Design of Dual Frequency Coupled Resonators Using DGS and Microstrip Resonators for Dual Band WPT Applications

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Abstract **─** This paper introduces a new design for a highly efficient and more compact size dual frequency wireless power transfer (WPT) system, which can operate at both 0.65 GHz and 1.56 GHz bands. The idea of the structure depends on designing a symmetrical system containing Tx and Rx. Each Tx and Rx has a feed line on the top layer with two stubs; each stub has different dimensions than the other one. The bottom layer contains two C-shaped defected ground structures (DGS). By changing the dimensions of one stub, the frequency resonance corresponds to this stub is changed without any change on the other resonance. The system has a size of 20×20 mm^2. Further, the system achieves efficiencies of 72 % and 89 % at 0.65 GHz and 1.56 GHz, respectively with a transmission distance of 8 mm. The proposed dual frequency WPT is implemented and verified. Good concurrences among electromagnetic (EM) simulations and the measurements have been attained. The system is suitable for recharging short-range applications.

Index Terms **─** Dual Band (DB), stub, Wireless Power Transfer (WPT).

I. INTRODUCTION

Wireless power transfer (WPT) technology comes with the promise of cutting the last cord by allowing recharge electronics devices as easily as data and the power will be transferred through the air without cables. WPT technology has been attracted many researchers in recent and previous periods for its impact in numerous prospective uses for instance sensor networks, controllable automated equipment (tablets, mobile phones, etc.), RFIDs, and so on [1-5]. The size of the system (particularly the receiver), the power transferring distance, and the efficiency are the furthermost key factors to be addressed in designing the building blocks of the WPT systems. Initially, the researchers have employed the coils for designing WPT systems and they have investigated the effects of the coil's parameters on the coupling efficiency and the working frequency. WPT is now applied as a viable method to power many types of devices including portable consumer electronics [6], electric vehicles [7], and biomedical implants [8]. Numerous of the short-range WPT methods are employing lumped components [9]. However, these components have sensible drawbacks in execution such as occupying an excessive space. In addition, they are lossy. Nonetheless, they are preferred in WPT applications at low frequencies.

Newly, defected ground structure (DGS) is the innovative technology that is presently used for designing WPT systems [10-13]. Some designs of the DGS are investigated and implemented for WPT like the C-shaped design [14]. Most of the published ideas investigate the usage of the modified DGS for obtaining single band operations [15].

Lately, they have improved the DGS to realize a dual band near-field WPT system [16-18]. However, the dual-band WPT has many benefits over the single band systems as implemented in [16]. The authors in [10] studied the WPT system by employing the DGS technique. Firstly, they suggested an H-shaped DGS with a size of 25×25 mm^2 and an efficiency of 68% at 0.3 GHz at a transmission distance of 5 mm. Secondly, the structure is enhanced and developed to be semi H-shaped. The system has a size of 20×20 mm^2 with an efficiency of 73%. In [11], a dual frequency system is proposed. Further, it depends on two circular DGS resonators whereas each circular is responsible for frequency resonance. The system has a size of 30×15 mm^2 and the efficiencies are 71% and 71% at 0.3 GHz and 0.7 GHz with a transmission distance of 16 mm. In [17], a dual band system is proposed with a size of 12.5×8.9 cm^2 and efficiencies of 78% and 70.6% at 6.78 MHz and 200 kHz, respectively. In [19], the author

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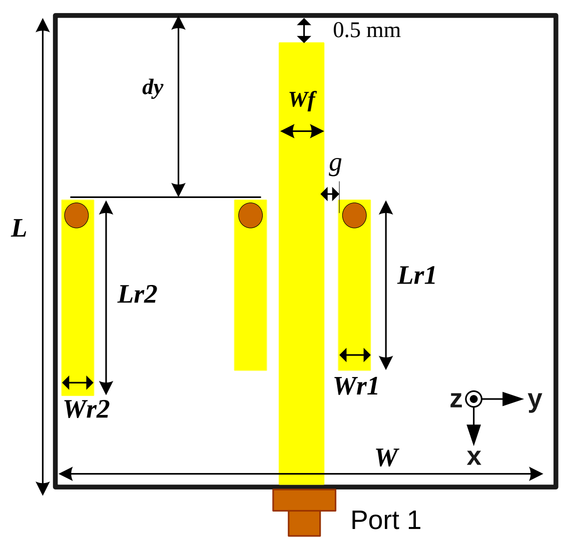
introduced a dual-band rectifying circuit for wireless power transmission working at 2.45 GHz and 5.8 GHz. This system showed peak RF-to-DC efficiencies of 66.8% and 51.5% at 2.45 GHz and 5.8 GHz, respectively.

Recently, the DGS resonators are extensively explored for single and dual band operations of the WPT applications [10-12,15,18-22].

In this paper, a new dual frequency WPT system is proposed. The system introduces a new idea which designs two stubs with different sizes for obtaining dual band frequencies. The size of the system is 20 × 20 mm^2 with efficiencies of 72% and 89% at 0.65 and 1.56 GHz, respectively.

II. COUPLED RESONATOR DESIGN

Listed below the configuration of the suggested dual frequency system. Figure 1 (a) shows the top view which contains a feed line with a width of *W_f* and a length of 19.5 mm. The stubs are designed on the top with different sizes, that responsible for dual band frequency operation. Figure 1 (b) shows the bottom layer which contains a C-shaped DGS with the same shorted points connected with the top view. The design parameters are recorded in Table 1. Figure 2 (a) shows the setting of the suggested geometry of the coupled resonators which are parted by a space of *h* mm. Figure 2 (b) represents the equivalent circuit of the system. The equivalent circuit presents a dual band resonance circuit and each circuit is considered as a separate one. The equivalent circuit contains (L_{p1} and C_{p1}) which are the parallel elements of the tank circuit related to the first resonance frequency and (L_{p3} and C_{p3}) are related to the second resonance frequency.



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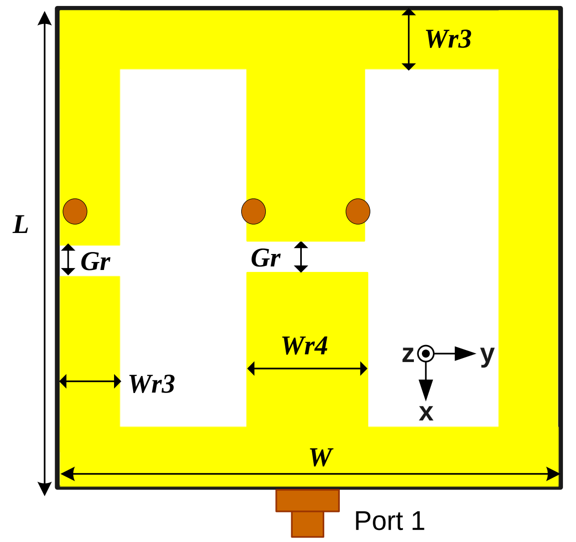
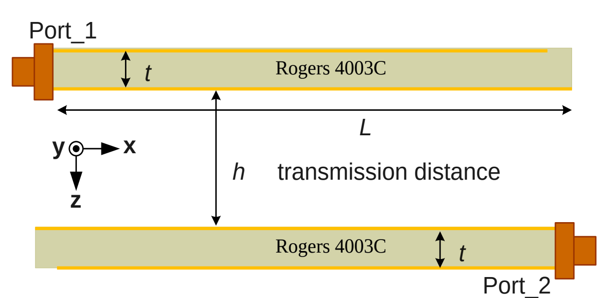


(b)

Fig. 1. Top and bottom layers of the proposed design: (a) top layer and (b) bottom layer.

Table 1: List of parameters

Parameter	Value / Type
Substrate	Rogers 4003C
ε_r	3.55
Thickness of substrate (*t*)	0.83 mm
L	20 mm
Lr1	8 mm
Lr2	11 mm
Wr1	1.5 mm
g	0.5 mm
W_f	2 mm
Wr2	1.75 mm
W	20 mm
Gr	0.5 mm
Wr3	2 mm
Wr4	5.5 mm



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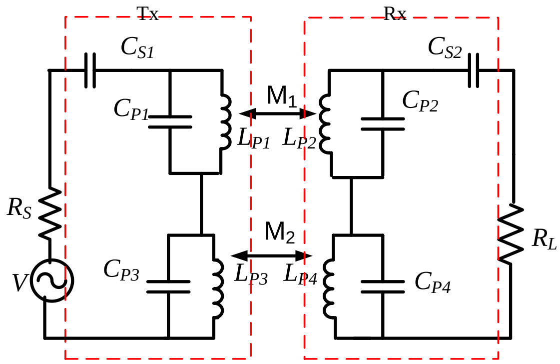

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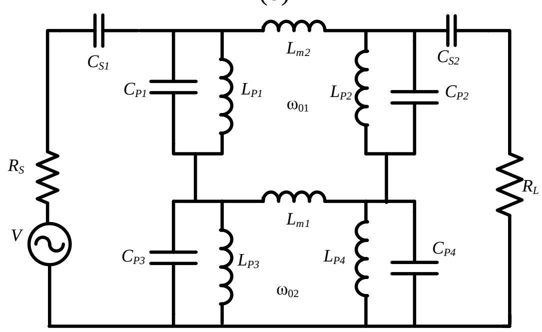


(c)

Fig. 2. Equivalent circuit and 3-D view. (a) 3-D view. (b) The equivalent circuit of the system. (c) The pi-equivalent circuit (π) of the system.

It is desired to compute and extract the values of the equivalent circuit parameters (C_p, L_p, L_{m1}, L_{m2}, and C_s) from the simulation consequences for validations. Where M_1 and M_2 are the mutual couplings between two resonators [22], L_{m1} and L_{m2} are the mutual inductances [22], and C_s is the series capacitance. Equations (1) and (2) are employed to calculate the equivalent circuit parameters [21]:

$$C_P = \frac{5 f_c}{\pi[{f_0}^2 - {f_c}^2]} \quad pF, \tag{1}$$

$$L_P = \frac{250}{C_P[\pi f_0]^2} \quad nH, \tag{2}$$

where f_c is the cutoff frequency and f_o is the center resonance frequency at each band alone.

At the first resonance frequency, the frequencies are f_{c1} = 0.59372 GHz and f_{o1} = 0.64793 GHz. By substitution in equation (1) and (2), the extracted parameters are $C_{p1} = C_{p2}$ = 14 pF and $L_{p1} = L_{p2}$ = 4.29 nH. In the same way at the second resonance frequency, the frequencies are f_{c2} = 1.4516 GHz and f_{o2} = 1.5613 GHz. By substitution in equation (1) and (2), the extracted parameters are $C_{p3} = C_{p4}$ = 6.98 pF and $L_{p3} = L_{p4}$ = 1.48 nH.

Figure 3 compares the simulation results of the equivalent circuit of the proposed design employing the extracted parameters using the advanced design system (ADS) and the electromagnetic (EM) simulation by the computer simulation technology (CST). The used EM simulator is a 3D full wave solver based on a numerical analysis technique using finite difference time domain (FDTD) approach that computes the S-parameters. As a result, acceptable correspondence is observed between the two results.

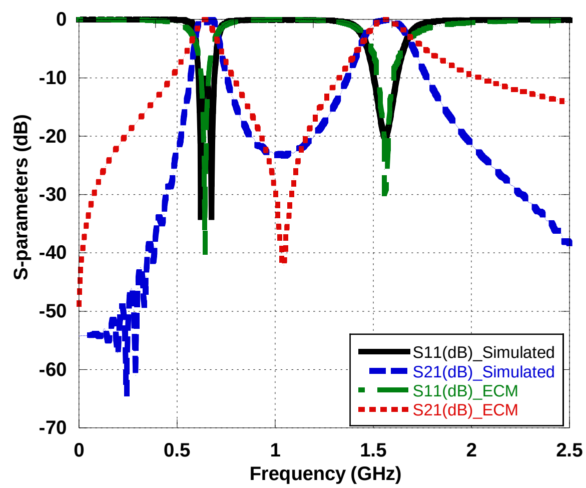
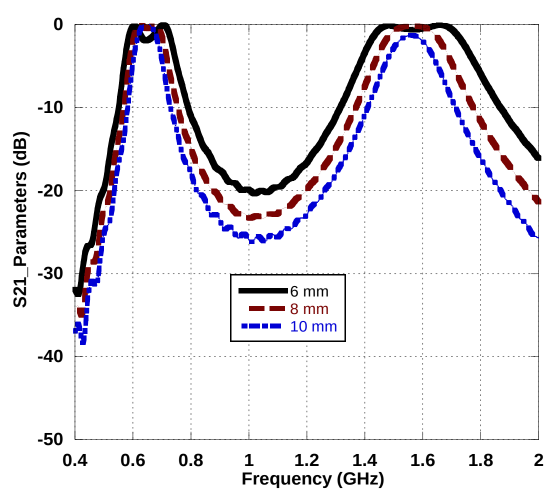


Fig. 3. Comparison between the equivalent circuit (ADS) and EM simulation (CST).

A. The study of transmission distance h

Figure (4) demonstrates the effect of the distance h on the S-parameters. To find out the optimum distance amid Tx (transmitter) and Rx (receiver), the transmission distances are examined within multiple ranges at 6 mm, 8 mm, and 10 mm. The splitting between Tx and Rx is noticeable at 6 mm, while the two resonances are acceptable at 10 mm as discussed in [10]. From this study, the 8 mm separation is a suitable transmission distance to be used for this design.



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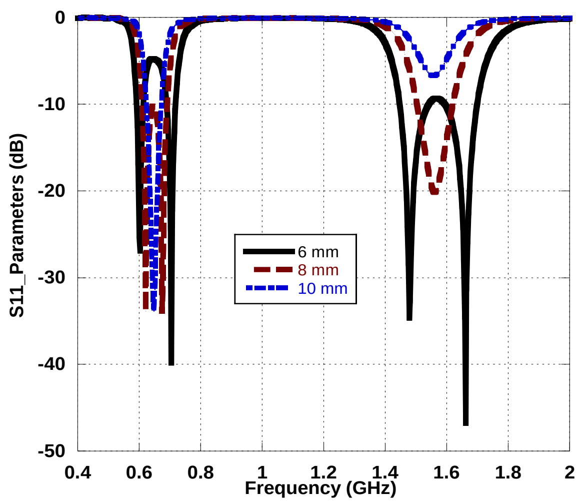
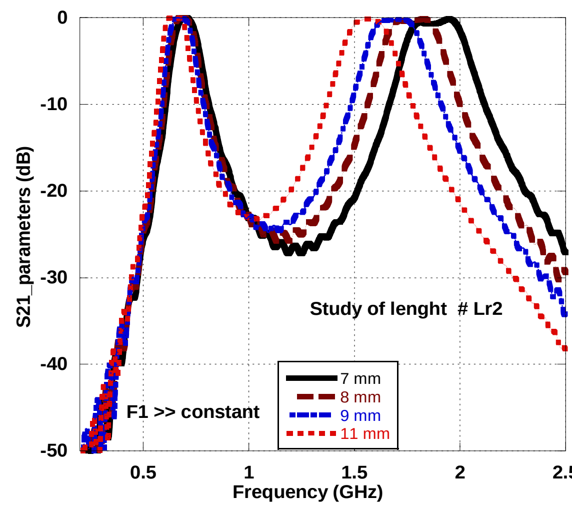


(b)

Fig. 4. The study of transmission distance *h*: (a) S21 parameters and (b) S11 parameters.

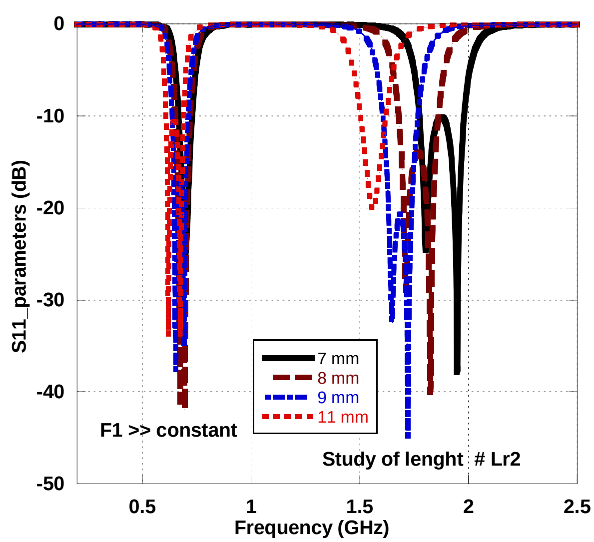


(b)

Fig. 5. Parametric study of the length *Lr2*: (a) S11 parameters and (b) S21 parameters.

B. Parametric study of Lr2

Figure 5 shows the effect of changing the length of *Lr2* from 7 mm to 11 mm. The study displays the changing of the second resonance without any effect on the first resonance frequency. This is suitable for controlling the second resonance while the first resonance is kept constant.



(a)

III. EXPERIMENTAL RESULTS

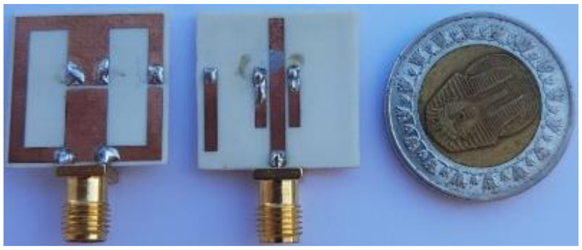
The proposed construction is fabricated and verified for validations with the specifications in Table 1. The fabrication of the proposed structure was done by a photolithographic method and the layers of the fabricated prototype are shown in Fig. 6 (a). Figure 6 (b) shows the configuration of the proposed structure at a separation distance of 8 mm. The measurements are done using the R&S ZVB20 vector network analyzer. The photograph of the fabricated sample is shown in Fig. 6 (a). Figure 6 (c) shows the comparison of the simulation and the measurements. The obtained measurements are in good correspondence with the simulation as displayed in Fig. 6 (c).

The coupling efficiency (η) of the system is calculated using equation (3) [10,20]. The figure of merits (FoM) demonstrates the performance of the system and calculated using equation (4) [10,20]. The measurement results are presented in Fig. 6 (c). The system achieved efficiencies of 72% and 89% at 0.65 GHz and 1.56 GHz at a transmission distance of 8 mm. The estimated FoMs using equation (4) are 0.288 and 0.356 at 0.65 GHz and 1.56 GHz, respectively:

$$\eta = \frac{|S_{21}|^2}{1-|S_{11}|^2}, \tag{3}$$

$$FoM = \eta \times \frac{h}{\sqrt{A}}, \tag{4}$$

where η is the coupling efficiency and *A* is the total area of the resonator.



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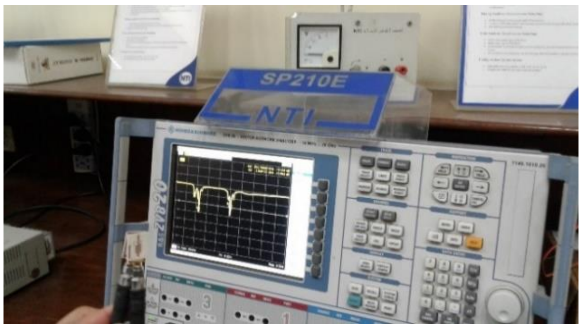

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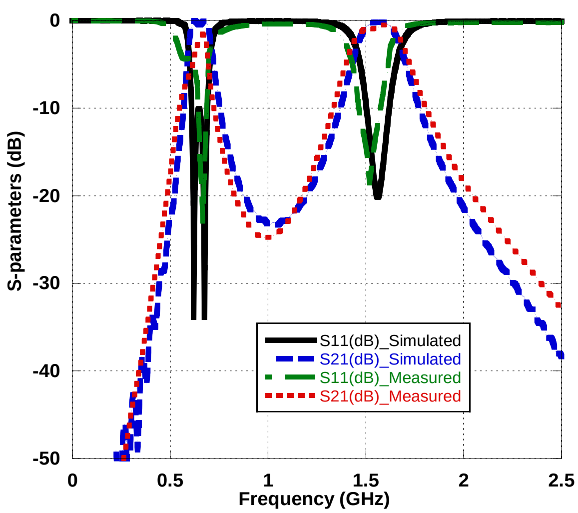

(c)

Fig. 6. The fabricated structure and experimental measurements. (a) Top and bottom views. (b) Measurement setting at a distance of 8 mm. (c) comparison between the measurement and simulation at a distance of 8 mm.

Table 2 offers a comparison between the proposed structure and other recent works in terms of size, FoM, efficiency, and separation distance. From Table 2, the proposed design has worthy FoM and size compared to the previous cited works.

Table 2: The differences between the suggested structure and previous works

System	[21]	[17]	[22]	This work
MHz	570 and 2440	0.2 and 6.78	280 and 490	650 and 1560
h (mm)	12	25	6	8
η_{WPT}%	69 and 81	70.6 and 78	91.2 and 79.43	72 and 89
FoM	0.331 and 0.388	0.17 and 0.19	0.27and 0.23	0.288 and 0.356
Size (mm^2)	25 × 25	125 × 89	20 × 20	20 × 20

IV. CONCLUSION

The dual frequency system is designed, analyzed, and fabricated. The system achieved efficiencies of 72% and 89% at 0.65 GHz and 1.56 GHz, correspondingly at 8 mm separation. The system has a compact size which is suitable for recharging electronics devices and biomedical devices. The experimental performance of the suggested design is in an appropriate concurrence with the simulated one.

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