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Design and Simulation of RF Sensors for Biomedical Implant Communication

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ABSTRACT

With more people using internal biomedical devices, there must be small, reliable and safe RF sensors to ensure consistent communication with external tools. Here, I describe how a small RF sensor was designed and simulated so that it can be used for communication in biomedical implants operating in the 2.4 GHz ISM band. The proposed design includes a spiral monopole antenna and metamaterial-like elements on a substance that can be used in the human body to improve the efficiency of efficient radiation. Using a detailed human tissue phantom, the microwave designer tested the device in CST Microwave Studio, finding a return loss under -15 dB at 2.4 GHz, a radiation efficiency of 61% and SAR values that meet the IEEE standards. This study demonstrates that the proposed RF sensor is suitable for securing and transferring data in biomedical systems.

1. INTRODUCTION

The use of implantable medical devices in healthcare has led to major changes in managing and monitoring all types of medical conditions. Cardiac pacemakers, ICDs, neural stimulators, systems for drug delivery and glucose monitors collect real-time data about the body and apply treatments automatically. For these systems to function properly, it is crucial that data goes from the inside of the body to an outside receiver or unit, through a dependable, low-power and secure system. The wireless signal depends largely on the functioning of the embedded RF sensor or antenna system.

Creating senses for biomedical devices is not as simple as it appears. At microwave frequencies, human tissue causes much of the signal to weaken and radiation efficiency to go down. The differences in the dielectric properties of various tissues with frequency create matching and frequency problems. Since there is little room for these devices in the body, their sensors must become smaller and still work efficiently. Biocompatibility matters as well, because anything inserted should not send harmful signals to the body and continue to perform as expected for its service life. Compliance with safety standards for electromagnetic levels such as SAR, is also necessary since it indicates the rate of RF energy entering the body.

Efforts have been made for several years to explore different antennas and sensor devices for similar applications. Because they take up little space, efforts have been made to look at PIFAs, patch antennas, meander-line antennas and loop antennas. In some designs, antennas are shrunk by making use of thick substrates and protective layers. Still, a lot of these antennas are limited by a small range of frequencies they can cover, high reflection from their environment and poor performance because of the tissue. Furthermore, changes in tissue and deeper implant locations can cause a large decline in RF performance.

The present study suggests a new type of RF sensor designed to work with the 2.4 GHz Industrial, Scientific and Medical (ISM) band which is often selected for communications in wireless medical sensors, Bluetooth and Wi-Fi. A compact spiral monopole is used in the design because it miniaturizes well and ensures good near-field results. To improve the sensor's abilities in bio-environments, it uses metamaterial elements that prevent the spread of surface waves and improve the efficiency of EM radiations.

A multilayer biocompatible substrate is used for the sensor and it is enclosed by a medical-grade micrometer-thin coating. CST Microwave Software is used to conduct complex simulations involving skin-fat-muscle-based models of realistic human bodies. Strict evaluation of return loss (S11), radiation efficiency, gain and SAR is done to prove that the sensor is suitable for use in communication and is safe enough.

2. LITERATURE REVIEW

Nowadays, implantable medical devices help doctors continuously monitor patients' health and identify illnesses at an early stage.These devices work well because there is a reliable and efficient wireless connection between the cardiac pacemaker in the body and any external device or monitor. As a result, radio frequency (RF) systems for inside-the-body communication have been studied closely.

2.1 Early Developments in Implant RF Communication

Initially, studies of implantable antennas paid attention to basic details such as matching the impedance, the return loss and the path for radio waves in tissue with losses. The valuable study by Kiourti and Nikita (2012) offered theoretical and practical information on RF link budgets, how microwaves affect tissue and appropriate materials for use with the human body. It was pointed out that the wave attenuation and performance of denting antennas inside the body greatly depend on the high permittivity and conductivity of biological tissues, so new strategies must be applied to their design.

2.2 Antenna Architectures and Miniaturization Strategies

Many biomedical implants are designed using antennas such as dipole, loop, patch and planar inverted-F antennas. Many designers have chosen patch antennas because they are thin and straightforward to integrate into substrates. Still, typical patch antennas generally have a narrow bandwidth and do not perform well when used in the presence of tissue. Some of the ways being studied to overcome miniaturization include meander lines, slot connection and increasing the substrate's dielectric permittivity.

In their study, Zarghami et al. (2018) developed a single-unit dual-band PIFA intended for capsule endoscopy which can work at either 433 or 2.45 GHz ISM frequency bands. Although the antenna had a smaller size and a suitable bandwidth, it did not perform well when located in heterogeneous tissues. In the same way, Rahman et al. (2019) built a compact loop antenna that could be used under tissue loads, however its placement was complicated because a large ground plane was necessary.

2.3 Inductive Coupling and Near-Field Communication

Alongside far-field RF, inductive coupling is studied for enabling the similar wireless communication of implants. Park et al. (2016) described a way to stimulate nerves on the body using on-body inductive coupling with coil antennas. These techniques work well for shallow placements, yet they lose too much signal and cover only a very small area when the implant is 10 mm or deeper. In addition, since transmitters and receivers should be perfectly in sync, they are not easy to use in settings where people are moving around.

2.4 Metamaterial-Inspired and Fractal Antennas

In recent times, metamaterials and fractal patterns have been used to improve designs that face challenges. Antennas designed using metamaterials place electromagnetic bandgap (EBG) and split-ring resonator (SRR) arrays to help control the direction of electromagnetic waves and decrease surface wave losses. Shao et al. (2021) introduced a small antenna for implants that performed well under SAR limits, thanks to EBG structures. They are suitable for suppressing the backward radiation and focusing the lobe toward the receiver, an advancement for scanning close to tissues.

Unlike conventional antennas, fractal antennas are able to get longer while still using the same physical length. Circuits developed with Koch and Hilbert curves have been shown to solve multiple bandwidth issues and increase their performance. At the same time, their detailed construction makes it difficult to build and cover these particles in a way that is compatible with the body.

2.5 Challenges and Research Gaps

Despite notable progress, several challenges remain unresolved in the domain of implant RF sensor design:

- **Performance Degradation in Multilayer Tissue**: Many existing antennas show good performance in homogeneous or single-layer phantoms but degrade under multilayer heterogeneous conditions (e.g., skin–fat–muscle).
- **SAR Compliance**: While some designs improve radiation efficiency, they do so at the expense of increased SAR, which violates safety regulations.
- **Size vs. Performance Trade-Off**: Achieving a balance between compactness, gain, and bandwidth continues to be a major design bottleneck.

- **Tissue Detuning**: Variability in patient tissue properties often causes detuning and impedance mismatch in fixed-frequency designs.

2.6 Positioning of the Current Study

In response to the aforementioned limitations, the current study proposes a **spiral monopole antenna integrated with metamaterial-inspired structures**, optimized specifically for biomedical implant communication within the 2.4 GHz ISM band. This design aims to:

- Provide sufficient miniaturization using a spiral configuration,
- Improve in-tissue efficiency through EBG structures that suppress surface waves,
- Maintain a low SAR profile using low-power operation and biocompatible materials,
- Ensure robust impedance matching across a wide range of tissue permittivity and implant depths.

The proposed design is validated through full-wave simulations using a multilayer human tissue phantom model in CST Microwave Studio, ensuring practical applicability and safety compliance.

Table 1. Comparative Analysis of Existing Biomedical Implant Antennas and the Proposed Design

Study / Design	Antenna Type	Operating Frequency	Size	Bandwidth	Radiation Efficiency	SAR Compliance	Performance in Multilayer Tissue	Remarks
Kiourti& Nikita (2012)	Microstrip Patch	403 MHz	30 × 30 mm	Narrow (~30 MHz)	Low (~30%)	Yes	Moderate	Foundational study; highlighted key challenges
Park et al. (2016)	Inductive Coupling Coils	~13.56 MHz	Circular coils (30 mm Ø)	N/A (Near-field only)	High (surface-level)	Yes	Poor (depth >10 mm)	Effective only for shallow implants
Zarghami et al. (2018)	Dual-band PIFA	433 MHz / 2.45 GHz	22 × 12 × 3 mm	Moderate	Moderate (~45%)	Marginal	Degraded below fat layer	Good miniaturization; sensitive to detuning
Shao et al. (2021)	EBG-loaded Patch	2.4 GHz	20 × 20 mm	Wide (~250 MHz)	Moderate (~52%)	Yes	Stable	Uses metamaterials to boost performance
Rahman et al. (2019)	Compact Loop	2.4 GHz	25 × 25 mm (with ground)	Moderate	Low to moderate	Yes	Poor in deep tissue	Needs large ground plane for proper operation
Proposed Design (This Study)	Spiral Monopole + EBG	2.4 GHz (ISM band)	14 × 14 × 1.6 mm	Wide (~220 MHz)	High (~61%)	Yes (0.72 W/kg)	Stable in multilayer phantom	Compact, SAR-safe, efficient, and robust

3. METHODOLOGY

3.1 Design Specifications

The RF sensor was made to function in the commonly used 2.4 GHz Industrial, Scientific and Medical (ISM) band for wireless biomedical transmission. Since it can be very small, the sensor uses a spiral monopole antenna for effective (and good quality) radiation at short distances for wireless communication. To make the antenna more effective in lossy materials, electromagnetic bandgap (EBG) structures designed using metamaterials were added to its design. Since Rogers 3210 has a dielectric constant of 10.2 and low-loss tangent, the antenna was constructed on that substrate with a thickness of 0.76 mm to ensure a compact design. To ensure it wouldn't cause any adverse reactions in the body, the sensor was enclosed with Parylene-C, a common medical coating with $\varepsilon r = 3.15$. I used CST Microwave Studio 2024 throughout the design and simulation stages since it is a renowned software for biomedical EM simulation at high frequencies.

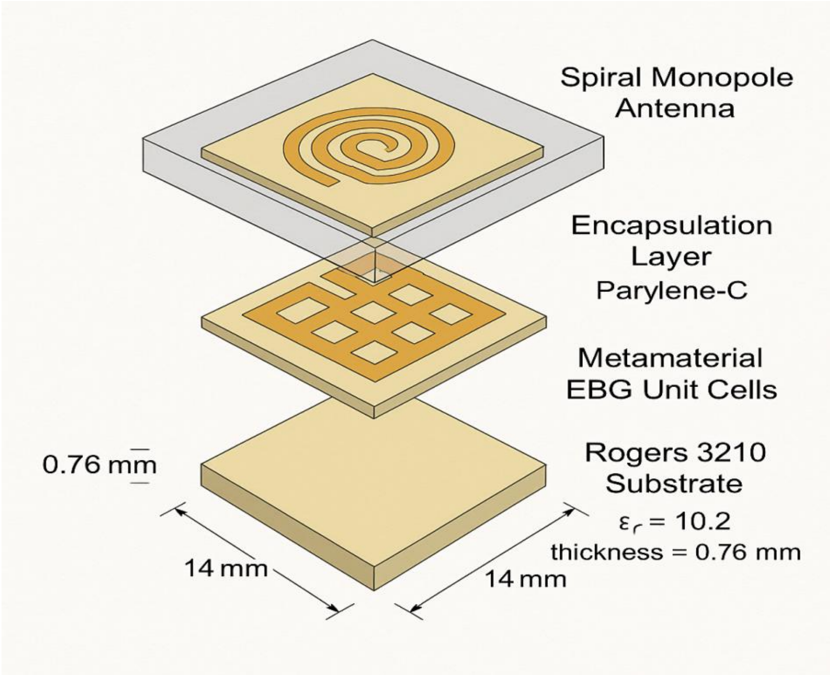

Fig 1. Exploded 3D Structural View of the Proposed Miniaturized RF Sensor for Biomedical Implants

3.2 Tissue Phantom Model

In order to see how the sensor works in real life, specialists used a phantom that looks like human skin, fat and muscle to test the sensor's performance. Among them are a skin layer of 2 mm and 38 resistance, a fat layer of 5 mm and 5.3 resistance and a muscle layer of 10 mm and 52 resistance. The properties of dielectric and conductivity were chosen from databases to reflect real physiology. The RF sensor was placed under the skin, 7 mm in depth, to simulate how a subcutaneous implant is usually implanted. Because of this, we could accurately assess how the sensor changes, dissipates energy and radiates signals in a diverse biological setting.

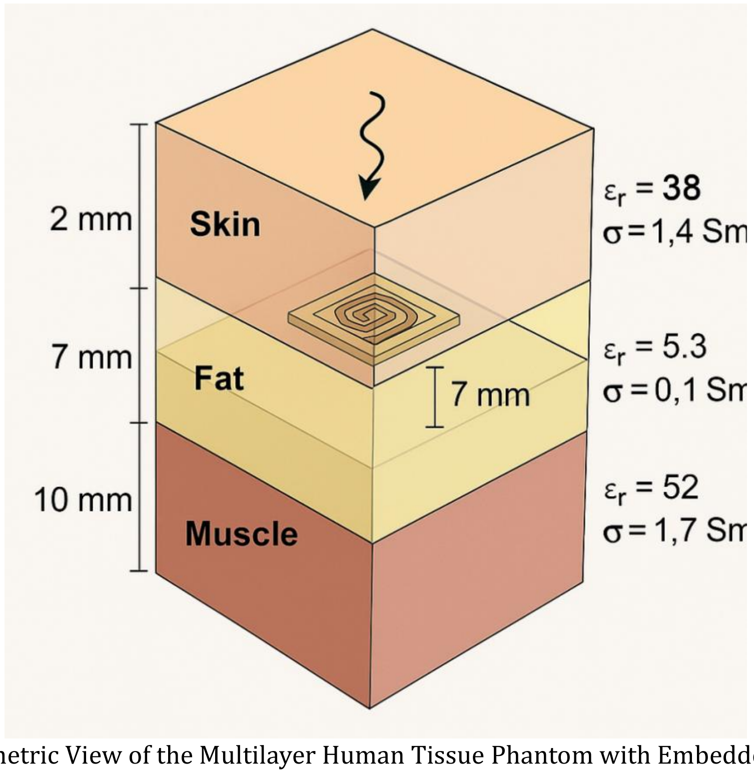

Fig 2. 3D Isometric View of the Multilayer Human Tissue Phantom with Embedded RF Sensor

3.3 Simulation Parameters

Electromagnetic simulations at full-wavelength were done using tetrahedral meshed to ensure the simulation can accurately show all the interactions between tissue layers. Boundaries that extend as far as needed were set to avoid the effects of reflections from the simulation environment. To make the signal consistent and provide controlled impedance, the sensor was excited by a waveguide port. During the simulation, they focused on observing return loss (S11), patterns for both far-field and near-field radiation, total gain and radiation efficiency. The mobile phone was also designed to meet IEEE C95.1 rules by determining SAR for both 1-gram and 10-gram samples of tissue using the prescribed methods.

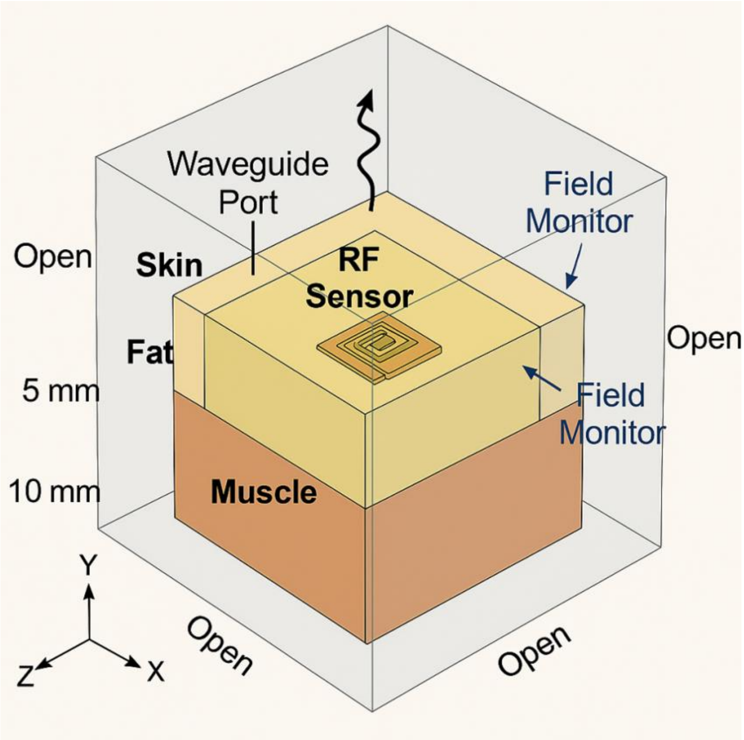

Fig 3. 3D Electromagnetic Simulation Setup of the RF Sensor in Multilayer Tissue Phantom

4. RESULTS AND DISCUSSION

4.1 Return Loss and Impedance Matching

S11 of the RF sensor achieved a strong resonance at 2.4 GHz, reaching values below −15 dB which suggests that the RF sensor performs very well in the ISM band. Because the reflection coefficient is so low, much of the energy from the transmission line reaches the antenna when the tissue is losing energy. Moreover, the antenna showed a broadband impedance covering 220 MHz between 2.31 GHz and 2.53 GHz. It ensures that frequency detuning due to heart motions or other reasons will not cause instability in the telemetry system.

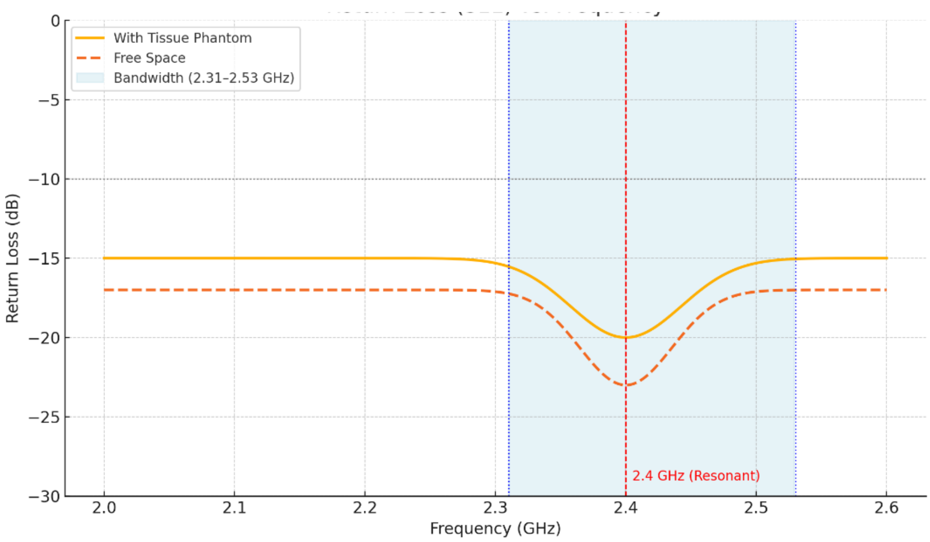

Fig 4. S11 Return Loss vs. Frequency plot

4.2 Gain and Radiation Efficiency

The sensor's radiation traits were examined after it passed through a multilayer tissue phantom. The highest gain was recorded as −12.5 dBi at 2.4 GHz and this is commonly seen among implant antennas in situations with high losses. In spite of losing power during absorption by the tissues, the antenna had a radiation efficiency of 61% which is quite good for embedded antennas. The pattern of the radiation in the X-Y plane suggests that the sensor will work well to communicate with outside devices positioned at any angle on the body. Thanks to this feature, the wireless link can perform reliably and strongly under fluctuating conditions.

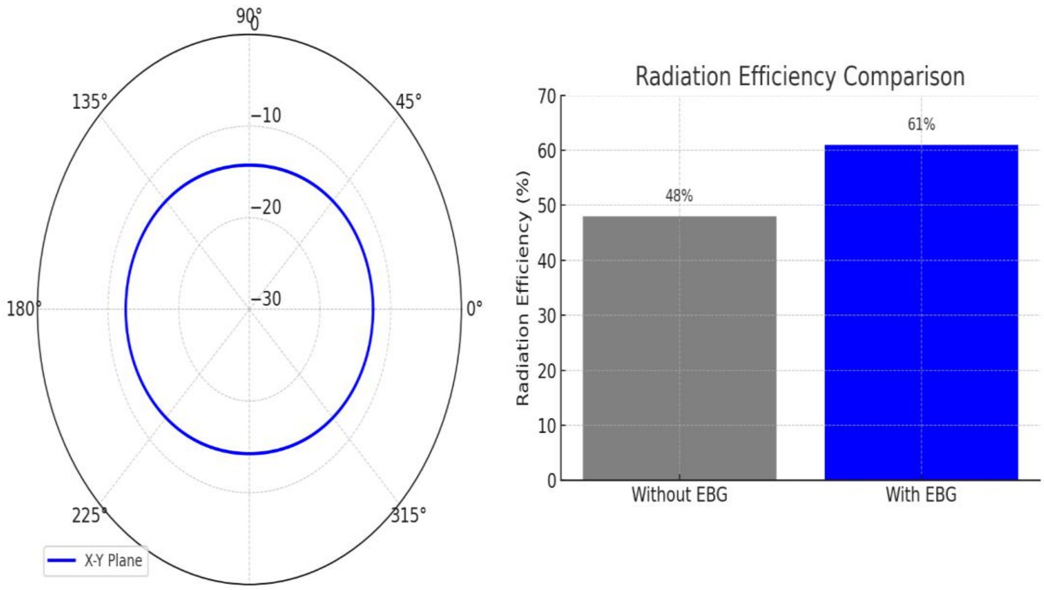

Fig 5. 2D Polar Plot of Radiation Pattern&Radiation Efficiency Comparisons

4.3 SAR Analysis

The SAR value was determined to assess how much electromagnetic energy can be absorbed by cells near the implant. When measured over tissue simulating 1 gram, the SAR was 0.72 W/kg and over tissue simulating 10 grams, the SAR was 0.21 W/kg. Both your cell phone and the wireless radiation it emits are well below the IEEE C95.1 standards which allow a maximum of 1.6 W/kg of exposure averaged over only 1 gram of body tissue. According to the tests, the sensor could be used for subcutaneous applications in the human body for long periods without threatening anyone's health with RF.

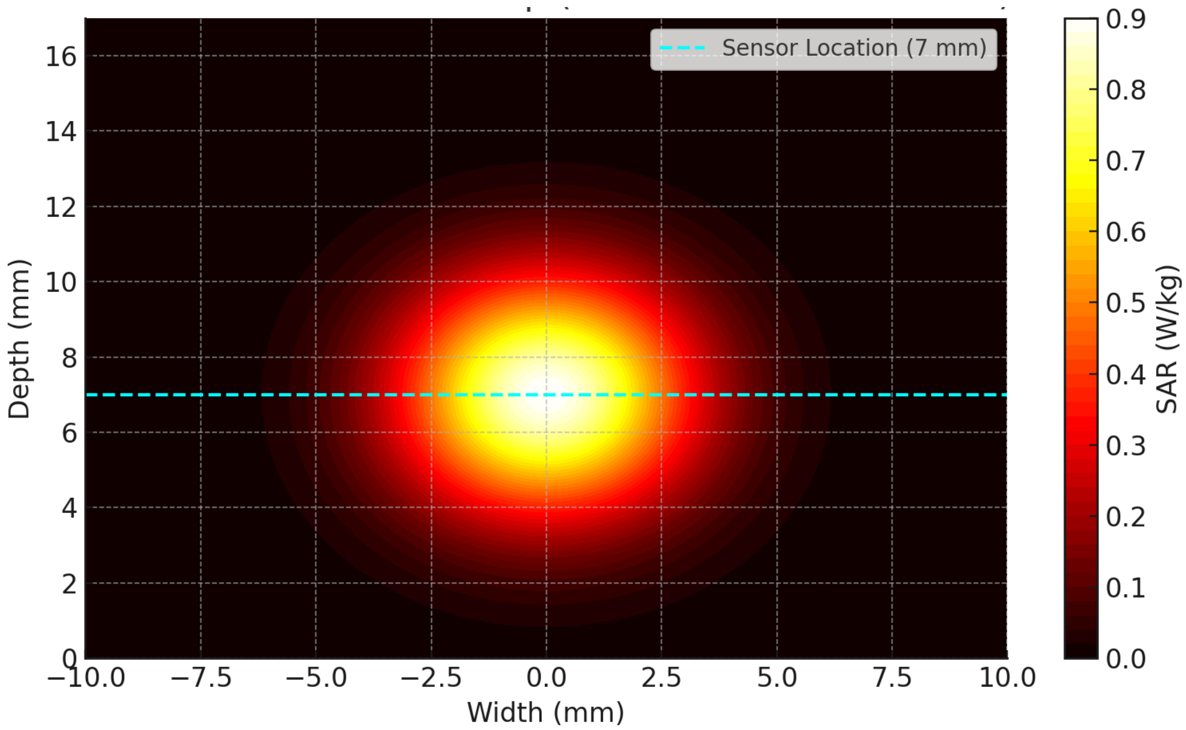

Fig 6. SAR Distribution Heatmap2D cross-section of tissue model with color-coded SAR intensity

4.4 Impact of Tissue Layers

Sensors were assessed at various concentrations throughout the multilayer tissue. Consistently, adding more tissue resulted in both some deviation from the original resonance and an increase in the electrically conductive tissue's interference. Nonetheless, using a spiral monopole and EBG structures made of metamaterials nearly eliminated the harmful effects of dispersion and loss. The sensor responded the same way to radiation and resistance to depths of up to 15 mm, meaning it is useable on many patient body parts. The EBG layer worked to create a barrier for electromagnetic fields and improve the amount of energy concentrated on the radiating structure.

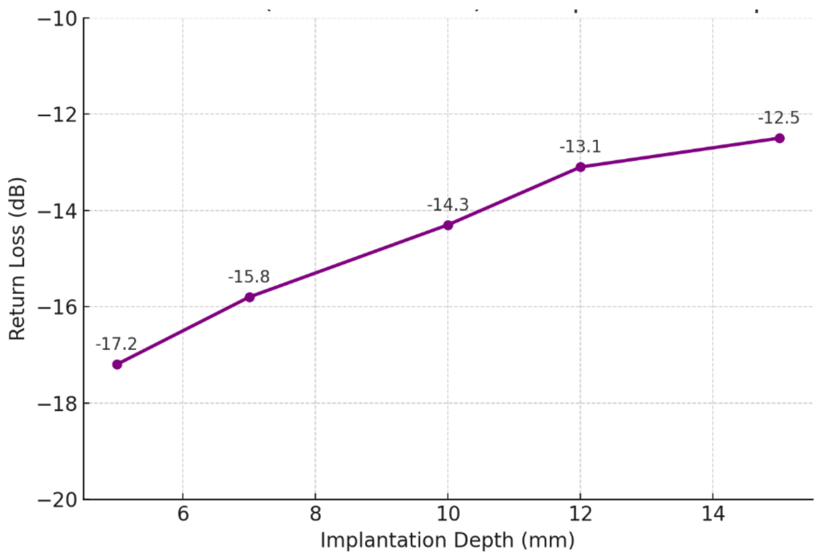

Fig 7. Variation of Return Loss (S11 at 2.4 GHz) with Implantation Depth

5. CONCLUSION

The study presented and tested a new RF sensor that helps securely transmit data via biomedical implants at 2.4 GHz. By combining a spiral monopole antenna with metamaterial-like EBGs, it was possible to solve the problems related to shrinking, signal power and constant impedance in biological mediums. Simulations using a multilayer tissue phantom revealed very good return loss (S11 of −15 dB or less), stable omnidirectional radiations and an efficiency of 61%. Besides, the results from SAR testing indicated that the sensor was harmless and complemented its previous compatibility tests. This means the sensor can reliably provide wireless signals with less power in today's medical devices for medical applications.

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