A Compact Bio-inspired Microstrip Antenna (Bi-MPA) for Medical Microwave Imaging Applications

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Abstract. This paper introduces a novel bio-inspired wideband antenna, meticulously designed for medical microwave imaging applications, spanning a compact dimension of $0.3 \times 0.26\,\lambda_0$ at 3 GHz, this flexible antenna is engineered to operate over an extensive frequency range from 2.6 GHz to 8 GHz. Drawing inspiration from natural structures, the antenna design incorporates bio-mimetic principles to optimize its performance for use in the demanding field of medical imaging, where precision and reliability are paramount. The proposed antenna achieves a peak gain of 1.6 dBi, ensuring good-quality imaging by facilitating deep tissue penetration and enhanced resolution capabilities. This work not only demonstrates the feasibility of integrating bio-inspired designs, but also highlights the significant potential of such antennas in improving the efficacy of medical diagnostic tools. Through rigorous simulation and testing, the antenna exhibits exceptional performance metrics, making it a promising solution for next-generation medical imaging technologies. This research paves the way for future advancements in antenna design, leveraging the untapped potential of bio-inspired concepts to meet the critical needs of medical imaging applications.

Keywords: Bio-inspired · Medical Microwave Imaging (MMWI) · Medical diagnosis · Compact size

1 Introduction

Recent advancements in medical imaging have paved the way for innovative diagnostic techniques, with microwave imaging emerging as a promising non-invasive method. The development of efficient and compact antennas is crucial for the effectiveness of

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medical microwave imaging systems. This research paper introduces a novel bio-inspired microstrip antenna (Bi-MPA) meticulously designed for medical microwave imaging applications. The concept of bio-inspired designs has gained traction in various fields, including antenna engineering, due to their potential to mimic the efficient structures found in nature [1–9].

Wideband antennas, in particular, have been highlighted for their capability to achieve wide bandwidth and reduced dimensions, which are essential for effective microwave imaging in medical diagnostics [10, 11]. The exploration of bio-inspired shapes in antenna design has led to innovative developments across various applications. In [12], a leaf-shaped, bio-inspired circular-polarized UHF RFID tag is introduced, optimized using characteristic mode analysis. This design enhances the read range on metal plates and low-permittivity substrates, showcasing the potential of natural shapes in improving RFID tag performance. Similarly, [13] presents a dual-band binary branch fractal bionic antenna with a binary tree fractal structure, tailored for mobile applications. This design achieves dual-broadband functionality and compactness, essential for modern mobile terminals. Bio-inspired shapes are utilized to enhance antenna performance, demonstrating the effectiveness in achieving wide bandwidth and high gain [14–21].

The exploration of bio-inspired shapes in antenna design has led to innovative and effective solutions across medical applications. Introduces a compact wideband antenna for body implantable applications using an asymmetric complementary split-ring resonator structure [7]. Various bio-inspired shapes in antenna design for medical purposes include an epsilon [8], leaf-shaped [12], binary tree fractal bionic structure [13]. These designs illustrate the diverse and impactful ways in which bio-inspired shapes can enhance antenna performance and functionality.

This paper aims to build upon these advancements by introducing a bio-inspired wideband antenna that operates over an extensive frequency range from 2.6 GHz to 8 GHz. The proposed Bi-MPA is engineered with a compact size of 30×26 mm^2 and incorporates bio-mimetic principles to optimize its performance for medical microwave imaging. The antenna's design and characteristics are expected to facilitate deep tissue penetration and enhanced resolution capabilities, thereby improving the efficacy of medical diagnostic tools.

2 Antenna Design

The initial concept for the bio-inspired UWB antenna was derived from the study of natural forms and structures. The design mimics biological patterns that exhibit unique electromagnetic properties conducive to wideband frequency reception and efficient radiation patterns. In particular, the antenna takes inspiration from the vein structures of leaves, which are known for their intricate and multifunctional network layouts. This biological analogy serves as the foundation for the antenna's structural design. The antenna, as visualized in the accompanying image, measures approximately 30 x 26 mm^2, indicating a compact form factor suitable for medical imaging applications where space constraints are common. The bio-inspired design elements are evident in the branching metal structures that resemble the venation of a leaf (Fig. 1 and Table 1).

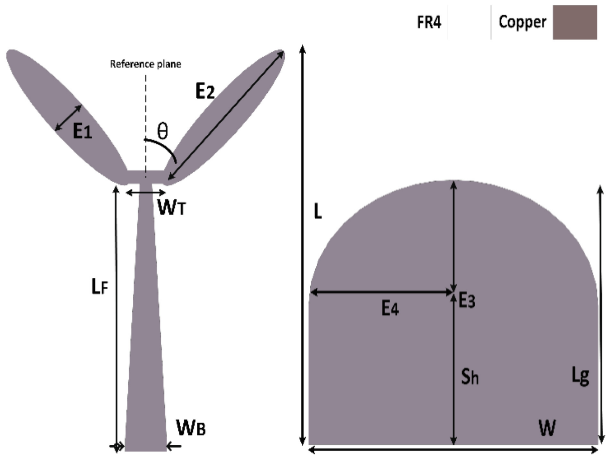


Fig. 1. The design of the suggested antenna, (a) Radiating element with elliptical petal shape, (b) tapered ground plane

Table 1. Design Parameters of the Proposed Antenna

Parameter	Value (mm)	Parameter	Value (mm)
W	26	E_3	9
L_F	20	S_h	10
W_B	3.4	L	30
E_1	3	W_T	4
E_2	14	E_4	13

3 Simulation and Results

The concept of bio-inspired design, drawing inspiration from natural structures and processes, has been increasingly applied in engineering to solve complex problems. In antenna design, this approach aims to exploit the inherent efficiencies of biological systems to improve performance metrics such as bandwidth, gain, and multi-directional radiation patterns. By integrating these bio-inspired principles, the proposed UWB antenna seeks to surpass the limitations of conventional designs, offering significant advancements in medical imaging quality and reliability.

The simulation process and the resulting data are presented through a series of graphs, each depicting a different aspect of the antenna's performance.

Figure 2 shows the simulated return loss (S_{11}) across a frequency range of 2 to 8 GHz. The curve indicates a minimum return loss of below -15 dB, suggesting a good impedance match at the resonant frequencies. The return loss is significantly low at particular frequencies, which implies that the antenna is well-tuned for those specific points in the spectrum.

The graph in Fig. 3, illustrates the antenna's gain over the same frequency range. The gain peaks at just above 1 dB and then gradually decreases as the frequency increases. The antenna exhibits a positive gain across most of the lower frequency band, indicating that it is effective in radiating the input signal. However, the gain drops below 0 dB as the frequency approaches 8 GHz, which may indicate less effective radiation at higher frequencies.

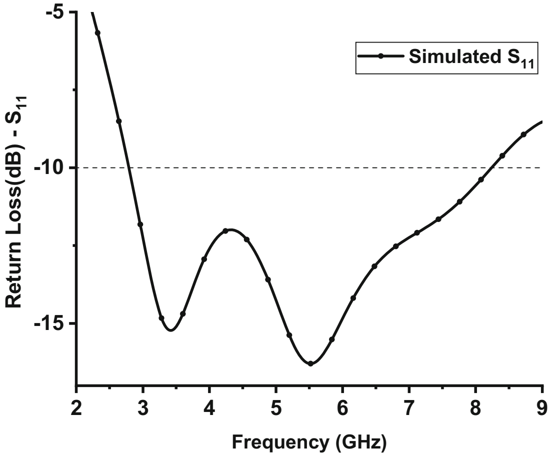


Fig. 2. Simulated S11 parameter of the antenna.

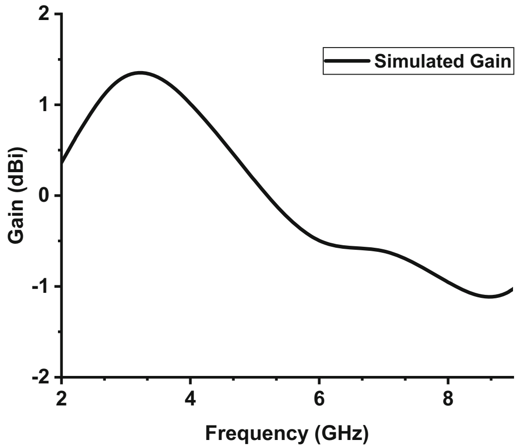


Fig. 3. Simulated gain of the antenna.

Figure 4 represents the amplitude of the radiated signal over time in nanoseconds. It shows the input direct wave and the output reflected wave. The input signal exhibits a strong direct wave, while the reflected signal is significantly weaker, suggesting that the antenna has a good radiation efficiency with minimal reflection.

The results presented in Fig. 5 demonstrate the radiation patterns of the antenna at frequencies of 3, 4, 5, and 6 GHz. A clear trend emerges as the frequency increases: the main lobe becomes more focused, and the antenna's directivity significantly enhances. This is particularly evident at the higher frequencies, where the intensity and directionality of the main lobe are more pronounced. While this improved directivity indicates better performance in terms of concentrating energy in the desired direction, it also suggests a potential increase in side lobe radiation. Such side lobes could pose challenges related to system interference. Understanding these radiation patterns is crucial for assessing the antenna's behavior in real-world applications, guiding communication system design decisions, especially regarding frequency selection based on the desired radiation characteristics.

These results collectively indicate the antenna's performance in terms of impedance matching, radiation efficiency, and gain across the tested frequency spectrum. The low return loss in certain frequencies correlates with the higher gains, which is desirable in antenna performance for the intended applications. The time-domain analysis provides an additional layer of understanding of the antenna's behavior in actual operation, confirming its suitability for the expected use case.

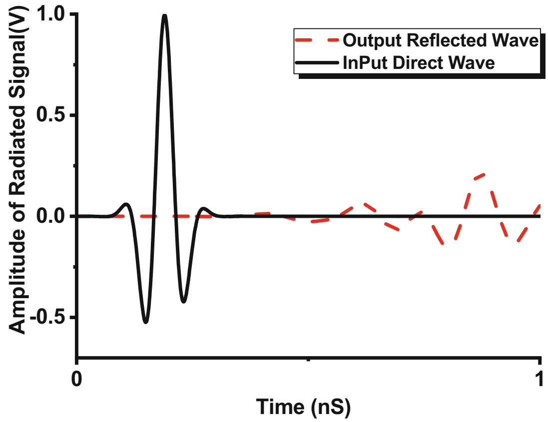
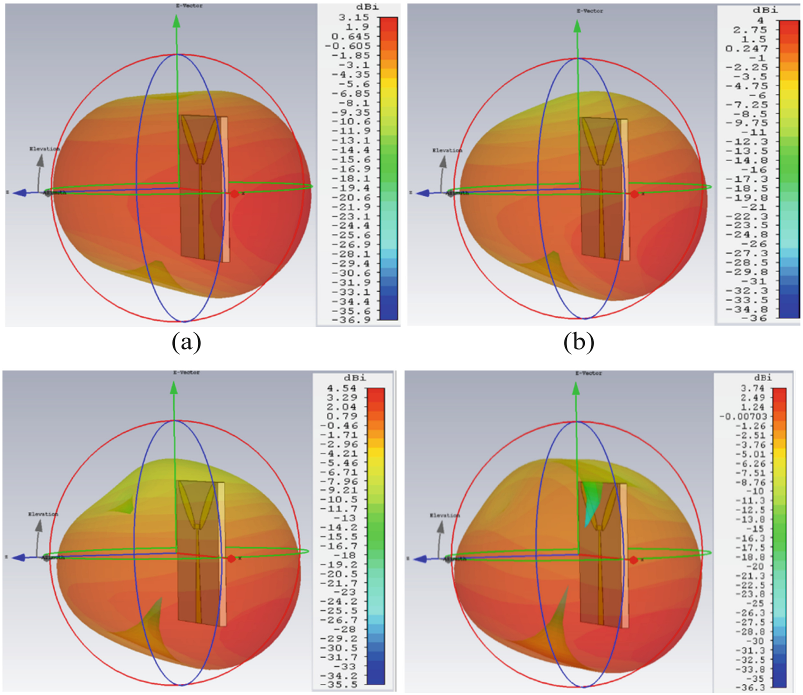


Fig. 4. Time-domain response of the antenna.

4 Comparison of Microwave Imaging Antennas for Medical Applications

A Comparison of various microwave imaging antennas highlights the trade-offs among operating frequency, gain, size, and specific medical applications. The current study achieves a balanced performance, operating over a broad frequency range with moderate peak gain and compact dimensions, making it highly suitable for general microwave



(a) (b)

(c) (d)

Fig. 5. The figure illustrates the 3D radiation patterns of the antenna at four distinct operating frequencies, highlighting its directivity and performance at (a) 3 GHz (b) 4 GHz (c) 5 GHz (d) 6 GHz

medical imaging purposes. On the other hand, a study focused on breast cancer screening utilizes a narrower frequency range with larger physical dimensions and a slightly reduced bandwidth [22]. Another work on wearable imaging technology offers the broadest bandwidth (109%) but at the expense of increased size [23]. Meanwhile, research tailored for brain tumor detection delivers the highest gain (6.66 dBi) but requires significantly larger dimensions [24]. Lastly, a study concerning cancer detection operates within a narrow frequency range, achieving the smallest bandwidth and physical dimensions [25], exemplifying the diverse design approaches optimized for specific medical imaging applications (Table 2).

Table 2. Comparative Analysis of Microwave Imaging Antennas for Medical Application

Reference	Operating Frequency Range (GHz)	Peak Gain (dBi)	Dimensions (mm^2)	Bandwidth (%)	Application
22	2.0–5.0	Not specified	44.5 × 66.9	75%	Breast cancer imaging
23	1.198–4.055	2.9	70 × 50	109%	Wearable medical imaging
24	1.5–3.3	6.66	150 × 150	74%	Brain tumor detection
25	2.3–2.5	1.21	27 × 20	8.30%	Microwave cancer detection
This Work	**2.6–8.0**	**1.6**	**30 × 26**	**87.50%**	**Microwave Medical Imaging (MWMI)**

5 Conclusion

This paper introduces a novel Bi-MPA meticulously designed for medical microwave imaging applications. The antenna, inspired by natural structures such as the vein patterns of leaves, demonstrates a compact size of 30 × 26 mm^2 and operates over an extensive frequency range from 2.6 GHz to 8 GHz. The incorporation of bio-mimetic principles in the antenna design has proven to be effective in achieving wide bandwidth and reduced dimensions, which are crucial for medical diagnostics. Through rigorous simulation and testing, the proposed Bi-MPA has exhibited exceptional performance metrics, including a peak gain of 1.6 dBi, which ensures good-quality imaging by facilitating deep tissue penetration and enhanced resolution capabilities.

This work not only highlights the potential of bio-inspired designs in antenna engineering but also underscores their significance in improving the efficacy of medical diagnostic tools. The exploration of natural shapes and structures in antenna design has led to innovative solutions that can meet the critical needs of medical imaging applications. The successful implementation of the Bi-MPA paves the way for future advancements in antenna design, leveraging bio-inspired concepts to address the evolving challenges in medical imaging technologies. Overall, this research contributes to the ongoing efforts in developing efficient and compact antennas for non-invasive medical diagnostics, offering promising prospects for enhanced medical imaging and patient care.

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