Strong Resonant Coupling for Short-range Wireless Power Transfer Applications Using Defected Ground Structures

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Abstract — This paper presents a new structure for highly efficient short-range wireless power transfer. The proposed structure is based on strongly coupled resonators using H-slot defected ground structures. An equivalent circuit model for H-slot coupled resonators is introduced. Measurement results for the new proposed structure show a power transfer efficiency of 70% at 15 mm distance between driver and load resonators. Experimental measurements have shown good agreement with electromagnetic and circuit simulations.

Index Terms — Wireless power transfer, defected ground structures, electromagnetic coupling, strong resonant coupling.

I. INTRODUCTION

The growing demand of wireless power transfer (WPT) technology, especially non-radiative techniques, is interesting for its wide potential applications like RFIDs, implanted medical devices, electric vehicles, and portable electronic devices [1]-[3]. Non-radiative or near field techniques are based on inductive or capacitive coupling for short-range applications, and resonant inductive coupling for mid-range applications. Inductive coupling is the most popular technique for high power transfer, and is usually applied at the lower frequency region [4]. 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 [5]. On the other hand, strong resonant coupling uses intermediate resonators with high Q-factors to increase the total efficiency of transferred power [6].

Most of the near field WPT methods have depended upon lumped elements such as inductors and capacitors. For low frequency applications, these elements are bulky and lossy. Other designs have used printed spirals with surface mounted capacitors to get more compact WPT systems that are suitable for board-to-board applications and biomedical implants, as reported in [7], [8], but somehow experience low efficiency.

Quasi-lumped elements, based on defected ground structures (DGS), have been proposed for RF/Microwave applications to implement band-pass and band-stop filters with low profiles [9]-[12]. 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. We propose here to use these structures as building blocks for short-range WPT through electromagnetic resonant coupling. In [11], a comparative study has been performed between different shapes of DGSs, used to get the same band rejection response. This study has proved that H-slot DGS, among other shapes, has the smallest size and the highest Q-factor.

In this paper, circuit models of single and coupled H-slot DGS resonators are introduced. Full wave commercial electromagnetic simulator (CST microwave studio) and circuit simulator (ADS) are used to design and simulate the proposed structures transmission, reflection, and coupling performance. An enhancement in the power transfer efficiency is applied by using strong resonant coupling through high Q-factor intermediate resonators. Measurement results have confirmed the validity of the results achieved in simulations.

II. MODELING & DESIGN

Fig. 1 shows the schematic of proposed H-slot DGS with its circuit model. As illustrated in the PCB layout in Fig. 1(c), the top layer is a 50Ω microstrip line with length L_f and width W_f. a stub of length S is added for impedance matching and resonant frequency adjustements, and can easily be represented by a series capacitance C_S. The bottom layer is a ground plane defected by an H-slot. From microwave theories if we introduce a defect with any shape underneath a uniform microstrip transmission line, the fields of the dominant mode will be distorted and higher order modes must be excited. This phenomenon prevents power transmission to the other terminal and can be described using an LC circuit as shown in Fig. 1(b). The suspended power through defected slot can be transferred to another resonator through coupling.

The equivalent circuit parameters are extracted from the simulated scattering parameters as

$$L = 2Z_0\left(\frac{\omega_0^2 - \omega_l^2}{\omega_l \omega_0^2}\right) \tag{1}$$

$$C = \frac{1}{\omega_0^2 L} \tag{2}$$

$$C_s = \frac{\tan(\beta S)}{\omega_0 Z_0} \tag{3}$$

Where ω_0 is the resonant angular frequency, ω_l is the 3-dB lower cutoff frequency, β is the wave number, S is the stub length and Z_0 is the characteristic impedance of the microstrip line. The quality factor Q can be defined by

$$Q = \frac{\omega_0}{\Delta\omega} \tag{4}$$

Where $\Delta\omega$ is the 3-dB angular frequency bandwidth.

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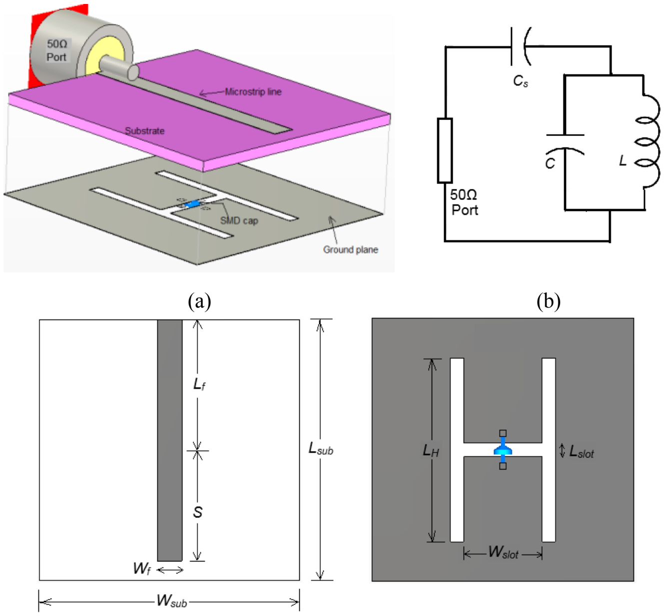


(a) (b)

(c)

Fig. 1. Schematic of H-slot resonator (a) 3-D view. (b) Circuit model. (c) PCB layout.

The new proposed structure for short-range WPT is composed of two H-slot coupled resonators set back-to-back as shown in Fig. 2(a). This structure is simulated using CST using the dimensions in Table I. Rogers RO4003C substrate with dielectric permittivity ε_r = 3.38 and thickness of 0.813 mm is used. A surface mounted (SMD) capacitor of 1.5 pF is added to the slot to increase the effective capacitance of resonator while miniaturizing the structure [13], [14]. The coupling performance is investigated by changing the distance h between the two resonators. As shown in Fig. 2(c), for distances less than h = 3.5 mm, strong coupling causes frequency splitting and two frequency peaks appear around the central frequency f_s [15]. These two peaks are called electric and magnetic walls f_e and f_m. At distances greater than h = 3.5 mm, the transferred power is weak due to the weakness of coupling. The mutual coupling coefficient can be defined as

$$K = \frac{L_m}{L} = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} \qquad (5)$$

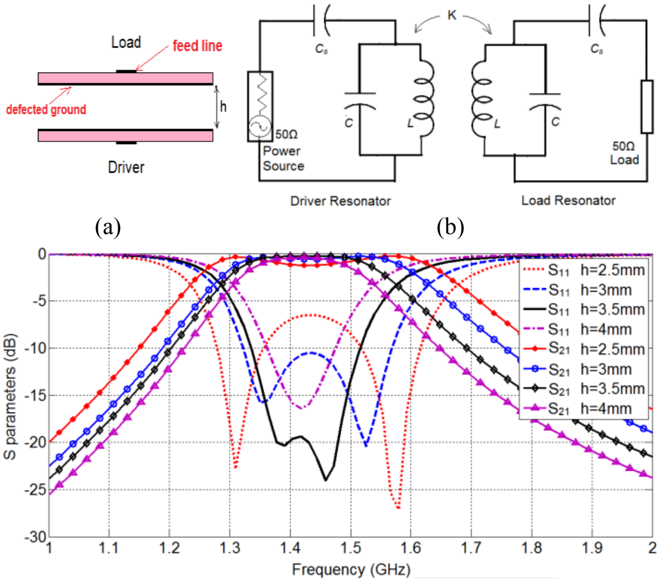
Where K is the coupling coefficient and L_m is the mutual inductance.

Substituting the simulated S-parameters in (1)-(3) and (5), we get L = 3 nH, C = 3.2 pF, C_s = 1.15 pF, and K = 0.12. Fig. 3 shows good agreement between EM simulations, circuit simulations, and measurements. Experimental measurements of the fabricated WPT structure indicated an insertion loss S_{21} = -0.68 dB and reflection S_{11} = -23 dB at a central frequency of 1.43 GHz and bandwidth of 200 MHz. As shown in Fig. 4, the maximum power transfer is achieved at a distance h = 3.5 mm with 92% and 85% simulated and measured efficiencies respectively. Fig. 5 shows the magnetic field distribution that is responsible for magnetic coupling between driver and load resonators.

TABLE I

DESIGN PARAMETERS OF H-SLOT RESONATOR

Dimension	L_{sub}	W_{sub}	L_f	W_f	S	L_{slot}	L_H	W_{slot}
Value (mm)	20	20	10	1.9	9.5	1	14	6



(a) (b)

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Fig. 2. New proposed WPT structure (a) schematic of coupled H-slot resonators. (b) Circuit model. (c) Coupling performance at different distances h.

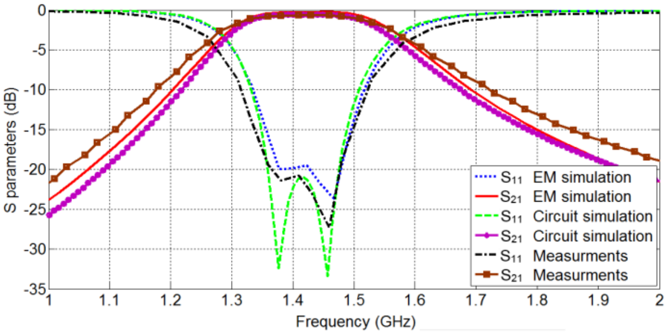


Fig. 3. Simulations vs. measurement results for WPT S-parameters at distance h = 3.5 mm.

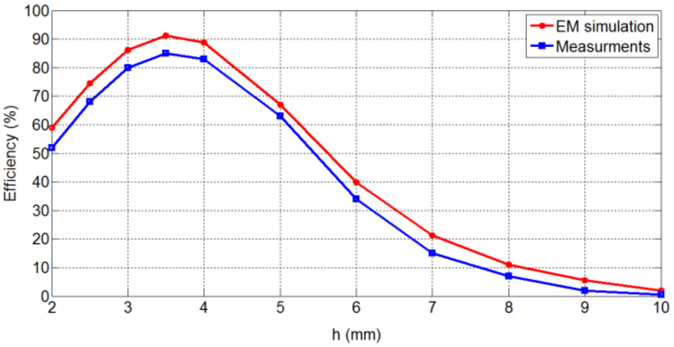
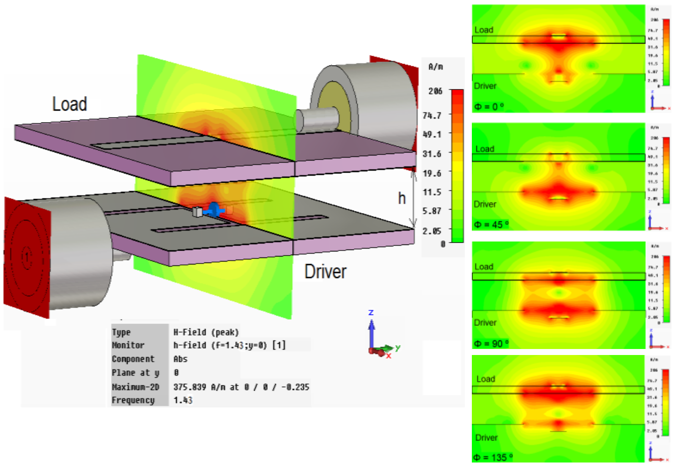


Fig. 4. Simulations vs. measurement results for WPT efficiency at different separation distances h.



(a) (b)

Fig. 5. Magnetic field distribution at plane y = 0 (a) Peak amplitude. (b) Distribution at different phases.

III. STRONG RESONANT COUPLING

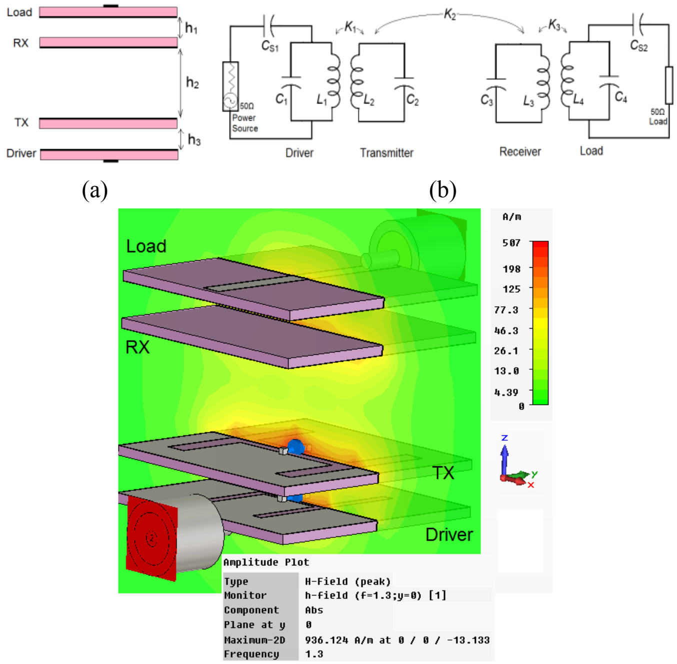
The power transfer efficiency for two and four coupled resonators can be given as in (6), (7) respectively, where Q_d, Q_t, Q_r, and Q_l are the Q-factors for driver, transmitter, receiver, and load resonators [16].

$$\eta = \frac{k^2 Q_d Q_l}{\left(1+k^2 Q_d Q_l\right)} \tag{6}$$

$$\eta = \frac{k_1^2 Q_d Q_t}{\left(1+k_1^2 Q_d Q_t\right)} \frac{k_2^2 Q_t Q_r}{\left(1+k_2^2 Q_t Q_r\right)} \frac{k_3^2 Q_r Q_l}{\left(1+k_3^2 Q_r Q_l\right)} \tag{7}$$

Fig. 6(a) shows the proposed structure for strongly coupled WPT system using intermediate resonators. The driver and load resonators are H-slot DGS resonators similar to the resonators used in Section II. Transmitter and receiver resonators have only one metal layer, which is the bottom layer. The bottom layer of these resonators is a ground plane defected by an H-slot with L_{slot} = 11 mm, L_H = 14 mm, W_{slot} = 2 mm. An SMD capacitor of 1.5 pF is added with the slot to increase the equivalent capacitance introducing resonators with high Q-factor and compact size.

The new proposed structure is implemented and simulated using CST as shown in Fig. 6(c). The coupling performance is investigated by changing the separation distances h_1, h_2, and h_3. It was found that maximum power transfer is achieved at distances $h_1 = h_3 = 3$ mm and $h_2 = 9$ mm with an insertion loss $S_{21} = -0.7$ dB and reflection $S_{11} = -17$ dB at central frequency of 1.3 GHz. The equivalent circuit parameters, shown in Fig. 6(b), are extracted from the simulated S-parameters. We get $L_1 = L_4 = 3.1$ nH, $L_2 = L_3 = 4.3$ nH, $C_1 = C_4 = 3.4$ pF, $C_2 = C_3 = 3.45$ pF, $C_{s1} = C_{s2} = 1.15$ pF, and $K_1 = K_3 = 0.075$, and $K_2 = 0.03$. Fig. 7(a) shows the measurement setup of the fabricated WPT system using a network analyzer (Agilent N5227A) after making full two-port calibration. Fig. 7(b) shows good agreement between simulated and measured S-parameters for the proposed strongly coupled WPT system.



(a) (b)

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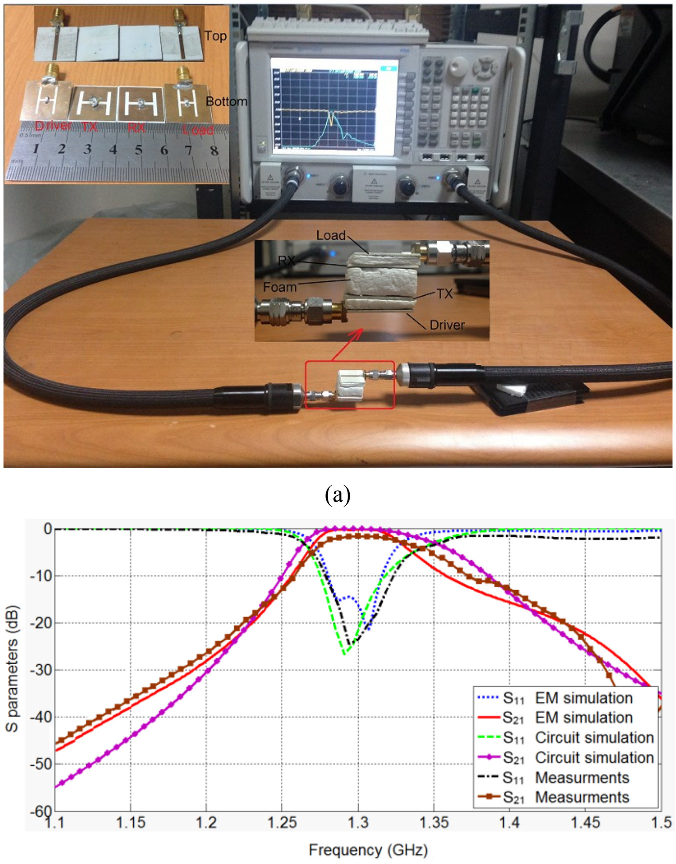
Fig. 6. New proposed strongly coupled WPT system (a) Schematic. (b) Circuit model. (c) EM simulation with magnetic field distribution at $h_1 = h_3 = 3$ mm and $h_2 = 9$ mm.



(a)

(b)

Fig. 7. (a) Measurement setup of fabricated strongly coupled WPT system. (b) Simulation vs. measurement results.

From Fig.7 (b), we can conclude that a maximum measured efficiency of 70% can be achieved at distances $h_1 = h_3 = 3$ mm and $h_2 = 9$ mm. Table II shows a comparison between this work and other designs to get compact structures. According to the calculated figure of merit in (8), the comparison study shows how the proposed compact design can perform with good efficiency.

$$FOM = \frac{Efficiency \times Distance}{\sqrt{Size}} \cdot \qquad (8)$$

TABLE II

COMPARATIVE STUDY WITH OTHER WPT SYSTEMS

WPT system	*Frequency* (*MHz*)	*Size* (*mm²*)	*Efficiency* (*%*)	*Distance* (*mm*)	*FOM*
This work	1430	20 x 20	85	3.5	0.148
[7]	110	15 x 10	30	3	0.073
[17]	5	70 x 70	85	10	0.121
[18]	3.4	120 X 120	85	20	0.142

IV. CONCLUSION & FUTURE WORK

This paper presents a novel technique for short-range WPT applications. This technique depends upon quasi lumped element resonators using H-slot DGSs. Design and circuit model analysis for single H-slot resonator are introduced. The coupling performance has been investigated for 2 and 4 H-slot coupled resonators. Maximum measured efficiency of 85% at distance 3.5 mm has been achieved using traditional resonant coupling, while efficiency of 70% at effective distance 9 mm has been achieved using strong resonant coupling. Validation of the design theory has been verified by good agreement between EM simulations, circuit simulations and experimental measurements.

Usage of high operating frequency is to get more compact structures that can be embedded in many applications. In future, it is proposed to use other slot shapes that can achieve strong coupling. SMD capacitors with high capacitance values could be used to design compact structures that resonate at low frequencies.

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