Transmission efficiency improvement using Shielded Loop Antenna for Coupled-resonant Wireless Power Transfer

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Abstract:
Impedance matching mechanism of shielded loop antenna for coupled-resonant wireless power transfer is discussed. It is known that transmission efficiency of the shielded loop antenna is improved as compared with the loop antenna. In this report, we investigate the mechanism of transmission efficiency improvement in shielded loop antenna through equivalent circuit analysis. As a result, impedance matching is achieved due to the capacitance between the inner conductor and the outer conductor to improve transmission efficiency.

Keywords: Wireless power transfer, Coupled resonance, Shielded loop, Impedance matching, Loop antenna

Classification: Antennas and propagation

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1 Introduction

In recent years, wireless power transfer (WPT) technology is getting large interests [1]. Magnetic coupling WPT technology has been applied in low-power portable electronic devices and electric vehicles (EVs) wireless charging.

There are two types of antennas used for magnetic coupling WPT: self-resonant type [2] and LC resonant type [3]. Self-resonant coupler has a function not only coupling but also impedance matching of imaginary part because the resonator has inductive and capacitive components [4]. However, since the self-resonant coupler has strong electric field around the resonator, resonant frequency is affected by surrounding objects. In the LC resonant type, coupler (i.e. coupling coil) has a function of only coupling, thus resonant capacitor is used [4]. Because the electric field is concentrated within the connected matching circuits, it is not affected much by the external dielectric.

In the conventional LC resonant type, a loop antenna with resonant capacitor has been used [5]. To achieve high efficiency, it is necessary to increase kQ product. The kQ product is composed of coupling coefficient $k$ and Q factor [6]. The coupling coefficient $k$ is represented by the difference between the magnetic field coupling coefficient $k_m$ and the electric field coupling coefficient $k_e$. Thus, $k$ is increased by reducing the value of the electric field coupling coefficient $k_e$ [7].

Shielded loop antenna has been used as a magnetic field sensor [8] because this antenna can suppress sensitivity of electric field coupling. It is reported that by using the shielded loop antenna for LC-resonant WPT for an aim of reducing electric-field coupling to increase kQ product, transmission efficiency is improved [9]. However, the mechanism for improving transmission efficiency has not been clarified.

In this report, we clarify the mechanism of improvement of transmission efficiency using a shielded loop antenna. First, in order to elucidate the mechanism, a shielded loop antenna is represented by an equivalent circuit. After that, frequency characteristics and distance characteristics were obtained by method of moment (MoM). Finally, the mechanism of improvement of transmission efficiency is clarified from the equivalent circuit.

2 Structure of shielded loop antenna

Structure of a shielded loop antenna is shown in Fig.1. This structure is made of a coaxial cable. Both the inner and the outer conductors are connected at the end of the coaxial cable. There is a gap in a part of the outer conductor to prevent
current flows on the outer conductor. The sensitivity to the magnetic field is not suppressed by the outer conductor. The sensitivity to the electric field is suppressed by the outer conductor.

Fig.1. Structure of shielded loop antenna

3 Equivalent circuit analysis

In order to investigate the mechanism of transmission efficiency improvement, conventional one-turn loop antenna and shielded loop antenna for LC resonator is compared through equivalent circuit analysis. The conventional loop antenna and the shielded loop antenna has same loop diameter.

An equivalent circuit of a conventional loop antenna is shown in Fig.2 (a) (i). Loop antenna can be represented by an inductor. A series capacitor $C_{s1}$ is connected for resonance. In this case, only the loop antenna acts as a coupler for power transfer. To achieve complex-conjugate matching, freedom of two is necessary in matching circuit to adjust real and imaginary part of the impedance. In this circuit topology, only one parameter: $C_{s1}$ can be changed.

A loop antenna with shunt capacitor $C_p$ is shown in Fig.2 (a) (ii). The shunt capacitor represents stray capacitance between the inner and the outer conductor of the shielded loop antenna. A series capacitor $C_{s2}$ is also connected for resonance. From viewpoint of conjugate matching, this circuit topology has freedom of two: $C_{s2}$ and $C_p$. Thus, conjugate matching can be achieved.

An equivalent circuit of the shielded loop antenna is shown in Fig.2 (a) (iii). In this case, the coupler (i.e. shielded loop antenna) is represented by inductor and capacitor.

To determine the parameters of equivalent circuit, numerical simulation using method-of-moment (MoM) is conducted. Simulation model is shown in Fig.2 (b). The Tx loop has port 1 and the Rx loop has port 2. Radius of these antennas is 600 mm. A capacitor is connected to each antenna to resonate at 6.78 MHz. Copper (conductivity $\sigma = 58.13 \times 10^6$ S/m) is used for a conductor material of the antenna. Equivalent circuit parameters are determined so that the input impedance of the equivalent circuit becomes identical to the result of MoM. The resultant parameters are shown in Fig.2 (c).

To verify the adequateness of the equivalent circuit, frequency characteristics of the imaginary part of the impedance are shown in Fig.2 (d). Input impedance obtained by equivalent circuit (Eq) and MoM is in good accordance. From this
result, the shielded loop antenna can be represented by the equivalent circuit in Fig.2 (a).

![Equivalent circuit of antennas](image)

i. One-turn loop

ii. One-turn loop with $C_p$

iii. Shielded loop

(a) Equivalent circuit of antennas

![Simulation model](image)

(b) Simulation model

| $L_c$ [μH] | $C_{s1}$ [pF] | $C_{s2}$ [pF] | $C_p$ [pF] |
|------------|---------------|---------------|-------------|
| 2.59       | 219.0         | 182.8         | 37.4        |

(c) Parameters of equivalent circuit

![Frequency characteristics of Impedance](image)

(d) Frequency characteristics of Impedance (Imaginary part)

Fig.2. Equivalent circuit analysis
4 Transmission efficiency

Frequency characteristics of input impedance calculated by MoM are shown in Fig.3 (a). It is shown that the loop antenna with capacitor $C_p$ has the same frequency characteristics as the shielded loop antenna.

The distance characteristic of $S_{21}$ calculated by MoM is shown in Fig.3 (b). Transmission distance over 80% efficiency of the shielded loop is extended by 67.4% compared to the one-turn loop antenna. On the other hand, Transmission efficiency of the loop with shunt capacitor is identical to that of shielded loop antenna. This means that the transmission-efficiency improve effect of the shielded loop antenna is due to the impedance matching effect of the stray capacitance between the inner conductor and the outer conductor.

5 Conclusion

In this paper, we investigated the mechanism of transmission efficiency improvement in shielded loop antenna for wireless power transfer. Numerical simulation demonstrates that transmission distance over 80% efficiency of shielded loop antenna was 67.4% extended compared to the one-turn loop antenna. Equivalent circuit analysis shows that input impedance of the shielded loop antenna can be explained by the one-turn loop antenna and a capacitor which represents stray capacitance between the inner and the outer conductor. Since this circuit topology has freedom of two, conjugate matching was achieved to improve
transmission efficiency.

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