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Conformal Strongly Coupled Magnetic Resonance Systems With Extended Range

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ABSTRACT In this paper, a simple design for extending the range of a Wireless Power Transfer (WPT) system is presented. The design consists of a traditional Conformal Strongly Coupled Magnetic Resonance (CSCMR) system that incorporates a repeater resonator, known as the U-loop resonator. Simulated and measured results show that the proposed system with the U-loop provides larger efficiency at transfer distances beyond its original optimal efficiency, achieving a peak efficiency of greater than 70% at a distance equivalent to the diameter of the U-loop, up to distances of 480 mm. The proposed system can also maintain efficiencies greater than 60% irrespective of the angular position of the receiver (RX) around the U-loop.

INDEX TERMS Wireless power transfer, SCMR, U-loop, relay resonator.

I. INTRODUCTION

Wireless Power Transfer (WPT) systems were first explored by Nikola Tesla, who studied wireless transmission of power over a resonant system in the 1890's [1]. However, for many years since then, WPT was an under-researched field with no significant advances until the 1960's, when WPT systems for biomedical applications began to re-emerge due to the commercial availability of Litz wires [2]–[4]. In the 1980's, advances in power electronics enabled modern WPT systems to operate under high frequency conditions thereby allowing them to provide high Quality factors (Q-factors), which are needed for efficient power transfer [5]. Recently, there has been increased demand for technologies such as electric vehicles, sensor networks, microrobots, mobile devices, implantable/wearable devices, and RFID tags to be powered through wireless links. This demand has stimulated research for low-cost, safe, mid-range WPT systems. Near-field WPT systems that utilize the Inductive Power Transfer (IPT) method [6] have been used in numerous applications. IPT is an effective wireless charging method in cases where the transmitter (TX) and receiver (RX) are close to each other. However, this method suffers from a transmission range limited only to a few centimeters and exhibits low (i.e., less than 50%) Power Transfer Efficiency (PTE) at mid-range distances.

The Strongly Coupled Magnetic Resonance (SCMR) [7] and Conformal SCMR (CSCMR) methods [8]–[9] provide efficient WPT at maximum distances on the order of the size of the resonators used at the TX and RX. Beyond this optimal transmission range, the efficiency of SCMR systems drops very quickly. Therefore, extending the range of SCMR is challenging and it is needed for several applications.

Different approaches have been used to extend the range of WPT systems. Passive repeater coils in a domino arrangement have been used [10]–[11]. Even though relay resonators are able to increase the PTE at longer distances, in many applications their use is not practical as these additional resonators use a substantial amount of space directly along the power transmission path. To remedy these limitations, [12] introduced a single-relay resonator (known as the U-coil) which is planar along the transfer distance and perpendicular between the TX/RX coils. The U-coil increased the PTE of an IPT two-coil system, which operated at a 1-meter distance, by a factor of ten. A similar approach was used in [13], where TX and RX elements, which are coplanar to U-coil resonators, were used to guide the transmission of power at a distance of over 5 m, while sustaining an efficiency of over 50%. Thus, WPT systems with U-coils can be used to transfer power in applications, where resonators in domino arrangements are not suitable as the space between TX and RX cannot have any obstructions. Such applications include charging of home/kitchen appliances and mobile/wearable devices.

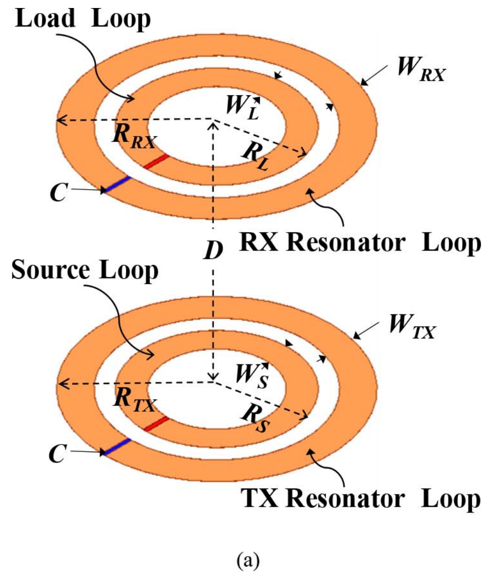
In this paper, a simpler relay resonator (known as the U-loop) is used to achieve the following: (a) increase the PTE at longer distances, i.e., extend the WPT range, (b) provide misalignment insensitivity and (c) provide consistently high PTE along various locations around and within the U-loop. Notably, this work advances the designs of [12], [13] by: (a) utilizing a CSCMR method of WPT instead of an IPT method, (b) introducing a simpler and easier to manufacture passive resonator loop instead of a large resonant coil, and (c) studying the performance of the proposed WPT system for different locations of the RX in respect to the U-loop. To the best of our knowledge, this is the first work to investigate SCMR systems with such relay resonators and perform a detailed misalignment study for different locations of the RX around and within the relay resonator.

This paper is organized as follows. Section II presents the proposed design topology with a theoretical equivalent model. The simulated and measured results are presented in Section III and key findings are discussed in Section IV. Finally, conclusions are drawn in Section V.

II. CSCMR WITH U-LOOP

A. PROPOSED DESIGN

The traditional CSCMR system with identical TX and RX elements is shown in Fig. 1(a). The TX (or RX) element consists of a source (or load) loop coplanar with a resonator loop that is terminated on a lumped capacitor. The capacitor is chosen to resonate the system at its maximum Q-factor. A 180 pF lumped capacitor (*C*) was used for our design. Our proposed CSCMR system with a U-loop is depicted in Fig. 1(b). The U-loop is a single loop of 60 mm radius and a lumped capacitor (C_U) that is determined by the system's maximum Q-factor condition. All the geometrical parameters of our CSCMR system with the U-loop are as follows: $R_S = R_L = 19$ mm, $W_S = W_L = 6$ mm, $R_U = 60$ mm, $R_{TX} = R_{RX} = 30$ mm, $W_{TX} = W_{RX} = W_U = 7$ mm, $D_U = 120$ mm and $D = 60$ mm and are shown in detail in Fig. 1.



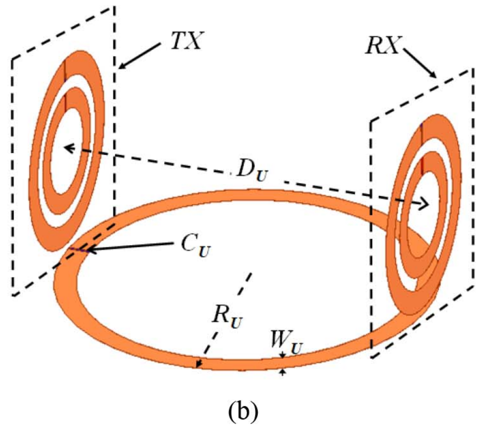


FIGURE 1. 3D view of a (a) traditional CSCMR, (b) proposed CSCMR with U-loop.

B. EQUIVALENT CIRCUIT MODEL

CSCMR is based on the magnetic resonance principle, which was introduced by [7]. Such resonant structures require high reactance to resistance ratios which can be described as Q-factor [14]. The Q-factor is the ratio of energy stored to energy lost. Therefore, high Q-factor for TX and RX CSCMR elements are needed to achieve high efficiencies. By adding relay resonators, the Q-factor of a WPT system increases and the number of resonant modes also increases [15]. The equivalent circuit of a CSCMR structure with multiple resonators (see Fig. 2) can be described by the following matrix [8], [17]–[19]:

$$\begin{bmatrix} V_S \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_S & j\omega M_{1,2} & j\omega M_{1,3} & j\omega M_{1,4} & j\omega M_{1,5} \\ j\omega M_{2,1} & Z_2 & j\omega M_{2,3} & j\omega M_{2,4} & j\omega M_{2,5} \\ j\omega M_{3,1} & j\omega M_{3,2} & Z_3 & j\omega M_{3,4} & j\omega M_{3,5} \\ j\omega M_{4,1} & j\omega M_{4,2} & j\omega M_{4,3} & Z_4 & j\omega M_{4,5} \\ j\omega M_{5,1} & j\omega M_{5,2} & j\omega M_{5,3} & j\omega M_{5,4} & Z_L \end{bmatrix} \times \begin{bmatrix} I_S \\ I_2 \\ I_3 \\ I_4 \\ I_L \end{bmatrix} \quad (1)$$

where V_S, ω, $M_{n,m}$, I, and Z are the voltage of the source, angular frequency, mutual inductance, current, and self-impedance, respectively (the subscripts n, S and L represent n^{th} resonator, source and load loops, respectively). For the interested reader, a detailed analytical model that predicts the efficiency of CSCMR systems with multiple resonators can be found in [8].

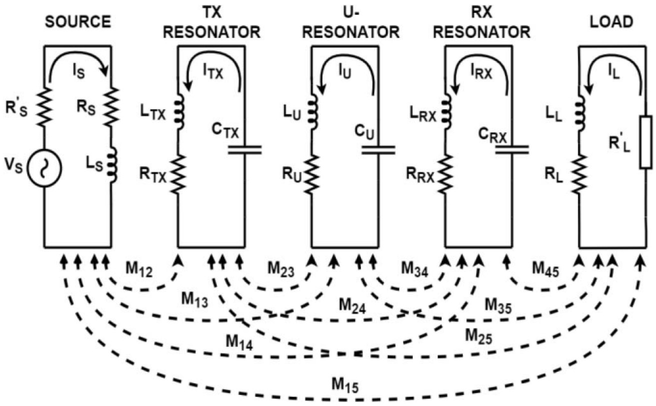


FIGURE 2. Equivalent circuit model of CSCMR with U-loop resonator.

FIGURE 3. Prototype of the proposed CSCMR system with a simplified U-loop.

III. FABRICATION AND MEASUREMENTS

The prototype of the proposed design is depicted in Fig. 3. The U-loop relay resonator, as well as the TX and the RX elements of our design, are constructed on a thin Kapton film substrate with $\varepsilon_r = 3.34$ and thickness of 0.05 mm. The efficiency, η, of our system was measured using a Keysight Vector Network Analyzer (VNA) and it was defined as $\eta = |S12|^2$. All simulations were performed using ANSYS HFSS.

A. TRADITIONAL CSCMR WITHOUT U-LOOP

First, the efficiency of the CSCMR system of Fig. 1(a) without the U-loop (i.e., traditional CSCMR system) is measured and simulated. Fig. 4 shows these results for different TX/RX distances, D, between 60 mm to 140 mm. It is clearly seen that beyond a transfer distance of 80 mm, the efficiency begins to significantly decrease by approximately a factor of two per 20 mm. This illustrates that traditional CSCMR systems provide a limited range, which is typically equal to the maximum dimension of the resonator (this is also the case for SCMR systems). Therefore, there is a need for a new method that can extend the range of CSCMR systems. This is achieved in the following section by adding the U-loop. The slight difference between the simulated and measured resonant frequency can be attributed to fabrication errors.

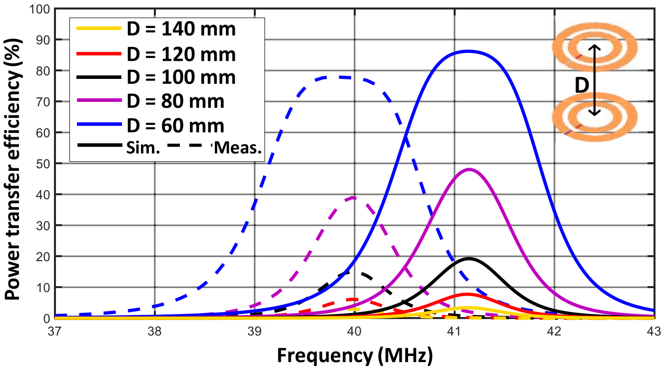


FIGURE 4. Measured and simulated efficiency of the traditional CSCMR system at various distances, D.

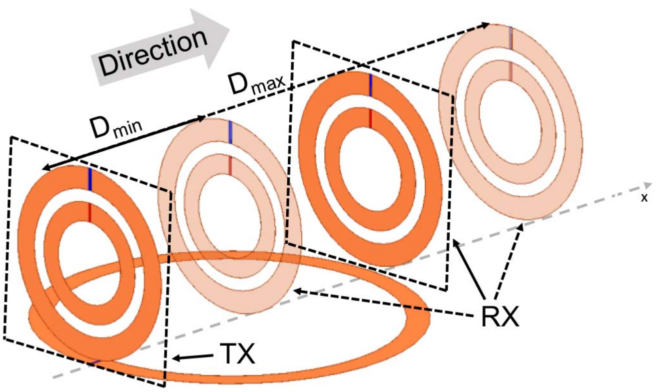


FIGURE 5. 3-D view of the CSCMR system with the U-loop for distances between TX and RX of D_{min}, D_U, and D_{max}.

B. CSCMR WITH 60 MM RADIUS U-LOOP

The measured and simulated results of the proposed CSCMR system with the U-loop (shown in Fig. 3) are compared at different distances, D, from D_{min} = 60 mm to D_{max} = 140 mm (as shown in Fig. 5) for a lumped capacitor, C_U, of 56 pF and 82 pF in Figs. 6(a) and 6(b), respectively. These results show that the main resonance of the system occurs at a different frequency depending on the value of C_U. For both values of C_U, the proposed CSCMR system provides maximum efficiency of 73% at an extended range of D_U = 120 mm and near the resonant frequency of the original CSCMR system without the U-loop (i.e., 40 MHz). Furthermore, for a range between 100–120 mm, the proposed CSCMR system with the U-loop maintains an efficiency that is higher than 60%. Also, this system provides high efficiency at the original transfer distance of 60 mm.

In conclusion, the proposed CSCMR system provides higher efficiency than the traditional CSCMR system for distances that are longer than 80 mm. Specifically, at 120 mm the proposed system has an efficiency that is 10 times higher

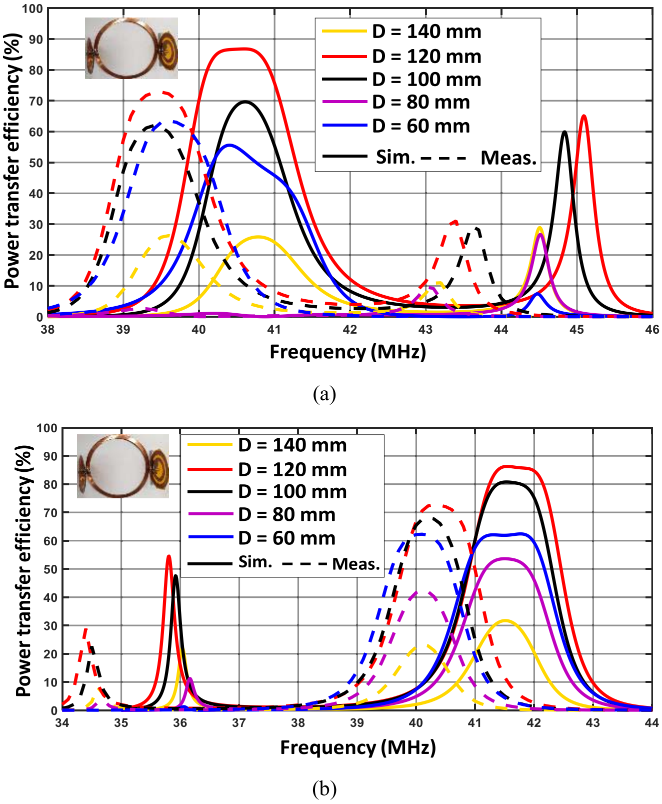


FIGURE 6. Measured and simulated efficiency of CSCMR system with U-loop at various distances and for a lumped capacitor (a) C_U = 56 pF and (b) C_U = 82 pF.

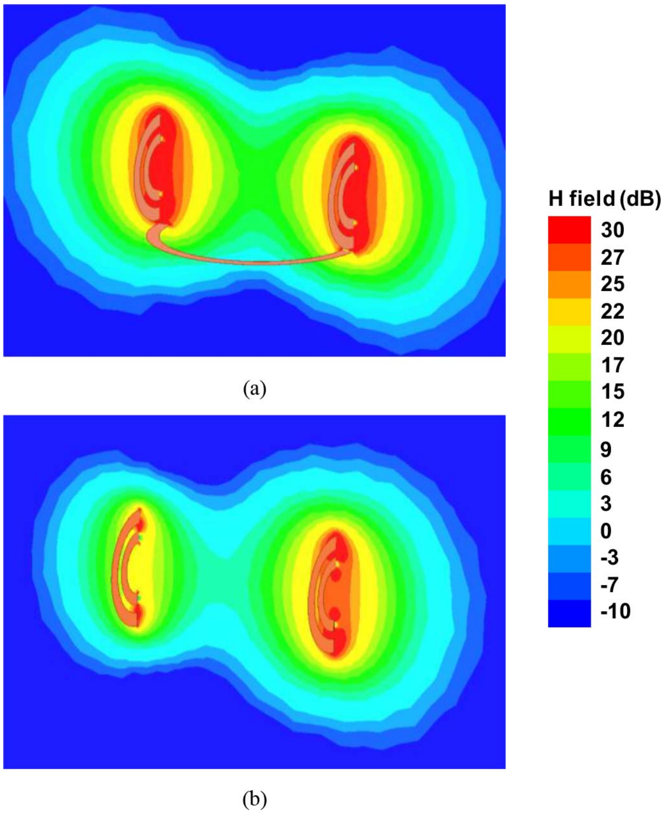


FIGURE 7. Magnetic-field distribution of CSCMR system at the resonance frequency for a distance of 120 mm (a) with U-loop and (b) without U-loop.

than the one of the traditional systems. Moreover, the traditional CSCMR system exhibits higher efficiency than the proposed CSCMR system only at 60 mm. Specifically, the efficiency of the systems with and without the U-loop are 60% and 80%, respectively. Notably, at $D = 80$ mm, the proposed CSCMR system with $C_U = 56$ pF exhibits approximately zero efficiency near the original operating frequency, whereas the system with $C_U = 82$ pF exhibits a 40% efficiency. This implies that the capacitor of the U-loop affects the efficiency of the system depending on the distances and needs to be carefully picked depending on the application. Also, based on the results of Figs. 6(a) and 6(b), it can be seen that a second resonance appears due to the presence of the U-loop. This phenomenon was studied in detail by [15], which proved that the insertion of an odd number of relay resonators introduces three split resonant modes. At first glance, the PTE responses in Figs. 6(a) and 6(b) seem to show only two resonant modes. However, upon closer examination, it is understood that the third resonant mode is not visible in these cases as two of the resonances have converged to the same frequency (see Section III-E for detailed explanation).

The magnetic field intensities (H-field) of the CSCMR systems with and without U-loop at their respective simulated resonance frequencies of 41.2 MHz and 41.4MHz and distance $D = 120$ mm are illustrated in Figs. 7(a) and 7(b). WPT systems require high magnetic flux through the TX and RX elements in order to provide high efficiency. The field distributions in Fig. 7 show that in the area between the two coupled TX/RX loops, the H-field intensity of the system without the U-loop is significantly smaller than the one with the U-loop. This indicates that the magnetic flux through the TX/RX loops is low, thereby explaining the low efficiency of the traditional CSCMR system (i.e., without the U-loop) at this distance. However, in our proposed system, the U-loop allows the magnetic flux to pass through it, thereby establishing strong coupling of the TX/RX resonators and in turn providing high efficiency at the distance of 120 mm. The process in which the U-loop can facilitate the power transfer can be explained by Faraday's law of induction, based on a change in the magnetic field (flux) going through a conductive loop or coil which induces an electromotive force (EMF), which in turn induces a current on the conductor [16]. In our case, the power source is exciting the source loop with an electric current, which creates a time-varying magnetic field (as described by Ampere's law [16]). This field induces an EMF that enables the TX to efficiently couple its energy to the U-loop. Also, this coupling occurs between the U-loop and the RX, thereby enabling us to efficiently transfer power from the TX to the RX at extended distances.

C. EFFECT OF INCREASING THE U-LOOP DIAMETER AND TRANSFER DISTANCE

In this section, the diameter of the U-loop is increased using a step of 60 mm. The starting case at 60 mm distance does

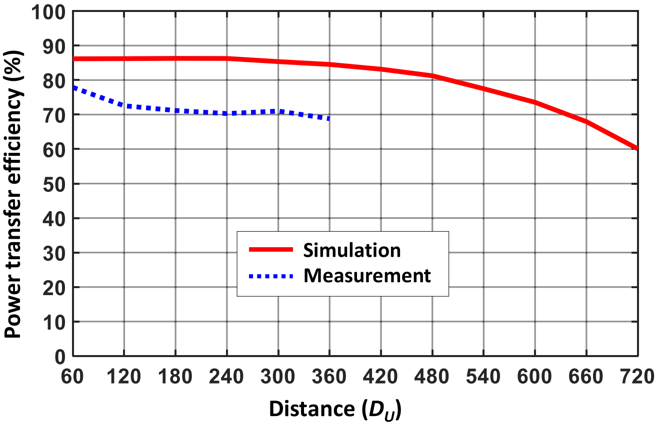


FIGURE 8. Measured and simulated efficiency of CSCMR systems with U- loop at various distances, D_U, that are equal to the diameter of the U-loop.

not have a U-loop. All, other cases have a U-loop with a diameter that is equal to the distance between the TX and RX resonators (D_U). In our simulations, the maximum D_U is 720 mm, while in our measurements the maximum D_U is 360 mm. This maximum distance in our measurements was determined by the maximum U-loop that we could accurately fabricate in our laboratory. Notably, the frequency at which each design achieved its maximum efficiency was not always exactly the same, but all of them were within the range of 41±0.5 MHz in simulations and 40±0.5 MHz in measurements. The measured efficiency is approximately 15% less than the simulated one. This is attributed to: (a) the losses of the capacitors that are not included in our simulations, as they are simulated as ideal lossless elements, and (b) fabrication tolerances of our prototypes.

The simulated and measured efficiency at various distances, D_U, (and corresponding equal U-loop diameters) are compared in Fig. 8. The simulated results indicate that for distances larger than 480 mm the efficiency begins to decay and drops down to approximately 60% at the maximum distance of 720 mm. However, at transfer distances below 480 mm, the simulated efficiency remains higher than 80%. A slight discrepancy occurs between simulation and measurements when the U-loop is absent (60 mm). Specifically, in simulations the addition of the U-loop does not immediately cause a drop in efficiency, whereas in measurements a drop of around 5% is encountered. This small difference is attributed to compounding fabrication and capacitor losses.

D. RX ORIENTED PARALLEL WITH U-LOOP

Here, the performance of the proposed CSCMR system is examined for the case where the RX is parallel to the U-loop. Specifically, the RX is positioned 10 mm above the U-loop and measurements are conducted at different locations within the U-loop with $R_U = 120$ mm, as shown in Fig. 9. The TX is perpendicular to the U-loop as in previous scenarios (see Fig. 9).

The measured results for top, center, right, bottom and left locations (see Fig. 9) are plotted in Fig. 10. The

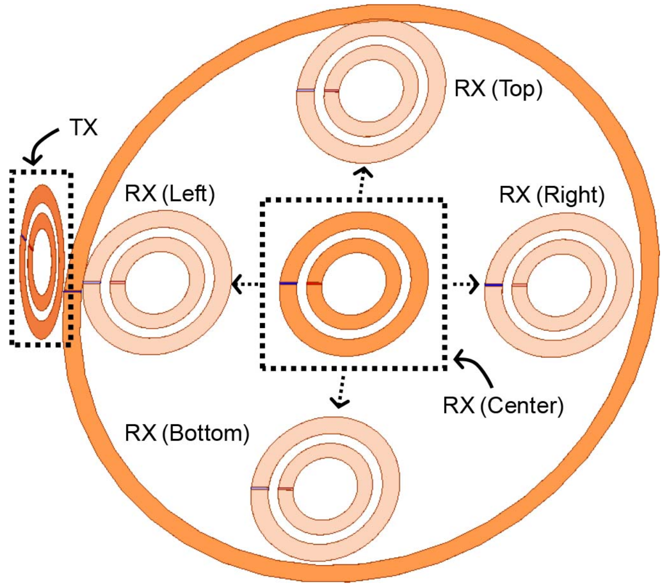


FIGURE 9. RX is parallel to the U-loop and it is placed at various positions within a U-loop with $R_U = 120$ mm.

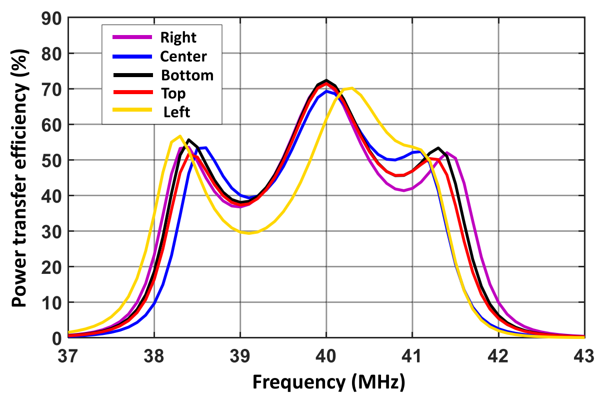


FIGURE 10. Measured efficiency for the cases shown in Fig. 9.

results demonstrate that any location within the U-loop, the proposed CSMCR system exhibits approximately the same response. The largest deviation occurs when the RX is placed at the left side location of the U-loop. In all other cases, the efficiency of the system at the resonant frequency of 40 MHz is between 69% and 72%. These results are especially applicable for mobile device and drone charging and can lead to the development of wireless charging pads that cover significantly large areas.

E. ANALYSIS OF RESONANT MODES

As mentioned previously, the addition of the U-loop resonator can generate three resonances as predicted by [15]. The three different resonant modes shift in frequency depending on the lumped capacitor of the U-loop. This is shown in the simulated results depicted in Fig. 11. For $C_U = 55$ pF, two of the resonant modes converge to the same frequency of 40.5 MHz, and the other resonant frequency peak occurs at 45.5 MHz with significantly lowered PTE. When the

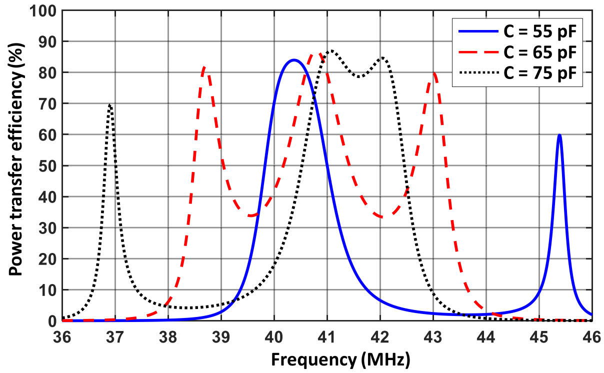


FIGURE 11. Simulated efficiency of CSCMR system with U-loop of varying lumped capacitance.

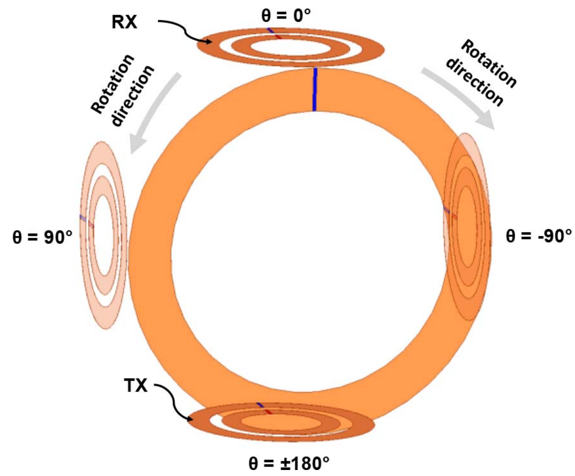
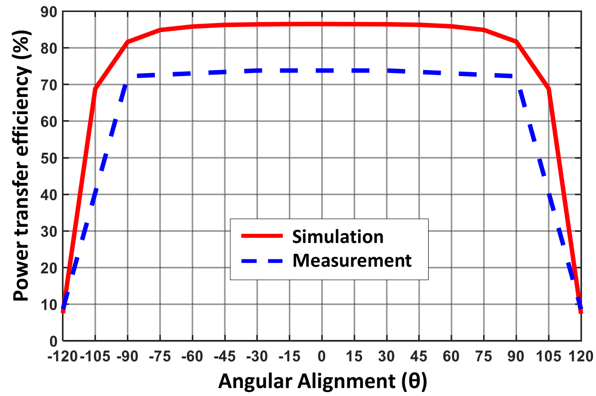


FIGURE 12. 3-D view of CSCMR system with U-loop for different angular positions of the RX around the U-loop.

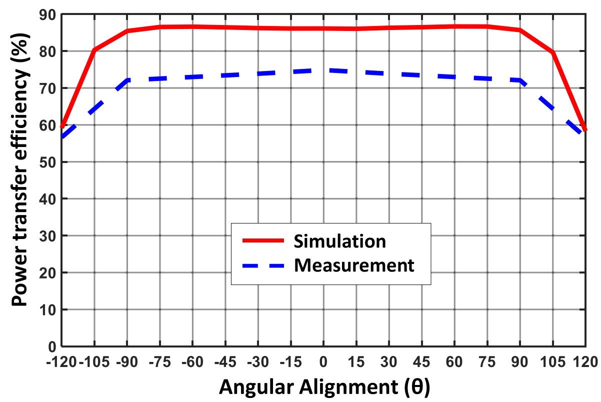
lumped capacitor of the U-loop increases to $C_U = 65$ pF, three distinct resonances appear at 38.75 MHz, 40.75 MHz and 43MHz and they exhibit similar peak efficiencies. Also, when the lumped capacitor further increases to $C_U = 75$ pF, two resonances start to converge at the same frequency of 41.5 MHz, while the other peak shifts downward at just under 37 MHz with a slightly lower PTE.

F. MISALIGNMENT INSENSITIVITY

This section studies the performance of the proposed CSCMR system for various angular positions of the RX around the U-loop, as shown in Fig. 12. Specifically, the RX was placed at angular positions from $\theta = -120°$, to $\theta = 120°$ around the U-loop. The corresponding simulated and measured efficiencies at these positions are shown in Fig. 13. The measured efficiency is approximately 15% less than the simulated one due to the losses of the capacitors that are not included in our simulations (as they are simulated as ideal lossless elements) and fabrication tolerances of our prototypes. Due to the U-loop's symmetry, the same response is expected at their corresponding opposite angles (i.e., the cases for $\theta = -90°$ and $\theta = 90°$ will exhibit the same efficiency). The results shown in Fig. 13, indicate that the measured efficiency of our CSCMR system remains higher than 70% for angular positions, θ, between $-90°$ and $90°$ and for both values of the U-loop's capacitor. However, for values below $\theta = -105°$ and values above $\theta = 105°$, our CSCMR system with $C_U = 82$ pF experiences a frequency split, which reduces its efficiency to approximately 65%, as shown in Fig. 13(b). On the contrary, for these angular positions, the system with $C_U = 56$ pF experiences a significant reduction in its efficiency to approximately 10%, as shown in Fig. 13(a). These results reinforce the idea that the capacitor of the U-loop affects the system's efficiency not only at different distances but also at different angular positions.



(a)



(b)

FIGURE 13. Measured and simulated efficiency of the proposed CSCMR system at various angular alignments around the U-loop for a lumped capacitor: (a) $C_U = 56$ pF, and (b) $C_U = 82$ pF.

IV. KEY FINDINGS

In this research, a relay resonator, namely U-loop, was introduced and studied for the CSCMR WPT method. Our findings prove that relay resonators can be used in CSCMR systems to provide high efficiency at extended ranges. To compare our work to previously published research, the relevant parameters of different WPT systems are compared in Table 1. Specifically, in [8], a broadband WPT system was developed that had a high PTE of 84.2% and a transfer

TABLE 1. Performance comparisons of previous works to this work.

Reference	Parameter					
	WPT Method	Frequency	Maximum Dimension of TX/RX (mm)	Electrical Size of TX/RX Diameter (λ)	Power Transfer Distance (mm)	PTE (%)
This Work	CSCMR	40 MHz	60	0.00801	360	70.0
[8]	CSCMR	165 MHz	104	0.0572	60	84.2
[9]	CSCMR	20 MHz	64	0.00427	60	70.0
[12]	IPT	86.2 KHz	600	0.000173	1000	87.8
[13]	IPT	90.9 KHz	400	0.000121	1600	79.0

range that is 6 times shorter than the one of our proposed design. Additionally, the TX and RX elements in [8] were electrically large (i.e., diameter of 0.0572), due to their large physical size and relatively high operational frequency. In [9], a multilayer configuration of CSCMR was presented for miniaturization purposes. However, this system provided its peak efficiency (i.e., 70%) at a transmission distance of only 60 mm, which is significantly smaller than our high-efficiency transmission range of 360 mm. While the PTEs of both systems in [8] and [9] are similar to the PTE of our proposed system, they operated properly only when their RX directly faced their TX at a distance of 60 mm, whereas our system provides significant freedom for the placement of the RX compared to the TX in terms of alignment and range.

In [12] and [13], a WPT system utilizing the IPT method with a U-coil exhibited a PTE of 87.8% and 79% with an extended range of 1000 mm and 1600 mm, respectively. While these systems maintained a small electrical size, they exhibited a large physical size to achieve this performance. Therefore, the systems of [12] and [13] are limited to fewer applications, as their large dimensions make them unsuitable for small devices that must use RX elements with small footprints. Furthermore, in [12] and [13], the positions of the RX elements were fixed and the PTEs were not reported for different RX orientations.

The key original aspects of our work compared to the previous work are summarized here. In our work, the proposed CSCMR system with a U-loop provides extended range while maintaining high efficiency at multiple positions, which are not limited to the edges of the U-loop. In fact, when the RX is parallel to the U-loop, high efficiency is achieved at any location within the U-loop. Therefore, the performance of our CSCMR system remains consistent thereby providing high efficiency at different RX placements. To our knowledge, this has not been achieved before. Specifically, the significantly long range of our system in conjunction with the relatively small RX/TX elements, and our simpler relay resonator design, distinguish our work from previously published designs. Additionally, CSCMR WPT systems with U-loops have not been studied before, whereas here a detailed study of such systems is presented in terms of their range and placement of the RX. Our work also underlines the potential of our proposed system for various important applications, such as, charging pads for mobile devices and unmanned aerial vehicles.

V. CONCLUSION

This paper integrates a U-loop, which was proposed by [12] and [13], in CSCMR systems and examines the performance of these systems. The novelty of our work compared to [12] and [13] is supported by the following points: (a) CSCMR is used here instead of inductive coupling, (b) a simple and easy to fabricate loop resonator is proposed here instead of a resonator coil that occupies significantly larger volume, and (c) the performance of our proposed system for different positions and orientations of the RX around and within the U-loop is thoroughly studied. Our results show that the U-loop resonator extends the optimal transmission distance and performs significantly better than a traditional CSCMR system at distances beyond 80 mm. Also, the proposed system maintains efficiency above 60% for a range of angular positions (θ between $-120°$ and $120°$) of the RX around the U-loop. Furthermore, when the RX is parallel to the U-loop, our system still provides high-efficiency for all locations within the U-loop. Therefore, our proposed CSCMR system with the U-loop can be applicable for charging mobile devices, which are placed parallel as well as perpendicular to the charging pad. This would provide more freedom to the users that charge their devices. Finally, the lumped capacitor of the U-loop influences the performance of this system in terms of its resonant frequency and efficiency at various distances and angular positions of the RX.

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