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RESEARCH AND FABRICATION OF METAMATERIALS WITH LOCALIZED MAGNETIC FIELDS FOR WIRELESS POWER TRANSFER SYSTEMS OPERATING IN THE MHZ RANGE

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INTRODUCTION

1. Significance and Necessity of the Research

Nowadays, Wireless Power Transfer (WPT) holds significant potential for applications across a wide range of fields, from military technologies to everyday life. Based on the operating principle and frequency range, WPT systems are typically classified into three categories: (i) short-range WPT, (ii) mid-range WPT, and (iii) long-range WPT. In short-range WPT systems utilizing magnetic fields, power is transferred directly from the transmitter to the receiver via electromagnetic induction. This method is referred to as Inductive Coupling - WPT (IC-WPT). In contrast, mid-range WPT systems employ magnetic fields and rely on a pair of resonators. Power is transferred through magnetic resonance coupling between the two resonators at high frequencies, a mechanism known as Magnetic Resonant WPT (MR-WPT). The physical mechanisms underlying these systems can be explained by the interaction between the transmitter and receiver via magnetic fields whose intensity decreases with distance. Recently, research efforts have increasingly focused on MR-WPT due to its advantage in extending transmission distance. However, the achievable transmission distance and system efficiency still fall short of practical requirements. To ensure near-field WPT operation, the transmission distance must lie within the near-field region, defined as being less than $\lambda/2\pi$ from the source. In such cases, the MHz frequency range is identified as the most suitable. Simultaneously, various industrial alliances, corporations, and research institutes have also recognized the MHz frequency band as a promising range for enabling WPT applications across multiple sectors.

Metamaterials are artificially engineered materials that exhibit unique electromagnetic properties not found in conventional materials. Magnetic Metamaterials (MM), which possess negative or near-zero magnetic permeability, have been demonstrated to enhance the decaying magnetic field between transmitting and receiving resonant coils. As a result, they have been employed to improve the efficiency of MR-WPT systems. In alignment with global research trends, since 2009, Prof. Dr. Vu Dinh Lam has initiated studies on metamaterials at the Institute of Materials Science. His research group has focused on addressing several key issues, including the electromagnetic properties and operational mechanisms of various types of metamaterials, the flexible control of such materials, and their implementation in a range of application domains.

At the time this dissertation was being developed, the application of MMs in MR-WPT systems operating in the MHz frequency range was receiving significant attention from research groups worldwide. In Vietnam, this research direction has also begun to attract interest from groups at the Institute of Materials Science and from Dr. Le Minh Thuy's team at Hanoi University of Science and Technology. Although the use of MMs in MR-WPT has led to improvements in both transmission efficiency and distance, several critical limitations remain: i) The transmission efficiency and distance are still below practical requirements. Moreover, studies on the key parameters affecting system performance remain limited and fragmented; ii) Most MM structures applied in MR-WPT are planar, which restricts their integration into applications that demand flexible surfaces, such as those that need to be bent, rolled, or folded. Additionally, most MMs exhibit homogeneous structures, which limits their capability in applications requiring localized magnetic field enhancement; iii) MMs have also been studied for their ability to guide magnetic energy within material structures. However, 1-D MMs suffer from limited applicability. Although homogeneous 2-D MMs offer broader application potential, they still show limited performance due to the lack of magnetic field localization capability.

Accordingly, this dissertation aims to elucidate the physical nature of MM applied in WPT; investigate the fundamental parameters of the MR-

WPT system; design and fabricate flexible MM that can be rolled or folded to enhance system efficiency; and design and fabricate MM with localized magnetic fields to improve the efficiency and mobility of MR-WPT systems, while also enhancing magnetic energy transfer within the MM structure.

2. Research Objectives of the Dissertation

To clarify the electromagnetic characteristics of MM applied in WPT systems operating in the MHz frequency range.

To fabricate metamaterials with localized magnetic fields for WPT systems operating in the MHz range, aiming to enhance the efficiency of MR-WPT systems and to improve magnetic energy propagation within the material structures.

3. Main Research Contents of the Dissertation

Conduct an overview study of MM, WPT systems, and the application of MM in WPT operating in the MHz range.

Investigate the parameters affecting the performance of a basic MR-WPT system, and design and fabricate MM to enhance the efficiency of the MR-WPT system under both ideal alignment conditions and in the presence of axial and/or angular misalignments.

Research, design, and fabrication of flexible MM and the ability to bend, aimed at enhancing the performance of the MR-WPT system.

Research, design, and fabrication of non-homogeneous 2-D MM applied to enhance the propagation of magnetic field energy within the material structure.

CHAPTER 1. OVERVIEW OF MM OPERATING IN THE MHz FREQUENCY RANGE APPLIED TO WPT

1.1. History of the Formation and Development of WPT

WPT refers to the transfer of energy from a source to a load without using physical conductors. It originated in 1899 when Nikola Tesla first demonstrated WPT using an electric field at 150 kHz. However, WPT gained significant attention in 2007 when a research team at MIT introduced a magnetically coupled resonant system enabling efficient non-radiative power transfer. Since then, various organizations have established WPT standards, and numerous studies have explored its mechanisms, frequency ranges, and power levels to enhance practical applications - improving efficiency, transmission distance, and system flexibility.

1.2. Classification, principles and applications of WPT

1.2.1. Classification of WPT

a) Near-field and far-field regions in electromagnetic wave propagation

Based on the distance from the electromagnetic source, it is divided into three regions: near-field, transition and far-field. When the distance from the source is less than the wavelength λ, it is the near-field region, including the reaction near-field region and the emission near-field region. The reaction near-field region is within $\lambda/2\pi$ from the source, and propagation does not occur.

b) Near-field WPT: Near-field WPT is classified into two types: capacitive (electric field-based) WPT and inductive (magnetic field-based) WPT.

c) IC-WPT and MR-WPT

IC-WPT systems provide various solutions for wireless charging applications but are limited by short transmission distances due to rapid magnetic field attenuation. MR-WPT systems, consisting of four coils, utilize two resonant structures operating at the same frequency to enhance coupling and improve overall power transfer efficiency.

1.2.2. Principle of near-field magnetic WPT

The operating principles of both IC-WPT and MR-WPT are based on electromagnetic induction. The key difference lies in the use of high-frequency resonators in MR-WPT systems. These resonant coils are not directly connected to the power source or load, allowing them to achieve a high quality factor *Q*. As a result, energy can be transferred over longer distances compared to conventional inductive coupling.

1.2.3. Applications of WPT in MHz frequency range

In recent years, WPT has been increasingly used across various industries and fields. In the MHz range, the frequency bands 2.050–2.150 MHz, 6.765–6.795 MHz, and 13.553–13.567 MHz have received particular attention.

a) WPT applications in consumer electronics

According to a 2020 report by the Continental Automated Buildings Association, WPT holds significant potential for consumer electronics applications.

(b) WPT applications in wearable electronic devices

Wearable electronic devices capable of collecting various physiological information from the human body have been and are being used in many fields. Some studies on the application of WPT for wearable devices have been conducted, such as efficient distributed WPT systems for multiple wearable sensors, gloves, etc.

c) WPT applications in implantable medical devices

Implantable medical devices using WPT have been put into use, reducing disease rates and improving patients' quality of life, while also enhancing the effectiveness of diagnosis and treatment.

1.3. Metamaterials applied in MR-WPT in MHz frequency range

1.3.1. Metamaterials

a) Permittivity and permeability: The electromagnetic parameters representing the properties of the transformation material (permittivity, permeability) can be obtained from the effective medium theory and can be obtained by the S-parameter retrieval method. In 2004, X. D. Chen's research group proposed a more accurate method to calculate those parameters.

b) Transforming materials with negative permeability: MM usually operate at low MHz and mainly with magnetic fields. Thanks to negative permeability, MM have the ability to amplify the damped magnetic field in the near field region, which helps to improve the performance of the WPT system.

1.3.2. MM in MHz frequency range applied in MR-WPT

a) History of research on the application of MM in WPT systems

The use of MM to enhance the performance and distance of MR-WPT has been shown in many publications since 2010.

b) Mechanism of MR-WPT using MM in the MHz frequency range

Through many studies, it has been shown that MM have the ability to amplify the damped magnetic field generated from the transmitting resonant coil or increase the number of magnetic flux lines sent through the receiving resonant coil, thereby improving performance.

c) The role of MM for MR-WPT systems in the MHz frequency range

* Enhancement of transmission efficiency

* Compensating for misalignment

* Reducing magnetic leakage – increasing safety

1.3.3. Magnetic field energy propagation in MM structures

MMs can support the propagation of magnetic energy within their structure. This magnetic energy propagation is enabled by the coupling between unit cells arranged in a specific order.

1.4. Conclusion of Chapter 1

This chapter has provided an overview of WPT and the application of MMs in WPT systems operating in the MHz frequency range, leading to the following conclusions:

WPT has a history spanning over a century, but it has only seen significant development in the past two decades. MR-WPT systems have demonstrated application potential in various fields; however, limitations remain in terms of transmission distance, efficiency, and system adaptability.

MR-WPT systems operate based on the fundamental principle of magnetic (evanescent) field coupling between the transmitting and receiving resonators. MM shave been shown to enhance evanescent magnetic fields emitted from the transmitting coil, making them suitable for improving MR-WPT systems. Accordingly, the use of MMs in MR-WPT can help overcome the existing challenges of such systems. Nevertheless, most MM structures currently studied and applied in MR-WPT are flat, fabricated on rigid substrates, and exhibit homogeneous properties. These characteristics limit their use in applications requiring flexible configurability, such as coiling, folding, bending, or directional energy guiding.

CHAPTER 2. RESEARCH METHODS

In this dissertation, to study MM applied in WPT in the MHz range, we employ methods including theoretical calculations and modeling, simulations combined with experiments.

2.1. Theoretical calculation and modeling methods

2.1.1. Modeling the components in MR-WPT using MM

The MR-WPT system using MM consists of components with a unit cell structure of MM operating in the low MHz frequency range. These components are modeled using an *LC* circuit equivalent to the resonance frequency:

$$f_0 = \frac{1}{2\pi\sqrt{L\left(C_0 + C_{\text{ext}}\right)}} \tag{2.1}$$

2.1.2. Calculation of performance of MR-WPT system using MM, electromagnetic characteristics of MM

a) Efficiency of the MR-WPT system: The system efficiency is defined and calculated using Equation (1.9) in Chapter 1.

b) Magnetic permeability of the MM: The effective permeability of the MM is calculated based on a Lorentzian-type resonance model, as presented in Equation (1.23) in Chapter 1.

2.2. Simulation method

The electromagnetic properties of the MM and the MR-WPT system are simulated using CST software based on the finite integration technique to determine key parameters when electromagnetic waves interact with the MM. This includes extracting the field distribution, current density, and analyzing the system's characteristics.

2.3. Experimental method

2.3.1. Fabrication of MM and MR-WPT systems in the MHz frequency range

For MM with a dielectric-metal structure operating in the MHz range, the fabrication method involves 7 main steps: mask creation, applying photosensitive layer, exposure, developing, etching the metal layer, removing the photosensitive material, and welding (capacitor).

2.3.2. Measurement of the characteristics of the MR-WPT system using MM in the MHz frequency range

The experimental results of the dissertation were measured at the Institute of Materials Science, Vietnam Academy of Science and Technology, using the Rohde & Schwarz ZNB20 vector network analyzer system. The measurement results are expressed as the transmission coefficient S_{21}.

2.4. Conclusions of chapter 2

Chapter 2 presents the research methods used in the dissertation, including: theoretical calculations and modeling, simulation, and experimentation. These are effective methods in the research of metamaterials in general and MM in particular. These have been widely used by domestic and international scientists, providing high reliability.

CHAPTER 3. STUDY ON THE PARAMETERS OF THE BASIC MR-WPT SYSTEM AND DESIGN, FABRICATION OF MM TO ENHANCE THE SYSTEM PERFORMANCE

This chapter presents the results of investigating MR-WPT system parameters and design, fabrication of MM to enhance performance.

3.1. Research and survey on parameters affecting the performance of basic MR-WPT system

3.1.1. Design of the MR-WPT system

In this study, we design a symmetric MR-WPT system, where the electrical conductivity and the size of the conductive medium, as well as the operating frequency of the system, can be varied.

3.1.2. Investigation of parameters affecting the MR-WPT system' performance

3.1.2.1. Theoretical analysis

3.1.2.2. Simulation

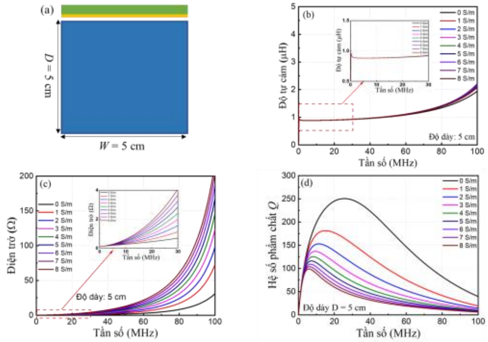

Figure 3.4. (a) Schematic of the simulation setup of the resonant coil placed near the conducting block; dependence of the resonant coil parameters on frequency at different conducting masses: (b) inductance *L*, (c) resistance *R*, (d) quality factor.

When the conductivity of the medium increases, the resistance of the resonant coils increases while the inductance changes only slightly, leading to a decrease in the Q factor of the coil or a reduction in the system's efficiency. The rate of decrease in Q at different frequencies varies significantly, and as the conductivity of the medium increases, the frequency at which the maximum Q is achieved shifts to a lower frequency range.

As the thickness of the conductive block increases, the resistance of the resonant coil increases, while the inductance changes only slightly, resulting in a decrease in the quality factor or a reduction in the system's efficiency. At the same time, the frequency required to achieve maximum Q also decreases from 25.6 MHz to 6.5 MHz, meaning that a greater conductive block thickness requires a lower optimal frequency.

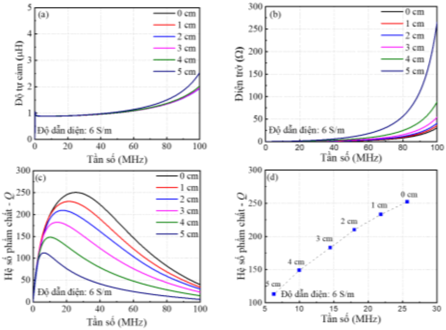

Figure 3.5. Dependence of the parameters of the resonant coil on frequency at different thicknesses of the conductor block: (a) inductance, (b) resistance, (c) quality factor and (d) maximum quality factor.

3.1.3. Fabrication and measurement of the MR-WPT system at two different frequency ranges

The MR-WPT system in a medium with a variable conductivity and operating at two ranges of 10 MHz and 20 MHz was fabricated and the system performance was determined to confirm the analysis in the previous sections.

The measurement results show that the efficiency of the systems in the 10 MHz range decreases when the conductivity increases from 0, 1, 2, 4 and 8 S/m and is 60%, 58%, 55%, 51% and 45%, respectively. Thus, increasing conductivity leads to a decrease in system efficiency due to eddy currents in the conductive block. Comparing the survey results of the two systems, it can be seen that: in pure water, the *Q* of the resonant coil at 20 MHz is larger than 10 MHz, so the 20 MHz system obtains an efficiency of 70% (greater than the efficiency of 60% for the 10 MHz system). This means that in a non-conductive medium, the 20 MHz system is better than the 10 MHz system, and the opposite trend occurs in a conductive medium.

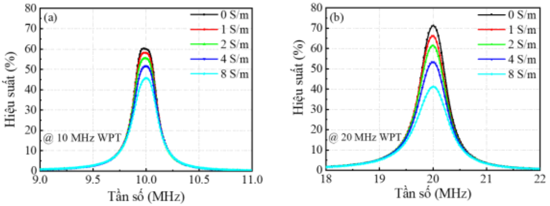

Figure 3.7. Measured performance dependence on operating frequency of MR-WPT systems with different conductivities: (a) MR-WPT operating at 10 MHz range, (b) MR-WPT operating at 20 MHz range.

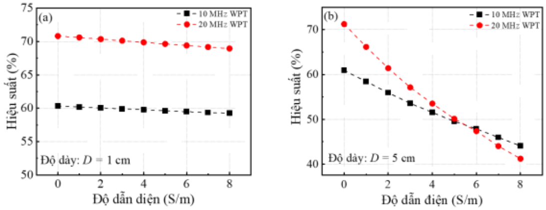

Figure 3.8. Dependence of measured transmission efficiency of MR-WPT systems on conductivity in the cases: (a) the thickness of the conductive block is 1 cm, (b) the thickness of the conductive block is 5 cm.

Figure 3.8(a) shows the measured performance of the system in the presence of a conductive block with D = 1 cm and a conductivity from 0 to 8 S/m. The results show that, at the same conductivity, the 20 MHz system achieves a higher performance than the 10 MHz system. The performance of the 20 MHz system decreases faster with increasing conductivity, but there is no significant difference. As the thickness of the conductive block increases, more energy is dissipated in the medium, the performance of all systems decreases significantly, the 20 MHz system has a much faster performance decrease. At small conductivity, the performance of the 20 MHz system is higher, but when the conductivity is greater than 6 S/m, the performance of the 10 MHz system is higher.

3.2. MR-WPT system using flexible MM slab that can be rolled or folded

3.2.1. Design of MR-WPT system using rollable or foldable flexible MM slab.

In this study, a symmetric MR-WPT system integrating flexible MM slab that can be rolled or folded is proposed.

3.2.2. Simulation and analysis of MR-WPT system using flexible MM slab that can be rolled or folded

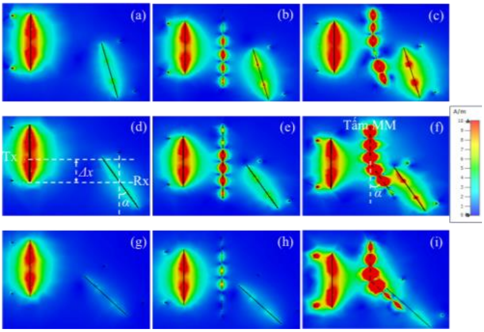

Figure 3.15. Simulation results of magnetic field distribution in MR-WPT system when Rx is offset Δx = 100 mm and the angular deviation is 15°, 30°, 45° respectively in the following cases: (a), (d), (g) when the system without MM slab; (b), (e), (h) when the system with a straight MM slab; (c), (f), (i) when the system has a MM slab folded at an angle corresponding to the deviation angle of Rx.

The results of the magnetic field distribution survey of MR-WPT systems with Rx misalignment Δx = 100 mm and at different misalignment angles (15°, 30°, 45°) and the results of the transmission coefficient extraction through the performance calculation of the systems in those configurations all show good agreement.

Table 3.3. Transmission coefficient and efficiency of MR-WPT system with Rx receiving resonant coil offset Δx = 100 mm, angular deviation α = 15°, 30° and 45° using MM slab that can be folded according to the deviation angle of Rx

Offset angle		MR-WPT system error	MR-WPT system deviation with straight MM slab	MR-WPT system deviation with folded MM slab
15°	S_{21}	0.36	0.51	0.61
	η (%)	12.96	26.01	37.21
30°	S_{21}	0.29	0.42	0.54
	η (%)	8.41	17.64	29.16
45°	S_{21}	0.16	0.21	0.28
	η (%)	2.56	4.41	7.84

3.2.3. Fabrication and measurement of MR-WPT systems using flexible MM slab that can be rolled or folded

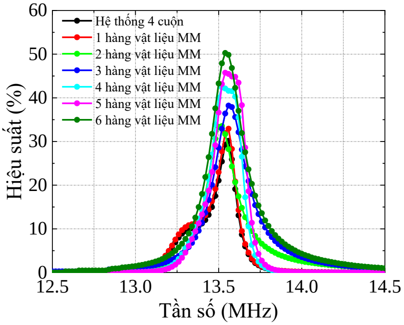

Figure 3.17. Measurement performance of the original MR-WPT system and when using the rollable MM slab with each row of MM unit cells as illustrated in Figure 3.13 at the transmission distance $d_{\text{Tx-Rx}}$ = 250 mm.

The measurement results of the MR-WPT system performance at the transmission distance of 250 mm for different configurations show good agreement with the simulation results of magnetic field distribution, transmission coefficient extraction, and efficiency calculation. The performance of the MR-WPT system with Rx off-axis Δx = 100 mm and deviations at different angles from 0° to 45° is shown in Figure 3.20 with small deviations compared to the simulation results in Table 3.3. These results demonstrate that the MM slab can flexibly fold in the direction of Rx misalignment, which is highly effective in practical applications where Rx is subjected to both axial and angular misalignment.

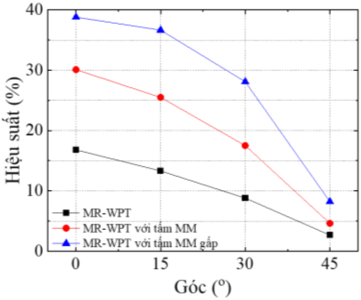

Figure 3.20. Measured transmission efficiency peaks of the MR-WPT system when the axial deviation Δx = 100 mm and the angular deviation *α* are 0°, 15°, 30°, 45° respectively as illustrated in Figure 3.15(a-i).

3.3. Conclusion of chapter 3

Through the study of chapter 3, we obtained some conclusions as follows:

i) The performance of the MR-WPT system in the MHz range depends on the quality factor Q of the resonant coils, determined by inductance L and resistance R. These parameters are influenced by conductivity, conductive block size, and operating frequency. In a conductive environment, increased conductivity raises the radiation resistance due to eddy currents at high frequencies, reducing Q and efficiency. When the conductive block thickness is less than the transmission distance, the system operates at higher frequencies (20 MHz) with better efficiency, decreasing slowly as conductivity increases. At thickness equal to the transmission distance, there is an optimal conductivity: below this value, higher frequencies (20 MHz) are more efficient, while above it, lower frequencies (10 MHz) are more effective, with efficiency decreasing more slowly as conductivity rises.

ii) The design and fabrication of flexible MM slab that can be rolled or folded enhances the performance of the symmetric MR-WPT system in both cases: without misalignment and with both axial and angular misalignment. Specifically, in the case of using rollable MM slab, the maximum system efficiency was significantly improved from 30% without using MM slab to 50.5% with using the entire slab. When using a foldable MM slab parallel to Rx and simultaneously with axial and angular misalignment, the system efficiency was significantly improved, specifically, with 100 mm axial misalignment and 30^o angular misalignment, the system efficiency increased from 8.8% to 28.1%.

CHAPTER 4. RESEARCH ON MANUFACTURING OF FLEXIBLE MM WITH LOCALIZED MAGNETIC FIELD FOR APPLICATION IN ENHANCEMENT OF MR-WPT SYSTEM PERFORMANCE

In this chapter, the dissertation presents the results of designing and manufacturing flexible MM structures with localized magnetic fields due to the design of resonant cavities to enhance the efficiency, distance, and applicability of the system.

4.1. Resonant cavity and cavity formation mechanism

Resonant cavities or magnetic energy concentration regions are proposed to control the strength and shape of the magnetic field localization. The mechanism of operation is illustrated in Figure 4.1. The physical mechanism for cavity formation can be explained by the Fano interference effect between the unit cells. When the MM slab is resonant with the cavity, all the unit cells resonate at the f_{loc} except the central cell which is tuned to resonate at f_0. This results in a high intensity transmission peak around f_0. Thus, at the location of uint cells other than the cavity, the surface wave propagation is blocked by the forbidden band; results in a confined magnetic field within the cavity.

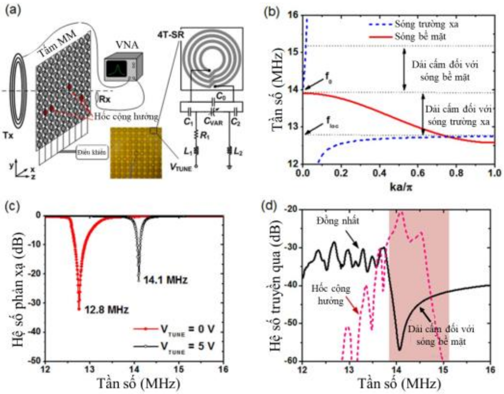

Figure 1. (a) Schematic and photo of the active metasurface with the tunable unit cell, showing the distance between the Tx coil (Rx probe) and metasurface (20 cm and 5 cm, respectively). (b) Dispersion characteristics of MIWs and propagating waves. (c) Measured reflection of a single unit cell. (d) Transmission for uniform and defective metasurfaces, measured using a Tx coil and Rx probe.

4.2. Flexible MM slab with resonant cavity and bendable application in enhancing MR-WPT system performance

4.2.1. Design of flexible MM slab with resonant cavity and bendable for application in MR-WPT system

In this study, an asymmetric MR-WPT system integrating a flexible MM slab with a resonant cavity and a bendable one operating at a frequency range of 13.56 MHz is proposed.

4.2.2. Simulation of MR-WPT system using flexible MM slab with resonant cavity and bendable

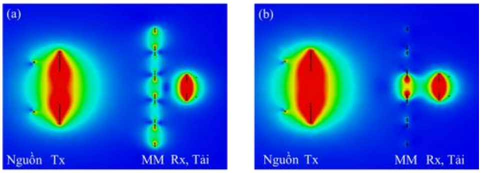

Figure 4.5. Simulation results of magnetic field distribution in MR-WPT system: (a) with homogeneous MM, (b) with non-homogeneous MM slab.

The results show that the non-uniform MM slab (with a cavity at the center of the slab) enhances the magnetic field strength near the pickup coil, thereby enhancing the performance of the MR-WPT system.

The results also indicate that both homogeneous and heterogeneous MM slabs can improve the system performance in bending.

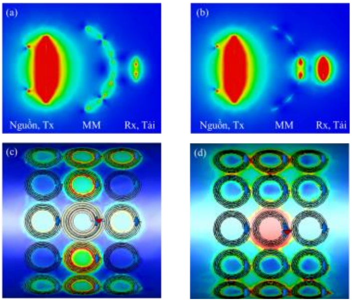

Figure 4.6. Simulation results of magnetic field distribution in MR-WPT system using flexible MM slab: (a) homogeneous MM and (b) heterogeneous MM slab. Simulation results of magnetic field distribution on MM slab with: (c) homogeneous MM and (d) heterogeneous MM slab.

4.2.3. Fabrication and experimental measurement of MR-WPT system using flexible MM slab with resonant cavity and bendable

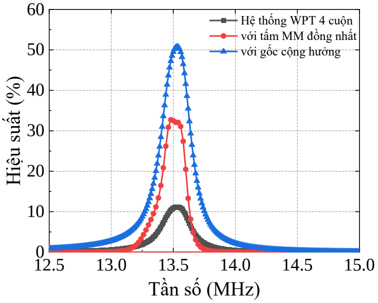

Figure 4.8. Measured performance of the MR-WPT system in the following cases: without MM slab (4-coils MR-WPT system), with homogeneous MM slab, and with MM slab with resonant cavity.

The measured efficiencies of the MR-WPT systems in three configurations (dTx-Meta = 150 mm, dMeta-Rx = 50 mm) were 11.5%, 32.3%, and 52% for the original, homogeneous MM slab, and heterogeneous MM slab systems, respectively. This demonstrates that the cavity design at the center of the MM slab significantly enhances system efficiency. Changing the curvature of the MM slab increased system efficiency at large bending radii and decreased it at small radii, with a maximum efficiency of 34.8% at a 150 mm bending radius for the homogeneous MM system and 55.1% for the heterogeneous MM system.

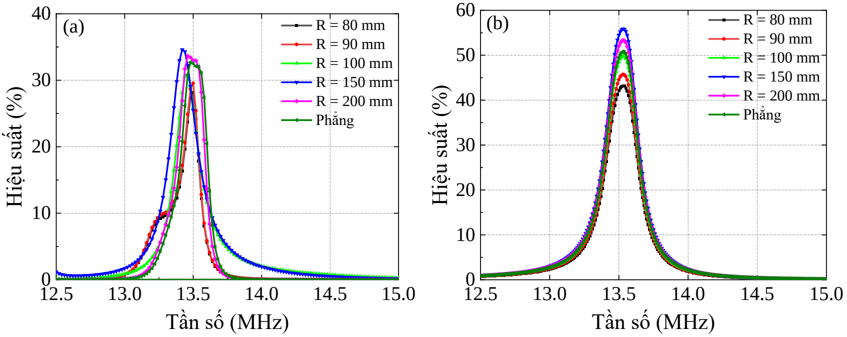

Figure 4.9. Measured performance of the MR-WPT system as a function of frequency with different curvature radii when using: (a) homogeneous MM slab and (b) heterogeneous MM slab.

4.3. Conclusion of chapter 4

In this chapter, by simulation and experiment, we have proposed, designed and fabricated a flexible MM structure with a resonant cavity and can be bent to enhance the performance of the asymmetric MR-WPT system operating at 13.56 MHz. Using this MM slab in a flat configuration has significantly improved the maximum efficiency of the system, from 11.5% for the original system to 32.3% for the system using a homogeneous slab and to 52% when using a slab with a resonant cavity. When using a bent MM slab, there exists a curvature radius of 150 mm where the maximum efficiency of the system has increased from 32.3% to 34.8% when using a homogeneous MM slab and has increased from 52% to 55.1% when using a MM slab with a resonant cavity at the center of the slab.

CHAPTER 5. DESIGN AND FABRICATION OF INHOMOGENEOUS 2D MM WITH LOCALIZED MAGNETIC FIELDS FOR ENHANCED MAGNETIC ENERGY TRANSFER IN MATERIAL STRUCTURES

Chapter 5 of the dissertation presents the results of design and fabrication of a non-uniform 2-D MM slab with localized magnetic field using a series of resonant cavities to enhance the propagation of magnetic energy in the slab.

5.1. Propagation of magnetic energy in 1-D MM structures

5.1.1. Design of MM unit cell

As in previous chapters, the proposed MM in this chapter features a unit cell structure composed of a circular spiral integrated with an external capacitor.

5.1.2. Characteristics of the MM unit cell

The MM unit cell is designed with a resonant frequency of 20 MHz.

5.1.3. Propagation of magnetic energy in a 1D MM unit cell chain

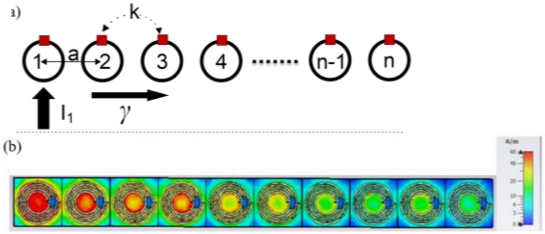

Figure 5.3. (a) Schematic diagram of the 1-D MM unit cell chain, (b) simulation results of magnetic field distribution in the 9-cell 1-D MM unit cell chain.

The magnetic field distribution on each element of the 1-D MM chain consisting of 9 resonant coils was investigated. The results showed that the magnetic field is concentrated in the 1-D MM chain and has high intensity at the center of the spirals. The magnetic field intensity is reduced when the unit cell is far from the source due to the attenuation on each MM unit cell.

Thus, the 1-D MM chain shows the ability to propagate magnetic energy in the structure.

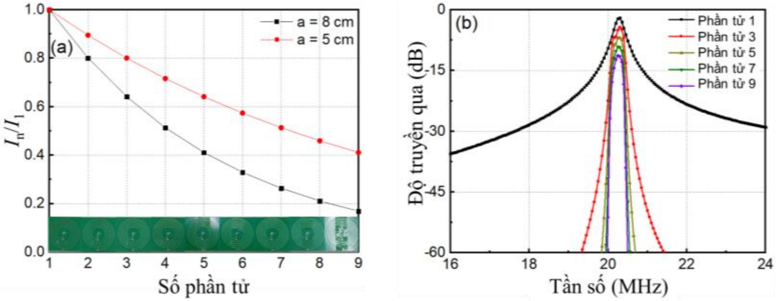

Figure 5.4. (a) Calculated results of the current ratio of the nth element to the first element, (b) measured transmittance at some elements in the 1-D MM chain.

Figure 5.4(b) shows the measured magnetic energy propagation in the MM chain. The resulting transmittance peaks are −1.6; − 4.03; − 6.86; − 8.98 and − 11.23 dB at 20.3 MHz when the number of resonant coils is 1; 3; 5; 7 and 9, respectively. Since the magnetic energy propagation occurs only on the surface of the MM chain in the low MHz range, the radiation loss can be neglected. Therefore, the reduction of magnetic energy in the MM chain is due to the Ohmic loss in the MM unit cells.

5.2. Propagation of magnetic energy in heterogeneous 2-D MM

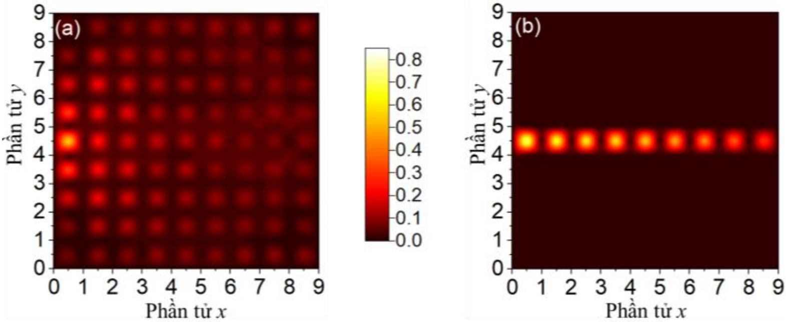

Figure 5.6. Magnetic field intensity measured at 20.3 MHz in: (a) homogeneous 2-D MM slab and (b) inhomogeneous 2-D MM slab.

From the 1-D MM chain, a 2-D MM slab is proposed, consisting of 9 × 9 unit cells. The size of the 2-D MM slab is 45 × 45 cm^2. The magnetic field energy propagation path configuration is designed.

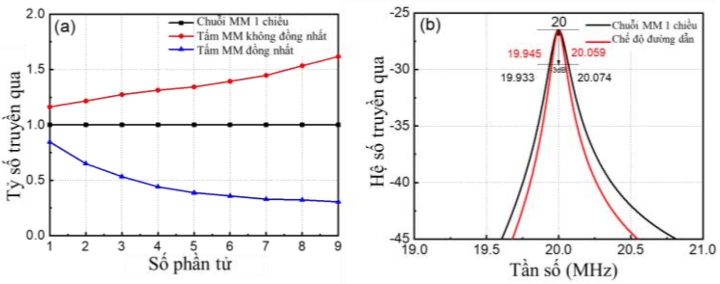

Figure 5.7. (a) Comparison of measured magnetic energy propagation for three configurations: 1-D MM chain (black), homogeneous MM slab (blue), heterogeneous MM slab (red) (b) measured transmission coefficient in weak coupling mode to extract the quality factor of the MM unit cell in the 1-D MM chain and of the heterogeneous MM slab.

The results show that at the 9th basic cell in the magnetic energy propagation path of the homogeneous 2-D MM slab, the transmission ratio is 0.31 - meaning that the energy leaks to other parts of the slab when the number of unit cell elements increases and causes a large attenuation in the propagation process; at the 9th unit cell in the magnetic energy propagation path of the non-homogeneous 2-D MM slab, the transmission ratio reaches 1.62, which is 5.2 times higher than that of the homogeneous 2-D MM slab.

5.3. Conclusion of chapter 5

In this chapter, we designed and fabricated an MM structure operating at MHz to enhance magnetic energy propagation efficiency. The proposed non-uniform 2-D MM slab consists of 9 × 9 unit cells, with resonant cavities arranged to create a magnetic energy propagation path. By localizing the magnetic field along the path, the propagation efficiency in the non-uniform 2-D MM slab increased 5.2 times compared to the homogeneous 2-D MM slab.

CONCLUSIONS

The dissertation entitled "*Research and fabrication of metamaterials with localized magnetic fields for wireless power transfer systems operating in the MHz range*" was carried out at the Graduate University of Science and Technology and the Institute of Materials Science, Vietnam Academy of Science and Technology. The research focused on designing and fabricating metamaterials with localized magnetic fields for WPT systems in the MHz range, aiming to enhance system efficiency, transmission distance, and adaptability in conductive environments or flexible configurations. Key findings have been published in four SCIE-indexed international journals, two national journals, and one national scientific conference proceeding.

The dissertation has fulfilled its objectives and yielded key results contributing to materials science in general and metamaterials research in particular, as follows:

1. Clarified the electromagnetic characteristics of MM applied in MR-WPT systems operating in the MHz frequency range. The MM structure functions as an amplifier for the decaying magnetic field emitted by the transmitting resonator, thereby enhancing the magnetic field received by the receiving resonator. As a result, it improves the overall transmission efficiency and range of the system.

2. Investigated the parameters affecting the transmission efficiency of MR-WPT systems in MHz frequency ranges within conductive environments. System efficiency is influenced by the quality factor, inductance, and resistance of resonators, which depend on conductivity, block size, and operating frequency. Increased conductivity raises radiation resistance due to high-frequency eddy currents, reducing the quality factor and efficiency. When the conductive block thickness is smaller than the transmission distance, the system operates more efficiently at 20 MHz, with slower efficiency degradation as conductivity increases. At equal thickness

and transmission distance, an optimal conductivity exists: below this value, 20 MHz performs better, while above it, 10 MHz becomes more efficient, with slower efficiency degradation as conductivity increases.

3. Designed and fabricated a single flexible MM sheet that can be rolled or folded, operating in the MHz frequency range, to enhance both the transmission efficiency and mechanical adaptability of symmetric MR-WPT systems. Using the rolled MM sheet increased the system efficiency from 30% (without MM) to 50.5% (with the full sheet). When the sheet was folded in parallel with the receiving coil, in a misaligned setup with 100 mm axial offset and 30° angular deviation, the system efficiency increased from 8.8% to 28.1%.

4. Designed and fabricated a single MM slab with localized magnetic fields and integrated resonant cavities, which can be bent to a limited degree, for improving the efficiency and spatial adaptability of MR-WPT systems. This MM structure significantly enhanced the system's peak efficiency: from 11.5% (without MM) to 32.3% using a homogeneous MM slab, and up to 52% when using a slab with a resonant cavity at its center. When the slab was bent at an optimal curvature radius of 150 mm, the system's maximum efficiency further increased - from 32.3% to 34.8% with the homogeneous slab, and from 52% to 55.1% with the cavity slab.

5. Designed and fabricated a single non-homogeneous 2D MM slab with localized magnetic fields and a tunable resonant cavity chain, operating in the MHz frequency range, for enhancing magnetic energy propagation within the material structure. The MM slab consists of a 9 × 9 unit cell array. When a resonant cavity chain was placed at the center of the slab, magnetic energy propagation was enhanced by a factor of 5.2 compared to that in a homogeneous 2D MM slab.

The dissertation contributes to advancing metamaterials research, particularly the application of MM in MHz-range WPT systems.

NEW CONTRIBUTIONS OF THE DISSERTATION

The dissertation has focused on addressing and completing new problems related to the electromagnetic properties of MM operating in the MHz frequency range for WPT, specifically:

1. Clarify the electromagnetic nature of MM used in MHz-frequency WPT systems to improve the system’s overall efficiency.

2. Investigate the parameters affecting the transmission efficiency of MR-WPT systems operating in the MHz frequency range (below 30 MHz) within conductive environments, where the electrical conductivity ranges from 0 to 8 S/m. The investigated parameters include the conductivity and size of the conductive medium, as well as the system’s operating frequency.

3. Design and fabricate a flexible MM sheet that can be rolled or folded to enhance both the transmission efficiency and the mobility of the WPT system. The proposed MM sheet improves system performance under both ideal alignment and in the presence of misalignments, including a 100 mm axial shift and angular deviations.

4. Design and fabricate a flexible MM slab featuring localized magnetic fields enabled by integrated resonant cavities, capable of bending and operating in the MHz frequency range for MR-WPT applications. This MM slab enhances both transmission efficiency and system mobility. A bending radius of 150 mm is identified as the optimal condition under which the system achieves maximum efficiency, applicable to both homogeneous MM slabs and those with resonant cavities.

5. Design and fabricate a non-homogeneous 2D MM slab with localized magnetic fields, operating in the MHz frequency range, featuring a central array of resonant cavities. This structure enhances the propagation efficiency of magnetic energy within the material by a factor of 5.2 compared to a homogeneous 2D MM slab.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

1. Thanh Son Pham, Thao Duy Nguyen, Bui Son Tung, Bui Xuan Khuyen, Thu Trang Hoang, Quang Minh Ngo, **Le Thi Hong Hiep** & Vu Dinh Lam, "*Optimal frequency for magnetic resonant wireless power transfer in conducting medium*", Scientific Reports **11**, 18690 (2021).

2. Le Thi Hong Hiep, Thanh Son Pham, Bui Xuan Khuyen, Bui Son Tung, Quang Minh Ngo, Nguyen Thi Hien, Nguyen Thai Minh and Vu Dinh Lam, "*Enhanced transmission efficiency of magneto-inductive wave propagating in non-homogeneous 2-D magnetic metamaterial array*", Physica Scripta **97**, 025504 (2022).

3. Le Thi Hong Hiep, Bui Xuan Khuyen, Bui Son Tung, Quang Minh Ngo, Vu Dinh Lam and Thanh Son Pham, "*Flexible Magnetic Metasurface with Defect Cavity for Wireless Power Transfer System*", Materials **15**, 6583 (2022).

4. Le Thi Hong Hiep, Huu Nguyen Bui, Bui Son Tung, Vu Dinh Lam, Bui Xuan Khuyen, Thanh Son Pham, "*Enhanced efficiency of magnetic resonant wireless power transfer system using rollable and foldable metasurface based on polyimide substrate*", Applied Physics A **130**, 521 (2024).

5. Thanh Son Pham, Bui Xuan Khuyen, Bui Son Tung, **Le Thi Hong Hiep,** Vu Dinh Lam, *"A critical review on wireless power transfer systems using Metamaterials",* Vietnam Journal of Science and Technology **60** (4), 587-613 (2022).

6. Le Thi Hong Hiep, Pham Thanh Son, Bui Xuan Khuyen, Bui Son Tung, Tran Văn Huynh, Vu Dinh Lam, "*optimize the efficiency of the wireless power transfer system using the quality factor of the resonator*", TNU Journal of Science and Technology **228** (14), 222-229 (2023).

7. Le Thi Hong Hiep, Pham Thanh Son, Bui Xuan Khuyen, Bui Son Tung, Tran Văn Huynh, Vu Dinh Lam, "*Research on the location of the magnetic metamaterial slab to optimize the performance of the magnetic resonant wireless power transfer system*", The 13th National Conference on Solid State Physics & Materials Science (SPMS 2023), 702-705 (2023).