Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Multilayer graphene-based rectenna for RF energy harvesting at the 2.4 GHz band

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ARTICLE INFO

Article history:
Received 22 December 2024
Received in revised form
27 April 2025
Accepted 1 May 2025

Keywords:
RF energy harvesting
Multilayer graphene
Rectenna efficiency
Impedance matching
Output voltage

ABSTRACT

This research examines the efficiency of copper, single-layer graphene, and multilayer graphene rectennas for radio frequency (RF) energy harvesting at a resonant frequency of 2.4 GHz. Using advanced simulation software, key antenna parameters such as return loss (S11), Voltage Standing Wave Ratio (VSWR), gain, and output voltage were analyzed to evaluate the performance of the designed antennas in capturing and converting RF energy. The results show that the multilayer graphene antenna provides the best performance, with a return loss of -44.53 dB and a VSWR of about 1.01, indicating excellent impedance matching and minimal power reflection. Although the copper antenna achieved the highest gain of 5.63 dB, the multilayer graphene antenna showed a similar gain of 5.47 dB, with only a small difference in effective radiated power. In addition, the multilayer graphene antenna produced the highest output voltage among the three types, highlighting its potential for RF energy harvesting. These findings suggest that multilayer graphene can improve the energy harvesting performance of rectennas by enhancing impedance matching and maximizing voltage output. Therefore, multilayer graphene appears to be a promising alternative to traditional copper materials for RF energy harvesting applications, especially for powering low-energy devices such as wireless sensors and Internet of Things (IoT) technologies.

1. Introduction

Technological advancement, conceptualized by the Fourth Industrial Revolution (4IR) over the past decade, pushes forward a wave of rapid development in wireless systems such as wearable electronics and Internet of Things (IoT) devices (Carbajales et al., 2015). These technological innovations are quickly gaining traction across multiple sectors, such as healthcare, where wearable sensors are used to monitor vital signals of the patients in real time, and consumer electronics, where smart devices enable seamless interaction among the connected environments (Bao and Chen, 2016). IoT systems revolutionize the automotive and industrial sectors by enhancing automation and data-driven processes. As smart cities are gaining popularity among the population, IoT systems are being deployed for multiple use cases, such as infrastructure management, energy efficiency, and environmental monitoring. To cope with ever-evolving technology, the need for sustainable, long-lasting, and autonomous power solutions proves to be critical to keep up with technology (Chen et al., 2014). This led to the growing interest in energy harvesting techniques, which hold great potential to power these low-energy devices while extending the operational lifetime without the need for frequent battery replacements.

Energy harvesting refers to the process of capturing energy from the surrounding environment and converting it into usable electrical power (Chao et al., 2014; Ullah et al., 2022). The implementation of energy harvesting effectively enables electronic devices to function effectively in situations without the need for conventional power sources, thus effectively removing or reducing the need for wiring or frequent battery replacements (Chen et al., 2014). Among the current energy harvesting strategies, such as solar, wind, and thermal energy, this research mainly focuses on RF energy harvesting. RF

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https://doi.org/10.21833/ijaas.2025.05.011
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energy harvesting is the process of capturing and converting the ambient RF electromagnetic waves into usable electrical energy (Tran et al., 2017). As compared to other energy harvesting methods, RF energy harvesting has the capability to produce a continuous and sustainable energy source due to the abundance of RF signals in the ambient environment (Prauzek et al., 2018). This energy harvesting technique is particularly useful in powering low-energy devices such as sensors, IoT devices, and wearable electronics, therefore effectively avoiding the need for frequent battery replacements or wired power supplies.

Rectenna, a portmanteau of rectifying antenna, is used to harvest RF energy captured from the environment (Zhang et al., 2024). For the past decade, various research has been made on the improvement of the rectenna for wireless RF energy harvesting to improve the output of the rectenna, mainly the DC power harvested and conversion efficiency, to effectively substitute conventional power sources. For the RF energy harvesting technique to be effectively used to power low-energy devices and wearable electronics, the designed rectenna needs to achieve several properties, such as being flexible, lightweight, mechanically robust, resistant to corrosion, and having high conversion efficiency. For centuries, the conventional material used in almost all electronic devices has been copper due to the material's high conductivity and stability. However, due to the heat dissipated from the copper material during the operation of these electronic devices caused by the copper's resistance, the energy converted into heat is often wasted. As such, multiple research projects have been carried out to substitute the conventional copper material used in rectenna to further enhance the energy harvesting capabilities of the rectenna. One of the potential candidates to act as the metal patch and ground of the rectenna instead of the copper material is carbon materials. Among the discovered carbon materials, graphene stands out among its peers due to its outstanding properties, such as excellent electrical and thermal conductivity (Cheah et al., 2024). Graphene is a one-atom-thick, two-dimensional carbon material structured in a unique honeycomb lattice carbon atom structure (Zhen and Zhu, 2018). The unique structure of the graphene material enables the material to exhibit higher charge carrier mobility and electrical conductivity (Ram et al., 2023). The unique structure of the graphene material also allows the implementation of multilayer graphene architecture, enabling further tuning of its characteristics (Krajewska et al., 2017). When in a multilayer structure, the interlayer interaction of the graphene layers can influence the overall conductivity and flexibility of the graphene structure, making the multilayer graphene material a potential good substitute for the copper material (Akbari et al., 2011). Hence, this paper aims to evaluate the performance of copper, single-layer graphene, and multilayer graphene as the core materials for the antenna in an RF energy harvesting system.

2. Proposed design

2.1. Antenna

Among the common antenna designs, microstrip patch antennas are one of the more popular antenna designs that are researched due to their ease of design and fabrication (Islam et al., 2018). The designed microstrip patch antenna can be printed directly onto a circuit board, which makes it easy to fabricate, low-cost, and have a low profile. The patch antenna design consists of a patch antenna and microstrip transmission line sitting on top of the substrate with a metal ground below (Shinohara, 2013). Conventionally, the high-conductivity metal used as the core material of the antenna is made up of copper. In this paper, the inset feed microstrip patch antenna is designed using the CST Studio Suite software.

To design the microstrip patch antenna, essential parameters such as the operation frequency, type of substrate material, dielectric constant, height of substrate, and the input impedance were first determined. Table 1 is used to show the values used in this research.

Table 1: Essential parameter values

Resonant frequency	f_o	2.4 GHz
Dielectric constant	ε_r	4.3
Height of substrate	h	1.6 mm
Input impedance	R_{in}	50 Ω
Material type	FR-4	

The parameters of the microstrip patch antenna are then calculated using the formulas below:

$$Patch\ Width\ (Wp) = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}} \quad (1)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W_p}\right]^{-\frac{1}{2}} \quad (2)$$

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \quad (3)$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W_p}{h}+0.8\right)} \quad (4)$$

$$Patch\ Length\ (Lp) = L_{eff} - 2\Delta L \quad (5)$$

where, f_r is the resonant frequency; W_p is the patch width; h is the thickness of the dielectric substrate; ε_r is the dielectric constant of the substrate; c is the speed of light: 3 x 10^8. After obtaining the patch parameters, the inset feed length (y_o) and width (x_o) need to be measured, as these parameters could affect the input impedance to some extent. Variation of the inset feed length would produce changes in the return loss, while variation of feed width would produce changes in the resonant frequency. The inset width is typically half of that of the feed width (W_f), while the length of the inset feed is an optimized value. The formulas for the inset feed length and width are calculated with the following formulas:

$$W_f = \frac{7.48 \times h}{e^{\left(z_o \frac{\sqrt{\varepsilon_r+1.41}}{87}\right)}} - 1.25 \times t \quad (6)$$

$$y_o = \frac{Lp}{\pi} \cos^{-1}\left(\sqrt{\frac{Z_o}{R_{in}}}\right) \quad (7)$$

where, W_f is the microstrip feed width; y_o is the inset length; Z_o is the input impedance; R_{in} is the input resistance. After finishing the initial calculation as the estimation of the parameters of the antenna, the antenna structure is modelled and simulated with the help of the CST Studio software. The structure of the antenna is shown in Fig. 1.

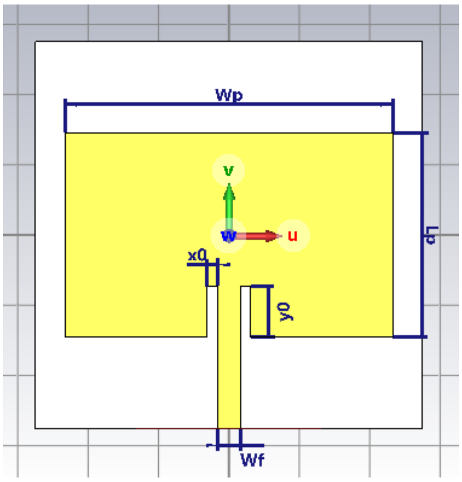

Fig. 1: Model of microstrip patch antenna

The antenna structure is then optimized using the parameter sweep function of the CST Studio Suite software to obtain the best result of the antenna under given circumstances. Table 2 presents the parameter values that are calculated and the parameter values after the optimization process.

2.2. Rectifier circuit

After the design of the antenna is finalized using the CST Studio Suite software, the rectifier circuit then needs to be designed with the help of the Advanced Design System (ADS) software. The rectifier circuit is one of the core components of the RF energy harvesting system, as the circuit converts the received alternating current (AC) power into direct current (DC) power. As such, it is important that the rectifier circuit is properly designed to ensure that the performance of the rectifier circuit would not negatively impact the overall performance and conversion efficiency of the RF energy harvesting system. In this research, the Greinacher voltage doubler is employed as the rectifier circuit as it can provide improved performance with minimal additional components compared to its counterparts, effectively reducing the size and weight of the rectenna (Subbyal et al., 2022). The HSMS2860 Schottky diode acts as the primary component of the rectifier circuit, as the Schottky diode is used as the rectifier of the circuit. Schottky diodes are normally employed in RF energy harvesting systems, as these diodes normally have high reverse leakage current and low reverse breakdown voltage, which greatly improves the output of the rectifier circuit. By utilizing the Greinacher voltage doubler circuit as the rectifier circuit for the rectenna, the DC output voltage of the system can be effectively improved while maintaining a reduced component count, which would ensure the overall efficiency of the rectifier system. The proposed Greinacher voltage doubler circuit is shown in Fig. 2.

Table 2: Calculated and optimized parameter values

Parameter	Calculated value (mm)	Optimized value (mm)
Patch width (Wp)	38.73	46.5
Patch length (Lp)	30.11	29.00
Feed width (Wf)	2.95	3.17
Inset length (y0)	7.3	7.16
Inset width (x0)	1.475	1.5

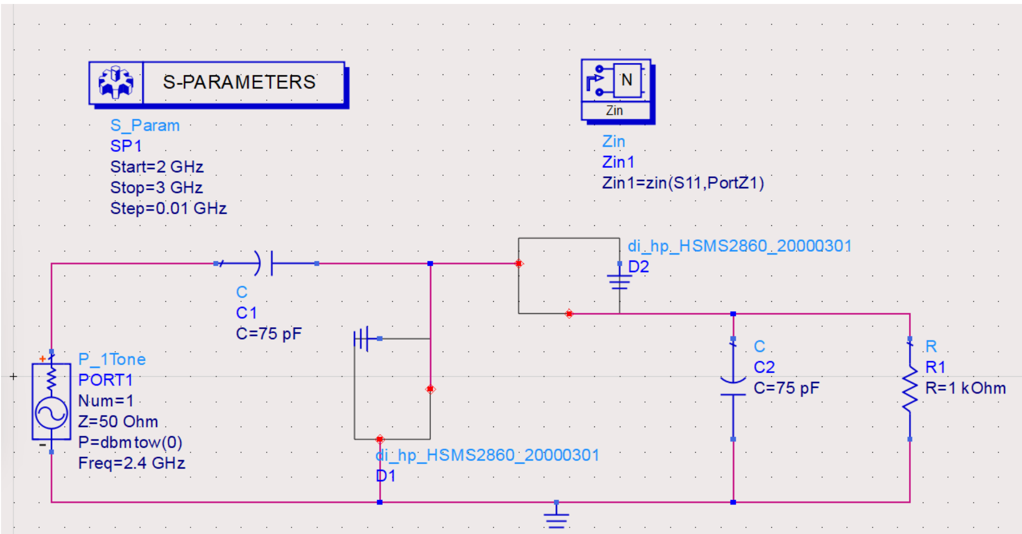

Fig. 2: Proposed Greinacher voltage doubler circuit

2.3. Rectenna

After completing the design process of both the antenna and rectifying circuit, the final proposed design of the rectenna can then be designed using the ADS software. The S-parameter of the antenna is exported using the CST software into ADS to model the characteristics of the antenna. The modelled antenna is then connected to the rectifying circuit with the help of the Smith Chart tool to match the impedance of both antenna and rectifying circuit, ensuring maximum power transfer while minimizing reflection loss (Le et al., 2008; Papotto et al., 2011). The impedance matching circuit designed using the Smith Chart tool is shown in Fig. 3, while the full design of the rectenna is shown in Fig. 4.

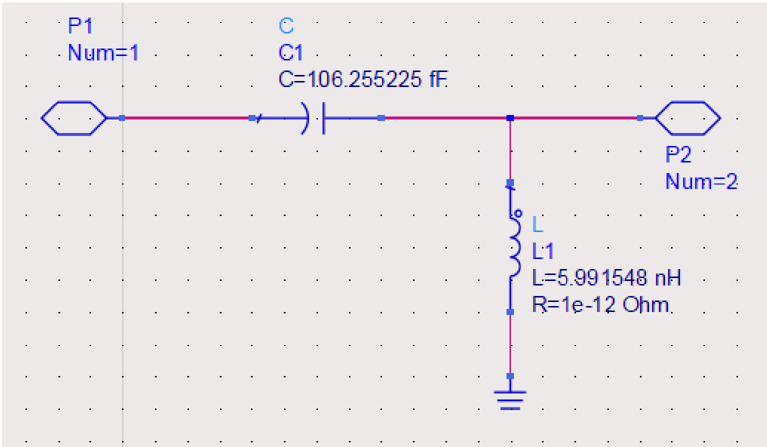

Fig. 3: Impedance matching circuit

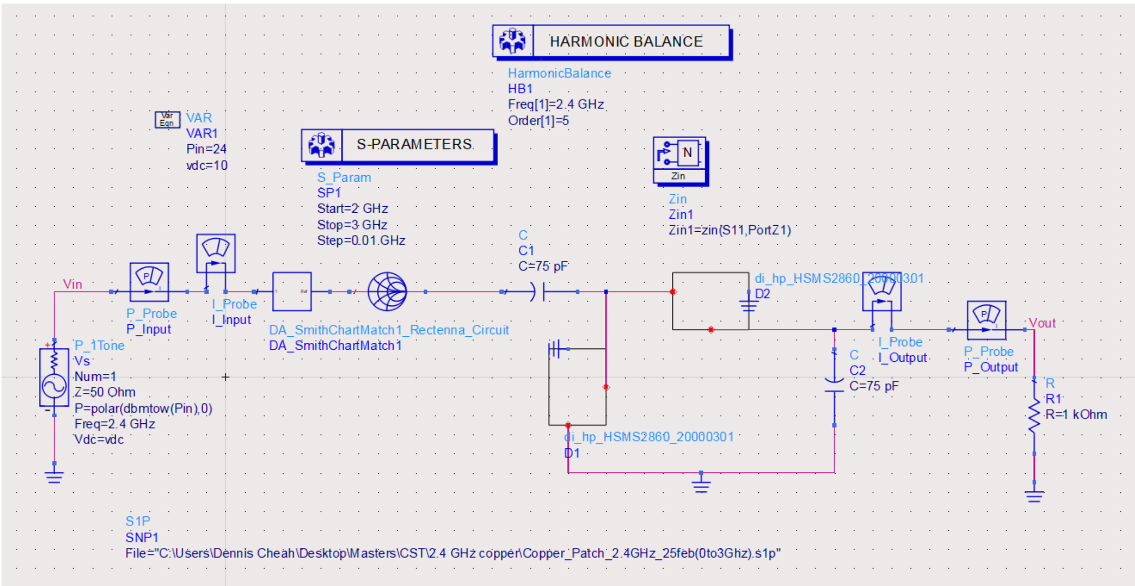

Fig. 4: Proposed design of the rectenna

3. Results and discussion

As the aim of the research is to investigate the effect of multilayer graphene as a substitute for copper metal for RF energy harvesting purposes, the designed antenna is simulated with copper, single-layer graphene, and multilayer graphene to elucidate the performance of the multilayer graphene material.

3.1. S-parameters

As shown in the Figs. 5, 6, and 7, the simulated results of the return loss (S_{11}) are the lowest when multilayer graphene is deployed at -44.53 dB, while the S_{11} of copper is at -29.83 dB, with the resonant frequency of all three designs to be approximately 2.4 GHz. The return loss of the multilayer graphene antenna decreased by around -15.7 dB when compared to the copper antenna, indicating a marked improvement in the impedance matching and energy absorption efficiency. As a lower return loss indicates a lower amount of power being reflected to the source, this allows the multilayer graphene antenna to capture and transfer a higher amount of incident energy into the rectifying circuit. This improvement in power absorption shows that the multilayer graphene antenna can utilize more of the transmitted power, which enhances the efficiency of the RF energy harvesting system. As graphene possesses unique electrical properties, especially in the case of multilayer configurations, this contributes to a better impedance matching ability and reduced energy loss, making the multilayer graphene material superior to copper in terms of maximizing harvested energy.

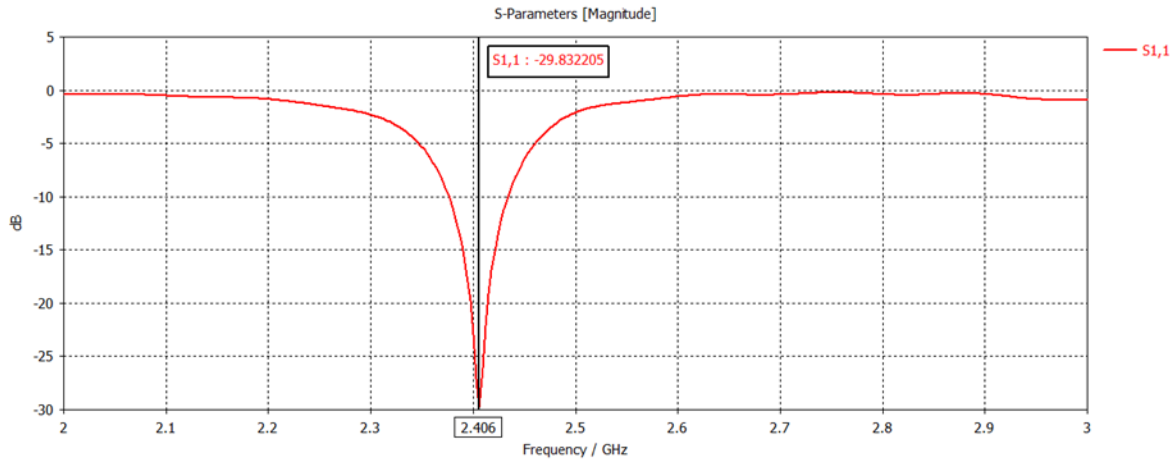

Fig. 5: The return loss of the copper antenna

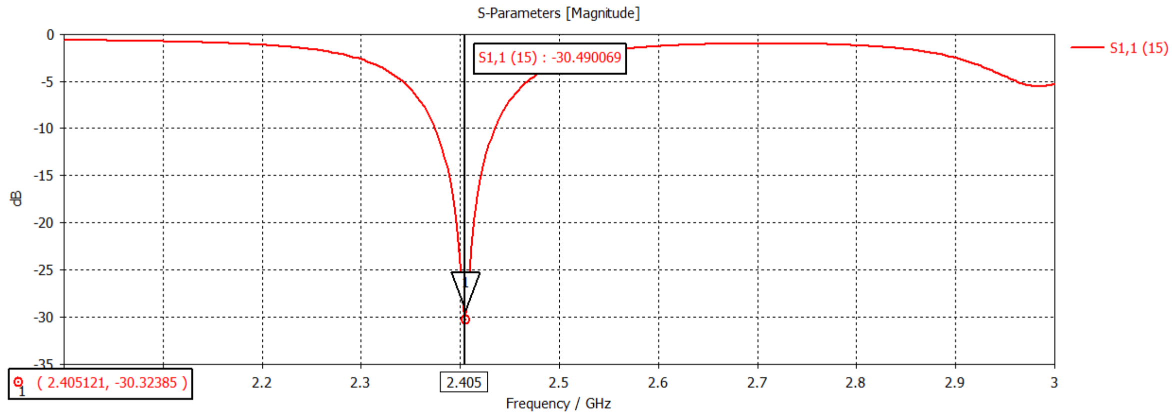

Fig. 6: The return loss of a single-layer graphene antenna

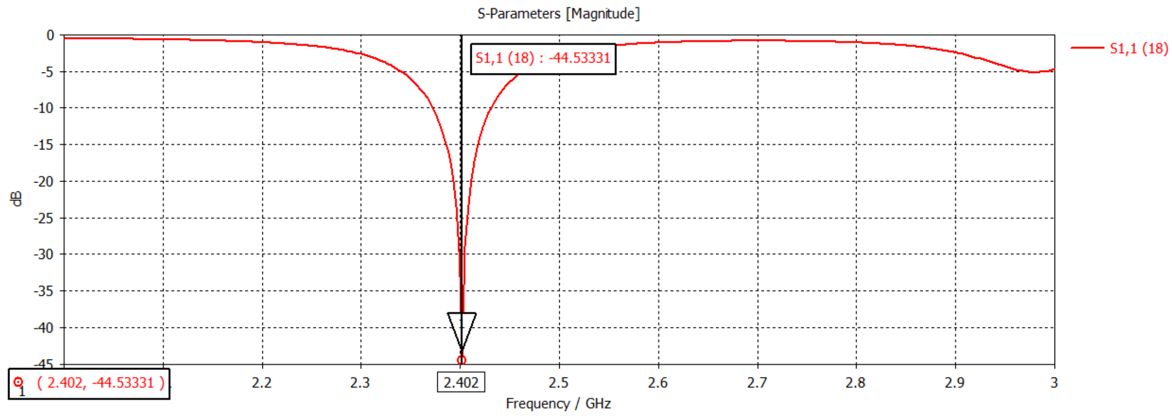

Fig. 7: The return loss of the multilayer graphene antenna

3.2. Voltage standing wave ratio (VSWR)

Voltage Standing Wave Ratio (VSWR) is a key indicator of impedance matching and power transfer in RF systems. As can be seen through Figs. 8, 9, and 10 multilayer graphene antenna exhibits the lowest VSWR of approximately 2.402, while copper antenna exhibits a VSWR of approximately 2.406 as seen in Fig. 8. As a VSWR value close to 1 indicates near perfect impedance matching, the multilayer graphene antenna designed in this study can have better impedance matching than the copper antenna as well as the single layer graphene antenna. The improved impedance matching of the multilayer antenna design allows the antenna to be able to capture and convert a greater amount of available ambient RF energy into usable power. Furthermore, the improved VSWR of the multilayer graphene antenna structure contributes significantly to improving the overall performance and efficiency of the RF energy harvesting system.

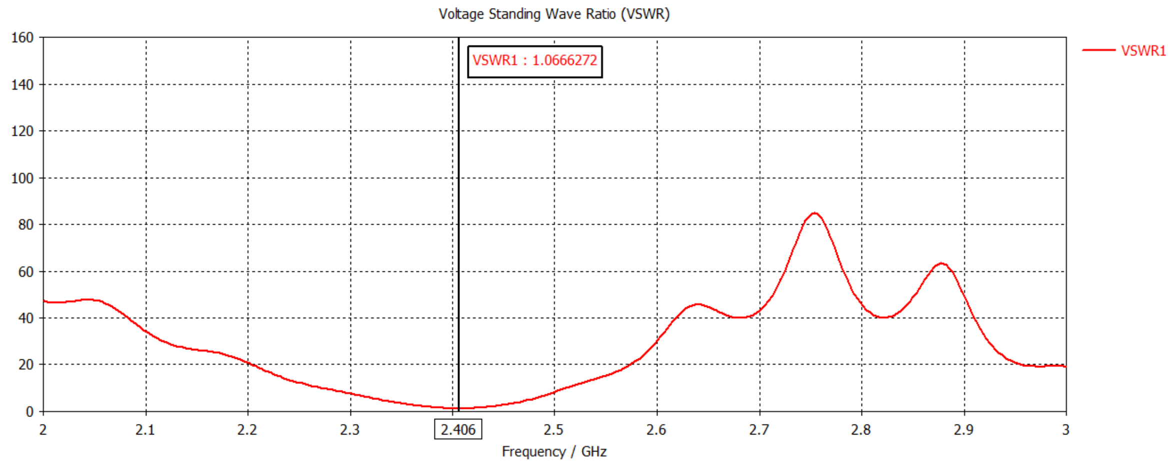

Fig. 8: The VSWR of the copper antenna

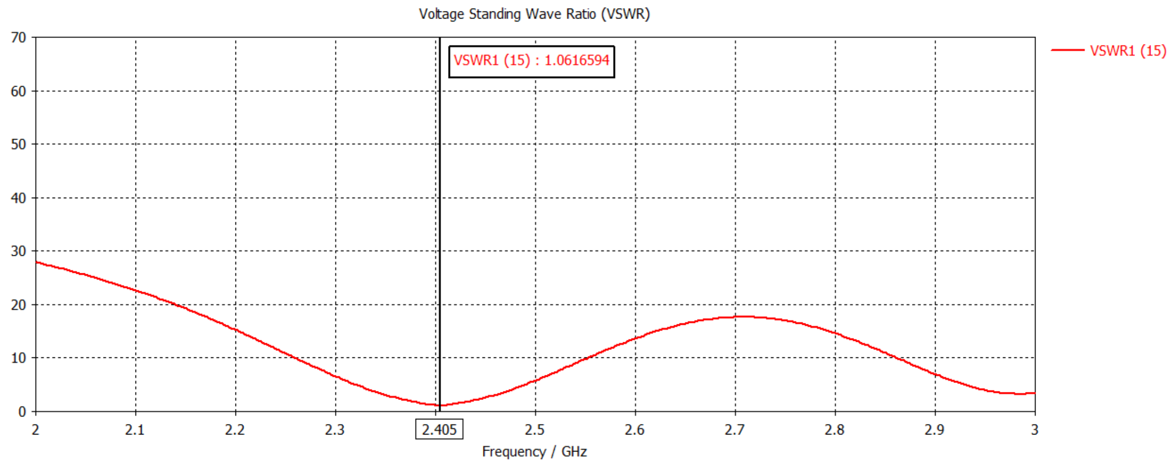

Fig. 9: The VSWR of the double-layer graphene antenna

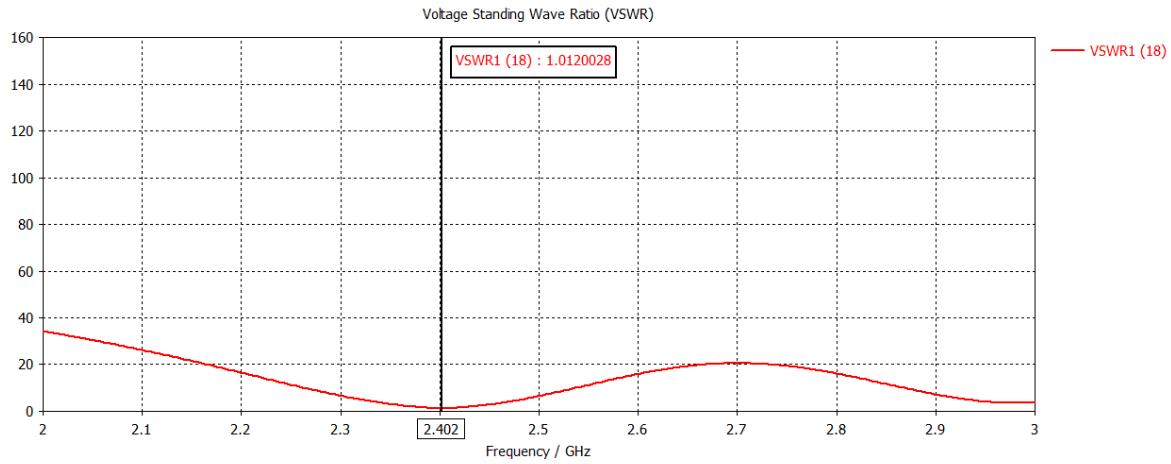

Fig. 10: The VSWR of a single-layer graphene antenna

3.3. Gain (dBi)

In terms of gain of the antenna, the copper antenna exhibits the highest gain at 5.63 dBi in Fig. 11, while the single-layer graphene antenna exhibits the lowest gain at 5.17 dBi in Fig. 12. Although the gain of the multilayer graphene antenna is lower than that of the copper antenna, as seen in Fig. 13 at 5.47 dBi, the small difference in gain of 0.16 dBi would only translate to a change in effective radiated power of around 3.8%, which would not heavily impact the power of the multilayer graphene antenna. The effective increase of 0.3 dBi from the single-layer graphene antenna to the multilayer graphene antenna, on the other hand, is worth taking note of as this increase in gain can signify that the implementation of the multilayer graphene structure can be substantially improved with a better design of the multilayer graphene architecture. The 0.3 dBi increase can be roughly translated to an increase of 7% in effective radiated power. This increase in gain indicates that the usage of a multilayer graphene structure is able to meaningfully enhance the performance of the RF energy harvesting system, enabling more efficient power capture and potentially better system reliability. Thus, the results highlight the multilayer graphene structure as a promising material for optimizing gain while balancing the impedance matching and efficiency in RF energy harvesting applications.

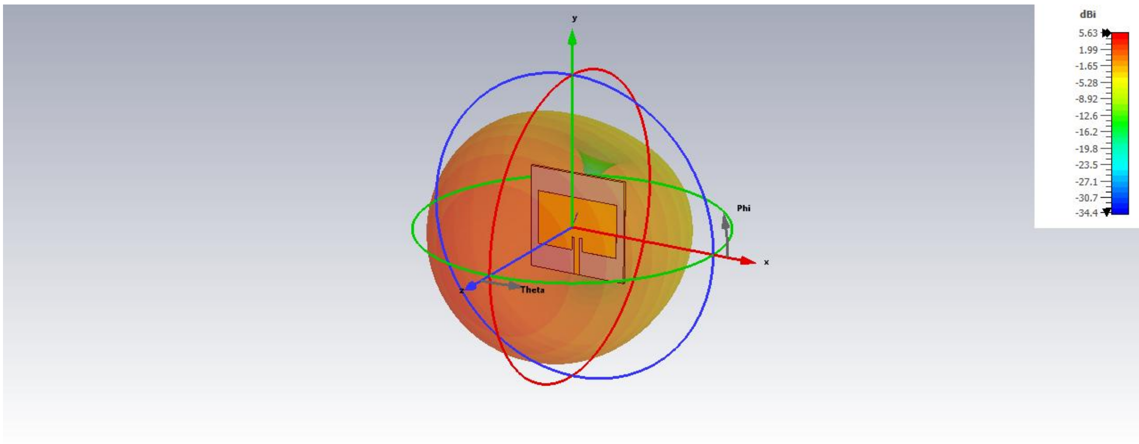

Fig. 11: Gain of the copper antenna

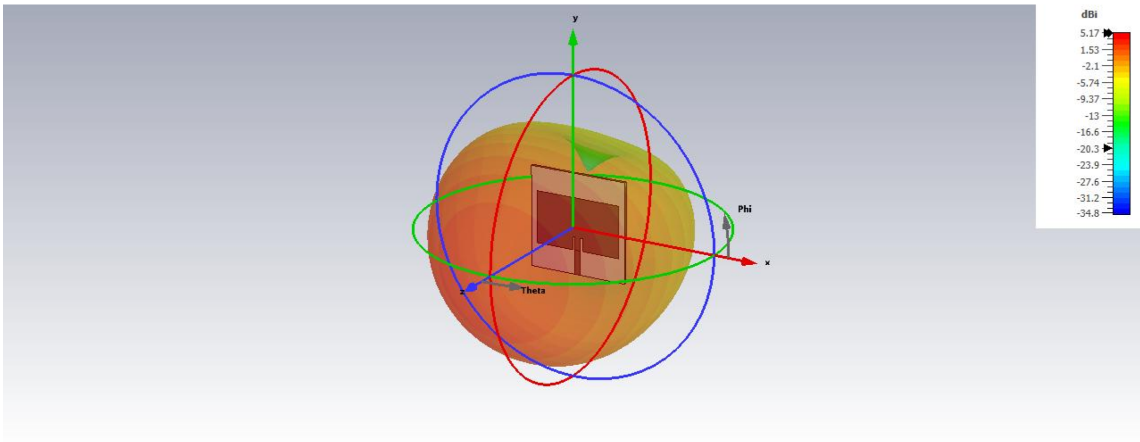

Fig. 12: Gain of the single-layer graphene antenna

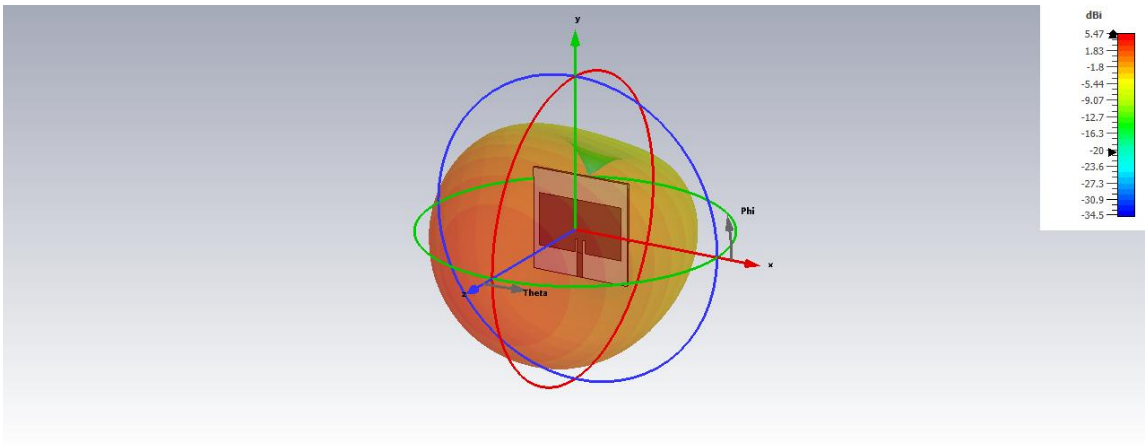

Fig. 13: Gain of the multilayer graphene antenna

3.4. Output of rectenna system

Figs. 14, 15, and 16 show the output of the rectenna as an RF energy harvesting system when connected to the three different material antennas. The comparison of the voltage output of the energy harvesting system between the copper, single-layer, and multilayer graphene antennas demonstrates the importance of material choice for RF energy harvesting efficiency. The results show a clear indication in the progression of output voltage, with the copper antenna achieving an initial voltage output of 3.184V, the single-layer graphene antenna reaching 3.271V, and the multilayer graphene antenna reaching 3.320V. The incremental increase in voltage output can indicate that the graphene material, due to its unique structure and excellent properties such as high electrical conductivity and impedance matching, can effectively enhance the RF energy harvesting ability of the rectenna. The multilayer graphene antenna design provides a significant advantage as it effectively reduces resistance while increasing surface conductivity. The findings in this research confirm that the usage of a layered graphene structure can effectively improve the output of the RF energy harvesting system when compared to the monolayer and copper antenna, making the multilayer graphene structure a promising material for RF energy harvesting systems to efficiently power low-powered applications.

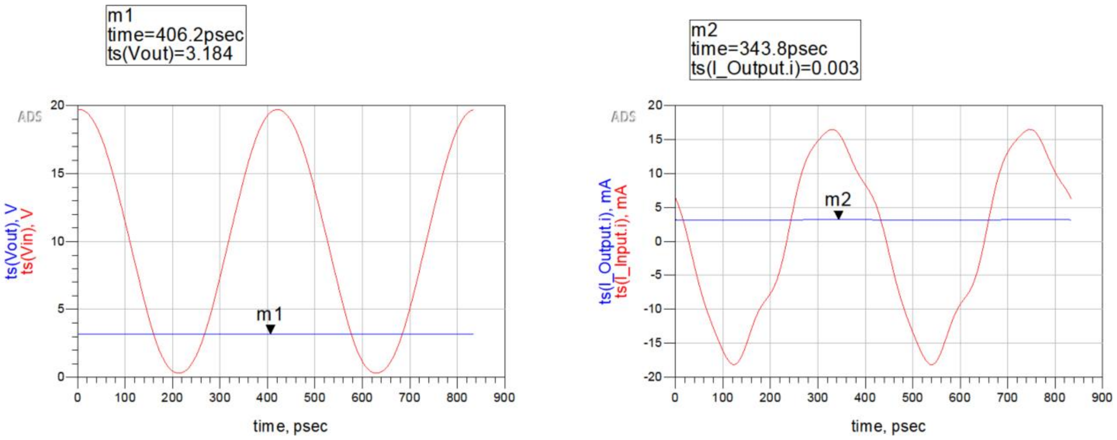

Fig. 14: Voltage and current output of the rectenna system using a copper antenna

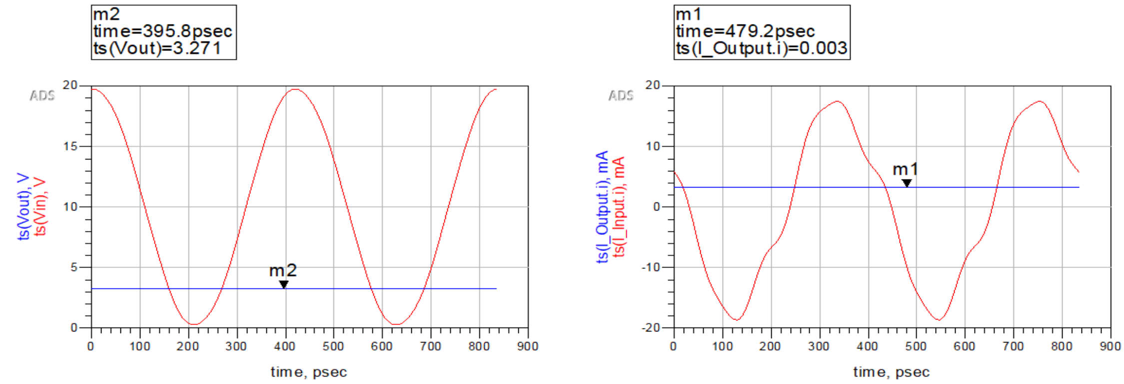

Fig. 15: Voltage and current output of the rectenna system using a single-layer graphene antenna

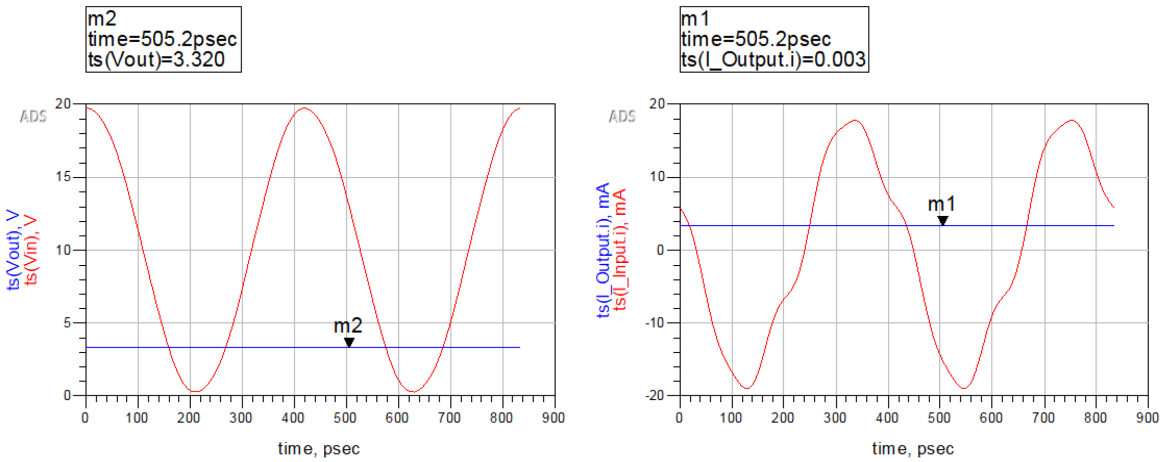

Fig. 16: Voltage and current output of the rectenna system using multilayer graphene antenna

3.5. Challenges and limitations of graphene replacing copper

Despite graphene showing its potential as a replacement for copper in RF energy harvesting systems, there are several challenges that need to be resolved before adopting graphene as a replacement for copper material. One such challenge is the issues faced in the mass production of high-quality graphene. Current methods in the production of graphene face a significant challenge in achieving a balance between the quality and quantity of graphene produced. High-quality graphene material is essential in RF energy harvesting applications as the graphene requires minimal defects, while the current large-scale production methods would often compromise the quality of graphene produced (Zhu et al., 2018). Although the emergence of methods such as CVD and electrochemical exfoliation shows promising signs, the scaling of these processes to meet the industrial demands while ensuring the quality of graphene remains a challenge (Yang et al., 2016; Zhong et al., 2015).

While both graphene and copper have their own advantages and limitations in the field of RF energy harvesting applications, copper remains the industry standard due to its mature fabrication process as well as its outstanding properties. By having a mature fabrication process and infrastructure, the fabrication of the copper-based antenna is at a much lower cost when compared to a high-quality multilayer graphene due to techniques such as CVD requiring high temperatures, as well as requiring vacuum conditions to produce. While there exist alternative fabrication methods of multilayer graphene antenna, such as LIG and screen printing, it is still lacking in the cost efficiency department compared to the conventional processing of copper.

Graphene is considered a promising material because of its unique properties, including flexibility, low weight, and high sustainability. Although copper has higher electrical conductivity in direct comparison, graphene's electrical performance can be improved through layer optimization and advanced doping techniques. These improvements make graphene suitable for high-frequency applications. Additionally, graphene’s smooth surface helps reduce signal loss, unlike copper, which can suffer from surface roughness and oxidation. Copper's tendency to oxidize reduces its performance over time, especially in humid or corrosive environments, and often requires protective coatings, making the manufacturing process more complex. In contrast, graphene is more resistant to environmental conditions and does not corrode like copper. Its chemical stability also enhances the long-term reliability of graphene-based antennas, especially in harsh environments.

From an environmental perspective, graphene is more eco-friendly, which is important as industries move toward greener technologies. Graphene can be produced using abundant carbon sources, while copper requires mining and refining processes that can harm the environment through soil degradation, water pollution, and high carbon emissions. The extraction of copper is also energy-intensive and contributes to resource depletion, especially when producing industrial-grade copper for RF energy harvesting. In contrast, multilayer graphene antennas can be produced using more sustainable methods, such as LIG, which results in a smaller environmental footprint. This makes graphene more suitable for industries aiming to adopt environmentally friendly practices.

In RF energy harvesting systems, the lifetime and reliability of the systems are crucial to maintain a sustained performance of the system over time. While the fabricated prototype of the RF energy harvesting system might exhibit exceptional properties, various environmental and operational factors could influence the performance of the system over time. In comparison with copper, which undergoes oxidation and surface degradation, graphene’s atomic structure can provide an inherent resistance towards corrosion. Corrosion testing of both graphene and copper antennas shows that the graphene-based antenna can maintain steady electrical properties after over 336 hours of salt spray corrosion testing, while the copper-based antenna shows rapid degradation in its performance (Hui et al., 2023). However, proper encapsulation still needs to be performed using materials such as polymer coatings to enhance the durability and stability of the RF system’s performance, as it will reduce the exposure of the graphene material to environmental conditions such as high humidity and prolonged UV radiation, which might cause surface contamination. The long-term durability of the graphene antenna was also tested by using accelerated aging tests which indicate that the graphene material is still able to maintain its conductive properties over time which would balance out its higher initial fabrication costs over copper as it reduces the need to replace the antenna in RF energy harvesting systems (Lukacs and Pietrikova, 2022).

4. Future works

Although this research shows the potential of using multilayer graphene as the main material for antennas in RF energy harvesting systems, several areas still require further investigation to ensure that multilayer graphene rectennas are suitable for real-world applications. Future research should focus on experimental validation, system scalability, performance optimization, environmental impact assessment, and testing for specific applications.

As this research is a simulation-based study, experimental validation of the simulated results is required to verify the feasibility of the proposed design beyond simulations. The fabrication of the physical prototype can be achieved through the help of several techniques such as laser-induced graphene (LIG) printing, chemical vapor deposition (CVD) and screen printing, which allows the creation of flexible and compact antenna structures on various substrates which includes polymers and textiles, further enhancing the applicability of the antenna in diverse environments (Ram et al., 2021; Sindhu et al., 2021). After the graphene layer is successfully printed onto the antenna, its shape can be defined using methods such as photolithography, laser ablation, or by using a screen mask during the screen-printing process. The antenna can then be combined with other rectifier components, such as a Schottky diode and capacitors, to create a fully functional prototype. This prototype can be tested and validated using a Vector Network Analyzer (VNA) to measure key performance metrics such as return loss, Voltage Standing Wave Ratio (VSWR), and gain, and to compare these results with simulation data. Additional testing in an anechoic chamber allows for controlled measurements of the antenna's radiation pattern, gain, directivity, and overall efficiency. Finally, the voltage output and power conversion efficiency of the rectenna can be evaluated using an oscilloscope and a power detector.

To further optimize the prototype after being validated, further research on topics such as reducing the loss in graphene-to-metal contact interface, impedance matching between antenna and rectifier, as well as exploring alternative substrate materials, can be conducted to further enhance the feasibility of multilayer graphene rectenna as an efficient RF energy harvesting system.

5. Conclusions

In this study, the performance of the copper, single-layer graphene, and multilayer graphene antennas when deployed in an RF energy harvesting system with a resonant frequency of 2.4 GHz was compared. With the help of advanced simulation software, it can be observed that the multilayer graphene antenna achieved the lowest return loss and VSWR, which indicates that the multilayer graphene antenna has the most optimal impedance matching and power transfer among the proposed designs. Although the gain exhibited by the copper antenna is the highest at 5.63 dBi, the multilayer graphene antenna does not fall behind significantly, demonstrating a competitive gain of 5.47 dBi. The effective increase in gain from the monolayer graphene antenna to the multilayer graphene antenna of 0.3 dBi further validates the effectiveness of deploying a multilayer graphene structure in enhancing the power-capturing capabilities of the antenna. Furthermore, the multilayer graphene antenna produces the highest amount of voltage output when used in the RF energy harvesting system, highlighting the potential of the multilayer graphene structure in powering low-powered energy applications.

Overall, the findings of this study show that multilayer graphene has strong potential and could serve as a suitable alternative to conventional copper in improving the performance of RF energy harvesting systems. Its improved impedance matching, competitive gain, and voltage output make multilayer graphene a promising replacement for copper. This study adds to the growing body of research on graphene-based materials in RF energy harvesting, highlighting their advantages and potential use in sustainable power solutions, such as powering wireless sensors and IoT devices.

List of abbreviations

4IR	Fourth industrial revolution
AC	Alternating current
ADS	Advanced design system
CST	Computer simulation technology (CST Studio Suite software)
CVD	Chemical vapor deposition
DC	Direct current
GHz	Gigahertz
IoT	Internet of things
LIG	Laser-induced graphene
Lp	Patch length
RF	Radio frequency
Rin	Input impedance
S11	Return loss
VNA	Vector network analyzer
VSWR	Voltage standing wave ratio
Wf	Feed width
Wp	Patch width
dB	Decibel
dBi	Decibel relative to isotropic radiator
fo	Resonant frequency
h	Height of substrate
x0	Inset width
y0	Inset length
εr	Dielectric constant
Ω	Ohm

Acknowledgment

The authors gratefully acknowledge financial support by Xiamen University Malaysia under Research Fund Grant No: XMUMRF/2025-C15/IECE/0059 and XMUMRF/2023-C12/IECE/0047.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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