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ANALYSIS OF GRAPHENE PYTHAGORAS TREE FRACTAL ANTENNA WITH THIN SIO_2 SUBSTRATE IN TERAHERTZ REGIME

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Abstract

The Pythagoras Tree Fractal patch is considered on a SiO_2 substrate thickness of 1.5 µm to radiate at four frequencies of 4.975THz, 5.38THz, 6.73THz, and 7.61THz with Voltage Standing Wave Ratio (VSWR) ≤ 2. This is a very creative fractal design of a multiband THz antenna, based on a very thin graphene layer, the study proved a value in terms of high radiation efficiency and high gain, at the level of current research we made a comparison study where the design has evidently huge potential regarding applicability for telecommunication technology in the terahertz regime. The demand for high-performance terahertz (THz) antennas has increased significantly in recent years due to their potential applications in various fields such as medical imaging, security screening, and wireless communications. In this paper, the authors present an analysis of a graphene Pythagoras Tree Fractal (GPTF) antenna with a thin SiO2 substrate for THz regime. The GPTF antenna is designed using a fractal geometry approach, which provides multiple resonant frequencies and enhances the overall radiation efficiency. The thin SiO2 substrate is used to reduce the substrate losses and improve the radiation performance of the antenna. The authors use the Finite-Difference Time-Domain (FDTD) software to simulate the performance of the proposed antenna. The results show that the proposed antenna exhibits high gain, low return loss, and wide bandwidth, making it a promising candidate for THz applications.

1. Introduction

In To meet the growing needs in terms of data transmission, 4th and 5th generation telecommunications systems (4G and 5G) have been developed in which smart and multi-band

antennas play a very important role. But the successes of 4G and especially 5G telephony have boosted the use of data in new areas such as Big Data and artificial intelligence (AI) that the extension to ever higher frequency bands is becoming necessary. This is the case of communication in the terahertz band which will undoubtedly pose challenges in terms of antenna design. Indeed, much lower wavelengths will impose smaller antenna dimensions; therefore, intrinsic losses will increase leading to lower efficiency. The replacement of metal radiating elements by graphene in THz frequencies is a solution proposed by several research teams. Indeed, the very high mobility allows graphene to support the propagation of the Surface Plasmon Polaritons (SPPs) waves and the resulting lower plasma frequency allows the graphene of a few micrometers to resonate in the terahertz band [1-10]. The developments of dual bands graphene-based THz antennas are considered [2-5].

The manuscript designed a Pythagoras tree fractal (4^{th} order) antenna using micrometer-scale graphene. The technique uses a graphene for Terahertz application and uses Pythagoras tree fractal (4^{th} order) geometry for antenna to support multiband. The Pythagoras Tree Fractal patch is considered on a SiO_2 substrate (dielectric permittivity $\varepsilon_r = 3.9$) thickness of 1.5 µm. We illustrate the various parameters as return loss, VSWR≤ 2, high gain, high radiation efficiency for multi-band by using a very thin layer of graphene as the radiating patch and a thin SiO2 substrate. The Numerical results are given by using a full wave electromagnetic simulator based on FDTD method.

In the field of electromagnetics, numerical simulations play a crucial role in designing and optimizing various electromagnetic devices and systems. The FDTD method is one of the most widely used numerical techniques to solve electromagnetic problems. The FDTD method discretizes both time and space domains and solves Maxwell's equations numerically.

The CST Studio Suite is a widely used electromagnetic simulation software that utilizes the FDTD method to solve complex electromagnetic problems. It is a full-wave simulation software that provides accurate and efficient solutions for various electromagnetic applications. CST offers a user-friendly interface and powerful visualization tools that enable engineers and researchers to design, optimize and analyze a wide range of electromagnetic systems, such as antennas, microwave circuits, and electromagnetic compatibility.

The numerical results obtained by using a full wave electromagnetic simulator based on the FDTD method provide valuable insights into the behavior of electromagnetic systems. These results help in understanding the complex interactions between electromagnetic fields and materials and aid in the design and optimization of electromagnetic systems.

2. The theory and antenna designs

The original theory regarding conductivity properties of graphene is described. Where the conductivity of graphene consists of two parts: the intraband transition $\sigma_{\text{int } ra}$ and interband transition $\sigma_{\text{int } er}$ [1-4]. The graphene can be modeled similar an infinitesimally thin metal with a 2D tensor surface conductivity of $\sigma_{total} = \sigma_{\text{int } ra} + \sigma_{\text{int } er}$. At the lower THz frequencies, we can ignore the interband conductivity due to the Pauli's blocking effect, and the total conductivity of graphene is influenced by the intraband contribution [1-4]. We can estimate the surface conductivity of graphene by using Kubo's formula [1-4]. The modeling of graphene is represented as a layer of material with the Drude like intraband support by [1-4],

$$\sigma_{intra}(\omega) = \frac{2e^2 k_B T\, i}{\pi\hbar^2\left(\omega + i\tau^{-1}\right)} \ln\left[2\cosh\left[\frac{\mu_c}{2k_B T}\right]\right] \tag{1}$$

We present the interband contribution by [1-4],

$$\sigma_{\text{int } er}(\omega) = \frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right) + i\frac{4\omega}{\pi}\int_0^{\infty}\frac{H(\varepsilon) - H\left(\frac{\omega}{2}\right)}{\omega^2 - 4\varepsilon^2}d\varepsilon\right] \tag{2}$$

H is the Heaviside step function by [1-4],

$$H(\varepsilon) = \frac{\sinh\left[\frac{\hbar\varepsilon}{k_B T}\right]}{\cosh\left[\frac{\mu_c}{k_B T}\right] + \cosh\left[\frac{\hbar\varepsilon}{k_B T}\right]} \tag{3}$$

Where, e is the electronic charge, k_B is the Boltzmann constant, T is the temperature, $\hbar$ is the reduced Plank's constant, μ_c is the chemical potential, τ is the relaxation time, ω is the frequency and ε is energy bands.

The table 1 provides the parameters of graphene. We use the Algorithm given by [11-15] to describe in detail how an arbitrary binary hierarchy can be recursively transformed into a Pythagoras Tree visualization (see fig.1). Pythagoras Tree Fractal (4^{th} order) patch is made of a very thin layer of graphene deposit on a SiO_2 substrate layer, which deposited on a layer of graphene ground plan (see fig.2). The table 2 provides the dimensions.

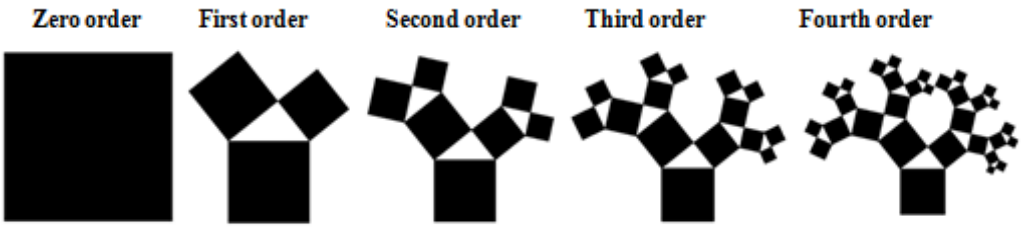


Figure 1. the fourth iterations of Pythagoras Tree Fractal

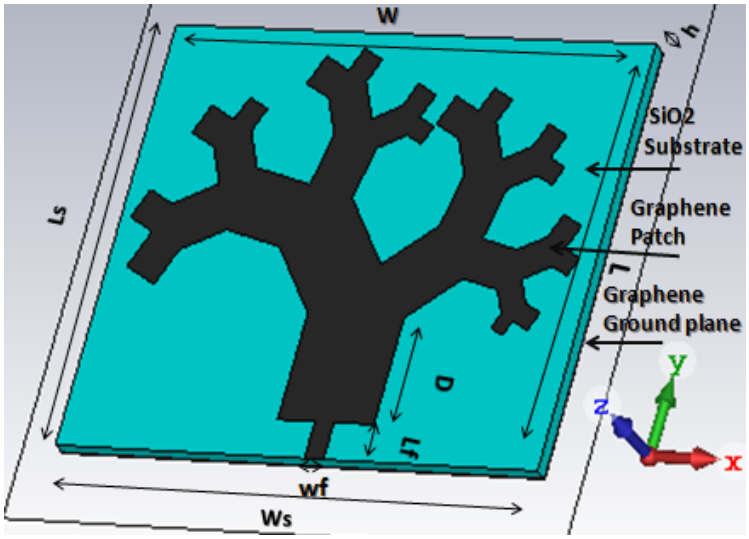


Figure 2. Graphene based Pythagoras Tree Fractal (4th order) patch antenna

Table 1. The key parameters for graphene

Parameter	*Values*
Thickness	50 nm
Relaxation Time (τ)	1 ps
Temperature (T)	300 K
Chemical Potential (μ_c)	2 eV

Table 2. The Geometric parameters of this graphene Pythagoras Tree Fractal patch antenna.

Parameter	*Dimensions (μm)*
Patch length (L)	38.5272
Patch width (W)	47.3070
Substrate length (Ls)	50
Substrate width (Ws)	40
Substrate height (h)	1.5
Patch length Zero order (D)	10
Microstrip feed length (Lf)	3
Microstrip feed width (Wf)	2

3. Results and discussion

The result of simulation obtained for module of coefficient of reflexion is represented in the Fig.3 for fractal graphene patch vs. fractal copper patch. We observe the scaling down copper patch to a micrometer scale leads to severe attenuation. On the other hand, the graphene based antenna manifests significantly lower losses, resulting in more sharp resonances compared to the copper version.

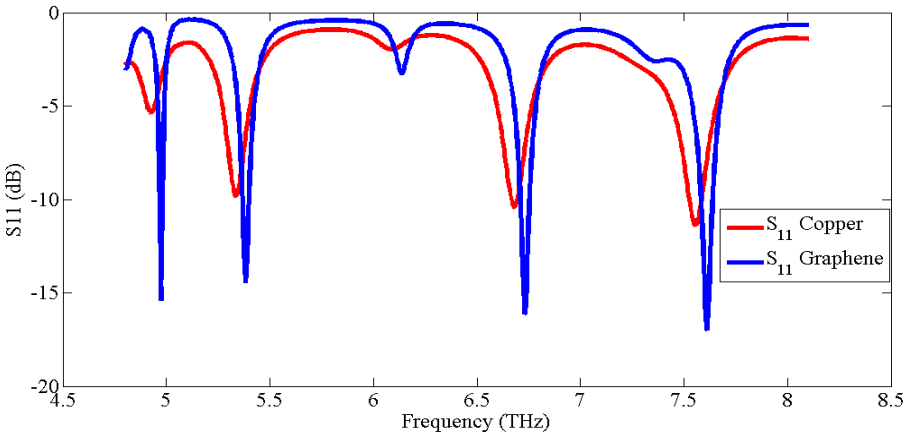
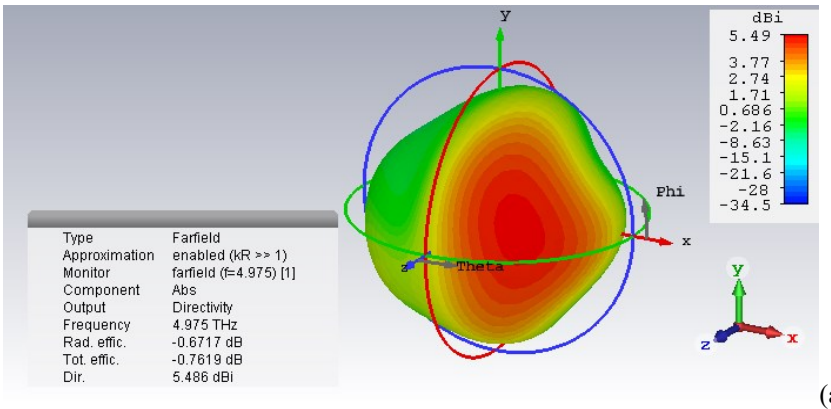
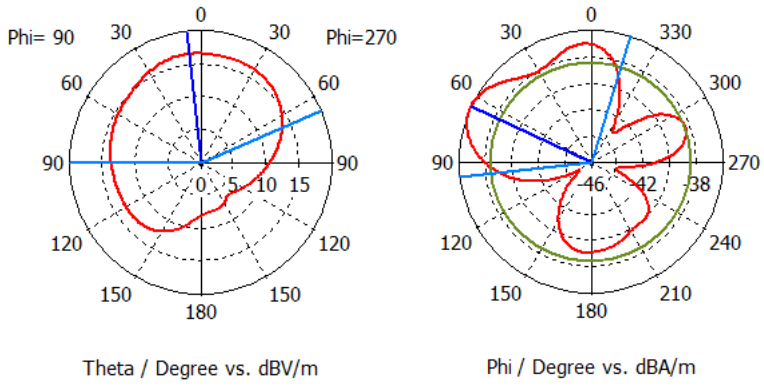


Figure 3. Frequency dependences of S_{11} parameter for fractal graphene patch vs. fractal copper patch

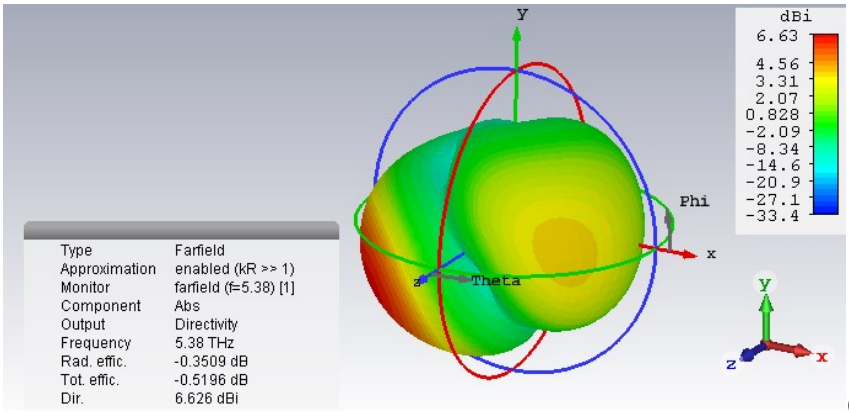


(a)

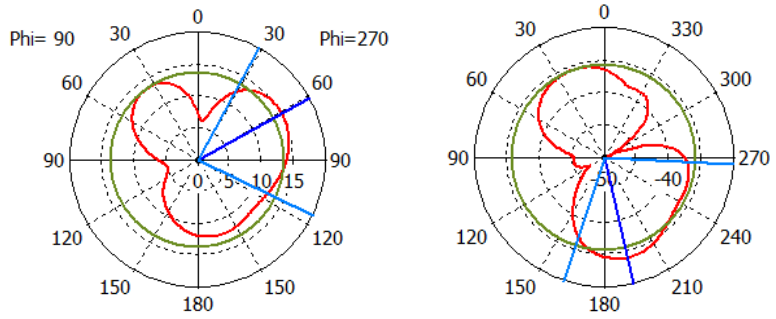


(b)

Figure 4. (a) 3D Radiation Pattern observed at 4.975 THz (b) its cross sections by E Plane (Φ= 90°) and H Plane (θ= 90°) pattern at 4.975 THz

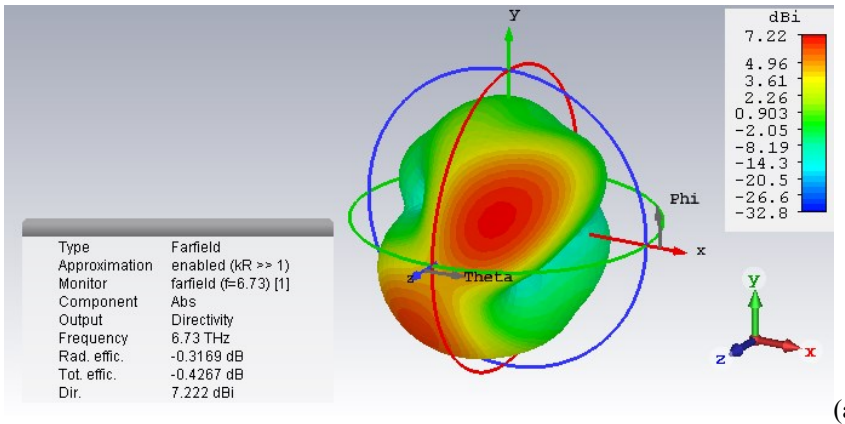


(a)

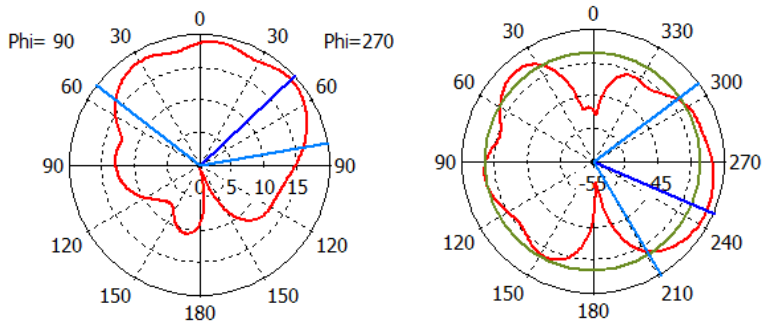


(b)

Figure 5. (a) 3D Radiation Pattern observed at 5.38 THz (b) its cross sections by E Plane (Φ= 90°) and H Plane (θ= 90°) pattern at 5.38 THz

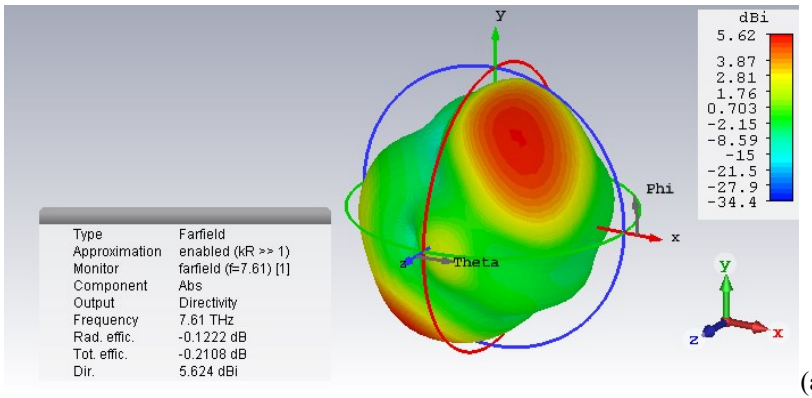


(a)

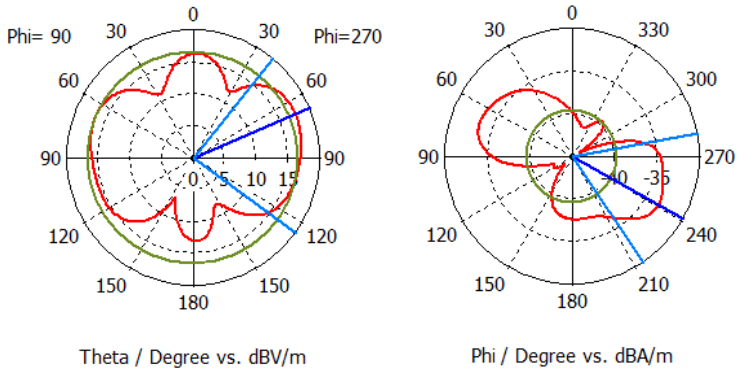


(b)

Figure 6. (a) 3D Radiation Pattern observed at 6.73 THz (b) its cross sections by E Plane (Φ= 90°) and H Plane (θ= 90°) pattern at 6.73 THz.



(a)



(b)

Figure 7. (a) 3D Radiation Pattern observed at 7.61 THz (b) its cross sections by E Plane (Φ= 90°) and H Plane (θ= 90°) pattern at 7.61 THz.

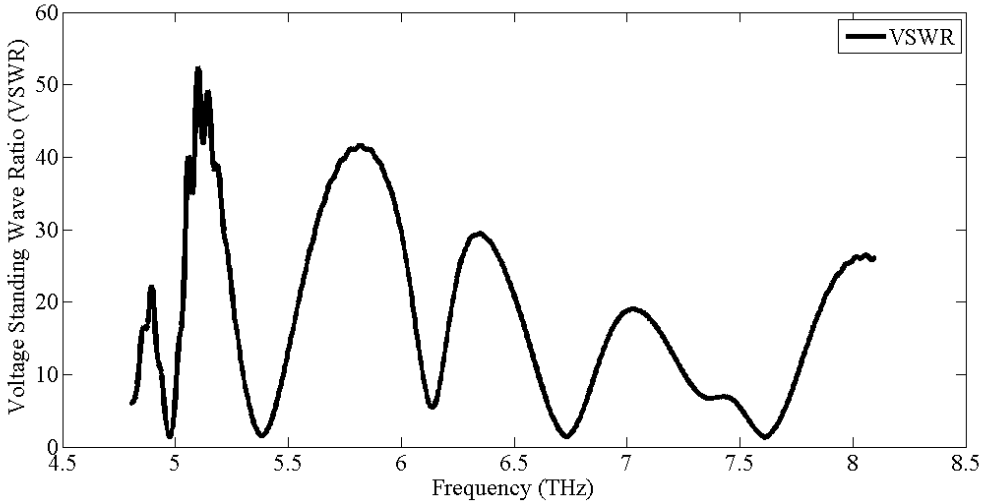


Figure 8. Voltage Standing Wave Ratio (VSWR) for substrate thickness of 1.5 µm

The radiation pattern is the representation of radiation properties of the antenna as a function of space coordinates (Φ, θ). It is determined in the far field region where the spatial distribution of the radiated power does not depend on the distance.

For the Pythagoras Tree Fractal fourth order, the corresponding 3D radiation patterns with E & H plane patterns are given in Figs. 4, 5, 6, and 7, where the antennas radiate mainly in the Z direction with excellent radiation patterns. From the E-plane (Y-Z plane) with Φ= 90° , we find that the antenna is radiating exactly in the Z direction with a very small back lobe of –1.4 dB at 5.38 THz, and –0.9dB at 7.61THz. The main lobe is in the Z direction with angular width of 156.3°, 87.1°, 132.1°, and 86.4° at 4.975 THz, 5.38 THz, 6.73 THz, and 7.61 THz respectively. At 7,61THz the radiation is mainly in the Y direction. For ϕ=90°, radiation represent two deformed main lobes, the main lobe is in the direction θ≈65°. For Φ =0°, radiation is symmetric and bidirectional in the direction of θ≈240° with good radiation in the front. In the operating frequency bands, the antenna radiates very efficiently at the resonant frequencies, with a high radiation efficiency over 80%. The augmentation of the resonant frequency is followed by increasing the efficiency. We need to mention that side lobes are negligible which conclude that our antenna matches with the feed line especially with the high efficiency values.

From Fig. 8, we can see that the corresponding (VSWR) ≤ 2, we find values are: 1.33, 1.46, 1.37, and 1.328 for 4.975 THz and 5.38 THz and 6.73 THz, and 7.61 THz respectively.

According to the Pythagoras Tree Fractal antenna performance analysis (see Table 3), four bands were obtained at 4.975THz, 5.38THz, 6.73THz and 7.61THz. The performance of this antenna at each band, return loss, efficiency, bandwidth is given in Table 3, and compared to results already published [2], [10].

Our fractal antenna shows a very high gain between 4.8 to 6.9dBi. Comparing our results with the references in table 3, we can see that our antenna represents the best directivity and highest gain (7.2dBi, 6.9dB) at 6,73 THz and the highest efficiency with 95.2% at 7.61THz.

For example (see Table 3), a silicon (the dielectric permittivity 11.9) substrate with the thickness 45 μm produces the antenna resonate at two bands [2]. In the literature [10], the fractal square-ring geometry and a thin (3.25 μm) silicon substrate are used to provide the antenna resonances at two or three frequency bands. In this research the Pythagoras Tree Fractal (4^{th} order) patch is considered on a SiO_2 substrate (dielectric permittivity $\varepsilon_r = 3.9$) small thickness of 1.5 μm are used to offer the antenna resonances at four frequency bands with good enough performance characteristics.

The study provides insights into the design and performance of fractal antennas with graphene and thin substrates for THz applications. This work can be used as a basis for future research in the development of THz antennas and their applications. Overall, the proposed

antenna has the potential to contribute to the development of high-performance THz systems for various applications in medicine, [16] security, satellite, and wireless communications such as 5G network, imaging and nano-sensors, modern communication devices, etc.

Table 3. Comparison of different performance characteristics for our antenna and its analogues

Antenna	Directivity (dBi)	VSWR	S_{11} (dB)	Bands (THz)	Gain (dB)	Bandwidth BW (GHz)	Efficiency (%)	Substrate Height (µm)
Ref. [2]	2.72/6.23	≤ 2	-17/-22	2.48/ 2.48 Dual Band	2.7/6.03	115.1/140.5	87.3/53.47	Silicon 45
Ref. [10]	3.12/3.85/ 4.62	1.044/1.30 /1.267	–33.7/–17.72 /–18.59	1.91/3.167/ 4.26 (tri-band)	-	186.29/ 438.75/264	-	Silicon 3.25
Pythagoras Tree	5.486/6.626/ 7.222/5.624	1.33/1.46/ 1.37/1.328	-16.98/-14.46 -16.11/-17.02	4.975/5.38/ 6.73/7.61 (Four-bands)	4.814/6.27/ 6.905/5.5	16.5/32.7/ 46.5/58.2	83.91/88.72 /90.7/95.26	SiO_2 1.5

4. Conclusion

In conclusion, this paper, we have proposed a new approach to support multiband resonances using graphene-based Pythagoras Tree Fractal (4^{th} order) patch antenna. We have built a prototype and performed simulations, regarding impedance, gain, return loss, the far-field radiation pattern and polarization characteristics. Through the results, the proposed antennas have great advantages to add new solutions in telecommunication at four frequency bands in terahertz regime.

This article presents an analysis of a novel graphene Pythagoras Tree Fractal antenna with a thin SiO2 substrate for THz regime. The fractal geometry approach is used to design the antenna, which provides multiple resonant frequencies and improves the overall radiation efficiency. The use of a thin SiO2 substrate helps to reduce substrate losses and improve the radiation performance of the antenna. The results obtained through simulations using a finite element method-based software show that the proposed antenna has high gain, low return loss, and wide bandwidth, making it a promising candidate for THz applications.

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