Cross interference suppression methodology by printed circuit board type metamaterial in multi-frequency multi-load magnetically coupled resonant wireless power transfer system

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Abstract

The prosperity of market in multi-charging devices has made the researches on multi-load magnetically coupled resonant (MCR) wireless power transfer (WPT) technique be an urgent issue nowadays. For the sake of load recognition and controllable power distribution, the concept of multi-frequency excitation was introduced into multi-load MCR WPT systems. However, the transferred power components at different frequencies inevitably suffer the cross interference at receivers, which negatively affects the accuracy of load recognition and power distribution. To suppress the cross interference, a methodology by using the metamaterial composed of a printed circuit board (PCB) spiral inductor and a lumped capacitor was proposed. The concept of equivalent mutual inductance ($M_{eq}$) was presented to quantitatively describe the influence of metamaterials on the couplings between the transmitting (Tx) and receiving (Rx) coils. By magnetic field simulation, a series of $M_{eq}$ curves versus operating frequency under different metamaterial parameters were plotted and an optimal design was adopted to suppress the power components at non-targeted frequencies. Moreover, a detailed circuit model was built to characterize the output power of multiple loads after introducing the metamaterial. Finally, the experiments from a prototype was carried out and the experimental results verified the effectiveness of proposed suppression methodology.

1 INTRODUCTION

With the rapid demands for convenient and safe wireless charging for multiple devices, the multi-load magnetically coupled resonant wireless power transfer (MCR WPT) technologies have attracted an increasing attention due to the advantage of simultaneous non-contact power transfer to multiple loads with separate receiving coils [1–3]. However, previous researches on multi-load MCR WPT mainly focus on single-frequency excitation with all receivers tuned at the same resonant frequency, which is difficult to fulfill the load recognition and diverse power requirements for multiple loads [4–6]. As a result, the multi-frequency MCR WPT systems have been investigated recently with fruitful research results [7–12].

However, the introduction of multi-frequency excitation into multi-load WPT systems will inevitably put forward the issue of cross interference among receivers, which will influence on the targeted power distribution and closed-loop control realization. To block the power at irrelevant frequencies from transferring to receivers, a double-frequency WPT system with operating frequencies of 500 and 600 kHz was investigated [13], and an auxiliary circuit based on band-pass and band-notch filters was proposed to prevent the power components at non-targeted frequencies from flowing into the receivers. In [14], a frequency bifurcation method was presented in the resonant WPT system to simultaneously charge multiple loads designed with different operating frequencies, and the cross interference between the adjacent load coils is almost negligible. In [15], three types of compensation circuits by utilizing the impedance characteristics of series and parallel resonant networks were introduced at receivers. Although the cross interference was suppressed effectively, the massive and heavy
magnetic components increase the system volume and overall power losses.

Electromagnetic metamaterial is a kind of artificially designed functional material that can change the electromagnetic fields distribution and present diverse electromagnetic characteristics. It is expected to be potentially used in many fields such as electromagnetic wave absorption, invisible cloak and magnetic resonance imaging [16–18], where the frequencies are much higher than that in WPT systems. In recent years, the researches of metamaterials for WPT systems have gradually increased, such as enhancing the capability of power transfer or suppressing magnetic fields at specific frequency to achieve magnetic shielding [19–22].

Due to the electromagnetic field modulation capability of metamaterial, in this paper, the metamaterial is used to potentially change the magnetic coupling between the transmitting (Tx) and receiving (Rx) coils at specific frequency, and further suppress the cross interference at receivers. The main contributions of this paper are listed in the following:

1. A double-frequency double-load MCR WPT system with single Tx coil was investigated as an example. Based on the equivalent circuit model, the cross interference under different load conditions was analysed, which shows that the cross interference will be more obvious when the load resistance increases.

2. A printed circuit board (PCB) type metamaterial was introduced into receivers, and the concept of equivalent mutual inductance, $M_{eq}$ was defined from the perspective of the induced voltage in Rx coils to represent the coupling coefficient between Tx and Rx coils after introducing metamaterials.

3. Metamaterials with different parameters were modelled, and the corresponding equivalent mutual inductance curves were plotted based on magnetic simulation results to contribute to the parameters design.

The system prototype was built up to carry out experiments. The experimental results are well in accordance with theoretical analysis and effectively confirm the validity of proposed method.

2  CROSS INTERFERENCE ANALYSIS OF DOUBLE-FREQUENCY DOUBLE-LOAD MCR WPT SYSTEM

2.1  System configuration

Figure 1 shows the configuration of multi-frequency multi-load MCR WPT system proposed in [8]. As illustrated, the Tx resonant tank is driven by multiple half-bridge inverters that operate at different switching frequencies, namely $f_1, f_2, \ldots, f_n$. The transformers are utilized to integrate the excitation voltages with different frequencies in the output of each inverter. For simplicity, a double-frequency double-load MCR WPT system is employed as an example. The equivalent circuit of this system based on fundamental harmonic analysis (FHA) method is shown in Figure 2, where $R_P, R_{S1}$ and $R_{S2}$ represent the series resistance of Tx and Rx coils and represent the power loss, $R_{S1}$ and $R_{S2}$ represent the loss of Rx coils and rectifier diodes, while $R_P$ represents the loss from Tx coil, transformers and power devices of inverters.

As depicted in Figure 2, phasors $\hat{U}_{in}^{(1)}$ and $\hat{U}_{in}^{(2)}$ stand for the fundamental harmonics of excitation voltages at $f_1$ and $f_2$, and the rms values can be expressed as:

$$U_{in}^{(1)} = \frac{\hat{U}_{in}^{(1)}}{\pi} = \frac{\sqrt{2}}{\pi} V_{in}, \quad U_{in}^{(2)} = \frac{\hat{U}_{in}^{(2)}}{\pi} = \frac{\sqrt{2}}{\pi} V_{in}$$ (1)

Phasors $\hat{I}_{P}^{(1)}, \hat{I}_{P}^{(2)}, \hat{I}_{S1}^{(1)}, \hat{I}_{S1}^{(2)}, \hat{I}_{S2}^{(1)}, \hat{I}_{S2}^{(2)}$ represent the fundamental harmonics of Tx and Rx currents at $f_1$ and $f_2$, respectively.

**FIGURE 1  Configuration of multi-frequency multi-load magnetically coupled resonant (MCR) wireless power transfer (WPT) system**
respectively. $R_{L1_{eq}}$ and $R_{L2_{eq}}$ are the equivalent load resistances looking from the double-voltage rectifiers, which can be expressed by real load resistances $R_{L1}$ and $R_{L2}$,

$$R_{L1_{eq}} = \frac{2}{\pi^2} R_{L1}, \quad R_{L2_{eq}} = \frac{2}{\pi^2} R_{L2}$$  \hspace{1cm} (2)

The transmitter and receivers are designed to resonate at different frequencies named as $f_{Tx}, f_{S1r}$ and $f_{S2r}$. To realize high transfer efficiency, the resonant frequencies of two receivers are tuned at two switching frequencies respectively [23]:

$$f_{S1r} = f_1, \quad f_{S2r} = f_2$$  \hspace{1cm} (3)

In this case, the output power of loads can be modulated by tuning $f_{Tx}$ in the vicinity of $f_1$ and $f_2$, then the specific power distribution can be realized [8]. The output power of two loads at $f_i$ ($i = 1$ or 2) can be given by,

$$P_{o1}^{(i)} = \frac{U_{in}^{(i)} \left( \omega L_{PS1} + j \omega C_{PS1} \right) R_{L1_{eq}}}{Z_{in}^{(i)}}$$ \hspace{1cm} (4)

$$P_{o2}^{(i)} = \frac{U_{in}^{(i)} \left( \omega L_{PS2} + j \omega C_{PS2} \right) R_{L2_{eq}}}{Z_{in}^{(i)}}$$ \hspace{1cm} (5)

where,

$$\omega_i = 2\pi f_i$$ \hspace{1cm} (6)

$$Z_{p}^{(i)} = R_p + j(\omega L_p - 1/\omega C_p)$$ \hspace{1cm} (7)

$$Z_{S1}^{(i)} = R_{S1} + R_{L1_{eq}} + j(\omega L_{S1} - 1/\omega C_{S1})$$ \hspace{1cm} (8)

$$Z_{S2}^{(i)} = R_{S2} + R_{L2_{eq}} + j(\omega L_{S2} - 1/\omega C_{S2})$$ \hspace{1cm} (9)

### 2.2 Cross interference analysis

A specific coil example with detailed dimensions and layout is depicted in Figure 3, where Tx and Rx coils are wound in the form of solenoid and placed coaxially. The self-inductances of coils and mutual inductances between them can be obtained by simulated Z-parameter results in electromagnetic simulation software ANSYS HFSS [24]. In this case, the simulation results are listed as follows: $L_p = L_{S1} = L_{S2} = 20.13 \mu H, M_{PS1} = M_{PS2} = 1.73 \mu H, M_{SIS2} = 0.39 \mu H$.

From Equations (4), (5), (11) and (12), we can obtain the output power of loads by MATLAB for cross interference analysis. Figure 4 shows the power components at $f_1$, $f_2$ and total output power of loads versus $f_{Tx}$, where the specifications are: $V_{in} = 24 V, f_1 = f_{S1r} = 185$ kHz, $f_2 = f_{S2r} = 215$ kHz.

**FIGURE 2** Equivalent circuit model of double-frequency double-load MCR WPT system

**FIGURE 3** HFSS model of coils

**FIGURE 4** Power components vs $f_{Tx}$
The load resistances are classified by three cases: \( R_{L1} = R_{L2} = 10 \Omega \), \( R_{L1} = R_{L2} = 30 \Omega \), \( R_{L1} = R_{L2} = 50 \Omega \). In the case of \( R_{L1} = R_{L2} = 10 \Omega \), as shown in Figure 4(a), the total output power \( P_{o1}, P_{o2} \) are mainly dominated by the power components \( P_{o1}^{(1)}, P_{o2}^{(2)} \), in which the operating frequency equals to Rx resonant frequency. Here the load only receives the power component at its own resonant frequency (targeted frequency) and blocks the power components at other frequencies (non-targeted frequency), which will be in favor of the power distribution as the curves are monotonous between two resonant frequencies. In the cases of \( R_{L1} = R_{L2} = 30 \) and \( 50 \Omega \), as shown in Figure 4(b) and (c), another peak power point corresponding to the power component at non-targeted frequency appears, which means that cross interference owing to non-targeted frequency components occurs between loads. Meanwhile, when the load resistances increase, the influence of cross interference will be worse. As the curves are no longer monotonous, it will be difficult to fulfill the power distribution and closed-loop control.

3 | MAGNETIC FIELD DESIGN OF METAMATERIAL

Metamaterials can enhance or decrease the magnetic field strength in WPT systems through deliberate design. For cross interference suppression in this paper, metamaterials can be utilized to reduce the coupling between Tx and Rx coils at non-targeted frequency, thus blocking the transfer channel of corresponding power components.

3.1 | Magnetic field model

In most WPT applications with metamaterial, the operating frequency is usually above megahertz and even higher. For the frequency range at hundreds of kilohertz, the metamaterial unit should achieve as high inductance as possible in a limited area to reduce its resonant frequency. Therefore, a double-layered...
TABLE 1 Parameter representations of metamaterial unit

| Parameter | Specification                                  |
|-----------|------------------------------------------------|
| a         | Side length of the unit                        |
| C         | Compensation capacitors                        |
| d         | Thickness of substrate                         |
| N         | Number of turns in a single layer              |
| s         | Pattern space                                  |
| t         | Thickness of copper                            |
| w         | Pattern width                                  |

spiral structure is employed, and the main parameters of the typical metamaterial unit is shown in Figure 5. The detailed description of parameters is listed in Table 1.

Figure 6 shows the complete magnetic field model of the system with metamaterial slabs, as illustrated, each metamaterial slab is composed of four identical units. The compensation capacitor in each unit is employed to reduce the resonant frequency of unit. In order to minimize the impact of slabs on other receivers, two slabs are placed outside two Rx coils respectively, which is used to reduce the coupling between Tx coil and Rx coils at non-targeted frequency.

To reduce the memory consumption and simulation time, a simplified model that only includes the Tx coil, one Rx oil to be suppressed and the accompanied slab is adopted, as shown in Figure 7. The distance between Rx coil and slab is defined as dis, which is a key influential factor to the suppression effect. The influence of the other receiver and slab is neglected due to the long distance between two Rx coils and metamaterial slabs. It should be noted that, if the transmission distance is close enough, the mutual inductance between Rx coils cannot be ignored, and then the complete simulation model in Figure 6 should be used instead of the simplified simulation model in Figure 7.

3.2 Equivalent mutual inductance

According to Faraday law of electromagnetic induction, the magnetic flux passing through a coil can be measured by its induced voltage. Therefore, the coupling coefficient between Tx and Rx coils can be represented by induced voltage in Rx coil when Tx current remains constant. Based on that, an extended concept of equivalent mutual inductance, $M_{eq}$ is defined to quantitatively describe the influence of introduced metamaterials on the system.

Figure 8 depicts the phasor diagram of induced voltage in Rx coil with and without metamaterial slab. As shown...
in Figure 8(a), the induced voltage without slab is merely determined by \(T_x\) coil,

\[
U_{\text{ind}} = U_{\text{ind}, P} = -j\omega M_{PS} I_P
\]  \hspace{1cm} (13)

While in the other case, as given in Figure 8(b), the induced voltage is composed of two parts,

\[
U'_{\text{ind}} = -j\omega M_{PS} I_P + U_{\text{MTM}}
\]  \hspace{1cm} (14)

where, \(U_{\text{MTM}}\) is induced by the metamaterial slab and can be decomposed into two components, \(\text{Im}(U_{\text{MTM}})\) and \(\text{Re}(U_{\text{MTM}})\). \(\text{Im}(U_{\text{MTM}})\) presents the same or opposite direction with \(U_{\text{ind}, P}\), meaning it can enhance or degrade the magnetic field excited by \(T_x\) coil. \(\text{Re}(U_{\text{MTM}})\) is perpendicular to \(U_{\text{ind}, P}\), which is a new voltage component introduced by the metamaterial slab. Therefore,

\[
U'_{\text{ind}} = U_{\text{ind}, P} + \text{Im}(U_{\text{MTM}}) + \text{Re}(U_{\text{MTM}})
\]  \hspace{1cm} (15)

The equivalent mutual inductance \(M_{eq}\) is defined as:

\[
M_{eq} = \frac{U'_{\text{ind}}}{-j\omega I_P} = \frac{[U_{\text{ind}, P} + \text{Im}(U_{\text{MTM}})] + \text{Re}(U_{\text{MTM}})}{-j\omega I_P}
\]  \hspace{1cm} (16)

where

\[
jM_{eq, \text{im}} = \frac{\text{Re}(U_{\text{MTM}})}{-j\omega I_P}
\]  \hspace{1cm} (17)

\[
M_{eq, \text{re}} = \frac{U_{\text{ind}, P} + \text{Im}(U_{\text{MTM}})}{-j\omega I_P}
\]  \hspace{1cm} (18)

It is obvious that \(M_{eq}\) is not a real number, which is different from traditional mutual inductances, such as \(M_{PS1}\) or \(M_{PS2}\). \(M_{eq}\) represents the coupling coefficient between \(T_x\) and \(R_x\) coils after introducing the metamaterial slabs, and will change along with the frequency.

As mentioned above, if the equivalent mutual inductance between \(T_x\) and \(R_x\) coils at non-targeted frequencies can be reduced by the metamaterial slab, the induced voltage on the \(R_x\) coil will decrease and the output power components at non-targeted frequencies will be suppressed. Therefore, for the case in this paper, the design guideline for cross interference suppression can be simplified to minimize the absolute value of \(M_{eq}\), \(|M_{eq}|\) between \(T_x\) coil and \(R_x1\) (\(R_x2\)) coil at \(f_2\) (\(f_1\)).

### 3.3 Comparison of equivalent mutual inductance under various metamaterial parameters

In the following, the modelling and simulation of metamaterial slab with different parameters are carried out and the equivalent mutual inductance curves are plotted based on simulation results. The relationship between metamaterial parameters and variation trend of curves are analysed, which provides a guideline for the selection of optimal parameters.

#### 3.3.1 Different compensation capacitances

The compensation capacitance of each unit is an important parameter in metamaterial design. Figure 9 depicts the curves of \(|M_{eq}|\) versus the operating frequency under various compensation capacitances. When the metamaterial is not employed, the \(|M_{eq}|\) value equals the original mutual inductance (\(1.73 \mu\text{H}\)) as shown by dashed line. While in the other case,
3.3.2 Different metamaterial slab positions

The distance between the Rx coil and the metamaterial slab, dis, is also crucial to the cross interference suppression. In the following, the equivalent mutual inductance is analysed under different positions of metamaterial slab. Figure 10 shows the curves of $|M_{eq}|$, in which, $a = 160$ mm, $C = 18$ nF and dis is given by 2, 20, 50 and 80 mm, respectively. As shown in Figure 10, the minimum $|M_{eq}|$ gradually increases along with dis and corresponding frequency also decreases slightly. Therefore, to minimize $|M_{eq}|$ between Tx and Rx coils at the non-targeted frequency, the metamaterial slab should be placed close to Rx coil.

3.3.3 Different unit sizes

The unit size mainly determines the self-inductance of the metamaterial slab and will further modulate the suppression frequency. Meanwhile, it will also influence the suppression performance at non-targeted frequencies and power transfer at targeted frequency. To investigate that, dis is fixed at 2 mm, and the suppression frequency is uniformly tuned to 185 kHz as an example. Figure 11 shows the simulated curves of $|M_{eq}|$ under different side length $a$. From Figure 11, when $a = 80$ or 180 mm, the minimum $|M_{eq}|$ are still relatively high, which means small or large unit sizes are both not preferred due to the possible poor suppression performance. When $a$ is selected between 100 and 160 mm, the metamaterial slab exhibits a good characteristic as the minimum $|M_{eq}|$ is quite low. Among them, the unit with $a = 120$ mm achieves the lowest $|M_{eq}|$. However, $|M_{eq}|$ at the targeted frequency, 215 kHz in this case, is too small to transfer the rated power as expected, so the trade-off between the required power at the targeted frequency and the cross interference suppression at the non-targeted frequency should be considered. Table 2 shows $|M_{eq}|$ at 185 and 215 kHz under different unit sizes. As illustrated, when $a = 160$ mm, $|M_{eq}|$ at...
185 kHz is approximately the same as that when \( a = 100 \) or 140 mm, but \( |M| \) at 215 kHz approaches the maximum, so \( a = 160 \) mm will be a good choice in this case as it will not be detrimental to the targeted power transfer.

### 3.4 Parameter design guideline

From previous analysis on simulated equivalent mutual inductance under different metamaterial parameters, three design guidelines are proposed in the following for cross interference suppression: (1) \( |M| \) at non-targeted frequencies should be reduced as much as possible; (2) \( |M| \) at targeted frequencies should maintain at a relatively high level; (3) The metamaterial slab should be placed together with the Rx coil and the distance between them should be small. Based on these guidelines, the distance between Rx coil and the metamaterial slab \( d \) is set to 2 mm and the unit side length \( a \) is set to 160 mm in this paper. By tuning the compensation capacitances at each slab to 18.35 and 24.74 nF respectively, Figure 12 gives the curves of \( |M| \) between Tx and Rx coils with and without metamaterial slabs, where the unit parameters are listed as follows: \( d = 1.6 \) mm, \( N = 10, w = 4 \) mm, \( s = 2 \) mm, \( t = 70 \) µm. As shown, with the selected metamaterial slabs, a desirable reduction of equivalent mutual inductance between Tx and Rx coils at non-targeted frequencies (185 and 215 kHz) can be achieved respectively, then the cross interference from non-targeted frequencies will be potentially suppressed.

Figures 13 and 14 show the magnetic field distribution around Tx and Rx coils with and without metamaterial slabs. The observation frequency is set at 185 and 215 kHz, which are the target frequencies of Rx1 and Rx2 and the non-targeted frequencies to be suppressed by slab 2 and slab 1. It is obvious that the magnetic field strength at 215 kHz near the Rx1 coil and that at 185 kHz near the Rx2 coil are greatly attenuated, meaning that the power at non-targeted frequencies near both Rx coils are significantly reduced and the corresponding power transfer are effectively blocked.

### 4 CIRCUIT MODEL ANALYSIS OF THE SYSTEM WITH METAMATERIAL SLABS

To describe the output power characteristics of double-frequency double-load system with metamaterial slabs, a circuit model is established in this section, where each metamaterial unit is equivalent to a closed RLC loop. Figure 15 shows the diagram of the circuit model, in which the four units in slab 1 for suppressing the component at 215 kHz are demonstrated by the subscripts \( m1-m4 \) and the units in slab 2 to suppress the component at 185 kHz are denoted by the subscripts \( n1-n4 \). The self-inductances, compensation capacitances and ESRs of units are defined as \( L_{m1-m4} \), \( C_{m1-m4} \), \( C_{n1-n4} \).
FIGURE 14  Magnetic field distribution at different frequencies with metamaterial slabs. (a) 185 kHz, (b) 215 kHz.

FIGURE 15  Circuit model of double-frequency double-load system with metamaterial slabs.
and \( R_{m1} \sim R_{m4} \) \( (R_{n1} \sim R_{n4}) \), respectively.

\[
\left[ \begin{array}{cccccccc}
Z_{p}^{(i)} & j\omega M_{pS1} & j\omega M_{pS2} & j\omega M_{pS3} & \cdots & j\omega M_{pS4} & j\omega M_{pP1} & j\omega M_{pP2} & \cdots & j\omega M_{pP4} \\
j\omega M_{pS1} & Z_{n1}^{(i)} & -j\omega M_{nS12} & j\omega M_{nS13} & \cdots & -j\omega M_{nS14} & j\omega M_{nP1} & j\omega M_{nP2} & \cdots & j\omega M_{nP4} \\
j\omega M_{pS2} & -j\omega M_{nS12} & Z_{n2}^{(i)} & -j\omega M_{nS23} & \cdots & -j\omega M_{nS24} & j\omega M_{nP1} & j\omega M_{nP2} & \cdots & j\omega M_{nP4} \\
j\omega M_{pS3} & -j\omega M_{nS13} & -j\omega M_{nS23} & Z_{n3}^{(i)} & \cdots & -j\omega M_{nS34} & j\omega M_{nP1} & j\omega M_{nP2} & \cdots & j\omega M_{nP4} \\
j\omega M_{pS4} & -j\omega M_{nS14} & -j\omega M_{nS24} & -j\omega M_{nS34} & Z_{n4}^{(i)} & j\omega M_{nP1} & j\omega M_{nP2} & \cdots & j\omega M_{nP4} \\
\end{array} \right]
\]

\[
\begin{bmatrix}
I_{p}^{(i)} \\
I_{S1}^{(i)} \\
I_{S2}^{(i)} \\
I_{m1}^{(i)} \\
I_{m2}^{(i)} \\
I_{m3}^{(i)} \\
I_{m4}^{(i)} \\
U_{in}^{(i)}
\end{bmatrix}
\]

\[
(19)
\]

where

\[
Z_{m}^{(i)} = R_{m} + j \left( \omega L_{m} - \frac{1}{\omega C_{m}} \right), \quad j = 1 - 4 \quad (20)
\]

\[
Z_{n}^{(i)} = R_{n} + j \left( \omega L_{n} - \frac{1}{\omega C_{n}} \right), \quad k = 1 - 4 \quad (21)
\]

From Figure 15, the relationship between the voltages and currents in Tx, Rx coils and metamaterial units can be illustrated as Equation (19). The impedances of units at \( f_{i} \) are named as \( Z_{m}^{(i)} \), \( Z_{n}^{(i)}, \) \( (j, k = 1 - 4) \) respectively, as given in Equations (20) and (21). Considering the introduced metamaterial slabs, the overall system totally consists of 11 self-inductances in Tx coil, Rx coils, units and 55 mutual inductances between them, as listed in Figure 16. By solving the matrix equations in Equation (19) by MATLAB, the currents of receivers at two operating frequencies \( f_{S1}, f_{S2} \) can be obtained, and then the output power components of two loads at different frequencies can be further calculated.

Figure 17 illustrates the non-targeted power and total output power of two loads versus \( f_{Pr} \), where \( R_{L1} = R_{L2} = 50 \, \Omega \).
FIGURE 17 Output power of two loads after the introduction of metamaterial slabs ($R_{L1} = R_{L2} = 50 \, \Omega$)

Compared with Figure 4(c), the power component at 185 kHz is completely blocked in Rx2 coil, and the power component at 215 kHz is reduced significantly in Rx1 coil. The suppression effect is convincingly proved based on proposed circuit model.

5 EXPERIMENTAL VERIFICATIONS

To validate the theoretical analysis, a prototype of double-frequency double-load MCR WPT system was implemented in the laboratory, as shown in Figure 18. The specific parameters are listed in Table 3.

Figures 19 and 20 show the resonant currents of two receivers, $i_{s1}$ and $i_{s2}$, and their fast Fourier transform (FFT) results, in which, $f_{Pr_1}$ is selected at 185 and 215 kHz, $R_{L1} = R_{L2} = 50 \, \Omega$. As depicted in FFT results, each current is obviously composed of two components at 185 and 215 kHz, which proves the cross interference exists between two receivers. Especially, as shown in Figures 19(b) and 20(a), the current component in $i_{s2}$ ($i_{s1}$) at the non-targeted frequency (Rx1@215 kHz, Rx2@185 kHz) is even higher than that at the targeted frequency (Rx1@185 kHz, Rx2@215 kHz).

Figure 21 shows the calculated and experimental results of output power without metamaterial slabs. It is observed that the experimental results are well in agreement with the theoretical curves. Due to the cross interference, an extra peak power point
**TABLE 3** Parameters of the prototype

| Parameter | Symbol | Value |
|-----------|--------|-------|
| Input voltage | $V_{in}$ | 24 V |
| Inductance of Tx coil | $L_p$ | 22 µH |
| ESR of $L_p$ | $R_p$ | 0.35 Ω |
| Inductance of Rx1 coil | $L_{S1}$ | 21.1 µH |
| Capacitor of Rx1 | $C_{S1}$ | 34.89 nF |
| ESR of $L_{S1}$ | $R_{S1}$ | 0.15 Ω |
| Inductance of Rx2 coil | $L_{S2}$ | 21.1 µH |
| Capacitor of Rx2 | $C_{S2}$ | 25.68 nF |
| ESR of $L_{S2}$ | $R_{S2}$ | 0.15 Ω |
| Operating frequencies | $f_1$, $f_2$ | 185 kHz, 215 kHz |
| Load case 1 | $R_{L1}$, $R_{L2}$ | 30 Ω |
| Load case 2 | $R_{L1}$, $R_{L2}$ | 50 Ω |

**TABLE 4** Lumped parameters of metamaterial units

| Parameters | Slab 1 | Slab 2 |
|------------|-------|-------|
| Self-inductance | $L_{m1}$ | $L_{m4}$ | 36.94 µH | $L_{m1}$ | $L_{m4}$ | 36.94 µH |
| ESR | $R_{m1}$ | $R_{m4}$ | 1.03 Ω | $R_{m1}$ | $R_{m4}$ | 1.03 Ω |
| Compensation capacitance | $C_{m1}$ | 25.05 nF | $C_{m4}$ | 18.70 nF |
| | $C_{m2}$ | 25.03 nF | $C_{m3}$ | 18.71 nF |
| | $C_{m3}$ | 25.05 nF | $C_{m4}$ | 18.58 nF |
| | $C_{m4}$ | 25.08 nF | $C_{m4}$ | 18.68 nF |

**FIGURE 21** Output power curves of two loads without metamaterial slabs. (a) $R_{L1} = R_{L2} = 30$ Ω, (b) $R_{L1} = R_{L2} = 50$ Ω

**FIGURE 22** Resonant currents of two Rxs and their FFT results with metamaterial slabs ($f_{Pr} = 185$ kHz, $R_{L1} = R_{L2} = 50$ Ω). (a) Rx1, (b) Rx2

appears in each curve when $f_{Pr}$ is modulated to the non-targeted frequency. Moreover, the extra peak value increases along with the load resistances, which indicates the influence of the cross interference on the system output power is more severe at light load.

To verify the effectiveness of the proposed metamaterial slabs, the experiments with introduced metamaterial units are carried out, and the lumped parameters of the metamaterial units are listed in Table 4, where the self-inductance is measured when the dimension and shape of the material unit is predetermined, and the compensation capacitance is designed to minimize the $|M_{eq}|$ between Tx and Rx coils at non-targeted frequencies by simulation.

Figures 22 and 23 show the waveforms of $i_{s1}$, $i_{s2}$, and their FFT results with metamaterial slabs. As illustrated in
Figures 22(b) and 23(a), the current components at 185 kHz (215 kHz) in $i_{s2}$ ($i_{s1}$) are significantly suppressed compared with Figures 19(b) and 20(a). While in Figures 22(a) and 23(b), the current components at 215 kHz (185 kHz) in $i_{s1}$ ($i_{s2}$) are completely eliminated in comparison with Figures 19(a) and 20(b). Thus, it can be concluded that the cross interference in receivers is effectively suppressed by the proposed metamaterial slabs.

Figure 24 depicts the output power curves of two loads with metamaterial slabs. As shown, in each curve, the peak points of the output power resulted by the non-targeted frequency component are almost eliminated compared with Figure 21, which also verifies the feasibility of the proposed suppression method.

Figure 25 illustrates the system transfer efficiency without and with metamaterial slabs under different load conditions. Although the metamaterial slabs contribute to suppress the cross interference, the transfer efficiency degradation due to introduced slabs occurs inevitably, especially within the frequency range between 200 and 225 kHz, which mainly attributes to the decrease of equivalent mutual inductance caused by the metamaterial slabs.

6 Conclusion

Multi-frequency multi-load MCR WPT can be potentially used in the applications of distributed implants, wireless sensor networks and micro robots etc. To suppress the cross interference in this system, a method by using the PCB type metamaterial was proposed. To quantitatively describe the influence of introduced metamaterial slab on the WPT system, the concept of equivalent mutual inductance was defined from the perspective of induced voltage on Rx coils. A comprehensive analysis on the metamaterial slabs with different parameters were implemented by considering the variation tendency of the equivalent mutual inductance. Based on that, the parameters design guideline for metamaterial slabs was proposed to lower the equivalent mutual inductance at the non-targeted frequencies and maintain that at the targeted frequencies. Furthermore, an equivalent circuit model was built by taking the mutual inductances between all Tx, Rx coils and metamaterial units into considerations, and the output power of loads was obtained accordingly. From the experimental results in a specific prototype, it can be concluded that the cross interference between Rx coils is effectively suppressed by the proposed methodology. Considering the additional loss from the metamaterial, the effective measures to further improve the overall efficiency should be investigated in the future.
ACKNOWLEDGEMENTS

This work was financially sponsored by the National Natural Science Foundation of China (51877103), and the Six Talent Peaks Project of Jiangsu Province, China (XYNQC-006).

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How to cite this article: Liu F, Ding Z. Cross interference suppression methodology by printed circuit board type metamaterial in multi-frequency multi-load magnetically coupled resonant wireless power transfer system. IET Power Electron. 2021;14:169–182. https://doi.org/10.1049/pel.2.12021