A critical review of metamaterial in wireless power transfer system

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Abstract

Wireless power transfer (WPT) is a promising charging method without physical contact for the electronic products energy supply. However, low transfer efficiency, short transmission distance, as well as the electromagnetic (EM) leakage are commonly main bottlenecks of the WPT technology in the practical applications. The electromagnetic metamaterials (EMMMs) used in WPT system have opened up a brand-new approach for better transfer properties and EM shielding. This paper is intended to provide an overview of the current studies and breakthroughs of the WPT technology based on EMMMs. First, we demonstrate the fundamentals of the WPT based on the magnetic resonant coupling. Then, various key considerations of the EMMMs, such as working mechanisms, fabrications have been taken into account in detail. Moreover, the applications of EMMM in WPT systems are elaborated. Finally, the technical challenges in connection with working frequency and design miniaturization are investigated in this paper. This novel interdisciplinary technology shows important meanings on the extensive application of energy transmission in the future.

1 | INTRODUCTION

Wireless power transfer (WPT) technology has been used in a large number of practical applications, such as electric vehicles, implantable medical devices, portable electronics and Internet of Things [1–6]. In general, the transmission distance is restricted and the power transfer efficiency (PTE) is limited in the WPT system. The main reason is that the coupling efficiency between the resonators drops sharply when the coil-to-coil distance increases [7]. In addition, when the WPT systems deliver energy, the electromagnetic (EM) noise is unavoidably generated and harmful to electrical products, even to the human beings [8]. Therefore, some measures should be taken to reduce the EM radiation without affecting system performance in the WPT charging devices.

In order to achieve high PTE over a long distance, resonance coils with large sizes are usually adopted, which increases the volume of the system. However, it should be noted that the high-PTE systems make sense under the large transmission distance for the system. In the recent year, numerous studies have been put forward to increase the distance between coils in the previous reported papers, which can be mainly classified into three categories: the multiple coils, high quality factor (Q) and magnetic core.

1. Multiple coils: In [9–13], the repeater coils or relay resonators in the form of domino are used to provide the energy for the load. An efficient WPT system over a long distance can be obtained through the coupling and energy transfer of multiple coils. However, due to the existence of many relay coils between the transmitter and receiver, the system practicability is reduced heavily. In addition, the system efficiency decreases sharply as the relay coils deviate from the designated position. There is no doubt that these structures have great advantages in special industrial situations, such as flexible alternative current transmission system (FACTS) [14] or high-voltage insulation (HVI) strings [15].

2. High Q-factor: In [16], it has been pointed out PTE can be expressed by Equation (1) under the weakly coupled condition.

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where, \( Q_t \) and \( Q_r \) denote the quality factors of two coils, respectively. It can be obviously seen that PTE can be greatly improved by adopting high-Q coils. In [17], a self-resonant structure based on foil layer with a \( Q \)-factor of 1183 was proposed which achieved PTE of 94% at relatively large transfer distance compared to the solid or lize wire. In [18], the coils of quality factor up to 1000 were employed to achieve PTE of 10% when the transmission distances is about nine times than the radius of the coils. In [19], a negative impedance converter was applied in the receiving coil to significantly enhance \( Q \)-factor from 76 to 1640, which contributed to the high PTE of 29%. For a high \( Q \)-factor, the working frequencies for the WPT systems are typically in several hundreds of kilohertz, even about ten mega hertz [20]. Nevertheless, high \( Q \)-factor will lead to large voltage stresses on the transfer coils since the reactive current or voltage that the coils bear should be \( Q \) times the corresponding actual power current or voltage. In addition, the high frequency would lead to narrow band and the precise control strategy will be demanded.

1. Magnetic core: For a traditional WPT system based on magnetically coupled resonators, the Litz wire or copper tube was used to reduce the coil resistance for high energy efficiency [21]. The maximum PTE depends heavily on the strong magnetic coupling between the coils. Compared to the air-core resonators, the coils with high permeability materials, especially ferrite cores, were used to improve magnetic coupling [22, 23]. KAIST has done a large amount of research about the long-distance WPT system by using magnetic dipole coil with ferrite core [24–27]. Nevertheless, the demagnetization field is inevitably generated in the process of magnetization. In order to reduce the influence of demagnetization, ferrite core with a larger volume need to be used, which limits the practical application [28]. Additionally, the core loss is supposed to be considered as well.

In fact, there are other ways reported previously to address this problem, such as impedance matching [29–32], circuit topology optimization [33–35] and implementation of superconductors [36, 37]. These methods have their own strengths and weaknesses, which need to be further analysed in future.

Along with the increasing researches on the WPT systems, the EM security also receives a great deal of attentions. EMF leakage can adversely affect the several electronic equipment and the human body. The International Commission on Non-ionizing Radiation Protection (ICNIRP) guidelines have been published in 1998, 2010 and 2020 and announced the standards to protect the humans in various electric and magnetic fields [38–40]. Numerous studies have been done to reduce the EM noise and meet the international standard. In [41], it has presented an overview of related EMF shielding and reduction methods for different application occasions, especially a passive shielding methodology. For a passive shielding means, the ferrite and Aluminium plate are commonly used in WPT system as the shielding materials [42–46]. Beyond that, the active shielding methods, such as changing the circuit topology [47, 48] and adding the conductor current loop [49], also have been proposed. Through using the extra system design to generate the opposite magnetic field, the EMF leakage can be reduced. In fact, the studies on EMF safety of the WPT system are not sufficient and will be research hotspot in the process of civil application.

As mentioned above, two research topics in the WPT field, achieving high PTE with a large distance and cancelling EMF noise, are burning problems to be solved, especially for the Mid-range WPT system (the transmission distance is approximately twice the diameter of coils). Beyond all expectations, the interesting breakthrough in the area of the electromagnetic metamaterials (EMMMs) developed by Pentry [50] has opened up a creative and innovative paradigm for refocusing propagating waves and amplifying evanescent waves as a ‘perfect lens’. The abilities of the EMMMs can be fully applied to WPT system for PTE enhancement. Later advances in this cross domain further show that the EMMMs with different fabrications can shield the EMF around WPT system as well. The two main issues about WPT development can be settled by the EMMMs ingeniously. The studies for EMMM-based WPT system have attracted a great many of attentions from the academic researchers and industrial engineers.

Several papers have presented an overview of WPT systems based on EMMMs [51–54]. Alphones et.al. [51] briefly analysed the transfer theory for EMMM assisted WPT system by equivalent circuit method. In [52], this paper reviewed previously reported studies on the WPT systems with EMMMs and, in particular, discussed the application prospect of the EMMM-based WPT system in electric vehicle contactless charging. In [53], this paper focused on the EM properties, progress and fabrication of EMMMs at great length. In [54], previous studies of WPT systems using EMMMs were illustrated comprehensively. However, the theoretical analysis of WPT systems without EMMMs in these review papers was insufficient. In addition, these papers rarely summarized the working mechanism of EMMMs in WPT systems together and simply discussed evanescent wave amplification and negative refraction properties of EMMMs separately. It cannot provide elaborate theoretical guidance for EMMMs-based WPT systems and difficult to understand for researchers, especially electrical engineers. Moreover, EMMMs with near-zero relative permeability, which can shield the EM leakage in the WPT systems, were not introduced in these papers. Nevertheless, the shielding effect of EMMMs shows significant meanings due to the burning problem of EM noise in the WPT systems [55].

Compared to other review papers in the state of the art, the main advantages of this review are as follows:

1. The fundamentals of WPT systems and EMMMs are elaborated more comprehensively, especially four main theoretical analysis methods for EMMMs-based WPT systems.
2. The theory and application of Mu-Near-Zero EMMMs in the WPT systems for EM leakage reduction are discussed.
FIGURE 1 Category of the WPT technology

and related progresses are expounded specifically. More importantly, the combination of two types of EMMMs, focused EMMMs (Mu-Negative-Magnetic) and shielding EMMMs (Mu-Near-Zero) is also introduced in this paper first.

3. Several key questions of WPT systems with EMMMs are explained for better illustration, such as frequency splitting, impedance matching, property extraction and parameter measurement of EMMMs. Besides, unlike traditional WPT systems, the expression of transfer efficiency has its own common definition.

4. All kinds of transmission performance improvements of EMMMs assisted WPT systems are described thoroughly. Future challenges and development trends are also given clearly.

This review paper is organized as follows. In Section 2, this paper will elaborate the basic principle of the WPT systems based on the magnetic resonant coupling. Section 3 will analyse the electromagnetic properties of EMMMs comprehensively, including working mechanism, design and fabrication of the focused EMMMs and shielding EMMMs. Several technical bottlenecks of the EMMMs are also discussed. In Section 4, various EMMM-based WPT applications will be introduced to analyse the important role of EMMMs. In Section 5, the challenges and future directions will be discussed. Finally, the conclusion will be drawn in Section 6.

2 | FUNDAMENTALS OF WPT BASED ON THE MAGNETIC FIELD RESONANCE

The category of the WPT technology under study is shown in Figure 1 [56]. Compared with other popular WPT technologies, such as inductive power transfer (IPT) [57, 58], capacitive coupled power transfer (CCPT) [59, 60] and microwave power transfer (MPT) [61, 62], the magnetic-coupled resonance (MCR) can not only achieve higher PTE and larger transfer energy at near-field distance but possess great misalignment tolerance between the coils. In this paper, we mainly focus on the basic principle of WPT using MCR type. More importantly, this kind of charging technology is also adopted in the most of the studies for the EMMM-based WPT systems.

2.1 | Fundamental principle of WPT based on magnetically coupled resonance

In general, the MCR-WPT system is composed of resonance coils, as well as power electronic converter, such as a power inverter, a rectifier and a chopper circuit. However, for high-frequency WPT systems (MHz above), the efficient converter is no longer applicable since the switching frequency is limited by switching speed and loss of the semiconductor switches. Hence, the RF power amplifier is commonly used in the resonant system [20]. The typical configuration of the MCR-WPT system is shown in Figure 2. The energy is transferred from the transmitting (Tx) coil to the receiving (Rx) coil by strongly coupled magnetic resonances. Therefore, PTE is dependent on the distance between the resonators, the shape of the coils and circuit

FIGURE 2 Typical configuration of the MCR-WPT system

FIGURE 3 (a) Simplified circuit model of 2-coil WPT system. (b) The mapping circuit from secondary port to primary port. (c) The mapping circuit from primary port to secondary port

FIGURE 4 PTE as a function of load resistance and coupling coefficient k for the simplified circuit model
control techniques (impedence matching, frequency stability
and soft-switching technique etc.).

In recent years, 2-coil and 4-coil WPT systems have always been the research hotspots. Figure 3(a) shows the simplified circuit model of 2-coil WPT system. Tx and Rx coils are connected by mutual inductance \((M_{12})\). Figure 3(b,c) depicts reflected equivalent circuit of the primary and secondary side [21], where the Rx port and Tx port reflect to each other. \(Z_f\) represents the reflected impedance and can be expressed as:

\[
Z_f = \frac{\left(\omega M_{12}\right)^2}{R_2 + R_1 + j/\omega (R_1 + R_2)}
\]

(2)

According to the circuit model and the Kirchhoff Voltage Law (KVL), the voltage equation of 2-coil WPT system can be achieved as:

\[
\begin{bmatrix}
V_s \\
0
\end{bmatrix} = \begin{bmatrix}
R_1 + R_2 + j/\omega L_1 - 1/\omega C_1 \\
j/\omega M_{12} \\
R_2 + j/\omega L_2 - 1/\omega C_2 + R_1
\end{bmatrix} \begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
\]

(3)

\(P_L\) denotes the output power of the load resistance, and PTE is defined as the ratio of the output power to input power. \(P_L\) and PTE can be derived as follows in Equation (4) when the resonators are tuned at the same resonant frequency,

\[
\begin{align*}
P_L &= \frac{(\omega M_{12})^2 R_1}{(R_2 + R_1 + \frac{1}{\omega C_1}) \left(\omega M_{12}\right)^2 + (R_1 + R_2) (R_1 + R_2)} \\
\text{PTE} &= \frac{(\omega M_{12})^2 R_1}{(\omega M_{12})^2 (R_2 + R_1) + \frac{1}{\omega C_2} (R_2 + R_1) (R_1 + R_2)}
\end{align*}
\]

(4)

Note that PTE can be also calculated through the reflected circuit from secondary port to primary port. According to the ratio of resistance at resonance, PTE can be expressed by,

\[
\text{PTE} = \frac{Z_f}{Z_f + R_1 + R_L} \cdot \frac{R_L}{R_2 + R_1}
\]

(5)

When magnetic coupling between two coils is determined, optimal load \(R_{L,\text{max}}\) can be gained by using the following equation:

\[
R_{L,\text{max}} = \sqrt{\frac{R_2}{R_1} \left(\omega_0 M_{12}\right)^2 + \frac{R_2}{\omega_0 C_2} \left(\partial \text{PTE} / \partial R_L = 0\right)}
\]

(6)

Considering the relatively small internal resistance of power source, \(R_0\) can be commonly neglected for theoretical analysis. Therefore, the simplified transfer efficiency can be written as:

\[
\text{PTE} = \frac{\alpha k^2 Q_1 Q_2}{(1 + \alpha)^2 + (1 + \alpha)k^2 Q_1 Q_2}
\]

(7)

where, \(Q_1\) and \(Q_2\) are the quality factors of Tx can Rx coil, respectively. \(\alpha = R_L / R_2\) denotes the load factor and \(k\) is defined as coupling coefficient between the coils. The equation can be further simplified as Equation (1) when the transmission distance is large and the coils are under weakly coupled conditions. It can be apparently seen that PTE is mainly dependent on the quality factor \(Q\) and the coupling coefficient \(k\) between the two coils. The mutual coupling can be greatly improved for EMMM-based WPT system due to the peculiar EM properties of EMMM, which leads to the PTE enhancement accordingly. The transfer efficiency function Equation (7) can be plotted in Figure 4. It can be found that there is optimal \(R_L\) to maximum PTE for a given \(k\) value and PTE can be enhanced as \(k\) increases.

Compared to 2-coil MCR-WPT systems, 4-coil systems have also received worldwide attention since this coil structure can
greatly improve the performance of WPT system. Figure 5 depicts the basic structure of 4-coil WPT system. In general, both the driven and load loop are single copper loops and Tx and Rx ports are multi-turn coils. In some cases, two coils in the middle will rely on self-resonance. The copper wire has its own resonance frequency because of the self-inductance of the coil and the stray capacitances between the spiral wires [20]. However, in most instances, additional capacitances are welded to eliminate the imaginary part and used to tune the resonance frequency. In addition, it can reduce the environment impact on the system since the parasitic parameters are sensitive to the surroundings, such as the humidity, temperature and even the human activity [63, 64].

Based on the simplified model and KVL, the voltage equation of 4-coil WPT system can be written as:

$$\begin{bmatrix} V' \\ \text{0} \\ \text{0} \end{bmatrix} = \begin{bmatrix} R_1 + R_{i} + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) & j\omega M_{12} \\ j\omega M_{12} & R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \\ j\omega M_{13} & j\omega M_{14} & R_3 + j\left(\omega L_3 - \frac{1}{\omega C_3}\right) \\ j\omega M_{14} & j\omega M_{24} & R_4 + R_{i} + j\left(\omega L_4 - \frac{1}{\omega C_4}\right) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

$V'$ and $R_{i}$ are the reflected source and resistance from the driven loop to the Tx coil, respectively. $Z'$ denotes the reflected impedance from the load loop to the Rx coil. Hence, PTE and output power calculations in analogy with those of 2-coil system. In addition, numerous papers reported previously have studies 4-coil WPT systems [67–73]. In contrast with 2-coil systems, 4-coil systems have several unique considerations, such as impedance matching method [65] the frequency splitting phenomenon [67–69]. In [21], detailed analysis on the 2-coil and 4-coil systems have been presented and main key research points have been also elaborated. Figure 7 depicts the frequency splitting of 4-coil WPT system. It can be obviously seen that frequency splitting occurs in WPT system under the over-coupling condition ($k$ is large). $|S_{21}|$ can reach the maximum at a critical coupling point and at resonant frequency.

Note that, one of the biggest advantages of 4-coil structure is that we can achieve the impedance matching through adjusting the distance between the driven/load loop and Tx/Rx coil without changing the system parameter settings. Figure 8 shows the 3D diagram of $|S_{21}|$ varies with $k_{12}$ and $k_{34}$ When the transmission distance is determined, the coupling coefficient between two coils can be changed by adjusting the distance between coils, so as to achieve the maximum efficiency.

This tuning strategy is always used for 4-coil WPT system based on EMMMS. The distances between the coils are tuned in order that the WPT system can be matched with the network analyser for maximum power transfer when EMMMS slab is inserted between the transmission coils. Additionally, the frequency splitting will occur when EMMMS slab is moved close to the coils due to strong coupling between the EMMMS slab and the coils. In the following sections, these research issues will be discussed in detail.

## 3 | EMMMS FUNDAMENTAL

EMMMs are novel class of man-made fabricated materials that present many exotic EM properties, such as evanescent wave amplification [50], reversed Doppler Effect [74] and negative refraction [75]. EMMMs show great potentials in industrial and military applications due to strong and flexible ability of achieving peculiar desired EM properties. Therefore, EMMMs have exerted a considerable influence on a large number of applications, such as invisible cloak [76, 77], super-resolution imaging (namely ‘superlens’) [78] and novel RFID antennas [79, 80].
3.1 Theoretical analyses for EMMM-based WPT system

Among the properties of EMMM, the evanescent wave amplification is the most important consideration and of interest to resonant-coupling WPT systems. Up to now, there are mainly four kinds of theoretical analyses to explain the principle of PTE enhancement in EMMM-based WPT systems, namely negative refraction effect, magnetic dipole coupling theory, Magneto-Inductive Wave (MIW) theory and equivalent circuit method.

3.1.1 Negative refraction effect

According to the Maxwell equations, the wave vector \( k \), electric field intensity \( E \) and magnetic field intensity \( B \) satisfy the left-handed rule for EMMM. In electromagnetism, the refractive index can be expressed by the relative permittivity and permeability

\[
 n^2 = \mu_r \varepsilon_r, \quad (9)
\]

In general, for the conventional materials, the definition of \( n \) is \( n = +\sqrt{\mu_r \varepsilon_r} \), without the consideration of \( n = -\sqrt{\mu_r \varepsilon_r} \). However, new studies have been made by Veselago in 1968 [86]. In this reference, the rightness of media was introduced and these parameters \( \varepsilon \) and \( \mu \) were extended to real number field. The modified Snell’s law can be written.

\[
\frac{\sin \varphi}{\sin \psi} = \frac{n_2}{n_1} = \frac{p_2}{p_1} \sqrt{\frac{\mu_2 \varepsilon_2}{\mu_1 \varepsilon_1}} \quad (10)
\]

\( \varphi \) and \( \psi \) are the angle of incidence and refraction when the EM wave are incident on a EMMM slab, respectively. \( p_1 \) and \( p_2 \) are the rightness of two different media. The material is traditional (right-handed) if \( p = +1 \) or EMMM (left-handed) if \( p = -1 \). Based on Equation (10), EM wave is bent twice when it passes through the media interface with different rightness.

As mentioned above, in deep sub-wavelength domain, the electrical field and magnetic field are uncoupled. The EMMM with negative permeability is sufficient to achieve the negative refraction and the amplification of near-field evanescent wave. Because the resonant-coupling WPT depends on the near-field evanescent wave, the EMMM with negative \( \mu_r \) can focus the magnetic field and enhance PTE. According to the boundary conditions of the magnetic medium interface, the refraction law of the outgoing magnetic field can be expressed as:

\[
\frac{\tan \varphi}{\tan \psi} = \frac{\mu_{r1}}{\mu_{r2}} \quad (11)
\]

In [84], the incident magnetic field, which is generated by Tx resonant coil, will change in the opposite direction when it enters inside the EMMM, and alters again when the magnetic field passes through EMMM. The diagram of the boundary condition of the magnetic field between the air and EMMM is shown in Figure 10 [87]. It can be found the EMMM has the

![Figure 9](image)

Four categories according to the polarity of \( \varepsilon \) and \( \mu \)

In general, EM properties of EMMMs can be described by the constitutive parameters, such as the permittivity (\( \varepsilon \)), permeability (\( \mu \)) and chirality (\( \kappa \)). In [81], the perfect lens can be obtained by possessing both negative \( \varepsilon \) and \( \mu \) (namely negative refractive index). Negative refraction can be achieved when the EM wave passes through two surfaces with opposite refractive index. In addition, a negative index of refraction was also verified experimentally by using the 2D array of repeated copper-strip unit cell [82]. This was followed by a large number of studies and experiments in microwave, visible light and other frequency bands. It should be noted that these properties of EMMMs derive from the special structure of the EMMM, not the properties of the base materials.

Commonly, the size of EMMM unit cell is far smaller than the working wavelength and numerous units can present an overall EM effect, so the EMMM slab can be regarded as effective media [83]. Negative permeability (\( \mu < 0 \)), negative permittivity (\( \varepsilon < 0 \)) and negative refractive index (\( \eta < 0 \), namely both \( \mu < 0 \) and \( \varepsilon < 0 \) simultaneously) are peculiar EM properties and can be achieved by the EMMMs. According to the polarity of \( \varepsilon \) and \( \mu \), the material can be classified into four categories, including three types of EMMMs, as shown in Figure 9 [84]. Theoretically, evanescent wave amplification can be achieved by ensuring that only one parameter is negative [85]. Additionally, while in the radiation field the magnetic field and electrical field are invariably comparable, in the near field the \( E/H \) ratio can be greatly suppressed, thus in the low-frequency quasi-static field, the electric field and magnetic field are usually decoupled. For most MCR-WPT systems, the power is transferred between resonators by near-field evanescent waves. Therefore, the EMMM with an only negative-\( \mu \) can enhance the near-field coupling between resonant coils, regardless of the polarity of the permeability. It can greatly simplify the analysis and design process of EMMMs. In mostly reported papers, the negative-\( \mu \) EMMMs are universally employed for the WPT systems.
3.1.2 Magnetic dipole coupling theory

Urzhumov et al. [88] proposed a simplified model of a magnetic dipole, which consisted of the two single-turn coils coupled though a homogeneous medium (probably anisotropic), as shown in Figure 11. The medium will affect the mutual inductance between the magnetic dipoles as well as self-inductances. If the medium is composed of EMMM with special EM constitutive parameter tensors, then it is theoretically possible to design EMMM so that two separate magnetic dipoles are completely coupled.

In this paper, mutual inductance between two magnetic dipoles with/without EMMMs is derived in detail and can be written as:

$$M_{21} = \frac{-\mu_0 A_1 A_2}{4\pi} \frac{b}{a(2\alpha D)^3} \Phi_L(-\frac{b}{a}, 3, u)$$  \hspace{1cm} (13)

where $\mu_v$ is the relative permeability of the homogeneous medium in which the magnetic dipole is located, $A_i$ denotes the area of magnetic dipole and $d$ is the distance between the magnetic dipoles $(d = D + d_1 + d_2)$. $\alpha$ represents the anisotropic ratio of the EMMM EM constitutive parameter ($\alpha = (\mu_x/\mu_z)^{1/2}$). $a$, $b$ and $\alpha$ are constants of EMMM and can be expressed

$$a = -\left(\frac{\alpha}{\mu_v} + 1\right)^2$$  \hspace{1cm} (14)

$$b = \left(\frac{\alpha}{\mu_v} - 1\right)^2$$  \hspace{1cm} (15)

$$b = \frac{4\alpha}{\mu_x \mu_z}$$  \hspace{1cm} (16)

Note that the permittivity and permeability tensors of the EMMM are assumed uniaxial. The Cartesian components are,

$$\varepsilon = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix}, \mu = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{bmatrix}$$  \hspace{1cm} (17)

$$u = (\alpha D + d_1 + d_2)/(2\alpha D)$$ and $\Phi_L$ is a special function and defined as

$$\Phi_L(\zeta, s, \alpha) = \sum_{n=0}^{\infty} \frac{\zeta^n}{(n + \alpha)^s}$$  \hspace{1cm} (18)

Compared to the mutual inductance, the influence of EMMM on self-induction of magnetic dipoles is negligible. Eventually, by calculating the ratio of $M_{21}$ to $M_{21}^{vac}$, it can be obtained that the degree of coupling between the two magnetic dipoles can be enhanced by the EMMM.

However, magnetic dipole coupling theory is just suitable for plane shape of the EMMM. In addition, when the radius of the coil should be small enough (the ratio of the radius to the wavelength corresponding to the operating frequency is approximately $10^{-5}$), the analysis and calculation are accurate. This is because the larger coil radius no longer satisfies the condition of the magnetic dipole approximation.

3.1.3 MIW theory

WPT systems using a great number of resonating relay coils or domino form have been reported widely in the previous paper [9–15]. Such structures, frequently known as magneto-inductive waveguides are known to carry signals in magnetic resonance imaging as MIW. As a form of propagation, MIWs only exist in a certain types of EMMM formed based on the inductive-coupled resonant circuits [89–91]. The WPT systems based on
EMMMs arranged in a line (1D) or planar 2D arrays can be explained and designed through MIW theory [92, 93]. A schematic presentation of a typical 1D EMMM is shown in Figure 12. It is similar to a coupled mechanical oscillator system, which consists of a number of single-array resonators coupled each other through the mutual inductance between neighbouring cells. Each EMMM cell can be regarded as a simplified RLC resonant circuits and the equivalent circuit model of this system can be depicted as Figure 13. Assuming that a resonant current is excited in one unit cell and the mutual coupling leads to a current being induced in the nearest-neighbour unit cell, then forming the propagation of a MIW [94]. Based on the Kirchhoff Voltage Law (KVL) and mutual coupling theory, the equivalent circuit can be derived analytically by the equations:

\[
\begin{align*}
V_3 + R_3I_3 + ZI_1 + j\omega M_{12}I_2 &= 0 \\
j\omega M_{12}I_1 + ZI_2 + j\omega M_{23}I_3 &= 0 \\
j\omega M_{23}I_2 + ZI_3 + j\omega M_{34}I_4 &= 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
j\omega M_{n-1,n-1}I_{n-1} + ZI_n + j\omega M_{n,n+1}I_{n+1} &= 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
j\omega M_{n,n-1}I_{n-1} + ZI_n + R_nI_n &= 0
\end{align*}
\]

(19)

Here, \( Z \) is the impedance of each cell and can be given as:

\[
Z = R + j(\omega L - 1/\omega C)
\]

(20)

where \( V_3 \) and \( R_3 \) are the voltage and internal resistance of the source, respectively. \( R, L, \) and \( C \) are equivalent resistance, self-inductance and capacitance of the unit cell, respectively. \( M \) is mutual inductance between two adjacent resonators. It is worth noting that according to the MIW theory, the current flowing in each unit cell of 1D magneto-inductive waveguide can be expressed as \( i = I_0 e^{(a+jb)t} \) due to the wave travelling along the EMMM, where \( a \) and \( b \) are the attenuation and wave vector, respectively, and \( d \) is the period of the cells. The attenuation in each unit cell, which represents the wave reduction along the EMMM can be written as:

\[
\alpha d = \sinh^{-1}\left(\frac{1}{kQ}\right)
\]

(21)

where \( k \) and \( Q \) denote the coupling coefficient and quality factor, respectively. The transmission efficiency for WPT systems based on MIW theory can be calculated by

\[
\eta = \frac{S_{21}^2 (1 + Z_0/R_L)}{1 - S_{11}^2}
\]

(22)

where the S-parameter can be obtained by vector network analyser (VNA), and \( Z_0 \) and \( R_L \) is the characteristic input impedance and load resistance, respectively. Detailed theoretical description of the MIW theory in EMMM-based WPT can be seen in the studies [92–94]. The researches about the MIW theory in the WPT system based on the EMMM are insufficient and this technology can be tamed to supply targeted power delivery with dynamic control unit for practical application in the future.

### 3.1.4 Equivalent circuit method

Inspired by the MIW theory, theoretical analyses for EMMM-based WPT system can be described by the equivalent circuit method [55]. As mentioned in the three theories above, these analytical ways have been displayed based on traditional microwave technologies and are difficult to understand by the electrical engineers [95]. In addition, these methods do not include the effect of the real implementation of EMMM. In general, most studies of the EMMM-based WPT system focus on the frequency of MHz range for consumer electronics. The wavelength of current is far larger than the system dimension, including EMMM slab and resonant coils size. Hence, we can assume that the current flowing in each part is identical and in phase and the whole system can be viewed as lump circuit model, in which the distribution of the parameters are ignored. As shown in Figure 14(a,b), each unit cell of EMMM can be regarded as a RLC resonator. Therefore, the overall equivalent circuit model of typical four-coil WPT system based on the EMMM can be demonstrated in Figure 14(c).
Based on the mutual coupling theories and the KVL, the transfer efficiency and power can be obtained subsequently when the coupling relationship between each element is calculated. The formula can be expressed as Equation (22) with array EMMM slab loaded between coils. The method can helpful for engineers’ understanding and promote the EMMM-based WPT system in the industrial application. In particular, it is significant to enlarge the transfer power (up to few kW) at a low frequency region (from 10 kHz up to 20 MHz), to promote commercial applications in the fields of electric vehicles and energy storage. Hence, in future studies, more attention should be paid to obtain high power EMMM at a low frequency region. Obviously, the microwave technologies is not suitable for lower frequency and high power. A novel analysis method- equivalent circuit method will play a huge role in the future research.

As mentioned above, through changing the structure and parameters, EMMM can present exotic EM properties including EM shielding, which is also interesting to the researchers in a related field. However, the studies on the WPT system based on EMMM with near-zero permeability of shielding property are lacking. To the best knowledge of the authors, the articles reported so far have mainly focused on the Fresnel transmission and reflection formulas, which are used to explain the shielding effect of EMMM with near-zero permeability [96, 97].

Equivalent circuit model can also be used to explain the shield principle of the EM leakage in WPT systems. And this approach is very efficient in explaining the role of EMMM-based WPT system.

### 3.2 Design and Fabrication of EMMM

In the past work, EMMSs have been commonly used in absorber, super-resolution and micro-strip antenna, etc. The operating frequency of these applications concentrated in the microwave band (300 MHz–300 GHz) and beyond. However, the working frequency of conventional WPT system ranges from 10 kHz in Tesla’s report [98] to almost 200 MHz [99]. Therefore, it is particularly important to design EMMM suitable for WPT systems. For most EMMM-based WPT systems, the resonant frequencies are generally set to MHz considering both WPT performance and EMMM fabrication, especially ISM band (6.78 or 13.56 MHz). Numerous factors need to be taken into account critically in the process of EMMM design and fabrication, such as dimension, weight and loss.

To achieve the relevant peculiarity of EMMM, the artificial fabrications need to present effective media properties. The designs of EMMM are usually based on printed resonators, such as spiral resonators (SR) and split ring resonators (SRR). These structural units are arranged periodically, perpendicular or parallel to the system axis for the control of the effective ε and μ. In order to achieve the deep sub wavelength, the size of EMMM unit is often much less than one hundredth of the wavelength corresponding to the operating frequency. It has been reported that EMMM slab with larger dimension results in higher PTE enhancement. However, EMMM size is supposed to minimize during the process of design and fabrication generally. On one hand, EMMM unit cannot be large at random since a great enough sampling of exciting source is demanded to investigate all the properties of an ideal EMMM. On other hand, most electrical applications possess a limit of size for actual use. Even though, the sizes of the EMMM are too large for practical WPT systems. For example, 3D EMMM slabs for mid-range WPT systems have been adopted for PTE improvement [100, 101]. Figure 15(a,b) depict the side view and top view of 3D EMMM slab. Figure 15(c) shows the size comparison between the coils and EMMM slab. It is obviously seen that the structures of EMMM are too large and thick in size for WPT systems. Therefore, in order to make EMMM-based WPT systems more practical, a great number of means have been reported to minimize the unit cell dimension for compact EMMM structure.

All kinds of resonant particles using two metal levels are compared and investigated for EMMM miniaturization in [102]. It has also illustrated that the geometry and topology of the units play a critical part in size reduction. Therefore, a double-layer structure of EMMM unit cell has been reported in several articles for compact systems [88, 103]. In [84], a thin dual-layer printed circuit board (PCB) EMMM unit cell was proposed, as shown in Figure 16. Relatively tiny unit was designed with a size of 37.2 mm × 37.2 mm, the thickness of 1.6 mm and 18 turns square spiral coil on both sides of a high dielectric constant layer (connecting through VIAs). Compared to the conventional PCBs, the EMMM unit of thin PCB type has a great many advantages, such as easy fabrication, light weight and low cost. In [103], SR, fabricated by two spiral copper layers with opposite winding directions, can be printed on both levels of a substrate. For EMMM unit cell of SR or SRR structure, the number of turns or rings was generally increased to reduce the working frequency of the system [102, 104–105]. Other ways, such as adding auxiliary capacitance [106–108] and broadside coupling were also adopted to achieve the compact size of unit cell furtherly.
FIGURE 15 The structure of 3D EMMM. (a) Side view. (b) Top view. (c) Experiment setup of WPT system including 3D EMMM structure

FIGURE 16 The Structure of EMMM unit cell of dual-layer PCB

FIGURE 17 The structure sketch of the unit cell proposed in [109, 110]

In [109], a novel unit cell structure of ferrite loaded solenoid was proposed as a greatly compact and low-frequency EMMM fabrication, with a size of $\sim \lambda/10000$. The multi-layer helix was adopted to increase inductance and stray capacitance for self-resonance of the unit cell. The structure of fabricated EMMM unit cell is shown as Figure 17(a). In [110], a cubic high dielectric resonator (CHDR) EMMM was presented for long-range WPT system. The CHDR unit cell took advantage of a combination of a high permittivity dielectric and low dielectric background Teflon, as shown in Figure 17(b).

### 3.3 EMMM loss

Although EMMM has been proved to enhance PTE effectively and extend the transfer range largely in many articles, EMMM slab has its own loss. If the EMMM unit cell is designed inappropriately, the loss may be greater than the increase in PTE. Such as 3D EMMM in the WPT system, the bulky volumetric structures will increase the loss inevitably. Therefore, a thin and compact shape of EMMM is desirable for low loss, easy fabrication and practical application.

As mentioned before, a copper-based EMMM slab is commonly designed and used in WPT systems. However, the properties of EMMM depend heavily on the polarization, though the coupling improvement of medium has a little effect on the diagonal elements of the permeability tensors [111]. Moreover, the other disadvantages are that this structure causes ohmic loss at a high-frequency condition and lower $Q$ of the system. High-$Q$ resonant inclusion is desirable because it leads to lower losses. For instance, the spiral-type resonator has a higher $Q$ than the split-ring resonators, so it has been always used in EMMM design in the WPT system [107]. In general, the diametric substrates, such as FR-4, Rogers and Teflon are usually adopted as carrier by taking performance and fabrication into consideration. Notice that the selection of substrate is also closely related to the effective capacitance of the unit cell. Unfortunately, according to the state-of-the-art studies, in-depth researches on the loss in EMMM-based WPT system are insufficient and need to further study in the near future.

### 3.4 Several technical questions on EMMM

#### 3.4.1 Simulation analysis and property extraction

For EMMM-based WPT system, the simulation method play an extremely significant role in the evaluation and analysis for the system performances. There are mainly two kinds of 3D EM simulation software, namely High Frequency Structure Simulator (HFSS), CST Microwave Studio. The magnetic field distribution can be demonstrated and evaluated readily in the simulation with/without EMMM, the difference of EMMM placement or misalignment. In addition, S-parameter (especially $S_{11}$ and $S_{21}$) is usually emulated for the extraction of the EMMM equivalent parameters, mainly the relative permeability. In simulation, the EMMM unit cell is regarded as equivalent medium. And the incident plane wave vector is parallel to the equivalent medium and the magnetic field component is perpendicular to the incident medium periodic unit. Further, these
parameters can be extracted by the retrieval method [112–114], as shown in Figure 18. The strip width, the interval, the number of turn and the thickness of the substrate can be optimized to achieve the optimal structure, as shown in Figure 19.

3.4.2 EMMM validation

The resonance frequency of EMMM unit cell can be verified by using waveguide boundary conditions [85, 97–98] after the unit cell has been fabricated. To be specific, the resonator to be tested is placed in the middle of two non-resonant loops, as shown in Figure 20(a). The resonant frequency can be obtained by observing the curve of $S_{21}$ in the screen, as shown in the Figure 20(b). It can be seen that the resonant frequency of the Tx/Rx coil is 13.56 MHz. Bearing in mind that the resonance frequency of EMMM unit cell is smaller than the working frequency of system, since negative permeability is achieved above the self-resonance frequency.

In addition, the mutual impedance can be measured between two coils with/without EMMM by similar experimental setup. Therefore, the EMMM properties of evanescent wave enhancement and PTE improvement can also be verified accordingly [109].

4 EMMM IN THE WPT SYSTEM

Although the theoretical analysis on the EMMM-based WPT system have been put forward as early as the beginning of the 21st century, the experimental realization was firstly conducted
by Wang et al. in 2011 [85]. After nearly a decade of research ceaselessly, a great many breakthroughs have been made in this field. Broadly speaking, EMMM slab used in the WPT system has four major functions: PTE improvement, transfer distance increase, misalignment tolerance and EMF shielding effect. This section will overview these four key purposes of EMMM in WPT systems.

4.1 PTE improvement

For WPT system, PTE is one of the most significant technical focuses in the system design, analysis and optimization process. Figure 21 shows the efficiencies of each part along the transmission path. Among these efficiencies, system energy efficiency ($\eta_s$), namely PTE and transmission efficiency ($\eta_t$) are two main concerns. $\eta_s$ is the ratio of the load output power to total input power from the excitation source, considering all the losses and representing the whole system efficiency. $\eta_t$ refers to the power ratio of the receiving to transmitting coil (coil-to-coil efficiency), standing for the coupling ability of the magnetic resonators. Notice that it is the insertion of EMMM that improves the coupling strength between the two coils, thus increasing transfer efficiency.

In general, the working frequencies of EMMM-assisted WPT systems are beyond MHz by trade-off in numerous studies, which leads to the use of RF power amplifiers rather than traditional switching power supply. For the sake of the simplicity, the vector network analyser is always used to measure the overall efficiency of the system when the transfer power is not considered [85]. The diagram of the typical EMMM-based four-coil WPT system can be shown in Figure 22.

The entire WPT system can be regarded as a two-port network (one port being the input, fed by the source, and the other the output, feeding the load). Power transfer can be represented in terms of linear magnitude scattering parameters ($S_{21}$), which can be measured with a vector network analyser experimentally. The measurement of the $S_{21}$ of a linear two-port network by test fixtureing is shown as Figure 23. The equivalent $S_{21}$ can be expressed as follow [110, 111]

$$S_{21} = \frac{b_2}{a_2} = \frac{V_2}{V_1} \mid_{a_2=0} = 2 \frac{V_2}{V_1}$$

(24)

$S_{21}$ can simply be regarded as twice the voltage gain when an output load impedance is the same as a Thevenin source impedance ($R_0$). Bear in mind that $|S_{21}|^2$ associates with the signal power gain of the subject network intimately. Specifically,

$$|S_{21}|^2 = \left(2 \frac{V_2}{V_1}\right)^2 = \frac{|V_2|^2}{|V_1|^2}$$

(25)

This equation represents the maximum possible power deliverable by the signal source applied at the input port. And $|S_{21}|^2$ is widely used to characterize the PTE in the WPT system (PTE $= |S_{21}|^2$) [115, 116]. For the WPT system with the EMMM slab, this formula can also illustrate that the EMMM slab has an improvement in PTE directly. Many previous studies have adopted this formula to demonstrate the PTE improvement of the EMMM in the WPT system [84, 85, 96, 107]. However, the power amplifier is still needed for the system to transmit large power at high frequency since the output power of the vector network analyser is mW level and only for efficiency measurement.

Ideally, EMMM with a negative permeability can concentrate the EMF between the resonators and improve PTE accordingly. In [84], thin PCB-type EMMM was proposed to improve PTE at 6.78 MHz in WPT system. The dual-layer unit cell with small dimension (3.72 cm $\times$ 3.72 cm size and 1.6 mm thickness) was designed to achieve the negative relative permeability ($-0.1$). A PCB substrate with a high dielectric constant was used to decrease the resonant frequency because of the increased capacitance. In addition, various EMMM parameters, such as the number of turns, the dielectric constant of substrate, the number of PCB layers and the thickness of unit cell substrates were analysed and optimized to achieve the optimal structure of EMMM. Eventually, the 5 $\times$ 5-array EMMM slab with compact structure is fabricated to fit the resonators’ size. Figure 24(a,b) show the magnetic field distribution with/without EMMM slab.
Magnetic field distribution. (a) Without EMMM. (b) With EMMM

The compact EMMM structure in the WPT and the experimental results proposed by [105, 113] using HFSS software. It is obviously seen that EMMM can concentrate the magnetic field and then improve the PTE. Moreover, the surrounding EMF around the WPT system reduces due to focusing performance of the EMMMs.

In [109], a novel compact EMMM with ferrite-loaded solenoid unit cell, working at 5.574 MHz was designed. EMMM slab with $6 \times 6 \times 2$ cm$^3$ size was fabricated by taking the evanescent wave and compactness into account. Effective properties of the EMMM were extracted by CST Microwave Studio. The simulated results show that the proposed EMMM is anisotropic material, which possesses the air properties along x- and y-direction while a Lorentzian dispersion along z-direction. Figure 25(a) shows the experimental setup of two-coil single-turn WPT system based on EMMM. The measured and simulated PTEs with/without EMMM were shown in Figure 25(b). It can be seen that PTE enhancement can be achieved compared with the traditional WPT system at the same distance. The situation of multi-turn WPT system was also discussed in this reference paper. In [117], a compact EMMM slab of dual-layer printed SRs were fabricated for the telemetry system. A $4 \times 4$ array of unit cells has been through incident plane wave which is perpendicular to the plane of the EMMM slab. The experimental setup of two-coil EMMM-assisted WPT is shown in Figure 25(c). A series of experiments have been conducted to verify the PTE enhancement of the EMMM, including the cases of EMMM slab close to Tx coil and the case of EMMM slab adjacent to Rx coil for different positions. It showed the improvements in PTE exist with almost all cases for WPT system based on EMMM. In addition, the offset in coil positions was also discussed in terms of the practical application of the telemetry system. The experimental results were shown in Figure 25(d) and indicated the EMMM still has great performance in increasing PTE.

Transfer distance enhancement

It is well known that PTE decays sharply when the transmission distance increases. In general, EMMM slab is used widely in the mid-range WPT system considering both practicality and reliability. Actually, the term mid-range is not defined strictly in the research field. It is commonly believed that mid-range distance refers to the transfer distance is about twice the diameter of the resonant coil. In this condition, the EMMM has a huge power to increase PTE in mid-range domain.

It is worth noting that practical working distance is less than the coil-to-coil distance since the EMMM slab is usually inserted in the middle between coils. Figure 26(a,b) depict the differences between the working distance and resonance-coil distance. In industrial application scenarios, the working distance has been determined, the insertion of EMMM slab would only be meaningful when PTE is improved even at the enhanced coil separation. Therefore, EMMM slab had better be positioned near the coil to increase practical transfer distance. However, the frequency splitting caused by coils and EMMM slab placed close together is also an issue worth studying.

Misalignment tolerance

For WPT systems, if the spatial freedom degree can be improved, the system would have larger practical value since the misalignment of resonant coils always happen in the electric
equipment. However, the PTE of WPT system will decrease rapidly when the misalignment between the coils occurs due to the reduction of the mutual coupling of the resonators. In order to reduce the influence of misalignment on PTE, several methods have been proposed in previous papers, such as coil design [118–121], control strategy [122, 123] and capacitance compensation [124]. The introduction of EMMM can also creatively solve the misalignment issue of the WPT system. In [125], the WPT system of the lateral and angular misalignment of the Tx coil with/without EMMM were simulated and the magnetic field distributions were shown displayed. In addition, the threshold distances of the EMMM-based WPT system were also discussed in the paper.

In [112], the receiver misalignment under the misorientation and displacement for EMMM-assisted WPT system were analysed. The simulated comparison of PTE among different misaligned angle and distance were shown in Figure 27. It can be found magically that the PTEs of the WPT system still maintain high even when large misalignment of the Tx coil occurs.

Kang et al. [126] proposed a multiple-receiver WPT system based on EMMM, which consisting of two EMMM slabs inserted near two Rx coils. The comparative experiments have been carried out with/without EMMM at the Tx coil. The experimental results show the PTE can be largely improved when the deflection angle of the Rx is less than 45° and proved that EMMM has greatly enhanced system spatial degrees of freedom.

### 4.4 Shielding effect

Large EMF noise can be generated inevitably for the wireless charging system, which would be harmful to the electronic components, even the human beings. Therefore, more importance to the issue of electromagnetic pollution should be attached. An effective and simple ways to reduce the EMF noise is to use a shielding material, such as the ferrite and metallic plate [41]. These two methods have own advantages and disadvantages. For example, the ferrite can improve the coupling coefficient between the resonators. However, ferrite can be brittle and not suitable for high frequency [44–46]. Metallic plate, especially aluminium plate, has simple structure, whereas hard to meet system performance [42, 43]. EMMMs are artificial materials whose peculiar properties vary with their structures and components. It has been proved that EMMM with near-zero relative permeability has a great shielding effect for the EMF [55, 96, 97, 127, 128]. Compared to the two materials mentioned above, the biggest advantage of EMMM is to shield only wanted frequency band while allowing the other EMF or electromagnetic waves through.

In [96], theoretical analysis of Fresnel transmission and reflection formulas has been conducted to explain the principle of the shielding effect. Just like the EMMM of the negative permeability, EMMM slab was fabricated by the 3×3 plate array of unit cells. In general, this kind of EMMM slab was is placed behind the Rx coil. 3D simulation by the HFSS has been carried on and the magnetic field with/without EMMM were shown as Figure 28.

In [55], the combination of two types of EMMMs was firstly proposed for PTE improvement and EM leakage reduction in WPT systems. The equivalent circuit model was adopted to explain the working mechanism for WPT systems with EMMMs, which can be easily understood by electrical engineers. Two different performances of EMMMs can be achieved by varying the tuning capacitance on the same PCB. As shown in Figure 29, it can be obviously seen that PTE was largely improved and EMF leakage was greatly reduced due to the insertion of two kinds of EMMMs. The positions of EMMMs slab from the Rx coil was also discussed in the paper. Form the results in Figure 29(d), it can be found that the EMMM slab shows great shielding effect when it was near the Rx coil.
Performances of the EMMM-assisted WPT system in the previous works are compared, as listed in Table 1. The WPT technique based on EMMMs is developing rapidly in recent years and draws increasing attention to more and more researchers. For WPT performances, the transmission distance, system efficiency and EMF leakage are critical criteria candidates and eternal issues to be solved. In this section, this paper will present some key technical challenges and indicate future development trends for WPT system based on EMMM.

### 5.1 Technical challenges

1. Operating frequency and output power: Most EMMM-based WPT systems operate at microwave frequencies or even higher. However, the WPT systems used in industrial applications are usually working at a frequency of kHz. For instance, the operating frequencies of EV are commonly selected as 81.38–90.00 kHz, which represent the nominal frequency range for light-duty passenger EV (the standard J2954 drafted by the Society of Automotive Engineers) [129]. In addition, these systems only concentrate on the low power level applications due to high frequency, such as household equipment [85, 100] and laptop applications [103] and biomedical implants [109, 112].

2. Placement location: As mentioned above, the transmission distance is coil-to-coil separation in the conventional WPT systems, whereas the practical working range becomes the distance between the EMMM slab and the coil (Tx/Rx coil). When the EMMM slab is placed in the middle of the coils, the working distance is reduced almost in half, even though the efficiency is greatly improved. The effect of EMMM makes sense only when the practical working distance meets the requirements and PTE is enhanced simultaneously compared to conventional systems.

3. Miniaturization and lightweight design: In the state-of-the-art studies on the WPT system with EMMM, these systems consist of sample sizes which are very large. For some small charging systems, such as biomedical telemetry systems and portable electronic devices, large systems may not be practical. In addition, the insertion of EMMM will increase the overall weight of the WPT system inevitably. Lightweight design of the EMMMs need to be considered thoroughly. Moreover, the EMMM also introduces the extra loss into WPT system, which directly affects the PTE improvement of the systems. Too large or many array unit cells of the EMMM slab would cause a significant increase in loss.

4. EMF shielding: The researches on the shielding EMMM in the WPT systems are insufficient. Compared to the traditional shielding materials, such as the ferrite and aluminium plate, the EMMM slab has great promising advantages since the EMMM can shield the EMF and EM wave of specific frequency without affecting other desired frequency band. Most shielding EMMM slabs are placed in the middle or on both ends of the coils. Actually, the EMF outside the transfer channel need to be also taken into account seriously.

### 5.2 Future development trends

In response to the challenges presented above, future directions on WPT systems with EMMMs can be given as follows.

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**FIGURE 28** EM distribution (a) without shielding EMMM. (b) With shielding EMMM

**FIGURE 29** Combination of two kinds of EMMMs in the WPT systems. (a) EM distribution without EMMMs. (b) EM distribution with two kinds of EMMMs. (c) PTE improvement. (d) Shielding effect

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**TABLE 1** Performance comparison of main state-of-the-art papers (‘-’ means not given)

| Ref.   | Coil scheme       | EMMM structure       | Normalized distance | Working frequency (MHz) | PTE improvement (%) | Power (W) | Shielding effect | Misalignment |
|--------|-------------------|----------------------|---------------------|-------------------------|---------------------|-----------|------------------|--------------|
| [84]   | Two-coil, spiral  | 5 × 5 arrays,       | ~2.7                | 6.78                    | 44.2                | –         | 3.49-dBm         | –            |
|        |                   | Dual-layer PCB      |                     |                         |                     |           | Reduction        |              |
|        | [85]              | Four-coil, spiral   | 9 × 9 arrays        | 2.5                     | 27.12               | 30        | 40               | –            |
|        | [87]              | Four-coil structure | 2 × 2 unit cells    | ~2.3                    | 13.56               | 41.7      | 2.8              | –            |
| [96]   | Four-coil, helix  | 3 × 3 arrays        | 4                    | 13.56                   | 12.06               | –         | 62.09%           | (Reduction)  |
| [97]   | Small, non-      | Double-side,        | 11                  | 13.56                   | –                   | –         | ~16 dB           | (Attenuation  |
|        | resonant          | rotated              |                     |                         |                     |           | factor)          |              |
| [100]  | Two-coil, spiral  | 1-slab, 2-slab,     | ~5                   | 6.78                    | 13.3 (1-slab),      | 15        | –                | –            |
|        |                   | 2D, 3D              |                     |                         | 20.7 (2-slab),      |           |                  |              |
|        |                   |                      |                     |                         | 9.0 (2D), 24.0 (3D) |           |                  |              |
| [101]  | Four-coil, spiral | 4 × 5 × 1 arrays, 3D| ~7.5                | 6.5                     | 33 (1 m),           | –         | –                | Peak PTE 47.58% (Angle misalignment of 90 degree)|
|        |                   | structure            |                     |                         | 7.5(1.5 m)         |           |                  |              |
| [103]  | Three-coil       | 2 × 3 arrays        | ~1.7                | 6.78                    | 27                  | –         | –                | –            |
| [106]  | Four-coil, helix | 5 × 5 arrays        | 2, 4                | 2.8                     | 4.26 (2), 9.13 (4)  | 5         | –                | –            |
| [107]  | Four-coil, spiral| 5 × 5 arrays        | ~3.5, ~4.9          | 6.5                     | 34.4 (~3.5), 20.1 (~4.9) | –       | –                | –            |
| [108]  | Two-coil, spiral  | 3 × 4 arrays        | 1.5                 | 1.3                     | ~10                 | 4 (Maximum) | –                | –            |
| [109]  | Two-coil spiral  | Single layer of 77 cells | ~2.25              | 2.57                    | 10                  | –         | –                | –            |
| [112]  | Two-coil, single turn| 3 × 3 CHDR           | ~2.6                | Above GHz               | 52                  | 0.56 (Maximum) | –         | >50% (Angle/displacement misalignment) |
| [125]  | Four-coil, spiral | 5 × 5 arrays        | ~3                   | 6.6                     | 32.6 (Maximum)     | –         | –                | 33.1% improvement (Lateral) 32.9% improvement (Angular)|

1. Reduce working frequency and increase transfer power: High frequency will present great challenges to efficient switching converters. Low transfer power will be detrimental to industrial applications of EMMMs-based WPT systems. Therefore, the possibility to extend the EMMMs concepts and applications to the kHz and high power are promising research hotspots in future studies.

2. Adjust insertion position: Most studies concentrate on putting EMMMs in transmission path, especially for focused EMMMs, which will limit system transmission distance inevitably. Therefore, EMMM slab located adjacent to the coil is a growing trend.

3. Miniaturization, lightweight and portability: The EMMMs with a bulky size are not practical for many application scenarios, and even increase the overall weight of the system and cause great losses. How to address this technical problem will be the focus in near future. Several measures can be taken for miniaturization, lightweight and compactness, such as the use of new material and the analysis for insertion loss minimum. Optimal design of structural configurations and fabrication of the EMMM is another effective method.

4. Energy security: EM safety will be another pivotal technical bottleneck before the final industrial applications. It is exciting that the EMMMs can also solve the issue of EM leakage tactfully. Therefore, the studies on the hybrid EMMM, which both has focusing and shielding effects are also an inevitable tendency.

In addition, other research topics, such as dynamically tunable EMMMs, optimization design for structural fabrication...
of EMMMs, and better theoretical analysis for EMMM-based WPT systems, will be other important topics in near future.

6 | CONCLUSION

In this paper, the EMMM-based WPT system were overviewed with focus on principle, design and fabrication, typical applications and technical challenges. Regarding to the working mechanism of the MCR-WPT systems, traditional 2-coil and 4-coil WPT systems were elaborated and compared briefly. Some technical issues (the frequency splitting and impedance matching), which can occur in the WPT system with EMMM were also illustrated. In Section III and IV, the fundamentals and fabrications of EMMM associated with WPT field were expounded in detail. In addition, the typical applications of EMMM in the WPT system, such as PTE improvement, transfer distance increase, misalignment tolerance and EMF shielding effect, were outlined based on some high-quality references. Finally, the technical challenges and unsolved issues were proposed for promising analysis. By surveying the EMMM-based WPT technology, this paper offers researchers and engineers a big future and points out the direction on the WPT systems with EMMMs.

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