A New Design for Compact Size Wireless Power Transfer Applications Using Spiral Defected Ground Structures

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Abstract. *In this article, a new wireless power transfer (WPT) design is proposed for improving the efficiency of the system. The suggested system contains two spiral defected ground structure (DGS) resonators coupled back-to-back. A band-pass filter is then to be designed for the wireless power to be transferred from the transmitter unit to the receiver unit. The DGS resonators are loaded through chip capacitors for miniaturization. The proposed structures are fabricated and tested. The proposed system has the highest efficiency of 97.7% at a transmission distance of 10 mm which is suitable for biomedical applications. Both simulated and experimental results are in good concurrence.*

Keywords

Defected ground structure (DGS), spiral, wireless power transfer (WPT)

1. Introduction

The technology of wireless power transfer (WPT) has attracted a significant concentration in recent days that caused by the growing demand of the wireless applications like portable electronic devices, biomedical implants, and wireless buried sensors. It is not impossible to transfer energy over an air without any cables by WPT [1]. WPT is an extremely useful technology that has numerous applications and benefits. Cell phones, laptops, and other mobile devices could function without ever having to be plugged in, cars could drive on highways burning no fossil fuels; wireless power even has the potential to solve much of the renewable energy issues [2], [3], [4], [5]. The energy between the two parts of the system can be conveyed through an air in WPT by the fields produced by the charged of particles. The air gap is linked by renovating the energy into a shape that can transportable over the air. In the receiver, the operable electric current can be obtained from the energy which is transformed into an oscillating field which can be transferred through the air. The energy can be transmitted through an electric field, magnetic field, or electromagnetic (EM) field such as microwaves, radio waves, or even light. The classification of the WPT system can be classified according to power and distance between the transmitter and the receiver [2]. Different implementation techniques of WPT are investigated using the near-field (inductive/capacitive) coupling techniques and the far-field (RF/Microwaves/Laser beams) radiative techniques [3], [6].

Defected ground structures (DGSs) are the slots or the defects which are incorporated on the ground plane of microwave planar circuits. Placement of DGS resonators under the transmission line introduces changes in the propagation of the waves along the line enhancing some parameters in the circuit. Moreover, new materials like the artificial materials can be used to improve the characteristics of the microwave planar circuits like filters [7] and antennas [8] and also to be suitable for transmission of the high data rate. This technique can be used to improve the performance of the WPT systems.

Technology	Range	Frequency	Antenna type	Applications
Inductive coupling	Short	Hz-MHz	3-D wire loops and helical antennas	Induction heater cookers circuits, charging electric vehicles, and electric toothbrush
Resonant inductive coupling	Mid-	MHz-GHz	Tuned wire coils and printed resonant spirals	Charging portable devices, biomedical implants, RFIDs, and smart cards.
Capacitive coupling	Short	kHz-MHz	Electrodes	Charging portable devices and smart cards.
RF and microwaves	Long	GHz	Rectenna and phased arrays	Solar power satellites and powering drone aircraft
Light waves	Long	THz	Laser beams, lenses, and photocells	Powering drone aircraft using photovoltaic cell panels

Tab. 1. The different techniques of WPT.

In [7], the authors studied the H-shaped resonators for WPT system at 5 mm distance with an efficiency of 85%. However, the system size is 25 × 25 mm^2. In [2], the authors studied two different shapes of the DGS (H-shaped and semi-H-shaped) for WPT. The H-shaped DGS WPT system has a size of 20 × 20 mm^2 and an efficiency of 68% at distance of 13 mm while the semi-H-shaped DGS WPT system has an efficiency of 73% at a transmission distance of 25 mm and the total size of the system is 21 × 21 mm^2. In [8], the authors propose a new structure which contains two compact C-shaped resonators allowing the transmission of the power without cables through 15 mm distance between the transmitter and the receiver with an efficiency of 69%. However, the total system size is 25 × 25 mm^2. The author in [9] introduces a new design for WPT that depends on asymmetric design for the transmitter and the receiver. Furthermore, the transmitter size is 120 × 120 mm^2 and the receiver size is 80 × 80 mm^2 while the system operates at an efficiency of 54.5% and a transmission distance of 30 mm. In [10], the author presented a system depending on a dual band antenna with resonators for biotelemetry applications. The authors in [11] are studied the most important applications for WPT and the methods for powering sensors which are embedded in buildings by using rechargeable batteries. These rechargeable batteries can be recharged using WPT.

This brief summarizes the modeling and the analysis of a WPT system using DGS resonators in Sec. 2. Section 3 presents the fabrication and the measurement of the suggested WPT system for verifications. Finally, a summary concludes the main results in Sec. 4.

2. WPT System Modeling and Analysis

2.1 Single Spiral DGS Band Stop Filter

Figure 1 shows the configuration of the suggested spiral DGS. The spiral DGS are constructed and etched on the bottom side of the substrate. The spiral DGS has a metallic width of M_s and the etched gab is G_s. The 50Ω feed line is constructed on the top side and it has a width of W_f and a length of L_s. The capacitor C_1 is placed at the open end of the etched spiral DGS for miniaturizing and adjusting the resonance frequency. The system is designed on Roger 3003 ($\varepsilon_r = 3$) with a thickness of 0.762 mm.

In Tab. 2, the parameters of the suggested design are listed which are used in simulation using computer simulation technology (CST) microwave studio. In Fig. 2, the equivalent circuit of the design is extracted and the frequency response is presented which is equivalent to a one pole band stop filter (BSF) operating at 0.26 GHz. The extracted equivalent circuit includes the inductances L_P which existence is due to the spiral DGS. In addition, the capacitance C_P is existent due to the SMD lumped capacitor which is inserted in the slot of the spiral DGS to operate at the resonance frequency of 260 MHz and to minimize the design area. This resonance frequency was chosen at the low-frequency range to check the reliability of the design and to validate the theory behind the proposed idea. Additionally, to compare with other designs operating at the low-frequency ranges as investigated in [2].

Two SMD capacitors are added to the gab of the spiral DGS for improving the quality factor with miniaturized

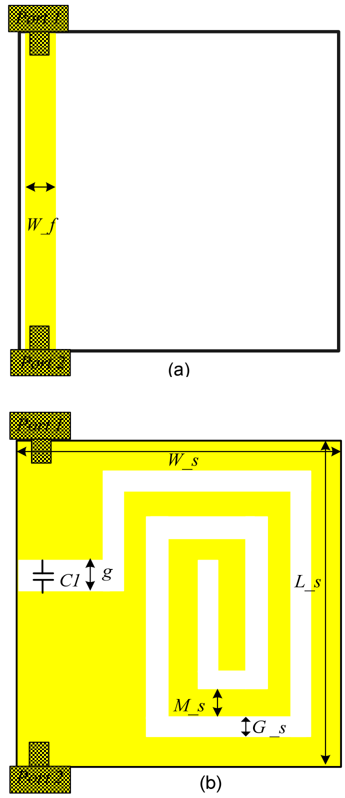
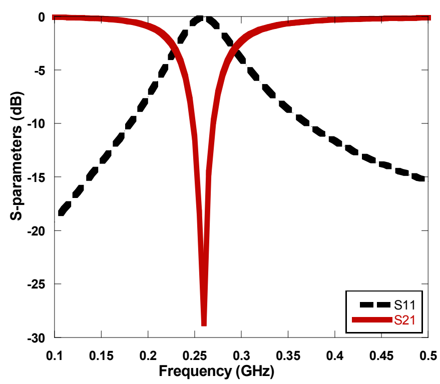


Fig. 1. Single spiral DGS. (a) Top side. (b) Bottom side.

parameter	value
W_s	20 mm
L_s	20 mm
G_s	1 mm
M_s	2 mm
g	1.5 mm
W_f	1.9 mm
C_1	8 pF
C_2	4 pF

Tab. 2. The optimized design parameters of the proposed spiral DGS.



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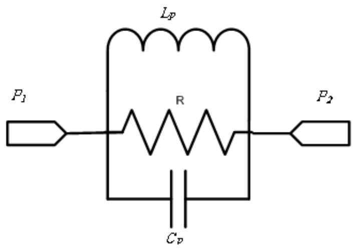


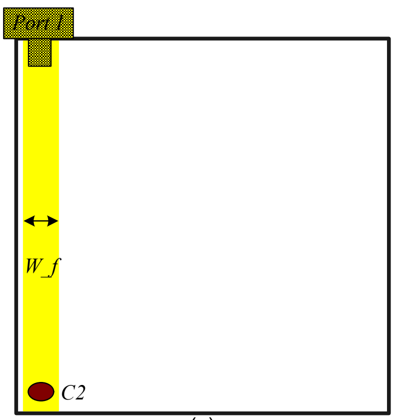
(b)

Fig. 2. The S-parameters and the equivalent circuit model: (a) S-parameters of the single spiral DGS using ADS. (b) The equivalent circuit of the model.

resonator by increasing the equivalent capacitance without increasing the total size as described in [12].

2.2 Coupled Spiral DGS WPT System

The investigation of the two coupled spiral DGS is presented in this part. Each transmitter and receiver is constructed from the BSF that was designed in the previous section. The used single spiral DGS resonator is shown in Fig. 3 after adding the matching capacitor C_2. When two DGS resonators are coupled back to back, it results in a bandpass characteristic, and the power is transferred from the source to the load through the coupled DGS resonators. In Fig. 4(a) two coupled spiral DGS are separated from each other by a distance h. In the simulation part, the two resonators are separated from each other by an air with a permittivity of $\varepsilon_r = 1$. An SMD capacitor C_2 is added between the top and the bottom layer at the end of the 50 ohms transmission line for adjusting the resonance frequency and the impedance matching as shown in Fig. 3. In Fig. 4(b) the equivalent circuit of the suggested design is presented. The equivalent circuit contains the inductances L_{p1} and L_{P2} (where $L_{p1} = L_{P2}$) which exist due to the spiral DGS in both TX and RX. In addition, the capacitances C_{P1} and C_{P2} (where $C_{P1} = C_{P2}$) are existent due to the SMD lumped capacitors which are inserted in the slot of the spiral DGS in both TX and RX. Also, the C_{LS} capacitor is due to the inserted series capacitor C_2 which is connected between the top and the bottom layers and used for impedance matching.



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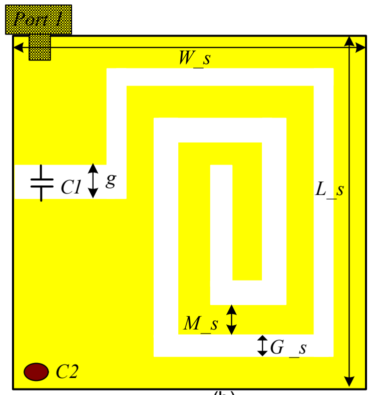

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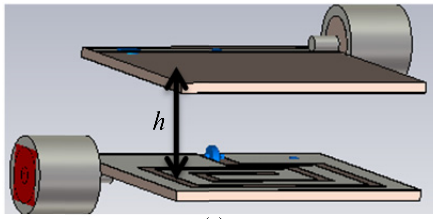
Fig. 3. The suggested spiral DGS TX/RX. (a) Top side. (b) Bottom side.



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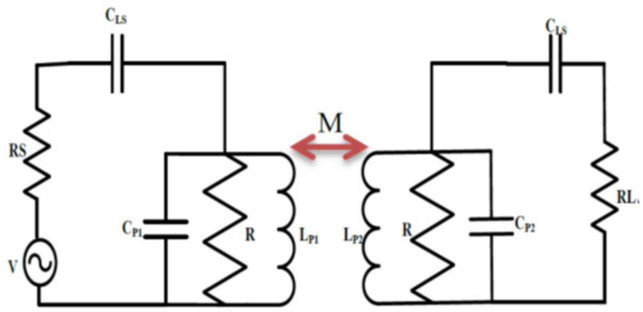


(b)

Fig. 4. The proposed WPT system. (a) 3-D view. (b) Circuit model.

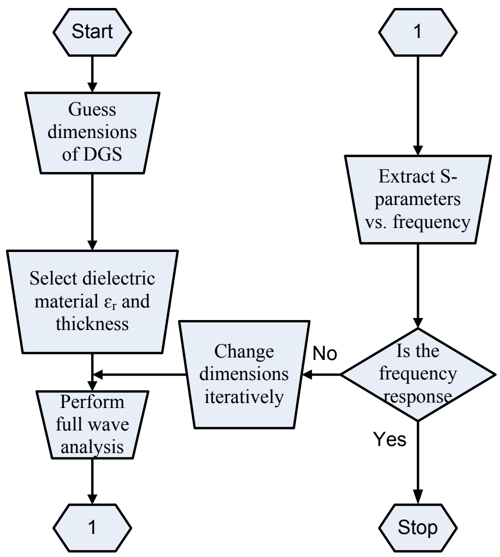
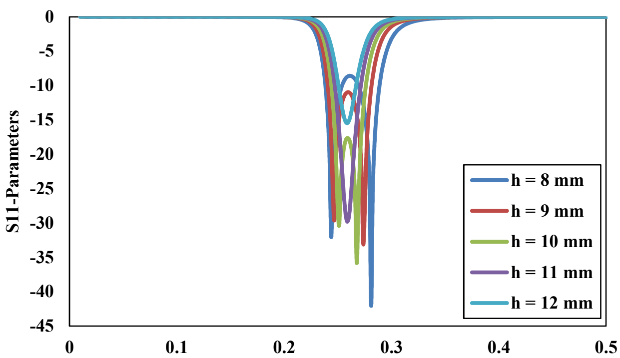


Fig. 5. Design flowchart.



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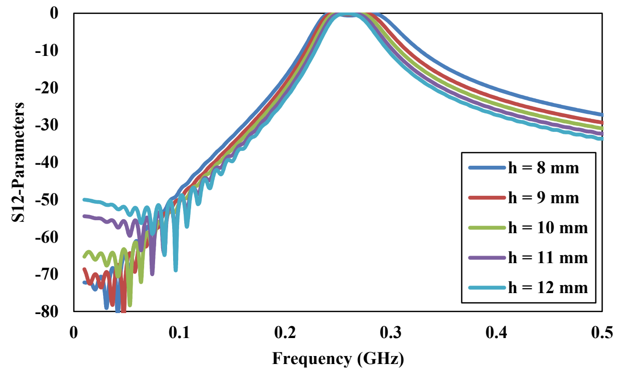


(b)

Fig. 6. The effect of the spacing *h* on the performance. (a) $|S_{11}|$ parameters. (b) $|S_{21}|$ parameters.

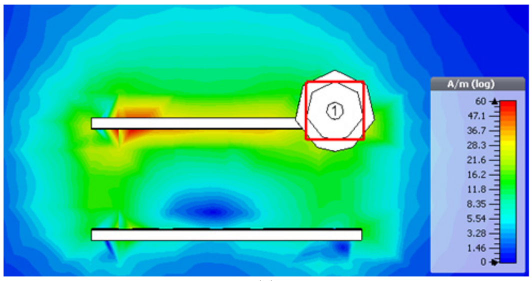
The flowchart in Fig. 5 presents an analytical design procedure for the proposed WPT system. Generally, this design procedure can be used to design a DGS WPT system operating at the desired resonance frequency.

By studying the effect of the spacing *h* between the transmitter and the receiver on the performance of the system, the spacing *h* is varied for from 8 mm to 12 mm while the coupling varies from high to small values at the selected distances as presented in Fig. 6. The splitting appears at short distances where each resonator is acting as a load to the other with high coupling.

Figure 7 shows the magnetic field distribution that is responsible for magnetic coupling between two resonators at the operating frequency of 260 MHz at different phases.

3. Experimental Results

The suggested system was simulated and optimized using CST microwave studio. The fabrication of the system was done by a photolithographic technique and the layers of the fabricated prototype are shown in Fig. 8(a) and (b). The power transfer efficiency is defined as the coupling efficiency between two resonators which is derived in [10]. For comparing the performance of the system, the suggested system's Figure of Merit (FoM) can be computed by using (2) from [12]. The measurement results are shown in Fig. 8(c) and (d) where $|S_{21}|$ equals –0.1 dB and $|S_{11}|$ equals –28 dB. By substitution in (1), the system achieves an efficiency of 97.7% at the transmission distance *h* of 10 mm and the resonance frequency is 260 MHz. The total size of the system is 20 × 20 mm^2 and the achieved FoM is 0.4885 using (2). Moreover, it is obvious that there is good concurrence between EM simulations and experimental results. Table 3 presents the differences between the proposed design and the other previous work. According to the calculated FoM, the presented comparisons in Tab. 3 show that the proposed design has a good efficiency and a compact size compared to other designs. The comparisons between the suggested work and the other work such as in [9], [2], and [10] confirm that the suggested system is more compact and achieves higher FoM than the mentioned structures. Although the structure of semi-H shaped in [2]



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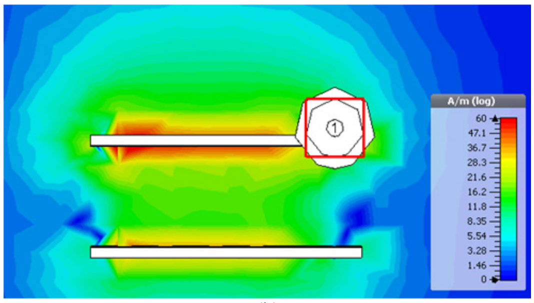

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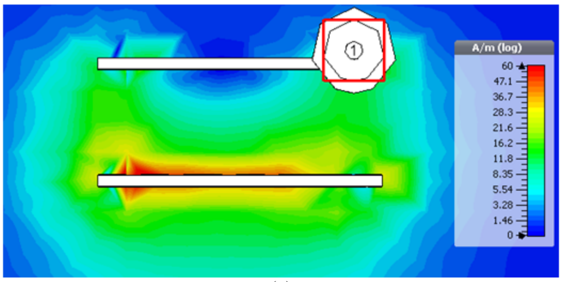

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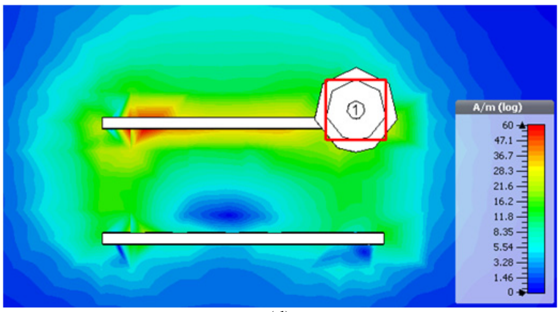


(d)

Fig. 7. Simulated magnetic field distributions of the proposed WPT system at 260 MHz at different phases. (a) $\Phi = 0°$. (b) $\Phi = 45°$. (c) $\Phi = 135°$. (d) $\Phi = 180°$.

has high FoM but it has a large size and a low efficiency compared to the suggested work.

$$\eta = |S_{21}|^2 \left[\left(1 - |S_{11}|^2\right)\left(1 - |S_{22}|^2\right) \right]^{0.5}, \quad (1)$$

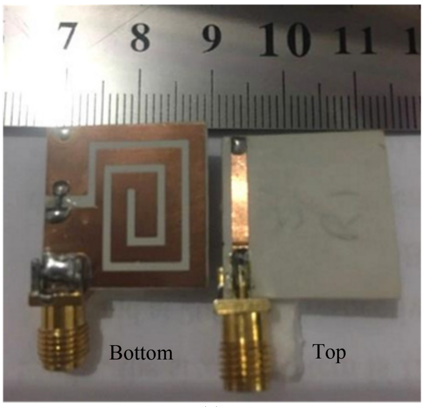
$$FoM = \frac{\eta h}{\sqrt{L_{\text{sub}} W_{\text{sub}}}}. \quad (2)$$

4. Conclusion

In this study, a high-efficiency compact WPT system employing spiral DGS resonators that are coupled back to back is proposed. The design theory and simulation results are in good agreement. Measurements show more than 97% efficiency at 260 MHz at a transmission distance of 10 mm. This work is suitable for charging of portable electronic devices, biomedical implants, and wireless buried sensors.

WPT system	Frequency (MHz)	Size (mm^2)	Efficiency (%)	Distance (mm)	FoM
This work	260	20×20	97.7	10	0.4885
[7]	1000	25×25	85	5	0.17
[2] (H-shape)	300	20×20	68	13	0.442
[2] (Semi H-shape)	300	21×21	73	25	0.8690
[8]	1000	25×25	69	15	0.414

Tab. 3. The differences between the suggested system with other previous works.



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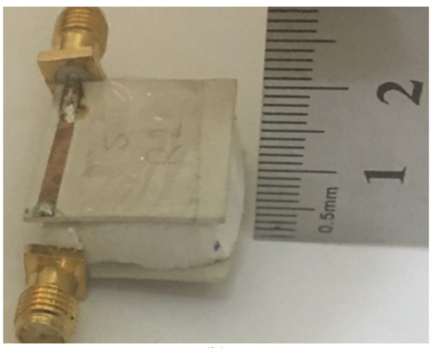

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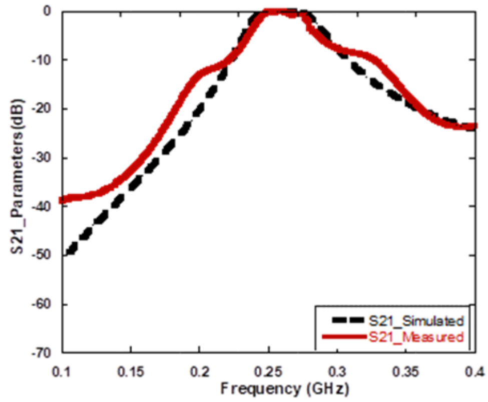

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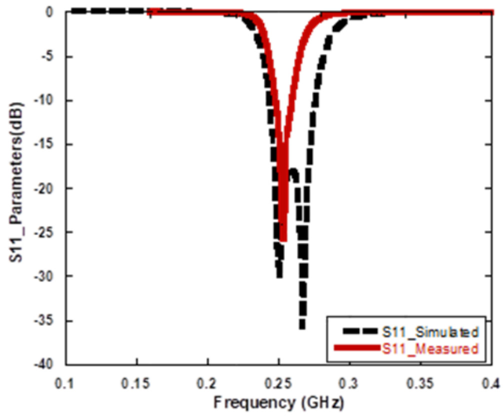

(d)

Fig. 8. The fabricated spiral DGS WPT system and the measured results. (a) The top layer and bottom layer. (b) Setting at 10 mm distance. (c) S_{21} results. (d) S_{11} results.

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