Performance Study of a Graphene Circular Patch Antenna for 6G Applications in the Terahertz Ultra-Wideband Spectrum

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Abstract. Graphene plays a big role in the proposed antennas for 6G applications due to its several characteristics, which help to overcome the different challenges, such as antenna miniaturization, high spectral efficiency, wide frequency range, and high data rate. Therefore, this paper presents a 6G circular patch antenna. It exploits graphene's ability to operate as a radiating element in the desired frequency range of 7.2–9.2 THz. The antenna is designed on a silicon substrate with a relative permittivity of 11, dimensions of 24 μm × 24 μm, and is simulated using CST Studio Suite. In addition, the design transforms the antenna from a narrowband configuration with a bandwidth of 0.33 THz into an ultra-wideband configuration with a bandwidth of 1.39 THz by employing a patch-cutting technique. The simulation results and equivalent circuit analysis demonstrate that the designed antenna satisfies the main requirements of 6G applications, including wideband performance, a gain of 7.44 dBi, a directivity of 7.59 dBi, a Voltage Standing Wave Ratio (VSWR) close to 1, and a high ra-diation efficiency reaching 95%.

1 Introduction

The demand for higher data rates exceeding those offered by 5G has spurred the development of next-generation technologies like 6G, targeting data throughputs in the vicinity of 1 Tbps. Consequently, researchers worldwide have initiated studies on 6G technology, with the University of Oulu in Finland launching its 6G Flagship in 2018 [1]. Similarly, Samsung Research initiated its 6G research efforts in 2020 [2]. Achieving this data rate target is expected to revolutionize the telecommunications field mainly by exploiting artificial intelligence (AI) technologies, thereby empowering 6G to deliver a diverse range of novel services, including holography, enhance the ultra-reliable and low latency communications more than 5G, develop the massive machine-type communications, improved the enhanced mobile broadband (eMBB), extended reality, sensing and three-dimensional mapping positioning [3-4].

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However, realizing these services and supporting the substantial data demands of 6G present several challenges, including the utilization of higher frequency bands, limitations of current materials, device capabilities, increased atmospheric attenuation and path loss.

To face the frequency challenges the THz range was proposed [6]. Graphene was among the good suggested materials based on its characteristics, first, high electrical conductivity and electron mobility allow electrons to move through the graphene with minimal scattering, so reducing the ohmic losses, improving the efficiency, enhance the energy transmission of the hardware like the antennas. Second, Surface Plasmon Polaritons (SPPs) supports operating efficiently at THz frequencies and miniaturizing the device's size. Third, Chemical Potential gives an efficient operation of THz by affecting the surface plasmon polariton (SPP) resonance [7]. Fourth, relaxation time increases the conductivity if its value is high, then improves the radiation antenna efficiency [8]. These advantages make the graphene existed in several researchers' papers, compare its efficiency with other materials (silver, copper and gold) [9], using it as main radiation part [10, 11, 12].

This paper aims to improve the bandwidth of a graphene microstrip patch antenna by using patch cutting technique (Remove a rectangular slot from the circular patch, and then adjust its dimensions until getting the appropriate values) to meet an ultra- wideband able to support 6G applications in the THz range [7.2 THz to 9.2THz], also it aims to clarify graphene's ability to operate in the same range.

The structure of this paper is as follows, Section 2 is about the antennas design. Section 3 presents the antennas simulations results. Section 4 shows the outcomes of proposed antennas. Section 5 is a conclusion.

2 Antenna design

The design of the circular microstrip patch antenna was performed using CST Studio Suite 2019.

2.1 Global view

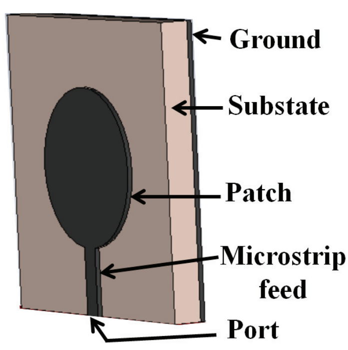


Fig. 1. Main circular microstrip patch antenna elements.

The equations to get the circular patch radius [13].

$$R_p = \frac{F}{\sqrt{\varepsilon_r}}\left[1 + \frac{2h}{\pi\varepsilon_r F}\left(\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right)\right]^{\frac{-1}{2}} \quad (1)$$

$$F = \frac{8.791\times10^9}{f\sqrt{\varepsilon_r}} \qquad \text{(f in THz)}$$

(2)

Where Rp is the circular patch's radius, f is the resonant frequency, F is the result from the previous equation, h is the substrate thickness, ε_r is the dielectric constant and B is the proposed antennas design.

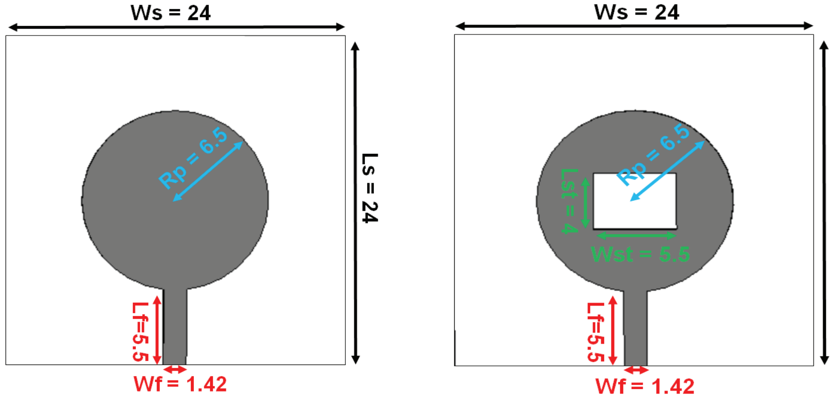
2.2 Proposed antennas design

In this section, the microstrip antenna design, dimensions, and materials used are presented. Both antennas are made of full ground. The used substrate is silicon with a permittivity of 11.9. The patch is made of graphene operating at a temperature of 300 K, with a Chemical potential of 2 eV and a relaxation time of 1 ps. The antennas are fed by 50 Ohm. The antennas parameters are summarized in Table1.

Table 1. Dimensions of the antennas.

Parameters	**Dimension (μm)**	**numbering**
Ws	24	Substrate width
Ls	24	Substrate length
h	2.4	Substrate thickness
Hg	0.4	Ground thickness
Wg	24	Ground plane width
Lg	24	Ground planelength
Rp	6.5	Radius of the patch
Hp	0.4	Patch thickness
Wst	5.5	Feedline width
Lst	4	Feedline length

Figures.2 shows the antennas layout and dimensions, before and after patch-cutting technique.



(a) Antenna a (b) Antenna b

Fig. 2. Antenna design layout_ (a) Circular patch, (b) Circular patch with Slot

3 Simulation

This section presents the difference between the S11 of the first designed antenna (antenna a) and the proposed antenna (antenna b) which achieved after modifying the graphene characteristics (mainly chemical potential and relaxation time) and slot's dimensions then choosing the most appropriate values as clarified on Fig.2-(b).

Fig.3 shows the S11 reflection coefficient simulation for both antennas, antenna a in red and antenna b in blue. The first one has an S11 of -29.95 dB, a narrow bandwidth of 0.33 THz (8.58 to 8.92) and resonance frequency of 8.76 THz. The second one has a large bandwidth about 1.39 THz (7.59 to 8.98) and S11 arrived at -52.48 dB.

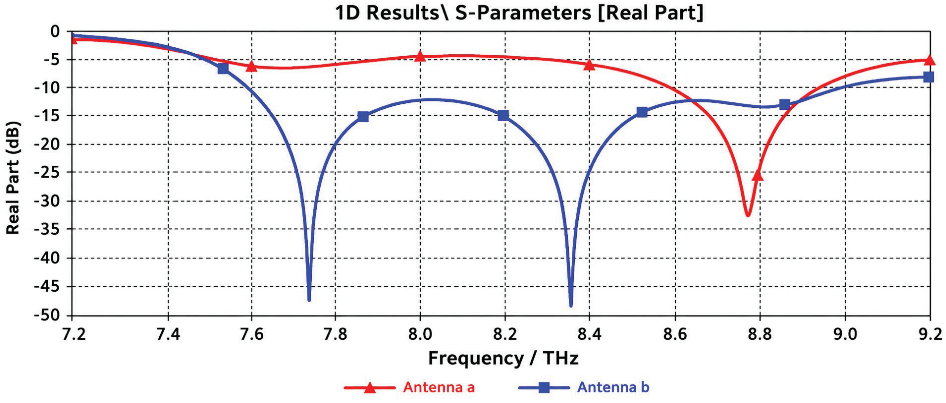


Fig. 3. Simulated S11 of antenna a and antenna b.

4 Simulation

Proposed antenna's outcomes, gain directivity, VSWR, current density, 3D radiation, radiation pattern, and the equivalent circuit will be shown in this section, as well as a discussion about the advantage of the proposed antenna.

As the fig.3 shows, the using of graphene as a radiator gave a good S11 parameter at the THz frequency, which show the ability of this material to give a suitable adapta-tion in the high frequency range, also after the optimization based on the patch cutting technique the antenna b gave an Ultra-Wideband around 3.39 TH that allows to support the needed 6G data rate.

4.1 Realized Gain and directivity

The proposed antenna has a good realized gain in the desired bandwidth (where the S11 value is less than -10) arrived at 7.42 dBi, directivity achieved 7.59 dB, and gain with 7.44 dBi. These respectable values can support 6G applications to overcome path loss and wave attenuation.

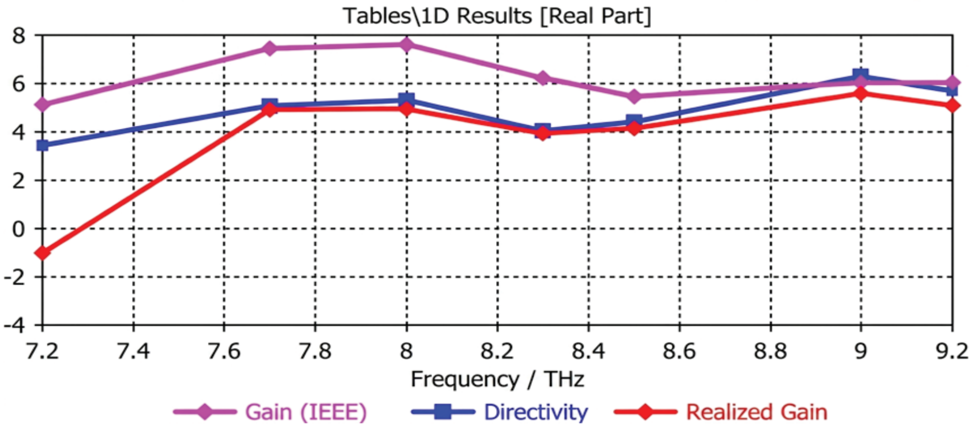


Fig. 4. Antenna b's Directivity, gain, and Realized Gain.

4.2 Efficiency

Antenna b has a good efficiency, reaching 95% at the obtained bandwidth 1.39 THz as shown in Fig.5.

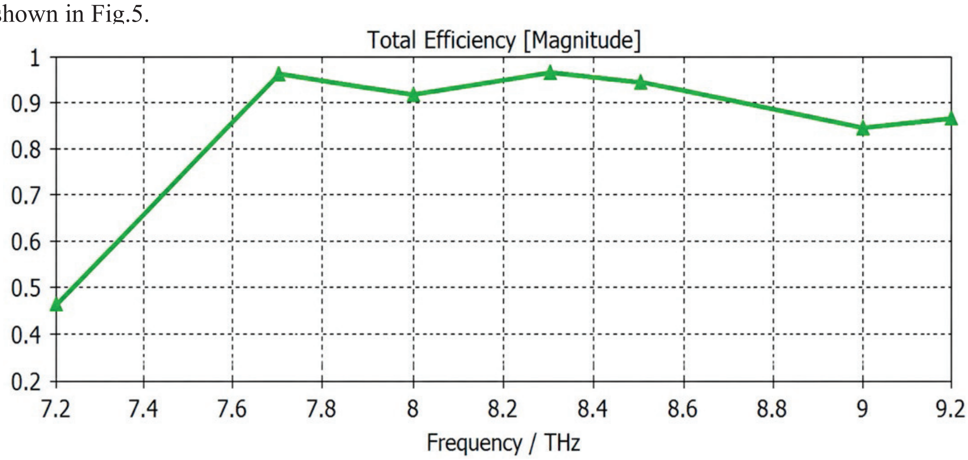


Fig. 5. Antenna b's Efficiency

4.3 Voltage Standing Wave Ratio (VSWR)

The suggested antenna's VSWR value is around 1.01 at obtained Ultra-Wideband, which ensures an acceptable matching between the antenna and the feedline

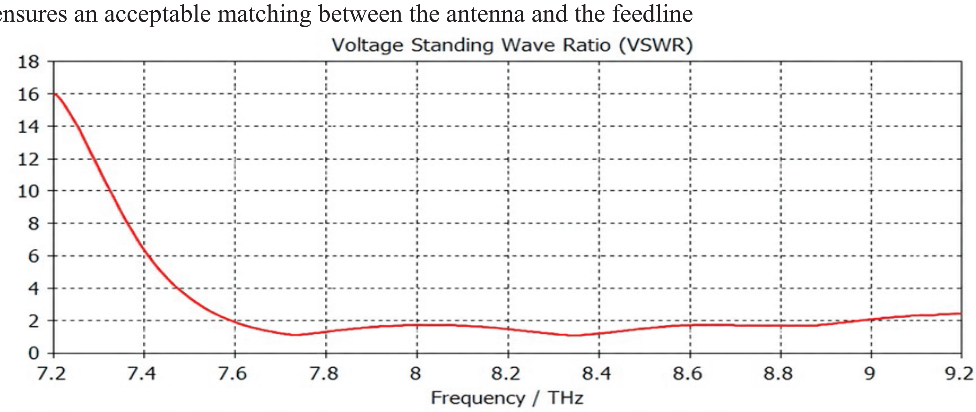


Fig. 6. Antenna b's VSWR

4.4 2D Radiation Pattern

The radiation pattern is the variation of the radiation power as a function of the direction away from the antenna.

Fig.7 offers the Radiation Pattern of antenna b at two chosen frequencies where the S11 has good values: 7.7 THz and 8.3 THz in both the E-plane (phi = 0°) and H-plane (phi = 90°). The patterns exhibit a directional radiation behaviour, except in the E Plan of 8.3 THz is a relatively wider beam. The minimal presence of side lobes suggests efficient radiation and limited power wasted in undesired directions. These results confirm that the proposed antenna exhibits stable radiation characteristics across the operating band, which is essential for high-frequency terahertz applications.

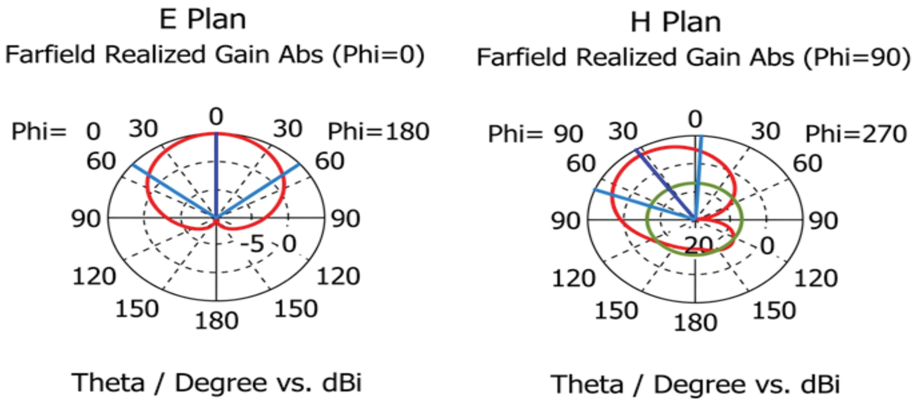


Fig. 7. (a) Radiation Pattern on E-Plane and H-Plane at 7.7 THz.

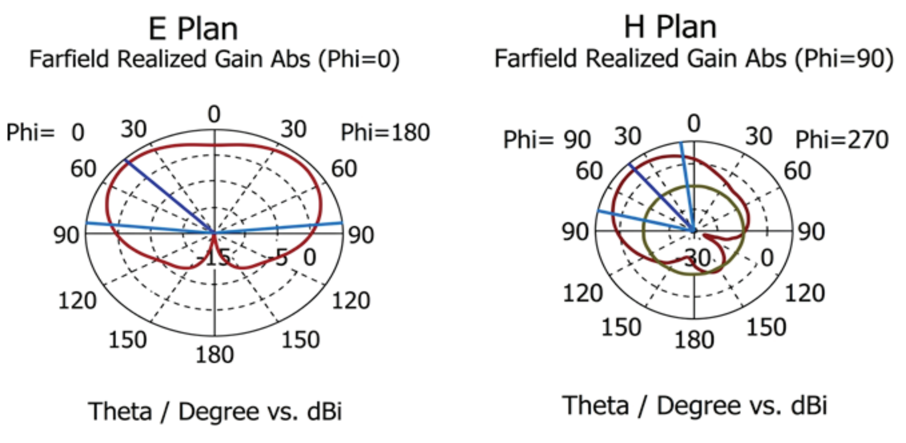


Fig. 7. (b) Radiation Pattern on E-Plane and H-Plane at 8.3 THz.

4.5 3D Radiation pattern

The antenna b's 3D radiation pattern of realized gain at 7.7 THz and 8.3 THz are illustrated in Fig.8, This radiation ensures the obtained realized gain values at the main lobe's edge and the antenna's directivity, as shown in the 2D radiation pattern.

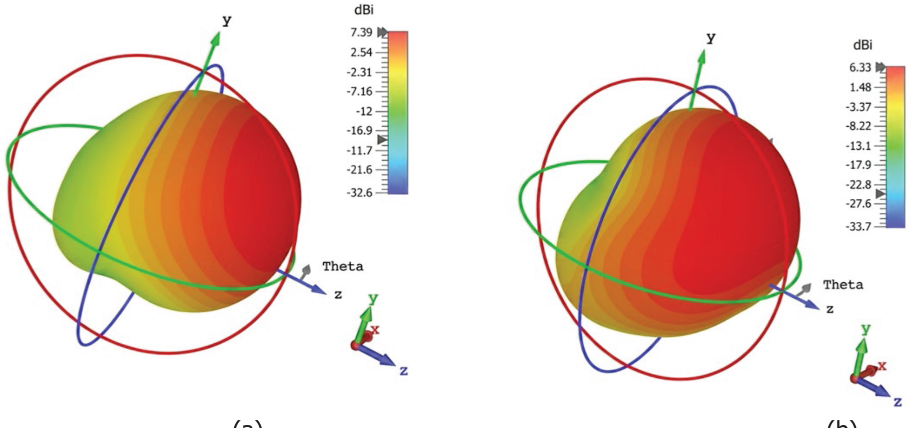


Fig. 8. Antenna b's 3D radiation pattern of gain, (a) at 7.7 THz and (b) at 8.3 THz.

4.6 Current density distribution

Fig.9 presents the current density distribution of antenna b at the two frequencies 7.7 THz and 8.3 THz.

The observation of the current density distribution gives a good understanding of how the current propagates over the radiation part, because of that Fig-(a) shows the current density distribution at the frequency 7.7 THz, in this last, the density of current is high (in red color) on the patch boundary which confirms that this area is the responsible for the communication of this frequency. Fig-(b) clarifies that the responsible area for 8.3 THz's communication is located around the slot, where the current density is strong.

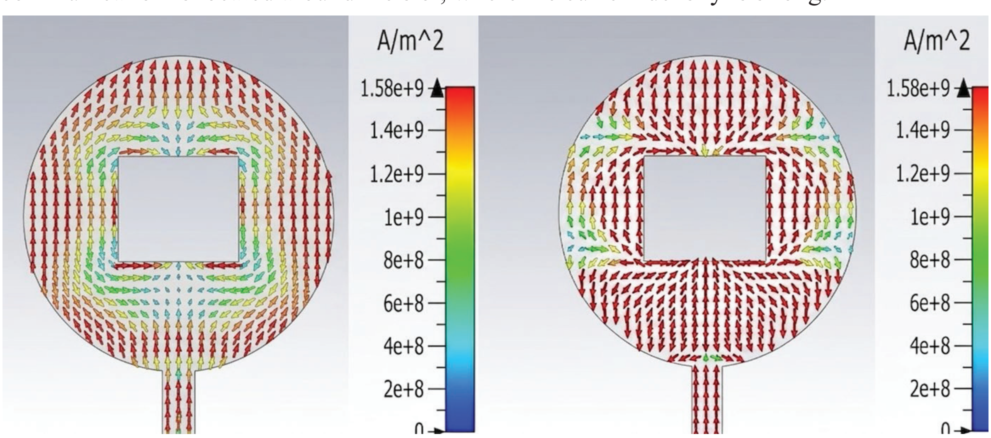


Fig. 9. Antenna b's Current density distribution, (a) at 7.7 THz, (b) at 8.3 THz

4.7 Equivalent circuit

In order to study the broadband behaviour of the ultra-wideband of antenna b, an equivalent circuit model was developed using the Advanced Design System (ADS), it's a combining of four parallel RLC circuits connected in series as illustrated in Fig.10 (a), the S11 parameters of this last is in green as clarified in Fig.10 (b) it has a Ultra-wideband around 4 THz and include the obtained CST's broadband.

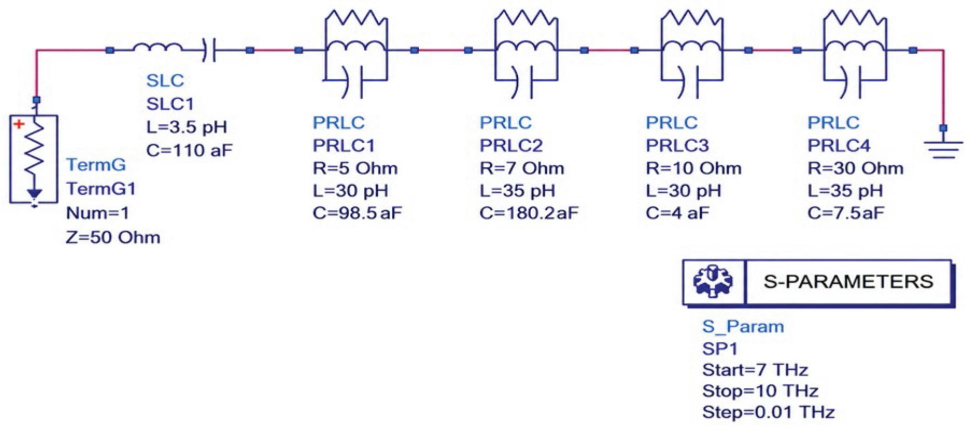


Fig. 10. (a) The equivalent circuit of Antenna b.

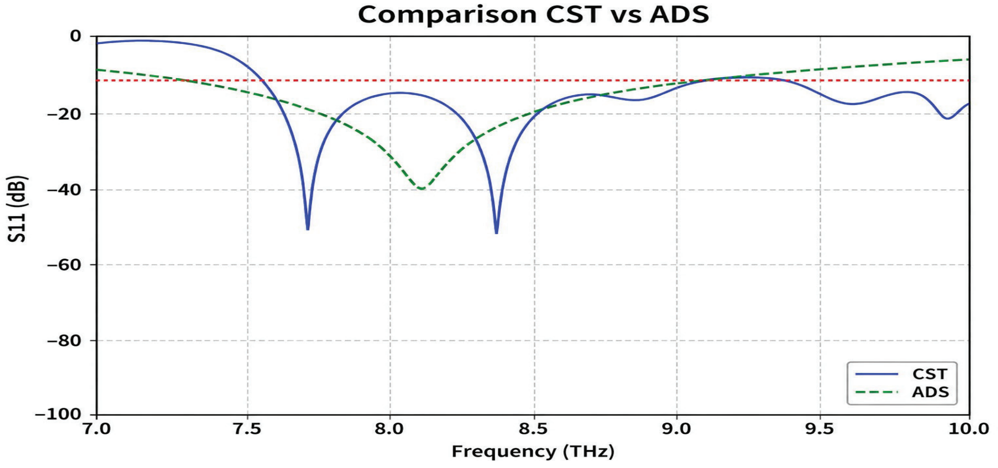


Fig. 10. (b) S11 of CST and of ADS.

4.8 Comparison

Table 2. Comparison between this paper and some other papers in the same topic .

Parameters	Material	Bandwidth	Gain	Ref
107 GHz	Copper Rogers RO3003	12.5 GHz	25.3 dBi	[13]
300 GHz	Graphene Flexible polyimide	86.66 GHz	5.4 dBi	[4]
150 GHz	Rogers RT-5880	17 GHz	18.3 dBi	[14]
2-4 THz	Rogers RO3003	from 2.45 to 2.55 THz and 3.3 to 3.75 THz	appropriate to 6G applications	[15]
7.2-9.2 THz	Graphene Silicon	1.39 THz	7.44 dBi	This paper

The table clarifies the added value of this paper, it gives a good bandwidth to 6G application and an appropriate gain.

5 Conclusion

The proposed antenna outcomes ensure that the graphene is an appropriate material to operate in the high frequency. Since the 6G applications will need a high data rate compared to the 5G throughput, the chosen range 7.2 to 9.2 THz and the obtained Ultra-wideband around 3.4 THz plus the realized gain values make this antenna able to support the 6G THz applications.

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