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Compact Wireless Power Transfer System Using Defected Ground Bandstop Filters

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*Abstract*— This letter presents a new design for wireless power transfer (WPT) applications using two coupled bandstop filters (BSF). The stopband is created by etching a defected structure on the ground plane, and the power is transferred through electromagnetic (EM) resonant coupling when the two BSFs are coupled back to back. An equivalent circuit model of the proposed WPT system is extracted. Verification of the proposed design is performed through a good agreement between the EM simulation, circuit simulation, and measurement results. The proposed system achieves a measured WPT efficiency of 68.5% at a transmission distance of 50 mm using a compact size (40x40mm2). This results in a figure of merit of the proposed system to be 0.856 and the ratio of transmission distance/lateral size is 1.25 that is the highest among the WPT systems proposed so far using planar structures.

*Index Terms*— Bandstop filter, electromagnetic resonant coupling, defected ground structures, wireless power transfer

# INTRODUCTION

T

HE near-field wireless power transfer (WPT) system has recently become popular because of its many applications in biomedical implants, wireless buried sensors, portable electronics devices and so on [1]-[7]. In addition, as near-field WPT systems are non-radiative, they are considered to be safe for health. However, the realization of a higher efficiency in a longer power transmission distance with a compact size is one of the most important design issues to develop an effective and practical WPT system. To reduce the size, strongly coupled printed spirals were proposed for the transmitting (TX) and receiving (RX) terminals where inductively coupled feeds were used on each terminal to realize the input/output impedance matching [5]-[7]. A 5 turn self-resonant printed spiral was used to achieve a WPT efficiency of 43.6% at a maximum power transmission distance/√area (*h*/*D*o) of 0.83 [5]. In [6], auxiliary strips have been applied to increase the quality factor and realize a WPT efficiency of 81.7% at *h*/*D*o = 1. Furthermore, the multilayers stacked spirals with shorting walls were applied to increase the quality factor and the mutual coupling [7], where an efficiency of 84.4% at *h*/*D*o = 1 was achieved. However, in [6], [7] the TX/RX spirals were designed on the same plane with the feed loops and stacked substrates were piled up to accumulate the inductance. In spite of the increased fabrication complexity in the stacked substrates, the available area for the inner loop is limited, which limits further improvement of matching, mutual coupling and quality factor correspondingly.

Previously, the authors of this letter employed quasi-lumped elements based on defected ground structures (DGS) for wireless power transfer for the first time [8], [9]. When DGS is etched on the opposite side of a signal line, a stopband will be generated [10]-[12] that prevents the power transmission from one port to the other. DGS might have different shapes on the ground plane such as H-shape, square shape, dumbell or spiral [11] where the fields of the dominant mode will be distorted and higher order modes must be excited [10]. Hence, the DGS behaves like a bandstop filter (BSF). When two BSFs are coupled back-to-back [8], [9], the suspended power is transferred to the load and vice-versa.

A comparative study of different shapes of DGSs to synthesize the same stopband response was performed in [12], and had shown that the H-shape had the smallest size and the highest Q-factor. The authors of this letter demonstrated the basic idea of using H-shape DGS for WPT in [8] and achieved a WPT efficiency of 80% at *h*/*D*o = 0.2. Then, we improved the performance using strong resonant coupling in [9] to achieve a WPT efficiency of 70% at *h*/*D*o = 0.45.

In this letter, a technique to improve the inductance of the H-shape DGS is proposed, and its effectiveness to increase the transmission distance of the WPT system is investigated through the designed, EM simulated, and experimental results. One of the advantages of the proposed DGS WPT system over the conventional WPT system [5]-[7] is the feeding topology. In the proposed system, the power is transferred from/to the source/load through electrical coupling. This results in two distinct advantages. First, the external quality factor can be easily optimized by an additional capacitor connected between the feed/load microstrip line and the DGS resonator. Second, there is more flexibility for optimization of the parameters of the DGS resonator such as the number of turns, thickness and so on compared to those in the conventional systems [5]-[7].

# Proposed DGS and its implementation to BSF design

Fig. 1 shows the schematic view of three types of DGS ((a) H-shape, (b) semi H-shape (square), and (c) two-turn square-shape) designed on Rogers substrate (RO3003) with permittivity *ε*r = 3, thickness = 0.76 mm, and metal thickness *t* = 18 μm. As the H-shape DGS is represented by two semi H-shape (square) connected in parallel, the semi H-shape (square-shape) DGS realizes twice of the inductance than that of the H-shape DGS. Furthermore, making two turns in square-shape as shown in Fig. 1(c) will lead to the additional inductance due to the increased current path which is investigated in this work. The inductance (*L*P) and resistance (*R*) of this structure are estimated by (1), (2), respectively [13], [14]. Where *D*o, *D*i are the outer and the inner diameters, *d* is the width and *s* is the slot between the turns,is the fill factor, *Rdc* is the DC resistance and *δ* is the skin depth.

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| Henry. | | | | (1) |
| , | | | |  |
| Ω. | | | | (2) |
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| (a) | (b) | | (c) | |
| Fig. 1. PCB layout of three different shapes of DGS (a) H-shape [9]. (b) Semi H-shape (square). (c) Two-turn square-shape (proposed in this letter). | | | | |
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| (a) | | (b) | | |
| Fig. 2. (a) Comparison of the inductance of the three types of DGS. (b) Comparison of the EM and circuit simulated |S-parameters| of the proposed two-turn square shape BSF with embedded equivalent circuit. | | | | |

Fig. 2(a) shows a comparison of the inductance of the three DGSs implemented in different areas (*D*o x *D*o) with the width *d* = 3.5 mm where the inductance of the proposed two-turn square-shape DGS is the largest among the others. The stopband response at *f*0 = 50 MHz is realized by the two-turn square-shape DGS (*D*o = 40 mm, *d* = 3.5 mm, *s* = 1.25 mm that give *L*P = 198 nH, and *R* = 0.18 Ω) loaded by a chip capacitor *C*P = 50 pF; such that ω02 = 1/√*L*P*C*P. This results in the Q-factor of the proposed DGS resonator to be 339, whereas the Q-factor of the resonators in [6] with/without auxillary strips was 324 and 274, respectively. Fig. 2(b) shows a comparison of the scattering parameters (|S-parameters|) simulated by the High-Frequency Structure Simulator (HFSS), and the equivalent circuit simulated by the Advanced Design System (ADS). The layout of proposed DGS resonator is shown in Fig. 3 (a) where the top layer is a 50 Ω feed line of a length (*L*f) and a width (*W*f) followed by a stub of a length (*L*st), and a width (*W*st) that is responsible for impedance matching and can easily be represented by the parallel plate capacitance (*C*st). The chip capacitor (*C*LS) is connected to obtain a perfect impedance matching (IM cap). The bottom layer is the proposed two-turn square-shape DGS. The equivalent circuit of the proposed WPT system using coupled two-turn square shape defected ground BSFs is shown in Fig. 3(b).

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| (a) | (b) |
| Fig. 3. (a) PCB layout of the realized TX/RX resonators used in the proposed WPT system using two-turn square shape DGSs. (b) Equivalent circuit model of the proposed WPT system. | |

# Proposed WPT System and Verification

The following steps illustrate the design flow for the proposed WPT system:

1. Define the resonant frequency (*f*0 = 50 MHz in this work).
2. Define the size (), and the transmission disatnce (*h*). (In this work we assume = 40 mm, =50 mm).
3. Determine *d* and *s* that provide the maximum *U*-factor ( product) and so [15]. (In this work we determined *d* = 3.5 mm and *s* = 1.25 mm).
4. Determine and by using (1), (2). (In this work, we calculated = 198 nH, and = 0.18 Ω).
5. Using ω02 = 1/√*L*P*C*P, calculate *C*P to get the desired resonance frequency. The mutual inductance (*M*) between the coupled resonators is calculated as [Eq. (7) of ref .16].
6. Apply the equivalent circuit on ADS using the calculated values of *L*P, *R*, *C*P and *M.*
7. Find *C*st and *C*LS for impedance matching, and tune *C*P , then estimate the efficiency *η* = |S21|2. After that, verify the circuit simulation by HFSS for fine tuning and final optimization.

The optimized design parameters and *RLC* values of the proposed WPT system are summarized in Table 1.

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| TABLE I  Optimized Design Parameters, and *RLC* Values | | | | | | | | | | | | | | |
| Design dimensions (mm) | | | | | | | | Circuit parameters (*L*, *M* (nH), *C* (pF), *R* (Ω)) | | | | | | |
| *W*f | *L*f | *W*st | *L*st | *D*o | | *d* | *s* | *L*P | *R* | *C*P | *C*st | *C*LS | *M* | *k* |
| 1.5 | 20 | 2.5 | 10 | 40 | 3.5 | | 1.25 | 198 | 0.18 | 42 | 2 | 7 | 5.11 | 0.025 |

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| Fig. 4. Measurment setup of the fabricated WPT system. |
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| Fig. 5. Comparison between the simulated and the measured |S-parameters| of the proposed WPT system at a transmission distance *h* = 50 mm. |
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| Fig. 6. Comparison between the measured and the EM simultaed WPT efficiency *η* of the propsed WPT system at different transmission distances. |

Fig. 4 shows the measurement setup of the fabricated WPT system. Fig. 5 presents the simulated and the measured |S-parameters| at a transmission distance *h* = 50 mm. As shown, the proposed system operates at 50 MHz, and the measured results are in good agreement with the simulated results. Fig. 6 shows a comparison of the measured and the EM simulated efficiency of the proposed system at different transmission distances where a maximum efficiency of 68.5% was achieved at *h* = 50 mm, *h*/*D*o = 1.25, while the efficiency was 63% at the same *h*/*D*o ratio in [7]. This verifies our methodology to design a high efficiency and a compact WPT system.

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| TABLE II  Comparative Study With Recently Published Planar WPT systems | | | | | | | |
| WPT  system | Frequency  (MHz) | Size *D*o2  (mm2) | Distance  *h* (mm) | *h*/*D*o | Eff. *η* @ *h*/*D*o=1.25 | Max Eff.  *η* (%) | *FOM* |
| [5] | 50 | 120x120 | 100 | 0.83 | 8 | 43.6 | 0.36 |
| [6] | 13.5 | 100x100 | 100 | 1 | 55 | 81.7 | 0.817 |
| [7] 2-layer | 13.5 | 100 x 100 | 100 | 1 | 59 | 82.67 | 0.827 |
| [7] 3-layer | 13.5 | 100 x 100 | 100 | 1 | 63 | 84.38 | 0.844 |
| This work | 50 | 40 x 40 | 50 | 1.25 | 68.5 | 68.5 | 0.856 |

Table II summarizes the performance of the proposed WPT system and compares with recently published WPT systems using planar inductors. A Figure of Merit (*FoM*) calculated using the formula  [9] is used in this comparison. The *FoM* of this work is better than [7] without the stacked substrate and similar to those having stacked substrate. Moreover, we achieved a transmission distance *h* = 50mm, *h*/*D*o = 1.25, that exceeds the physical dimension of the WPT system with the highest WPT efficiency of 68.5% for the first time. This illustrates that if the number of turns will be increased in a DGS resonator, more compact WPT system with a high efficiency could be designed which will be considered in a future work.

# Conclusion

In this letter, a planar WPT system based on EM resonant coupling of two BSFs which are coupled back to back is presented. The BSF employs two-turn square-shape DGS to increase the inductance that realizes a WPT efficiency of 68.5% at *h*/*D*o = 1.25. Such high efficiency has been realized for the first time when the power transmission distance is larger than the lateral size of the WPT system.

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