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Analysis of RWPT Relays for Intermediate-Range Simultaneous Wireless Information and Power Transfer System

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Abstract—The increasing sophisticated power and communication demands have motivated a variety of research on simultaneous wireless information and power transfer system, aiming to provide higher power transfer efficiency and improved communication rate. This paper demonstrates that resonant wireless power transfer (RWPT) system with relays can be a candidate to reach these aims. Based on coupled resonator filter theory, mathematical equations for transmission efficiency and bandwidth are derived for arbitrary number of relays. Improved efficiency and bandwidth are verified by equations, simulation and experiments. Experimental results show that under the distance of two times the diameter of the resonator, system efficiency increases from 5.43% (no relay) to 29.47% (one relay) and 38.02% (two relays), with the fractional bandwidth broadened from 1.33% (no relay) to 3.31% (one relay) and 4.47% (two relays) at operation frequency of 42.55 MHz, providing available channel for simultaneous power and data transfer. The procedure for the design of relays is also listed in detail.

1. INTRODUCTION

The research on simultaneous wireless information and power transfer (SWIPT) [1] has been driven by the growing requirements of increasing sophisticated devices and scarce frequency resources. SWIPT refers to using the same electromagnetic field to transport both energy and information to the receiver. Its performance is usually assessed in terms of power transfer efficiency and frequency bandwidth available for communication.

Inductive wireless power transfer (IWPT) [2] has been employed in most of SWIPT systems such as radio frequency identification (RFID) tags and subcutaneous medical implants, but it is restricted to near-field transfer range. While far-field microwave power transfer integrating with wireless communications [1] for SWIPT suffers from the low power transfer efficiency. Resonant wireless power transfer (RWPT) [3] proposed by Massachusetts Institute of Technology in 2007 provides an efficient way for intermediate-range wireless power transfer. However, for high efficient power delivery, high quality factor resonators are required with narrow bandwidth, which is contradictory with the need of wide bandwidth in SWIPT. Moreover, its power transfer efficiency falls off rapidly beyond its effective range.

Experiments in [4] with multi-coil approach demonstrate the possibility that RWPT relay transfer could improve the frequency bandwidth. Meanwhile, it has been verified that the existence of relay resonators could increase the transmission distance [5]. These together make RWPT relay-technique a candidate for intermediate-range SWIPT. Unfortunately, little research has been carried out on this fact.

In this paper, filter-based [6] theory is adopted for RWPT relay analysis due to its simplicity, focusing on power transfer efficiency and bandwidth for intermediate-range SWIPT. By exponential

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function fitting the relationship between the coupling coefficient and the interval of resonators, system efficiency and fractional bandwidth is estimated in terms of the number of relays and the total transmission distance. The derived mathematical equations confirm the relay effect of improving the bandwidth. Besides, a simple and effective method to choose the number and deployment of relays is also detailed.

2. ANALYSIS OF RELAYS

2.1. Coupled Resonator Filter Theory for Relays

The general RWPT system with relays is arranged by inserting some relay resonators properly in between the transmitter (TX) and receiver (RX) resonators. Therefore, n relays indicate that there are $(n+2)$ resonators in the system, which can be modeled as $(n+2)$ stage of filter.

The abstract model and the equivalent coupled resonator filter model are demonstrated in Fig. 1. Power source with internal termination resistor is represented by the AC source and R_s. Resonators are modeled as series resonators L_i and C_i. Mutual couplings with coefficient $k_{i,i+1}$ are represented by impedance inverters $K_{i,i+1}$, and the load is represented by R_L. Assume these resonators resonating at a same frequency f_0. The cross-couplings of non-adjacent resonators are ignored for simplicity.

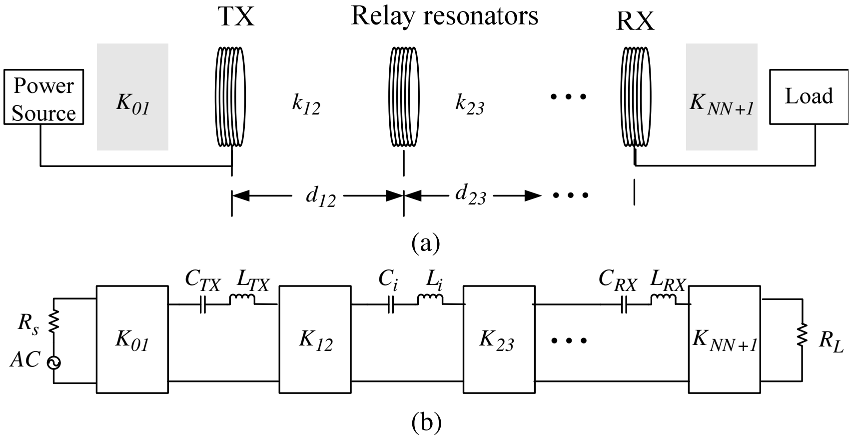

Figure 1. (a) The RWPT system with relays. (b) Equivalent coupled resonator filter model.

Once the stage (N) of the filter and fractional bandwidth (FBW) is fixed, coupling coefficients and external quality factor Q_e can be obtained from any filter design book [7].

$$\begin{aligned} k_{i,i+1}\,|_{i=1\sim N-1} &= FBW/\sqrt{g_i g_{i+1}} \\ (Q_e)_{source} &= g_0 g_1/FBW \\ (Q_e)_{load} &= g_N g_{N+1}/FBW \end{aligned} \tag{1}$$

where g_i is low-pass prototype filter element values. Given the number of the relays, and the coupling coefficients can be computed and achieved by altering the shape or the spacing between adjacent resonators, as illustrated in [6, 8]. The external Q_e of the input and output resonators can be realized by adjusting the characteristic impedance of K_{01} and K_{NN+1}, which can be realized by lumped circuit [6] or external coupling loop [3], in order to achieve impedance matching.

Though it is not the minimum mid-band loss filter, butterworth type prototype is preferred here for its maximally flat response which fits for communication. Therefore, g_i satisfy

$$\begin{aligned} &g_0 = g_{N+1} = 1 \\ &g_i = 2\sin\frac{(2i-1)}{2N}\pi, i = 1, 2, \cdots, N \end{aligned} \tag{2}$$

2.2. Efficiency and Fractional Bandwidth Estimation

For a given transmission distance D between the TX and RX, an arbitrary number of relays can be inserted.

$$D = \sum_{i=1}^{N-1} d_{i,i+1} \tag{3}$$

where $d_{i,i+1}$ is the interval between the ith and $(i+1)$th resonator.

Considering the electromagnetic fields around the resonators decreases exponentially as the function of distance [8], the coupling coefficient can be approximately fitted by an exponential function.

$$k_{i,i+1} = a\exp(bd_{i,i+1}) \tag{4}$$

where a and b are constant coefficients. a is positive, and b is negative. Combine Eqs. (1), (3) and (4), the arrangement of the relays and FBW become

$$d_{i,i+1} = \frac{1}{b}\ln\left(\frac{FBW}{a\sqrt{g_i g_{i+1}}}\right) \tag{5}$$

$$FBW = a\exp\left(\frac{bD}{N-1} + \frac{1}{2(N-1)}\sum_{i=1}^{N-1}\ln(g_i g_{i+1})\right) \tag{6}$$

Since the coefficient b and $\sum\limits_{i=1}^{N-1}\ln(g_i g_{i+1})$ is negative, FBW increases with the number of the relays.

Power transfer efficiency can be estimated by the following, when impedance matched ($|S_{11}| = 0$).

$$\eta = \frac{|S_{21}|^2}{1-|S_{11}|^2} \approx |S_{21}|^2 = 10^{-L_A|_{f=f_0}} = 10^{\left(-0.4343\sum\limits_{i=1}^{N}\frac{g_i}{FBWQ_i}\right)} \tag{7}$$

$L_A|_{f=f_0}$ is the estimated insertion loss at the resonant frequency of the dissipation [7]. Q_i is the unloaded quality factor of ith resonator.

Combining above formulas, transmission efficiency and FBW can be evaluated directivity in terms of transmission distance and the number of relays.

2.3. Design of Relays for SWIPT

With the model and estimation above, a feasible way can be proposed to design a RWPT relay system for SWIPT under fixed transmission distance. The steps are listed as below.

Step 1: The unloaded quality factor evaluation.

The unloaded quality factor Q of the resonators can be calculated according to the definition [5], with their resistance and inductance measured using an impedance analyzer. It can also be obtained with the measurement and algorithm in [9] using a vector network analyzer.

Step 2: Coupling coefficient measurement and fitting.

Considering the resonant frequency splits into different values due to the coupling when two resonators infinitely apart from each other, the coupling coefficient k for various intervals can be calculated by the measured spilt frequencies [3]. Meanwhile, since the response curve of k to the interval can be approximately fitted by an exponential function as indicated in Eq. (4), curve fitting can be easily achieved by mathematical tools like MATLAB, with the values of fitting coefficient a and b obtained.

Step 3: Power transfer efficiency and FBW estimation.

Using Eqs. (6), (7), the efficiency and FBW can be estimated for an arbitrary number of relays under given transmission distance.

Step 4: Relays arrangement.

With the estimation above, decision concerning the number of the relays can be made according to system requirement. Then the deployment of the relays can be determined by Eq. (5), realizing the target of design.

3. PRACTICAL VERIFICATION

Practical verifications have been made using four identical helical coils as Fig. 2. The radius of the coils is 10 cm, the height is 5.5 mm, and the number of turns is 5. The diameter of the copper wire is 0.5 mm. The designed transfer distance is 20 cm. The validation adopts the HFSS simulation and experimental research with GA4063 spectrum analyzer and TD3618C vector network analyzer.

Coils are tuned to resonate at the same frequency of 42.55 MHz, the unloaded quality factor Q of the four coils are measured and listed in Table 1. The measurement is varied with the simulated self-resonance frequency of 45.52 MHz and simulated Q, mainly caused by the error of the coil size, the substrate and the glue used for fixing the coils.

Figure 3 shows the average of measured coupling coefficient results and its fitting curves, as well as the simulated coefficient. From the figure, it can be noted that the measured results are consistent with simulation and the exponential function can fit well. Here, the corresponding fitting coefficients are $a = 0.280$, $b = -0.239$.

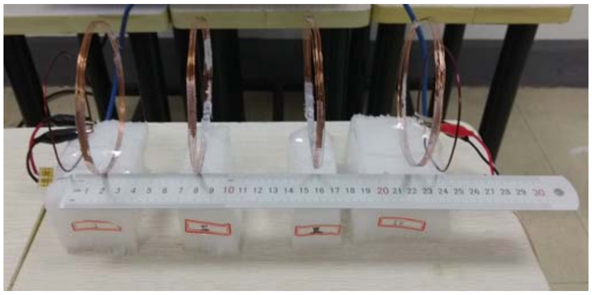

Figure 2. Helical coils used in the experiment.

Power transfer efficiency and FBW with various numbers of relays are estimated by formulas given earlier with different Q's for comparison. The plotted results in Fig. 4 indicate that FBW is not affected by Q and increases with the number of relays, while more relays add little effect on the system efficiency when reaching a certain number of relays.

Figure 5 plots the experimental frequency responses of the system with no relay, one relay and two relays. Table 2 lists the designed intervals between adjacent coils, simulated results (simulated Q of these coils is about 900), measured results and the estimated values of these systems. Simulation results are close to estimates. Though experimental results differ a lot, efficiency rises and bandwidth increases as expected. The difference may be due to the deviation of four coils' resonance frequency and the poor impedance matching.

Table 1. Unloaded quality factor of the four helical coils.

Unloaded quality factor			
Coil I	Coil II	Coil III	Coil IV
130.36	105.02	132.33	100.14

Table 2. Simulation and experimental results.

Interval (cm)			FBW (Estimated)	Simulation ($Q = 900$)			Experimental results (Q listed in Table 1)		
$d_{I,II}$	$d_{II,III}$	$d_{III,IV}$		FBW (Estimated)	η (Estimated)	η (Simulated)	FBW (Measured)	η (Estimated)	η (Measured)
20	\	\	0.33%	0.51%	38.87%	36.73%	1.33%	0.07%	5.43%
10	10	\	3.63%	3.60%	88.48%	87.42%	3.31%	38.90%	29.47%
6.05	7.90	6.05	7.84%	6.33%	92.86%	89.21%	4.47%	56.28%	38.02%

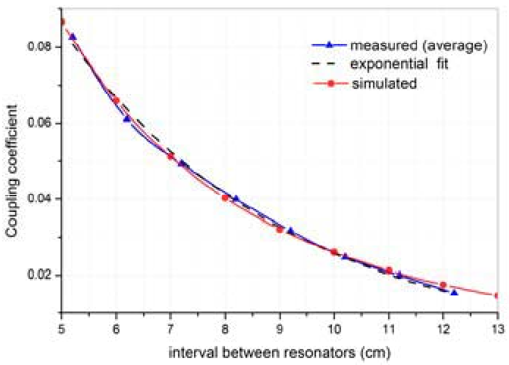

Figure 3. Coupling coefficient with respect to interval.

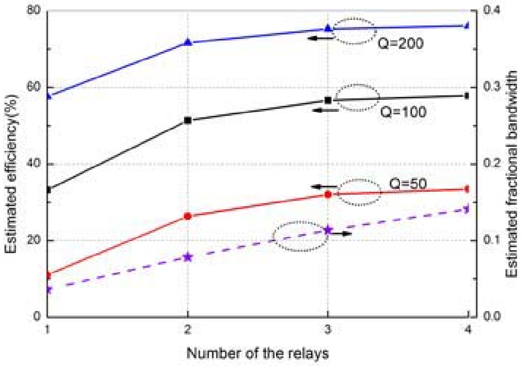

Figure 4. Estimated efficiency and fractional bandwidth versus the numbers of relays.

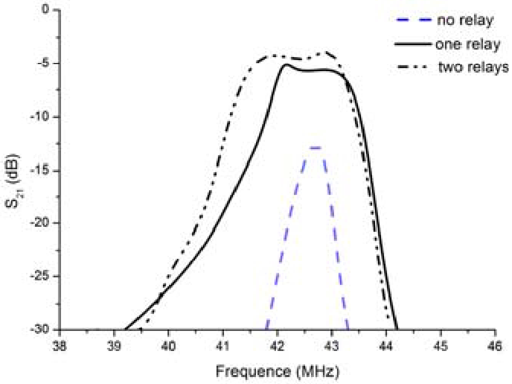

Figure 5. Measured frequency response.

4. CONCLUSION

In this paper, relay scheme is proposed for intermediate-range SWIPT. It is demonstrated that the bandwidth can be widened with the increase of relays, with acceptable power transfer efficiency. Based on coupled resonator filter theory, the simple design method and mathematical equations for efficiency and FBW provide the guideline for relays arrangement. It can be very useful in medical device, mechanical arms, etc. where the power transfer distance is almost fixed, and information transfer is simultaneously needed. Future research will be focused on the design of relays for SWIPT of variable transfer distance.

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