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Review TOEOC

Enhancing Terahertz Patch Antennas: The Role and Impact of Graphene

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Abstract

Terahertz (THz) communication systems are gaining increasing attention because of their ability for high-speed wireless data transmission, making them suitable for the 6th-generation wireless applications. Patch antennas, commonly used in these systems, play a crucial role in signal transmission and reception. There are various types of conductive materials available for patch antennas, but the unique characteristics of graphene make it a suitable choice. This study explores the significance and contribution of graphene in enhancing the performance of THz patch antennas. Graphene, a material structured in two-dimensions, has remarkable electrical and thermal properties and it has shown potential in improving antenna efficiency, bandwidth, and overall performance at terahertz frequencies. We discuss how incorporating graphene into patch antenna designs can address key challenges, such as miniaturization, high-speed operation, gain improvement and energy efficiency. By analyzing recent advancements and the potential benefits of graphene in antenna technology, this study provides insights into how this material can drive the next generation of THz communication systems. Terahertz (THz) frequency bands are being investigated more thoroughly to satisfy the growing need for extremely quick data transfer due to the quick development of wireless communication systems. Because of its capacity to provide large bandwidth and incredibly fast transfer rates, THz communication is anticipated to be essential to the development of 6th generation (6G) wireless networks. The patch antenna, which permits effective electromagnetic signal emission and receiving, is a key part of these systems. Because of its remarkable electrical, thermal, and structural properties, graphene stands out among the other materials taken into consideration for patch antenna design.

Keywords: Terahertz communication systems, patch antennas, graphene, wireless data transmission, terahertz frequencies, antenna technology

INTRODUCTION

As wireless technology becomes increasingly popular, network traffic has entered a period of rapid expansion, commonly described as the data traffic explosion [1]. A substantial number of applications are transitioning from conventional PC's to untethered gadgets like smart phones, which provide carriability and real-time capabilities. This transition, however, has led to a significant spike in network traffic and a shortage of available bandwidths. Projections suggest that market data rates could reach Gbit/s or even Tbit/s within the coming 8–10 years [2, 3]. To support these high-speed transmission demands, one promising approach is to investigate new frequency bands [4]. One such candidate is the Terahertz (THz) frequency band, situated in the unutilized region between microwave and infrared frequencies.

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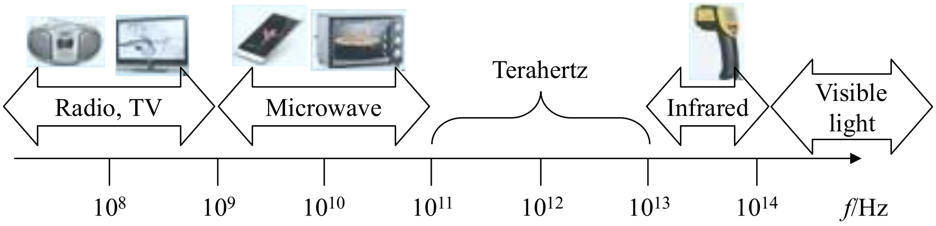

Figure 1. The positioning of THz band in EM spectrum

THz electromagnetic waves are typically defined within the range of 0.1 to 10 THz, which corresponds to the wavelengths between 0.03 and 3 mm [5]. Figure 1 illustrates the positioning of the THz band within the frequency spectrum.

Terahertz communication systems have attracted significant research interest due to the exceptional properties of terahertz waves. These include high spectral resolution, superior imaging capabilities, minimal signal degradation, wide bandwidth, non-ionizing properties, an extremely HF range, spatial diversity, reduced hindrance, and compact system design. Compared to mm waves, THz radiation offers a wider operational bandwidth, sturdier beam, and better information security and electromagnetic resilience. In comparison to light waves, terahertz radiations provide more efficiency and have stronger permeation capabilities [6]. So, THz waves enable numerous applications due to their unique advantages.

Practical implementations within the THz band comprises THz mobile connections, intra-chip communication, long range detection, terahertz-based WPAN, terahertz-based wireless connectivity (Tera-Wi-Fi), ultra-fast next generation IoT using terahertz technology, terabit-per-second unified access and backhaul networks, terahertz imaging for military and surveillance applications, terahertz spectral chemical analysis, next-generation cordless communication, high-precision radar, Terahertz communication modules, Terahertz imaging devices, and advanced security scanning [7, 8].

Antennas designed for Terahertz frequencies are attracting attention in the advancement of 6G wireless systems because of their capability for ultra-fast data transmission and extensive bandwidth. THz antennas serve a vital role in THz wireless network systems, as they are responsible for radiating and detecting THz waves. Their performance directly impacts the overall system quality, particularly in terms of operating bandwidth and gain. THz antennas are important devices in these systems as they facilitate speedy conveyance of energy and data from the starting point to the end point. Additionally, the characteristics of THz antennas are associated with information transfer rates, and the detection system’s operating range. As compared to the microwave antennas, THz antennas present several new challenges. Operating at extremely high frequencies significantly reduces the device size, while their packaging is constrained by material limitations and manufacturing processes. Another key challenge is ensuring efficient radiation at THz frequencies. As a result, THz antennas require more precise designs, advanced manufacturing materials, and innovative process technologies to meet the stringent demands of Terahertz wireless systems [9].

For the designing of the patch antenna for terahertz frequencies, various conductive materials can be used but graphene's unparalleled features make it highly suitable. The properties of graphene material are discussed later in the study.

GRAPHENE MATERIAL PROPERTIES

Graphene is an emerging material with significant potential for advanced functionalities in ultra-high-frequency transistors, signal controllers, remote nanodevices, flexible electronics, and systems operating in the terahertz range. Its utilization in antenna designing is driven by remarkable properties including size reduction, seamless incorporation of RF active components based on graphene, reconfigurable tuning capabilities, and structural adaptability [10, 11]. Graphene consists of a monolayer of graphite

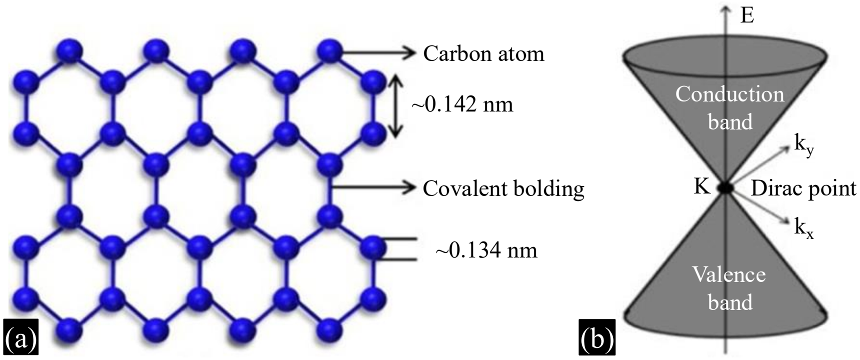

Figure 2. Graphene structure (a) Graphene's hex-patterned framework, (b) Band structure [12].

Table 1. Properties of graphene.

Properties	Value
Charge carrier mobility	~2×10^5 $m^2V^{-1}s^{-1}$
Electric current per unit area	~10^9 A/cm^2
Electron velocity at the Fermi level	~10^8 cm/s
Thermal conduction rate	~5000 $Wm^{-1}K^{-1}$
Tensile capacity	~150 million psi
Maximum stress capacity	42 N/m
Optical clarity	~97.7%
Maximum elastic strain	~20%
Band gap	0
Surface coverage	2360×10^4 cm^2/gm
Material depth	4×10^{-7}–1.8×10^{-7} cm

composed of atoms of carbon arranged in a hexagonal structured configuration incorporating a spacing of 0.142 nm, as illustrated in Figure 2(a) and (b). The initial breakthrough in isolating monolayer graphene from layered graphite was accomplished via mechanical exfoliation. Over time, various other synthesis methods have been developing, including chemical exfoliation, chemical vapor deposition, carbon segregation, and growth on SiC [13]. This material exhibits exceptional properties such as efficient conductivity, optical clarity, structural adaptability, robustness, and weather and chemical resilience, making it highly appropriate for implementation in antenna structures. The properties of graphene are given in Table 1. Graphene offers electrical conductivity with superior performance compared to copper and carbon nanotubes. Its key properties are thinness, flexibility, high mobility, high current density, and excellent transparency which make it an ideal choice for THz antenna design.

In 1947, Wallace presented the band structure of graphene as shown in Figure 2(a), which consists of a single layer of graphite [14]. Graphene demonstrates a set of exceptional properties due to its distinctive band framework. As illustrated in Figure 2(b), the conduction and valence bands form conical shapes that intersect at a point known as Dirac point. The availability of electronic states rises linearly as the energy shifts from the Dirac point. Unlike in metals, the behavior of the electrons in graphene is fundamentally different. In graphene, electrons exhibit zero effective mass and possess a velocity of approximately 10^6 m/s (equivalent to c/300, where c is the speed of light). Consequently, electron propagation in graphene resembles that of massless Dirac fermions. According to the theory of relativity, when m=0, the energy-momentum relationship becomes $E=cp$. In graphene, this is analogous to the linear dispersion relation $E=vf\,\hbar k$, where $p=\hbar k$ is the momentum, and vf is the Fermi velocity, approximately equal to 10^6 m/s. Thus, in graphene, electrons move at a speed nearly 300 times slower than that of light [12].

Graphene's Conductive Behavior under THz Frequency Range

Graphene's exceptional properties have sparked significant interest in the material. At terahertz frequencies, graphene is capable of supporting the generation of plasmon-polariton waves. Its surface conductivity can be accurately described using Kubo equations given from Eqs. (1)–(5) [15].

$$\sigma(\omega) = \sigma_{intra}(\omega) + \sigma_{inter}(\omega) \quad (1)$$

$$\sigma_{intraband}(S) = j\frac{2kT_0 q_e^2}{h(jr^{-1}h+h\omega)^2} lncosh\left(\frac{\mu_c}{2kT_0}\right) \quad (2)$$

$$\sigma_{inter} = \frac{q_e^2}{4\pi h}\left[\frac{2\mu_c-(\omega+j\tau^{-1})}{2\mu_c+(\omega+j\tau^{-1})}\right] \quad (3)$$

Here, $k=1.38\times10^{-23}$ J/K denotes the Boltzmann's constant, qe represents the charge, "h" is the reduced Plank's constant, μc stands for the chemical potential, T0 denotes the temperature, and Γ refers to the relaxation time, as defined by the Eq. (4).

$$\Gamma = \frac{\mu n}{e_g.v_f^2} \quad (4)$$

Here, vf represents the fermi velocity and n denotes the electron's mobility. The correlation between the chemical potential and the bias voltage is defined by Eq. (5).

$$V_g = \frac{q_e\mu_c^2 h}{\pi h^2 v_f^2 s_0 s_r} \quad (5)$$

Where, h denotes the substrate thickness and εr represents the relative permittivity of the substrate [15].

The conductivity of graphene is influenced by its Fermi energy (Ef), meaning it can be modulated by adjusting the Fermi energy level. This adjustment can be achieved dynamically through the electric field effect, using chemical doping. At the Dirac point, graphene's density of states is zero, resulting in low conductivity. By applying an electric field bias, additional electron or hole carriers are introduced, enabling dynamic control of its complex conductivity [12].

Although graphene's surface conductivity in terahertz (THz) frequency range is primarily due to intra-band transitions, its behavior differs across these frequencies. Figure 3 illustrates the real and imaginary components of graphene's surface conductivity at THz frequencies at room temperature. Since it is impractical to depict conductivity behavior across the entire frequency range from MW to THz, representative frequency ranges from both bands are shown in Figure 3.

While the electric field effect influences graphene's conductivity at MW and THz frequencies, the tunability of its complex conductivity varies. In contrast, as the frequency approaches the THz band,

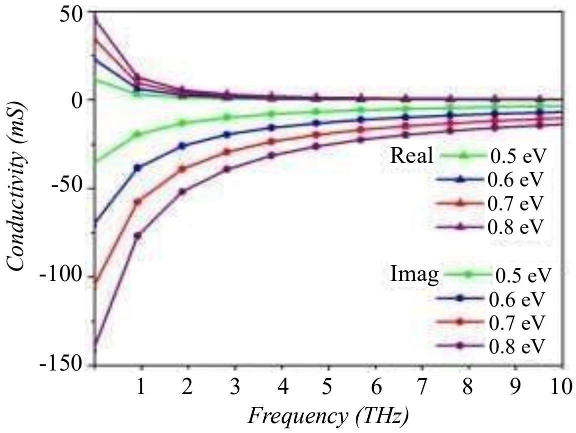

Figure 3. Graphene's complex conductivity (real and imaginary parts) at terahertz frequencies [12].

graphene's complex conductivity exhibits distinct behavior due to the support of surface plasmon polaritons (SPPs). In this range, the imaginary part of graphene's conductivity becomes more pronounced and undergoes significant changes under the electric field effect. Figure 3 illustrates this complex conductivity behavior in the THz band. This tunable conductivity enables frequency reconfigurability in planar microstrip metal antennas operating in the THz band [12].

Comparative Analysis of Graphene with Other Materials

Researchers and antenna engineers have explored various materials suitable for developing THz antennas within terahertz wireless systems, a task that remains both crucial and highly challenging. Literature reports the use of different radiating materials, including copper, graphene, carbon nanotubes, and gold, for THz antennas [16, 17].

Carbon nanotubes (CNTs) are cylinder-shaped molecules made up of carbon atoms organized in a continuous hexagonal framework and share the equivalent bonding configuration as graphene. A comparative overview of these three materials is presented in Table 2. Graphene, a monolayer form of graphite, exhibits outstanding electrical conductivity, offering superior functionality over copper and carbon nanotubes. Its key characteristics are thinness, flexibility, exceptional charge, transport capability, elevated current capacity, and exceptional transparency which make it an ideal material for THz antenna design. Graphene offers several advantages over copper and carbon nanotubes (CNTs) for THz patch antennas, making it a superior choice for next-generation THz communication systems. One of its key benefits is tunability, as its conductivity can be dynamically adjusted using electric field biasing, enabling real-time reconfigurability, something copper and CNTs lack.

Additionally, graphene exhibits exceptionally high carrier mobility and lower resistive losses, which significantly enhance efficiency at THz frequencies, whereas copper suffers from ohmic losses, and CNTs introduce interface scattering. Another crucial advantage is the potential of graphene to enable surface plasmon polaritons (SPPs), allowing for highly confined electromagnetic waves and improved miniaturization. Its ultra-thin, lightweight, and flexible nature makes it ideal for wearable and conformal antennas, unlike rigid copper or the integration challenges posed by CNTs. Moreover, graphene's high transparency (~97.7% transmittance) enables applications in optoelectronic THz systems, unlike opaque copper and CNTs. Its frequency-dependent complex conductivity allows for multi-band operation, enhancing reconfigurability in THz applications. Graphene’s properties, along with its capability to enable compact antenna designs for on-chip THz communications in emerging 5G and 6G networks, position it as a leading material for advanced THz antennas. It outperforms traditional materials in terms of efficiency, adaptability, and integration potential.

REVIEW OF RELATED WORKS

The THz antennas based on graphene material have been reviewed and analyzed. A graphene-based THz antenna was developed and evaluated in comparison with the conventional copper patch on a dielectric substrate (ϵr=3, h=0.9 mm, and tanδ=0.002) featuring dimensions of 179×211 μm^2 [18]. In another work [19], the antenna exhibited resonance at 0.68 THz with a return loss of –28 dB. It achieved a gain of 7.1 dBi, which is 1.37 dBi more than that of the copper patch. The top view schematic, return loss curve, and radiation pattern are presented in Figure 4.

Table 2. Comparison of various material properties.

Parameter	Copper	Graphene	CNT
Electrons mobility	32 $cm^2V^{-1}.S^{-1}$	2×10^5 $cm^2V^{-1}S^{-1}$	8×10^4 $cm^2V^{-1}.S^{-1}$
Current density	10^6 Acm^{-1}	10^9 Acm^{-1}	10^9 Acm^{-1}
Breaking strength	587 MPa	1.5TPa	5–500 GPa
Thermal conductance	400$Wm^{-1}K^{-1}$	5000$Wm^{-1}K^{-1}$	3000 $Wm^{-1}K^{-1}$
References	[16, 17]	[16, 17]	[16, 17]

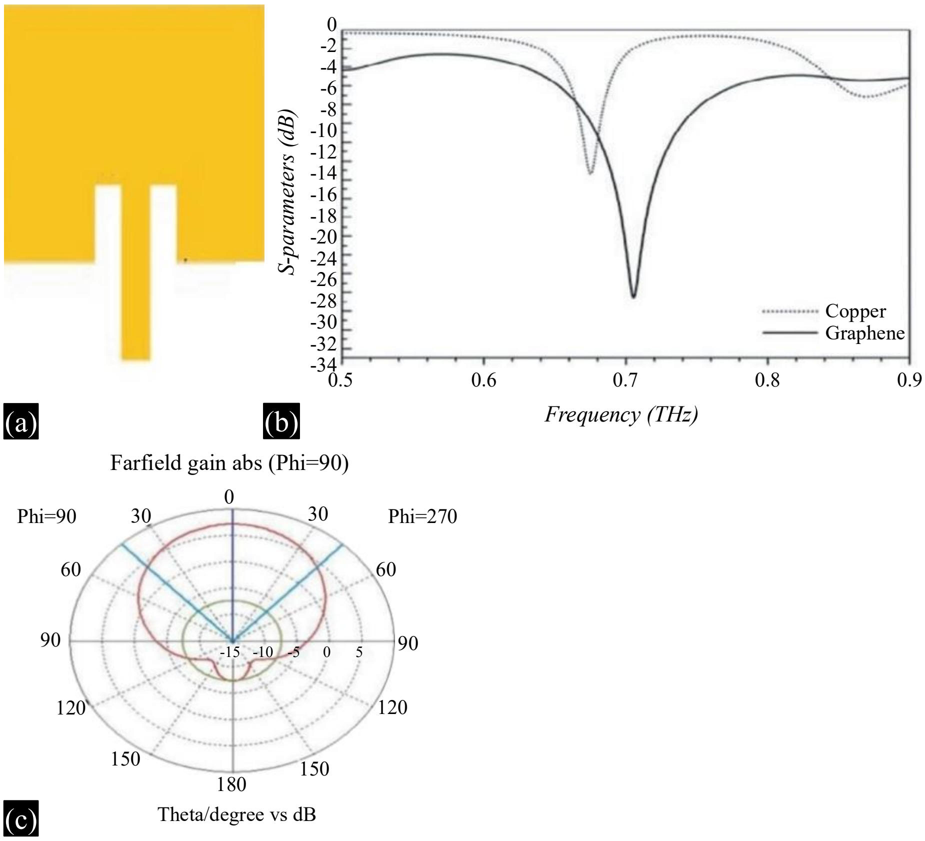

Figure 4. Terahertz reconfigurable antenna: schematic (a) top view, (b) Return loss curve, (c) radiation pattern [19].

Several researchers have explored THz antennas based on graphene nanoribbons (GNRs), which consist of narrow graphene strips (approximately 100 nm wide) known for their high conductivity and low noise. To enhance the antenna's bandwidth [20], a graphene-based antenna featuring a rectangular double-ring nanoribbon structure was developed on SiO2 substrate (ϵr=3.9, h=25 µm, and tanδ=0.002). The antenna's dimensions were 93×120 µm², and gold was employed as the ground plane. The antenna incorporated 10 graphene monolayers with a total depth of 3.4 nm to minimize losses and improve effectiveness. The performance was analyzed based on spacing between the two rings and their interconnection. The antenna achieved a gain of 6.0 dBi at a frequency of 1.06 THz with a radiation efficiency of 44% [20]. The diagram and schematic top view are depicted in Figure 5(a) and (b) while the return loss curve is illustrated in Figure 5(c).

A graphene nanoribbon-based antenna was designed on a polyimide substrate (ϵr=3.5, h=20 µm, and tanδ=0.008) with dimensions of 208.98×433.2 µm², operating within the 725–775 GHz band. The antenna achieved a gain of 5.71 dBi with a radiation efficiency of 86.58% at 750 GHz. The schematic top view, S11characteristics, and radiation pattern are shown in Figure 6(a)–(c) [21].

The antenna based on graphene material was evaluated on a glass substrate (ϵr=3.8, h=15 µm, and tanδ=0.00002) with dimensions of 190×150 µm^2, operating within the 0.98–1.06 THz band. The reported gain was 6.82 dBi, and effective radiated efficiency of 66.72% at 1000 GHz. The front view schematic, along with the return loss, and gain-directivity graph are presented in Figure 7(a)–(c) [22].

A circular graphene patch antenna was developed on a Si substrate (ϵr=11.9, h=1 µm, and tanδ=0.0012) for ultra-wideband THz applications. The design features reconfigurability through the application of an external DC bias voltage between the graphene disc and the ground plane. Figure 8(a)–(c) illustrates the front view schematic, return loss curve and radiation pattern [23].

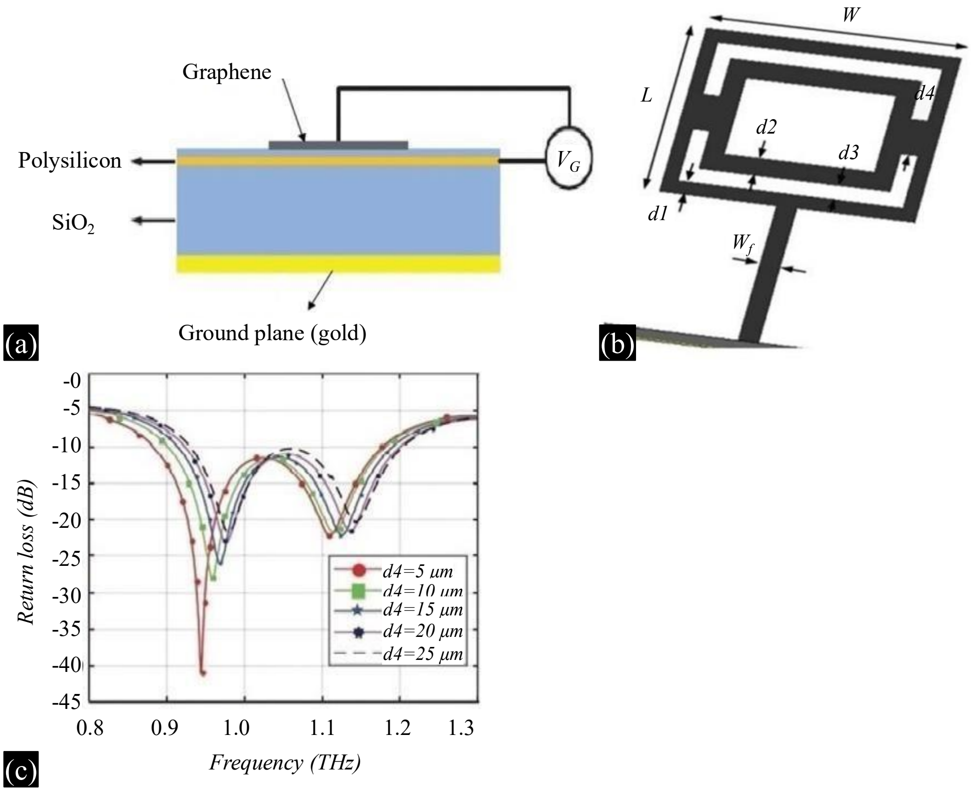

Figure 5. Double-ring nanoribbon graphene-based antenna: (a) block diagram, (b) schematic front view, (c) S-parameters [20].

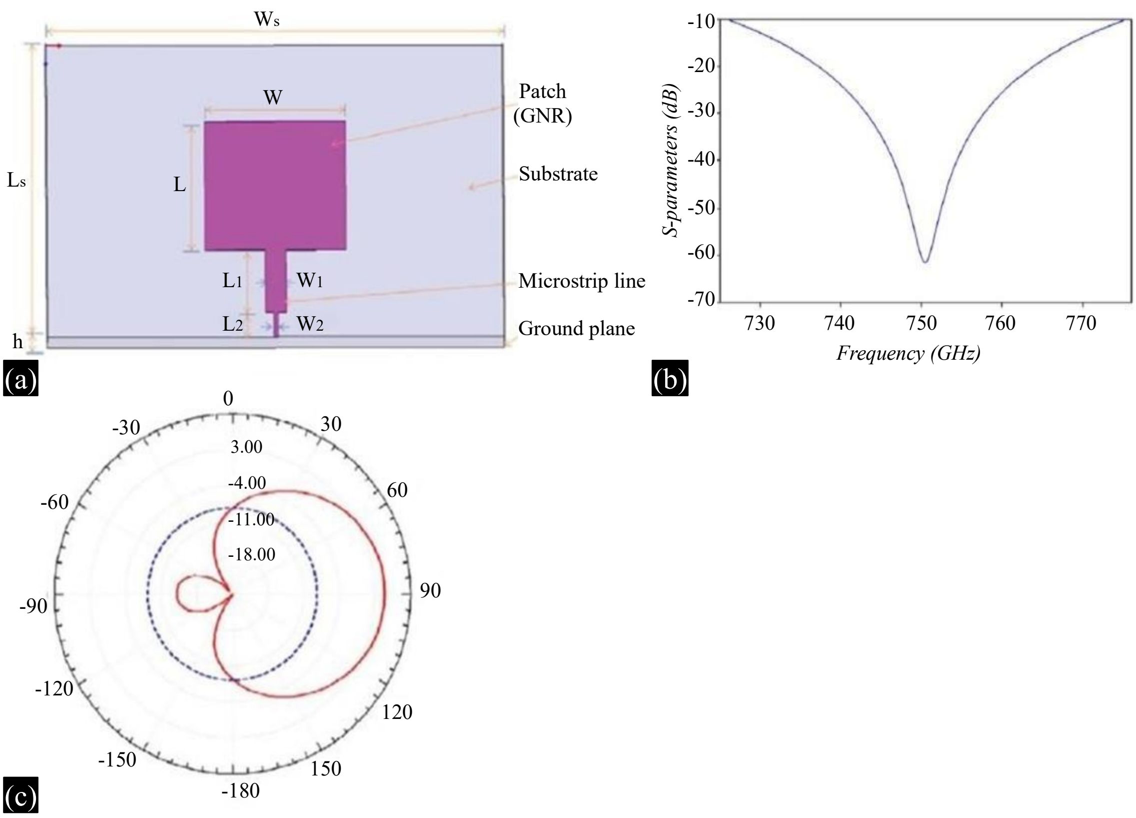

Figure 6. Graphene nano ribbon-based terahertz antenna: schematic (a) top view, (b) S11, (c)radiation characteristics [21].

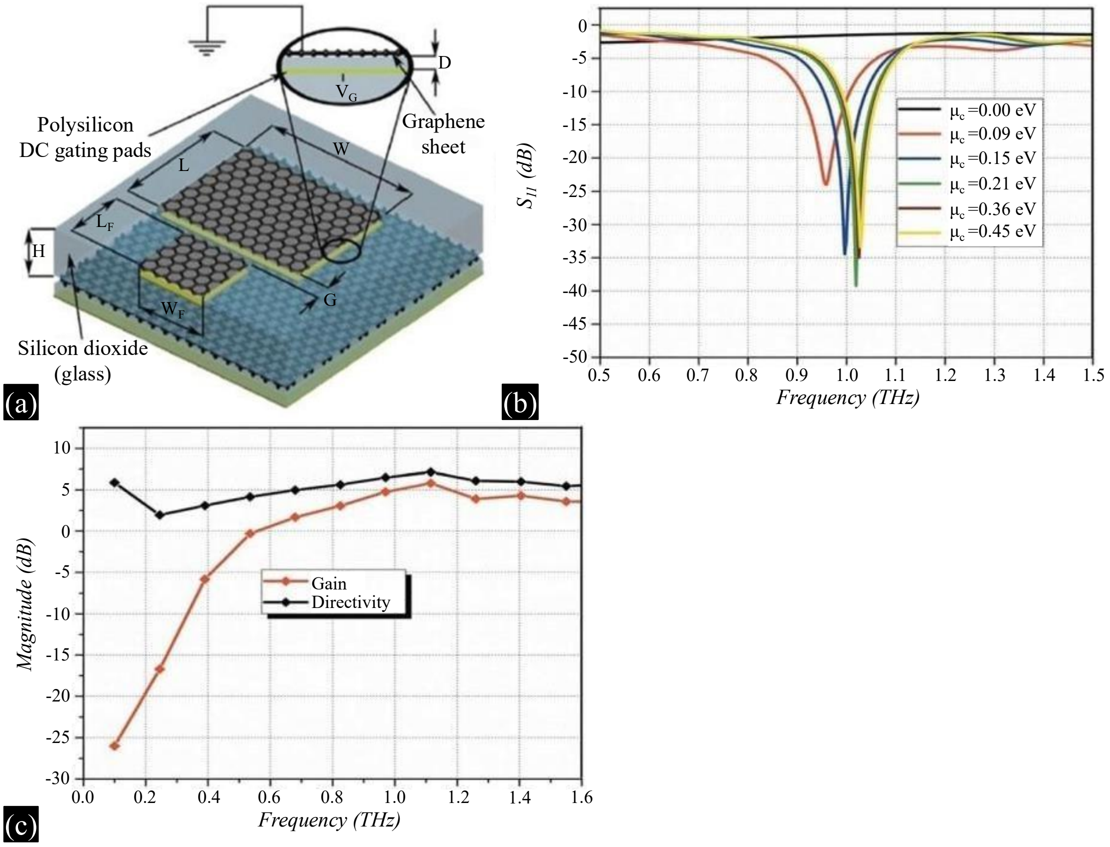

Figure 7. THz antenna based on Graphene nanoribbons: schematic (a) front view, (b) S-parameters, (c) radiation patterns [22].

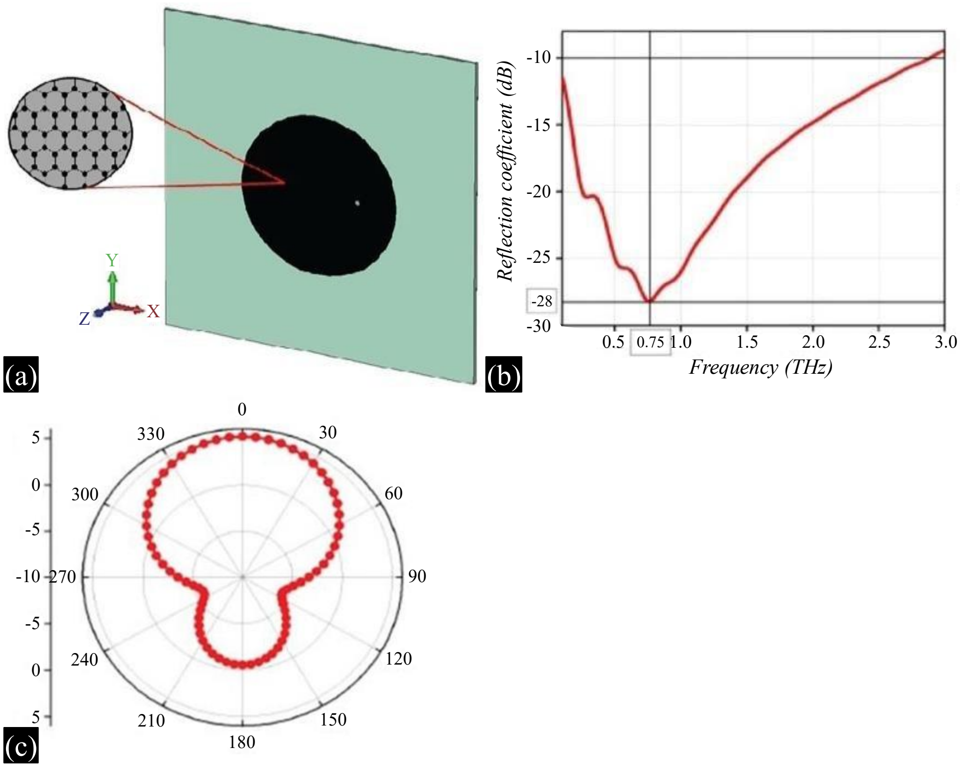

Figure 8. THz circular Graphene based antenna: schematic (a) front view, (b) Return loss curve, (c) radiation pattern [23].

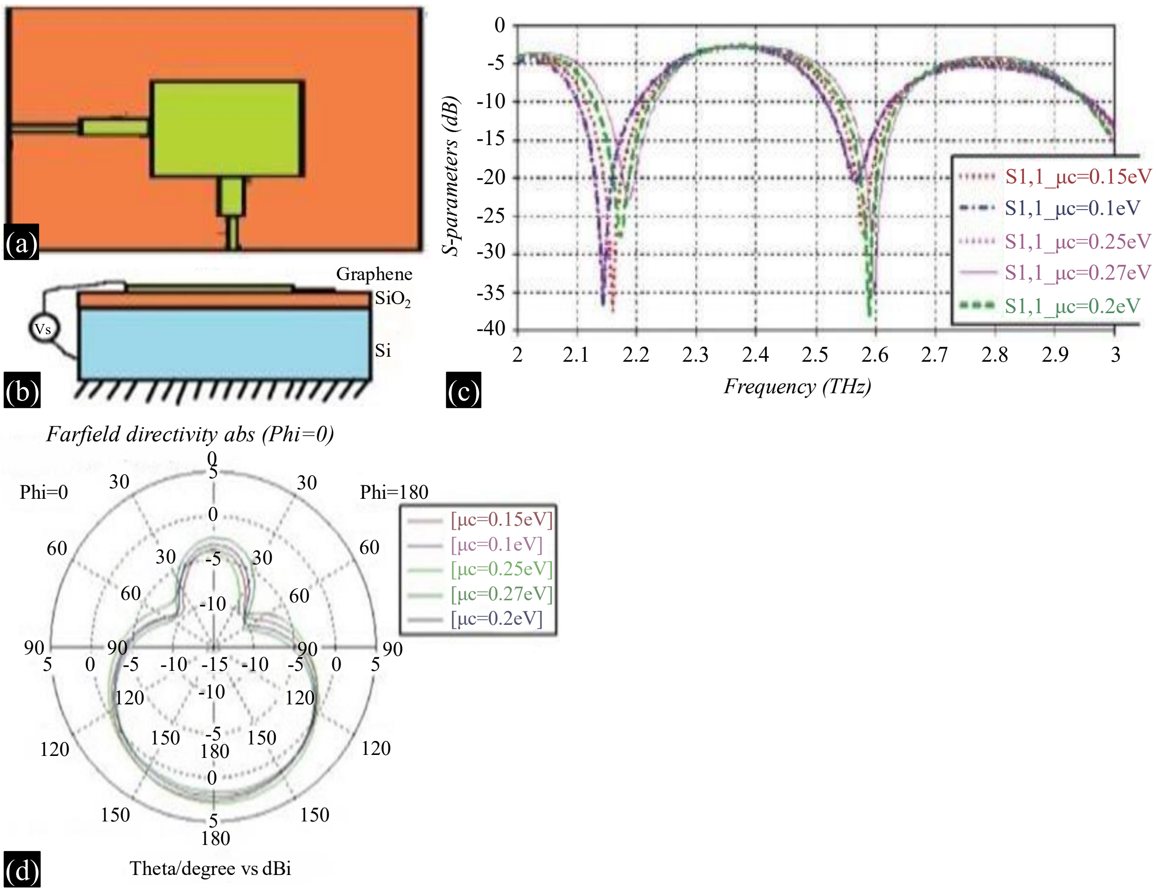

Figure 9. THz antenna featuring reconfigurable ability: schematic (a) top view, (b) side view, (c) S-parameter, (d) radiation pattern [24].

Table 3. Comparison F for Graphene based THz antennas.

Ref no.	Frequency (THz)	Antenna type	Gain (dBi)	Radiation efficiency (%)	Dimensions
[19]	0.7	Terahertz graphene based reconfigurable antenna	7.1	-	179×211
[20]	0.92–1.2	Double ring nanoribbon graphene- based antenna	6.0	44	93×120
[21]	0.725–0.775	Graphene nanoribbon-based THz antenna	5.71	86.58	208.98×433.2
[22]	0.98–1.06	Graphene based antenna	6.82	66.72	190×150
[24]	2.05–2.2	Beam reconfigurable dual band graphene antenna	7.19	64.12	100×100

A dual-band graphene antenna featuring beam reconfigurable ability was designed on an SiO_2 substrate (ϵr=11.9, h=μm, and tanδ=0.0012) for cordless on-chip applications. The beam direction could be dynamically adjusted by tuning the chemical potential between 0.1 and 0.27 eV. The antenna measuring 100×100 μm^2, operated across two frequency ranges of 2.15–2.2 and 2.56–2.6 THz. It achieved a peak gain of 7.19 dBi and a radiation efficiency of 64.12%. The schematic front and side views, return loss curve and radiation characteristics are presented in Figure 9(a)–(d) [24].

The comparison table for the reviewed graphene-based THz patch antennas based on frequency, type of antenna, gain, radiation efficiency and dimensions is given in Table 3. From the review and analysis, it is evident that graphene plays a crucial role in enhancing antenna performance. Its unique properties, including tunable conductivity, high carrier mobility, flexibility, and the ability to support surface plasmon polaritons (SPPs), contribute to improved gain, efficiency, and reconfigurability in THz antennas. These advantages make graphene a highly promising material for next-generation wireless communication systems.

CONCLUSION

Since its discovery, graphene has been thoroughly researched for its future implementations across various fields. Through DC conductivity measurements, it has demonstrated unique properties such as near-ballistic transport, the half-integer quantum Hall effect, and contributions to a new frontier in relativistic condensed matter physics. Various optical techniques have been refined to characterize graphene sheets, with optical microscopy emerging as a valuable tool for monitoring high volume manufacturing. With its impressive intrinsic qualities validated via mechanically exfoliated graphene, research efforts have shifted toward developing more cost-effective and technologically viable production methods. Processes like epitaxial growth, chemical vapor deposition, and wet chemical synthesis have shown promise for certain applications while presenting challenges for others. THz spectroscopy, combined with other superfast spectroscopic techniques, has significantly enhanced our knowledge of carrier behavior in graphene. Studies have provided insights into its intrinsic AC conductivity, eliminating the need for electrical contacts, and explored the mechanisms governing excited carrier cooling. Such research highlights graphene's potential for a wide range of applications while also revealing its limitations, which must be addressed before its full integration into functional devices. Several challenges remain. The idea that graphene perpetually retains a perfect two-dimensional crystalline structure, isolated from its external conditions, is often unrealistic. Improving graphene growth techniques presents a significant hurdle for materials scientists, while theoretical models must account for the complex interactions between graphene and its surroundings to accurately interpret experimental results. Additionally, a comprehensive understanding of ultrafast charge carriers' behavior in graphene is still lacking, posing a challenge for realizing THz-frequency devices based on graphene. Many proposed graphene-based applications remain conceptual rather than demonstrable. Nonetheless, investigation into this area is still at a preliminary phase, and continued advancements in THz spectroscopy tools are set to play a crucial role in driving its evolution. These techniques will be essential for probing graphene's high-frequency response, refining production methods, and evaluating the efficiency of emerging graphene-based devices.

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