International Journal of Web of Multidisciplinary Studies
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
website: https://ijwos.com
Volume 3 Issue 5 , May 2026
OPEN ACCESS
E-ISSN : 3049-2424
DOI: https://doi.org/10.71366/ijwos03052674122

Design and Analysis of a Compact Capsule Antenna for 2.45 GHz ISM Band Biomedical Applications

Illakiya KS[1], R. Sittalatchoumy[2]
[1,2] *Department of Electronics and Communication Anna University, CEG Campus, Chennai, India.*

Article Info

Article History:

Published:07 May 2026

Publication Issue:
Volume 3, Issue 5
May-2026

Page Number:
29-36

Corresponding Author:
Illakiya KS

Abstract:
This paper presents the design and simulation of a compact capsule antenna operating at the 2.45 GHz ISM band for biomedical applications. A miniaturized meandered microstrip patch antenna is designed using Rogers RT/duroid 5870 substrate to achieve size reduction while maintaining acceptable performance. The antenna is optimized to operate efficiently in a lossy human body environment. A partial ground plane is employed to improve impedance matching and bandwidth. Simulation results demonstrate satisfactory return loss, VSWR, and radiation characteristics suitable for in-body communication.

Keywords: Capsule antenna, ISM band, biomedical antenna, microstrip patch, CST, RT5870, miniaturization

1. Introduction

With the rapid development of implantable electronic medical care, micro-medical equipment has been widely promoted. In medical applications, the wireless capsule endoscopy (WCE) system is introduced to capture images of the digestive tract to detect the physiological state of human tissues to determine the physical health of the human body [1]-[10]. The antenna is an important component for realizing the wireless communication between the wireless capsule endoscope system inside the human body and the outside world. Due to the complex internal structure of the human body, with high dielectric constant, high loss and other characteristics, there are strict requirements on the performance of the antenna [2]-[10]. On the other hand, due to the miniaturization of the capsule system, the size of the antenna has to be reduced. If the antenna is attached to the surface of the capsule [3]-[4]- [10], a conformal structure can be formed.

Recent advancements in biomedical engineering have enabled the development of wireless capsule endoscopy systems for non-invasive diagnosis of gastrointestinal disorders. These systems require compact, low-power, and efficient antennas capable of operating reliably inside the human body. Designing antennas for in-body communication is challenging due to strict size constraints and the complex electromagnetic properties of biological tissues. Wireless capsule endoscopy and biomedical telemetry systems require compact and efficient antennas for reliable in-body communication. Designing antennas for such applications is challenging due to strict size constraints and the lossy nature of human tissues.

The 2.45 GHz ISM band is widely used for medical telemetry due to its global availability and compatibility with short-range communication systems. However, antenna performance at this frequency is significantly affected by the surrounding medium, which exhibits high dielectric constant and conductivity. These factors lead to increased signal attenuation, reduced radiation efficiency, and frequency detuning.

To address these challenges, this work proposes a miniaturized microstrip patch antenna using meander slot techniques and a partial ground plane. The design aims to achieve compact size, acceptable impedance matching, and stable radiation characteristics suitable for capsule applications.

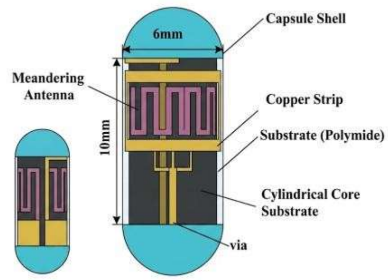


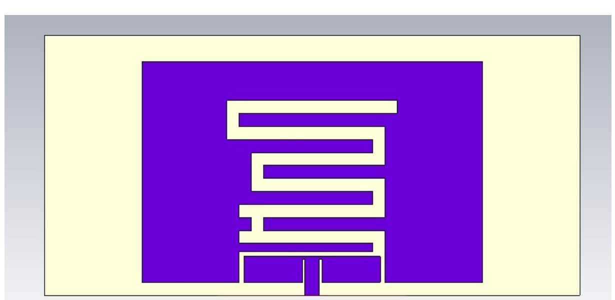
Fig. 1. Capsule antenna design after being wrapped

2.DESIGN CONSIDERATIONS FOR CAPSULE ANTENNA

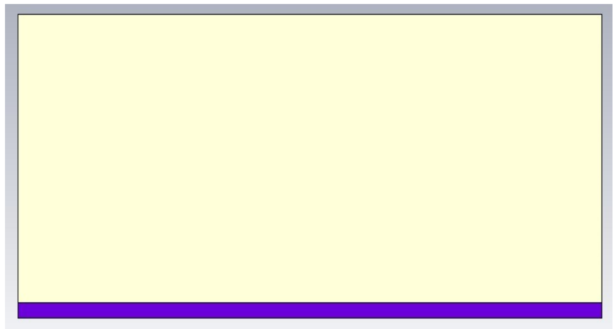
For biomedical applications, the antenna must be coated with biocompatible materials to prevent corrosion and ensure safe operation inside the human body. The Specific Absorption Rate (SAR) should also be within safe limits to avoid damage to tissues. Since the human body acts as a lossy medium, it significantly affects antenna performance by reducing radiation efficiency, shifting the resonant frequency, and increasing signal attenuation. Hence, these effects must be considered during the design process.

To evaluate performance under realistic conditions, a tissue-mimicking model is used. This model has a relative permittivity of 50–55 and conductivity of 1.5–2 S/m, with dimensions of $40 \times 40 \times 40$ mm^3. The antenna is placed inside this model to study its behavior in a lossy environment. This approach helps in understanding practical performance variations compared to free-space conditions. It also allows better optimization of the antenna parameters before real-world implementation.

Additionally, the antenna is designed to fit within the small size of a capsule, requiring miniaturization techniques such as slotting and meandering. A low-loss substrate is used to improve efficiency, while copper is selected to reduce ohmic losses. Proper impedance matching is achieved using a partial ground plane and optimized feed line dimensions to minimize reflection losses. These design choices collectively improve the reliability and performance of the antenna for in-body communication systems. Careful tuning of design parameters ensures stable operation within the desired frequency band. Overall, the proposed design offers a balance between compact size and acceptable performance for biomedical applications.



(a)



(b)

Fig. 2. Antenna structure (a). Front view (b). Back view

A. Material Selection

For practical biomedical implementation, gold coating may be applied to improve biocompatibility and corrosion resistance. The patch and ground are made of copper (annealed, $\sigma \approx 5.8 \times 10^7$ S/m), while the substrate used is RT/duroid 5870. The choice of substrate plays a crucial role in determining antenna size, efficiency, and bandwidth. In this design, Rogers RT/duroid 5870 is selected due to its low dielectric loss and stable performance at microwave frequencies. It has a dielectric constant (εr) of 2.33, loss tangent ($\tan\delta$) of 0.0012, and thickness of 0.508 mm. A lower dielectric constant improves radiation efficiency but increases antenna size, making miniaturization necessary to maintain compact dimensions. This is achieved using meander slots etched into the patch, which force the surface current to follow a longer path and effectively reduce the resonant frequency. Each slot has a width of 0.5 mm, spacing of 1 mm, and a depth of 7 mm, enabling the antenna to resonate at 2.45 GHz despite its reduced physical size.

The use of a low-loss substrate minimizes dielectric losses and improves overall efficiency, while copper ensures low ohmic losses due to its high conductivity. The substrate thickness is carefully selected to balance bandwidth and compactness, and surface roughness is considered to avoid performance degradation at higher frequencies. The chosen materials are compatible with standard PCB fabrication techniques, ensuring ease of implementation. Overall material selection plays a key role in achieving a balance between antenna size, efficiency, and bandwidth.

B. Antenna Geometry

The proposed antenna is based on a rectangular microstrip patch modified with meander slots to increase the effective electrical length without increasing physical size.

TABLE I. ANTENNA DIMENSIONS

Component	**Dimensions (in mm)**
Substrate	22 × 10 × 0.508
Patch	14 × 8.5 × 0.035
Ground plane	22 × 0.5 × 0.035
Feed line	0.6 × 1.4 ×0.035

The compact geometry ensures compatibility with typical capsule dimensions (length < 25 mm).

A partial ground plane is used instead of a full ground plane. This improves impedance matching and increases bandwidth by modifying the current distribution.

The feed dimensions are carefully chosen to ensure efficient power transfer and to minimize reflection losses. Meander slots are introduced to reduce the antenna size without significantly affecting its performance. The overall geometry of the antenna is optimized to achieve stable operation within the desired ISM frequency band. In addition, the design is kept simple so that it can be easily fabricated using standard PCB techniques. By fine-tuning the geometrical parameters, the resonant frequency and bandwidth can be adjusted effectively.

A microstrip line feed is used due to its simplicity and ease of fabrication. The feed line is designed for 50 Ω impedance matching by feed width of 2 mm and feed length of 6 mm as given in table 1. A waveguide port is defined at the feed end during simulation for excitation.

3.CAPSULE ANTENNA PERFORMANCE ANALYSIS

A. *Return Loss*

The simulated S11 parameter shows a distinct dip below

−10 dB near 2.45 GHz, indicating good impedance matching. The bandwidth is sufficient for ISM band operation. -13.3 dB result means that more than 95% of the power is being accepted by the antenna.

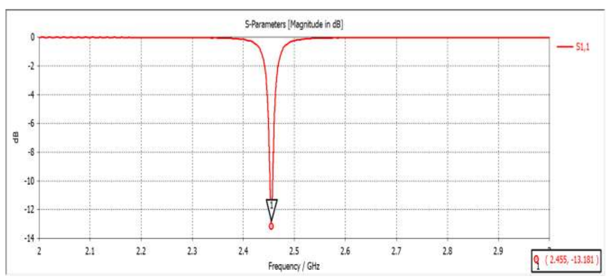


Fig. 3. The reflection coefficient of the antenna.

B. *VSWR*

A VSWR of 1.55 was achieved at 2.46 GHz, indicating that less than 5% of the incident power is reflected, which is critical for preserving the battery life of a miniaturized medical capsule. Maintaining a VSWR below 2.0 across the ISM band ensures stable communication and efficient power transfer between the feed line and antenna. This verification is essential for demonstrating that the antenna remains efficiently tuned even when subjected to the high- permittivity effects of the surrounding lossy tissue.

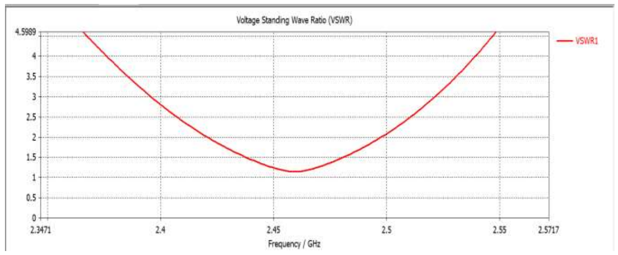
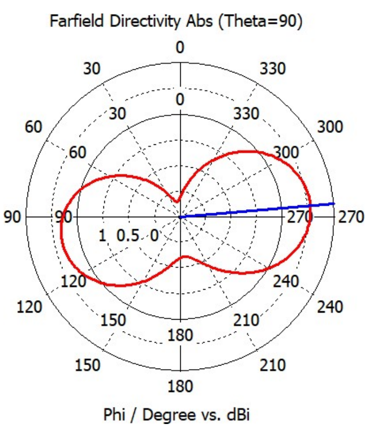


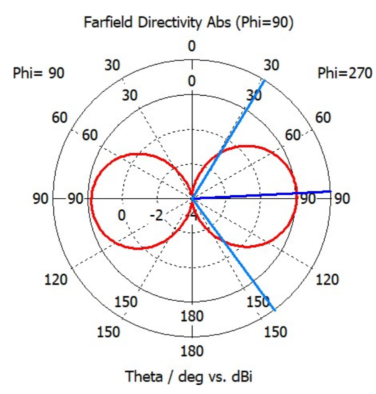
Fig. 4. VSWR

C. Radiation pattern

Fig. 4(a) demonstrates the omnidirectional nature of the antenna, which is desirable for capsule applications where orientation cannot be controlled. The figure shaped “eight” or "donut" is very typical for a meander or dipole-style antenna as it shows that antenna radiates strongly to the left and right but has a "null" or weak spot at the top and bottom. This blue line points toward 270º indicating the direction of maximum radiation.



(a)



(b)

Fig. 5. Radiation pattern (a). Theta= 90 (b). Phi= 90

D. Gain and Efficiency

The proposed meandered antenna achieves a radiation efficiency of 60% at the center frequency of 2.46 GHz. This indicates that the miniaturization techniques (meandering and partial ground) has maintained a high ratio of radiated power to internal losses, making it a viable candidate for low-power medical telemetry.

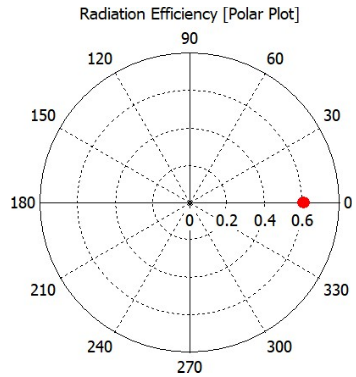


Fig. 6. Radiation efficiency

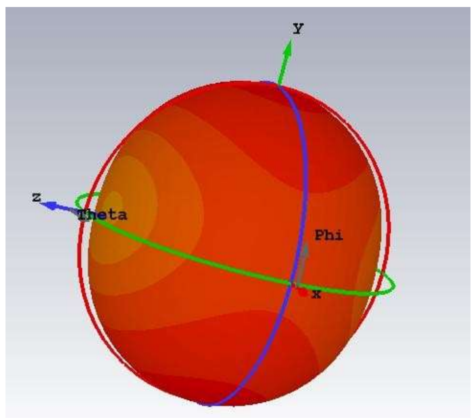


Fig. 7. 3D far-field pattern of the antenna.

Farfield analysis at 2.45 GHz reveals a near- omnidirectional radiation pattern, ensuring robust communication. The 3D radiation characteristics confirm that the design successfully balances miniaturization with the wide-angle coverage necessary for clinical telemetry applications.

I. COMPARISON OF WORK

Ref. No.	Author / Year	Antenna Type	Frequency Band	Size	Key Technique	Key Features	Limitations
[1]	B. Biswas (2020)	Miniaturized wideband antenna	Wideband (2–5 GHz approx.)	Compact	Meandered structure	Wide bandwidth, compact size	Complex design
[2]	M. J. Wang (2017)	Flexible antenna	Various	Flexible	Flexible materials	Suitable for capsule bending	Lower efficiency
[3]	S. Yun (2010)	Outer-wall loop antenna	UWB	Capsule wall	Loop design	Omnidirectional radiation	Fabrication complexity

[4]	P. M. Izdebski (2009)	Conformal antenna	~400 MHz – 2 GHz	Capsule size	Chandelier meander	High miniaturization	Narrow band
[5]	L. J. Xu (2014)	Implantable antenna	ISM band	Small	Bandwidth enhancement	Improved bandwidth	Reduced efficiency
[6]	J. Shang (2019)	UWB capsule antenna	UWB	Compact	Slotting technique	Wideband performance	Design complexity
[7]	J. Kim (2004)	Implanted antenna	Various	Varies	Simulation-based	Detailed body analysis	Not compact-focused
[8]	T. Karacolak (2008)	Dual-band antenna	Dual-band	Small	Matching optimization	Multi-band operation	Limited bandwidth
[9]	IEEE Std (1999)	Safety standard	3 kHz–300 GHz	—	SAR limits	Safety guidelines	Not a design
[10]	Y. Feng (2020)	Conformal UWB antenna	UWB	Capsule size	Conformal design	High bandwidth	Complex structure
	Proposed work	Meandered microstrip patch	2.45 GHz	Compact	Meandered slots and partial ground	Compact and good matching	-

4.CONCLUSION

In this work, a compact capsule antenna operating at the 2.45 GHz ISM band has been designed and analyzed for biomedical applications. The antenna employs a meandered microstrip patch configuration on an RT/duroid 5870 substrate to achieve size reduction while maintaining acceptable performance. The use of slotting techniques and a partial ground plane enables effective miniaturization and improved impedance matching within the limited capsule dimensions.

The antenna performance has been evaluated in a tissue- mimicking environment to account for the effects of the human body. Simulation results indicate that the proposed design achieves satisfactory return loss, VSWR, and radiation characteristics suitable for in-body communication. Although the presence of lossy tissues reduces gain and causes frequency detuning, these effects have been considered and compensated during the design process.

Compared to existing designs, the proposed antenna offers a good balance between compact size, structural simplicity, and performance. Hence, it can be considered a suitable candidate for applications such as wireless capsule endoscopy and biomedical telemetry systems.

References

1. B Biswas, A Karmakar, V Chandra, "Miniaturised wideband ingestible antenna for wireless capsule endoscopy," *IET Microwaves, Antennas & Propagation*, vol. 14, no. 4, pp. 293-301, Mar 2020.
2. M J Wang, L L Cai, H X Zheng, et al, "Research progress of flexible antenna technology for electronic capsules," *Electronic Components and Materials*, vol.36, no. 4, pp. 9-14, Apr 2017.
3. S.Yun, K.Kim, S.Nam, "Outer-Wall Loop Antenna for Ultrawideband Capsule Endoscope System,"

Antennas and Wireless Propagation Letters, vol. 9, no. 1, pp. 1135-1138, Nov 2010.

4. P M Izdebski, H Rajagopalan, Y Rahmat-Samii, “Conformal ingestible capsule antenna: A novel chandelier meandered design,” *IEEE Transactions on Antennas and Propagation*, vol.57, no. 4, pp. 900-909, Apr 2009.
5. L J Xu, Y X Guo, W Wu, “Bandwidth enhancement of an implantable antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1510-1513, Nov 2014.
6. J Shang, Y Yu, “An Ultrawideband Capsule Antenna for Biomedical Applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no.12, pp. 2548-2551, Dec 2019.
7. J Kim, Y Rahmat-Samii, “Implanted antennas inside a human body: Simulations, designs, and characterizations,” *IEEE Transactions on microwave theory and techniques*, vol. 52, no. 8,
8. pp. 1934-1943, Aug 2004.
9. T Karacolak, A Z Hood, E Topsakal, “Design of a dual-band implantable antenna and development of skin mimicking gels for continuous glucose monitoringc,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 4, pp. 1001-1008, Apr 2008.
10. IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz, IEEE Standard C95.1-1999, 1999.
11. Y. Feng, S. -P. Pan, J. -W. Li, P. Chen, L. Qi and G. -S. Li, "Design of Ultra-wideband Conformal Capsule Antenna for Wireless Capsule Endoscopy System," 2020 Cross Strait Radio Science & Wireless Technology Conference (CSRSWTC), Fuzhou, China, 2020, pp. 1-3, doi: 10.1109/CSRSWTC50769.2020.9372442