Miniaturized SRRs-Loaded Loop Structure for Enhanced Wireless Power Transmission

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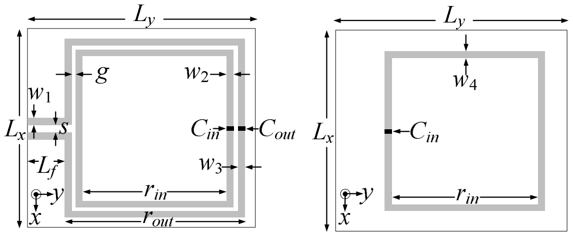
***Abstract* - A miniaturized design of metamaterial-inspired split-ring-resonators- (SRRs-) loaded loop structure is proposed for enhanced wireless power transmission (WPT) applications. The magneto-inductive coupling between transmitting and receiving loops is enhanced by respectively embedding a pair of SRRs inside the loops. The sizes of both the loop and SRRs are reduced by capacitive loading. The fabricated 13.56-MHz prototype design is very compact and measures only 49 mm × 49 mm. Though small in size, the impedance matching is also achieved by the capacitive loading. The proposed structure exhibits a satisfactory level of power transmission efficiency (PTE) of about 58%, comparable to the 64.2% PTE obtained in [1] with diameter of 80 mm.**

***Index Terms* — magneto-inductive coupling, metamaterials, wireless power transmission.**

I. INTRODUCTION

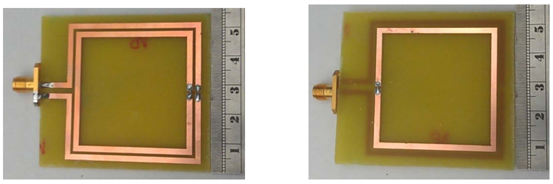
Power transmission efficiency (PTE) of wireless power transmission (WPT) systems has become an important issue due to the increasing emphases on energy saving and sustainability. Regarding health and safety, most WPT systems are operated at relatively lower frequency bands, at which the quasi-static approximation is applicable. When the magneto-inductive coupling mechanism is utilized, the near-field effect of small conducting loops results in a rapid fall-off of the PTE in free space as d^{-6}, where d is the distance between the transmitting (Tx) and receiving (Rx) loops. Therefore, how to improve PTE in WPT systems becomes a research hot spot [1]. In [1], an additional resonator with a higher resonant frequency is used to enhance the PTE by increasing the effective permeability of the power transmitter based on the strong paramagnetic response. However, the maximal dimensions of the additional resonators at both Tx and Rx loops are 187 mm and 80 mm, respectively. For applications in handheld devices, a smaller size of the entire receiving structure is preferred. In this work, a compact, metamaterial-inspired broadside-coupled split-ring resonators (BC-SRRs) are embedded within a small loop (49 mm × 49 mm) fed by a coplanar strip (CPS) to increase the effective permeability of the near zone of the loop to concentrate the magnetic flux. The size reduction and impedance matching are simultaneously achieved by loading the loop and the BC-SRRs with chip capacitors.

II. DESIGN, PROTOTYPE, AND RESULTS



(a) (b)

Fig. 1. Geometry of the proposed structure. (a) Top and (b) bottom views. (L_x = 54 mm, L_y = 61.5 mm, L_f = 10 mm, $w_1 = w_2 = w_3 = w_4$ = 2 mm, g = 1 mm, r_{out} = 49 mm, r_{in} = 39 mm, s = 2 mm, C_{out} = 180 pF, and C_{in} = 680 pF.)



(a) (b)

Fig. 2. Photographs of the proposed structure. (a) Top and (b) bottom views.

The geometry of the proposed loop structure is shown in Fig. 1. A 13.56-MHz prototype is designed and fabricated on a 1.6-mm FR4 dielectric slab (ε_r = 4.4 and tanδ = 0.02). The top and bottom metallic layers are made of 1-oz copper (about 35 μm thick). The outer square loop fed by a CPS is on the top layer of FR4, while the two inner BC-SRRs are placed respectively on the top and bottom layers. Each SRR can be regarded as a self inductance L as the split gap is small enough to be ignored. Besides, for size reduction, a 680-pF chip capacitor is placed across the split gap of each SRR, denoted as C_{in}. All the chip capacitors used in this work are the 0402 series from Murata. Neglecting the mutual coupling within the structure, the self inductance L and the loaded capacitor C_{in} form an L-C tank, whose resonant frequency can be predicted by

$$f = \frac{1}{2\pi\sqrt{LC_{in}}} \qquad (1)$$

For a given size of SRR, the self inductance L can be calculated by the formula proposed in [2]. Then, for a given resonant frequency, say 13.56 MHz, an initial guess of C_{in} can be determined by (1) and fine tuned for the desired resonant frequency by taking into account in full-wave simulations the mutual coupling between the two inner SRRs. Finally, for the square loop structure to be matched to the 50-Ω system impedance, a chip capacitor C_{out} is loaded in the middle of the arm opposite to the feeding point of the loop.

Fig. 2 shows the photos of the fabricated prototype. Fig. 3 shows the $|S_{11}|$ and $|S_{21}|$ responses when two identical pieces of the prototype loops are used at the Tx and Rx sites, respectively. The spacing between Tx and Rx loops is denoted as *d*. A very slight frequency shift between the simulated and measured results is observed, and it may be attributed to the fabrication error and parasitic effects within the chip capacitors. For d = 4 cm, the strong coupling between Tx and Rx loops leads to the split of the resonance, and hence a wider bandwidth. For d = 5 cm, the measured $|S_{11}|$ and $|S_{21}|$ of −12.93 dB and −2.65 dB are achieved, respectively. It must be mentioned that the input impedance of the proposed loop varies with *d* due to the near-field coupling effect. For d = 6 cm, the measured $|S_{11}|$ and $|S_{21}|$ degrade to −7.54 dB and –4.74 dB, respectively.

The PTE of the above WPT setup is mainly affected by three factors: dielectric loss, conductor loss, and the divergence of magnetic flux in the near zone. At 13.56 MHz, the conductor loss has a noticeable impact on the PTE as the skin depth of cooper is about 18 µm, comparable to the thickness of 1-oz copper cladding. It is also found that, as the copper is replaced by perfect conductor in the simulation, $|S_{21}|$ at 13.56 MHz increases to −1 dB for d = 5 cm. For a fair comparison, the PTE in this work is defined as

$$\eta = \frac{|S_{21}|^2}{1-|S_{11}|^2} \qquad (2)$$

where the input mismatch loss is excluded. Fig. 4 shows the simulated and measured PTE of the aforementioned WPT setup (d = 5 cm) using the proposed SRRs-embedded loop structure and that without. One can see that the proposed structure embedded with the inner SRRs does exhibit a higher efficiency over a considerable frequency range. In particular, the PTE is improved up to about 58% around 13.56 MHz. Besides, the simulated and measured results agree well.

The inner SRRs and the loaded capacitors C_{in} together function as a cavity, and it can store energy in a small volume so that the magnetic flux is confined within and concentrated. As a result, the PTE of the proposed loop structure is thus enhanced. From the perspective of metamaterials, the inner SRRs can be designed to manipulate the effective permeability $\mu_{r,eff}$ near the structure. $\mu_{r,eff}$ of the SRRs is extracted for d = 5 cm, and the extracted values are plotted in Fig. 5. The real part of $\mu_{r,eff}$ extracted is larger than unity within the frequency range of interest. Consequently, the magnetic flux is confined within or near the region with higher $\mu_{r,eff}$. This agrees well with the results shown in Fig. 4.

REFERENCES

[1] D. Ahn, M. Kiani, and M. Ghovanloo, “Enhanced wireless power transmission using strong paramagnetic response,” *IEEE Trans. Magn.*, vol. 50, no. 3, Mar. 2014.

[2] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media*, 2nd ed. Pergamon: Oxford, 1984, p. 124.

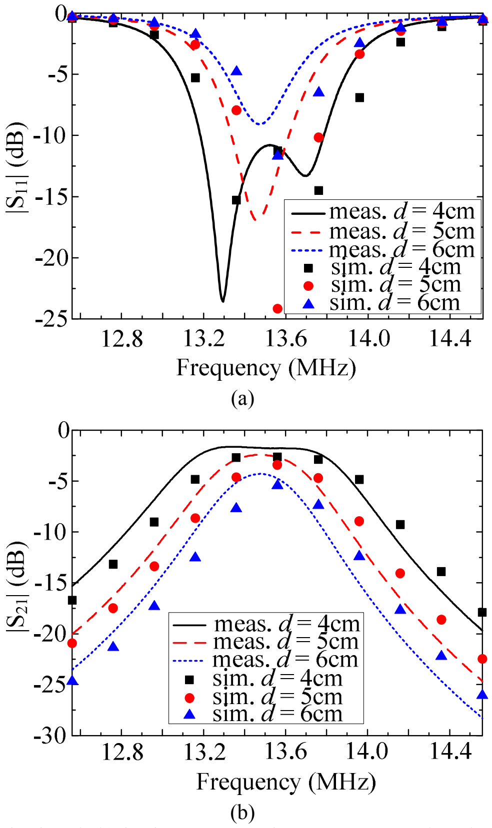


Fig. 3. (a) $|S_{11}|$ and (b) $|S_{21}|$ responses of a WPT setup using the proposed miniaturized SRRs-loaded loop structure.

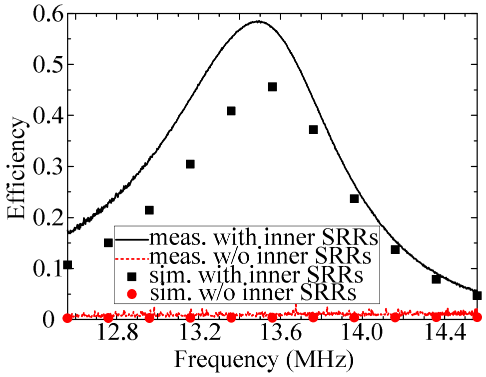


Fig. 4. Power transmission efficiency of the WPT setup using our proposed miniaturized loop structure for d = 5 cm.

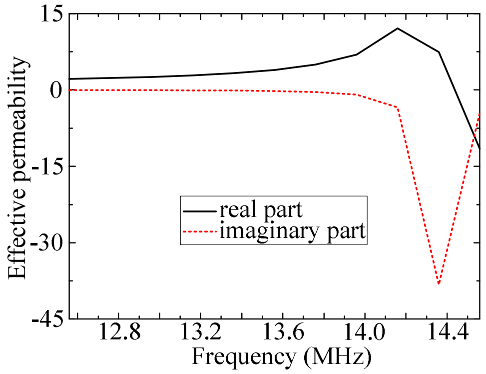


Fig. 5. Extracted effective permeability of inner SRRs used in the prototype.