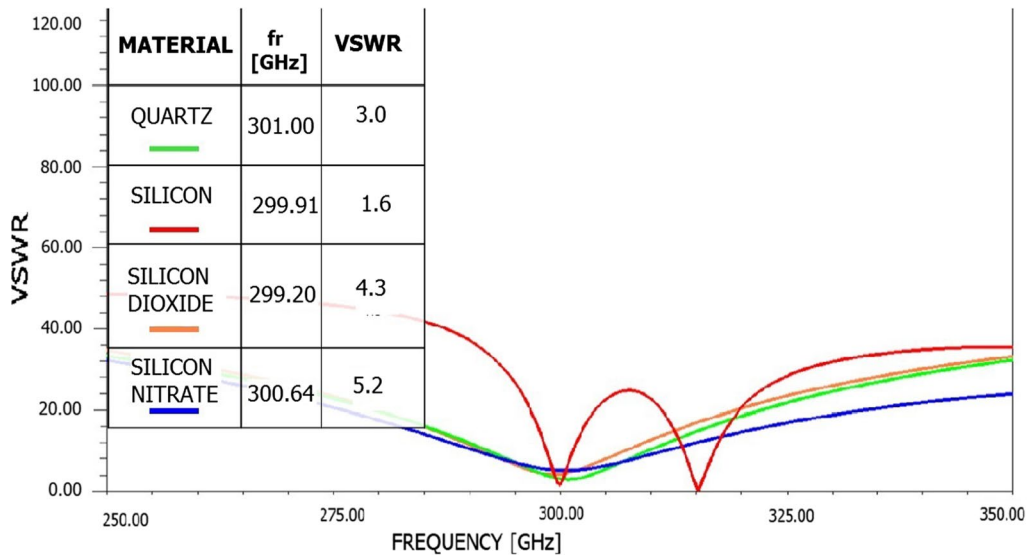

MATERIAL	fr [GHz]	VSWR
QUARTZ	301.00	3.0
SILICON	299.91	1.6
SILICON DIOXIDE	299.20	4.3
SILICON NITRATE	300.64	5.2

Fig. 9 VSWR of the microstrip patch antenna for quartz, silicon, silicon dioxide and silicon nitrate substrate materials.
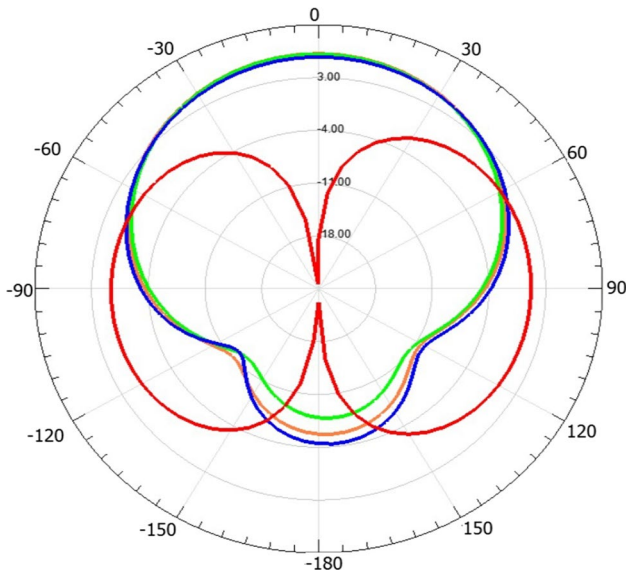

Fig. 10 Radiation pattern of E-Plane corresponding to the electric field (at 0°) of the microstrip patch antenna.
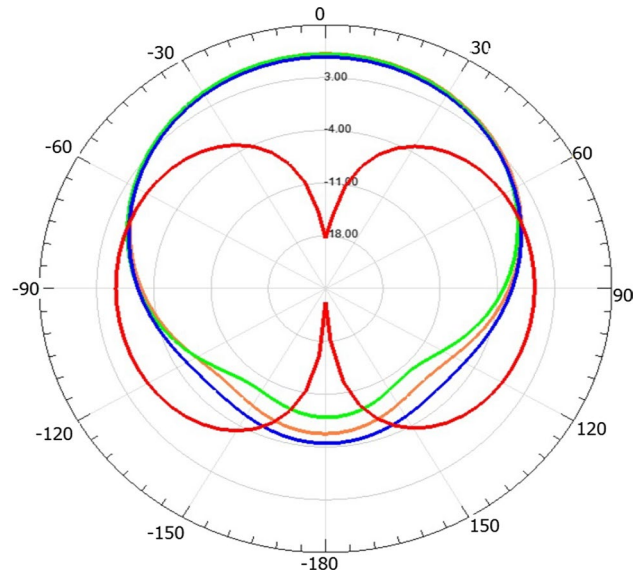

Fig. 11 Radiation pattern of H-Plane corresponding to the magnetic field (at 90°) of the microstrip patch antenna.

Table IV Performance comparison of the microstrip patch antenna with various substrate materials

Simulation parameters	Quartz	Silicon	SiO_2	Si_3N_3
Dielectric constant (ε_r)	3.78	11.9	4	7
Resonating frequency (GHz)	301.00	299.91	299.20	300.64
Return loss (dB)	-15.18	-20.62	-12.26	-10.61
VSWR	3.0	1.6	4.3	5.2
Radiation efficiency	100%	99.4%	100%	100%
-10 dB bandwidth (GHz)	8.4	1.49	5.77	4.92
Peak gain	4.10	1.32	4.14	3.76
Peak directivity (dB)	4.09	1.32	4.13	3.73

Table IV exhibits the performance of the antenna provided with all the simulation parameters. In Ref. 17, Rajni et al. obtained radiation efficiency of 100%, 98.4% and 87.9% for silicon nitride, aluminum oxide and boron nitride substrate materials, respectively. The proposed substrate materials showed radiation efficiencies of 100% for quartz, silicon dioxide, and silicon ditrate, whereas silicon showed 99.4% efficiency. Starting from quartz with a bandwidth of 8.4 GHz, all the other materials also exhibit a wide range of bandwidths, with silicon having the smallest bandwidth of 1.49 GHz. In Ref. 21, Kushwaha et al. reveals that two-dimensional photonic crystal-based antennas have a minimum reflection coefficient of -63.22 dB, maximum directivity of 6.81dBi, and radiation efficiency of 88.17% at 0.741 THz frequency. In Ref. 17, Bala et al. found that silicon nitride, aluminum oxide and boron nitride substrate materials have -10 dB bandwidth of 270 GHz, 240 GHz and 80 GHz, respectively. The substrate material of the proposed antenna has high gain values with silicon dioxide having the highest gain of 4.14, quartz with 4.10, followed by silicon nitrate with 3.76, and the smallest for silicon with 1.32 as a peak gain.

Testing Methods

It is an arduous task to examine the performance of an antenna in the THz regime. However, with the development of technology, adequate testing methods have been proposed. An efficient antenna measurement setup has been explained in Ref. 22 which is shown in Fig. 12. Micromachined circuits operated at 500–750 GHz have been tested, and performance was evaluated in Ref. 23 In Ref. 24, a THz antenna is tested using two hologram-based antenna test ranges centered at 322 GHz and 650 GHz. Since the proposed antenna is designed with a central operation frequency of 300 GHz, the testing can be performed as discussed in Ref. 24.

Conclusion

In this research, three distinct patch materials and four different substrate materials were examined on the performance of a microstrip patch antenna for the terahertz regime. The Ansys HFSS simulation software is utilized for numerical modeling of the designed antenna for working at 300 GHz frequency ranges. In addition to the regular patch and substrate materials, certain additional materials have been explored for enhanced performance. For the patch material
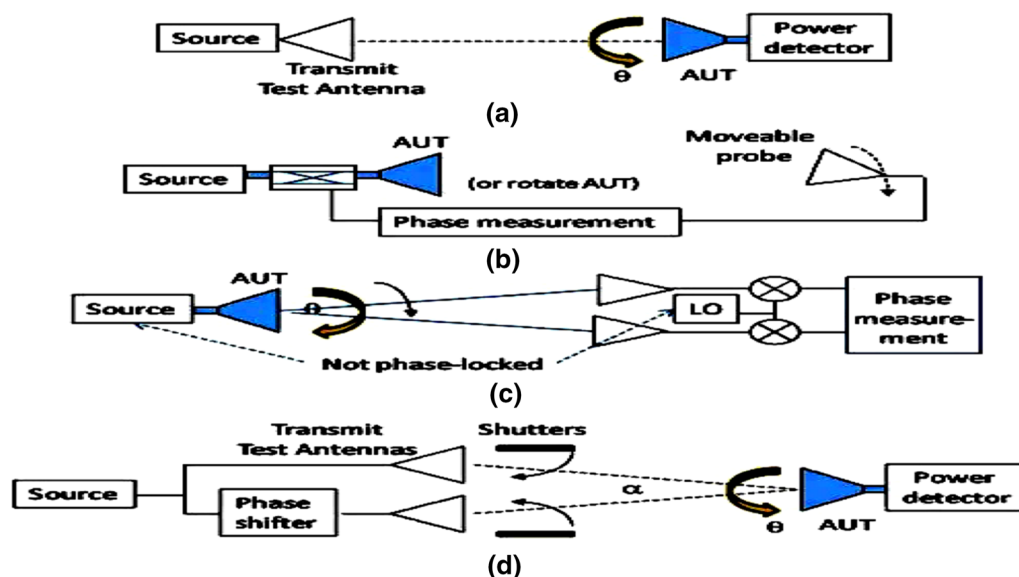
Fig. 12 An experimental setup for THz antenna measurement.

comparison, copper exhibits a maximum return loss value of -26.22 dB and a VSWR value of 0.8. Gold has an almost ideal radiation efficiency of 100%, and graphene shows a maximum bandwidth of 1.49 GHz. As for substrate material comparison, silicon attains a maximum return loss value of -20.62 dB and a VSWR value of 1.6. For all substrate materials, it is reported that an acceptable dB gain is obtained. As a result, it can be deduced that mostly all the substrate materials have achieved 100% radiation efficiency and have a high bandwidth up to 8.4 GHz.

Conflict of interest The authors declare that they have no conflict of interest.

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