Akinola, Segun; Leelakrishna, Reddy

Article

The enhancing energy efficiency in hyperthermia treatment : a frequency-reconfigurable L-Shape antenna design and analysis

Technology audit and production reserves

Reference: Akinola, Segun/Leelakrishna, Reddy (2024). The enhancing energy efficiency in hyperthermia treatment : a frequency-reconfigurable L-Shape antenna design and analysis. In: Technology audit and production reserves 1 (1/75), S. 43 - 50.
https://journals.uran.ua/tarp/article/download/298795/291539/689912.
doi:10.15587/2706-5448.2024.298795.

UDC 621.396.67:615.841
DOI: 10.15587/2706-5448.2024.298795

Segun Akinola,
Reddy Leelakrishna

THE ENHANCING ENERGY EFFICIENCY IN HYPERTHERMIA TREATMENT: A FREQUENCY-RECONFIGURABLE L-SHAPE ANTENNA DESIGN AND ANALYSIS

The object of research is a frequency-reconfigurable L-Shape antenna. This paper presents an innovative study focusing on the design and analysis of a frequency-reconfigurable L-Shape antenna with a specific application in Hyperthermia Treatment. The antenna, operating in the frequency range of 2.5 to 8 GHz, utilizes a varactor to achieve agility and simplify design, thereby reducing component count. Constructed with a Roggers RT5880 (lossy) substrate, the L-Shape configuration ensures optimal performance. The incorporation of a single varactor, acting as a junction capacitance, not only enables straightforward tuning but also contributes to enhanced energy efficiency by reducing overall power consumption in the reconfigurable antenna system. The study employed CST Microwave Studio's 3D Electromagnetic field simulation software for time domain solver-based simulations, with validation conducted using the frequency domain solver. Results from the simulations showcase the antenna's performance at different frequency states.

At the tuning state frequency of 2.7 GHz, the antenna exhibits an impressive gain of 1.905 dB and a directivity of 7.530 dB. Similarly, at the tuning state frequency of 6.89 GHz, the gain is measured at 6.806 dB with a directivity of 7.490 dB. The proposed L-Shape antenna design not only demonstrates significant potential for Hyperthermia Treatment, allowing targeted heating within the 2.5 to 8 GHz frequency range but also aligns with the multidisciplinary focus of medical science. This contribution reflects the commitment to advancing medical science through original research, fostering innovation, and promoting energy-efficient solutions with practical applications in clinical settings.

Keywords: *frequency reconfigurable, antenna, bandwidth, hyperthermia treatment, gain, varactor, directivity.*

Received date: 06.10.2023
Accepted date: 20.12.2023
Published date: 29.12.2023

How to cite
Akinola, S., Leelakrishna, R. (2024). The enhancing energy efficiency in hyperthermia treatment: a frequency-reconfigurable L-Shape antenna design and analysis. Technology Audit and Production Reserves, 1 (1 (75)), 43–50. doi: https://doi.org/10.15587/2706-5448.2024.298795

1. Introduction

Wireless communication systems have become an integral part of our daily lives, facilitating seamless connectivity and information exchange. With the ever-increasing demand for high-performance wireless networks, there is a growing need for antennas that can adapt to changing operating conditions and communication requirements. Reconfigurable antennas have emerged as a promising solution to address these challenges by enabling dynamic control of their operating parameters such as frequency, radiation pattern, polarization, and bandwidth [1]. Reconfigurable antennas offer several advantages over traditional fixed antennas. Their ability to dynamically adjust their operating characteristics allows for improved system performance, increased flexibility, and enhanced adaptability [2]. One key advantage of reconfigurable antennas is their frequency agility. By altering the resonant frequency, these antennas can operate across multiple frequency bands, enabling compatibility with diverse wireless communication standards and enhancing spectrum utilization [3].

This feature is particularly beneficial in scenarios where coexistence with various wireless systems is essential. Moreover, reconfigurable antennas provide the capability of beamforming. Beamforming is a technique that enables the antenna to concentrate the transmitted or received energy in a specific direction, thereby improving signal quality, coverage, and interference mitigation. By dynamically controlling the radiation pattern through reconfiguration, reconfigurable antennas can focus the energy in the desired direction, enhancing overall system performance [4]. This feature is crucial in applications such as cellular networks, where directed communication and efficient spectrum usage are vital. The design and implementation of reconfigurable antennas involve integrating various components and technologies. One common approach is the use of electronic switches and tunable elements such as varactors, MEMS (Micro-Electro-Mechanical Systems), and liquid crystals [5].

These components enable the reconfiguration of antenna parameters, allowing for dynamic control of frequency, radiation pattern, and polarization. The choice of components

ISSN 2664-9969

depends on factors such as desired reconfiguration capabilities, frequency range, power requirements, and size constraints. A significant area of research in reconfigurable antennas focuses on developing efficient reconfiguration techniques and optimizing antenna performance. Numerous studies have investigated different antenna designs and reconfiguration mechanisms [6]. A reconfigurable antenna design using electronically controlled switches to change the antenna's operating frequency [7]. They demonstrated improved performance and versatility compared to fixed-frequency antennas.

In another study, [8] presented a reconfigurable antenna design utilizing varactors for frequency tuning. It is investigated the impact of varactor characteristics on antenna performance and highlighted the importance of linearity and voltage handling capabilities for reliable operation. Additionally, in [9] proposed a reconfigurable antenna based on liquid crystal technology, allowing for polarization control. It is demonstrated the ability to switch between linear and circular polarization states, enabling flexible adaptation to different communication scenarios. Furthermore, researchers have explored the integration of reconfigurable antennas with other advanced technologies. In [10], the integration of reconfigurable antennas with cognitive radio systems enables intelligent spectrum sensing and adaptation. The studies show a lot of drawbacks in switches and diodes which includes, limited lifespan, slow switching speed, noise generation, size and complexity, voltage drop, reverse recovery and temperature dependence. Furthermore, existing study showcased the potential for enhanced spectrum utilization and improved coexistence with other wireless systems. Reconfigurable antennas offer a flexible and adaptive solution for modern wireless communication systems. Their ability to dynamically adjust operating parameters, such as frequency, radiation pattern, and polarization, enables improved system performance, increased spectrum utilization, and enhanced coverage. Ongoing research continues to explore new design approaches, reconfiguration mechanisms, and integration with other technologies to further optimize the performance of reconfigurable antennas. The single varactor advantages included continuous tenability, fast response time, size integration and low power consumption. This reconfigurable antenna is designed to operate at 2.5 to 8 GHz frequency for implantable medical devices, The ISM band (industrial scientific and medical) at this range is for fixed, mobile, radiolocation, and amateur satellite. This is good for implantable medical devices. Hyperthermia treatment is a therapeutic approach that involves selectively heating specific tissues in the body to higher temperatures, typically ranging from 40 to 45 degrees Celsius, to treat various medical conditions, including cancer [11]. This treatment modality exploits the sensitivity of cancer cells to heat, as they are known to be more vulnerable to elevated temperatures compared to normal healthy cells. By raising the temperature in targeted areas, hyperthermia treatment can enhance the effectiveness of other cancer treatments such as radiation therapy or chemotherapy [12]. The use of electromagnetic energy, including microwaves, within the frequency range of 2.5 to 8 GHz, has been explored as a means of delivering hyperthermia treatment. Microwaves can penetrate deep into the body and selectively heat cancerous tissues while minimizing damage to surrounding healthy cells [13–15]. The conformal and flexible slot antenna for treatment and ablation of cancerous tumor was proposed in [16], the main focus of the paper is using silicone layer surface skin instead of water bolus to reduce the percentage of burns on the skin surface and resolve problems cause by the layer of the bolus. The effect of this novel show that antenna performance at various stage, the centralization of muscle tissue reduces the side damage of hyperthermia.

In [17], a miniaturized folded dipole patch antenna design for biomedical application which operate at 1 GHz, the antenna side was reduce by 835 with lumped inductor places at the centre patch of the radiating which makes it suitable for hyperthermia, the proposed give an impendent band with 6 MHz. Several studies have demonstrated the potential of microwave hyperthermia in various cancer types, including breast cancer, head and neck cancer, and cervical cancer. This paper makes several significant contributions to the field of antenna design and its application in Hyperthermia Treatment, Novel L-Shape Reconfigurable Antenna: the paper presents a unique design of an L-Shape frequency reconfigurable antenna utilizing a varactor. This innovative antenna configuration offers improved agility and simplification in design, reducing component count and facilitating tuning mechanisms, frequency Range and Substrate Selection: The antenna operates within the wide frequency range of 2.5 to 8 GHz, enabling versatile applications.

The aim of this study encompasses both scientific and practical objectives, contributing to the understanding and application of frequency-reconfigurable L-Shape antennas.

The scientific objective involves the identification and exploration of key aspects related to the frequency-reconfigurable L-Shape antenna. This includes discerning underlying regularities, understanding the influence of a varactor on the antenna's performance, unraveling the mechanism of the tuning process, and developing a model for efficient design. The study also employs advanced simulation tools, such as CST Microwave Studio's 3D Electromagnetic field simulation software, to validate the proposed model and showcase the antenna's performance under different frequency states.

In the practical domain, the study aims to translate scientific insights into tangible benefits. The focus lies on the potential practical applications of the frequency-reconfigurable L-Shape antenna, particularly in Hyperthermia Treatment. By operating within the frequency range of 2.5 to 8 GHz, the antenna aims to enable targeted heating for therapeutic purposes. The integration of a single varactor not only simplifies the design but also enhances energy efficiency, making the antenna a promising solution for clinical settings.

The study anticipates that the innovative L-Shape antenna design will contribute to advancing medical science by providing a compact, lightweight, and versatile solution. It strives to foster innovation and promote energy-efficient solutions, aligning with the multidisciplinary focus of medical science. The ultimate goal is to facilitate the practical use of the antenna in clinical applications, specifically in Hyperthermia Treatment, reflecting the commitment to bridging the gap between theoretical advancements and real-world impact.

2. Materials and Methods

The first step is to identify the specific requirements and objectives of the antenna design. This includes determining the desired frequency range, bandwidth, radiation pattern, gain, and any other performance parameters [16]. Based on the requirements, different design concepts and approaches are explored. This involves researching existing literature, studying similar antenna designs, and considering innovative techniques such as varactor tuning, switched resonators, or reconfigurable metamaterials. This is the concept followed in this design. This antenna was designed with 3D Electromagnetic in an L-shape with Rogers RT5880 (lossy), 1.575 mm height of substrate, the ground plane use copper (annealed) with 90 mm length and width, 0.018 mm as the height of copper cladding layer, the patch 1 was designed with 60 mm length loaded with copper (annealed) and width is 30 mm. Patch 2 has a length of 30 mm and a width of 30 mm. Using a single varactor in an antenna reconfigurable system offers several benefits [17]. Firstly, it simplifies the overall design by reducing the number of components required. Instead of using multiple varactors, a single varactor can be employed to achieve the desired reconfigurability. This leads to cost savings in terms of component procurement and assembly. Furthermore, a single varactor simplifies the tuning process. With only one varactor to control, the tuning mechanism becomes more straightforward, allowing for easier optimization of antenna performance [18]. It also minimizes the complexity of the control circuitry associated with varactor tuning. Additionally, using a single varactor reduces the overall power consumption of the reconfigurable antenna system. With fewer varactors, there is less power dissipation, resulting in improved energy efficiency and a single varactor configuration enhances the reliability of the antenna system [19]. By eliminating the need for multiple varactors, potential points of failure are reduced, leading to improved system robustness and longevity. The single varactor uses 0.7 mm, after the first and second patches were created in the desired shape, the SMA connector was designed with a width of 15.8 mm, and 5.5 mm as the length of the SMA connector, 1.5 and height of the SMA connector, furthermore, the pin was added with the radius of the SMA connector pin is 0.55 mm, 7.4 mm as height. The dielectric coast is added with PTFE (lossy) as material, the radius is 1.95 m for dielectric, and the coat is loaded with copper in the CST library. The component made up of connectors was merged in a folder (SMA connector). The polygon was mapped out in each direction of the antenna and loaded with air, this was transformed to the edges at the back of the antenna and cut off. Two holes were created separately at the back where the SMA connection is placed. The center of the antenna was picked for the varactor, with internal resistance to be 2 ohms, an internal inductance is $0.05e^{-9}$, and $1.4e^{-12}$ as the varactor internal capacitance. The schematic antenna front and back dimension is presented in Fig. 1 and Table 1.

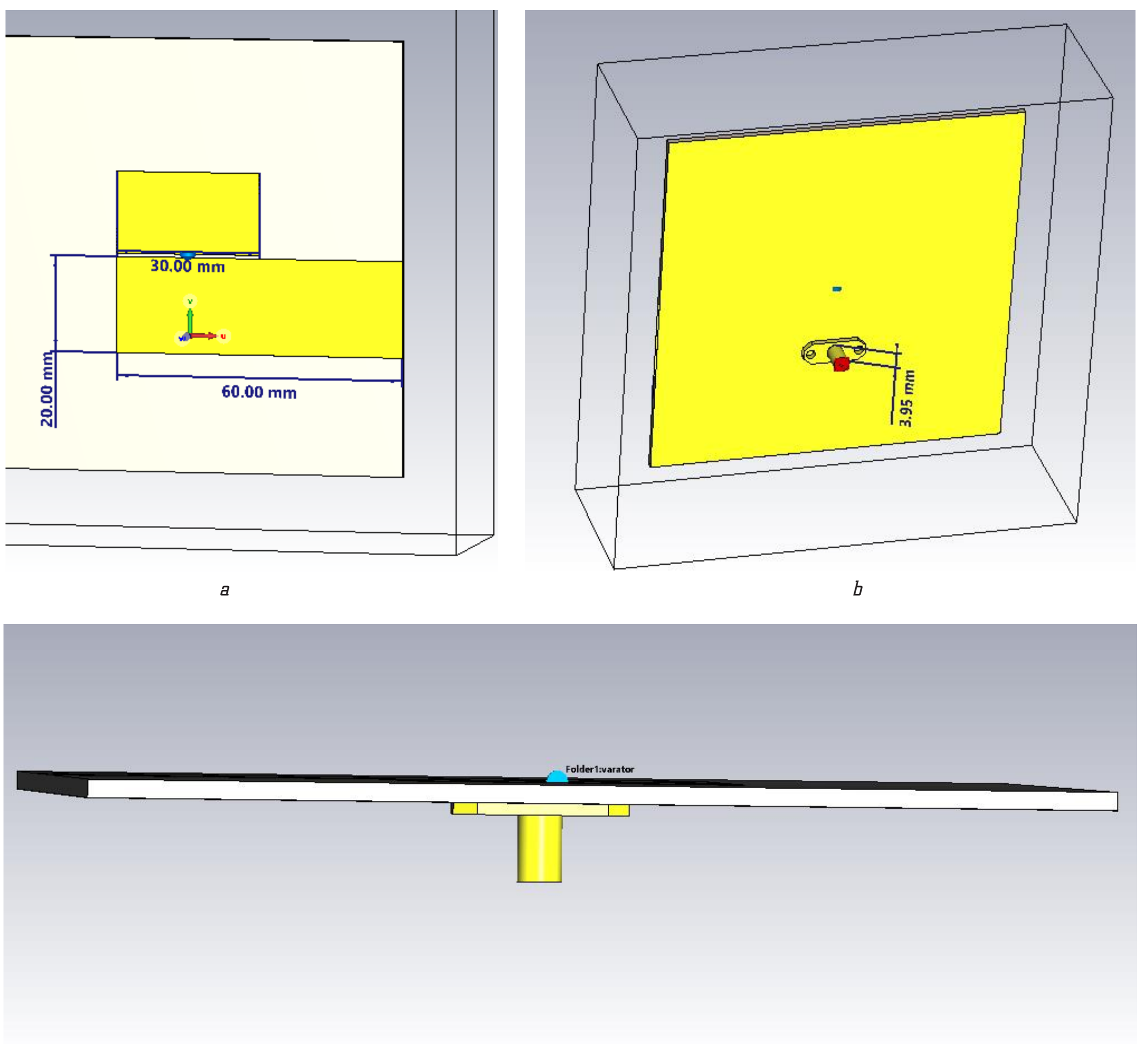


Fig. 1. Schematic of the proposed dimension: *a* – front view; *b* – back view; *c* – side view showing varactor

 ISSN 2664-9969

Table 1

Parameter lists

S/N	Descriptions	Value, mm
1	Width of the ground plane (*Wg*)	90
2	Length of the ground plane	90
3	Feed position	4
4	Varactor internal capacitance	$1.4e^{-12}$
5	Height of SMA connector base	1.5
6	Height of copper cladding layer	0.018
7	Height of substrate	1.575
8	Length of patch 1	20
9	Length of patch 2	17
10	Length of SMA connector base	5.5
11	Length of varactor	0.7
12	Varactor internal inductance	$0.05e^{-9}$
13	The radius of dielectric coast	1.95
14	The radius of the SMA connector pin	0.55
15	Varactor internal resistance	2
16	Width of patch 1	30
17	Width of patch 2	30
18	Width of SMA connector base	15.8

After all requirement has been made in the antenna it shows the antenna is ready for simulation.

3. Results and Discussion

The proposed antenna design holds immense potential for application in Hyperthermia Treatment, a therapeutic approach that utilizes targeted heating of specific tissues for therapeutic purposes, including cancer treatment. Operating within the frequency range of 2.5 to 8 GHz, this antenna design allows for precise heating of body areas in hyperthermia treatment applications. The proposed antenna was simulated with parameter sweep done which produce Fig. 2, after the frequency was adjusted to frequency of interest.

The obtained results for the turning state of the reconfigurable antenna showcase exceptional performance, demonstrating a remarkable return loss of $S_{11}=-27.633$ dB at 2.89 GHz, as illustrated in Fig. 3.

This outstanding return loss value signifies excellent impedance matching and efficient power transfer at the desired frequency, ensuring optimal performance with minimal signal loss. The measured return loss value reflects a high level of signal reflection suppression, contributing to enhanced antenna efficiency and overall system performance. These favourable return loss characteristics at the specified frequency validate the effectiveness of the antenna design and highlight its potential for diverse applications in wireless communication and other frequency-sensitive systems. Additionally, remarkable results are observed for the reconfigurable antenna, particularly at 6.89 GHz, where the return loss measures $S_{11}=-16.670$ dB, Fig. 4.

This indicates excellent impedance matching and minimal signal reflection at the designated frequency, ensuring efficient power transfer and maximum signal integrity. The measured return loss value indicates a significant reduction in signal loss and improved antenna performance. This low return loss at 6.89 GHz is crucial for applications requiring precise frequency operation and reliable communication. These results exemplify the effectiveness of the antenna design in achieving optimal performance within a specific frequency range, showcasing its potential for various wireless communication systems, radar applications, and other frequency-dependent applications. Moreover, Table 2 presents notable improvements in gain and directivity.

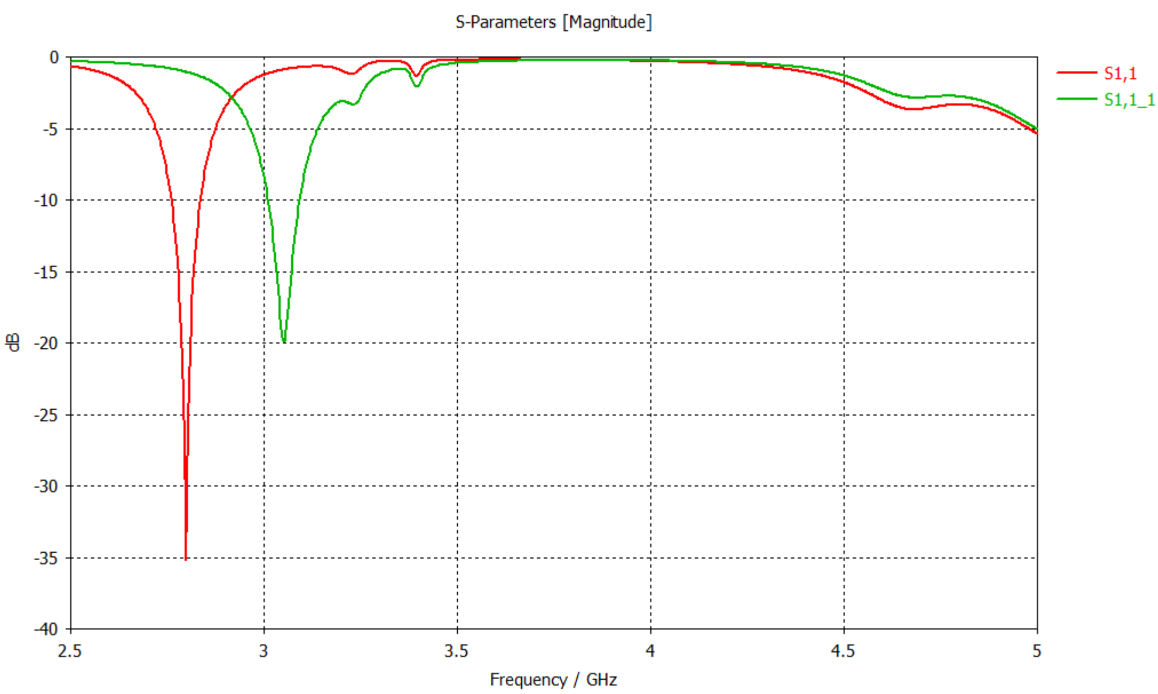


Fig. 2. Parameter sweep result

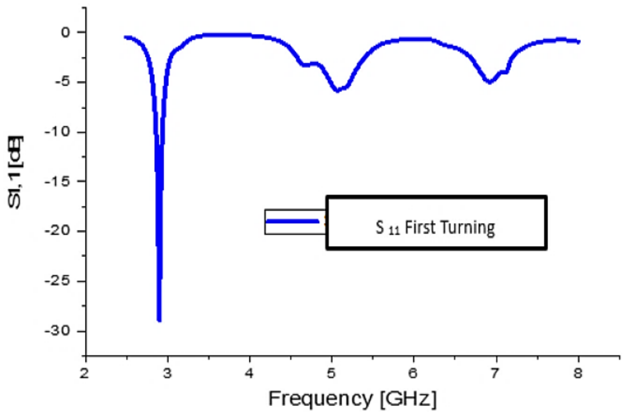


Fig. 3. Return loss S_{11} of first turning state

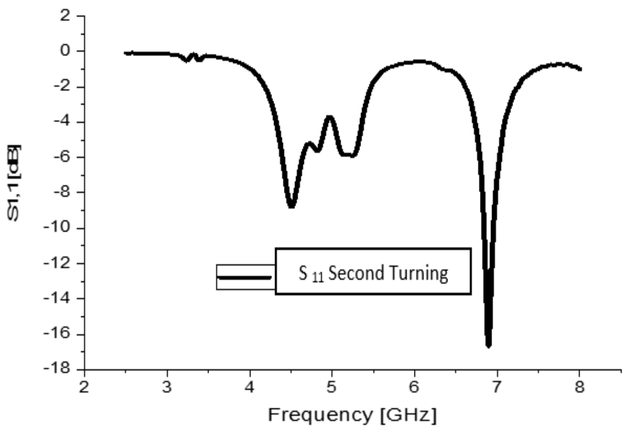


Fig. 4. Return loss S_{11} of second turning state

Table 2

Performance of the Proposed in State

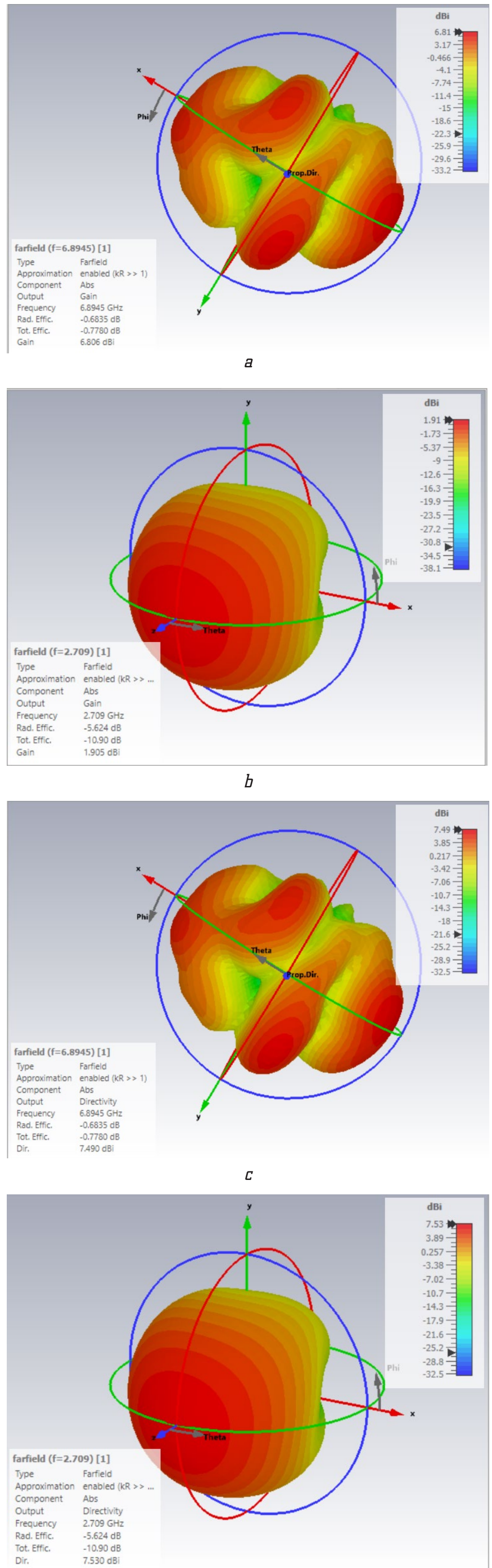
State	Frequency, GHz	Gain, dB	Directivity, dB
First Turning	2.709	1.905	7.530
Second Turning	6.89	6.806	7.490

The turning state exhibits a gain of 1.905 dB, while the second turning state demonstrates a gain of 6.806 dB. The directivity measures 7.530 dB for the turning state and 7.490 dB for the second state. These enhancements are also visually depicted in Fig. 5.

Additionally, Fig. 6 illustrates the return loss (S_{11}) for both the turning range states of the reconfigurable antenna.

In the first t state, the measured return loss at the frequency of interest (2.89 GHz) is $S_{11}=-27.633$ dB, indicating exceptional impedance matching and minimal signal reflection. The E and H field is presented in Fig. 7 and Fig. 8 at each state. This result validates efficient power transfer and optimal performance at the desired frequency. Similarly, in the second turning state, the return loss at 6.89 GHz is $S_{11}=-16.670$ dB, confirming effective impedance matching and reduced signal loss at this frequency.

Fig. 9 presented the surface current; the uniform surface current distribution helps produce a well-defined radiation pattern. The radiation pattern determines the directionality and shape of the antenna's radiated energy, the good surface current helps maintain the desired radiation pattern, resulting in better beam shaping and control.



a, *b*, *c*, *d*

Fig. 5. Gain and directivity each turning:
a – gain second tuning; *b* – gain first turning; *c* – directivity second turning; *d* – directivity first turning

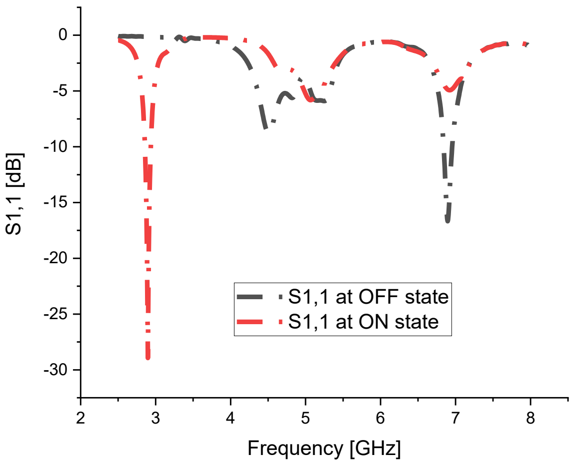
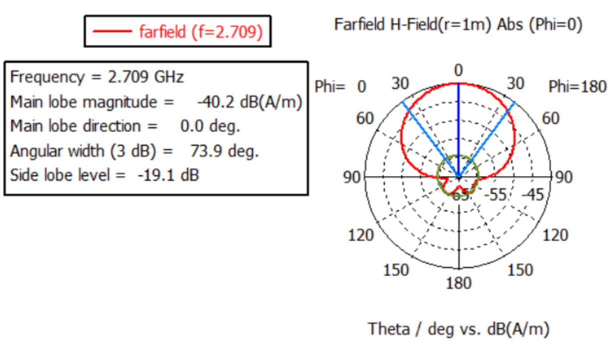
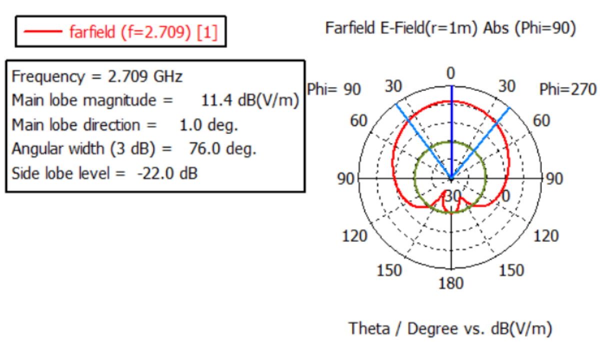


Fig. 6. Return loss S_{11} of both state

The favorable return loss values observed in both states further validate the antenna's design and its ability to operate efficiently across different frequencies, making it suitable for various wireless communication and frequency-dependent applications. The proposed model has several benefits for hyperthermia treatment application specifically the heating targeted body areas for therapeutic purposes which include cancer treatment, furthermore, the frequency range give control of health specific tissues, enhancing the effeteness of the treatment process. The proposed model result is considered good due to it significate gain enhancement achieved with the antenna state frequencies. This indicated the improved signal and transmission capabilities. making it suitable for high performance communication systems. The directivity value further demonstrates the antenna ability to focus and concentrate the radiated energy effectively.

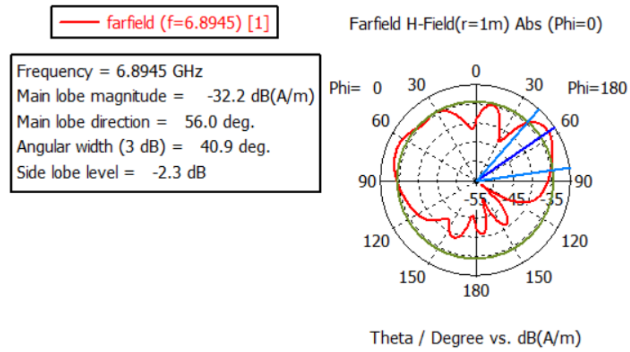


a

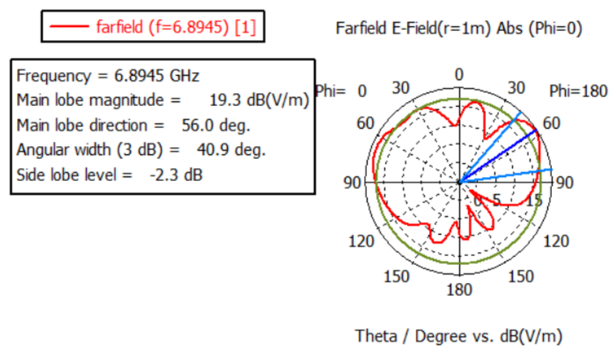


b

Fig. 7. *E* and *H* field at first turning state:
a – Phi = 0°; *b* – Phi = 90°

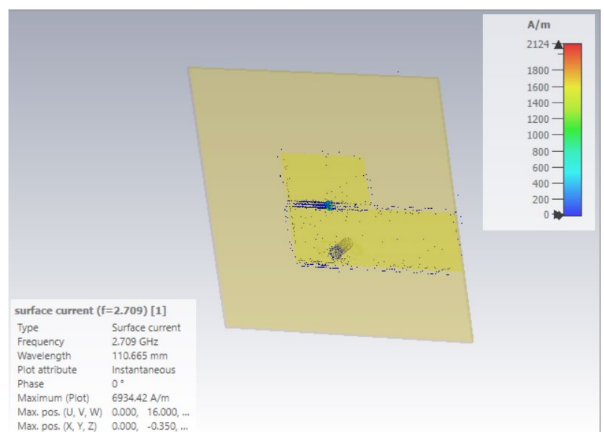


a

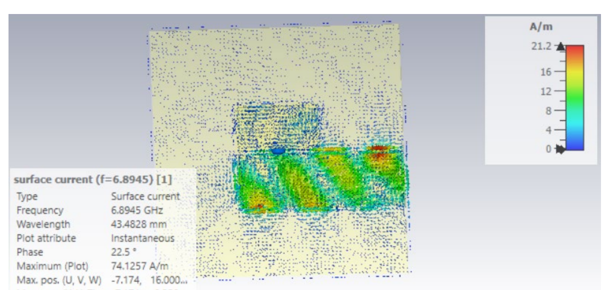


b

Fig. 8. *E* and *H* field at second turning state:
a – Phi = 0°; *b* – Phi = 90°



a



b

Fig. 9. Surface Current both state: *a* – On; *b* – Off

Table 3 proposed comparison show that the single varactor reconfigurable antenna has several key advantages over the antenna in the literature which has some drawback like switching speed limitation, power dissipation, forward voltage drops, reverse breakdown, limited current and packaging constraints.

Table 3

Comparison of results with other designs

S/N	Size	Frequency, GHz	Gain, dB	Antenna structure	Varactors	Feeding type	Source
1	97 mm	1.05, 1.2	2.0	Dipole with a single rectangle	5	Single-ended	[20]
2	31 mm	3.40, 2.42	3.5	1-layer patch	3	Single-ended	[21]
3	40 mm	2.4, 5.2	3.5	Annular slot	3	Single-ended	[22]
4	40 mm	2.6, 3.5	1.8	3-layer antenna	3	Differential	[23]
5	56 mm	2.5	1.3	1-layer patch	2	Single-ended	[24]
6	50 mm	433 MHz, 915 MHz	1.0	Lumped elements	2	Single-ended	[25]
7	30 mm	6.89, 2.709	6.806	2-layer patch	Single	Single-ended	This work

The advantage of using single varactor is, firstly, it offers a higher degree of configurability by employing a single varactor diode. This simplifies the design and control complexity, making it easier to implement and operate. The single varactor reconfigurable antenna exhibits improved performance in terms of frequency agility. It can dynamically tune its resonance frequency over a wide range, enabling efficient operation across multiple frequency bands without requiring additional external components or complex switching mechanisms. Moreover, this antenna configuration provides enhanced radiation pattern control. By adjusting the bias voltage applied to the varactor diode, the antenna's radiation pattern can be modified to achieve desired beam steering, beam shaping, or null steering capabilities.

This enables superior adaptability to change communication scenarios and improved link quality. Additionally, the single varactor reconfigurable antenna offers a compact size and reduced cost compared to alternative designs. The simplified structure and reduced component count make it suitable for integration into compact wireless devices, while also lowering production costs.

However, there some limitations, which should be considered for the results' applicability. The reliance on simulation environments, specific material characteristics, and the tuning mechanism's ideal conditions may not fully represent real-world scenarios. The antenna's performance, optimized for Hyperthermia Treatment, might not generalize to different frequency ranges or applications. Users replicating the results need to carefully consider substrate properties, varactor limitations, and potential challenges related to real-world interference. Furthermore, the clinical application of the antenna requires rigorous validation through trials to ensure safety and efficacy. In conclusion, while the study provides valuable insights into the scientific and practical aspects of the frequency-reconfigurable L-Shape antenna, users should exercise caution in applying the results to diverse and real-world settings, considering the outlined limitations for a comprehensive and accurate interpretation.

4. Conclusions

This paper has presented the design and analysis of an L-Shape frequency reconfigurable antenna utilizing a varactor. The antenna operates within the frequency range of 2.5 to 8 GHz and is constructed with an L-Shape configuration and a Roggers RT5880 (lossy) substrate with $\varepsilon=2.2$. The incorporation of a single varactor in the design brings agility to the antenna while simplifying the overall structure by reducing component count. This not only enables a straightforward tuning mechanism but also facilitates the optimization of antenna performance. Furthermore, the varactor contributes to improved energy efficiency by effectively reducing overall power consumption in the reconfigurable antenna system. The main contributions of this research include a compact and lightweight design, frequency agility, improved efficiency, and versatility adaptability. Simulation evaluations using CST Microwave Studio's 3D Electromagnetic field simulation software were performed, and validation was conducted using the frequency domain solver. The results demonstrate the effectiveness of the proposed antenna design. In the first tuning state at a frequency of 2.7 GHz, the antenna exhibits an enhanced gain of 1.905 dB and a directivity of 7.530 dB. In the second tuning state at a frequency of 6.89 GHz, the gain measures 6.806 dB with a directivity of 7.490 dB. The presented antenna design shows promise for application in Hyperthermia Treatment, which involves selective heating of specific tissues to higher temperatures for therapeutic purposes, including cancer treatment. Operating within the 2.5 to 8 GHz frequency range, this antenna design enables targeted heating of body areas in hyperthermia treatment applications. The research highlights the potential of the proposed antenna design for effective and efficient hyperthermia treatment. The achieved results demonstrate excellent impedance matching, efficient power transfer, and minimal signal loss at the desired frequencies. These characteristics contribute to enhanced antenna efficiency and overall system performance. The findings validate the effectiveness of the antenna design and suggest its suitability for various applications in the field of wireless communication and other frequency-sensitive systems. The reconfigurable antenna's ability to operate efficiently across different frequencies further enhances its potential for diverse wireless communication and frequency-dependent applications.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The research was performed without financial support.

ISSN 2664-9969

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The author confirms that she did not use artificial intelligence technologies when creating the current work.

References

1. Naveen Kumar, M., Venkata Narayana, M., Immadi, G., Satyanarayana, P., Navya, A. (2023). Analysis of a low-profile, dual band patch antenna for wireless applications. *AIMS Electronics and Electrical Engineering, 7 (2),* 171–186. doi: https://doi.org/10.3934/electreng.2023010
2. Hum, S. V., Perruisseau-Carrier, J. (2014). Reconfigurable Reflectarrays and Array Lenses for Dynamic Antenna Beam Control: A Review. *IEEE Transactions on Antennas and Propagation, 62 (1),* 183–198. doi: https://doi.org/10.1109/tap.2013.2287296
3. Songnan Yang, Chunna Zhang, Pan, H. K., Fathy, A. E., Nair, V. K. (2009). Frequency-Reconfigurable Antennas for Multiradio Wireless Platforms. *IEEE Microwave Magazine, 10 (1),* 66–83. doi: https://doi.org/10.1109/mmm.2008.930677
4. Aboufoul, T., Parini, C., Chen, X., Alomainy, A. (2013). Pattern-Reconfigurable Planar Circular Ultra-Wideband Monopole Antenna. *IEEE Transactions on Antennas and Propagation, 61 (10),* 4973–4980. doi: https://doi.org/10.1109/tap.2013.2274262
5. Bayraktar, O., Civi, O. A., Akin, T. (2012). Beam Switching Reflectarray Monolithically Integrated With RF MEMS Switches. *IEEE Transactions on Antennas and Propagation, 60 (2),* 854–862. doi: https://doi.org/10.1109/tap.2011.2173099
6. Christodoulou, C. G., Tawk, Y., Lane, S. A., Erwin, S. R. (2012). Reconfigurable Antennas for Wireless and Space Applications. *Proceedings of the IEEE, 100 (7),* 2250–2261. doi: https://doi.org/10.1109/jproc.2012.2188249
7. Haupt, R. L., Lanagan, M. (2013). Reconfigurable Antennas. *IEEE Antennas and Propagation Magazine, 55 (1),* 49–61. doi: https://doi.org/10.1109/map.2013.6474484
8. Alhamad, R., Almajali, E., Mahmoud, S. (2023). Electrical Reconfigurability in Modern 4G, 4G/5G and 5G Antennas: A Critical Review of Polarization and Frequency Reconfigurable Designs. *IEEE Access, 11,* 29215–29233. doi: https://doi.org/10.1109/access.2023.3260073
9. Ying, K., Gao, Z., Chen, S., Gao, X., Matthaiou, M., Zhang, R., Schober, R. (2024). Reconfigurable Massive MIMO: Harnessing the Power of the Electromagnetic Domain for Enhanced Information Transfer. *IEEE Wireless Communications,* 1–8. doi: https://doi.org/10.1109/mwc.014.2200418
10. Sexton, C., Kaminski, N. J., Marquez-Barja, J. M., Marchetti, N., DaSilva, L. A. (2017). 5G: Adaptable Networks Enabled by Versatile Radio Access Technologies. *IEEE Communications Surveys & Tutorials, 19 (2),* 688–720. doi: https://doi.org/10.1109/comst.2017.2652495
11. van der Zee, J. (2002). Heating the patient: a promising approach? *Annals of Oncology, 13 (8), 1173*–1184. doi: https://doi.org/10.1093/annonc/mdf280
12. Datta, N. R., Rogers, S., Ordóñez, S. G., Puric, E., Bodis, S. (2015). Hyperthermia and radiotherapy in the management of head and neck cancers: A systematic review and meta-analysis. *International Journal of Hyperthermia, 32 (1),* 31–40. doi: https://doi.org/10.3109/02656736.2015.1099746
13. Franckena, M., Lutgens, L. C., Koper, P. C., Kleynen, C. E., van der Steen-Banasik, E. M., Jobsen, J. J., Leer, J. W., Creutzberg, C. L., Dielwart, M. F., van Norden, Y., Canters, R. A. M., van Rhoon, G. C., van der Zee, J. (2009). Radiotherapy and Hyperthermia for Treatment of Primary Locally Advanced Cervix Cancer: Results in 378 Patients. *International Journal of Radiation Oncology*Biology*Physics, 73 (1),* 242–250. doi: https://doi.org/10.1016/j.ijrobp.2008.03.072
14. Seynhaeve, A. L. B., Amin, M., Haemmerich, D., van Rhoon, G. C., ten Hagen, T. L. M. (2020). Hyperthermia and smart drug delivery systems for solid tumor therapy. *Advanced Drug Delivery Reviews, 163-164,* 125–144. doi: https://doi.org/10.1016/j.addr.2020.02.004
15. Chang, M., Hou, Z., Wang, M., Li, C., Lin, J. (2020). Recent Advances in Hyperthermia Therapy-Based Synergistic Immunotherapy. *Advanced Materials, 33 (4).* doi: https://doi.org/10.1002/adma.202004788
16. Rajebi, S., Ghobadi, C., Nourinia, J., Mostafapour, E. (2019). SAR Enhancement of Slot Microstrip Antenna by Using Silicon Layer in Hyperthermia Applications. *Wireless Personal Communications, 111 (3),* 1761–1774. doi: https://doi.org/10.1007/s11277-019-06955-1
17. Chishti, A. R., Aziz, A., Aljaloud, K., Tahir, F. A., Abbasi, Q. H., Khan, Z. U., Hussain, R. (2023). A sub 1 GHz ultra miniaturized folded dipole patch antenna for biomedical applications. *Scientific Reports, 13 (1).* doi: https://doi.org/10.1038/s41598-023-36747-4
18. Rodrigo, D., Cetiner, B. A., Jofre, L. (2014). Frequency, Radiation Pattern and Polarization Reconfigurable Antenna Using a Parasitic Pixel Layer. *IEEE Transactions on Antennas and Propagation, 62 (6),* 3422–3427. doi: https://doi.org/10.1109/tap.2014.2314464
19. Venneri, F., Costanzo, S., Di Massa, G. (2012). Reconfigurable aperture-coupled reflectarray element tuned by single varactor diode. *Electronics Letters, 48 (2),* 68. doi: https://doi.org/10.1049/el.2011.3691
20. Nguyen-Trong, N., Hall, L., Fumeaux, C. (2016). A Frequency- and Pattern-Reconfigurable Center-Shorted Microstrip Antenna. *IEEE Antennas and Wireless Propagation Letters, 15,* 1955–1958. doi: https://doi.org/10.1109/lawp.2016.2544943
21. Chen, W., Lv, G., Liu, X., Wang, D., Ghannouchi, F. M. (2020). Doherty PAs for 5G Massive MIMO: Energy-Efficient Integrated DPA MMICs for Sub-6-GHz and mm-Wave 5G Massive MIMO Systems. *IEEE Microwave Magazine, 21 (5),* 78–93. doi: https://doi.org/10.1109/mmm.2020.2971183
22. Nguyen-Trong, N., Piotrowski, A., Fumeaux, C. (2017). A Frequency-Reconfigurable Dual-Band Low-Profile Monopolar Antenna. *IEEE Transactions on Antennas and Propagation, 65 (7),* 3336–3343. doi: https://doi.org/10.1109/tap.2017.2702664
23. Chen, G., Yang, X.-L., Wang, Y. (2012). Dual-Band Frequency-Reconfigurable Folded Slot Antenna for Wireless Communications. *IEEE Antennas and Wireless Propagation Letters, 11,* 1386–1389. doi: https://doi.org/10.1109/lawp.2012.2227293
24. Cetiner, B. A., Crusats, G. R., Jofre, L., Biyikli, N. (2010). RF MEMS Integrated Frequency Reconfigurable Annular Slot Antenna. *IEEE Transactions on Antennas and Propagation, 58 (3),* 626–632. doi: https://doi.org/10.1109/tap.2009.2039300
25. Tu, Z.-H., Li, W.-A., Chu, Q.-X. (2014). Single-Layer Differential CPW-Fed Notch-Band Tapered-Slot UWB Antenna. *IEEE Antennas and Wireless Propagation Letters, 13,* 1296–1299. doi: https://doi.org/10.1109/lawp.2014.2332355

✉***Segun Akinola,*** *Doctor of Electrical/Electronic Engineering, Johannesburg Business School, University of Johannesburg, Johannesburg, South Africa, e-mail: akinolaa@uj.ac.za, ORCID: https://orcid.org/0000-0003-1565-7825*

Reddy Leelakrishna, *Professor, Department of Physics, University of Johannesburg, Johannesburg, South Africa, ORCID: https://orcid.org/0000-0001-5922-6096*

✉*Corresponding author*