Asymmetric Strongly Coupled Printed Resonators for Wireless Charging Applications

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***Abstract*— This paper presents a simple compact design for wireless charging applications using asymmetric strongly coupled printed resonators (SCPR). The proposed resonators are further loaded by surface mounted (SMD) capacitors for miniaturization. The system consists of two substrates. The first transmitting substrate contains a driving loop on the top layer and the high Q-resonator on the bottom layer. Similarly, the second substrate contains the high Q-resonator as the receiver and a loop as the load. An equivalent circuit model is extracted. An analytic design method is proposed to get a high wireless power transfer (WPT) efficiency. Good agreement between electromagnetic simulations, circuit simulations, and measurements was achieved. The proposed system achieves a measured WPT efficiency of 60% at 100 MHz using a receiving resonator of size 20 mm x 20 mm away for a transmission distance of 35 mm from the transmitting resonator of size 30 mm x 30 mm.**

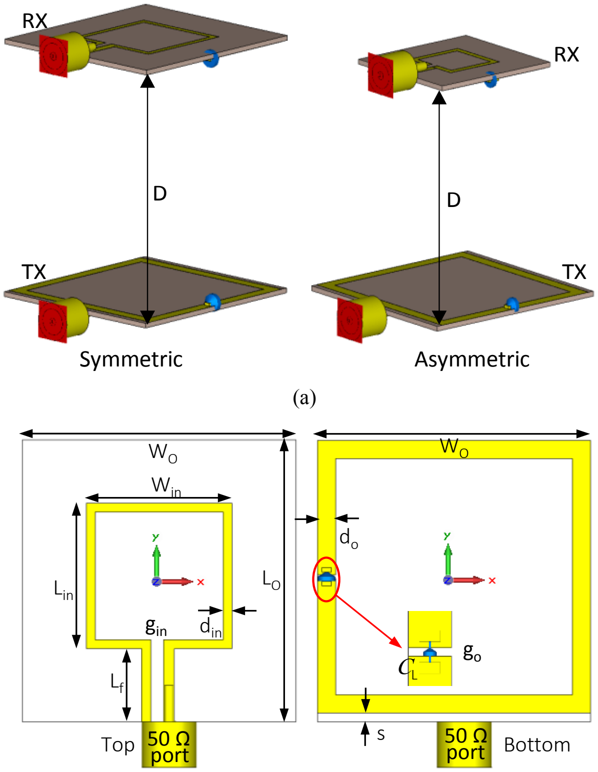
Keywords- capacitive loaded resonators; strong resonant coupling; wireless power transfer;

I. INTRODUCTION

The technology of Wireless Power Transfer (WPT) has enticed great attention due to its use in vital applications such as Radio Frequency Identification (RFID), biomedical implants, and electronic mobile devices charging [1]-[4]. The most popular WPT systems are based on near-field (non-radiative) coupling that is used for short-range and mid-range applications. Inductive and capacitive coupling types are used for short-range applications. Electromagnetic (EM) resonant coupling focuses the power at a narrow band, and is suitable for mid-range applications with high WPT efficiency [5]. In the design of near field WPT systems, transmitting high power at larger distance with compact size has been one of the most important issues. Furthermore, most of the vital wireless charging applications such as mobile devices and biomedical implants require compact structures at least at the receiving side. To increase the WPT efficiency, strong resonant coupling technique using high Q-factor intermediate resonators driven by inductive loops were presented [6]. Many authors suggested using vertical feed perpendicular to the substrate, and the Q-factor depends upon N-turn printed coils [7], [8]. All of them, proposed so far till now assumes symmetrical resonators size at the transmitting and receiving side, and their effectiveness has not been analyzed yet when asymmetric resonators are used.

In this paper, we propose a WPT system based on strongly coupled capacitive loaded printed resonators. The transmitting (TX) and Receiving (RX) resonators are composed of square shaped printed resonator on the bottom layer driven/loaded by inductive loop on the top layer. The effectiveness of asymmetry in resonator size is also analyzed and verified experimentally.

II. MODELING



(a)

(b)

Figure 1. The proposed symmetric and asymmetric WPT systems (a) Three dimentional view. (b) PCB layout of the top and the bottom layers.

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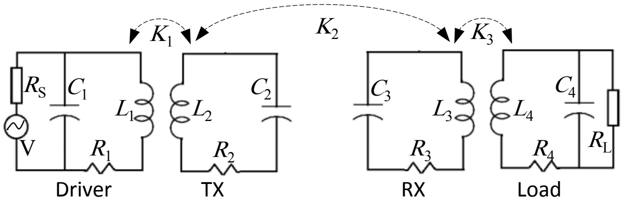


Figure 2. Equivalent Circuit model of the proposed symmetric and asymmetric WPT systems.

Fig. 1(a) presents the proposed WPT systems using symmetric and asymmetric SCPRs separated by a transmission distance D. Each resonator is composed of a driving/loading loop on the top layer and a single turn square-shaped printed resonator on the bottom layer as shown in Fig. 1(b). The equivalent circuit model is shown in Fig. 2. Each of the driver/load loops is a square shaped resonator with side length $W_{in} = L_{in}$ and track width d_{in}. The TX/RX loops are square shaped capacitive loaded resonator with side length $W_o = L_o - s$ and track width d_o. According to [9], [10], the inductance of a single turn square shaped loop can be calculated from (1). Where (1) is simplified form of [9, Ch. 2, Eq. (34)]. The inductance of the parallel feeding strips can be calculated using (2) [10, Ch. 5]. The series resistance of the inductor can be calculated from (3) by taking in consideration the skin effect, where R_{dc} is the dc resistance, l_c is the inductor length, and δ is the skin depth [11]. The gab capacitances are calculated from [12, Eq. (8)]. The mutual inductance and the coupling coefficient between the coupled resonators are calculated from (4), (5) respectively, as reported in [13].

The following steps explain an analytic design method for the proposed system to get higher WPT efficiency:

1- Define the required operating frequency for the proposed WPT system $f_0 = 100$ MHz.
2- The required transmission distance $D \geq 30$ mm.
3- Design the TX/RX resonators such that

$$\omega_0 = \frac{1}{\sqrt{L_2 C_2}} = \frac{1}{\sqrt{L_3 C_3}}$$

4- As explained in [14], the transmission distance that gives high WPT efficiency, approximately, equals the maximum dimension of the resonator. Hence, we start with the TX resonator with side length $W_{ot} = 30$ mm.
5- By substitution of $W = 30$ mm, and $d = 2$ mm in (1)-(3), we get $L_2 = 72$ nH, and $R_2 = 0.13\ \Omega$. From the formula in step 3, we need $C_2 = 36.5$ pF to get resonance at $f_0 = 100$ MHz. These values are the same in the case of the symmetric structures $L_2 = L_3$, $R_2 = R_3$, and $C_2 = C_3$,
6- For the asymmetric structures, we selected a smaller size for the RX (20 mm x 20 mm). By substitution of $W = 20$ mm, and $d = 2$ mm in (1)-(3), we get $L_3 = 40$ nH, $R_3 = 0.09\ \Omega$. From the formula in step 3, we need $C_3 = 63.5$ pF to get resonance at $f_0 = 100$ MHz.
7- The driver/load loops' side lengths and track widths are optimized to get a perfectly matched system.
8- The mutual inductances and the coupling coefficients are calculated from (4), (5).
9- The equivalent circuit is now ready to be implemented on ADS for optimization.
10- The optimized equivalent circuit parameters using ADS are used for a fine tuning using the EM simulator (CST).

$$L = 0.0467ea\left[\log\left(\frac{2ea^2}{t+d}\right) - \log(2.414ea)\right] + 0.0203ea\left[0.914 + \frac{0.2235}{a}(t+d)\right] \quad \mu\text{H, e} = 39.37 \tag{1}$$

Where a is the effective side length of the square loop ,

$a = W - \frac{d}{2}$,and d is the track width

$$\begin{gathered} L_P = 2L_a - 2M_a \quad \mu\text{H} \\ L_a = 0.2l\left(\ln\left(\frac{2l}{d+t}\right) + 0.5 + \frac{d+t}{3l}\right) \quad \mu\text{H} \\ M_a = 0.2l\left(\ln\left(\frac{2l}{d}\right) - 1 + \frac{d}{l}\right) \quad \mu\text{H} \end{gathered} \tag{2}$$

l is the feeding strip length = L_f

$$R = R_{dc}\frac{t}{\delta\left(1 - e^{-t/\delta}\right)\left(1 + \frac{t}{d}\right)}, \quad R_{dc} = \frac{l_c}{\sigma dt} \tag{3}$$

$$\begin{gathered} M_{ij} = \left(\frac{4}{\pi}\right)^2 \frac{\mu_0 \pi a_i^2 b_j^2}{2\left(a_i^2 + b_j^2 + z^2\right)^{3/2}}\left(1 + \frac{15}{32}\gamma_{ij}^2 + \frac{315}{1024}\gamma_{ij}^4\right) \\ a_i = W_i - \frac{d_i}{2}, \; b_j = W_j - \frac{d_j}{2} \\ \gamma_{ij} = \frac{2a_i b_j}{\left(a_i^2 + b_j^2 + z^2\right)} \end{gathered} \tag{4}$$

$$\begin{gathered} K_i = M_{ij} / \sqrt{L_i L_j} \\ K_1 = M_{12} / \sqrt{L_1 L_2}, \; K_2 = M_{23} / \sqrt{L_2 L_3}, \text{ and } K_3 = M_{34} / \sqrt{L_3 L_4} \end{gathered} \tag{5}$$

Table I shows the optimized design parameters of the proposed WPT systems using symmetric and asymmetric SCPRs. The WPT efficiency is calculated for both cases of symmetric and asymmetric using the formula:

$$\eta = |S_{21}|^2\left(\sqrt{\left(1 - |S_{11}|^2\right)\left(1 - |S_{22}|^2\right)}\right) \times 100\% \tag{6}$$

The driver/load loops' elements L_1, C_1, L_4, and C_4 are responsible for impedance matching of the whole system, especially in the case of asymmetric resonators. For such case, Fig. 3 illustrates the effect of the matching capacitor C_4 on the impedance matching and the WPT efficiency enhancements. The optimized value is found to be 33.2 pF which is realized by a feeding strips' capacitance of 0.2 pF and an SMD capacitor of 33 pF connected between the feeding strips in the asymmetric receiving resonator.

TABLE I. OPTIMIZED DESIGN PARAMETERS OF THE PROPOSED WPT SYSTEM USING SYMMETRIC AND ASYMMETRIC SCPRS AT 100 MHZ

<table>
<tr><th rowspan="3"></th><th colspan="12">Printed spiral planar resonators</th></tr>
<tr><th colspan="6"><i>Symmetric</i></th><th colspan="6"><i>Asymmetric</i></th></tr>
<tr><th colspan="3"><i>TX side</i></th><th colspan="3"><i>RX side</i></th><th colspan="3"><i>TX side</i></th><th colspan="3"><i>RX side</i></th></tr>
<tr><td>W_{in} (mm)</td><td colspan="3">16</td><td colspan="3">16</td><td colspan="3">16</td><td colspan="3">10</td></tr>
<tr><td>d_{in} (mm)</td><td colspan="3">1</td><td colspan="3">1</td><td colspan="3">1</td><td colspan="3">1</td></tr>
<tr><td>g_{in} (mm)</td><td colspan="3">1</td><td colspan="3">1</td><td colspan="3">1</td><td colspan="3">1</td></tr>
<tr><td>L_f (mm)</td><td colspan="3">7</td><td colspan="3">7</td><td colspan="3">7</td><td colspan="3">5</td></tr>
<tr><td>W_o (mm)</td><td colspan="3">30</td><td colspan="3">30</td><td colspan="3">30</td><td colspan="3">20</td></tr>
<tr><td>d_o (mm)</td><td colspan="3">2</td><td colspan="3">2</td><td colspan="3">2</td><td colspan="3">2</td></tr>
<tr><td>g_o (mm)</td><td colspan="3">0.4</td><td colspan="3">0.4</td><td colspan="3">0.4</td><td colspan="3">0.4</td></tr>
<tr><td>L_1, L_4 (nH)</td><td colspan="3">40</td><td colspan="3">40</td><td colspan="3">40</td><td colspan="3">20</td></tr>
<tr><td>L_2, L_3 (nH)</td><td colspan="3">70</td><td colspan="3">70</td><td colspan="3">70</td><td colspan="3">38</td></tr>
<tr><td>C_1, C_4 (pF)</td><td colspan="3">0.3</td><td colspan="3">0.3</td><td colspan="3">0.3</td><td colspan="3">33.2</td></tr>
<tr><td>C_2, C_3 (pF)</td><td colspan="3">35</td><td colspan="3">35</td><td colspan="3">35</td><td colspan="3">63</td></tr>
<tr><td>R_1, R_4 (Ω)</td><td colspan="3">0.14</td><td colspan="3">0.14</td><td colspan="3">0.14</td><td colspan="3">0.09</td></tr>
<tr><td>R_2, R_3 (Ω)</td><td colspan="3">0.13</td><td colspan="3">0.13</td><td colspan="3">0.13</td><td colspan="3">0.09</td></tr>
<tr><td>M_{12}, M_{23}, M_{34} (nH)</td><td colspan="2">12.9</td><td colspan="2">1.4</td><td colspan="2">12.9</td><td colspan="2">12.9</td><td colspan="2">0.9</td><td colspan="2">7.25</td></tr>
<tr><td>K_1, K_2, K_3</td><td colspan="2">0.27</td><td colspan="2">0.022</td><td colspan="2">0.27</td><td colspan="2">0.26</td><td colspan="2">0.02</td><td colspan="2">0.2</td></tr>
<tr><td>D (mm)</td><td colspan="6">40</td><td colspan="6">35</td></tr>
<tr><td>η (%) circuit sim.</td><td colspan="6">74</td><td colspan="6">73</td></tr>
<tr><td>η (%) EM sim.</td><td colspan="6">77</td><td colspan="6">72</td></tr>
</table>

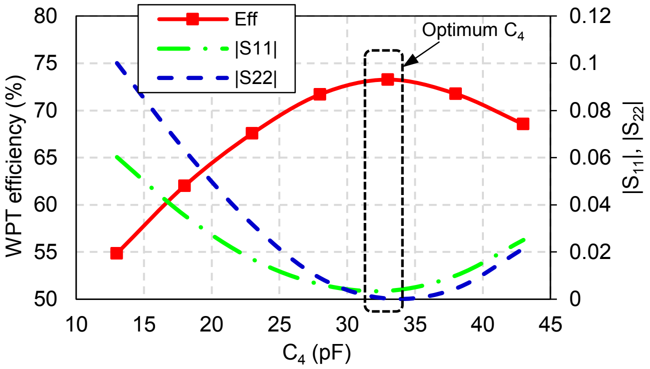
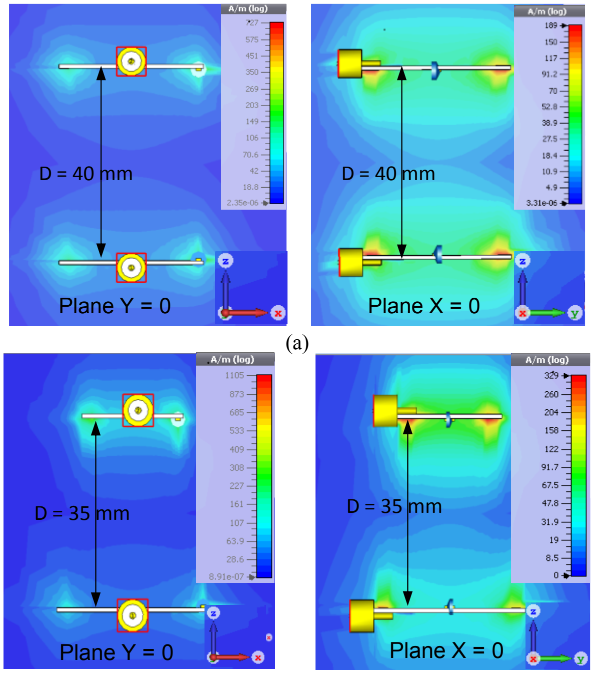


Figure 3. The simulated WPT efficiency and |S-parameters| of the asymmetric WPT system versus different values of the matching capacitor C_4.

III. SIMULATIONS AND MEASUREMENTS

The optimized designs are then simulated on ADS and CST. The designs are implemented on Rogers substrate (RO3003) with permittivity $\varepsilon_r = 3$, thickness $T_{sub} = 0.762$ mm, and metal thickness $t = 18$ µm. Fig. 4(a), (b) present a glance of the full wave EM simulation on CST through display of the simulated magnetic field distributions at planes X = 0, and Y = 0 for the symmetric and asymmetric WPT systems, respectively. Fig. 5, 6 show the 2-port measurement setup of the fabricated WPT systems using symmetric and asymmetric SCPRs using Keysight vector network analyzer PNA N5222A. The EM simulations, circuit simulations, and measurements of the symmetric and the asymmetric designs are compared on Fig. 7(a), (b), respectively. As shown, the proposed WPT systems operate at 100 MHz, and the measured results are in good agreement with both the EM and circuit simulated results. The measured results display that the proposed WPT systems are able to provide wireless power transmission with efficiency 63% at a transmission distance 40 mm using the symmetric resonators, and efficiency 60% at a transmission distance 35 mm using the asymmetric resonators. Fig. 8 presents a comparison of the measured WPT efficiency versus the transmission distance D for both symmetric and asymmetric structures.



(a)

(b)

Figure 4. Absolute magnetic field distribution of the proposed WPT system simulated on CST (a) Symmetric. (b) Asymmetric.

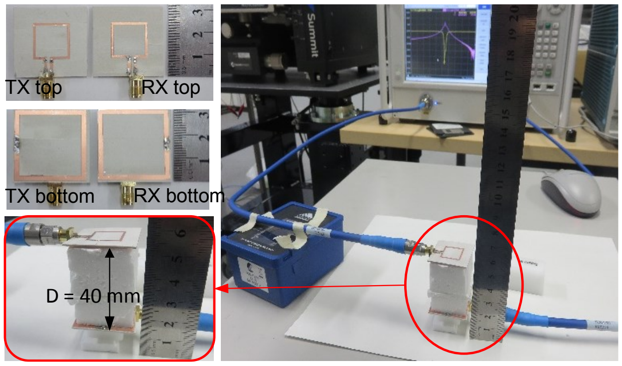


Figure 5. Measurment setup of the fabricated symmetric WPT system.

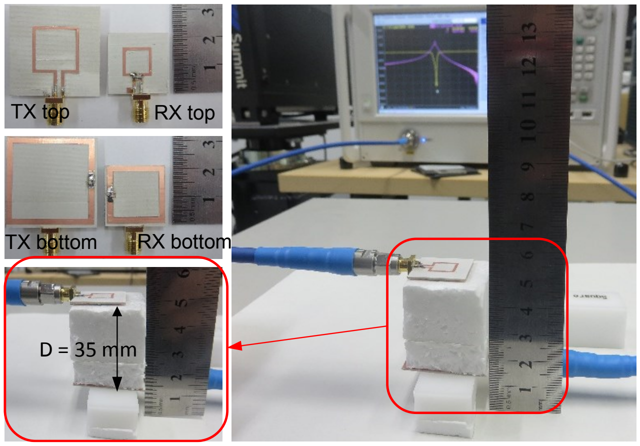
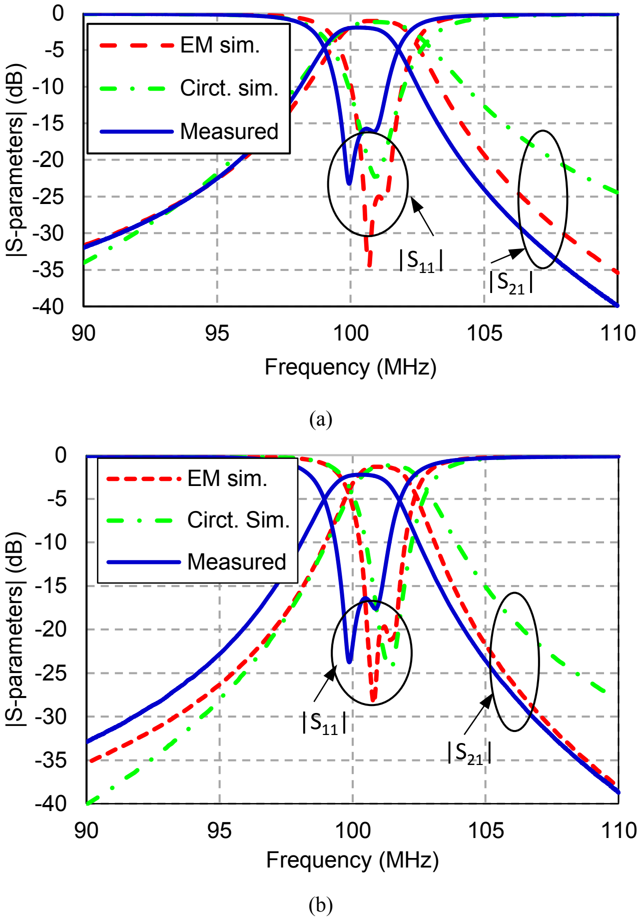


Figure 6. Measurment setup of the fabricated asymmetric WPT system.



(a)

(b)

Figure 7. Comparison of EM simulated, circuit simulated, and measured |S-parameters| of the optimized designs (a) Symmetric. (b) Asymmetric.

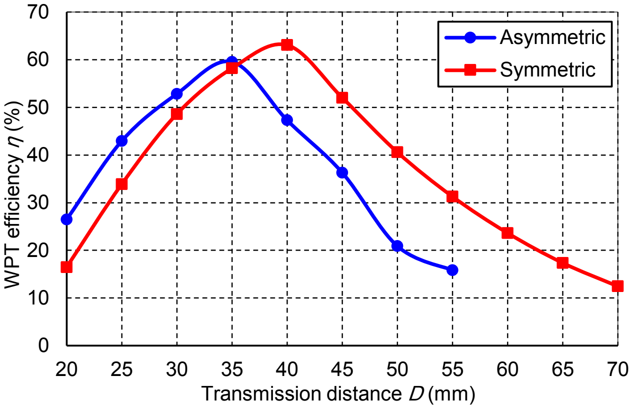


Figure 8. Comparison of the measured WPT efficiency versus the transmission distance for the fabricated symmetric and asymmetric designs.

Table II shows a comparison of the proposed WPT systems, using both approaches (Symmetric, and Asymmetric), with other compact SCPR WPT systems in terms of the Figure of Merit (*FoM*) formula in (7) [15]. ***D*** is the maximum transmission distance at tight coupling, η is the maximum WPT efficiency, and *Size_avg* is the geometrical mean of TX and RX size.

$$FOM = \frac{\eta \times D}{\sqrt{Size\_avg}} \tag{7}$$

$$Size\_avg = \sqrt{Size\_TX \times Size\_RX}$$

TABLE II. COMPARISON OF THE PROPOSED WPT SYSTEMS WITH OTHER COMPACT SCPR WPT SYSTEMS

	RX Size **(mm^2)**	***TX Size*** **(mm^2)**	***F*** **(MHz)**	**D (mm)**	**D/W$_r$***	**η (%)**	***FOM***
This work (Symmetric SCPR)	30x30		100	40	1.3	63	0.84
This work (Asymmetric SCPR)	20x20	30x30	100	35	1.75	60	0.857
[7]	120x120		50	100	0.83	43.6	0.36
[8]	100x100		13.5	100	1	80	0.8

* W$_r$ is the maximum dimension of the receiving resonator (RX)

CONCLUSION

In this paper, we have presented a compact size asymmetric WPT system. The asymmetry guarantees a small size receiver that is suitable for integration to wirelessly rechargeable medical implants or mobile devices which require small size. The proposed system uses intermediate high Q-factor printed resonators to enable for high WPT efficiency and large transmission distance. The proposed system is implemented on Rogers substrate (RO3003) and verified by the measurements. The fabricated prototype has a compact receiver size of 20x20 mm^2, a WPT efficiency of 60% and a transmission distance of 35 mm, which results in the *FoM* to be 0.857. This is the highest figure of merit among the WPT systems so far proposed using printed inductors.

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