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# From Filter to Mid-Range Wireless Power Transfer System

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**Abstract** — In this paper, a wireless power transfer (WPT) system based on two spiral magnetic-coupled resonators is studied and realized on the printed circuit board (PCB). For the mid-range energy transfer, the microwave filter design theory can be employed to explain the basic principle of magnetic induction in WPT system. Based on the filtering transfer function, the power transfer efficiency is defined by Scattering matrix. In particular, the transfer distance between two resonators can be easily optimized according to the filtering specifications. As an example, Chebyshev function is selected to synthesize the two-pole transmission peaks, which is so-called frequency splitting in power community. Then, the transfer distances can be determined from the required external Q-factor and coupling coefficient. Finally, a PCB-based WPT system fed by two loops is designed, implemented, and verified experimentally.

**Index Terms** — Microwave filters, wireless power transfer (WPT), Scattering matrix, transfer distances, transfer efficiency.

## I. INTRODUCTION

Since Tesla coil was proposed a hundred years ago, a massive research effort has been carried out on the new way of charging, wireless power transfer (WPT) or the so-called wireless energy transfer. The theory of analyzing the WPT system is mainly based on the quasi-static model or lumped-element circuit analysis. However, very limit work has been reported from the filter synthesis point of view [1]. Traditional analysis methods are hard to optimize the transfer distances, and most of the models are mainly based on the L-C resonant circuits or experimental results.

The aim of this paper is to clarify the relationship between microwave filters and WPT systems. From the filter design point of view, power transfer efficiency ( $\eta$ ) and transfer distances in a WPT system can be well defined through the filtering specifications. How to optimize or maximize the transfer distance becomes easier and mathematically achievable. Actually, the self-resonant coils used in the WPT system are magnetic-coupled resonators and can be modeled by the equivalent L-C resonant circuits. As explained in [1], the filter theory can be used to design a WPT system with spiral and loop coils around 25 MHz. On the other hand, the two transmission peaks in WPT system have also been studied in [2], [3] from the view points of the power analysis and electromagnetic field (EMF) analysis. However, the transfer distance cannot be easily optimized. Therefore, it is important to bridge the gap between the WPT system design and the traditional filter theory, including the

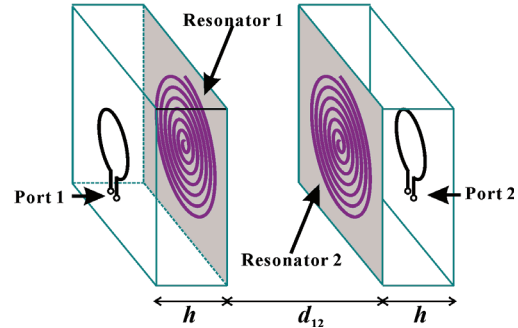


Fig. 1. Configuration of the PCB-based wireless power transfer system with two spiral magnetic-coupled resonators.

TABLE I RELATIONSHIP BETWEEN FILTER DESIGN AND WPT SYSTEM

<i>Filter Design</i>	<i>WPT System</i>
S-parameters/Insertion loss	Transfer Efficiency
Passband Ripples	Frequency Splitting
Transmission Poles	Transmission Peaks
Coupling Efficient	Coupling/Distance between resonators
External Q-factor	Coupling between resonator and I/O circuits
Weak Coupling	Long Transfer Distance
Strong Coupling	Near Transfer Distance

coupling matrix (CM) for coupled-resonator filter topologies. In this study, two square spiral resonators are firstly designed on the PCB substrates. Then, two square loops with the coplanar-waveguide (CPW) to coplanar stripline (CPS) transitions are employed to feed the resonators from another side of the PCB substrate. In this way, a two-pole filtering system is realized and verified experimentally. Importantly, the relationship between the filter design and WPT system is highlighted in Table I, which will be explained in details in the following sections.

## II. FILTER THEORY AND TRANSFER FUNCTION

The CM method design theory is an important technique for designing a coupled-resonator filter. It needs not consider the physical structure of the resonator itself. Especially for the narrow-band bandpass filter design, the coupling coefficients of intercoupled resonators and the external quality factors of the input and output resonators can be synthesized according to the

filtering specifications [4], [5]. Usually, the design procedure contains three steps:

1) Deciding the fractional bandwidth (FBW)

$$\text{FBW} = (\omega_1 - \omega_2) / \omega_0, \omega_0 = \sqrt{\omega_1 \omega_2} \quad (1)$$

where  $\omega_1$  and  $\omega_2$  are the upper and lower cutoff frequency, respectively, and the center frequency  $\omega_0$  can be chosen as the geometric mean of  $\omega_1$  and  $\omega_2$ .

2) Calculating the required external Q value

$$Q_{e01} = \frac{g_0 g_1}{\text{FBW}}, Q_{en, n+1} = \frac{g_n g_{n+1}}{\text{FBW}} \quad (2)$$

which are related to the distance between the loop and the spiral resonator. The elements  $g_0, g_1, g_n,$  and  $g_{n+1}$  are low-pass prototype filter elements and can be computed according to different filtering transfer functions. The subscript,  $n$ , denotes the order of the filter, and thus equals to the number of resonators and the in-band transmission poles.

3) Calculating the required coupling coefficients of the resonators

$$k_{i, i+1} = \frac{\text{FBW}}{g_i g_{i+1}}, i = 1, 2, \dots, n \quad (2)$$

which are related to the distances between the neighboring spirals. Since the  $g$  values are lowpass prototype filter elements and determined by the filter transfer function, we need to choose an appropriate transfer function for WPT system. The Chebyshev filter is superior to Butterworth filter when the order is not high. Especially, the frequency response of WPT system has ripples when the distance is short or the nearby coupling is strong. It is like Chebyshev filter, where the amplitude-squared transfer function can be written as

$$|S_{21}(j\Omega)|^2 = \frac{1}{1 + \epsilon^2 T_n^2(\xi/\Omega)} \quad (3)$$

which is equal to transfer efficiency  $\eta$  defined in [3]. And  $T_n(\Omega)$  is a Chebyshev function of the first kind of order  $n$ , which is defined as

$$T_n(\Omega) = \begin{cases} \cos(ncos^{-1}\Omega) & |\Omega| \leq 1 \\ \cosh(ncosh^{-1}\Omega) & |\Omega| \geq 1 \end{cases} \quad (4)$$

where  $\Omega$  is the angular frequency. As a design example, the passband ripple of a 2-stage system is chosen to be 0.01, while  $g_0=1, g_1=0.4489, g_2=0.4078,$  and  $g_3=1.1008$ .

### III. EXTRACTING EXTERNAL Q FACTOR AND COUPLING COEFFICIENT

In this design example, the square spiral resonators are chosen arbitrarily (11 mm × 11 mm, 4 turns, and strip width = strip space=5 mm). Here, the size of the square loops need to be determined since it is related to the external Q factor.

The external Q factor is defined as the ratio of stored energy to the energy lost in the external circuit, i.e. the feed circuit and the load circuit. Generally, the loaded Q factor is defined as:

$$\frac{1}{Q_L} = \frac{1}{Q_e} + \frac{1}{Q_u} \quad (5)$$

For a two-stage symmetric structure, the external Q factor could be derived from (5). For a singly loaded circuit,  $Q_{eg} = Q_{el} = 1/(1/Q_L - 1/Q_u)$ , where  $Q_{eg}$  and  $Q_{el}$  are the external Q factor in source circuit and load circuit respectively. In other words, the external Q factor is dependent on the magnetic flux from the loop antenna. Thus, it is decided by two factors: the size of the loop antenna and the distance between the loop and spiral. We put the spiral resonator on one side of the substrate, and the loop square on the other side of the substrate. Then, the distance between loop and spiral resonator is equal to the thickness of the substrate. Fig. 2(a) shows the extracted external Q-factor versus the side length of the square loop.

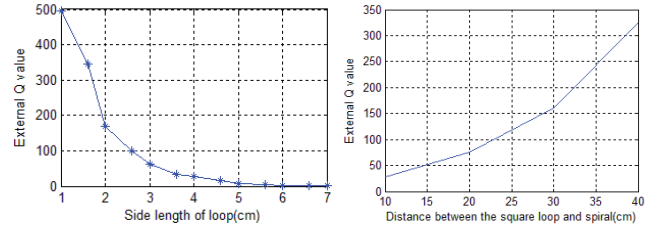


Fig. 2 (a) External Q value versus the loop size. (b) External Q value versus distance between loop and spiral resonator.

We can see that the external Q factor is increased as the distance in-between is increased, as shown in Fig. 2(b).

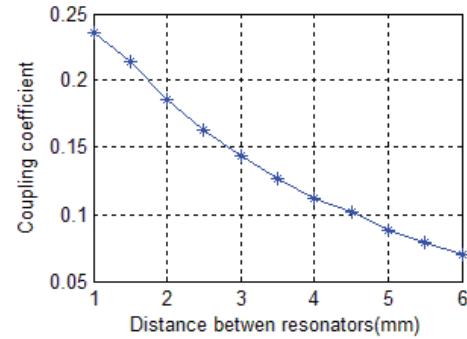


Fig. 3. Coupling coefficient versus distances between two resonators.

Generally speaking, coupling coefficient is defined as the ratio of coupled energy to stored energy. In the coupled resonator filter design, the coupling coefficient is given by [5]:

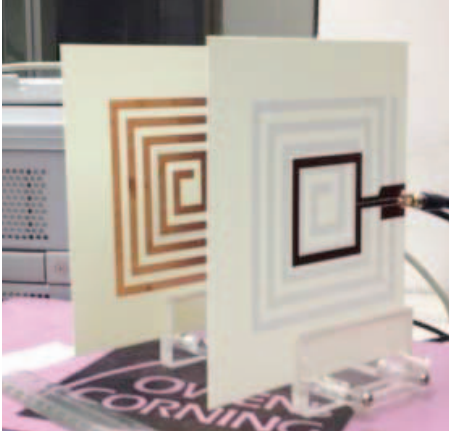


Fig. 4. Photograph of fabricated WPT system with two spiral resonators and two CPW/CPS fed loops.

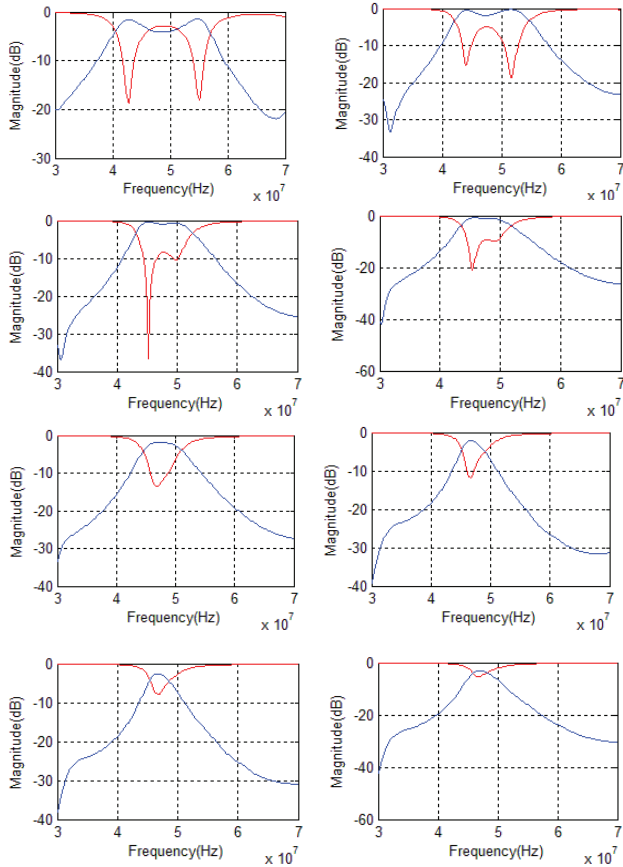


Fig. 5. The tendency of frequency response changes as distance increase from 20 mm to 90 mm.

$$k = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \quad (6)$$

It should be used to compute the coupling coefficient only under weak coupling, where  $f_1$  and  $f_2$  are the frequencies at

two resonant peaks. The relationship between coupling coefficient and the distance between the resonators is shown in Fig. 3. It is important to notice that the smaller the coupling coefficient is, the longer the corresponding distance in-between should be.

#### IV. EXPERIMENT RESULTS

Finally, the aforementioned design is implemented with the side loop length of 46 mm. The photograph of the fabricated two-resonator system is shown in Fig. 4.

Fig. 5 shows the measured results. It is easy to see the two transmission poles in the frequency response, as those also shown in [3]. When the two poles start to merge into one pole, the required coupling becomes weaker and the transfer efficiency is still maximum. As highlighted in Table I, the weaker coupling means the longer transfer distance, while the stronger coupling indicate the near field transfer with shorter distance. Based on the filter theory briefed in Section II, the bandwidth of the filter can be chosen to be as small as possible, in order to make two transmission peaks close to each other. In other words, the narrower bandwidth specified, the longer transfer distance obtained.

#### V. CONCLUSION

The filter design theory has been presented to explain the two transmission peaks in WPT system. Based on the specified filtering parameter, S-parameters have been synthesized and used to design the WPT system. From the microwave filter design point of view, the transfer distance and the efficiency of the WPT system can be well modeled and optimized accordingly.

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