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Research Article

Study on a New Double-layer Electromagnetic Shield Structure of a Magnetic Coupler

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Abstract

Wireless energy transmission (WPT) technology is a technology that utilizes space media to achieve electrical energy transmission. The WPT can effectively solve some problems of traditional power transmission, such as unsafety, unreliability, inconvenience and so on. The magnetic couple is a key component of the WPT system, and its performance has a significant impact on the further improvement of the WPT technology. In order to improve coupling performance and reduce magnetic leakage, ferrite cores and aluminum materials are widely used in the magnetic shielding layers, which will lead to the increase of volume, weight and cost of the magnetic couplers. In this paper, a new double-layer shield structure applicable to a magnetic coupler is presented. The proposed design is based on bar ferrite cores and nanocrystalline ribbons, modeled with electromagnetic simulation of a 3D finite element method. It is analyzed that the magnetic field distribution and the coupling characteristics of a DD coil in a new double-layer shielding structure. Simulation and experimental results verify the feasibility and validity of the proposed design. Compared to those of a conventional double-layer shielding structure, the amount of ferrite core is reduced by 71.2%, and the coupling coefficient is increased by 1.12%, respectively. The simulation and experimental results proved the correctness and practicability of the design of the composite shielding structure.

Keywords

Wireless Power Transfer, Magnetic Couple, Electromagnetic Shield, Finite Element Method

1. Introduction

The wireless power transfer (WPT) has become a research hotspot at home and abroad due to its good flexibility, security, reliability and convenience [1-3]. A magnetic coupler is a key component of WPT system, which is composed of transmitting coils, receiving coils and electromagnetic shield layers. As the medium of electromagnetic energy conversion, the structure design of a magnetic coupler directly affects the performance of a WPT system.

At present, the magnetic coupler has the following problems: (1) Small coupling coefficient between transmitting coils and receiving coils leads to low transmission efficiency of WPT system [4]. (2) Electromagnetic radiation produced by the magnetic coupler not only affects the normal operation of electronic equipment, but also endangers human health. (3)

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Ferrite and metal materials are widely used in shielding layers, resulting in high cost, heavy weight and difficult installation of the magnetic coupler [5]. These problems have seriously restricted the development of WPT. The optimization design of a magnetic coupler has become an urgent problem for the further development of WPT [6].

Domestic and foreign scholars have done a lot of research on the optimization design of a magnetic coupler coils and shielding layers [7-9]. RITURAJ G. et al. proposed a unipolar coil arrangement method for improving the coupling coefficient without ferrite material in wireless power transfer systems [10]. In their paper, when the coils self-inductance and external size are constant, the maximum coupling coefficient can be increased by 27.04% compared with the traditional coils. However, the coupling coefficient of the coils will decrease seriously when transmitting and receiving coils deviate. QIU H. et al. proposed a digital transmitter coil for wireless power transfer robust against variation of distance and lateral misalignment [11]. RITURAJ G. et al. proposed a new magnetic structure of unipolar rectangular coils in WPT system [1]. In their paper, it can minimize the ferrite volume while maintaining maximum coupling. In order to improve the coupling coefficient and effectively shield magnetic leakage, ferrite cores and aluminum materials are widely used in the magnetic shielding layers, which will lead to the increase of volume, weight and cost of the magnetic couplers [3, 12, 13]. ZENG H. et al proposed an optimized design scheme of a magnetic coupler core, which uses wheel magnetic core structure to reduce the amount of ferrite while coupling coefficient [14]. XIONG M. et al proposed a nanocrystalline cores shielding of a magnetic couple to reduce the weight of a magnetic coupler. Nanocrystalline cores have high flexibility and saturation magnetic density, but they have high eddy current loss at 85 kHz [15].

In this paper, a new double-layer shield structure applicable to a magnetic coupler is presented. The proposed design applies bar ferrite cores and nanocrystalline ribbons in order to reduce the amount ferrite and increase the coupling coefficient. Based on a 3D finite element method, the mathematical model of the magnetic coupler is established. It is analyzed that the magnetic field distribution and the coupling characteristics of a DD coil in a new double-layer shielding structure. Finally, an experimental platform of an inductively coupled power transform (ICPT) system is built to verify its validity of the double-layer shielding layer structure. Simulation and experimental results verify the feasibility and validity of the proposed design. Compared to those of a conventional double-layer shielding structure, the amount of ferrite core is reduced by 71.2%, and the coupling coefficient is increased by 1.12%, respectively.

2. Wireless Power Transfer System

In this paper, two single-tube inverter circuits are used to input in parallel in order to improve output power as shown in Figure 1. V_{DC} is the DC input voltage, and L_{x1}, C_{x1}, L_{x2}, C_{x2} are resonant circuits that convert voltage sources into current sources, respectively. Q_1 and Q_2 are switches of two single-tube inverter circuits. C_p is a compensation capacitance that is matched to the transmitting coil inductance L_p. C_s is a series compensation capacitance that is chosen to match the receiving coil inductance L_s. r_p and r_s are respectively the resistance of L_p and L_s. M is the mutual inductance of the primary coil and the second coil. Four diodes form a rectifier bridge. In Figure 1, the equivalent circuit of the magnetic coupler is shown in Figure 2.

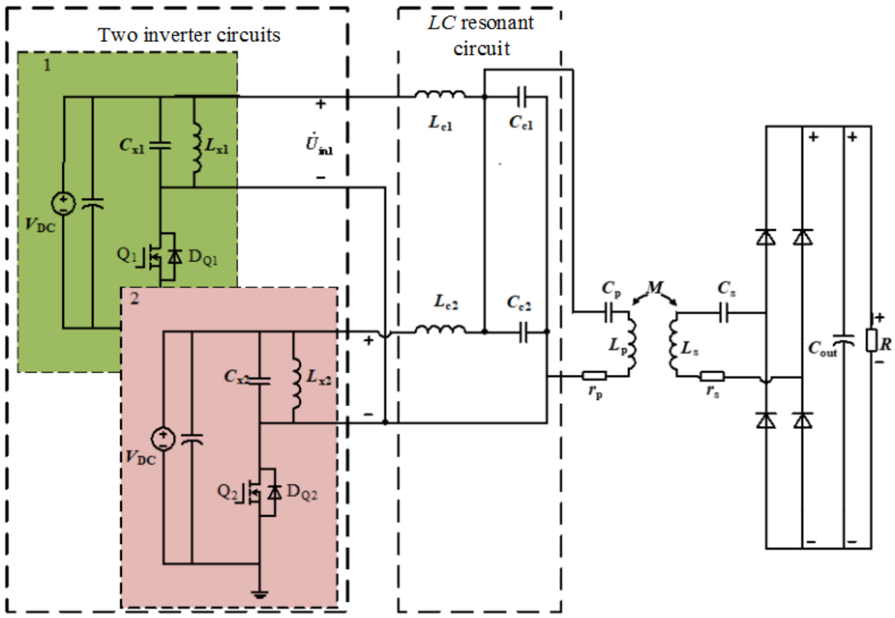


Figure 1. *Overall circuit diagram of the IPT system.*

The output voltage of the ICPT system is

$$\dot{U}_o = \frac{j\omega M\dot{I}_p}{R_{eq}+r_s} R_{eq} \tag{1}$$

The output power is

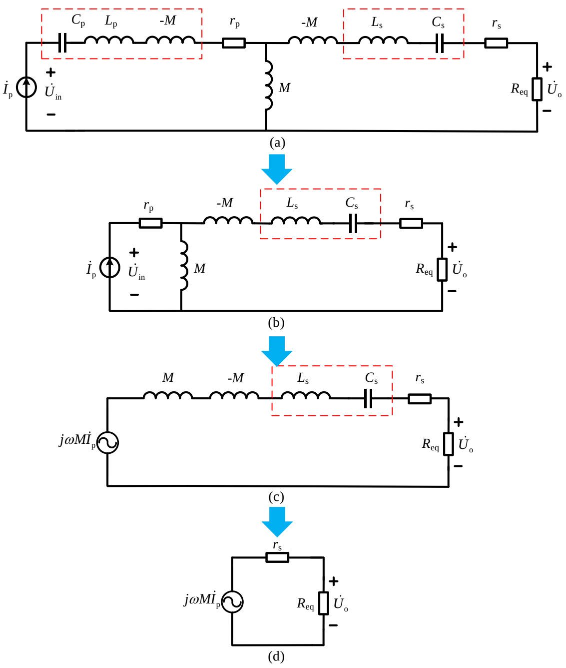


Figure 2. *Equivalent circuit of the magnetic coupler.*

$$P_o = \frac{U_o^2}{R_{eq}} = \frac{\omega^2 M^2 I_p^2}{(R_{eq}+r_s)^2} R_{eq} \tag{2}$$

The input can be expressed as

$$P_{in} = P_o + P_{r_p} + P_{r_s} \tag{3}$$

The transmission efficiency of the magnetic coupler can be obtained

$$\eta = \frac{P_o}{P_{in}} = \frac{P_o}{P_o + P_{r_p} + P_{r_s}} = \frac{\frac{\omega^2 M^2 I_p^2}{(R_{eq}+r_s)^2} R_{eq}}{\frac{\omega^2 M^2 I_p^2}{(R_{eq}+r_s)^2} R_{eq} + I_p^2 r_p + \frac{\omega^2 M^2 I_p^2}{(R_{eq}+r_s)^2} r_s} = \frac{1}{1 + \frac{r_s}{R_{eq}} + \frac{(R_{eq}+r_s)^2 r_p}{\omega^2 M^2 R_{eq}}} \tag{4}$$

The coupling coefficient can be expressed

$$k = \frac{M}{\sqrt{L_p L_s}} \tag{5}$$

It can be obtained from equations 4 and 5

$$\eta = \frac{1}{1 + \frac{r_s}{R_{eq}} + \frac{(R_{eq}+r_s)^2 r_p}{\omega^2 k^2 L_p L_s R_{eq}}} \tag{6}$$

The k and M are important parameters for designing the magnetic coupler in the ICPT system, as they reflect the transmission efficiency of the magnetic coupler.

3. Novel Magnetic Coupler Proposed

As a key component of ICPT system, the geometry of a magnetic coupler determines the magnetic field pattern and electromagnetic interference level. Enhanced magnetic couplers can improve the system power transmission capacity. At present, the single coil and the DD-type coil are widely used in a magnetic coupler. Based on reducing magnetic flux leakage, the DD-type is selected in this paper. As one of the means to suppress electromagnetic interference electromagnetic shielding is very important in the design of a magnetic coupler. Ferrite and metal materials are widely used in shielding layers, resulting in high cost, heavy weight and difficult installation of the magnetic coupler. In this paper, a new double-layer shield structure applicable to a magnetic coupler is presented. Based on bar ferrite and nanocrystalline ribbons, the proposed design is shown in Figure 3.

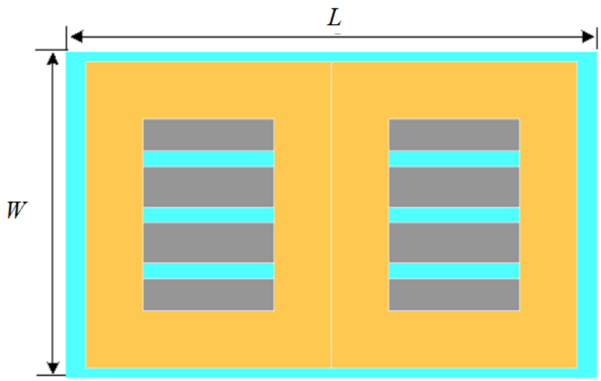


Figure 3. *A double-layer shield structure.*

Based on bar ferrite and nanocrystalline ribbons

In Figure 3, Yellow represents the coil, gray represents the ferrite magnetic core, and blue represents the nanocrystalline ribbons. L is the length of the nanocrystalline ribbons and L=260mm. W is the width of the nanocrystalline ribbons and

W =260mm. *T* is the layers number of the nanocrystalline ribbons and *T* =2. The operating frequency is set to 50Hz, the input DC voltage is 96V and the output voltage is 164V, and the corresponding magnetic field distribution of DD-type magnetic coupler is obtained by Jmag for 3D simulation as shown in Figure 4.

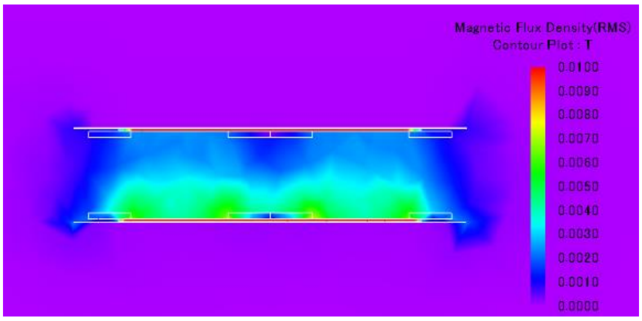


Figure 4. *Magnetic field distribution of a novel DD-type magnetic coupler.*

In order to observe conveniently the magnetic flux leakage of the magnetic coupler, three measuring lines are set up as shown in Figure 5.

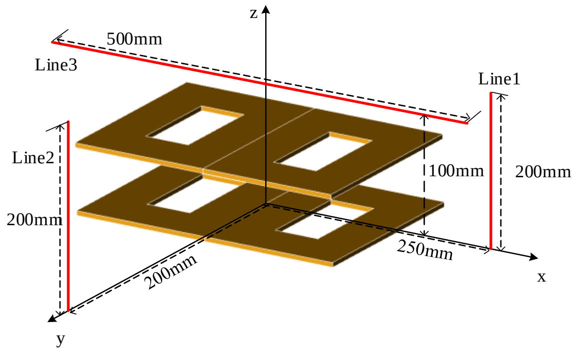


Figure 5. *Schematic diagram of three measuring lines.*

In Figure 5, Line1 is used to observe the magnetic flux leakage on the x side, Line2 is used to observe the magnetic flux leakage on the y side, and Line3 is used to observe the magnetic flux leakage above the receiving magnetic coupler. Compared with the traditional ferrite cores, the magnetic induction intensity curves on each measuring line of the nanocrystalline ribbons magnetic coupler are shown in Figure 6.

From Figure 6, adding the nanocrystalline ribbons can reduce the magnetic. the highest magnetic induction intensity of Line1are reduced by 48.8%, the highest magnetic induction intensity of Line2 are reduced by 41.1%, the highest magnetic induction intensity of Line3 reduced by 64.9%.

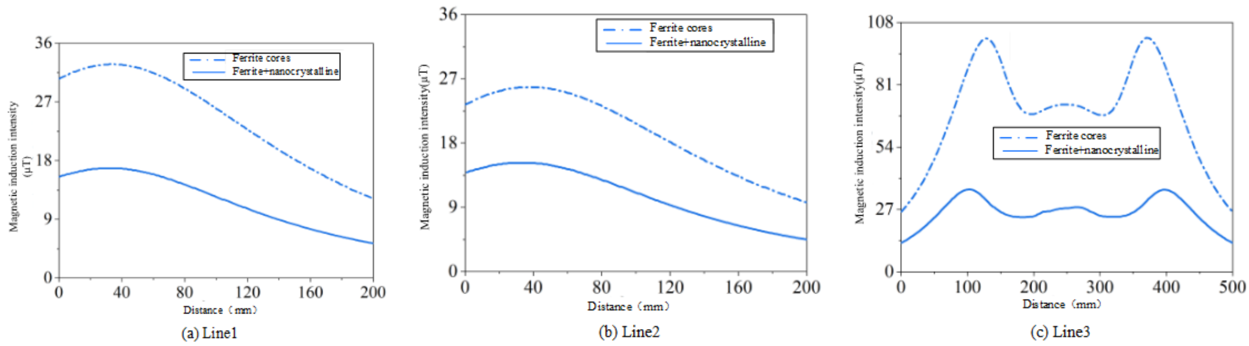


Figure 6. *Magnetic induction intensity curves on each measuring line of a magnetic coupler.*

The nanocrystalline ribbons length *L* is changed, and the changes of the coupling coefficient and magnetic flux leakage are shown in Figure 7.

The nanocrystalline ribbons width *W* is changed, and the changes of the coupling coefficient and magnetic flux leakage are shown in Figure 8.

The nanocrystalline ribbons layers *T* is changed, and the changes of the coupling coefficient and magnetic flux leakage are shown in Figure 9.

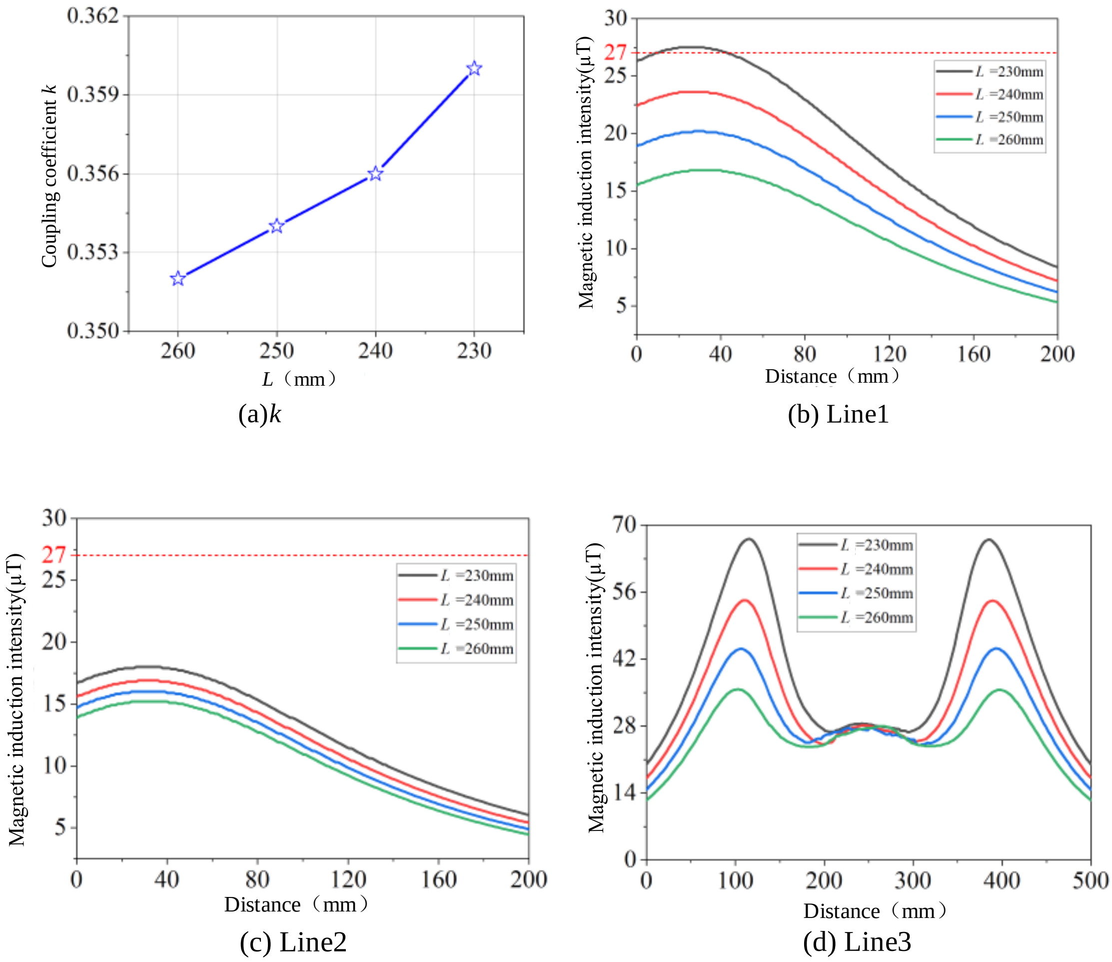
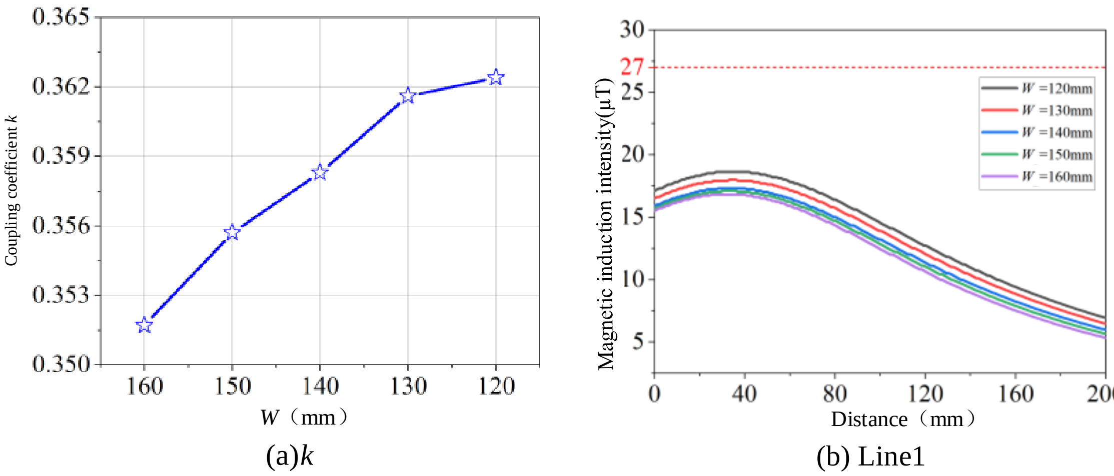


Figure 7. *Change curves of the coupling coefficient and the magnetic flux leakage with L change.*

From Figures 7, 8 and 9, it can be seen that the coupling coefficient *k* is improved with the nanocrystalline ribbons length *L* and width *W* decreased. When the nanocrystalline ribbons layers *T*, the coupling coefficient change can be ignored.



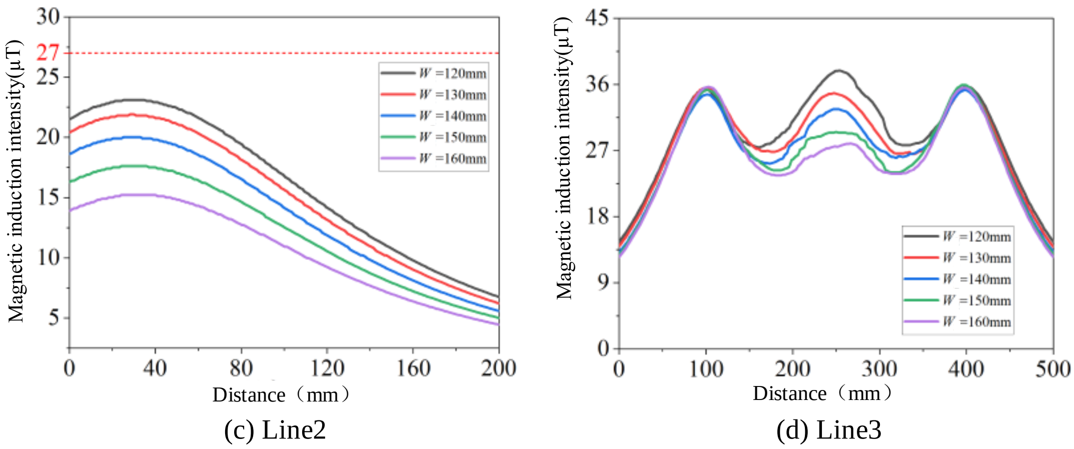


Figure 8. *Change curves of the coupling coefficient and the magnetic flux leakage with W change.*

In a word, the addition of nanocrystalline strip reduces the magnetic flux leakage level of magnetic couplers, but at the same time reduces the coupling coefficient. In order to reduce the reduction of coupling coefficient caused by the addition of nanocrystalline ribbons, the size parameters of nanocrystalline tapes should be optimized to minimize the size of nanocrystals when reaching the safety standard.

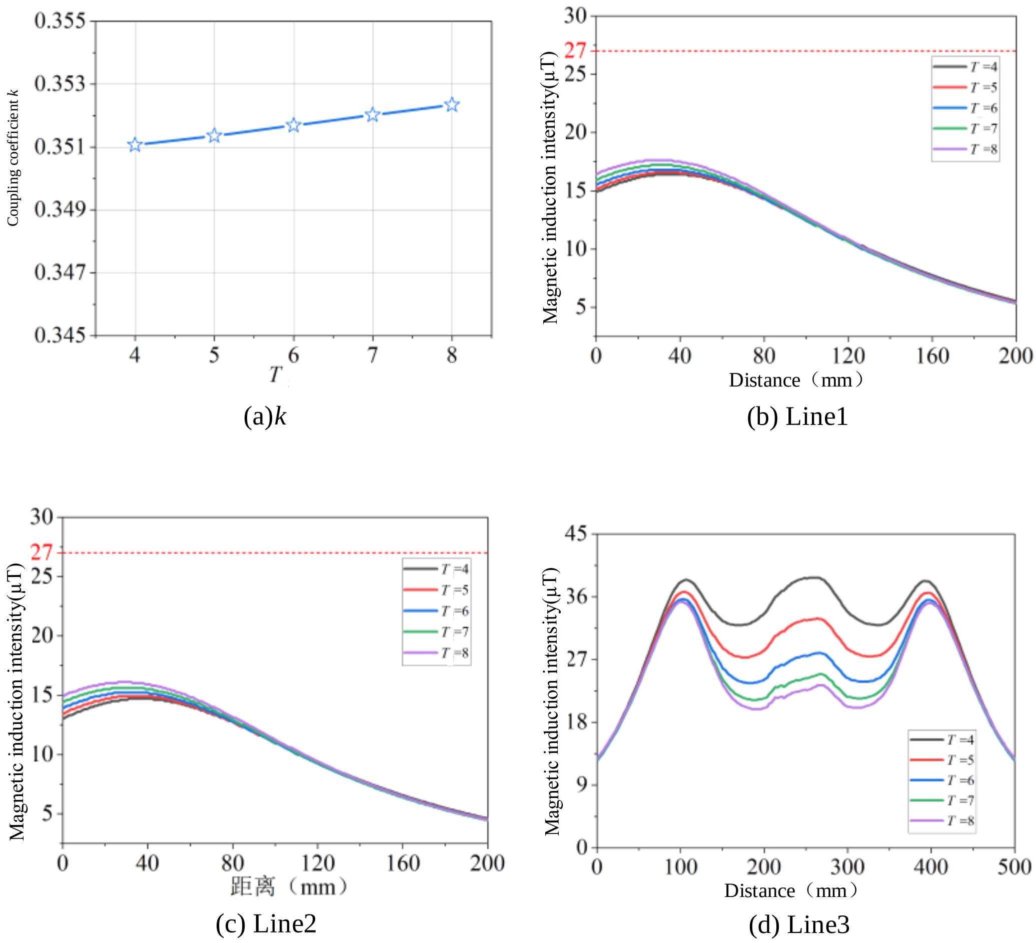


Figure 9. *Change curves of the coupling coefficient and the magnetic flux leakage with T change.*

4. Conclusion

In this paper, a novel DD-type magnetic coupler is designed. The proposed design is based on bar ferrite cores and nanocrystalline ribbons, modeled with electromagnetic simulation of a 3D finite element method. It is analyzed that the magnetic field distribution and the coupling characteristics of a DD coil in a new double-layer shielding structure. Simulation and experimental results verify the feasibility and validity of the proposed design. Compared to those of a conventional double-layer shielding structure, the amount of ferrite core is reduced by 71.2%, and the coupling coefficient is increased by 1.12%, respectively.

In the future research, we will add another conductive shielding layer to further improve the shielding effect against leakage magnetic flux. An aluminum foil is used instead of the aluminum plate in order to reduce the amount of aluminum and its impact on the side leakage magnetic the magnetic coupler. We will discuss on a three-layer composite shielding layer consisting of ferrite cores, nanocrystalline tapes, and aluminum foil, with the aim of reducing the amount of magnetic cores used and improving leakage magnetic.

Abbreviations

WPT	Wireless Energy Transmission
ICPT	Inductively Coupled Power Transform

Author Contributions

Jianfen Zheng: Conceptualization, Data curation, Formal Analysis

Lin Shan: Funding acquisition, Methodology, Resources

Lu Yun: Resources, Software

Zhao Fei: Resources, Supervision

Conflicts of Interest

We declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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