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A Low Profile Implantable Antenna for Heart Implants

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ABSTRACT:
The complex electromagnetic environment of the human body and its interaction with implantable electronic components often result in antenna detuning, making wide bandwidth a critical requirement for stable operation. This paper presents a compact implantable antenna designed for leadless cardiac pacemakers, featuring ultrawide bandwidth to mitigate detuning effects and enhance communication reliability. The antenna is optimized to operate efficiently within lossy biological tissues while maintaining a miniaturized form factor suitable for implantation. The proposed design supports multiple communication bands, including ISM, WMTS, and mid-field frequencies, enabling flexible and multi-functional biomedical applications. Parametric optimization is carried out to achieve improved impedance matching and radiation performance across The operating bands. Simulation results indicate stable gain characteristics and consistent radiation behavior despite variations in tissue properties. Safety considerations are addressed through detailed specific absorption rate (SAR) analysis, ensuring compliance with established regulatory limits. In addition, a comprehensive link budget analysis is performed to estimate communication range and assess system performance at different data rates. Experimental validation using tissue-equivalent phantoms demonstrates strong agreement between simulated and measured results, confirming the robustness and practical applicability of the proposed antenna design for implantable medical devices.

INTRODUCTION:
The proposed implantable antenna is designed following a systematic methodology to ensure compact size, wide bandwidth, and reliable operation within the lossy environment of human body tissues. Initially, the antenna geometry is conceptualized based on miniaturized microstrip structures, where techniques such as meandering, slotting, and effective current path elongation are incorporated to reduce the physical size while maintaining acceptable electromagnetic performance. A suitable high-permittivity substrate material is selected to further assist on antenna performance. The reflection coefficient (S11) is analyzed to ensure proper impedance matching, typically targeting values below –10 dB across the desired frequency bands. In addition, radiation characteristics such as gain, directivity, efficiency, and radiation pattern are evaluated to ensure stable communication performance despite the high attenuation caused by biological tissues.Since implantable devices operate under strict safety regulations, the Specific Absorption Rate (SAR) is calculated to quantify the electromagnetic energy absorbed by surrounding tissues.

Figure1:Several wireless implantable medical devices are used in human body.

THE SAR :

values are evaluated based on both 1 g and 10g tissue averaging standards to ensure compliance with international safety limits. Design modifications such as power control, geometry optimization, and insulation layers are applied when necessary to maintain SAR within permissible levels. Furthermore, the antenna is analyzed under different input power levels to understand its thermal and electromagnetic impact on human tissues .To assess the reliability of wireless communication, a detailed link budget analysis is performed by considering factors such as transmitted power, antenna gain, path loss through biological tissues, and receiver sensitivity. This analysis helps estimate the achievable communication range and data rate for various application scenarios. Both near-field and far-field communication mechanisms are considered, particularly for comparing inductive coupling and RF-based communication approaches. The antenna is also evaluated across multiple medical frequency bands, including MICS, MedRadio, and ISM, to ensure versatility and compatibility with different biomedical applications.For experimental validation, the optimized antenna design is fabricated using suitable biocompatible materials, ensuring that the structure can safely operate within the human body. Measurements are conducted using tissue-equivalent phantoms that replicate the dielectric properties of human tissues. Depending on the application, liquid, semisolid, or solid phantoms are prepared and used to experimentally evaluate antenna performance. Key parameters such as return loss, bandwidth, and radiation characteristics are measured and compared with simulation results. Any discrepancies are analyzed and minimized through iterative design refinement. The robustness of the antenna is examined by evaluating its performance under different orientations and positional variations within the tissue model. The impact of fabrication tolerances and material uncertainties is also considered to ensure practical reliability. The overall methodology integrates simulation, analytical evaluation, and experimental validation to develop a compact, efficient, and safe implantable antenna suitable for modern biomedical applications. This comprehensive approach ensures that the proposed design meets the stringent requirements of implantable medical devices in terms of size, performance, safety, and communication reliability.

EXISTING SYSTEM:

A miniaturized dual-band circularly polarized (CP) antenna is presented for wireless capsule endoscopy applications operating at 915 MHz and 2.45 GHz ISM bands. The proposed antenna is designed for deep-tissue implantation within a standard capsule size of 26 × 11 mm^2, while maintaining an ultra-compact radiator volume of 2.11 mm^3. The antenna achieves CP characteristics at both bands with satisfactory gain and employs a via-less ground plane for simplified fabrication. Miniaturization and CP performance are achieved by incorporating meandered slots in the radiating patch and open-ended slots in the ground plane. The antenna is initially simulated using HFSS within a homogeneous muscle phantom at a depth of 50 mm, and key parameters such as reflection coefficient, axial ratio bandwidth, and radiation characteristics are analyzed. Further validation is performed using a realistic human body model in XFdtd software. A parametric study is conducted to optimize slot dimensions and positions, demonstrating that variations in slot width, length, and placement significantly influence impedance matching and resonant frequencies. Optimal performance is achieved for specific parameter values, ensuring proper operation in both ISM bands.

PROPOSED METHOD:

The proposed system introduces a compact implantable antenna for leadless cardiac pacemakers, designed to achieve ultrawide bandwidth and stable performance in the lossy human body environment. The antenna uses a slotted radiating patch and ground plane modifications to enhance impedance matching and create multiple current paths for wideband operation. Reactive loading elements improve gain and resonance stability across biomedical frequency bands.

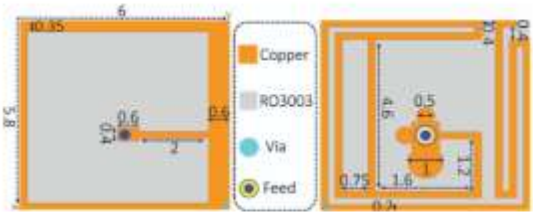

Figure 2: Proposed antenna structure

The antenna operates based on effective electrical length, where slot incorporation increases the current path and enables multiband behavior. Impedance matching is achieved by minimizing the reactive component of input impedance, ensuring efficient power transfer. Reflection coefficient and return loss analysis confirm wide bandwidth with low signal reflection.

Safety is ensured through SAR analysis, maintaining energy absorption within permissible limits. Communication reliability is evaluated using link budget analysis based on the Friis equation, estimating transmission range between the implant and external receiver.

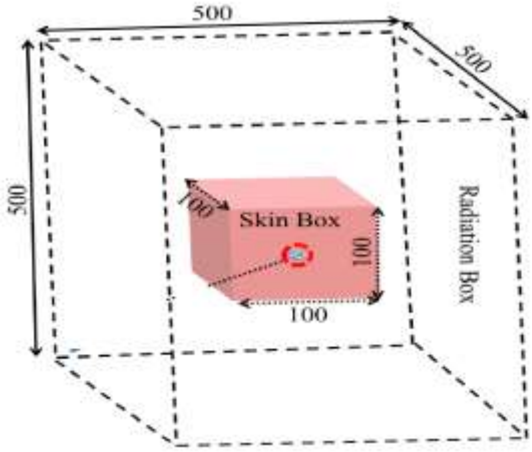

Figure 3:Skin phantom inside the antenna

The design is validated through simulations and experimental testing using tissue-equivalent phantoms. A homogeneous skin model is used with appropriate dielectric properties, and results show good agreement between simulated and measured performance, confirming the effectiveness of the proposed antenna for biomedical applications.

RADIATION PATTERN:

The radiation or antenna pattern describes the relative strength of the radiated field in various directions from the antenna, at a constant distance. The radiation pattern is a reception pattern as well, since it also describes the receiving properties of the antenna. The radiation pattern is three-dimensional, but usually the measured radiation patterns are a two dimensional slice of the three-dimensional pattern, in the horizontal or vertical planes.

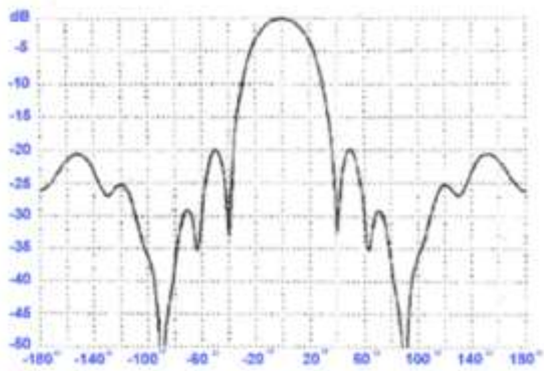

Figure 4:Radiation graph

These pattern measurements are presented in either a rectangular or a polar format. The following figure shows a rectangular plot presentation of a typical 10 element Yagi. The detail is good but it is difficult to visualize the antenna behavior at different directions.

Polar coordinate systems are used almost universally.

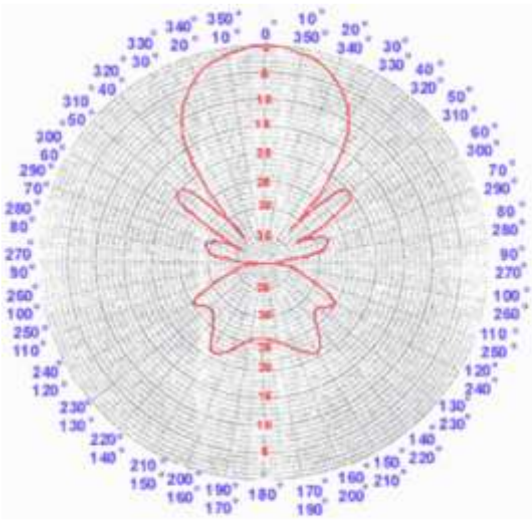

Figure 5: Polar coordinate graph

In the polar coordinate graph, points are located by projection along a rotating axis (radius) to an intersection with one of several concentric circles. Following is a polar plot of the same 10 element Yagi antenna.

Polar coordinate systems may be divided generally in two classes: *linear* and *logarithmic*. In the linear coordinate system, the concentric circles are equally spaced, and are graduated. Such a grid may be used to prepare a linear plot of the power contained in the signal. For ease of comparison, the equally spaced concentric circles may be replaced with appropriately placed circles representing the decibel response, referenced to 0 dB at the outer edge of the plot. In this kind of plot the minor lobes are suppressed. Lobes with peaks more than 15 dB or so below the main lobe disappear because of their small size. This grid enhances plots in which the antenna has a high directivity and small minor lobes. The voltage of the signal, rather than the power, can also be plotted on a linear coordinate system. In this case, too, the directivity is enhanced and the minor lobes suppressed, but not in the same degree as in the linear power grid.

BEAMWIDTH:

An antenna's beamwidth is usually understood to mean the half-power beamwidth.. The angular distance between the half power points is defined as the beamwidth. Half the power expressed in decibels is — 3dB, so the half power beamwidth is sometimes referred to as the 3Db beamwidth. Both horizontal and vertical beamwidths are usually considered.

Assuming that most of the radiated power is not divided into sidelobes, then the directive gain is inversely proportional to the beamwidth: as the beamwidth decreases, the directive gain increases.

SIDELOBES:

No antenna is able to radiate all the energy in one preferred direction. Some is inevitably radiated in other directions. The peaks are referred to as sidelobes, commonly specified in dB down from the main lobe.

NULLS:

In an antenna radiation pattern, a null is a zone in which the effective radiated power is at a minimum. A null often has a narrow directivity angle compared to that of the main beam. Thus, the null is useful for several purposes, such as suppression of interfering signals in a given direction.

Polarization :

Polarization is defined as the orientation of the electric field of an electromagnetic wave. Polarization is in general described by an ellipse. Two special cases of elliptical polarization are linear polarization and circular polarization. The initial polarization of a radio wave is determined by the antenna.

With linear polarization the electric field vector stays in the same plane all the time. Vertically polarized radiation is somewhat less affected by reflections over the transmission path. Omni directional antennas always have vertical polarization. With horizontal polarization, such reflections cause variations in received signal strength. Horizontal antennas are less likely to pick up man-made interference, which ordinarily is vertically polarized.

SIMULATION RESULTS:

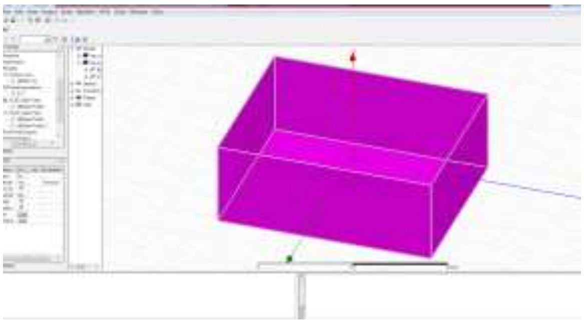

Figure 6: AIR BOX CREATION

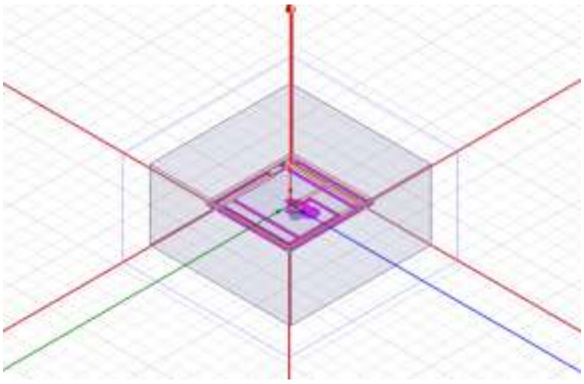

Figure 7: Human model formation

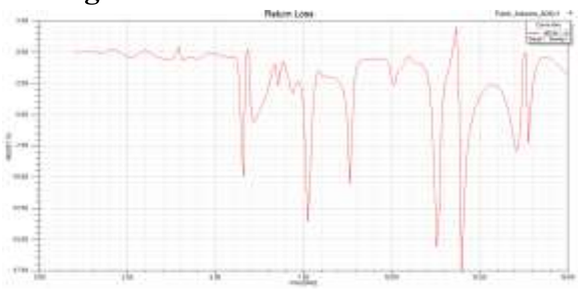

Figure 8:Return Loss

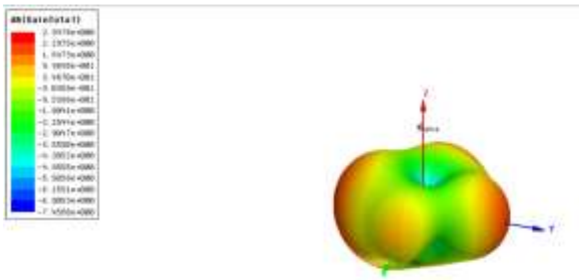

Figure 9: Gain

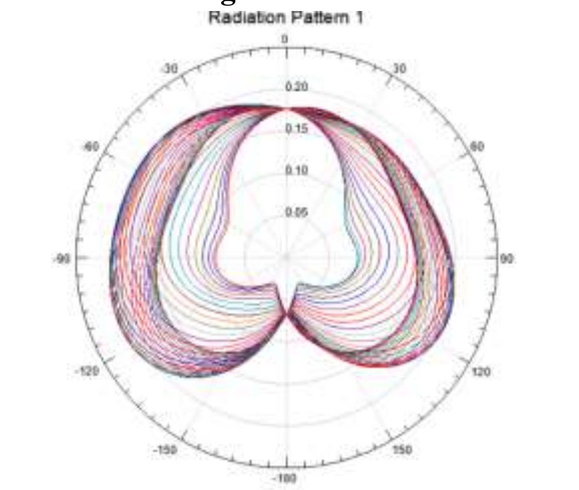

Figure 10: Radiation pattern

Parameter	**Existing** method	**Proposed method**
Gain	-4.4	-1.3
Volume	2.11	1.8

Table 2 : Performance analysis

FUTURE SCOPE:

The proposed implantable antenna can be further enhanced in several directions to improve its performance and applicability in advanced biomedical systems. Future work may focus on achieving further miniaturization while maintaining high efficiency, enabling integration into even smaller implantable devices. The design can be extended to support multi-band and reconfigurable operation, allowing dynamic adaptation to different medical communication standards. In addition, the use of flexible and biocompatible materials can be explored to improve patient comfort and long-term reliability. Advanced techniques such as metamaterials and artificial structures may be incorporated to enhance gain and bandwidth performance. The integration of the antenna with wireless power transfer systems can eliminate the need for batteries, increasing device lifetime.

Further investigation using realistic heterogeneous human body models and in-vivo testing can provide more accurate performance validation. The system can also be expanded for applications such as real-time health monitoring, IoT-based medical systems, and smart implants, improving the overall quality of healthcare and enabling next-generation biomedical technologies.

CONCLUSION:

This work presents a compact and efficient implantable antenna designed to achieve wideband performance for reliable biomedical communication applications, particularly in leadless cardiac pacemakers. The proposed design successfully addresses key challenges such as detuning, limited bandwidth, and signal degradation caused by the complex human body environment. By incorporating reactive loading techniques, optimized slot structures, and inductive elements, the antenna achieves improved impedance matching and stable operation across multiple communication bands .The system demonstrates effective performance in both simulation and experimental evaluations, confirming its capability to maintain consistent radiation characteristics and reliable data transmission. Safety considerations are also addressed through the analysis of energy absorption within biological tissues, ensuring suitability for implantable applications. Additionally, link budget analysis validates the feasibility of robust wireless communication between the implanted device and external systems. Overall, the proposed antenna provides a promising solution for next-generation implantable medical devices, offering compact size, enhanced bandwidth, and dependable performance, making it suitable for continuous monitoring and advanced healthcare applications.