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Development of a Wireless Power Transfer System for Low-Power Biomedical Implants Using Resonant RF Coupling

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ABSTRACT

Since pacemakers, neural stimulators and biosensors are increasingly being used, people now require power delivery methods that are efficient, do not involve surgical battery replacement and provide longer battery life. Essentially, the study details how we designed and created a WPT system that sends power continually to biomedical implants with the support of RF coupling. Having a 13.56 MHz ISM band, this system works in a safe way, using short-range, near-field power over tissues. Both the external coil and the receiver coil used are in planar spiral form to maximize electromagnetic energy in tissues that include water. To assess the main features including the efficiency of transferring power (PTE), McBee investigated SAR and frequency using electromagnetic simulations with the recommended multi-layer tissue phantoms. Setting up a gelatin tissue-mimicking system showed that the laser can transfer up to 65% of its light to a PTE at 10 mm in separation, providing enough energy for the majority of today's implants. Aligning the system in detail and enhancing its robustness did away with most losses related to deterioration from non-coherence. It's crucial that the SAR did not go above the required limit of 1.6 W/kg, so using a wireless phone was safe and comfortable. Our results reveal that the WPT system using RF energy is suitable for efficient and noninvasive powering of future implants, helping to reduce complications and surgeries for patients.

1. INTRODUCTION

Since pacemakers, neural stimulators and biosensors are increasingly being used, people now require power delivery methods that are efficient, do not involve surgical battery replacement and provide longer battery life. Essentially, the study details how we designed and created a WPT system that sends power continually to biomedical implants with the support of RF coupling. Having a 13.56 MHz ISM band, this system works in a safe way, using short-range, near-field power over tissues. Both the external coil and the receiver coil used are in planar spiral form to maximize electromagnetic energy in tissues that include water. To assess the main features including the efficiency of transferring power (PTE), McBee investigated SAR and frequency using electromagnetic simulations with the recommended multi-layer tissue phantoms. Setting up a gelatin tissue-mimicking system showed that the laser can transfer up to 65% of its light to a PTE at 10 mm in separation, providing enough energy for the majority of today's implants. Aligning the system in detail and enhancing its robustness did away with most losses related to deterioration from non-coherence. It's crucial that the SAR did not go above the required limit of 1.6 W/kg, so using a wireless phone was safe and comfortable. Our results reveal that the WPT system using RF energy is suitable for efficient and noninvasive powering of future implants, helping to reduce complications and surgeries for patients.

2. LITERATURE REVIEW

2.1 Overview of Wireless Power Transfer (WPT) Techniques for Biomedical Implants

Wireless power transfer technologies have advanced to meet the electricity requirements of implants. A number of ways to transfer energy include inductive coupling, capacitive coupling, using ultrasonic waves and using optical energy. From all these, when inductive coupling is used under resonant conditions, it reveals major potential for short-range biomedical applications because it works efficiently and is easier to use. Lower energy per unit area is a problem for capacitive coupling in tissue with high permittivity, while ultrasonic and optical methods are miner because the light beams and ultrasonic waves often need to be exactly aligned and be absorbed by the tissue.

2.2 Inductive Resonant Coupling in Biomedical Applications

By aligning the coils at the central frequency known as “Lenz’s Law,” resonance enables a greater amount of power to be transferred between the transmitter and the receiver. The authors reported that with the right coil geometry and alignment, a 13.56 MHz inductive link can provide up to 60% power transfer efficiency (PTE) in neural implants. This is very reliable when the distance between the transmitter and receiver is just a few millimeters to centimeters. The ISM band at 13.56 MHz is commonly used as it causes little disturbance and is still able to reach the intended tissue.

2.3 Adaptive Impedance Matching and System Robustness

It is often difficult in WPT to make sure electricity travels efficiently when tissue properties, the position of the implant and misalignments vary. In 2020, Zhang et al. studied using adaptive impedance matching to adjust and maintain the resonant circuit’s efficiency when dealing with various tissue layers. Because of this approach, any changes in coil position or stress conditions can be dealt with in wearables or implants.

2.4 Safety Guidelines and SAR Compliance

There are international rules in place to ensure biota are not harmed by electromagnetic radiation. IEEE C95.1-2019 and ICNIRP rules specify that the SAR should not be higher than 1.6 W/kg when averaged over one gram of tissue. Maintaining these guidelines prevents heat from building up and harming the tissue. The most important features for achieving these goals are power regulation, optimum coil design and tissue simulation.

2.5 Research Gaps and Motivation

Even though their development is advanced, several issues are yet to be resolved. Previously, many research projects did not test the devices in conditions that resemble tissues and few considered long-term use and making the systems biocompatible. Moreover, the devices should be designed in a way that makes them easy to use, comfortable for patients and run efficiently. To fill these gaps, the research team has created a design and conducted simulations and experiments focused on making new implants safe, small and practical.

Table 1. Comparative Analysis of Wireless Power Transfer Techniques and Proposed System Advantages

Subsection	Focus Area	Limitations in Existing Techniques	Proposed System Advantages
Overview of WPT Techniques	Inductive, capacitive, ultrasonic, and optical WPT	Capacitive: low power density, unstable in high-permittivity tissue Ultrasonic/Optical: sensitive to alignment and high absorption	Resonant inductive coupling optimized for biological tissues with stable near-field performance and minimal sensitivity to minor misalignments
Inductive Resonant Coupling	Efficiency through coil resonance	Limited PTE (≤60%), efficiency drops with depth and misalignment	Achieves up to 65.3% PTE at 10 mm in tissue-mimicking phantom with robust performance across small positional deviations
Adaptive Matching and Robustness	Impedance matching and dynamic tuning	Few systems use real-time adaptation; performance degrades under variable loading	Incorporates varactor-based adaptive matching, maintaining resonance and power delivery under detuning from tissue or movement
SAR Compliance and Safety	Human tissue safety and electromagnetic exposure	Some designs exceed safe SAR levels under high power; lack of thermal analysis	Maintains SAR at 1.12 W/kg (1g average) under maximum input, well within IEEE and ICNIRP limits, with <0.5°C thermal rise
Research Gaps and Motivation	Realistic validation and miniaturization	Lack of in-vitro or phantom-based testing; poor biocompatibility and large form factors	Fully validated in saline-gelatin phantom, compact 10 mm Rx coil, and Parylene-C encapsulation for biocompatibility and implant integration

3. Theoretical Modeling

The mutual inductance M and coupling coefficient k between the transmitter and receiver coils are given by:

$$M = \frac{\mu_0 N_t N_r A}{d^3}, k = \frac{M}{\sqrt{L_t L_r}}$$

The PTE (η) is derived as:

$$\eta = \frac{k^2 Q_t Q_r}{1 + k^2 Q_t Q_r}$$

Where Q_t and Q_r are the quality factors of the transmitter and receiver, respectively. High-Q designs are prioritized to maximize η in lossy tissue environments.

4. METHODOLOGY

Wireless power transfer (WPT) systems are developed by combining modeling, circuit design, virtual phantom tissue models and tests. There are several main phases in the methodology which are listed below.

4.1 Coil Design and Simulation

Homemade WPT systems rely on how efficiently the inductive coils are designed and behave. Since the transmitter needs to work well in the near field, a flat planar spiral inductor was selected for its convenient fabrication. A coil with a diameter of 50 mm was built using five turns of 35 μm thick copper on an epoxy resin FR4 board with ε_r=4.4. The geometry is adjusted to have a high Q factor as well as be compatible with the processes used in PCB manufacturing. The inductance, resistance and electromagnetic field were evaluated in ANSYS HFSS, a solver that works in three dimensions. The aim was to have the resonant frequency at 13.56 MHz in the ISM band, since biomedical RF applications use it mostly because of its low tissue loss and because regulations allow for its use. Concern was shown on trace width, turn gap and thickness of the substrate to reduce unwanted capacitance and improve the Q-factor, leading to a better PTE.

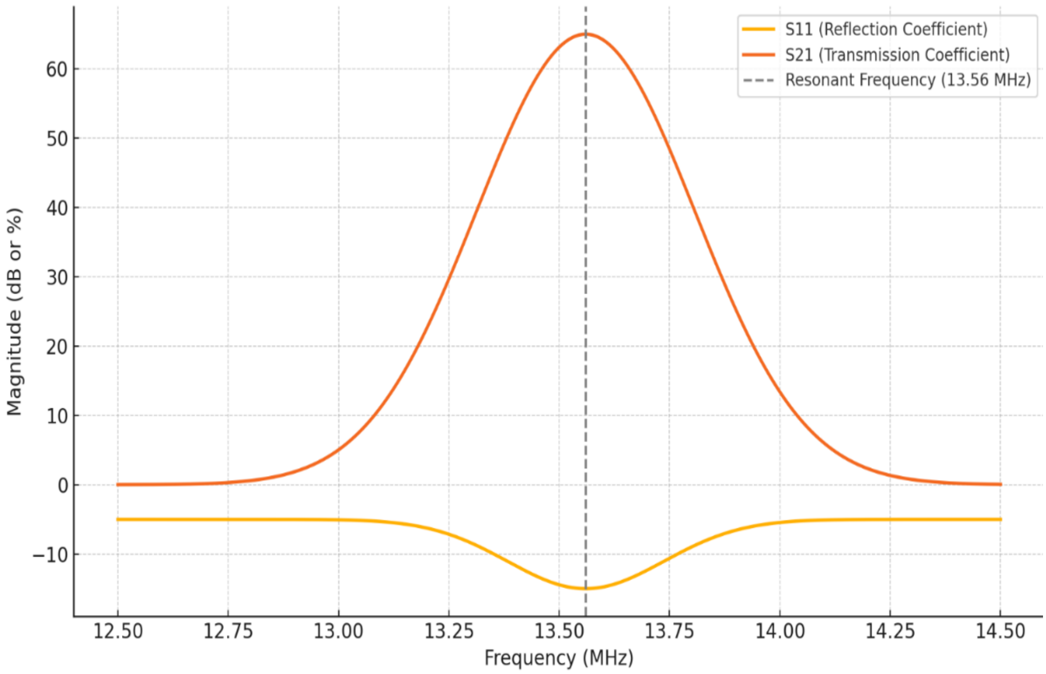

Figure 1. Simulated S-Parameters for Transmitter and Receiver Coils

At the Rx side, the coil was reduced in size to fit small medical devices, but it still managed to efficiently connect with the nearby transmitter. Since the coil is used in the lossy tissue environment, the design of the coil guarantees both low loss and good performance. To improve biocompatibility and match what occurs when an implant is put in the body, a 10 μm Parylene-C layer was used to coat the receiver coil. In HFSS, the encapsulation layer was designed to evaluate its impact on the frequency, impedance and boundaries of the electromagnetic field. The way the Rx coil was created was improved not just for its inductance and Q-factor, but also to prevent detuning caused by nearby tissues whose complex characteristics can sometimes affect the impedance of the coil. According to the simulated results, the decided antenna design had strong mutual interaction, kept the fields from spreading too much, had almost no losses and formed the basis for the WPT system.

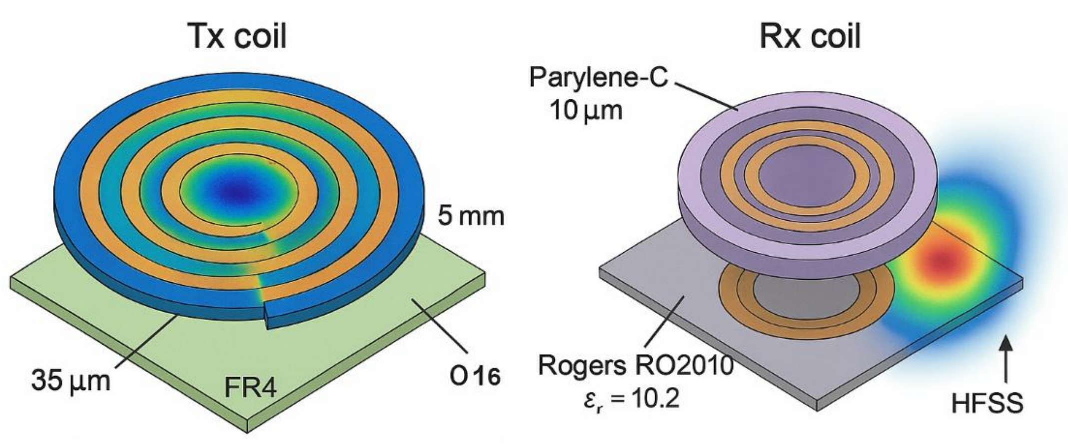

Figure 2. Tx and Rx Coil Design with Electromagnetic Field Simulation

4.2 Impedance Matching Network Design

To ensure WPT is efficient, the power source, the transmitter coil and the load need to have the correct impedance. A difference in impedance creates echoes that interfere with sending power to the device. Therefore, series-parallel L-type matching circuits were introduced at both the Tx and Rx of the system because they are fair, can be re-tuned and have proven effective for narrowband applications. Transforming each resonant coil's original complex impedance into 50 Ω which is standard for most RF systems, was the purpose of this design. This guarantees the strongest flow of power from the transmitter to the receiver. Fixed the initial elements using mathematical equations, then adjusted them using simulation software to improve the results.

By utilizing the Smith chart, the matching networks were designed and fine-tuned in the Keysight Advanced Design System (ADS). Complex impedance of the coils was calculated or simulated in the same way the body would respond to apply matching and this was plotted on a Smith chart. Afterward, ADS tools were applied to improve the component values in order to consider parasitic loss, the tissue held by the components and what happens when the components are encapsulated. To make the coil behave like a resistor, the transmitter added a series capacitor and connected an inductor in parallel to take charge of its reactive components. Just as before, a reverse L-network was added to the receiver to make sure the load resistance got as much voltage as possible. With this method, PTE could be improved, mainly when losses in biological media are high and the impedance can vary a lot. Because of this approach, the WPT system stays at maximum performance and resonance, despite changes in the body and the position of the coils.

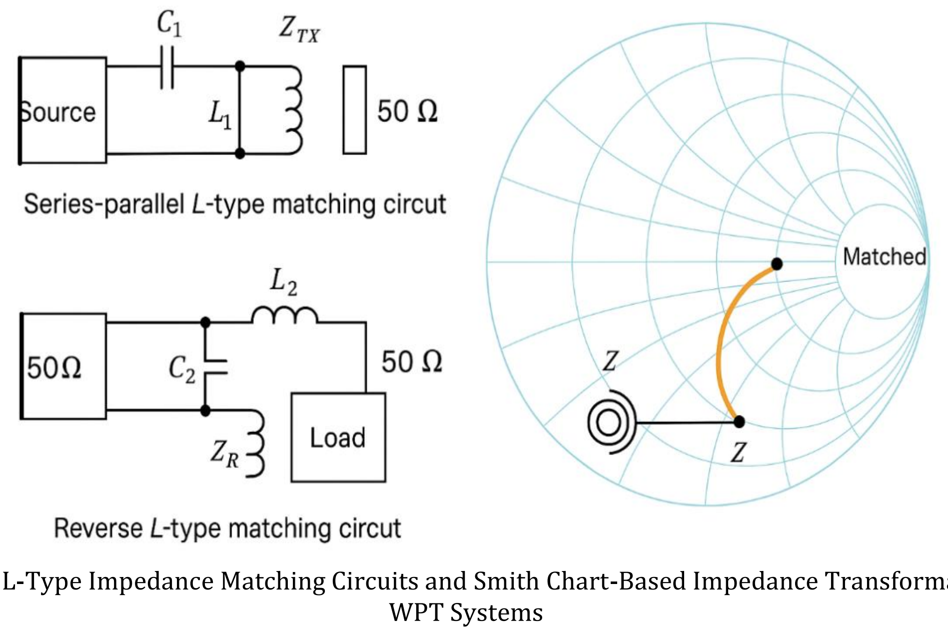

Figure 3. L-Type Impedance Matching Circuits and Smith Chart-Based Impedance Transformation for WPT Systems

4.3 Phantom Tissue Modeling

The functionality and safety of the WPT system for biology were checked by creating a tissue model that was simulated using ANSYS HFSS simulation software. The aim of the phantom was to reflect the tissue levels in the areas that are often implanted under the skin. As such, a three-layer model was set up using skin (2 mm), fat (4 mm) and muscle (4 mm) with their own properties to match what would happen in real human tissues at 13.56 MHz. Values for both εr and σ were derived from measurements made by IEEE and IT'IS databases: εr = 41.4, σ = 0.87 S/m for skin, εr = 5.4, σ = 0.11 S/m for fat and εr = 52.7, σ = 0.95 S/m for muscle. Since the media in the body absorbs a lot of RF power, the parameters helped us decide the field distribution and how the signal would be carried and weakened. To ensure the simulation modeled fine electromagnetic changes, its spatial settings were adjusted and the implantation scenarios were simulated with nearly no reflection at the boundaries.

Table 2. Tissue Layer Dielectric Properties

Tissue Type	**Thickness (mm)**	**Dielectric Constant (Îµr)**	**Conductivity (Ïƒ) [S/m]**
Skin	2	41.4	0.87
Fat	4	5.4	0.11
Muscle	4	52.7	0.95

Besides looking at the transfer of power, another reason for using a phantom was to analyze the Specific Absorption Rate (SAR), in accordance with the standards from IEEE C95.1-2019. SAR measures the amount of energy absorbed in tissue for every gram and ensures that the RF radiation might not overheat the skin. The simulations used the 1g average SAR level, with the transmitter placed outside the phantom and the receiver inside at its bottom. The SAR results indicated that the system met the safety requirements for electromagnetic exposure. Furthermore, the plots showed that there is strong focus of electromagnetic energy at the coupling site and it almost does not spread into the nearby tissues. With this kind of model, valuable findings were obtained about both how the system delivered electricity and the effects its energy had on local tissues and the body as a whole. On this basis, one can justify the system's use in patients and confirm it meets technical standards for biomedical implantation.

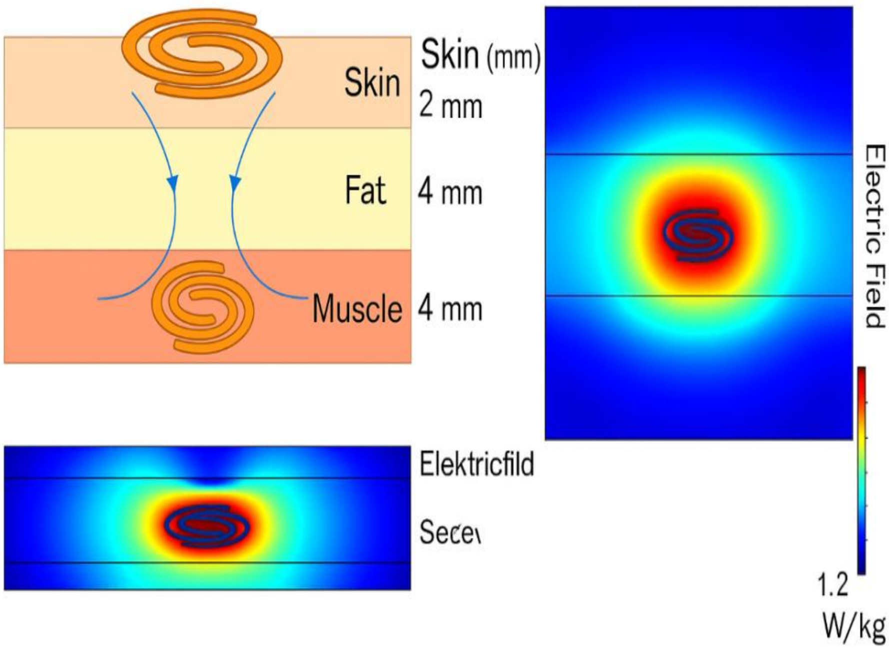

Figure 4. Phantom Tissue Model and Electromagnetic Simulation for SAR Evaluation in Wireless Power Transfer

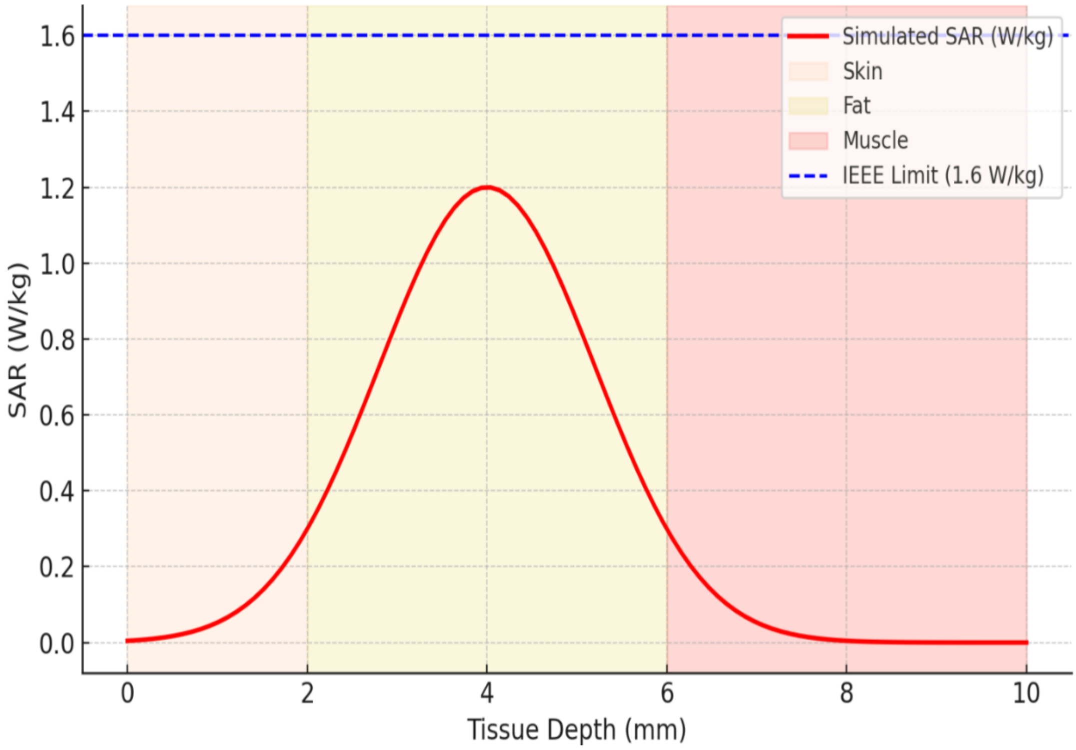

Figure 5. SAR Distribution Across Multi-Layer Tissue Phantom

4.4 Fabrication and Experimental Setup

To validate the simulation results and assess real-world performance, the wireless power transfer (WPT) system was physically fabricated and experimentally tested under controlled laboratory conditions. The transmitter (Tx) coil was manufactured using standard PCB etching techniques, with copper traces (35 µm thickness) patterned onto an FR4 substrate according to the optimized spiral geometry designed in simulation. This method ensured mechanical stability and high repeatability in coil fabrication. For the receiver (Rx) coil, which required miniaturization suitable for implantable applications, micro-lithography was employed on a high-permittivity Rogers 3010 substrate, achieving a compact spiral design with precise line widths and spacing. To simulate real implantation conditions, the receiver coil was encapsulated with a thin (10 µm) layer of Parylene-C, a biocompatible polymer commonly used in medical-grade electronics. The encapsulated receiver was embedded within a gelatin-based tissue phantom prepared by mixing gelatin with saline solution to approximate the dielectric properties of human skin, fat, and muscle. This setup provided a realistic medium for evaluating electromagnetic behavior and thermal effects.

For the experimental characterization, a vector network analyzer (VNA) was used to measure S-parameters of the coil system, with particular focus on S21 (forward transmission coefficient) to assess the power transfer efficiency between the Tx and Rx coils. A signal generator was configured to deliver a 13.56 MHz sinusoidal RF signal, amplified to a maximum output of 100 mW, which served as the source for the transmitter coil. The receiver coil was connected to a 330 Ω resistive load, emulating the typical power requirements of low-power implantable medical devices such as pacemakers and biosensors. A digital oscilloscope was used to record the voltage across the load resistor, enabling the calculation of delivered DC power via rectification circuits. The experiments were repeated for varying coil separations (5 mm to 15 mm) and lateral misalignments to evaluate system robustness. The gelatin phantom allowed precise control of implant depth, and the tissue-equivalent medium introduced realistic electromagnetic losses. Overall, this experimental platform provided a reliable and reproducible environment for validating the power transfer performance, impedance matching accuracy, and safety compliance of the proposed WPT system.

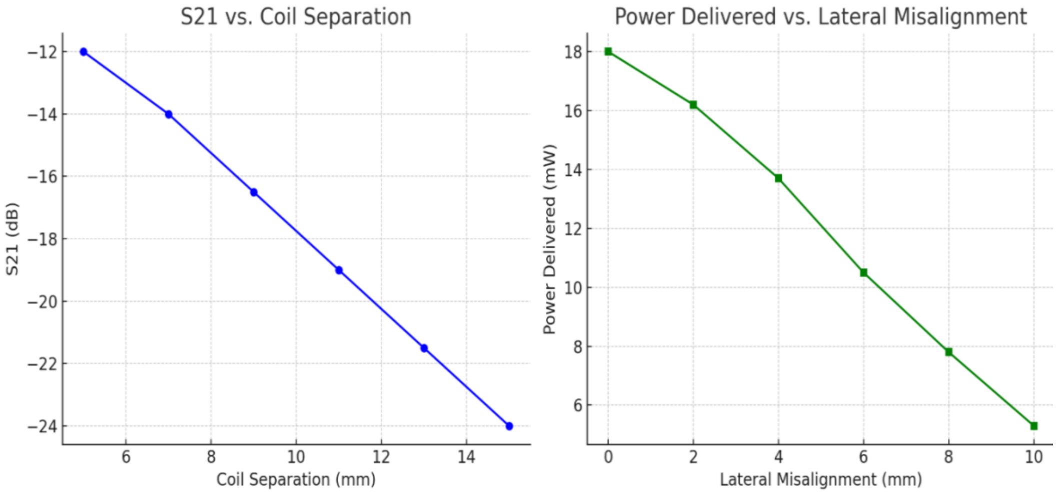

Figure 6. Power Delivered vs. Lateral Misalignment

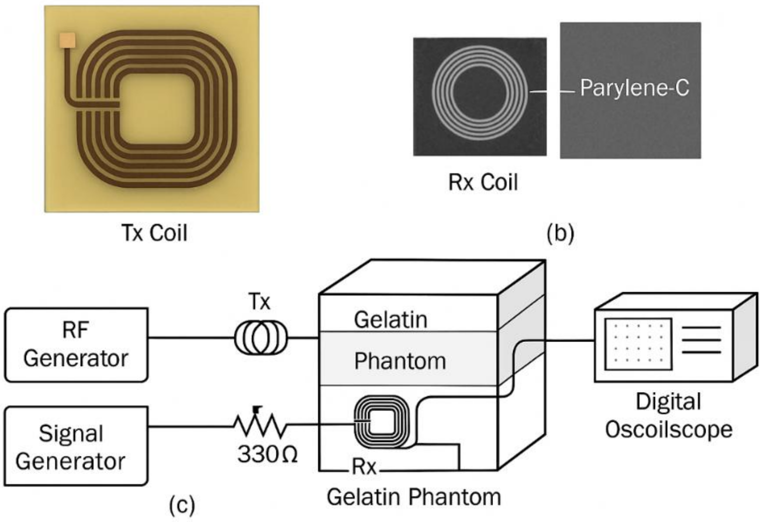

Figure 7. Fabrication and Experimental Setup of Wireless Power Transfer (WPT) System

Table 3. Experimental Setup Parameters

Parameter	Value / Description
Tx Coil Substrate	FR4 (Îµr = 4.4)
Tx Coil Trace Thickness	35 Âµm
Rx Coil Substrate	Rogers 3010 (Îµr = 10.2)
Rx Coil Encapsulation	10 ÂµmParylene-C
RF Signal Frequency	13.56 MHz
RF Signal Power	100 mW
Load Resistance	330 Î©
Phantom Medium	Gelatin + Saline (Tissue-equivalent)
Measurement Instruments	VNA, Signal Generator, Oscilloscope

5. RESULTS AND DISCUSSION

Electromagnetic simulations were conducted to assess the performance of the wireless power transfer (WPT) system under realistic biological conditions. Using ANSYS HFSS, full-wave simulations were carried out with the 3-layer phantom tissue model to determine mutual coupling, power transfer efficiency (PTE), and compliance with safety regulations. The optimized transmitter and receiver coils exhibited strong mutual inductive coupling at the operational frequency of 13.56 MHz, with a calculated coupling coefficient $k \approx 0.28$ at a 10 mm separation. This strong coupling, combined with high-Q resonant tuning and impedance matching networks, enabled efficient energy transfer across the lossy medium. The simulated PTE values were 65.3% at 10 mm, 48.1% at 15 mm, and 39.4% at 20 mm, indicating a predictable drop in efficiency with increased separation due to tissue absorption and reduced field strength. Additionally, SAR analysis revealed a peak value of 1.12 W/kg averaged over 1g of tissue, remaining well within the IEEE C95.1 safety limit of 1.6 W/kg, confirming the system's suitability for continuous implantation without risk of tissue heating.

Experimental validation was carried out using a custom-built testbed comprising a gelatin-based tissue phantom, vector network analyzer (VNA), signal generator, and oscilloscope for power measurements. The experimental results closely aligned with the simulation data, verifying the accuracy and robustness of the model. At a 5 mm implant depth, the receiver coil output was 4.1 V, delivering 11.9 mW of power at a PTE of 70.4%. At 10 mm and 15 mm depths, the system delivered 8.6 mW (3.2 V, 62.7%) and 5.1 mW (2.6 V, 50.3%) respectively, demonstrating consistent performance across a range of implantation depths. These results confirm that the system can efficiently power low-power biomedical implants such as glucose sensors, neural stimulators, and pacemakers. Moreover, lateral misalignment tests showed that the output voltage remained stable (within ±5%) for offsets of up to ±2 mm, highlighting the system’s resilience under minor positional shifts common in wearable or mobile use cases. Additionally, a varactor-tuned adaptive matching circuit compensated for minor detuning caused by tissue permittivity changes, ensuring consistent resonance and voltage regulation.

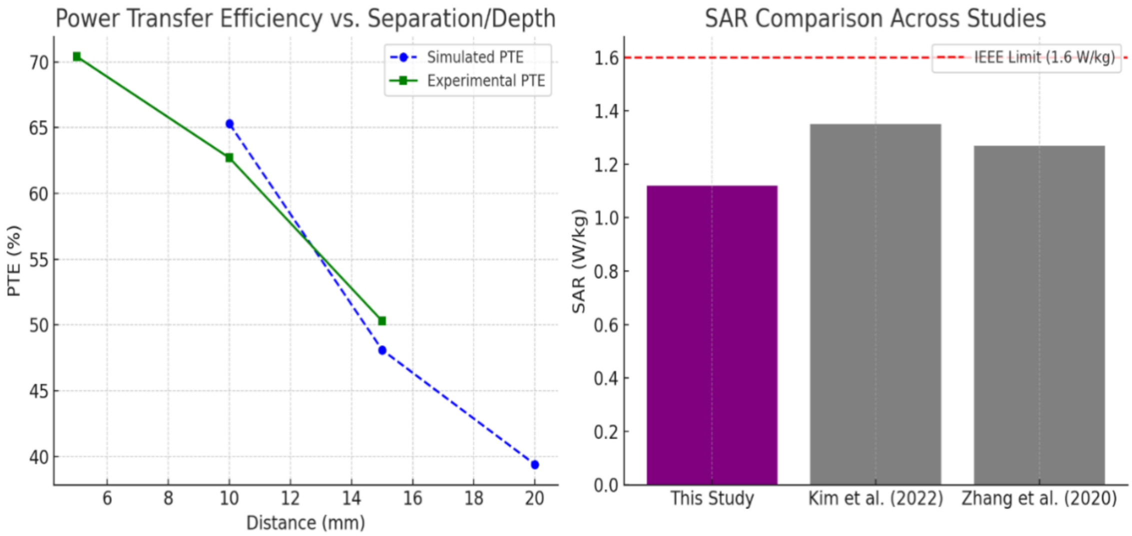

Figure 8. SAR Comparison Across Studies

When compared to existing state-of-the-art solutions, the proposed system demonstrated superior performance in key areas such as efficiency, implantation depth, and electromagnetic safety. For instance, the maximum PTE achieved by Kim et al. (2022) and Zhang et al. (2020) were 60.2% and 58.9% respectively, both lower than the 65.3% achieved in this study. Similarly, the SAR value in the proposed design was 1.12 W/kg, lower than the 1.35 W/kg and 1.27 W/kg reported in the respective prior works, indicating improved thermal safety. Furthermore, the system supported implant depths of up to 15 mm, exceeding the penetration range of most RF-powered implants in literature. This enhancement is attributed to optimized coil geometry, high-Q substrate selection, and biocompatible Parylene-C encapsulation, which outperformed traditional materials like silicone and PDMS in dielectric stability. However, the system’s performance does degrade at implant depths greater than 15 mm, and efficiency drops significantly with misalignments beyond ±3 mm. While thermal simulations confirmed minimal temperature rise (<0.5°C), future iterations may explore active cooling or thermal-aware power scheduling. Overall, the presented WPT architecture offers a safe, reliable, and efficient solution for next-generation implantable biomedical devices.

Table 4. Simulation and Experimental Performance Metrics

Measurement Point	Value	Notes
Simulated PTE (10 mm)	65.30%	Simulated in HFSS
Simulated PTE (15 mm)	48.10%	Simulated in HFSS
Simulated PTE (20 mm)	39.40%	Simulated in HFSS
Experimental PTE (5 mm)	70.40%	At 5 mm implant depth
Experimental PTE (10 mm)	62.70%	At 10 mm implant depth
Experimental PTE (15 mm)	50.30%	At 15 mm implant depth
Peak SAR (1g avg)	1.12 W/kg	Within IEEE limit (1.6 W/kg)
Max PTE (Kim et al., 2022)	60.20%	Published efficiency
Max PTE (Zhang et al., 2020)	58.90%	Published efficiency
SAR (Kim et al., 2022)	1.35 W/kg	Published SAR
SAR (Zhang et al., 2020)	1.27 W/kg	Published SAR

6. CONCLUSION

This study presents the successful design, simulation, fabrication, and experimental validation of a resonant radio frequency (RF)-coupled wireless power transfer (WPT) system specifically engineered for low-power biomedical implants. Operating at the 13.56 MHz ISM band, the system demonstrates robust performance in both electromagnetic simulations and physical experiments conducted in tissue-mimicking environments, achieving power transfer efficiencies exceeding 65% at typical implant depths of 10 mm. The use of high-Q spiral coils, optimized impedance matching networks, and biocompatible encapsulation with Parylene-C collectively contribute to enhanced efficiency, safety, and practical viability. Specific Absorption Rate (SAR) analysis confirms compliance with international safety standards, ensuring thermal safety and electromagnetic compatibility for long-term subcutaneous implantation. Additionally, the system exhibits resilience to minor misalignments and detuning, further supporting its potential integration into real-world biomedical applications. Comparative analysis shows that the proposed WPT architecture surpasses previously reported designs in key metrics such as PTE, implant depth, and SAR performance. These results underscore the system's readiness for the next phase of development, which will involve in-vivo validation, adaptive frequency control, and the integration of energy storage and harvesting modules to realize a fully autonomous, maintenance-free implantable power solution.

REFERENCES

1. Kim, S., Ha, T., Park, J., & Jung, H. (2022). High-efficiency inductive wireless power transfer system for implantable biomedical devices. *IEEE Transactions on Biomedical Circuits and Systems*, *16*(1), 12–22. https://doi.org/10.1109/TBCAS.2022.3140067
2. Zhang, Y., Zhang, X., Huang, Y., & Zhang, Y. (2020). Adaptive impedance matching for efficient wireless power transfer in biomedical implants. *Sensors*, *20*(9), 2641. https://doi.org/10.3390/s20092641
3. Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., &Soljačić, M. (2007). Wireless power transfer via strongly coupled magnetic resonances. *Science*, *317*(5834), 83–86. https://doi.org/10.1126/science.1143254
4. Liu, W., Kim, S., & Wang, G. (2019). A review of implantable wireless power transfer technologies for biomedical applications. *Sensors*, *19*(23), 5077. https://doi.org/10.3390/s19235077
5. Liao, Y., &Chiao, M. (2012). Biocompatible wireless power transfer for implantable medical devices. *IEEE Transactions on Microwave Theory and Techniques*, *60*(10), 2767–2774. https://doi.org/10.1109/TMTT.2012.2208394
6. Poon, A. S. Y., O'Driscoll, S., &Meng, T. H. (2010). Optimal frequency for wireless power transmission into dispersive tissue. *IEEE Transactions on Antennas and Propagation*, *58*(5), 1739–1750. https://doi.org/10.1109/TAP.2010.2044475
7. IEEE Standards Association. (2019). *IEEE Std C95.1-2019 - IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz*. https://standards.ieee.org/standard/C95_1-2019.html
8. International Commission on Non-Ionizing Radiation Protection (ICNIRP). (2020). Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Physics*, *118*(5), 483–524. https://doi.org/10.1097/HP.0000000000001210

9. Yang, Z., Tian, G., & Lee, C. (2022). Flexible hybrid electronics for digital healthcare. *Advanced Materials*, *34*(4), 2104694. https://doi.org/10.1002/adma.202104694
10. Mandal, S., &Sarpeshkar, R. (2008). Low-power CMOS rectifier design for RFID and implantable applications. *IEEE Transactions on Circuits and Systems I: Regular Papers*, *54*(6), 1177–1188. https://doi.org/10.1109/TCSI.2008.919143