International Journal of Electronics and Instrumentation Engineering (IJEIE)
Volume 3, Issue 1, January-June 2025, pp. 24-32, Article ID: IJEIE_03_01_003
Available online at https://iaeme.com/Home/issue/IJEIE?Volume=3&Issue=1
Journal ID: 2416-1724; DOI: https://doi.org/10.34218/IJEIE_03_01_003

MINIATURIZED ANTENNA FOR EMBEDDED MEDICAL ENDOSCOPY DEVICES

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ABSTRACT

Wireless Capsule Endoscopy (WCE) systems are transforming gastrointestinal diagnostics by providing non-invasive, real-time visualization of the digestive tract. A pivotal element of these systems is the antenna, which facilitates robust wireless communication between the internal capsule and external monitoring equipment. This study presents the design of a wideband antenna specifically engineered for WCE applications, addressing key challenges such as miniaturization, efficient radiation in lossy biological media, and broad impedance bandwidth. The antenna is designed to operate within the Industrial, Scientific, and Medical (ISM) band (2.4–2.5 GHz), capitalizing on its capability to deliver high data rates while maintaining sufficient tissue penetration. The design incorporates advanced methodologies, utilizing flexible and biocompatible materials to ensure compatibility with the capsule's curved structure and to uphold patient safety standards. Performance optimization is carried out through numerical simulations based on realistic human tissue phantoms, focusing on parameters such as gain, efficiency, and compliance with Specific Absorption Rate (SAR) limits. Experimental results validate the antenna's capacity to maintain consistent communication links across different tissue scenarios. The proposed *wideband antenna design enhances signal integrity and supports higher data throughput, positioning it as a strong candidate for integration into future WCE platforms.*

Keywords: Computer simulation technology (CST), Fractal, Industrial, scientific and medical bands, Wireless capsule endoscopy, Specific absorption rate.

Cite this Article: Karthigai Lakshimi S, Arun Kumar K.S, Amritha M. (2025). Miniaturized Antenna for Embedded Medical Endoscopy Devices. *International Journal of Electronics and Instrumentation Engineering (IJEIE)*, 3(1), 24–32.

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1. INTRODUCTION

The development of a wideband antenna for wireless endoscopy systems represents a significant advancement in modern medical diagnostics, aimed at improving the performance and reliability of minimally invasive procedures. These systems necessitate antennas capable of operating across a broad frequency spectrum to support high-speed data transmission, low latency, and consistent signal integrity within the inherently lossy environment of the human body. An effective wideband antenna must align with medical frequency allocations while overcoming constraints related to compact form factor, biocompatibility, and energy efficiency. By incorporating sophisticated antenna design strategies—such as size reduction, impedance matching, and the use of advanced materials—wireless endoscopic platforms can achieve reliable communication between the internal capsule and external receivers. This contributes to more accurate diagnostics, enhanced procedural efficiency, and improved patient care outcomes.

2. LITERATURE SURVEY

The pursuit of fractal-inspired, miniaturized wideband antennas for wireless capsule endoscopy (WCE) has attracted considerable interest due to the growing need for compact and efficient solutions in biomedical engineering. Fractal geometries, known for their self-repeating and space-efficient characteristics, have been extensively studied to facilitate antenna miniaturization while preserving wideband capabilities. Existing literature demonstrates that such designs offer improvements in impedance matching, bandwidth enhancement, and size reduction, making them highly suitable for integration into ingestible medical devices.

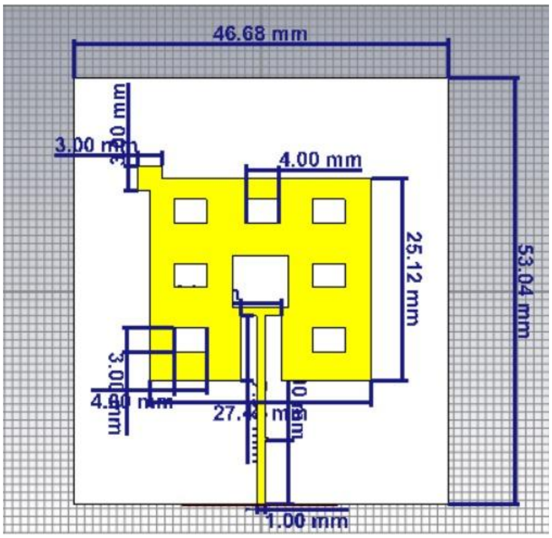
Various fractal configurations, including Sierpinski, Koch, and Hilbert curves, have been explored to optimize key performance metrics such as radiation efficiency, gain, and adherence to Specific Absorption Rate (SAR) regulations. In parallel, significant efforts have been directed toward selecting suitable biocompatible materials and refining fabrication processes to ensure the antenna's reliability and safety within the complex and absorptive environment of the gastrointestinal tract.

Recent developments in WCE antenna design have also considered alternative structures such as planar, helical, and conformal antennas, specifically adapted for operation within the human digestive system. Researchers have employed numerical simulations and anatomical phantom models to evaluate and enhance antenna performance under realistic physiological conditions. Additionally, adaptive impedance matching methods have been proposed to address detuning issues arising from varying tissue properties.

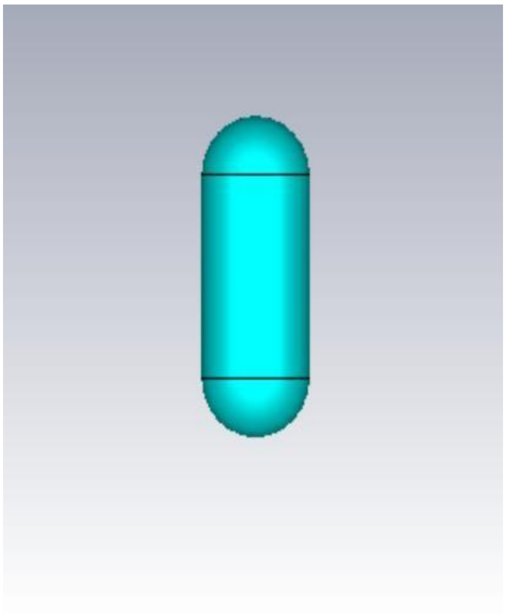
Experimental validation through both in vivo and ex vivo studies has further advanced the understanding of electromagnetic interactions within the body. Concurrently, there is a growing focus on energy-efficient antenna designs that incorporate low-power telemetry systems, aiming to prolong operational lifespan without compromising data transmission quality. Collectively, these advancements contribute to the ongoing evolution of wireless capsule endoscopy, facilitating high-resolution imaging and dependable communication in non-invasive diagnostic and therapeutic applications.

3. CAPSULE ANTENNA DESIGN

The proposed system introduces a miniaturized wideband patch antenna, incorporating a fractal geometry, specifically designed for wireless capsule endoscopy (WCE) applications operating within the 2450 MHz Industrial, Scientific, and Medical (ISM) band. The antenna's compact structure is achieved through the implementation of a Sierpinski fractal geometry, which not only reduces the physical dimensions but also contributes to enhanced performance characteristics. The antenna is fabricated using FR4, a commonly used lossy substrate material by CST (Computer Simulation Technology) studio suite software.



1 (a)



1 (b)

The figure 1(b) is the capsule antenna wrapping outer wall of the capsule

Figure 1(a) illustrates the fractal patch antenna design. In accordance with the structural specifications of the endoscopic capsule, the antenna is conformed to its outer surface, as depicted in Figure 1(b). This conformation ensures mechanical compatibility and optimal radiation performance within the intended biomedical environment.

Parametric simulations have been conducted comprehensively for this patch-based antenna configuration. Notably, the antenna is subjected to bending along the H-plane to evaluate its mechanical and electromagnetic robustness. Simulation results indicate that the antenna's resonant frequency and bandwidth characteristics remain stable under bending conditions, confirming its suitability for integration in flexible, body-conformal capsule systems.

Table 1 Optimized dimensions

Parameter	Value (mm)
W	20
L	13
W_g	9
L_g	1.3
W_f	1
g_f	0.2
g_p	1.2
g_m	0.6
g_s	0.2
W_b	1.2
W_p	6
L_a	1.5
L_b	1.2
Lm	2.2
W_a	2.2
W_m	0.5
L_p	5.2

The proposed antenna, mounted on the outer surface of the capsule, is simulated within a cubical, homogeneous muscle phantom. A cube with dimensions of 120 mm is selected, corresponding approximately to one free-space wavelength (λ_0) at the antenna's operating frequency of 2.45 GHz. This dimension is carefully chosen to minimize the excitation of unwanted spurious modes during simulation. The cubic phantom is intended to emulate the electromagnetic properties of human muscle tissue, providing a realistic environment for evaluating the antenna's performance.

4. RESULT

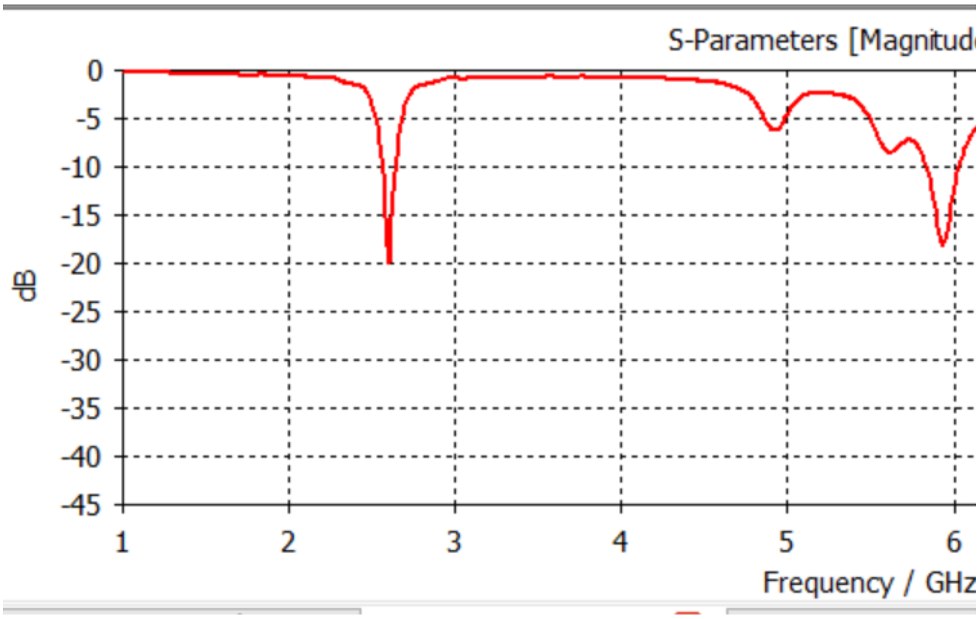


Fig 2. S parameter

The proposed miniaturized patch fractal antenna was tested inside a simulated muscle environment to evaluate its performance. The S-parameter (S_{11}) results show a clear resonance around 2.45 GHz, with values below -10 dB, indicating effective impedance matching and confirming its operation in the ISM band. Additional resonances at higher frequencies support its wideband behavior.

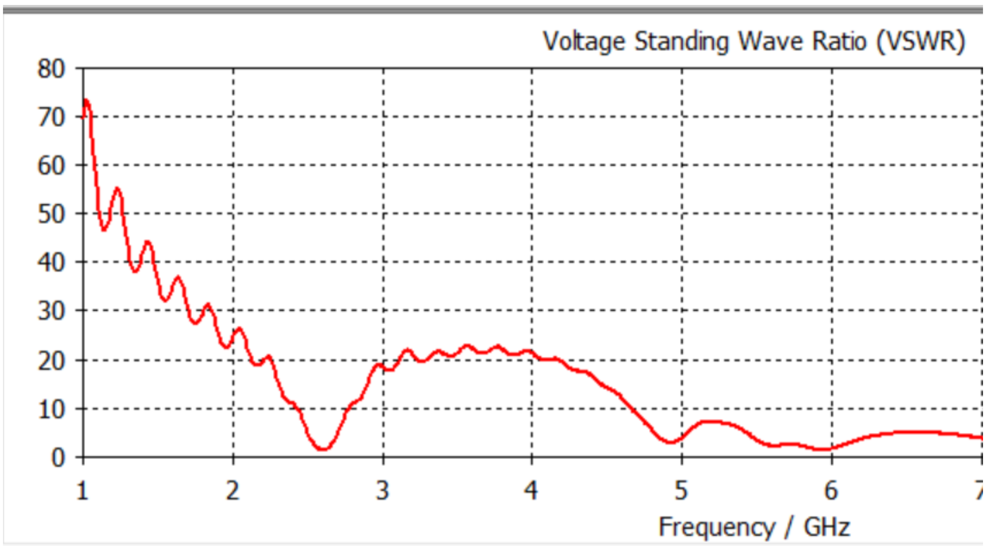


Fig 3. VSWR

The Voltage Standing Wave Ratio (VSWR) remains below 2 across the desired frequency range, showing that the antenna has minimal signal reflection and efficiently transmits power.

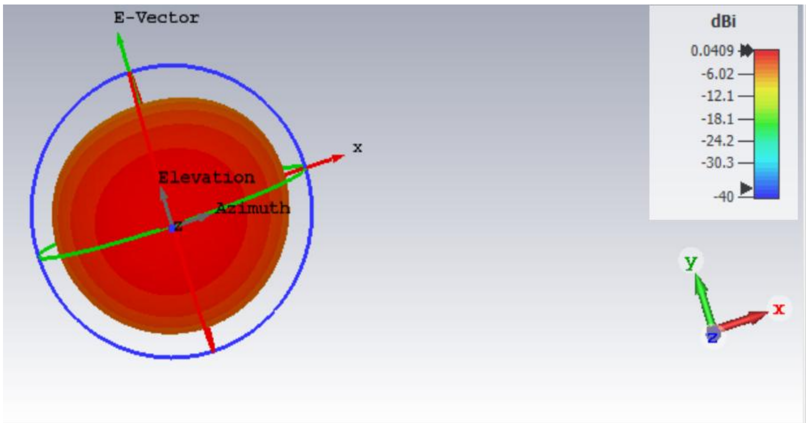


Fig 4. Gain in 3D

The 3D radiation pattern shows an almost omnidirectional coverage, which is useful for capsule endoscopy, where the device may rotate or change direction inside the body.

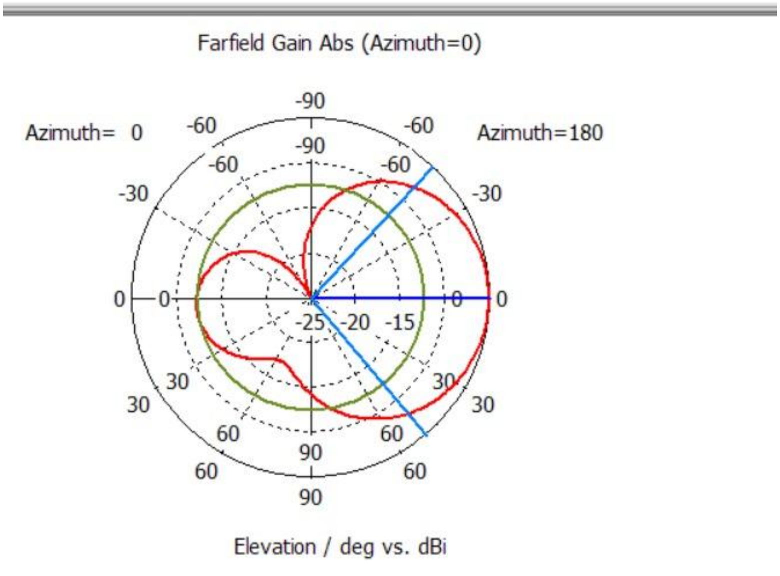


Fig 5. Gain in polar

The azimuthal gain plot displays a stable and symmetrical radiation pattern. Although the gain is slightly reduced due to the use of lossy FR4 material and the tissue-like environment, it is still suitable for short-range communication in medical applications.

5. CONCLUSION

The development and implementation of a miniaturized antenna for embedded medical endoscopic systems represent a notable advancement in biomedical engineering and wireless healthcare technology. This study demonstrates that, through careful selection of materials, geometric optimization, and precise impedance matching, it is feasible to design compact, high-performance antennas capable of operating effectively within the constrained environment of endoscopic applications.

The proposed antenna achieves a well-balanced compromise between size reduction and essential performance parameters such as impedance bandwidth, radiation efficiency, and gain—factors that are crucial for maintaining reliable in-body wireless communication.

Despite the design constraints, the applicability of this antenna extends across a wide range of biomedical domains. It is particularly well-suited for integration into wireless capsule endoscopy systems, minimally invasive diagnostic tools, implantable biosensors, and telemetry-based chronic health monitoring devices. Additionally, its potential for adaptation in other medical fields such as cardiology, neurology, and urology further emphasizes its versatility where compact and reliable wireless systems are required.

In summary, this work provides a strong foundation for the continued advancement of miniaturized medical antennas and highlights their pivotal role in shaping the future of wireless healthcare technologies and precision diagnostics. Future investigations may focus on adaptive antenna architectures, tunable impedance solutions, and novel biocompatible materials to address current limitations and further broaden the scope of clinical implementation.

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