# Design of Multi-frequency Coil for Capacitor-less Wireless Power Transfer using High Order Self-resonance of Open End Coil


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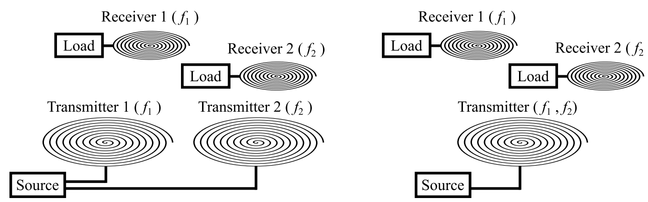
***Abstract*—Wireless power transfer is a popular research subject in recent years. Available frequency for wireless power transfer (WPT) is limited by the industrial, scientific, and medical (ISM) radio bands in MHz band and some laws. Depending on the application of wireless power transfer, different frequency bands are used. A single transmitter coil which can adapt to multiple frequency bands is needed for reducing number of transmitter coils. In this paper, transmitter coil design for multiple frequencies using high order resonant frequency is proposed. Main purpose of coil design is that first resonant frequency is allocated at 85 kHz for Electric Vehicles and second resonant frequencies of multi-frequency coil is allocated at ISM bands. Characteristics of proposed coil is confirmed by electromagnetic simulation and experiment.**


## I. INTRODUCTION

Magnetic resonant coupling of wireless power transfer (MRCWPT) is a popular research topic in recent years [1]. MRCWPT is superior to other WPT methods (e.g. magnetic induction, electric field coupling, microwave) in terms of transmission distance, efficiency and transmission power [2], [3]. Frequency characteristic of transmission coils is the dominant characteristic. For instance, Q value of the coil is the dominant factor in transmission efficiency and power [2].

This paper focuses on solving the problems of frequency compatibility. Some applications have specific resonant frequency due to limitation of ISM bands in MHz band. The frequency allocation for MHz range WPT are 6.78 MHz, 13.56 MHz and so on. Therefore, multiple high frequency bands are required when WPT technology is used universally at home, office and companies. Each application needs a resonant system in trasmitter side and receiver side respectively. In order to use multiple frequencies, many resonant coils and capacitors are needed which will be costly and occupying space at the source side (transmitter side). Therefore, design of a multiple self-resonant coil is proposed in this paper. The newly proposed coil design can reduce the number of trasmitter coils needed in WPT system because each transmitter coil can adapt to different frequencies.

Main porpose of coil design is that all resonant frequencies of multi-frequency coil are allocated at ISM bands. This paper presents a fundamental design method for multi-frequency coil. In section I, comparison between short end coil and open end coil is performed. Superiority of open end coil is explained in capacitor-less condition. In section II, electromagnetic simulation and experiment are performed to clarify the relationship between the shape of coil and frequency characteristics. In section III, multi-frequency band resonant coil is designed based on the relationship between shape of coil and frequency characteristics. In section IV, wireless power transfer characteristics of multi-frequency band resonant coil is verified using simulation and experiment.




(a) Conventional system (b) Proposed system

Fig. 1. Multiple frequency band WPT system

## II. SHORT END COILS AND OPEN END COILS

### A. Proposed system

Fig. 1(a) and Fig. 1(b) show the conventional two frequency system and proposed system respectively. Conventional system has two transmitter coils, but proposed system needs only one transmitter coil [4], [5]. The proposed system can reduce the number of transmitter coils. Proposed transmitter coil is designed to adapt to more than two resonant frequencies.

### B. Short end coil and open end coil

Transmission coils are generally divided into two types, the short end coil and the open end coil [6], [7], [8]. Fig. 2(a) shows the image of the coils respectively. In order to compare the two coils, transmission line theory is used. Input impedance, $Z_{\rm in}$ is shown in (1)

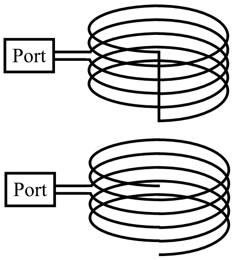
$$Z_{\rm in} = Z_0 \frac{Z_{\rm L} + jZ_0 \tan\beta l}{Z_0 + jZ_{\rm L}\tan\beta l} \tag{1}$$

where $Z_0$ and $Z_{\rm L}$ are the characteristic impedance and the load impedance respectively, $\beta$ is the phase constant ($\beta = \omega/c$, $\omega$: angular frequency, $c$: speed of light), $l$ is transmission line length, In the case of $Z_{\rm L} = 0$, (1) behaves as short end coil. $Z_{\rm in-short}$ is shown in (2).

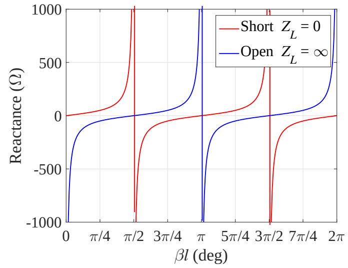
$$Z_{\rm in-short} = jZ_0 \tan\beta l \tag{2}$$

In the case of $Z_{\rm L} = \infty$, (1) behaves as open end coil. $Z_{\rm in-open}$ is shown in (3).

$$Z_{\rm in-open} = -jZ_0 \cot\beta l \tag{3}$$




(a) Image of coils




(b) Reactance characteristics

Fig. 2. Short end coil and open end coil

Assuming that $Z_0 = 50\ \Omega$, $Z_{\rm in}$ is calculated in Fig. 2(b) by using (2) and (3). From Fig. 2(b), under capacitor-less condition, open end coil has two lower self-resonant frequencies compared to short end coil. In order to use high order resonant frequency, resonant frequency should be lower in available frequency band. Therefore open end coil is superior to short end coil and is mainly discussed in this paper.

## III. Relationship between shape of coil and frequency characteristics

In order to clarify the variation of frequency characteristics by changing the coil shape, layer gap and wire pitch were changed. Fig. 3 shows the shape parameter of open end coil. In Fig. 3, $g_l$ is the layer gap, $p$ is the wire pitch. Copper wire was used for simulation and experiment, and the wire diameter is 2 mm. Radius of the coil is 150 mm, and number of turns is fixed to 2.5.

Fig. 4(a) and Fig. 4(b) show resistance and reactance vs. frequency plots for differet layer gaps, $g_l$ respectively. Unit of shape parameter is mm. As shown in Fig. 4(b), resonant and anti-resonant frequency are shifted by layer gap, $g_l$.

Fig. 4(c) and Fig. 4(d) show resistance and reactance vs. frequency plots for wire pitchs, $p$ respectively. As shown in Fig. 4(d), resonant frequency is not shifted, but anti-resonant frequency is shifted by wire pitch, $p$. This is a unique characteristics of the coil where the resonant frequency is not affected by the wire pitch, $p$. In coil design, it is clear that layer gap, $g_l$ should be used for adjustment of resonant frequency, and wire pitch $p$ should be used for minor adjustment of anti-resonant frequency.

In order to validate the simulation results, experiment was performed. Fig. 5(a) and Fig. 5(b) show experimental results by using actual coils. Experimental results have similar characteristics as the simulation results. Therefore, the relationship between coil shape and frequency characteristics is validated. Coil design method achieving for optimal frequency characteristics by changing coil shape is proposed in the next section.

## IV. Design of multi-frequency band self resonant open end coil

The target of proposed coil design is to achieve second resonant frequency at 13.56 MHz due to availability of ISM band as first coil design.

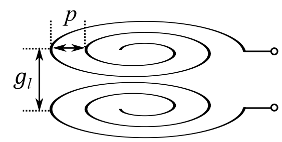
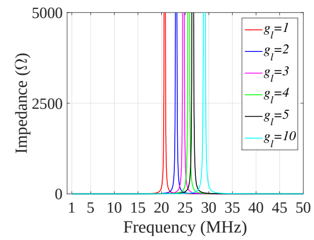
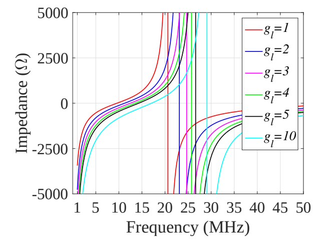


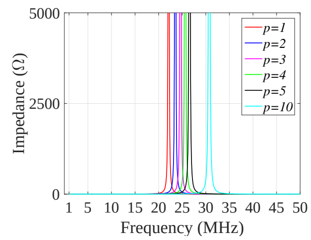

Fig. 3. Shape parameter of open end coil



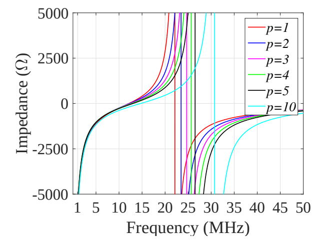

(a) Resistance vs. frequency for different layer gap $g_l$




(b) Reactance vs. frequency for different layer gap $g_l$

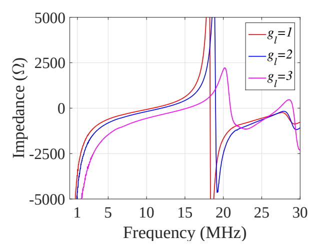



(c) Resistance vs. frequency for different wire pitch $p$

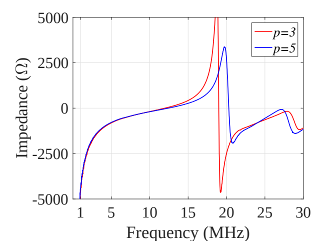



(d) Reactance vs. frequency for different wire pitch $p$

Fig. 4. Impedance vs. frequency for different shape parameter (Simulation)




(a) Reactance vs. frequency for different layer gap $g_l$




(b) Reactance vs. frequency for different wire pitch $p$

Fig. 5. Reactance vs. frequency for different shape parameter (Experiment)

Firstly, high order resonant frequency should be shifted to available frequency band. Wire length should be longer based on transmission line theory. From (3), the dominant parameter $\beta l$ is shown in (4).

$$\beta l = \frac{\omega}{c}\, l \tag{4}$$

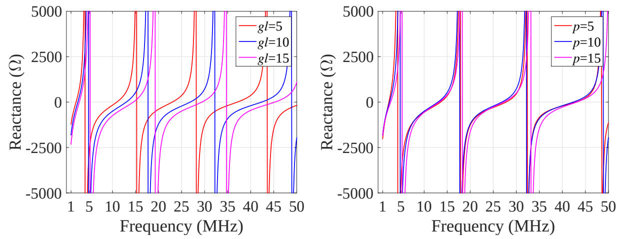
From (4), in order to create many resonant points in available frequency band, $l$ should be longer to achieve larger $\beta l$. When $\beta l$ is larger, the frequency range between two resonant frequency is smaller. The design method are based on expansion of the radius and increasing number of turns.

Secondly, the second resonant frequency is adjusted to target frequency by changing the layer gap, $g_l$ or wire pitch, $p$.

Fig. 6 shows reactance frequency plots vs. the shape pa-

TABLE I
RESONANT CHARACTERISTICS OF PROPOSED COIL

| | Simulated value (MHz) | Measured value (MHz) |
|---|---|---|
| First resonant | 2.5 | 2.2 |
| First anti-resonant | 4.8 | 3.9 |
| Second resonant | 13.0 | 12.4 |




(a) Reactance vs. frequency for different layer gap $g_l$

(b) Reactance vs. frequency for different wire pitch $p$

Fig. 6. Impedance of proposed coil vs. frequency for different shape parameter (Simulation)

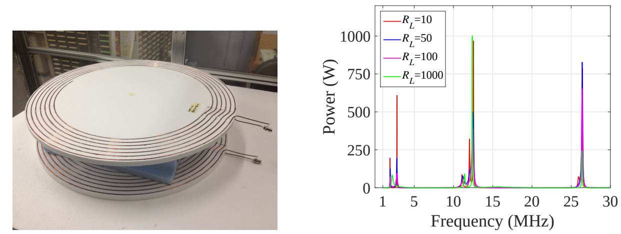
rameter for different $g_l$ and $p$. As for the designed condition, the radius is 300 mm, wire diameter is 2 mm, number of turns is 6.5. Optimal values of shape parameter are decided by comparing the shape vs. resonant frequency characteristics. From the results, $g_l$ and $p$ were decided to be 10 mm. Table I shows simulated and measured values. The experimental results agree with the simulation results. Second resonant frequency is successfully achieved at around 13.56 MHz.

## V. WIRELESS POWER TRANSFER CHARACTERISTICS

By using two newly designed multi-resonant coils, wireless power transfer characteristics are discussed. When resonant frequency of transmitter side and receiving side are matched, power is transferred. In the case of using two proposed multi-resonant coils, power can be transferred around resonant frequency of proposed coil, because resonant frequency in each side are matched.

In order to confirm how much electric power the designed coil can trasmit, experiment using actual coils was performed. Characteristics of wireless power transfer was measured by using network analyzer E5061B (Agilent Technologies). The gap between coils is 100 mm, and load resistance is changed (10, 50, 100, 1000 Ω). Received power is calculated by using measured S-parameter assuming that input voltage is 100 V. Fig. 7(a) shows the experimental setup. Fig. 7(b) shows the experimental result of receiving power. From the results, it is confirmed that power can be transmitted around the designed multiple resonant frequencies. At first resonant frequency (around 2.5 MHz), load resistance is 10 Ω, received power was 610 W. At second resonant frequency (around 13 MHz), received power was 968 W. At anti-resonant frequency (around 4.8 MHz), received power was very low at mW order.

In this case, power can be transmitted to receiver coils when resonant frequency of primary coil matches the resonant frequency of receiving coil. The designed coil can transmit power at more than two resonant frequencies to multiple




(a) Experimental setup

(b) Experimental result

Fig. 7. Power transmission characteristics

receivers which has different resonant frequencies. Design of multi-frequency coil was achieved.

## VI. CONCLUSION

The fundamental design method multi-frequency self-resonant open end coil using high order resonant frequency is proposed in this paper. The relationship between the shape of coil and frequency characteristics was found by simulaton and experiment. Layer gap can adjust the resonant and the anti-resonant frequency simultaneously. Wire pitch can adjust only the anti-resonant frequency. In order to use high order resonant frequency, a coil which has longer wire length than original coil was designed by using the relationships between the shape of coils and frequency characteristics. Target frequency was set at 13.56 MHz (ISM band) in coil design. The proposed coil can be used multi-frequency band, and simulation and experimental result show that proposed coil can transmit power at different frequencies. Therefore, design of multi-resonant open end coil was achieved. As future works, a coil design which all resonant frequencies are allocated in ISM bands will be performed by proposed design method.

## ACKNOWLEDGMENT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