Non-radiative wireless energy transfer with single layer dual-band printed spiral resonator

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Article Info	ABSTRACT
Article history:	Accomplishing equilibrium in terms of transfer efficiency for dual-band
Received Jan 2, 2019 Revised Mar 8, 2019 Accepted Mar 29, 2019	wireless energy transfer (WET) system remains as one of key concerns particularly in the implementation of a single transmitter device which supports simultaneous energy and data transfer functionality. Three stages of design method are discussed in addressing the aforementioned concern. A single layer dual-band printed spiral resonator for non-radiative wireless
Keywords:	energy transfer operating at 6.78 MHz and 13.56 MHz is presented. By employing multi-coil approach, measured power transfer efficiency for a
Dual-band Non-radiative Power transfer efficiency Printed spiral resonator	symmetrical link separated at axial distance of 30 mm are 72.34% and 74.02% at the respective frequency bands. When operating distance is varied between 30 mm to 38 mm, consistency of simulated peak transfer efficiency above 50% is achievable.
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1. INTRODUCTION

Multifunctional loops for simultaneous power and data or simultaneous wireless charging at different standards are made possible with coils designed to support more than one frequency band. There are currently two main standards for wireless charging. Wireless Power Consortium (WPC) or better known as Qi is one of the leading standard operating in low frequency (LF) band, 110 kHz to 205 kHz [1]. AirFuel Alliance is the merger between Power Matters Alliance (PMA) and the Alliance for Wireless Power (A4WP, also known as Rezence). A4WP employs magnetic resonance coupling technique operating at 6.78 MHz \pm 15 kHz [2] while both *Qi* and PMA engage in inductive charging method. The operating frequency for PMA standard is 277 kHz to 357 kHz [3].

There are two foremost approaches used in the design of dual-band coils specifically multi-coil [4-9], and single-coil approach [10-15]. The latter has a slight edge with lesser cross coupling [10]. Cross coupling mitigation is proposed with a coplanar coils structure while geometrical area reduction is considered with a coaxial structure [8]. Nevertheless, in order to concurrently capitalize on efficiency at two different frequencies in a single transmitter, it is recommended to design two separate coils which facilitate independent selection of inductance and quality factor [5]. A compact two circular DGS resonator with independent coupling is proposed in [16]. Concurrent high-power transfer is reported for both frequency bands investigated. Similar findings are reported in [17] using a single compensation network for dual mode inductor designed.

The challenge to achieve simultaneous high power transfer for dual-band frequency in single-coil approach is still achievable as demonstrated in [18-19] with the introduction of dual-band repeater or also known as intermediate coils. However, additional repeater means more space allocation is required beside frequency splitting occurrence for one of the frequency bands due to strong coupling. Furthermore, one needs

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to exercise caution in designing repeater as transfer efficiency is greatly affected by parasitic resistance originating from repeater. As such, a dual-band printed spiral resonator sharing a single substrate is proposed in this paper. With a space-conscious design, the proposed design aims to achieve a transfer efficiency balance between the designated frequencies bands.

2. RESEARCH METHOD

There are three design stages involved as illustrated in Figure 1. Full wave electromagnetic simulator tool, CST Microwave Studio is employed for modelling and optimization. The foundation of first loop resonator design is bounded by the restricted and preliminary geometrical values namely number of turns, n_{fl} , width and spacing of conductive trace, w_{fl} , s_{fl} . Initial stage encompasses design and optimization workflow of loop resonator to be functioning at the first resonance frequency. Innermost length of first loop resonator designed will then be acknowledged as another constraint parameter in designing second loop resonator in Stage B. If Stage B and Stage A are reversed, then the outermost length of second loop resonator. The final stage involves impedance matching where separate optimization processes are deem necessary in order to acquire concurrent maximum transfer efficiency for both frequency bands under investigation. The correlation between optimal transfer distance and outermost side length of loop at maximum excited magnetic field derived in [20] yields.



Figure 1. Three stages of simulation plan for dual-band printed spiral resonator

$$z_{op} = \ell_{out}(2.544)^{-1} \tag{1}$$

As such, a compromise will be performed in the selection of axial distance before initiating any impedance matching work particularly when there is significant variance between outermost length of the first and second loop resonator. An existing macro for matching circuits in CST Microwave Studio, Mini Match is employed to achieve simultaneous conjugate matching at 50-ohm port terminations and convergence at resonance frequencies. Comprises of a series and a shunt capacitor, *L*-match network is connected for both resonators which shares a single substrate. For a dual-band printed spiral resonator with transmitting terminals at port 1 and port 3, transfer efficiency can be extracted from transmission coefficients, S_{21} for first frequency band while S_{43} for the second frequency band.

Multi-coil approach is opted in designing inductive loops operating in more than one resonance frequency in order to achieve equilibrium in terms of transfer efficiency for all frequency bands under investigation. The resonance band concerned here is B1 at 6.78 MHz and B2 at 13.56 MHz. The total proposed dimension is 80 mm by 90 mm with a FR-4 thickness of 1.6 mm. As shown in Figure 2, outermost lengths of top layer, dt_o and bottom layer, db_o are 70 mm and 44.2 mm whereas the inner length of top layer, dt_i and bottom layer, db_o are 55.6 mm and 18.6 mm respectively. Square spiral resonator with copper thickness of 70 µm is designed on top layer which consists of three turns, n with varying widths and spacing denoted by wt_n and st_n . Similarly, bottom layer is designed with a diverse widths, wb_n and spacing, sb_n and additional turns to increase coil inductance. Fabricated dual-band design is depicted in Figure 3.

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Figure 2. Proposed dual-band design, (a) Top layer, (b) Bottom layer



Figure 3. Fabricated dual-band design, (a) Top layer, (b) Bottom layer

In order to achieve simultaneous conjugate matching at 50 ohm for 6.78 MHz and 13.56 MHz frequency bands, *L*-matching technique as proposed in [20] with a single series capacitor, C_s and a single parallel capacitor, C_p is utilized. Consequently, the total lumped elements employed on a transmitter is four capacitors for dual-band design. With inbuilt search algorithm in full wave finite element simulator, matching capacitors are determined to achieve resonance at *B1* and *B2*. Simulations are then repeated based on the closest available off-the-shelves surface mount device (SMD) capacitor values. Table 1 shows the list of initial, simulated and employed matching capacitor values. Port 1 and 3 represent source loops at 13.56 MHz and 6.78 MHz correspondingly.

 $\frac{\text{Table 1. Selected capacitor values for impedance matching}}{1 2 3}$

Port	1	2	3	4	
Initial Matching C _s (pF)	56.64	57.22	191.29	191.56	
Initial Matching C_p (pF)	67.29	68.89	644.87	644.66	
Simulated C_s (pF)	56	56	200	200	
Simulated C_p (pF)	68	68	620	620	
Employed C_s (pF)	56	56	200	200	
Employed C (rE)	(9	(0	150	150	
Employed C_p (pr)	08	08	470	470	

3. RESULTS AND ANALYSIS

3.1. Power transfer efficiency

Since the receiving loops are represented by port 2 and 4, the transfer efficiency for *B1* and *B2* bands can be derived from *S*-parameters, $|S_{21}|^2$ and $|S_{43}|^2$. Simulated and measured peak transfer efficiencies, $SimPTE_{pB1}$, $SimPTE_{pB2}$, $MeaPTE_{pB1}$ and $MeaPTE_{pB2}$ are tabulated in Table 2. The optimal axial distance, *z* for maximum axial magnetic field with reference to outermost side-length of loop, d_{to} and d_{bo} are determined based on (1). As such, the theoretical optimum distances, z_{B1} and z_{B2} computed based on proposed design are 17.37 mm and 27.52 mm. With a difference of about 10 mm, a distance selected should be of benefit for both frequency bands since both coils are etched on the same substrate. If distance selected is less than z_{B2} with the purpose of accomplishing an ideal PTE_{B1} , frequency splitting at *B2* will be inevitable due to over coupling when receiver coil is positioned too close with source coil. Hence, distance of 30 mm is opted as distance for simultaneous conjugate matching at the expense of highest possible PTE_{B1} . Simulations and measurements for axial distances ranging from 30 mm till 50 mm are performed with with an increment step of 2 mm to investigate on the possibility of sustaining efficiency as depicted in Figure 4 and Figure 5. Measurement setups with the aid of vector network analyser (VNA) are shown in the inset of Figure 4 and Figure 5 respectively.



Figure 4. Simulated and measured PTE (B1) under varied operating distance



Figure 5. Simulated and measured PTE (B2) under varied operating distance

It is observed that simulated *PTE* is around 80% for both frequency bands at distance of 30 mm when *L*-matchings are performed. Despite the fact that theoretical optimum axial distance for the lower band is ought to be lesser than 30 mm, the presence of loops at the top layer could contribute towards the enhanced coupling in the under-coupled region which is similar with the concept of four coils in magnetic resonance coupling [21-22]. The loops for higher band etched on the top layer represent the resonator while the loops at the bottom layer are the source driving loop at 6.78 MHz. Attempt has also been made to simulate similar design on a substrate with 25% reduction of thickness. *PTE* for *B1* is found to increase by approximately 2% from 80.64% to 82.66% while *PTE* for *B2* decrease by about 0.5% from 79.35% to 78.87%. Hence, the characteristic of the proposed design is not significantly affected by the thickness of substrate used. Measured peak *PTE* is 72.34% and 74.02% for the respective bands. Deviations between simulated and measured results could be due to deficiencies in fabrication process. Comparison with other works is summarized in Table 3. Proposed simulated design appears to perform well in terms of simplicity and space-conscious structure in addition to exhibiting balance between transfer efficiency of *B1* and *B1* without sacrificing peak transfer efficiency of either one.

Table 2. Simulated and measured peak transfer efficiency

Axial distance	$Sim_{f_{pBI}}$	$SimPTE_{pB1}$	$Sim_{f_{pB2}}$	$SimPTE_{pB2}$	$Mea_{f_{pBI}}$	$MeaPTE_{pB1}$	$Mea_{f_{pB2}}$	$MeaPTE_{pB2}$
(mm)	(MHz)	(%)	(MHz)	(%)	(MHz)	(%)	(MHz)	(%)
30	6.78	80.64	13.57	79.35	6.80	72.34	13.44	74.02
32	6.78	76.69	13.50	76.99	6.72	67.74	13.36	70.23
34	6.78	71.53	13.46	73.86	6.72	63.92	13.28	67.30
36	6.78	65.67	13.44	70.16	6.72	57.65	13.28	64.02
38	6.78	59.45	13.42	66.02	6.72	53.37	13.20	59.79
40	6.78	53.24	13.41	61.64	6.72	47.81	13.20	58.26
42	6.78	47.27	13.39	57.14	6.72	41.46	13.20	51.90
44	6.78	41.67	13.39	52.69	6.72	35.17	13.20	45.37
46	6.78	36.58	13.39	48.33	6.72	31.43	13.20	41.66
48	6.78	31.96	13.38	44.16	6.72	27.77	13.20	38.29
50	6.78	27.87	13.38	40.21	6.72	23.69	13.20	32.82

Table 3. Comparison with other works

Ref	$ef B1 PTE_{B1}(\%)$		$PTE_{BI}(\%)$ B2	$PTE_{P2}(\%)$	z TX Size		RX Size	Additional
	51	1 1 2 Bi (70)	52	1 1 <u>2</u> _{B2} (/v)	(mm)	(Width \times Length)	Tur bille	Structure
[19]	200	55	6.78	74	50	$120 \times 70 \text{ mm}^2$	120×70 mm ²	Dual-band
	kHz		MHz					Repeater
[5]	200	70.6	6.78	78	25	$125 \times 89 \text{ mm}^2$	78×66 mm ²	No
	kHz		MHz				(RX B1)	
							$71 \times 57 \text{ mm}^2$	
							(RX B2)	
[9]	200	70.8	6.78	70.3	50	125 mm	125 mm	No
	kHz	(Dual band TX)	MHz	(Dual band TX)		(diameter)	(diameter)	
		74.3		66.3				
		(Dual band RX)		(Dual band RX)				
[10]	6.78	81	13.56	66	50	200 mm (diameter)	200 mm	No
	MHz		MHz				(diameter)	
This	6.78	72.34	13.56	74.02	30	80×90 mm ²	80×90 mm ²	No
work	MHz		MHz					

Figure 6 reveals that consistency of simulated and measured peak transfer efficiency above 50% is feasible when operating distance is varied between 30 mm to 38 mm. In order to compare the decline of transfer efficiency with distance (m) usually at $1/d^{6}$ [23-24], the fitted equations derived from the simulated and measured plots are expressed by the following:

 $SimPTE_{pB1} = \frac{\alpha_s}{z^{1.88}}$ (2)

$$SimPTE_{pB2} = \frac{\beta_s}{z^{1.24}} \tag{3}$$

$$MeaPTE_{pB1} = \frac{\alpha_m}{z^{1.95}} \tag{4}$$

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$$MeaPTE_{pB2} = \frac{\beta_m}{z^{1.38}} \tag{5}$$

Where $\alpha_s = 0.1$, $\beta_{s=1.1}$, $\alpha_m = 0.1$, $\beta_{m=0.6}$



Figure 6. Simulated and measured peak transfer efficiencies for dual-band printed spiral resonator under axial displacement (30 mm $\le z \le 50$ mm)

3.2. Fractional bandwidth

The corresponding -3 dB fractional bandwidths (FBW) are evaluated from combined S_{11} and S_{33} reflection coefficient plots as depicted in Figure 7. The axial distance between a pair of symmetrical WET printed spiral resonators selected is 30 mm. Computed FBW at each band under observation is detailed in Table 4. This implies that the proposed design can be employed to facilitate adequate data transfer at B2. Fractional bandwidth [25] in percentage is expressed as:

$$FBW = \frac{100\%(\Delta f)}{f_c}$$
(6)

Table 4. Simulated and measured fractional bandwidth at -3dB									
Band	Sim_f_c (MHz)	$Sim_{\Delta f}(MHz)$	Sim_FBW (%)	Mea_f_c (MHz)	$Mea_\Delta f(MHz)$	Mea_FBW (%)			
B1	6.8	1.1019	16.20	6.8	1.04	15.29			
B2	13.52	2.1173	15.66	13.44	2.24	16.67			



Figure 7. Reflection coefficient plots for dual-band printed spiral resonator

3.3. Port isolation

The acceptable isolation for this design is established at 10 dB and above. As shown in Figure 8, the simulated isolation between trasmitters (S_{31}) and receivers (S_{42}) of both frequency bands are about 15 dB and 12 dB at 6.78 MHz and 13.56 MHz respectively. The corresponding measured S_{31} and S_{42} are about 11 dB and 10 dB. Isolation between *B1* transmitter and *B2* receiver as well as between *B2* transmitter and *B1* receiver are represented by S_{23} and S_{41} plots. Approximate simulated isolation of 16 dB and 14 dB while measured isolation of 17 dB and 15 dB at *B1* and *B2* are observed. This indicate that the proposed design can be implemented for multifunctional wireless energy transfer applications by meeting minimal isolation design threshold.



Figure 8. Transmission coefficient plots for dual-band printed spiral resonator

4. CONCLUSION

A single-layer dual-band printed spiral resonator is proposed and analyzed. This paper has essentially presented design approach based on electromagnetic full wave simulator. Design strategy employed is able to produce and achieve the targeted aim of transfer efficiency equilibrium between multiple bands without necessitating additional or intermediate loops, thereby maintaining a reduced footprint. Accomplishment in balance is inferred by the variation between transfer efficiency for both frequency bands under investigation which is only 1.68% at axial distance of 30 mm. This also indicates its suitability for single transmitter device implementation in wireless energy transfer system. There is also a prospect shown in retaining transfer efficiency when symmetrical link is deliberately positioned under various axial distances.

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