# Optimized shield design for reduction of EMF from wireless power transfer systems

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**Abstract:** In this paper, we proposed an optimized shield design for electromagnetic field (EMF) reduction from the wireless power transfer (WPT) system. Three different cases of shield design are examined in terms of strength of EMF and mutual inductance, which is directly related to power transfer efficiency. Analysis results show that when using both ferrite and conducting sheets as a shield for transmitter and receiver coils, a leakage magnetic field can be significantly reduced with negligible change in mutual inductance. Additionally, the effects of the conducting sheet's size and thickness on the EMF and the mutual inductance are also examined. Our investigation will be helpful to engineers designing modern WPT systems.
**Keywords:** wireless power transfer (WPT), electromagnetic field (EMF), shield design
**Classification:** Electromagnetic theory

## References

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## 1 Introduction

Wireless power transfer (WPT) technology has recently been used in a wide variety of devices including smartphones and tablets, as well as larger objects such as robots and electric vehicles [1, 2]. This technology allows us to charge various devices simultaneously using only a one charger and without plugging each device into a separate wired power adapter. Although WPT technologies provide the public with convenience, there is rising concern regarding the safety of human exposure to electromagnetic fields (EMFs), and electromagnetic interference (EMI) with other devices while wirelessly charging [3]. Accordingly, each country is adopting EMF regulations for electronic products. As more applications with WPT technologies are used, the electromagnetic environment becomes a more serious issue, and much effort is necessary to reduce the EMF and EMI from induced magnetic fields. To reduce the EMF from the WPT system, shielding is an important issue in the system design [1, 4]. In this paper, we examine several types of shield design by simulations using a commercial finite element method (FEM) solver [5], and thereby propose the best shielding design for the reduction of EMF from WPT systems, while keeping good power transfer efficiency. The accuracy of commercial FEM solver from ANSYS Maxwell in analyzing WPT structure has been well proven through tests which obtained good agreement with measurement [1].

## 2 Magnetic resonant WPT system

A WPT system based on magnetic resonance coupling, which is commonly used in electric vehicles and modern mobile devices, offers not only the highest power transfer efficiency but also high wireless transmission power at near distances. In a WPT system, there are two coils, a transmitter (Tx) coil and a receiver (Rx) coil. An alternating current in the Tx coil generates a magnetic field which induces voltage in the Rx coil. This voltage can be used to power a mobile device or charge a battery. Fig. 1 illustrates an equivalent circuit of the magnetic resonant WPT system for analysis of the power transfer efficiency between two coupled coils [1].

The power transfer efficiency, denoted $\eta$, is the ratio of the output power ($P_{\text{out}}$) of the load to the input power ($P_{\text{in}}$) generated by the Tx coil. Under a resonant condition, the power received by the Rx coil is maximal because the reactive parts of the system cancel out. The power transfer efficiency can then be written as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{R_L(\omega M)^2}{(R_L + R_2)\left[R_1(R_L + R_2) + (\omega M)^2\right]} \tag{1}$$
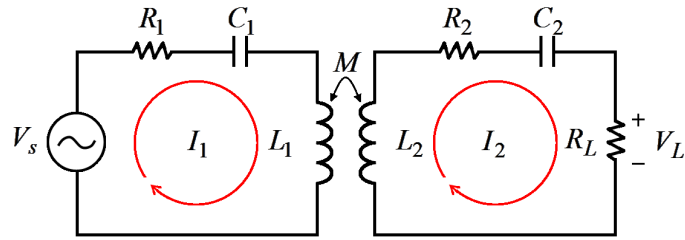
**Fig. 1.** Equivalent circuit of magnetic resonant wireless power transfer system.

where $R_1$ and $R_2$ represent the total effective series resistances of the Tx and Rx coils, respectively, $R_L$ is the equivalent load resistance, and $M$ is the mutual inductance between coils. If $R_L >> R_2$

$$\eta \approx \frac{1}{1 + R_1 R_L/(\omega M)^2}. \tag{2}$$

From (2), it is evident that larger mutual inductance implies higher efficiency. By using the magnetic materials with high permeability, a larger mutual inductance value can be achieved by enhancing magnetic coupling between the Tx and Rx coils. In addition, the mutual inductance is also affected by the shield design near the coils.
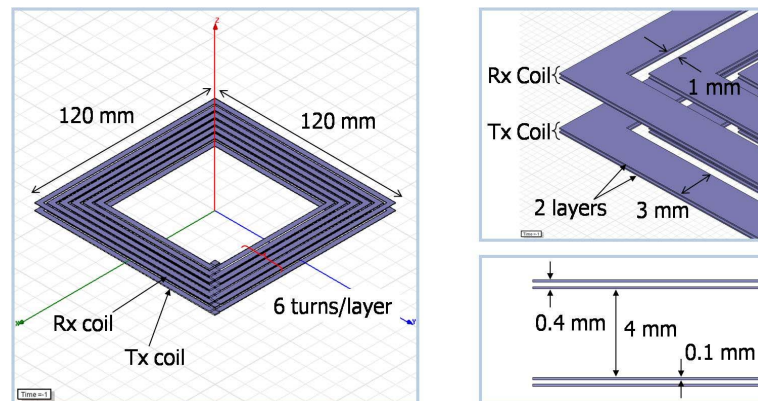


**Fig. 2.** Coil geometry for wireless power transfer.

## 3 Coil geometry

Fig. 2 shows the geometry and arrangement of Tx and Rx coils used to investigate an optimal shield design for laptop computer applications. The coils are planar square spiral shaped with the size of $120 \times 120\,\text{mm}^2$. Each coil consists of two-layered patterns. Each layer has 6 turns of copper strip trace and is connected through via. The trace dimension is $3\,\text{mm}$ in width and $0.1\,\text{mm}$ in thickness. The length of each coil is $4662\,\text{mm}$. The distance between the Tx coil and the Rx coil is $4\,\text{mm}$. Current at the Tx coil is $4.5\,\text{A}$ with a frequency of $100\,\text{kHz}$. The resistance of each coil is around $0.33\,\Omega$ as calculated by $R_{ac} = L/\left[w\sigma\delta(1 - e^{-t/\delta})\right]$ where $L$, $w$, and $t$ are coil

length, width, and thickness, respectively, and $\sigma$ and $\delta$ are the conductivity of copper and its skin depth at 100 kHz, respectively. Without loss of generality, it can be assumed that the loss from the coil is negligible compared to the transmitted power between the Tx and Rx coils.
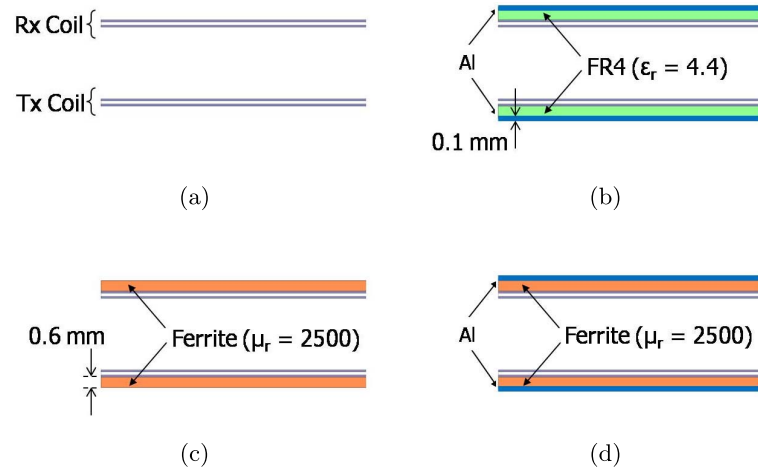


**Fig. 3.** WPT coil systems with three different shielding designs. (a) Only coil as a reference. (b) Coil with both an Al sheet and a dielectric sheet. (c) Coil with a ferrite sheet. (d) Coil with both a ferrite sheet and an Al sheet.

## 4 Shield designs

In general, there are two types of magnetic field shielding techniques using materials: one uses conductive material and the other utilizes magnetic material. When an electric conductor is placed in a time varying magnetic field, electric currents are necessarily induced in the conductor by electromagnetic induction. The magnetic field produced by the induced electric current, called an eddy current, tends in general to oppose the applied magnetic field. The magnetic fields produced by the circulating eddy currents attempt to cancel the larger external fields near the conductive surface, thereby generating a shielding effect. On the other hand, the traditional method for magnetic field shielding involves magnetic materials. These materials have magnetically high permeability, i.e., they have an extremely high capacity to concentrate magnetic flux through the material, providing a lower reluctance path than air. There are two basic types of magnetic materials: metallic, and metallic oxide or ceramics. The metallic magnetic materials such as iron and steel have not only high permeability but also high conductivity. Therefore, they have a significant loss at high frequency due to the eddy current. On the other hand, ceramic magnetic materials such as Ni-Zn and Mn-Zn ferrites have a very low conductivity. It means that the eddy current loss in the ferrite is negligible at low frequency.

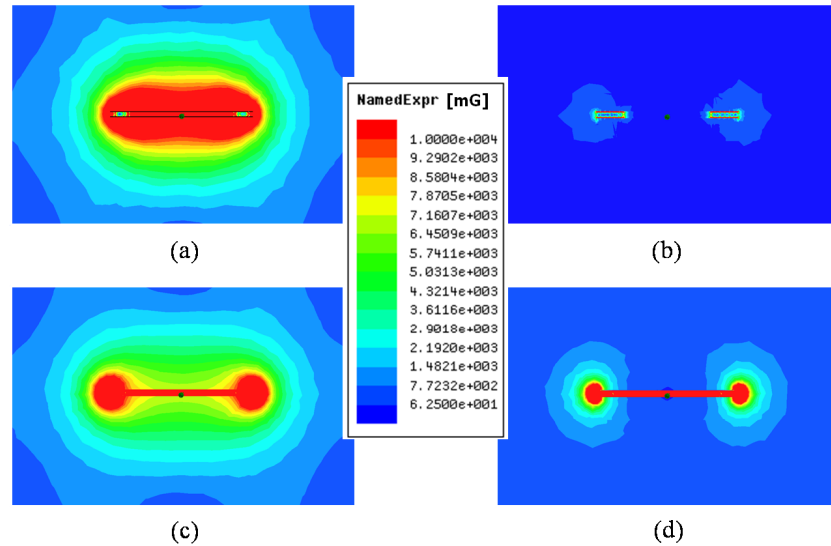In this study, aluminium (Al) and Mn-Zn ferrite sheets are applied to the

**Fig. 4.** Distributions of magnetic flux density for each shield case. (a) Only coil. (b) Coil with both an Al sheet and a dielectric sheet. (c) Coil with a ferrite sheet. (d) Coil with both a ferrite sheet and an Al sheet.

WPT's coil system so as to examine their shielding and EMF characteristics and then find an optimal shield design. Fig. 3 shows three different cases of shield design and only coil case as a reference structure. The first case of shield design uses both an Al sheet with 0.1 mm of thickness and a dielectric material (FR4) sheet with 0.6 mm of thickness. The second case utilizes only ferrite material ($\mu_r = 2500$, $\varepsilon_r = 12$) with 0.6 mm of thickness. The last shield design employs both a ferrite material sheet and an Al sheet. Since several commercial ferrite materials provide very low magnetic loss ($\tan \delta < 0.03$) at 100 kHz [6], the loss effect of the ferrite sheet can be ignored to calculate the power transfer efficiency and the mutual inductance.

## 5 Analysis results

Fig. 4 shows the distributions of magnetic flux density generated by the coils while using each shielding structure. Fig. 5 illustrates the shielding mechanisms of each shield case. When FR4 and Al sheets were used as a shield, the magnetic flux density is very low according to Lenz's law. The induced magnetic flux due to the eddy current on the Al sheet canceled the original incident magnetic field, and so the net magnetic field in the vicinity of the loop was significantly reduced as depicted in Fig. 5 (b). The cancelling magnetic flux due to the eddy current on the Al sheet makes the mutual inductance between the Tx and Rx coils smaller, leading to a low power transfer efficiency. In the case of using only ferrite as a shield, the magnetic field tended to concentrate in the low-reluctance magnetic material path, resulting in a decrease of the magnetic field behind the ferrite sheets, compared to the coil case only, as depicted in Fig. 5 (c). However, the fringing magnetic field still prevails around the coils' edge.
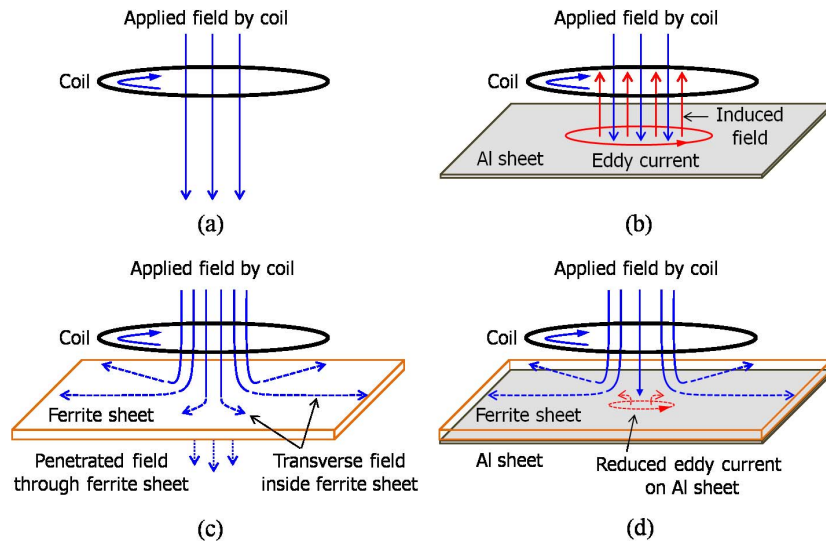
**Fig. 5.** Shielding mechanisms of each shield case. (a) Only coil. (b) Coil with both an Al sheet and a dielectric sheet. (c) Coil with a ferrite sheet. (d) Coil with both a ferrite sheet and an Al sheet.

When both the ferrite and Al sheets are employed, the ferrite sheet provides the applied magnetic field with a lower reluctance path than air. Thus, the normally incident magnetic field is converted into a transverse magnetic field inside the ferrite sheet, as shown in Fig. 5 (c). A minute portion of the incident magnetic field penetrates the ferrite sheet, which causes a significantly reduced eddy current on the Al sheet, as shown in Fig. 5 (d). Consequently, a ferrite sheet between the coil and the Al sheet can significantly reduce the canceling magnetic field generated by the induced eddy current on the Al sheet, which leads to maintain the higher efficiency in the case of the coil with a ferrite-only sheet. In addition, a leakage magnetic field around the coils can be reduced by the Al sheet.

Fig. 6 shows the mutual inductances between the Tx and Rx coils for each shield structure. In the case of the coils with both conductive and dielectric sheets, the mutual inductance was significantly reduced by the canceling
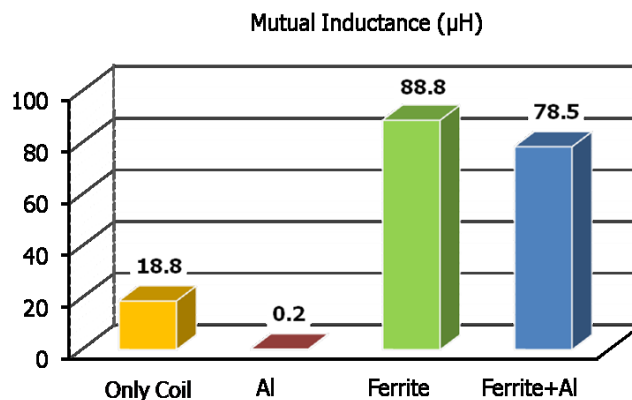


**Fig. 6.** Mutual inductance between the Tx and Rx coils for each shielding case.

magnetic field of the eddy current on the Al sheet. When a ferrite-only sheet was used as a shield, the mutual inductance of the coils was considerably increased by enhancing magnetic flux density inside the ferrite sheet. The ferrite-only case shows the highest mutual inductance among the four cases, meaning its power transfer efficiency is the best. A ferrite sheet can also help to reduce the leakage magnetic field by shunting the magnetic flux. However, a substantial leakage magnetic field still remains around the coil and shield as shown in Fig. 4 (c). When adding an Al sheet to the ferrite sheet as a shield, most of leakage field behind the shield disappears as shown in Fig. 4 (d). In this case, the mutual inductance also decreased slightly by the eddy current on the Al sheet. From the results of Figs. 4 and 6, the optimal shield design is the case which employs both ferrite and Al sheets. The fringing magnetic field around the coils is substantially reduced by the Al sheet, while the mutual inductance is maintained as much as that in the case using only a ferrite sheet.

Based on the equation of the power transfer efficiency in (2) and the mutual inductance in Fig. 6, we calculated how much the power transfer efficiency is decreased by the Al sheet in comparison with the power efficiency in the presence of only a ferrite sheet. From (2), the power transfer efficiency in the presence of only a ferrite sheet can be simply expressed as

$$\eta_{\text{ferrite}} = \frac{1}{1 + A/M^2} \tag{3}$$

where $A = R_1 R_L / \omega^2$ and $M$ is the mutual inductance between the Tx and Rx coils in the presence of a ferrite-only sheet. $A$ is a constant when $R_1$ and $R_L$ are determined and $\omega$ is fixed.

According to the mutual inductance value presented in Fig. 6, the mutual inductance in the presence of both a ferrite sheet and an Al sheet can be written as $0.88\,M$. Therefore, the power transfer efficiency in the presence of both a ferrite sheet and an Al sheet is

$$\eta_{\text{ferrite-Al}} = \frac{1}{1 + 1.28A/M^2}. \tag{4}$$

If the power transfer efficiency in the presence of only a ferrite sheet is supposed to be in the range of 70% to 90%, the power transfer efficiency in the presence of both a ferrite sheet and an Al sheet is in the range of 65% to 88%. As a result, the power transfer efficiency decreased by $2 \sim 5\%$ due to the Al sheet. Therefore, in designing an Al sheet it is necessary to consider the compromise between the power transfer efficiency and EMF shielding effectiveness.

Next, we examined the effect of the size and thickness of an Al sheet on the EMF and mutual inductance. Fig. 7 shows the simulation configuration to calculate the EMF at an observation point 50 mm away from the edge of the coils and 5 mm above the Al sheet. Fig. 8 shows the mutual inductances and EMFs at the observation point with varying sizes and thicknesses of the Al sheet. The effect of the field cancelation increased as the size of the Al sheet increased, and saturated beyond about 2 mm. Most of the
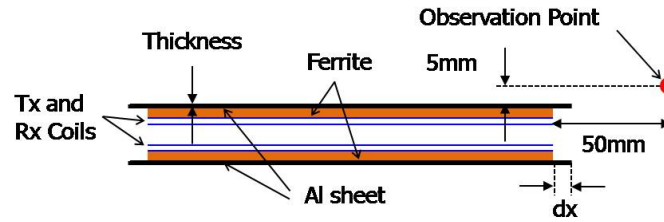
**Fig. 7.** Simulation configuration to calculate EMF at the observation point and mutual inductance between the Tx and Rx coils.
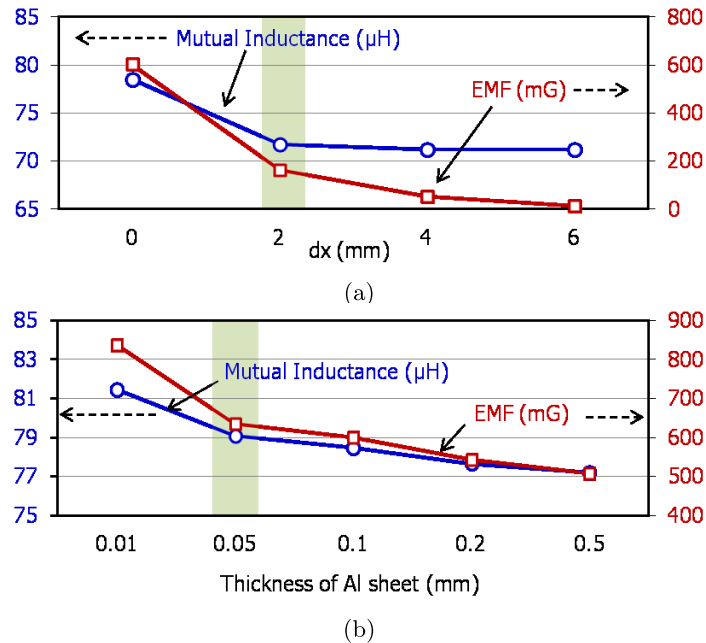


**Fig. 8.** EMF at the observation point and mutual inductance between the Tx and Rx coils as varying (a) the size and (b) thickness of an Al sheet.

fringing magnetic field was canceled out so that the mutual inductance and EMF do not change much as the size of the Al sheet is increased. We can determine an optimal shield size in order that low EMF and small shield size are simultaneously obtained. In this case, the optimal shield size is around 2 mm considering the EMF and mutual inductance. In the case of the shield metal thickness, as the thickness increased, both the mutual inductance and the EMF decreased. The EMF rapidly decreased at extremely thin thicknesses, and slowly decreased beyond 0.05 mm. Therefore, the overall reduction of EMF by increasing shield thickness is smaller than by increasing the size. Moreover, considering the trend of slim mobile devices, the thickness of the shield should be kept as thin as possible. From these results, we can conclude that increasing size of Al is more effective than increasing thickness.

## 6 Conclusion

The investigation and analysis of EMF reduction have been shown for the WPT coil system using optimal shield design. The shield with ferrite and

Al sheets together significantly reduced the EMF by reducing the fringing magnetic field while achieving high mutual inductance. The effects of an Al sheet size and thickness on the EMF and the mutual inductance were also examined. It was shown how to determine an optimal shield size and thickness in order that low EMF and high mutual inductance are simultaneously obtained. Our investigation in this study will certainly be helpful to engineers who are designing the shield structures of modern WPT systems, especially in mobile devices.