Using a Unique Technique for the Power Transfer Efficiency Improvement in Near-Field Planar Wireless Power Transfer Systems

Capstone Project Final Report

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Abstract:

This project work introduces an innovative sectionalizing technique to improve power transfer efficiency (PTE) for the realization of near field planar wireless power transfer (WPT) system. The work started from the comparative assessment of inductance characteristics of different coil configurations, resulting in the superiority and adoption of a square coil shape for further design. Afterwards, the realized WPT systems were developed by incorporating two similar resonating transmitter and receiver, positioned 25 mm apart. Initially, the impact of critical design parameters was thoroughly examined to ensure a resonance at 434 MHz for WPT systems realization. Specifically, three distinct systems, which are the traditional 1-coil, and the sectionalized 2- and 4-coil configurations, were developed, occupying an identical dimensions of 50×50 mm^2 for each of them. As a result, sectionalizing method achieved an improvement in PTE of 3% and 6% for the 2- and 4-coil structured systems correspondingly. In particular, the highest PTE of 79% was attained by sectionalized 4-coil WPT system, demonstrating the efficiency of suggested approach. Moreover, the effectiveness of the proposed 4-coil WPT system was confirmed through experimental testing. Additionally, different possible misalignment conditions, that could arise in real-world applications, were taken into the account to assess the performance of final design.

Contents

Chapter 1

Introduction

1.1 Background information and related works

Wireless Power Transfer (WPT) technology presents a novel approach to the delivery of electrical power that is essentially free from physical connectors. That means, in certain aspects, one gets to eliminate wire, cable, and even traditional power infrastructures. This would be an important foundational and revolutionary technology for many modern applications, especially in electronics. This is due to the fact that internet of things (IoT) devices, electric vehicles (EVs), and portable consumer electronics are being spread all over the world and need appropriate energy solutions that must be efficient, safe, and adaptive for various environments [1]. WPT systems are continuously improving, which could totally change the way of charging modern devices, reducing dependency on wired infrastructure.

WPT technologies are broadly classified into two categories depending on the range of power transfer: near-field and far-field systems. Far-field WPT, over a longer distance, makes use of radiative electromagnetic waves such as microwaves, while near-field WPT makes use of techniques such as inductive or magnetic resonant coupling over relatively shorter distances [2]. The advantages and disadvantages of all these techniques make them vary in different applications and uses.

Far-field WPT is mainly employed for those applications where there is a need to transfer power over longer distances using radiative electromagnetic waves. In [3], Valenta and Durgin reviewed in detail the far-field WPT systems that, through radio frequency (RF) energy harvesting, may enable the IoT devices to operate remotely. Devices can collect energy from the ambient RF signals to sustain their operations without replacing batteries, thus making far-field WPT very suitable for several applications involving a large number of installations such as environmental monitoring where deploying batteries can be fully impracticable. However, as Xia and Aissa noted in [4], far-field WPT has the drawback of very low efficiency in power transfer over long distances. They investigated the efficiency limits of far-field systems and found that substantial degradation of efficiency occurs with distance, therefore limiting practical applications in power needing devices. Taking into account this challenge, far-field WPT is used in low-power IoT applications where small fractions of energy can be enough to keep the devices running.

On the contrary, near-field WPT is indeed suitable for those applications where transmitter and receiver positioning usually exists within a few centimeters or millimeters away from each other. The first great benefit of near-field WPT lies in its higher efficiency compared with the systems of far-field transfer of energy, and hence it is pretty well recommended for the following applications: wireless charging of consumer electronics, medical devices, and EVs [5]. These advantages are achieved thanks to certain coupling mechanisms. Specifically, the near-field WPT systems are based on inductive or magnetic resonant coupling. In other words, the energy is transferred through the magnetic field created by a primary resonating transmitter to a secondary receiving resonator [6].

Inductive coupling is one among the most widely spread techniques in near-field WPT systems. This works on the principle of electromagnetic induction, that is a voltage generation in the secondary coil due to the alternating current in the primary coil, which are located near to each other [7]. It finds many successful applications in wireless chargers for smartphones, electric toothbrushes, and biomedical implants, where the efficiency of energy transfer should be maximized along with consideration of available space within the device and related safety issues for the whole system. For example, in [3], it was shown how printed spiral coils (PSCs) are used in the case of performance enhancement of inductively coupled systems. These coils can be printed directly on the circuit boards, which makes them highly useful in limited-space applications. Another major mechanism of near-field WPT is magnetic resonant coupling. Basically, it has transmitter and receiver sides tuning to the common resonant frequency, which leads to stronger coupling and higher PTE compared to inductive coupling [8]. Specifically, this technique is used in wireless EV charging and powering of biomedical implantable devices, where high efficiency is important [5]. Consequently, various design approaches were used to develop modern WPT systems, such as planar coils, defected ground structures (DGSs), and PSCs [9, 10, 11].

It is noteworthy, that the most of the current works on near field planar WPT systems are focused on the optimization of coil geometries and resonator system design for increasing PTE. Particularly, authors in [12], who compared different geometries of planar coils, discovered that various shapes have different performance results. That is why planar coils gained much interest due to their scalability and ease of embedding into small devices. Furthermore, numerous studies were done on improving the efficiency characteristics of WPT systems with planar coil design configuration due to the growing needs of their broadening applications [6]. Particularly, PTE is the most foundational factor, improving of which can decrease total charging duration [13]. For instance, developed PSC based WPT system sized of 66×66 mm^2 achieved a 50% PTE at 20 mm transfer distance [14]. Also, researchers in [11] reached 89.47% efficiency over 55 mm of double-D coil shaped system with 70×70 mm^2 size of resonators. Moreover, WPT systems with bulky dimensions of 425×425 mm^2, proposed in [10], resulted in PTE of 80% at 100 mm separation. All these developments demonstrate the strong connection between enhanced PTE and increased resonators' size, which can be impractical for space constrained applications. Therefore, there is still an urgent necessity for novel design techniques, which can simultaneously achieve compactness and high PTE characteristics.

Thus, this project proposes an innovative technique based on the *sectionalizing* principle to enhance PTE while keeping area of resonators compact. The sectionalizing approach maintain an effective balance between efficiency, complexity, and size. Moreover, it does not involve the incorporation of any external components such as compensation capacitors, inductors, or driving loops, which means that proposed method relies on only coil design parameters. Thus, critical design parameters of the square coil-based resonant structures were analyzed and fine-tuned to 433 MHz operational frequency. The development began from the design of conventional 1-coil WPT system with further extension to sectionalized 2- and 4- coil structures, with transmitter and receiver sizes of 50×50 mm^2. Subsequently, the implemented WPT systems demonstrated PTE improvements of 3% for the 2-coil and 6% for the 4-coil designs in comparison to the traditional 1-coil system. As a result, the realized 4-coil WPT system achieved a PTE of 79% over 25 mm distance. These findings underscore the efficiency of the sectionalizing method in improving PTE of planar WPT systems.

1.2 Ethical and Professional Responsibilities

- **Ethical Responsibility:**
  From the perspective of WPT systems designed for IoT applications, a number of considerations regarding ethical issues have to be considered. The most important ethical issue is that of health hazardousness due to prolonged exposure to electromagnetic fields (EMF). Even though the system in operation falls within regulated limits of EMF, equal consideration should be given to how the design remains within the safety threshold as set up by regulatory standards such as the IEEE. Transparency in the communication of these risks to stakeholders will help them be at ease with the safe usage of the technology. Besides safety, another major concern in any IoT application relates to privacy: The system, occasioned by power and information transfers or system diagnostics, may collect or accidently send sensitive information about users. The developers must ensure that adequate measures are taken as to security so that no unauthorized element gains access to such information. Further, the WPT system must be designed to reduce its footprint by minimizing energy waste and the use of recyclable or sustainable materials. To be more specific, consideration must be taken for avoidance of environmental damages and usage of environmentally friendly components and manufacturing processes. Taking all these seriously, the project contemplates a safe, secure, and ecologically sensitive implementation of WPT systems.

- **Informed Judgments:**
  Decisions made in the course of development and implementation regarding the WPT system should be as informed as possible, embedding technical and societal considerations in their making. A good technical-based project must be routed through comprehensive simulations, prototypes, and testing to make sure that efficiency, performance, and safety are optimal. Every decision should be based on data, derived from a known base of science and peer-reviewed studies, such as the ones performed for near-field WPT systems and resonant coupling methods. In addition to technical performance, though, societal implications also have to be considered: for example, the possible impact on users and the environment, and economic aspects need to be under constant reassessment during the system's life. Workshop and involvement from a multidisciplinary team: ethicists, environmental scientists, economists, and many others can all give relevant insights into the broader ramifications of deployment. Moreover, community response and stakeholder feedback are going to be integrated in order to ensure that the system is not only technically but also socially efficient. Informed by this knowledge base, innovation with ethical considerations will be done through a balanced approach; hence, the WPT system is more robust and acceptable

to technical and non-technical stakeholders

- **Global Context:**
WPT, therefore, has huge potential for application in IoT, which is important globally. While the technology under development targets specific regions, scalability and adaptability of the technology enable deployment in different world environments. Global implications vary between regions due to regulatory, cultural, and socio-economic factors. It will contribute, for instance, if the IoT network is very advanced in any developed country, to sustainability by facilitating the WPT system reducing energy consumption and hence battery replacement frequency. On the other hand, this might serve as an important tool in regions where electricity is not available to energize remote sensors or devices in off-grid villages. Maybe, most importantly, the regulation on electromagnetic emissions differs around the world, and one should know whether the WPT system will meet all international standards to avoid health risks or environmental hazards. In addition, the cultural acceptance of new technologies differs, and the system must adapt to local contexts. Following the suggestion of Shinohara [15], this technology can be modified to suit various regions by designing the WPT system in a modular and scalable fashion while remaining efficient and safe.

- **Economic Impact:**
It is important to discuss the economic impact of the WPT systems in both short-term and long-term views. In terms of short term perspectives, the WPT system technlogies reduce operating costs of any electrical systems by minimizing physical power connections and decreasing the frequency of battery replacements. Thus, this will give an opportunity to cut costs for industries or businesses that heavily rely on IoT technologies, such as agriculture, healthcare, and industrial automation. For example, smart agriculture using WPT can reduce the need to recharge batteries of sensors spread across large rural areas. On the other hand, in terms of long-term perspectives economic gains may require investments in developing WPT infrastructure, which could be unaffordable for small scale industries or resource poor regions. Additionally, the use of new materials and manufacturing processes in WPT system development may raise production costs in the early stages. However, as the technology spreads all over the world, these costs will gradually decrease as more companies will compete with each other offering lower prices, making WPT more affordable. Overall, the project's economic viability can be further improved by using low-cost, locally available materials to ensure the technology serves both high income and low income communities.

- **Environmental Impact:**
Another significant aspect that needs to be incorporated along with the WPT

system is the environmental factor. This generally includes energy efficiency and material sustainability. Specifically, one of the most significant ecological benefits of WPT systems includes a decrease in battery waste because, given that no wires are included, devices are able to get their power without constantly replacing or altering batteries. This is therefore extremely beneficial in IoT applications where sensors and devices are spread out over extensive locations. Second, in the design and deployment of a WPT system, energy efficiency is perhaps one of the most critical concerns that will reduce losses in power transmission. Specifically, wastage of a huge amount of energy through inefficient transmission would present enormous amounts of wastage, which means more energy consumption and therefore more carbon emissions. Here, once again another incentive of material choice in WPT system would be ecological: through using recyclable material, since the majority of echological influence of the system would be minimized. Otherwise, power for WPT systems would need to be obtained from renewable resources, e.g., solar or wind energy, in order to maximize sustainability further by reducing the system's overall ecological influence.

- **Societal Impact:**
  A WPT systems will contribute to wide impacts on the application level, in regards to IoT in society, from direct to indirect effects at the level of communities. The most vital aspect of this is ensuring greater access to technology at the heart of undeveloped areas. Since WPT is wireless and reliable, it will bridge the gap in the digital divide to allow deployment in IoT devices for environmental monitoring, healthcare, and education in remote areas. The system should be able to provide a sustainable and affordable solution for powering critical devices where access to electricity is limited. Besides, the capability of a WPT system to deliver power to devices without physical connections is very suitable for medical applications: powering of implanted devices and wearable health monitors for better patient care and quality of life [16]. However, job loss and other social issues, such as privacy-related concerns, must be addressed with due responsibility. Automation might actually lead to a contraction in the demand for low-level labor inputs where WPT systems are applied along with IoT technologies. Besides, privacy about collection and transmission of data from IoT devices raises concerns that robust security measures will have to be implemented, so that societal trust in the technology would be built.

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Chapter 2

Methodology

This section elaborates on the methodology used in the following research project to develop efficient WPT systems. Specifically, the design configuration of resonators, which is one of the most important part in near-field WPT systems development, has a critical impact on their performance. That is why resonators, which play the most significant role in performance characteristics, shall be optimally designed to contribute to the better performance of the system. In this matter, some traditional planar coil geometries are compared and analytically assessed in order to find the best configuration with the highest inductance (L), one of critical parameters of WPT systems. The higher the L value is, the stronger the coupling between resonators will be, thereby remarkably improving the efficiency of the WPT across the air gap [1]. Each coil type was carefully designed using advanced simulation tool such as Computer Simulation Technology (CST) for accuracy and reliability. Subsequently, superior coil geometry in terms of L was found, and it founded the ground for further WPT systems development.

The systematic design procedure of the 1-coil, 2-coil, and 4-coil WPT systems to achieve high PTE is outlined by the flowchart presented in Fig. 2.1. The design process starts with designing a WPT system employing a conventional 1-coil resonator. The design process involves an analysis of the impact of the design parameters on frequency. Once the optimal parameters have been selected and the targets are achieved, an effective 1-coil WPT structure is created by exploiting the two identical resonating elements separated by 25 mm. The design then proceeds to the 2-coil WPT structure through the sectionalizing method, where additional analyses are conducted, including the effect of vias and design parameters. Besides, the process is evaluated to determine if the objectives are achieved, and it results in a 2-coil system. Last but not least, the process is extended to the 4-coil WPT implementation by employing a sectionalizing technique for further enhancing PTE. At this stage, the same parameter analyses as for the 2-coil system are done following with necessary adjustments. In summary, this systematic approach

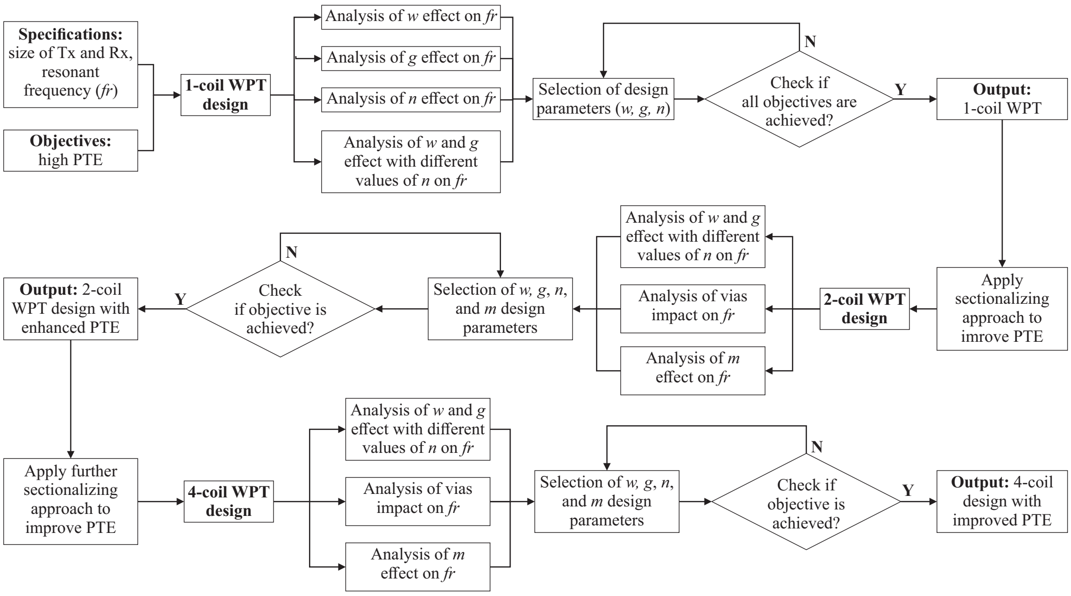


Figure 2.1: Flowchart of systematic design development of WPT systems.

presented as the detailed flowchart is applied to this research work to confirm the effectiveness of proposed PTE enhancement technique and identify the best possible sectionalized WPT system.

2.1 Different Coil Configurations Assessment

Four distinct planar coil configurations were analyzed, which are circular, square, hexagonal, and octagonal. Each resonator with certain coil type was made of specific substrate called Rogers RO4003C with 1.52 mm thickness, coated with outer layers of 0.0175 mm copper. The L for each coil shape was computed thanks to the formula given in Eq. (2.1) [17], where n represents the number of turns, μ_0 is the permeability of free space (1.2566×10^{-6} N/A^2), d_{avg} is the average diameter of the coil, p refers to the ratio of the outer-to-inner diameter difference over their sum, and K_1 and K_2 are constants specific to each coil shape.

$$L = K_1 \mu_0 \frac{n^2 d_{avg}}{1 + K_2 p}, \tag{2.1}$$

In evaluation, n was set equal to 3 for all coil configurations, and other values were set as per the geometry of the coil under consideration. Inner diameter varied with different coil configurations, while outer diameter was kept constant at 50 mm. For the square coil, d_{avg} was calculated as 40 mm, and p was 0.25. For the circular, octagonal, and hexagonal coils, d_{avg} declined to 38 mm and p increased to

0.316 due to space usage variances. Parameters and calculated values of L for the configurations are outlined in Table in Fig.2.2. The results indicated that square coil recorded maximum L of 627 nH, which beat the other setups, whose L values were around 460 nH. This enhanced performance of the square design is due to its best utilization of the given substrate area. Thus, the square coil structure was selected as the resonator design base for further development of the WPT system.

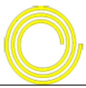
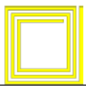
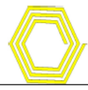
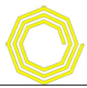
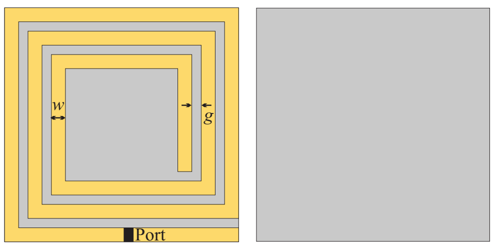
Coil type	Circular	Square	Hexagonal	Octagonal
Structure depiction				
K_1	2.25	2.34	2.33	2.25
K_2	3.492	2.75	3.82	3.55
d_{avg} (mm)	38	40	38	38
L (nH)	460	627	454	456

Figure 2.2: Various coil configuration types evaluation.

2.2 Development of Traditional 1-Coil WPT System

This section elaborates on the development of the traditional 1-coil WPT system with square configuration and assessment of its performance in simulation software environment. To be more specific, design process started with the aim to build a square shaped 1-square coil system operating at 434 MHz practical frequency. Thus, two identical resonating structures, one functioning as the transmitter and the other as the receiver, were implemented and separated by 25 mm transfer range. Figs. 2.3a and 2.3b illustrate the top and bottom views of the initial 1-coil WPT system. The very first design features a coil width of $w = 1$ mm, a gap between adjacent turns of $g = 1$ mm, and $n = 3$ turns. These parameters were selected to evaluate the fundamental performance of the 1-coil configuration.



(a) **(b)**

Figure 2.3: The traditional 1-coil design: (a) top side; (b) bottom side.

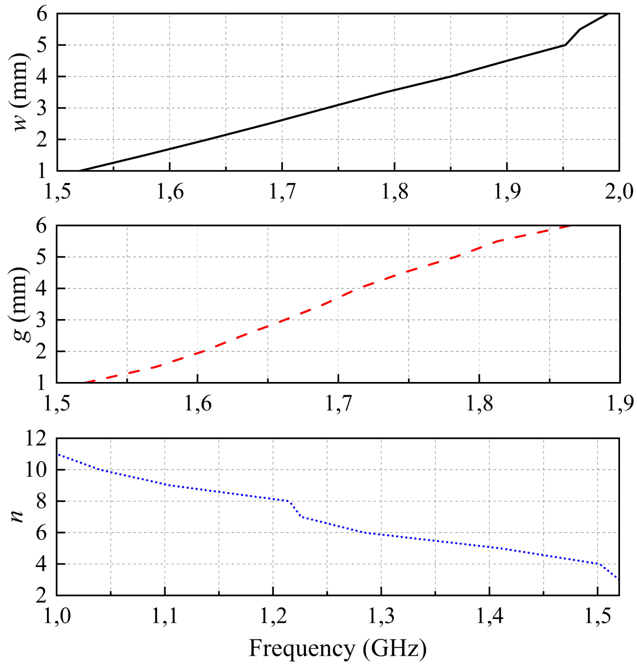


Figure 2.4: The impact of w, g, and n on the resonance.

One of the significant challenges in the realization of the WPT system without external capacitors is achieving resonance at the desired operating frequency. In this case, the operating frequency is determined entirely by the design parameters of the square coil, such as w, g, and n. Without the ability to independently adjust the resonant frequency using external capacitors, it becomes imperative to carefully analyze how these design parameters influence the system's performance. To address this, simulations were conducted in the CST software environment to investigate the relationship between the coil's design parameters and its resonance.

The simulation results, depicted in Fig. 2.4, demonstrate the impact of varying w, g, and n on the resonant frequency. Increasing w and g leads to the resonant frequency to be shifted toward higher values, whereas increasing n revealed the reverse behavior resulting in a shift toward lower frequency bands. This analyses highlights the need for precise design parameter tuning to achieve the desired operating frequency of 434 MHz. Based on the analysis, the design parameters were optimized to $n = 2$, $w = 11$ mm, and $g = 0.32$ mm, resulting in the development of 1-coil WPT system resonating at the target frequency.

Fig. 2.5 presents the electromagnetic (EM) simulation results of the optimized 1-coil WPT system. The transmission coefficient $|S_{21}|$ reaches -0.87 dB, indicating efficient energy transfer from the Tx to the Rx. Simultaneously, the reflection coefficient $|S_{11}|$ is observed to fall below -10 dB, signifying minimal energy reflection at the input port and ensuring optimal power delivery to the load [18].

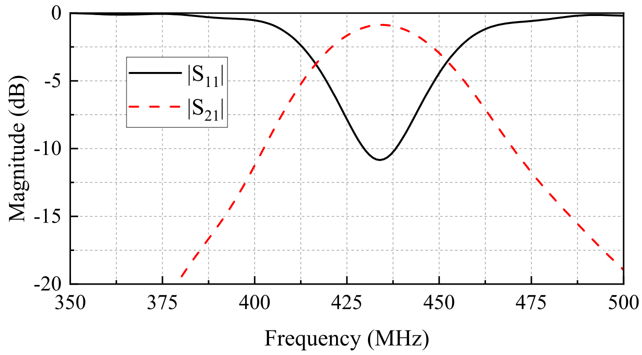


Figure 2.5: EM simulation results of the traditional 1-coil WPT system.

The system's performance was further analyzed by calculating the PTE, which is expressed as PTE = $|S_{21}|^2$, provided that $|S_{11}|$ remains below -10 dB [18]. Using the EM simulation results, the PTE of the conventional 1-coil WPT system was calculated as 82%. Therefore, this obtained high efficiency rate shows that initial aim to build effective 1-coil structure was reached.

2.3 Development of Sectionalized 2-Coil WPT System

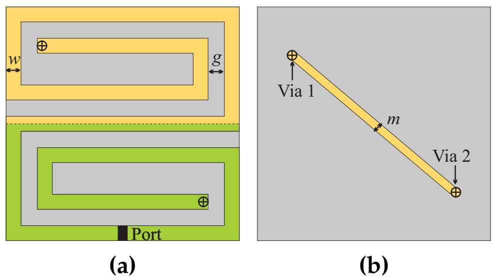


Figure 2.6: The sectionalized 2-coil design: (a) top side; (b) bottom side.

The 2-coil WPT system was developed by expanding the 1-coil setup using a sectionalizing method. The resonator design from top and bottom sides of the sectionalized 2-coil WPT system are shown in Figs. 2.6a and 2.6b. Notably, the dimensions of the overall circuit board remained the same with the size of 50×50 mm^2, but the incorporation of sectionalized two identical square coils was introduced. Thus, the parametric analysis was conducted, since the structure differs from the 1-coil. Specifically, the assessment of effect of w and g on resonance across different values of n is demonstrated in Fig. 2.7. This evaluation gave an opportunity to determine optimal design parameters, so that desired resonant frequency can be achieved. The analysis showed that, increasing w and g shift the

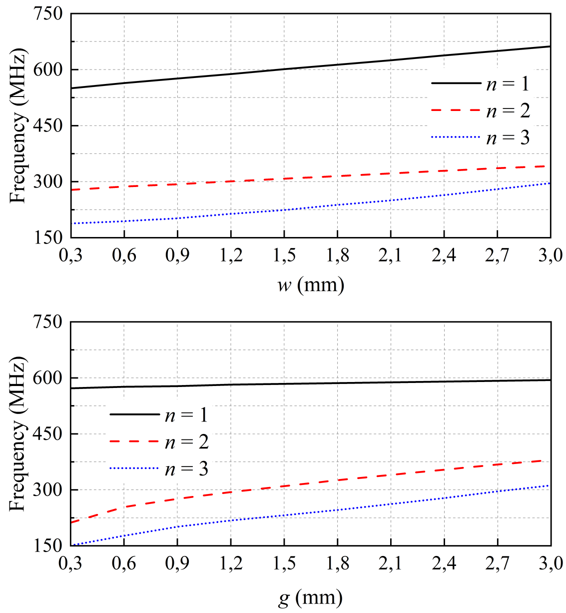


Figure 2.7: w and g effect on resonance of 2-coil WPT structure.

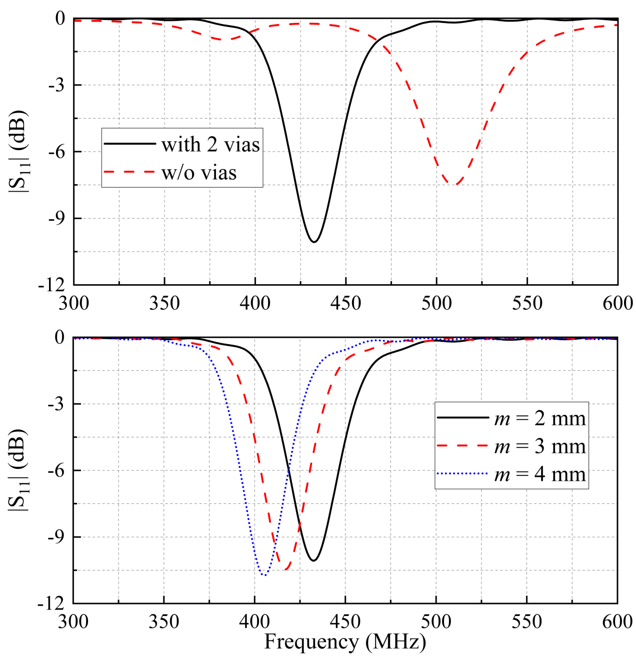


Figure 2.8: Effect of *vias* and m on the resonance of the 2-coil WPT system.

resonance toward higher values, while increasing n revealed the opposite trend. Additionally, the two spiral structures were connected by vias that were paired

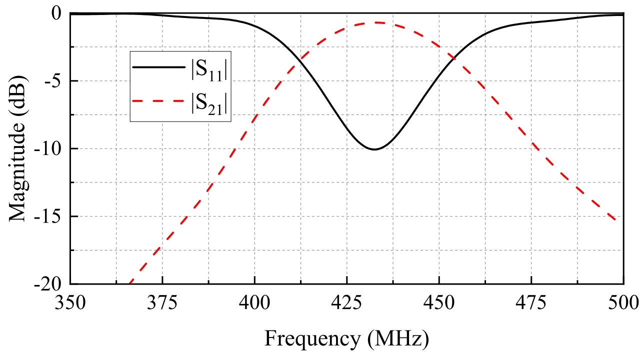


Figure 2.9: EM simulation results of the sectionalized 2-coil WPT system.

with metallic strip (MS) on the bottom layer with a total length of 50 mm. The inclusion of vias had an impact on the resonant frequency, which is thoroughly examined in Fig. 2.8. Specifically, integrating vias shifts the resonant frequency toward lower bands. The effect of the MS width (m) was also investigated, and it was found that the resonance happens at lower frequencies for larger m values.

As a result, the design parameters and the vias with MS were optimally fine-tuned to ensure the 2-coil WPT system operates at 434 MHz, which are $w = 3.2$ mm, $g = 3.5$ mm, $n = 2$, $m = 2$ mm, and a via radius of 1 mm. Fig. 2.9 illustrates the performance analysis of the developed 2-coil WPT system. Low reflection losses are indicated by the simulation results, which show that $|S_{11}|$ is below -10 dB. In contrast, $|S_{21}|$ achieves -0.71 dB, demonstrating a performance improvement over the 1-coil WPT setup. An achieved PTE of 85% is confirmed by the results corresponding to the 2-coil sectionalized WPT structure, confirming that the improved design yields increased operational efficiency.

2.4 Development of Sectionalized 4-Coil WPT System

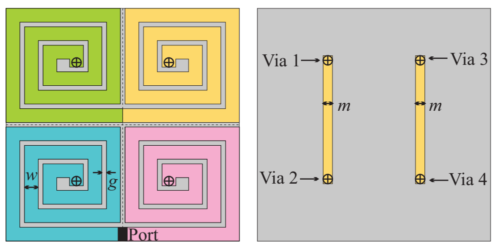


Figure 2.10: The sectionalized 4-coil design: (a) top side; (b) bottom side.

The sectionalizing method made it possible to efficiently position equivalent coils in the given set substrate space. Following this concept, the study progressed

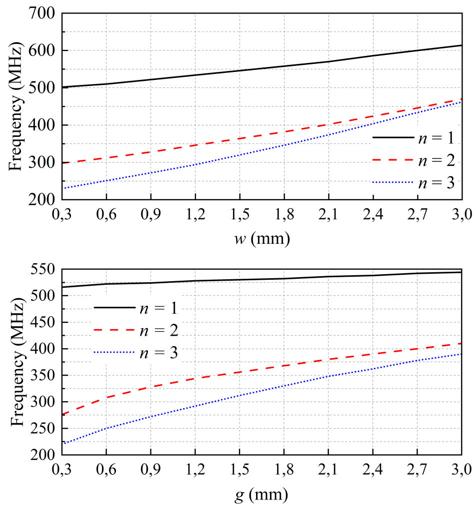


Figure 2.11: w and g effect on resonance of 4-coil WPT structure.

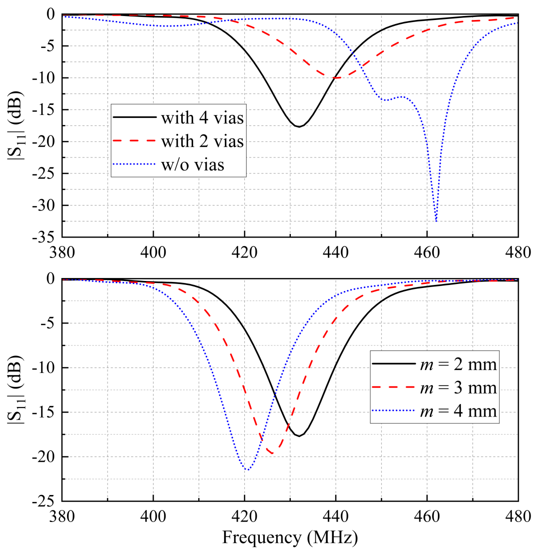


Figure 2.12: Effect of *vias* and m on the resonance of the 4-coil WPT system.

further to the design and optimization of a 4-coil WPT system at 434 MHz. The top and bottom views of the 4-coil resonator are illustrated in Figs. 2.10a and 2.10b. In order to achieve the maximum from the system, the same deep parametric study as it was for 2-coil has been performed for determining the effect of variation of w and g on resonance for increasing n, as presented in Fig. 2.11. As can be observed here, these trends are similar to those achieved in the 1-coil and the sectionalized 2-coil systems.

These studies were significant in determining the most effective parameter set

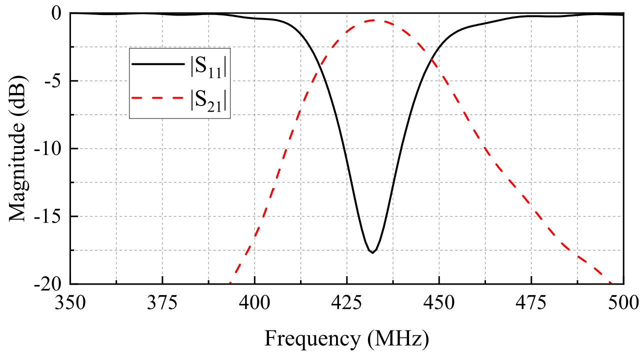


Figure 2.13: EM simulation results of the sectionalized 4-coil WPT system.

to maximize PTE at 434 MHz. Once more, like in past designs, vias were used to couple sectionalized coils and their effect on the resonance of the system was also investigated. The result, shown in Fig. 2.12, once more confirms that both the introduction of vias and increasing m reduce the resonant frequency. These findings guided the final design of the 4-coil WPT system with the following parameters, which were $w = 2.96$ mm, $g = 1$ mm, $n = 3$, $m = 2$ mm, and MS length and via radius 27.5 mm and 1 mm, respectively.

Table 2.1: Comparative evaluation of proposed 1-, 2- and 4-coil WPT systems.

WPT	$\|S_{11}\|$ (dB)	$\|S_{21}\|$ (dB)	PTE (%)
1-coil	−10.85	−0.87	82
2-coil	−10.07	−0.71	85
4-coil	−17.44	−0.53	88

The EM simulation results of the 4-coil design, which has been finished and calculated at a transfer distance of 25 mm, can be found in Fig. 2.13. The system yielded $|S_{21}| = -0.53$ dB and $|S_{11}| = -17.44$ dB, with a PTE of 88%. A comparative overview of the three WPT configurations is given in Table 2.1, highlighting the beneficial impact of the sectionalizing approach. That is, the PTE is increased by 3% in the 2-coil configuration and by 6% in the 4-coil design over the traditional 1-coil system.

In addition, surface current distribution analysis, as shown in Fig. 2.14, shows that the 4-coil structure yields a more uniform and higher current profile than the 1- and 2-coil structures. Uniform current achieves maximum electromagnetic coupling and hence maximum PTE [19]. For further assessment of performance, quality factor (Q) and coupling coefficient (k) for each configuration were calculated using respective Eqs. (2.2, 2.3) [19, 20]. In these formulas, ω_0 is the angular resonance frequency, $R_{Tx/Rx}$ is transmitting and receiving unit resistance from the impedance matrix (Z) of EM simulations, d is the distance of transmission, and A

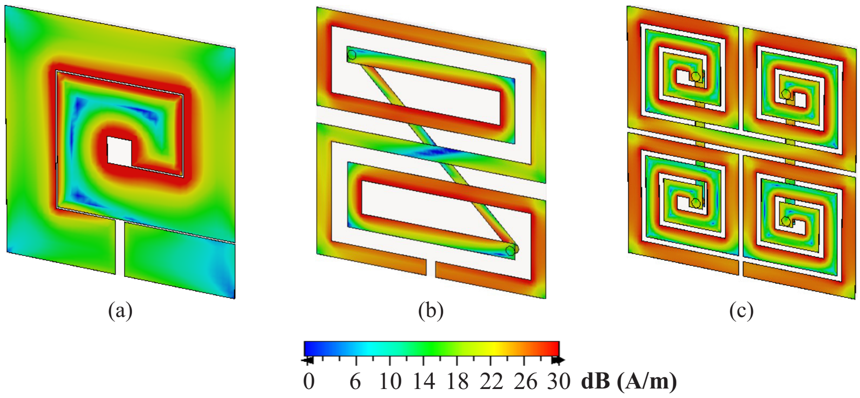


Figure 2.14: Analysis of surface current distribution: a) 1-coil; b) 2-coil; c) 4-coil.

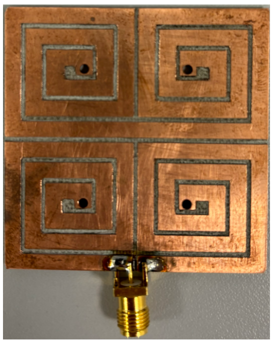
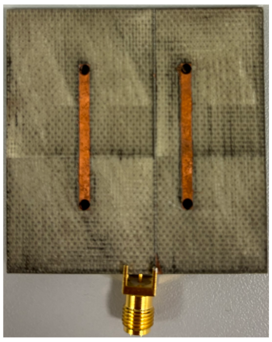
is the resonator area. The calculated Q factors were 7.06, 7.08, and 7.3 for the 1-, 2-, and 4-coil system, respectively, and the corresponding k values are 0.058, 0.060, and 0.064. These results nicely demonstrate that sectionalizing enhances coupling as well. As the result, sectionalized 4-coil WPT system outperformed 1- and 2-coil configurations.

$$Q = \sqrt{Q_{Tx}Q_{Rx}} \quad \text{where} \quad Q_{Tx/Rx} = \omega_0 \frac{L_{Tx/Rx}}{R_{Tx/Rx}}. \tag{2.2}$$

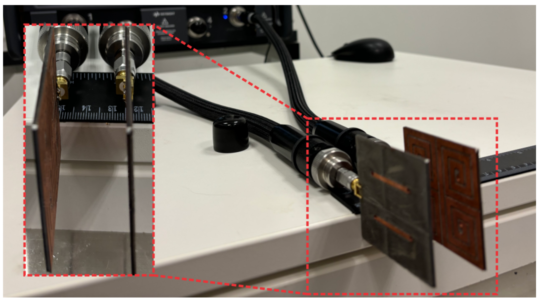
$$[Z] = \begin{bmatrix} R_{Tx} + j\omega_0 L_{Tx} & j\omega_0 M_S \\ j\omega_0 M_S & R_{Rx} + j\omega_0 L_{Rx} \end{bmatrix} \text{ and } k = \frac{\text{PTE} \times d}{Q\sqrt{A}}. \tag{2.3}$$

Chapter 3

Results and Discussion: Experimental Validation

(a) **(b)**



(c)

Figure 3.1: Fabricated resonators and practical experiment: (a) top side; (b) bottom side; (c) experimental measurement with a magnified section.

For experimental validation, the prototyped form of the designed 4-coil resonators is shown in Figs. 3.1a and 3.1b. Experimental arrangement of the designed

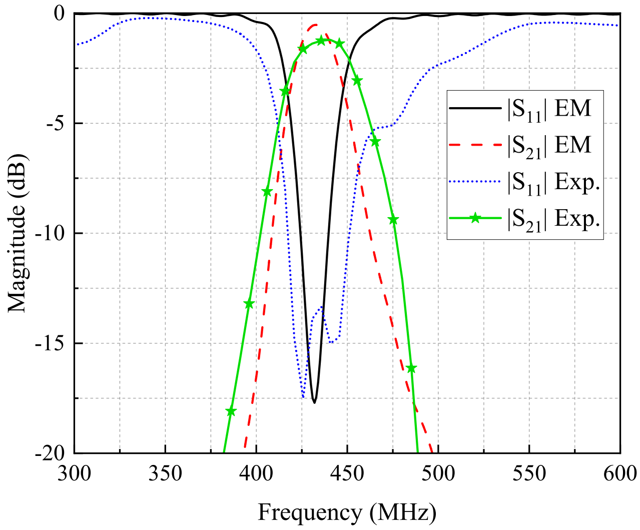


Figure 3.2: EM simulation and experimental results of 4-coil WPT system.

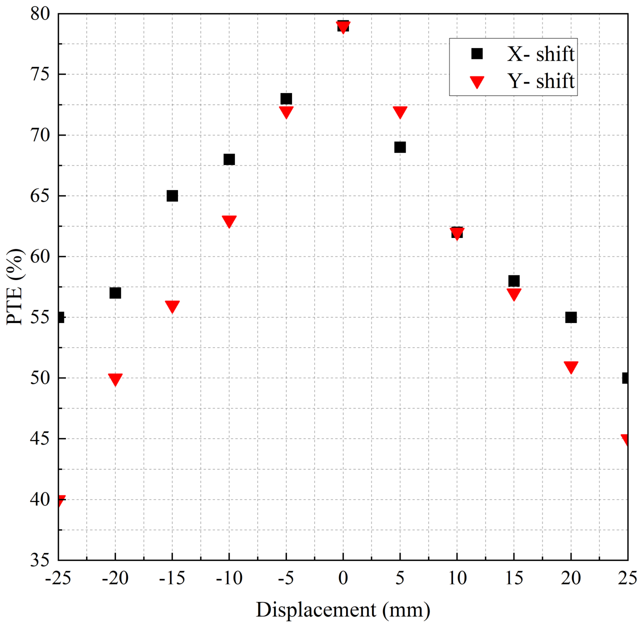


Figure 3.3: Misalignment analysis: PTE over X- and Y-shift.

4-coil WPT system is shown in Fig. 3.1c, where two identical resonator modules are placed 25 mm apart and connected to a vector network analyzer (PNA-X, N5247B) via sub-miniature version A (SMA) connectors. The comparative plot of simulated and measured results for the sectionalized WPT structure is shown in Fig. 3.2. From the plots, it can be observed that for both cases, $|S_{11}|$ is below -10 dB, which is a sign of good impedance matching. Experimentally, the system provides a PTE of 79%. Small discrepancies between EM simulation and measurement can be due to fabrication tolerance, soldering variation, and setup limitation. In summary, the achieved PTE confirms the efficiency of the sectionalized 4-coil system.

WPT systems in practice usage usually undergo misalignments, which can destroy stability in operation. For measuring the resistance of the system to such real-world scenarios, a comprehensive misalignment analysis was carried out, as illustrated in Fig. 3.3. The displacements in both horizontal (X-axis) and vertical (Y-axis) directions were taken in a range of ± 25 mm. For X-axis displacement, a shift of 5 mm leads to approximately a 6% reduction in PTE, to a minimum of 50% when $X = 25$ mm. For Y-axis misalignment, the reduction in PTE per displacement of 5 mm was 8%, with the lowest value of PTE being 40% at $Y = -25$ mm. These results indicate that the system's performance is influenced more significantly by Y-axis misalignment than by X-axis misalignment.

Chapter 4

Conclusion

This paper proposed and demonstrated an innovative sectionalizing technique to improve the PTE of near-field planar WPT systems. With an efficient sectionalizing method, the conventional 1-coil structure was extended into sectionalized 2-coil and 4-coil structures, all sharing the same substrate area. A complete parametric analysis was carried out in order to select the best geometrical parameters, which were w, g, n, MS width and vias, in order to resonate at the desired operating frequency of 434 MHz.

Simulation and experimental analysis results validated that the sectionalized structures play a profound role in shaping the system's performance. The 2-coil system demonstrated a 3% PTE improvement, whereas the 4-coil design experienced an impressive 6% rise above the base case 1-coil system. Experimental validation of the designed 4-coil WPT prototype showed a high PTE of 79% at a transfer distance of 25 mm, confirming the efficacy and feasibility of the proposed approach.

In addition, the robustness against alignment fluctuations of the system was also examined. The analysis of misalignment for X- and Y-directional displacements indicated that performance degradation of the system is more likely along the Y-axis. However, it was above acceptable levels of efficiency within a ± 30 mm range, indicating its feasibility for real-world application contexts.

Overall, the sectionalized 4-coil WPT system developed here successfully combines compactness with efficient power transmission and robustness to real world conditions. These characteristics make the proposed design methodology highly promising for numerous applications, including biomedical implants, consumer devices, and industrial control, where compact and efficient wireless power solutions are needed. Further development can focus on the development of the rectifier circuit to integrate this system in practical electronic devices.

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