Comparative study of coil resonators for wireless power transfer system in terms of transfer loss

Toshio Ishizaki¹a), Takuya Komori², Tetsuya Ishida², and Ikuo Awai²
1 Panasonic Corporation
I Kotari-yakemachi, Nagaokakyo, Kyoto 617–8520, Japan
2 Ryukoku University
I–5 Yokotani, Seta-ohe-cho, Otsu, Shiga, 520–2194 Japan
a) ishizaki.toshio@jp.panasonic.com

Abstract: For resonator-coupled wireless power transfer systems, various kinds of coil resonators are studied experimentally. First, it should be noted that those systems are explained by a two-pole band-pass filter model with electromagnetic coupling between resonators. Then transfer loss is estimated explicitly. Three kinds of coil resonators are compared quantitatively, a spiral coil, an edge-wise spiral coil, and a solenoidal coil. Unloaded Q, external Q, and coupling coefficient k are measured by experiments. Among them, the spiral coil is found to be suitable for the wireless power transfer. Simulation result shows good agreement with the experimental result and is supported with the experimental result. As a result, it is confirmed that the power transfer system can be designed by the conventional multi-stage filter theory. And the advantage of spiral coil is shown.

Keywords: wireless, power transfer, spiral, edge-wise spiral, solenoidal, loop, coupling

Classification: Microwave and millimeter wave devices, circuits, and systems

References
1 Introduction

The wireless power transfer is one of the most popular topics since MIT group has lighted a 100 W bulb by transmitting the electric power wirelessly from the source 1 m apart [1]. Since they used coupled two helical coils that also couple to the external circuits, it makes a two-stage bandpass filter.

The main feature of a wireless power transfer system includes large transfer distance and low transfer loss, and hence, the characteristics of the helical coils that make a coupled resonator system are crucial. We will study the unloaded Q and coupling coefficient \( k \) of the helical coil resonators parametrically whose product directly decides the transfer loss.

Our study is carried out experimentally and also by the electromagnetic field simulation, taking three types of resonators, spiral, edge-wise spiral and solenoidal coil resonators. We will compare them parametrically in terms of unloaded Q \((Q_u)\), external Q \((Q_e)\), coupling coefficient \( k \) and \( kQ_u \) product.

2 Basics of wireless power transfer

Fig. 1 shows the block diagram of a wireless power transfer system, where each I/O loop is coupled with a resonator. The distance between the I/O loop and the resonator is expressed as \( a \). The two resonators are coupled each other with distance \( d \) to construct a 2-pole bandpass filter. The electric power is transferred by the electromagnetic coupling between I/O loops and resonators.

![Fig. 1. Block diagram of wireless power transfer system](image)

So far, the system design has been on the trial-and-error base and an arbitrary coil, such as solenoidal coil, has been used as a resonator without any investigation. Once the principle of the power transfer system is interpreted by a bandpass filter model, however, its electrical performance is calculated by the conventional filter theory. The transfer loss can be easily estimated from Cohn’s equation [2, 3], which is expressed as

\[
L = 4.343 \sum_{i=1}^{N} \frac{g_i}{wQ_{ui}},
\]

(1)
where \( g_i \) is the \( g \)-parameter for the prototype low pass filter, \( Q_u \) is the unloaded \( Q \) for each resonator and \( N \) is the number of resonators. Now, the matching conditions for a two-pole BPF are given as

\[
Q_e = 1/k_e = g_0 g_1 / w = g_2 g_3 / w
\]

\[
k_{1,2} = \frac{w}{\sqrt{g_1 g_2}} = k,
\]

where \( Q_e \) is external \( Q \) for each resonator, \( k_{12} \) is the coupling coefficient between two resonators and \( w \) denotes the fractional bandwidth of the BPF. For two-pole BPF with Butterworth type, \( g_1 = g_2 = 1.414 \) and \( g_0 = g_3 = 1 \). Using eq. (3), eq. (1) is rewritten as

\[
L = 4.343 \sum_{i=1}^{2} \frac{1}{k Q_u_i}.
\]

If one uses the same resonators as shown in Fig. 1, the relation \( Q_u = Q_{u1} = Q_{u2} \) holds and eq. (4) is simplified into

\[
L = \frac{8.686}{k Q_u}.
\]

Validity of the simple expression for the transfer loss above has been confirmed by us experimentally [4]. Therefore, it is most important to know \( k Q_u \) product so as to estimate the transfer loss of resonator-coupled power transfer systems. Though \( Q_e \) (or \( k_e \)) does not affect the transfer loss directly as is known from eq. (4) or eq. (5), it dominates the circuit matching and may be reflected into the loss indirectly. Thus, it will be addressed later together with \( Q_u \).

3 Three types of coil resonators

Here, the resonators, a spiral coil, an edge-wise spiral coil, and a solenoidal coil are comparatively studied. Copper wire of 1.0 mmφ with insulating coat is used for making coil resonators. Fig. 2 is the photograph of I/O loop and coil resonators. Along the marker on the Styrene-foam board for exact positioning, the coil is formed by winding the copper wire.

The diameter of the I/O loop is 17 cm. The outer diameter of all the resonator coils is unified into 24.5 cm for fare comparison. The inter-line space of the spiral coil is 1 cm and the number of turn is 13. That of the edge-wise spiral coil is 2.5, while that of the solenoidal coil is 5, keeping each resonant frequency around 25 MHz. The pitch of the solenoidal coil is 1 cm.

4 Experimental results

The electrical performance of the resonators described in Sec. 3 is measured by using a Vector Network Analyzer. At first, the coupling coefficient between two identical resonators is measured for three types in the same configuration as Fig. 1, but with large \( a \) enough to keep the small perturbation of the loop to the helical resonator. The measured \( S_{21} \) exhibits two distinct
Fig. 2. I/O loop and coil resonators (a) I/O loop, (b) Spiral coil resonator, (c) Edge-wise spiral coil resonator, (d) Solenoidal coil resonator

peaks that correspond to the even- and odd-mode resonances of the coupled resonator. The coupling coefficient calculated from those peaks is drawn in Fig. 3 (a), showing that spiral coils give the largest value. For the spiral coil and the edge-wise spiral coil, the minimum measurement distances between resonators are 1 cm due to the thickness of the Styrene-foam board.

The reflection method proposed by Y. Kobayashi [5] is used for the measurement of unloaded Q and external Q (external $k$), giving the measured result in Figs. 3 (b) and (c). Though the external Q should be the same as the reciprocal of coupling coefficient for attaining the circuit matching as is known from eqs. (2) and (3), it is not small enough to comply with the strong coupling coefficient for any resonators studied here as is shown in Fig. 3 (c). It is because the single loop probe that we use for the excitation of the resonators does not couple strongly enough with them. We may need multiple-turn loop for those cases.

Since the unloaded Q does not change appreciably for different distance $a$ between the loop and resonator, we assume tentatively that they are constant irrespective of the distance between two resonators. As shown in Fig. 3, the spiral coil is most suitable for wireless power transfer system in terms of the transfer loss.
5 Simulation for spiral coil

Spiral coil resonator is analyzed by 3D EM simulator. The analyzing method is FEM (Finite Element Method) carried out by commercially available program of HFSS (Ansoft). The simulation parameters are as follows. The diameter is 23.4 cm and the number of turn is 12. The inter-line space of the spiral coil is 1 cm. The ohmic loss of metal wire is taken into account. But radiation loss is not included in the simulation. The resonance frequency calculated by the simulation is 24.7 MHz. The unloaded Q factor ($Q_u$) is 917.

These values show very good agreement with those obtained by experiments of 25.0 MHz and 839 mentioned in Sec. 4. The $Q_u$ obtained by experiment is a little bit lower than that of simulation. It might be caused by radiation. Unfortunately, it is not clear that the reason is due to radiation loss or simulation error at this moment. It is a remaining subject for the future work.

6 Conclusions

The wireless power transfer system are explicitly expressed as a bandpass filter, and thus the transfer loss is formulated by the conventional filter theory. Three types of coil resonators, spiral coil, edge-wise spiral coil and solenoidal coil, for wireless power transfer are comparatively studied for the first time. The quantities $Q_u$, $Q_e$, and $kQ_u$ product are measured by experiments. It is confirmed that the spiral coil among them is most suitable for small transfer loss, because $Q_u$ is high, $Q_e$ varies in the wider range, and $kQ_u$ product is high. Study on radiation $Q$ and miniaturization of resonators are still remaining subjects for the future work.