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EDITED BY
Muhammad Ikram,
King Abdullah University of Science and Technology, Saudi Arabia

REVIEWED BY
Ahmad Bazzi,
New York University Abu Dhabi, United Arab Emirates
Ruiqi Wang,
King Abdullah University of Science and Technology, Saudi Arabia

*CORRESPONDENCE
Sasmita Dash,
✉ sasmitadash30@gmail.com

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Graphene-based beam-reconfigurable liquid antenna for 5G mmWave wireless systems

Sasmita Dash*, Constantinos Psomas and Ioannis Krikidis

Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus

The advancement of wireless technologies has led to significant progress in antenna design in order to meet the continuously increasing demands. Liquid antennas have gained significant interest in research owing to their distinctive properties, such as being small, flexible, transparent, and capable of reconfiguration. Recently, graphene liquid has been considered for various applications because of its affordability, excellent conductivity, flexibility, transparency, and easy processing. This paper presents a beam-reconfigurable graphene liquid antenna. The movement of the graphene liquid within the microfluidic channel enables beam reconfiguration. The antenna is realized in a rectangular microfluidic channel made of polymethyl methacrylate over a liquid crystal polymer substrate. The proposed antenna performs beam-steering up to 360° with 7 dBi of gain and operates at 28 GHz with a wideband of 10-dB impedance bandwidth of over 20%. In particular, the main beam of the antenna reconfigures into six directions (0°, 45°, 135°, 180°, 225° and 315°)at the operating frequency. Moreover, the antenna offers a consistent reflection coefficient at 28 GHz in each of the six reconfigurable frequencies. Therefore, the proposed novel technique for designing reconfigurable antennas using graphene liquid holds great promise for 5G mmWave wireless communication systems.

KEYWORDS

graphene liquid, microfluidic, antenna, mmwave, beam reconfiguration, wireless communications

1 Introduction

Over the past few years, wireless communication systems have undergone significant revolutionary advancements. Fifth-generation (5G) wireless communications networks have already been deployed with the aim of providing high data rates (Chowdhury et al., 2020). In particular, 5G has been formally commercialized since 2019, using the millimeter wave (mmWave) and sub-6 GHz bands. However, the rapid growth in the number of smart devices and the emergence of the Internet of Everything (IoE) applications, which require energy-efficient, ultra-reliable and low-latency communications, will substantially burden the 5G wireless networks (Alsabah et al., 2021; Chowdhury et al., 2020). Therefore, the 5G paradigm will be further developed and expanded under sixth-generation (6G) technologies that will pursue wider coverage, higher rates, more connections, ultra-low latency, ultra-high positioning accuracy, integration of communications and sensing, more intelligence, more security, and better substitutability (Chowdhury et al., 2020). The mmWave communication systems offer significant advantages in terms of high data rates and bandwidth, spectrum availability, beamforming capabilities, high spatial resolution, and reduced latency, making them essential for the 5G wireless communication networks (Hong et al., 2021). However, wireless communications over the mmWave bands are susceptible by bad weather conditions and obstacles due to the signal's smaller wavelengths. Therefore, efficient antennas that overcome these limitations are important for the effective operation of future wireless systems.

In the present era of wireless communication systems, adaptability and diverse functionality stand out as the most attractive features in any communication device. Therefore, since the antenna is essential to these systems, the rapid progression towards 5G technologies necessitates the design of efficient antennas. Nevertheless, conventional antennas, usually made of conductive metals on stiff substrates, perform well but are not mechanically flexible. Moreover, exceeding certain limits in bending or stretching these antennas leads to irreversible structural deformations and even destruction (Alzoubi et al., 2011). As a consequence, metallic antennas' rigidity limits their use in application where flexibility is required. This motivates the need for more flexible and adaptable antennas, such as antennas using metallic liquids (Huang et al., 2021). Metallic liquids are a perfect substitute for flexible antenna applications due to their flowing properties and lack of deformation limits. Moreover, liquid metals in microfluidic channels maintain exceptional flexibility and mechanical stability without compromising their electrical properties (So et al., 2009). Therefore, metallic liquid antennas are perfect for antenna applications because of their exceptional flexibility, deformability, and high conductivity. Modern methods of fabricating antennas take advantage of the fluidic qualities of metallic liquids, such as 3D printing, injecting, or spraying metallic liquid onto rigid or flexible substrates. Liquid antennas can readily achieve reconfigurability through electrochemically controlled capillary action or micro pumping, in contrast to traditional techniques like high-frequency switching. Given these important benefits, there has been significant interest recently on the beneficial role of liquid antennas in wireless communication systems (Psomas et al., 2023; Wong et al., 2021). The basis for developing efficient liquid antennas is found in the special qualities of liquid materials, which have a major impact on antenna performance and design.

Liquid antennas capitalize on the mechanical properties of fluids, leveraging their ability to change shape and flow to create flexible, reconfigurable, and adaptable antenna structures for various applications (Huang et al., 2021). The presence of metallic liquid in fluidic channels allows the fluidic channel to take shape due to its low viscosity (Choi, 2014). Flexible substrates allow for the bending, folding, stretching, and twisting of liquid antennas, thereby withstanding various forms of mechanical deformation. However, due to their high degree of reversibility, they can instantly regain their original form (So et al., 2009). Because of their intrinsic flexibility, liquid materials serve as a viable substitute for rigid or solid conductors in the realm of flexible electronics (Varnava, 2019). The development of metallic liquid antennas is made possible by the fluidic properties of metallic liquids. By using metallic liquids as radiative elements instead of solid conductors like copper, it is possible to create antennas that are much more flexible and reconfigurable. Moreover, the high conductivity inherent in metallic liquids makes them particularly well-suited for antenna applications. Indeed, the fluidic properties of metallic liquids have enabled a wide range of metallic liquid antennas (Kosta and ChaIurvedi, 1989; Dey et al., 2016; Hayes et al., 2012; So et al. 2009; Morishita et al., 2013). Even when radiative elements are installed on rigid substrates, more flexibility and reconfigurability can be achieved due to the fluidic nature of liquid materials. Metallic liquids have been used to develop flexible and reconfigurable antennas since the late 80s (Kosta and ChaIurvedi, 1989). One notable example of a metallic liquid is mercury (Hg). The fluidic and conductive nature of mercury allows for the design of reconfigurable metallic liquid antennas (Dey et al., 2016). However, the toxic nature and high cost of mercury impose limitations on its use for antennas. Alternative metallic liquid materials typically manifest as alloys composed of conductive nanoparticles. A well-known alloy for liquid antenna consists of gallium and indium has been explored in several antenna designs (Hayes et al., 2012; So et al., 2009; Morishita et al., 2013).

Recently, metallic liquid antennas employing graphene liquid, a novel metallic liquid material, have been designed (Dash et al., 2023). In comparison to traditional metallic liquid antennas made of mercury and gallium indium alloy (EGaIn), graphene-based liquid antennas exhibit superior electromagnetic performance. Since its discovery in 2004 Novoselov et al. (2004), the superior properties of graphene, including high electrical conductivity (= ~10^6), high mechanical tensile strength (= ~130 GPa) and high thermal conductivity (= ~5000 W/m.K), have led to a great deal of current research interest and a wide range of practical applications. Graphene-based metasurface designs have garnered significant research interest in recent years (Dhote et al., 2023; Molero et al., 2021). Reconfigurable intelligent surfaces based on metamaterials open new possibilities for future sensing and wireless communication systems (Wang et al., 2024; Bazzi and Chafii, 2025). Due to the high electron mobility within the hexagonally arranged carbon atoms of graphene, it exhibits an electrical conductivity of the order of 10^6 S/m (Sruti and Jagannadham, 2010). Hence, the conductivity of the graphene liquid is sufficient for its use as an antenna candidate, ensuring high efficiency. Moreover, since graphene does not melt when heated, it lacks a defined melting point. Instead, it undergoes sublimation at temperatures around 3,600 K.

Table 1 presents the material properties of graphene liquid in comparison to conventional metallic liquids such as mercury and EGaIn. The comparison highlights that graphene liquid is a promising candidate for liquid antennas, offering advantages over traditional metallic liquids. Graphene's higher electrical conductivity and optical transparency provide significant advantages over EGaIn, particularly in applications where both high conductivity and optical transparency are required. Graphene's higher conductivity makes it ideal for ultra-fast electronics, flexible circuits, and antennas. Graphene is nearly transparent, absorbing only 2.3% of visible light, making it an excellent material for transparent conductive films, touchscreens, and optoelectronic devices. EGaIn is completely opaque, limiting its use in applications requiring optical transparency. Moreover, graphene liquid proves to be safe for industrial use and is environmentally friendly. As a result, graphene liquid has many

TABLE 1 Material properties of graphene compared to other conventional metallic liquid.

Parameter	Graphnee	Mercury	EGaIn
Electrical Conductivity	50×10^6 (S/m)	1×10^6 (S/m)	3.4×10^6 (S/m)
Thermal Conductivity	~5000 W/m · K	~8 W/m · K	~50 W/m · K
Melting Temperature	Does not melt (sublimes at 3,600 K)	−38.87°C	16°C
Density	~2000 kg/m^3	~6000 kg/m^3	~13000 kg/m^3
Viscosity	1 – 1000 mPa · s	~1.5 mPa · s	~2 mPa · s
Optical Transparency	highly transparent ~97%	Completely opaque	Near-total opacity
Thermal stability	High up to ~3000°C	Low	Moderate

applications in various industries (Marlinda et al., 2023). The extensive research focus in recent years has led to the utilization of graphene inks for flexible electronics, wireless connectivity, and Internet of Things (IoT) applications (Yang and Wang, 2016; Pan et al., 2018). In addition to its flexibility, the stability and biocompatibility of graphene have gained interest as a promising candidate for applications in neuroscience, cardiac science, and biomedical engineering (Garcia-Cortadella et al., 2021; Gao et al., 2024). Therefore, it is no surprise that, during the last decade, graphene has been proven to be a well-known material for efficient antenna design (Dash et al., 2020; Dash and Patnaik, 2021). Nevertheless, designs for graphene-based liquid antennas remain unexplored. To the authors' knowledge, graphene conductive liquid for beam reconfigurable antenna is considered in this work for the first time. Compared to conventional metallic liquid antennas that use mercury and EGaIn, graphene liquid antenna performs better in terms of gain, bandwidth, reflection coefficient, as well as radiation efficiency (Dash et al., 2023). Additionally, it offers reconfigurability and the potential for integration into advanced communication systems. These advantages make it a compelling alternative, particularly for applications requiring flexibility and dynamic reconfiguration. In this work, we introduce a new method for designing a beam-reconfigurable antenna that uses graphene liquid inside a microfluidic channel. The various states and reconfigurations of the proposed liquid antenna are made possible by the fluidic property of the graphene liquid. In the present work, the main beam is reconfigured in different directions by moving the graphene liquid to different locations. The movement of the graphene liquid within the microfluidic channel is used to investigate a reconfiguration mechanism for the antenna beams. The antenna is realized in a rectangular-shaped poly methyl methacrylate microfluidic channel over a liquid crystal polymer substrate. The primary contributions of the paper are provided below:

- A microfluidically beam-reconfigurable antenna based on graphene liquid for mmWave communication systems is proposed. The antenna design concept utilizes the unique properties of the graphene liquid and uses its movement inside the microfluidic channel in order to provide the new degree of performance in the liquid antenna systems. The proposed graphene-based liquid antenna is realized in a rectangular poly methyl methacrylate microfluidic channel over a liquid crystal polymer substrate.
- We design and numerically analyze the microfluidically graphene-based beam-reconfigurable liquid antenna for mmWave systems by using the finite element method (FEM)-based electromagnetic (EM) simulator.
- The performance of the proposed antenna is investigated by considering the movement of the graphene liquid inside the microfluidic channel and the characteristics of the liquid at different locations inside the microfluidic channel. It is demonstrated that the antenna's radiation direction is reconfigurable, covering up to 360° angle with six beams at an operational frequency of 28 GHz.
- Finally, we investigate the performance of the proposed graphene-based liquid antenna in terms of gain, efficiency, bandwidth, reconfigurability, design flexibility and safety.

2 Design and analysis of beam reconfigurable graphene-liquid antenna

2.1 Antenna design

We design and numerically analyze the proposed graphene-based liquid antenna over mmWave frequency bands. The antenna consists the graphene liquid (≈ 1 ml volume) in a rectangular-shaped poly methyl methacrylate microfluidic channel (length $Lc = 13.74$ mm, width $Wc = 9.12$ mm, and diameter $Dc = 0.75$ mm) and placed over a metallic grounded liquid crystal polymer substrate of dimension $(17.4 \times 12.4 \times 1)$ mm^3. Platinum metal is taken into consideration as the ground plane for the proposed antenna structure. A polymethyl methacrylate microfluidic channel over a liquid crystal polymer substrate is a promising solution for reducing graphene liquid pocket formation. It provides flow control, improves adhesion, and enhances uniformity. A polymethyl methacrylate microfluidic structure provides a confined flow path for graphene liquid, ensuring consistent spreading and reduced void formation. By controlling flow dynamics (e.g., via capillary action or micropumps), the graphene liquid can be evenly distributed, minimizing unpredictable pocket formation. The liquid crystal polymer substrate is flexible, chemically stable, and has low surface roughness, making it a suitable base for uniform graphene deposition. Unlike rigid substrates like silicon, the liquid crystal polymer substrate can conform to microfluidic structures, reducing unwanted gaps or air pockets. The

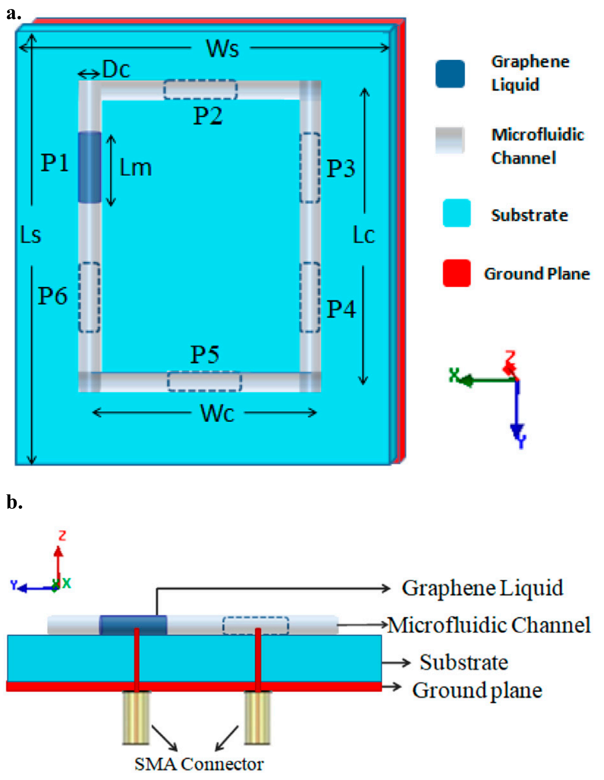

FIGURE 1
Schematic of the proposed graphene-based liquid antenna. **(a)** 3D view. **(b)** Cross-sectional view.

polymethyl methacrylate can act as an interface layer between graphene liquid and liquid crystal polymer substrate, improving surface wettability and adhesion. Moreover, the liquid crystal polymer substrate has low moisture absorption and good dielectric properties, making it ideal for graphene liquid antenna applications.

Figure 1 illustrate the proposed microfluidically graphene-based liquid antenna. The dimensions of the antenna are optimized for the operating frequency of 28 GHz. Table 2 displays the geometrical dimensions of antenna. The proposed antenna is designed, analyzed and its performance is validated using the FEM-based Ansoft HFSS software by ANSYS HFSS (2021). The center-fed single probe method is used to excite the antenna. The antenna's ground plane (bottom layer) is a metal sheet that is electrically connected to an SMA connector's external conductor. The feeding probe is electrically connected to the SMA's internal conductor and inserts into the metallic liquid from its bottom center. In six locations P1, P2, P3, P4, P5, and P6, six SMA connectors are connected. The volume of liquid has a role in the frequency reconfiguration of the antenna and the radiation pattern is reconfigured by the movement of liquid at different locations within the microfluidic channel. In order to achieve antenna beam reconfigurability, the position of the graphene liquid relocates into different positions in the microfluidic channel.

Since this graphene liquid antenna is excited by only one port at a time, the antenna evaluates only S11 for the active port. The S11 parameter has been evaluated for return loss analysis, ensuring that reflection at the excited port is minimized for efficient radiation at the desired frequencies. S12 typically represents transmission between two simultaneously active ports, which does not apply in this case because, at any given time, only one port is excited. However, when the graphene liquid moves and shifts excitation to a second port, a new S11 measurement is performed for that configuration. This means that each state of the antenna has its own S11 evaluation, but no direct S12 measurement exists. In this design, where a single port is active at any time, the essential performance metrics include: S11 for impedance matching at each excitation state, radiation patterns to analyze beam steering effectiveness, gain and efficiency to evaluate antenna performance.

2.2 EM simulation

The Ansys HFSS, an FEM-based electromagnetic (EM) solver, is used to validate the proposed designed graphene-based liquid antenna with a resonant frequency of 28 GHz ANSYS HFSS (2021). The antenna is realized by considering a fixed volume (≈ 1 ml) of graphene liquid into a poly methyl methacrylate microfluidic channel (length Lc = 13.74 mm, width Wc = 9.12 mm, and diameter Dc = 0.75 mm) over a metallic grounded liquid crystal polymer substrate of dimensions $(17.39 \times 12.40 \times 1)$ mm^3. The platinum metal is used as a ground plane for the proposed antenna structure. The ground plane of the proposed antenna is made of platinum metal. The antenna structures' dimensions and graphene liquid volume are optimized for the 28 GHz operating frequency.

For the modelling of the graphene liquid in the FEM-based EM solver, it is essential to model the conductive liquid with the surface conductivity σ_s (Equation 1) of graphene in the operational frequency 28 GHz according to Kubo formalism Gusynin et al. (2006). In the EM simulator, the graphene liquid is thus represented as a conductive liquid with a surface conductivity σ_s.

$$\sigma_s = -j\frac{e^2 K_B T}{\pi\hbar^2\left(\omega - j\tau^{-1}\right)}\left[\frac{\mu_c}{K_B T} + 2\ln\left(\exp\left(-\frac{\mu_c}{K_B T}\right) + 1\right)\right], \qquad (1)$$

where K_B stands for Boltzmann's constant, $\hbar$ for reduced Planck's constant, T for temperature, μ_c for chemical potential, τ for relaxation time, ω for angular frequency, e for electronic charge, and j for imaginary unit.

The graphene liquid flows in the microfluidic channel from one position to another. In the present work, six positions of graphene liquid in the microfluidic channel are considered. The center-fed single probe method is used to excite the antenna. The antenna is

TABLE 2 The geometrical dimensions of the proposed liquid antenna.

Ls (mm)	Ws (mm)	Lc (mm)	Wc (mm)	Dc (mm)	Lm (mm)
17.39	12.40	13.74	9.12	0.75	3

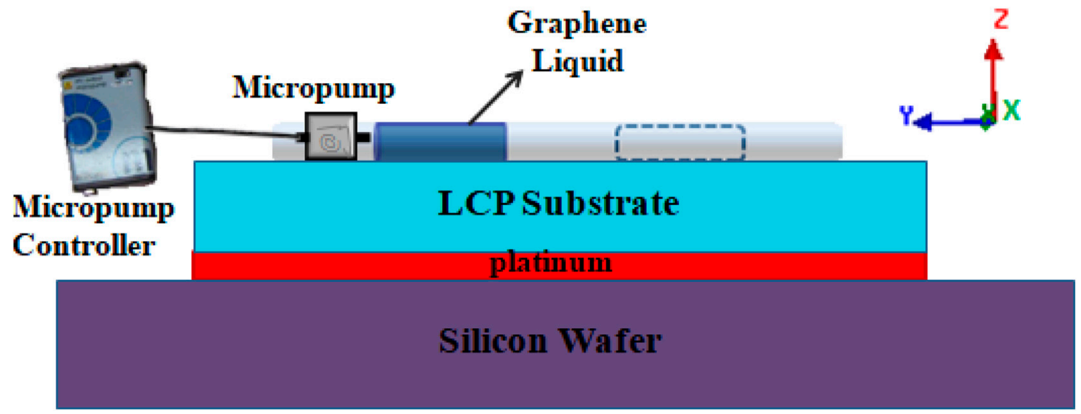

FIGURE 2
The fabrication feasibility of the proposed graphene-based liquid antenna.

excited at the centre of graphene liquid radiating elements, like dipoles. In order to feed the graphene liquid antenna in a microfluidic channel, the external conductor of the SMA connector connected to the ground plane. The feeding probe is electrically connected to the inner conductor of the SMA and inserted into the graphene liquid from the bottom center, as shown in Figure 1b. To attain six working modes and beam reconfigurability, six feeding ports are created in six positions. Impedance matching must be accomplished in order to guarantee the antenna's maximum radiation. Figure 3 illustrates the behavior of antenna impedance matching. It is evident that for each of the six graphene liquid positions, the antenna has a well-matched resonant frequency at 28 GHz.

2.3 Fabrication feasibility

The fabrication feasibility of the proposed graphene-based liquid antenna can be explained using Figure 2. The graphene liquid antenna can be mechanically supported by a silicon wafer sample. The graphene-based liquid antenna can be realized by injecting graphene liquid into a poly methyl methacrylate microfluidic channel ($\epsilon_r = 2.55$, $\tan\ \delta = 0.002$) over a metallic grounded liquid crystal polymer substrate ($\epsilon_r = 2.9$, $\tan\ \delta = 0.0025$) (Ling et al., 2015; Dey et al., 2016). The soft lithographic processes can be used to fabricate microfluidic channel (Xia and Whitesides, 1998; So et al., 2009; Dey et al., 2016). The microfluidic channel of poly methyl methacrylate elastomer can be sealed with a thin and flat sheet of liquid crystal polymer based substrate layer (Dey et al., 2016; Rodrigo et al., 2012). The graphene liquid can first be injected using a syringe into the polymethyl methacrylate channel to fill the microfluidic that defines the radiating element. The micropump unit will reconfigure the liquid volume of the antenna in the microfluidic channel. During the practical realization of the graphene liquid antenna, six SMA connectors in six locations P1, P2, P3, P4, P5, and P6 can be employed. Six feeding ports can be created in six positions to attain six working modes and beam reconfigurability. The graphene liquid flows in the microfluidic channel from one position to another. With the use of a micropump controller through microfluidic techniques, the location of the graphene liquid within the microfluidic channel can be adjusted to achieve the intended outcome. The main beam of antenna is reconfigured when the graphene liquid is displaced from one position to another. Physical displacement of the graphene liquid can be achieved through microfluidic techniques like pumping or electrowetting (Rodrigo et al., 2012). Digital microfluidics is also a new consideration for the physical displacement of metallic liquid in microfluidic channel (Wan et al., 2006).

Reconfigurability is one of the important advantages of the proposed graphene-based liquid antenna. The antenna's operating frequency can be tuned by varying the volume and shape of the graphene liquid. The volume of liquid has a role in the frequency reconfiguration of the antenna and the radiation pattern is reconfigured by the movement of liquid at various positions within the microfluidic channel. By utilizing the micropump unit to alter the graphene liquid configuration inside the microfluidic channel, the antenna achieves beam reconfigurability.

2.4 Result analysis

The reflection coefficient of the microfluidically graphene-based liquid antenna at six different positions P1, P2, P3, P4, P5 and P6 are shown in Figure 3. It can be noticed that the proposed antenna resonates at 28 GHz in six different positions P1, P2, P3, P4, P5 and P6. The antenna resonant frequency remains the same for all six positions in the microfluidic channel. The antenna offers a wideband of 10-dB impedance bandwidth of 22%. Consequently, six distinct operation states are made possible by the fluidic property of the graphene liquid in the microfluidic channel. The loss characteristics of the graphene liquid in the considered operational frequency bands can be further noticed in Figure 3. The graphene liquid antenna exhibits low losses at 28 GHz frequency. These antenna losses are significantly influenced by the conductivity of the material. Therefore, due to its high conductivity, the graphene liquid antenna has a low loss.

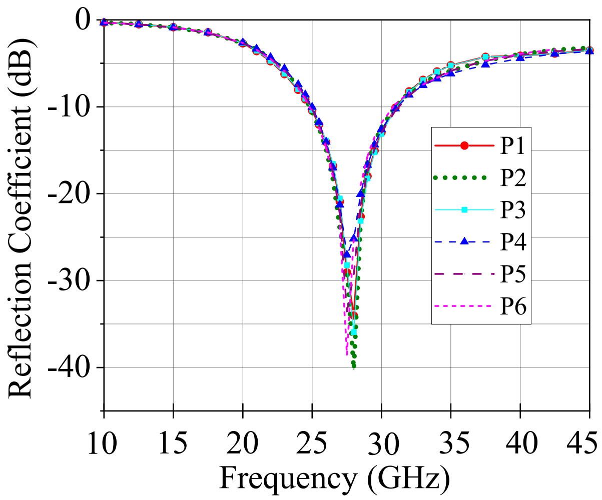

FIGURE 3
S_{11} parameter of the proposed antenna for six different positions of the graphene liquid.

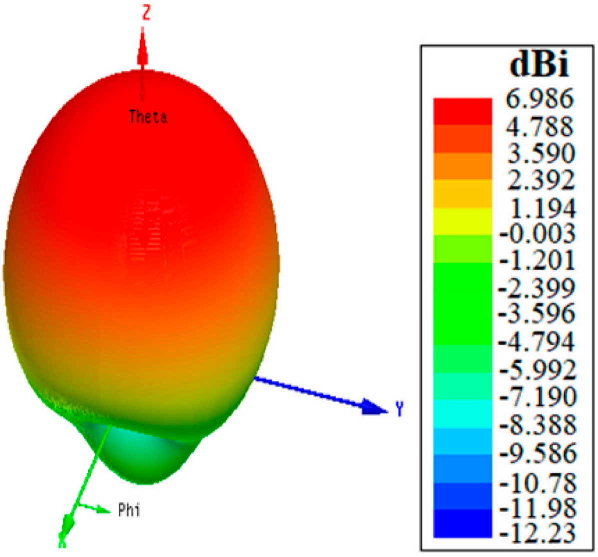

FIGURE 5
3D far-field radiation pattern of the graphene-based liquid antenna at 28 GHz.

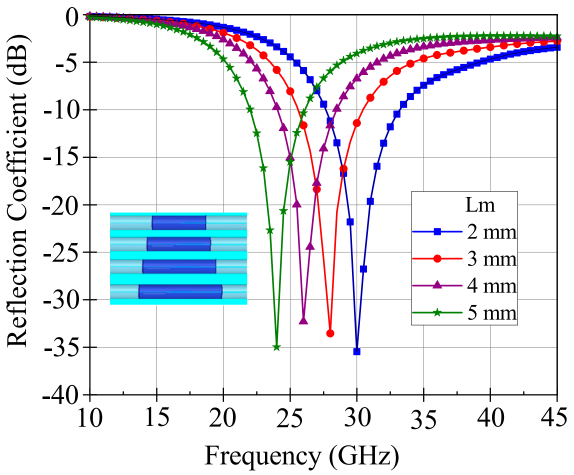

FIGURE 4
S_{11} parameter of the proposed antenna for different volumes of the graphene liquid.

The volume of the graphene liquid in a microfluidic channel plays a significant role in operating at different frequencies. Figure 4 shows the reflection coefficient of antenna at different liquid volumes to illustrate how the liquid volume affects the antenna performance. The reflection performance of the graphene liquid antenna is analyzed for different volumes, with Lm varying between 2 mm and 5 mm. The antenna operates at different frequencies between 24 GHz and 30 GHz by varying the volume of the liquid in the microfluidic channel from Lm = 2 mm–5 mm, which is clearly marked in Figure 4. Furthermore, it can be noticed that an antenna with a smaller liquid volume leads to higher operational frequency, whereas an antenna with a higher liquid volume operates at a lower frequency. The antenna resonates at 30 GHz, 28 GHz, 26 GHz, and 24 GHz when Lm = 2 mm, 3 mm, 4 mm and 5 mm are considered, respectively. The resonant frequency decreases with the volume of liquid and can be dynamically controlled in a wide frequency range.

The proposed graphene-based liquid antenna at 28 GHz attains a unidirectional symmetrical radiation pattern with a gain of 7 dBi, as illustrated in Figure 5. The antenna's gain and radiation efficiency over the frequency bands 10–45 GHz are shown in Figure 6. Over the considered frequency bands, the antenna's radiation efficiency exceeds 60%. Figure 8 shows the normalized radiation patterns of the proposed graphene liquid antenna at 28 GHz. The proposed antenna provides a reduced back lobe radiation with front-to-back ratio of 10 dB, which can be observed in Figure 8. Beam reconfiguration and six different operation states are made possible by the flow of the graphene liquid into six distinct locations within the microfluidic channel. The proposed graphene-based liquid antenna with six beams is presented in Figure 7. The antenna's normalized radiation patterns in six modes are shown in Figure 8. By appropriately choosing the location of the graphene liquid within the microfluidic channel, the antenna can be directed in D2 ($\theta = 0^\circ$), D3 ($\theta = 45^\circ$), D4 ($\theta = 135^\circ$), D5 ($\theta = 180^\circ$), D6 ($\theta = 225^\circ$), and D1 ($\theta = 315^\circ$) directions. At an operational frequency 28 GHz, the antenna reconfigures the main beam direction, covering a 360° angle. Table 3 lists the antenna main beam directions for each graphene liquid locations. The 3D pattern shows the highly directional beam. The beam width appears wider when the radiation pattern is normalized and plotted in 2D (Figure 8). This difference arises due to normalization effects and scaling in 2D plots. In 2D normalized radiation plots, power levels are scaled relative to the peak. The normalized radiation plot does not reflect absolute gain, only the relative power distribution. The proposed antenna provides $<40^\circ$ HPBW (half power beam width).

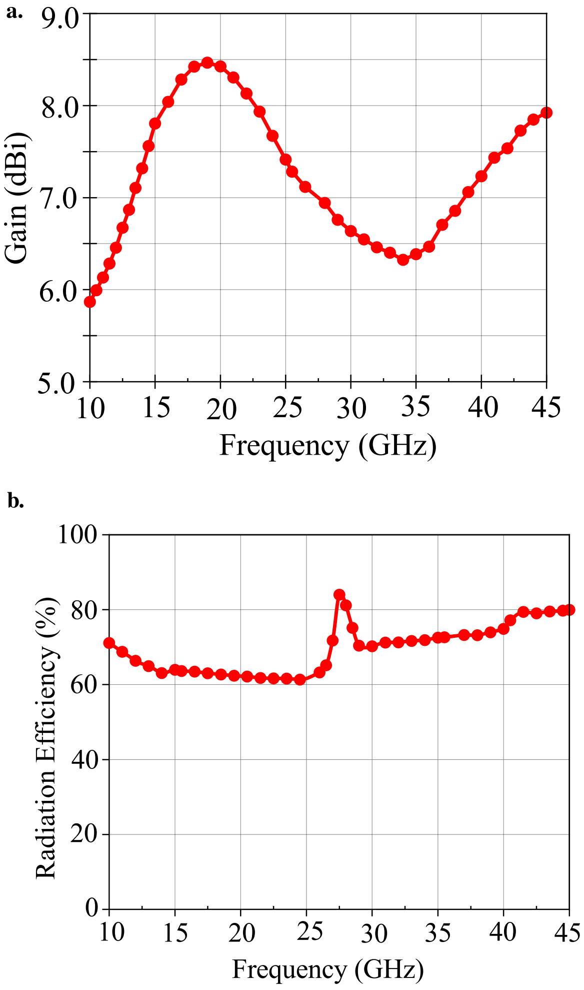

FIGURE 6
Radiation Gain and Radiation efficiency of the antenna over the frequency band 10–45 GHz. **(a)** Radiation Gain. **(b)** Radiation efficiency.

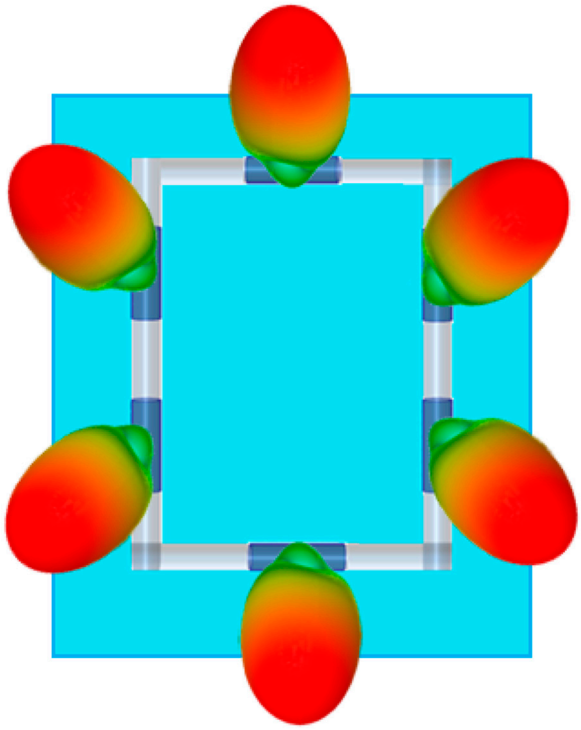

FIGURE 7
Six working modes of the graphene-based liquid antenna.

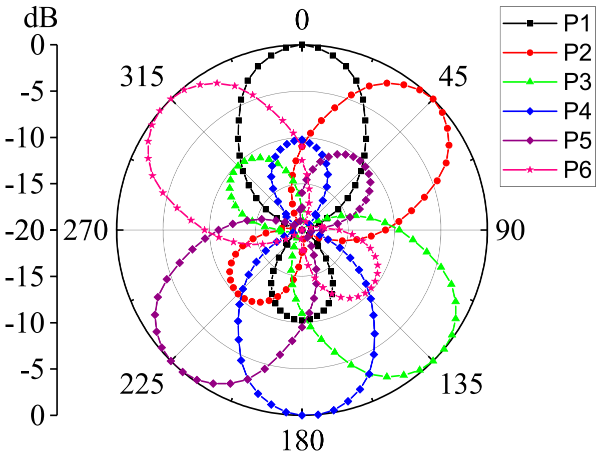

FIGURE 8
The normalized radiation pattern of the graphene-based liquid antenna in six working modes at 28 GHz.

3 Discussion

With the growth of wireless communication networks, there have been significant technological advancements in antenna design in order to meet the ever-growing requirements of users Kumar et al. (2020). Therefore, the utilization of high-performance antennas to increase coverage and reduce the complexity of a system is required (Alibakhshikenari et al., 2022; Marasco et al., 2022; Marasco Parchin et al., 2023; Hasan et al., 2022). It is thus expected that 5G antennas will be effective in terms of polarization, gain/directivity, bandwidth, efficiency, etc.

Applications requiring mechanically flexible antennas can benefit from the use of liquid antennas. The conductive metals used to make conventional antennas, like copper, make them extremely effective but unfortunately rigid. On the other hand, liquid antennas are capable of providing the required flexibility and reconfigurability. For this reason, they have recently gained significant interest in the research community of wireless communications. Fluidic and conductivity characteristics are the primary determinants of metallic liquid antenna performance. As such, a graphene-based liquid antenna performs better than the EGaIn and Mercury liquid antenna counterparts, in terms of gain, bandwidth, reflection coefficient, and radiation efficiency (Dash et al., 2023).

Graphene-based liquid antennas represent a revolutionary advancement in the field of wireless communications and antenna technology. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, offers exceptional electrical,

TABLE 3 Main beam direction of the antenna in different positions of the graphene liquid.

Position of graphene-liquid	Beam direction
P2	D2 (0°)
P3	D3 (45°)
P4	D4 (135°)
P5	D5 (180°)
P6	D6 (225°)
P1	D1 (315°)

mechanical, and thermal properties. When graphene is in liquid form, it has highly conductive and flexible behaviour that can be used to create antennas with unprecedented characteristics. Graphene production techniques have advanced significantly, leading to more cost-effective methods for large-scale production. Additionally, the liquid nature of these antennas simplifies manufacturing processes and reduces material waste, further enhancing their cost-effectiveness and scalability compared to conventional antennas. Graphene-based liquid antennas can be easily modelled into different shapes and allow for seamless integration into a wide range of devices and structures. Graphene's exceptional electronic characteristics allow for the development of antennas that can operate at a wide range of frequencies. This wideband performance is crucial for modern communication systems that must support multiple wireless standards and frequencies simultaneously. Graphene exhibits exceptional electrical conductivity and low electromagnetic losses, resulting in antennas with high efficiency and minimal signal degradation. This characteristic is particularly important for applications requiring long-range communications or operation in challenging environments with high interference or attenuation.

The overall electromagnetic performance of a liquid antenna is influenced by multiple parameters, including losses, flexibility, adaptability, reconfigurability, density, oxidation effect, and residue formation. Beyond conductivity, graphene-based liquid antennas offer additional advantages, such as lower density, higher mechanical flexibility, transparency, environmental stability and the ability to be easily processed in microfluidic channels. Graphene metallic liquids also offer advantages in terms of oxidation mitigation and reduced residue formation, which helps maintain stable electrical properties, ensuring better long-term reliability and environmental stability. Furthermore, graphene's tunable conductivity enables dynamic impedance matching and beam reconfiguration, making it particularly well-suited for reconfigurable antenna applications. In contrast, EGaIn has certain limitations, such as higher density, susceptibility to oxidation, and potential toxicity, which can affect long-term performance. The high density and oxidation-prone nature of EGaIn alloys can degrade the antenna performance over time. Thus, graphene-based liquid antennas provide superior overall performance making them more suitable for next-generation reconfigurable and flexible wireless communication systems. The reconfigurability of graphene-based liquid antennas in a microfluidic channel is an additional benefit. Additional degrees of freedom are made possible by the fluidic nature of liquid materials, which improves reconfigurability. In graphene liquid antennas, frequency reconfiguration and beam reconfiguration can be accomplished by adjusting the liquid volume and liquid movement within the microfluidic channel at different locations. This tunability allows for adaptive antenna designs that can optimize performance based on network dynamics (e.g., due to mobility), changing environmental conditions or communication requirements. In this way, graphene-based liquid antennas address the need for high-performance, flexible, and adaptable antennas in modern communication systems. Their unique combination of properties offers significant advantages over conventional antennas, paving the way for 5G mmWave wireless communication system.

4 Conclusion

A microfluidically beam-reconfigurable directional antenna using graphene liquid for the mmWave wireless communication system was presented in this work. The reconfiguration mechanism of the proposed antenna is based on the movement of the graphene liquid inside the microfluidic channel. The antenna is realized in a rectangular-shaped poly methyl methacrylate microfluidic channel over a liquid crystal polymer substrate. The antenna is reconfigured in its radiation direction, covering up to 360° angles with six beams ($0^\circ, 45^\circ, 135^\circ, 180^\circ, 225^\circ$ and 315° at an operational frequency of 28 GHz. Moreover, the antenna provides a wideband of bandwidth about 22% and a gain of 7 dBi. Furthermore, frequency reconfiguration is achieved by controlling the volume of the liquid inside the microfluidic channel. The presented results reveal that the proposed graphene-based liquid antenna is promising for future applications in wireless communications. As next-generation wireless networks demand high-performance antennas, the proposed microfluidically beam-reconfigurable antenna using graphene liquid will cater to the needs of the ever-growing network users.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SD: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Writing–original draft, Writing–review and editing. CP: Project administration, Resources, Supervision, Writing–review and editing, Conceptualization, Formal Analysis, Methodology, Validation, Visualization. IK: Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing–review and editing, Conceptualization, Formal Analysis, Methodology, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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