Strong resonant coupling for short-range wireless power transfer using defected ground structures

Sherif Hekal[1], Adel B. Abdel-Rahman[1], Ahmed Allam[1], Ramesh K. Pokharel[2], H. Kanaya[2], and H. Jia[2]
[1] ECE department, Egypt-Japan University of Science and Technology, Alex, Egypt, sherif.hekal@ejust.edu.eg
[2] Faculty of Information Science and Electrical Engineering, Kyushu University, Fukuoka, Japan

***Abstract*—In this paper, we present a new idea for highly efficient short-range wireless power transfer based on defected ground structures via strongly coupled magnetic resonance. An equivalent circuit model for using H-slot defected ground structures as coupled resonators is introduced. Measurement results for the new proposed structure show a power transfer efficiency of 82% at 9 mm distance between driver and load resonators. Experimental measurements have shown good agreement with theoretical and simulation results.**

Keywords-wirless power transfer; defected gorund structures; EM resonant coupling; strong resonant coupling

I. Introduction

The technology of wireless power transfer (WPT) has attracted a great interest for its wide potential applications such as RFIDs, biomedical implants, wireless buried sensors, and portable electronic devices. The implementation methods of WPT can be classified into two main techniques: near-field and far-field. The short-range and mid-range WPT can be achieved based on near field coupling, which can be divided into three types: inductive coupling, EM resonant coupling, and strong resonant coupling. Inductive coupling is the most popular technique for high power transfer, and is usually applied at the lower frequency region [1]. At higher frequencies, the resonant type becomes a good choice. Resonant circuits focus the power at a certain frequency, so that power transfer efficiency can be improved [2]. Strong coupling uses intermediate resonators with high Q-factors to increase the total efficiency of the proposed WPT system [3]. Far field technology is usually applied for long distance transfer based on radiated waves like radio waves, Microwave links, or laser beams.

Most of the near field WPT methods depend upon lumped elements such as inductors and capacitors. For low frequency applications, these elements are bulky and lossy. Quasi-lumped elements, based on defected ground structures (DGS), can act as resonant circuits [4]. These structures have been proposed for RF/Microwave applications to implement band-pass and band-stop filters with low profiles. These compact structures have small dimensions and low cost; which make them suitable for high frequency and small size applications such as portable electronic devices and biomedical implants. As shown in Fig. 1, we have verified that DGSs, acting as resonators, can be coupled at definite distances to transfer power. the new proposed WPT system using H-slot coupled resonators can transfer power with efficiency of 85% at distance 3.5 mm and resonant frequency 1.43 GHz. Design at GHz range is introduced to obtain miniaturized structures that can be embedded in portable and biomedical devices.

In this paper, we present a modification that can be applied to the short-range wireless power transfer system, shown in Fig. 1. An enhancement in the power transfer efficiency is implemented by using strong resonant coupling through high Q-factor intermediate resonator. Electromagnetic and circuit simulators are used to design and simulate the proposed structures transmission, reflection, and coupling performance. Measurement results have confirmed the validity of the results achieved in simulations.

II. Two Coupled H-slot Resonators

In this section, we discuss the new idea of using DGSs in WPT applications. Fig. 1(a) and (b) show the implementation of short-range WPT system using two H-slot coupled resonators set back-to-back, and their equivalent circuit models respectively. The simulated and measured power transfer efficiencies are shown in Fig. 1 (c).

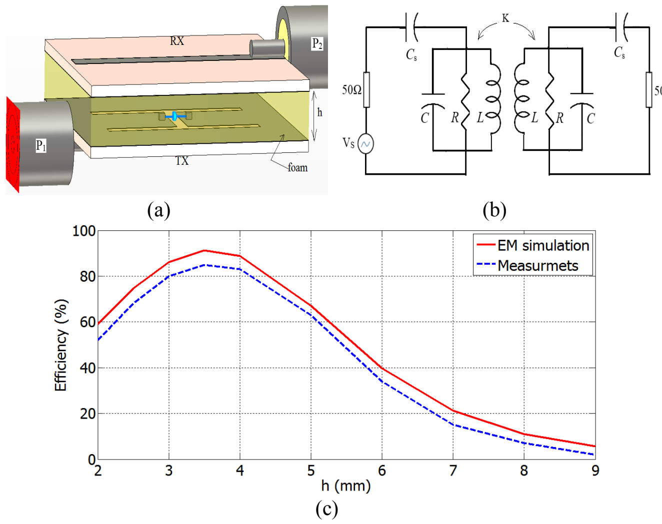

Figure 1. New proposed WPT system using two H-slot coupled resonators (a) EM simulator implementation. (b) Equivalent circuit (c) Simulated and measured power transfer efficiency.

III. Strong Resonant Coupling

The power transfer efficiency for two and three coupled resonators can be given as in (1), (2) respectively, where Q_d, Q_l, and Q_t are the Q-factors for driver, load, and transmitter (intermediate) resonators [5].

$$\eta = \frac{k^2 Q_d Q_l}{\left(1 + k^2 Q_d Q_l\right)} \quad (1)$$

$$\eta \approx \frac{k_1^2 Q_d Q_t}{\left(1 + k_1^2 Q_d Q_t\right)} \frac{k_2^2 Q_t Q_l}{\left(1 + k_2^2 Q_t Q_l\right)} = \eta_{dt} \eta_{tl} . \quad (2)$$

Fig. 2(a) shows the proposed structure for short-range WPT system strongly coupled using single intermediate resonator. The distance between driver and transmitter is h_1, and the distance between transmitter and load is h_2. The driver and load resonators are H-slot DGS resonators where the top layer is a feed line of width = 1.9 mm and length = 10 mm ended by stub of length S = 9.5 mm. The stub acts as series capacitance C_S for impedance matching. The bottom layer of the three resonators is a ground plane defected by an H-slot as shown in Fig. 2(b), using the dimensions shown in Table I. A capacitor of 1.4 pF is added with the slot to increase the equivalent capacitance introducing resonators with high Q-factor and compact size.

TABLE I. DESIGN PARAMETERS OF STRONGLY COUPLED WPT

Resonator type	Resonator parameters			
	L=W (mm)	*Lslot (mm)*	*Wslot (mm)*	*LH (mm)*
Driver/Load	20	6	1	14
Transmitter	20	10	1.9	14

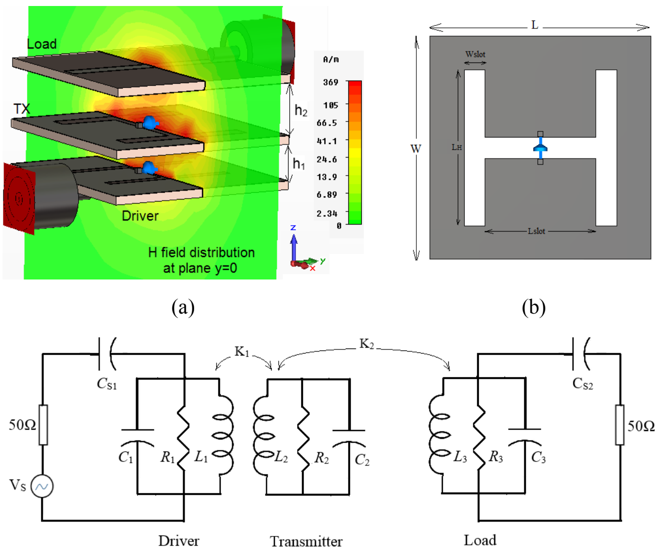

Figure 2. Strong resonant coupling (a) Schematics of driver, TX, and load resonators. (b) Bottom layer of H-slot resonator. (c) Equivalent circuit.

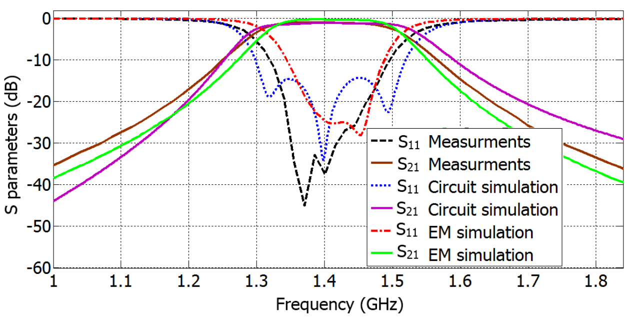

Figure 3. S-parameters of the proposed structure using strong resonant coupling

The proposed structure, shown in Fig. 2 (a), is simulated by EM simulator (CST microwave studio) using the design parameters in Table I. Foam layers of permittivity ε_r = 1.2 and thickness h_1 and h_2 are used to separate between resonators. The coupling performance is examined by changing the separation distances h_1 and h_2. EM simulation results have shown that at distances h_1 = 3 mm and h_2 = 5 mm, power transfer can be achieved with an efficiency of 85% at resonant frequency 1.4 GHz. The equivalent circuit parameters (R, L, and C) for each resonator are extracted from their EM simulation results as in [4] and the series capacitance by $C_S = \tan(\beta S)/\omega_0 Z_0$. By substitution, we get $C_{S1} = C_{S2}$ = 1.15 pF, $L_1 = L_3$ = 3.2 nH, L_2 = 4.75 nH, $C_1 = C_3$ = 3 pF, C_2 = 2.7 pF, $R_1 = R_3$ = 3.2 KΩ, and R_2 = 2.5 KΩ. Fig. 3 shows good agreement between the measured and simulated S-parameters for the new proposed WPT system using strong resonant coupling.

IV. EXPERIMENTAL SETUP AND RESULTS

The measurement setup for the fabricated WPT system using a network analyzer (Agilent N5227A) is shown in Fig 4(a). It can be inferred from Fig. 4(b) that an efficiency of 82% can be achieved at distance 9 mm with strong resonant coupling compared to an efficiency of 5% with traditional systems.

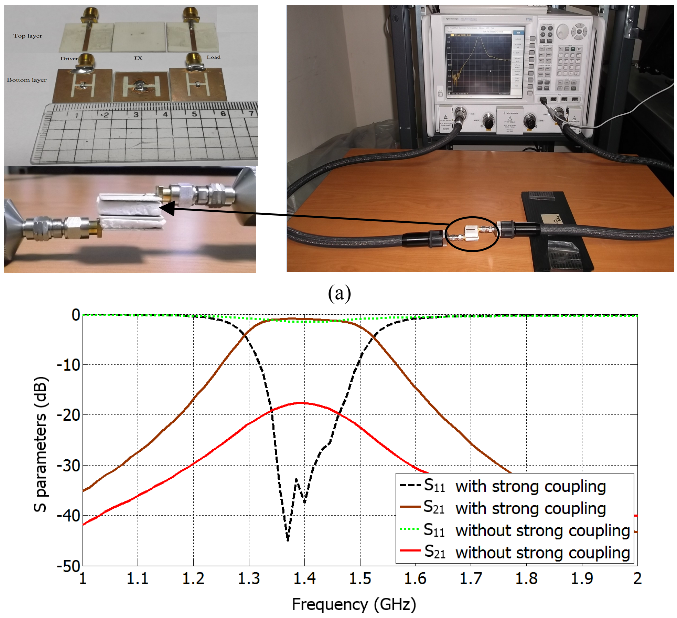

Figure 4. Measured S-parameters for the proposed WPT system with/without strong resonant coupling

REFERENCES

[1] C.-J. Chen, T.-H. Chu, C.-L. Lin, and Z.-C. Jou, "A Study of Loosely Coupled Coils for Wireless Power Transfer," IEEE Trans. Circuits Syst. II Express Briefs, vol. 57, no. 7, pp. 536–540, Jul. 2010.

[2] B. L. Cannon, J. F. Hoburg, D. D. Stancil, and S. C. Goldstein, "Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers," IEEE Trans. On Power Electron., vol. 24, no. 7, pp. 1819–1825, Jul. 2009.

[3] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless energy transfer via strongly coupled magnetic resonances," Science, vol. 317, pp. 83–85, 2007.

[4] D.-J. Woo, T.-K. Lee, J.-W. Lee, C.-S. Pyo, and W. Choi, "Novel U-slot and V-slot DGSs for bandstop filter with improved Q factor," IEEE Trans. Microw. Theory Tech., vol. 54, no. 6, pp. 2840–2847, Jun. 2006.

[5] A. K. RamRakhyani and G. Lazzi, "On the design of efficient multicoil telemetry system for biomedical implants," IEEE Trans. Biomed. Circuits Syst., vol. 7, no. 1, pp. 11–23, Feb. 2013.