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# RESEARCH ON THE STRUCTURE AND PROPERTIES OF MULTIFUNCTIONAL METAMATERIALS FOR ELECTROMAGNETIC WAVE ABSORPTION AND POLARIZATION CONVERSION

**DOCTORAL DISSERTATION SUMMARY IN MATERIAL SCIENCE**

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# INTRODUCTION

Some of the most promising applications of metamaterials (MMs) include the development of electromagnetic wave absorbers and polarization converters.

Research on metamaterial absorbers (MA) primarily aims to broaden the operational bandwidth, enhance absorption efficiency, and adjust the frequency range from microwave to optical frequencies. Additionally, efforts are being made to minimize the influence of wave polarization and incident angles on absorption performance. Meanwhile, due to the capability of MMs to manipulate wave amplitude and phase, metamaterial-based polarization converters (MPC) have also gained significant research interest. Potential applications of MPC include radar cross-section (RCS) reduction, smart antennas, and other advanced technologies. Research in this field focuses on improving polarization conversion efficiency and expanding the operational bandwidth across various frequency ranges.

Although existing MMs have achieved high performance and compact designs for applications as absorbers or polarization converters, these structures currently operate in only one specific function—either absorption or polarization conversion. However, certain systems require multifunctionality, compact size, and adaptability. Specifically, the ability to switch between polarization conversion and electromagnetic wave absorption is crucial for electromagnetic field measurement components, antenna design, and applications requiring low RCS.

To date, initial studies on multifunctional metamaterials (MFM) that integrate both absorption and polarization conversion capabilities have been proposed. These studies mainly explore the following approaches: (1) Mechanical tuning, where structural modifications such as zig-zag or origami-based designs allow for dynamic adjustment of functionalities [10, 11]. (2) Integration of electronic components, such as diodes, to achieve tunable electromagnetic responses [12-14]. (3) Incorporation of phase-change materials, such as graphene or $VO_2$, enabling tunable absorption and polarization conversion without altering the original structure [5, 15-17]. (4) Water-based metamaterials, a novel and promising approach leveraging water's high dielectric loss over a broad frequency range, which enhances broadband absorption [18-20].

While these approaches have demonstrated effective performance within specific frequency ranges, existing designs still face challenges. Many have complex structures that make fabrication difficult, while others exhibit limited bandwidths, making them unsuitable for broadband applications. Additionally, some designs fail to achieve high performance in both absorption and polarization conversion modes simultaneously. Furthermore, the physical mechanisms governing the multifunctional behavior of these materials have not yet been comprehensively explored.

In Vietnam, research on metamaterials is steadily growing, with contributions from various research groups at universities and institutes. Most studies have focused on electromagnetic wave-absorbing materials, whereas research on polarization-converting and multifunctional metamaterials remains limited. Initial research on MFMs has been conducted at the Academy of Science and Technology by Dr. Lê Văn Long, who proposed a diode-integrated structure [21]. The results demonstrated the potential of combining electromagnetic wave absorption and polarization conversion functionalities.

**Research objectives**

This dissertation aims to investigate the operating mechanisms of MMs that exhibit both absorption and polarization conversion properties. The goal is to design and fabricate MFM structures capable of switching between these two functionalities in the GHz and THz frequency ranges. The proposed designs feature:

Compact structures suitable for practical applications.

High absorption and polarization conversion efficiency across a broad frequency range.

Minimal sensitivity to incident angles and wave polarization angles, ensuring stable performance under varying conditions.

By achieving these objectives, this research aims to contribute to the development of next-generation multifunctional metamaterials for advanced electromagnetic applications.

**Research objectives**

Design and investigate the properties of MFM capable of switching between high-efficiency, broadband absorption and polarization conversion modes in both the GHz and THz frequency ranges.

Fabricate a multifunctional metamaterial capable of switching between absorption and polarization conversion modes in the GHz frequency range.

Elucidate the physical mechanisms governing the absorption and polarization conversion functionalities of multifunctional metamaterials.

**Research content**

Investigate the operating mechanisms of MMs with both absorption and polarization conversion properties.

Study the structure and investigate the influence of various parameters on the performance of MFM capable of switching between absorption and polarization conversion in the GHz and THz frequency ranges.

Fabricate compact MFM capable of switching between absorption and polarization conversion modes in the GHz frequency range.

# CHAPTER 1: OVERVIEW OF ELECTROMAGNETIC WAVE-ABSORBING AND POLARIZATION-CONVERTING METAMATERIALS

## 1.1. Overview of metamaterials

MMs are engineered materials made of "meta-atoms" that are much smaller than the operating wavelength. They can manipulate electromagnetic parameters like permittivity and permeability, allowing control over wave propagation. This enables MMs to exhibit unique properties such as negative refractive indices and invisibility cloaks. MMs are also used to enhance radar wave absorption, improve antenna performance, and optimize sensor efficiency.

## 1.2. Metamaterial absorbers and polarization converters

### *1.2.1. Metamaterial absorbers and application*

The unit cell structure of modern MA typically consists of three layers: a top layer with periodically arranged metallic resonators, a middle dielectric substrate layer, and a bottom continuous metallic film layer. The design principle of MA is based on impedance matching, which reduces reflection when electromagnetic waves interact with the material’s surface. MA have opened up significant potential for RF frequency applications, ranging from microwave to optical frequencies.

### *1.2.2. Metamaterial polarization converter and application*

MPC have gained considerable research interest due to their ability to manipulate the amplitude and phase of electromagnetic waves. To achieve effective polarization conversion, the interaction between electromagnetic waves and the material must generate significant reflected or transmitted waves with the desired polarization state (TE or TM). When an incident wave with a specific polarization (e.g., TE) strikes the material, the asymmetric properties of the metamaterial surface induce reflected and transmitted components with different polarization states, leading to the polarization conversion effect.

## 1.3. Muntifunction metamaterial absorbers and polarization converters

#### ***1.3.1. Some design approaches for muntifunction metamaterial absorbers and polarization converters***

Several design approaches have been proposed, including:

*Integration of electronic components diodes*

One of the commonly adopted approaches for reconfiguring metamaterial metasurfaces is the integration of electronic components such as diodes. This method enables multifunctional operation by utilizing diodes as external switches to dynamically control the transition between absorption mode and polarization conversion mode.

*Mechanical shape reconfiguration method*

Modern MMs can be designed with flexible and reconfigurable structures, allowing bending, stretching, and even transformation into arbitrary shapes. Compared to conventional planar MMs, non-planar MMs offer several advantages, including multifunctional integration, material miniaturization, and enhanced electromagnetic wave absorption performance.

*Integration of water-based materials*

Recently, water-based materials have gained attention in the design of MFM for electromagnetic wave absorption and polarization conversion. Water exhibits high dielectric loss over a broad frequency range, making it an effective medium for achieving broadband absorption.

*Integration of phase-change materials*

The combination of metasurfaces with phase-change materials, such as chalcogenide GeSbTe, vanadium dioxide ($VO_2$), and graphene, has been proposed for developing MFM with switchable absorption and polarization conversion functions. Graphene-based MFM: These structures enable dynamic switching between absorption mode and polarization conversion mode by tuning the chemical potential of graphene. $VO_2$-Integrated MFM: The transition between absorption and polarization conversion modes is controlled by altering the state of $VO_2$ from a dielectric phase to a metallic phase. This phase transition can be triggered by temperature changes, external electric fields, or optical excitation.

#### *1.3.2. Aplication of muntifunction metamaterial absorbers and polarization converters*

Absorbers are used to absorb and dissipate the impact of electromagnetic waves, while polarization converters have the ability to adjust the polarization state of incident waves. These devices have been extensively studied in recent years for a wide range of applications, including military, telecommunications, security, and sensing.

### 1.4. Chapter conclusion 1

To establish the absorption mechanism in MMs, the fundamental MMs structures typically consist of a three-layer configuration: metal–dielectric–metal. The top metallic layer features a resonant structure, which enables impedance matching with the surrounding medium. The bottom metallic layer acts as a reflector, preventing electromagnetic waves from propagating beyond the material and ensuring that the waves are primarily absorbed within the middle dielectric layer. Additionally, for polarization conversion, the symmetry of the unit cell structure in MMs plays a crucial role in the design. When the symmetry of the structure relative to the incident field is broken, the metamaterial can generate electromagnetic responses in different directions compared to the incident field. As a result, the polarization state of the transmitted or reflected electromagnetic wave is altered relative to the incident wave's polarization state.

## CHAPTER 2. RESEARCH METHODOLOGY

### 2.1. Theoretical calculation method

#### *2.1.1. Equivalent circuit*

The equivalent circuit model is a simple and effective solution for impedance matching by designing appropriate resistor and conductor element models within the metal-dielectric-metal (MPA) structure.

***2.1.2. Method for calculating the input impedance of the structure***

Impedance matching in MA is a crucial factor in optimizing absorption performance. The input impedance Z of the structure is calculated using the following expression:

$$Z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}},$$

When the input impedance Z of the MA satisfies the impedance matching condition with the impedance of the surrounding medium (where the real part of Z is approximately 1 and the imaginary part is close to 0), the reflected waves are minimized, enhancing the absorption of electromagnetic waves.

***2.1.3. Calculation of absorption efficiency and polarization conversion efficiency***

The absorption efficiency of the MMs structure with absorption characteristics is calculated using the following expression: $A(\omega) = 1 - R(\omega) - T(\omega)$

where $R(\omega) = |S_{11}|^2$ and $T(\omega) = |S_{21}|^2$ orrespond to the reflection and transmission coefficients, respectively, as functions of frequency.

The polarization conversion efficiency of the MMs structure with absorption characteristics is calculated using the following expression:

$$PCR = \frac{|R_{xy}|^2}{|R_{xy}|^2 + |R_{yy}|^2}.$$

where $R_{xy} = E_{rx} / E_{iy}$ and $R_{yy} = E_{ry} / E_{iy}$ which correspond to the cross-polarization and co-polarization reflection coefficients of the reflected wave, respectively.

### 2.2. Simulation method

The electromagnetic characteristics of MMs and MFM are simulated using CST software, which employs the finite integration technique to determine key parameters when electromagnetic waves interact with the material. In this process, the distribution of electromagnetic fields, current density, and other relevant parameters are extracted from the simulation results as data for analyzing the properties of MMs and MFM.

### 2.3. Fabrication and experimental measurement method

MPC and water-integrated MFM operating in the GHz frequency range are studied through experimental fabrication methods. The MPC samples are fabricated using photolithography, while the water-integrated MFM absorbers and polarization converters are manufactured using a combination of photolithography and 3D printing technology.

After fabrication, the electromagnetic characteristics of the MMs are measured using a Rohde & Schwarz ZNB20 vector network analyzer. The measured results are then analyzed and compared with theoretical calculations and simulation data.

### 2.4. Chapter Conclusion 2

Chapter 2 presents the research methods, including theoretical calculations, simulations using CST software, fabrication, and experimental measurements. These research methods are highly accurate and reliable, and they are widely used in MMs studies.

## CHAPTER 3. DESIGN AND INVESTIGATION METAMATERIALS ABSORPTION AND POLARIZATION CONVERSION CHARACTERISTICS

### 3.1. Design and Analysis of the Absorption Properties of MA Operating in the THz Frequency Range

### *3.1.1. Design of MA operating in the THz frequency range*

The proposed MA structure consists of a perforated circular disk with a square-shaped hole, incorporating vanadium dioxide ($VO_2$) as a phase-change material.

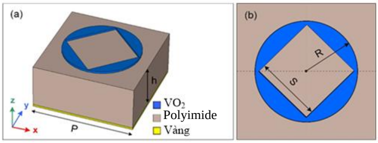


**Figure 3.3.** *Basic unit cell of the proposed MA: (a) 3D image and (b) top view image.*

### *3.1.2.* Analysis of the absorption properties of the MA operating in the THz frequency range

The optimized design demonstrates that as the conductivity of $VO_2$ increases from $2\times10^2$ S/m to $2\times10^5$ S/m, the absorption of the MA gradually increases from 4% to 98%. Additionally, the absorption bandwidth is also expanded.

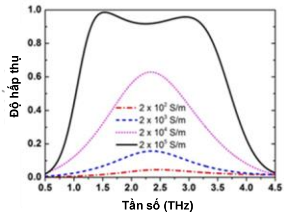


***Figure 3.4.*** *Absorption Spectrum for Different Conductivity Values of $VO_2$*

The analysis of the electric field distribution on the top layer of the structure reveals that when $VO_2$ is in the dielectric phase, it remains nearly transparent to electromagnetic waves in the THz frequency range. In this state, most of the electromagnetic waves pass through the $VO_2$ layer and the dielectric layer, then reflect back from the bottom metallic substrate.

When $VO_2$ transitions to the metallic phase, the electric field becomes strongly concentrated along the inner edges of the square aperture and the outer perimeter of the circular disk in the $VO_2$ layer. This concentration corresponds to an increase in the absorption efficiency of the MA.

Calculations of the input impedance Z of the structure indicate that within the frequency range of 1.25 to 3.5 THz, the real and imaginary parts of Z are approximately 1 and 0, respectively. This confirms the high absorption efficiency of the MA within its operational frequency band.

#### *3.1.3. Effect of resonant layer thickness on MA absorption*

Simulation results indicate that the thickness ttt of the resonant surface layer significantly influences the absorption performance of MA. As the thickness t of the $VO_2$ layer increases, the absorption efficiency tends to decrease. However, the absorption bandwidth exhibits a slight increase.

#### *3.1.4. Effect of incident angle on MA absorption efficiency*

When $VO_2$ is in the metallic phase, the structure maintains high absorption efficiency for incident angles up to 60°. In contrast, when $VO_2$ is in the dielectric phase, the absorption remains very low across all incident angles and polarization angles, indicating that most of the incoming electromagnetic waves are reflected.

Additionally, the proposed MA exhibits polarization insensitivity due to the symmetric nature of its structure.

A comparison of the proposed MA with previous $VO_2$-based MAs demonstrates its superior performance, featuring a simpler design, ease of fabrication, the widest absorption bandwidth, and robustness against incident angle variations.

### 3.2. Design and analysis of the electromagnetic wave polarization-conversion metamaterial

#### *3.2.1. Design of the MPC for S- and C-band applications*

In this section, we propose a simple design of a MPC based on a slotted resonant ring structure for applications in the S-band (2–4 GHz) and C-band (4–8 GHz). The design achieves a polarization conversion efficiency (PCE) greater than 90% over the frequency range from 2 GHz to 8.45 GHz, fully covering both the S- and C-bands, with a relative bandwidth (RBW) of 123.4%.

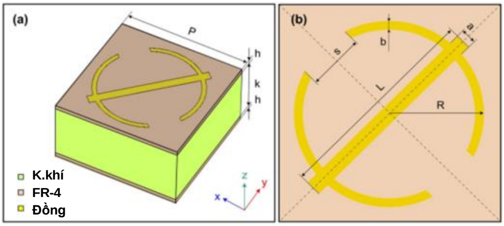


***Figure 3.11.*** *(a) 3D view and (b) Top-layer view of the unit cell of the proposed MPC.*

The operating principle of the structure is analyzed by examining the co-polarized and cross-polarized reflection coefficients of the reflected wave in the uv coordinate system, which is rotated 45° relative to the xy-axis.

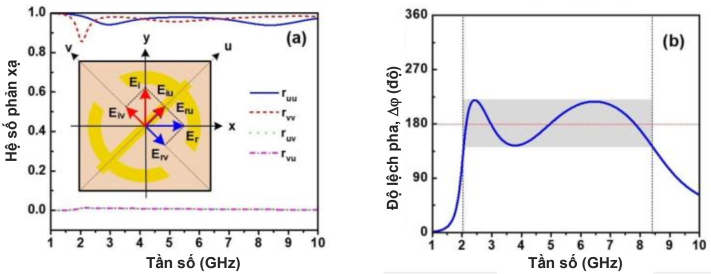


**Figure 3.13.** *(a) Schematic of electric field decomposition along the u- and v-axes and the magnitudes of the reflection coefficients along these axes; (b) Phase difference of the reflection coefficients for the uu and vv components.*

The magnitudes of $r_{uu}$và $r_{vv}$ are approximately 1, while $r_{uv}$và $r_{vu}$ are nearly 0 within the frequency range of 2 to 8.45 GHz. This result confirms that the reflected wave undergoes a precise 90° rotation relative to the incident wave.

To further understand the physical mechanism of the polarization conversion process, the surface current distribution on the metallic layer is analyzed at four resonance frequencies.

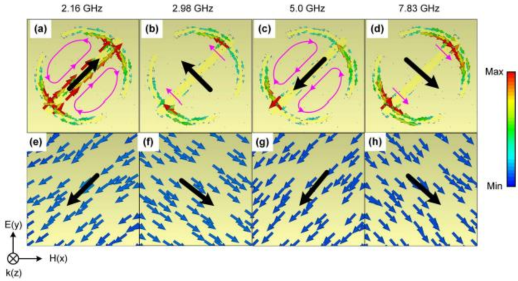


**Figure 3.15.** *Simulated surface current distribution on the top and bottom layers of the unit cell at four resonance frequencies.*

Additionally, the effects of air layer thickness and incident wave angle on polarization conversion efficiency were investigated. The results indicate that introducing an air layer significantly enhances the polarization conversion efficiency at resonance peaks. Meanwhile, the incident angle has only a minor impact on the conversion performance.

The MPC prototype was fabricated using the photolithography method, and its electromagnetic characteristics were measured using a vector network analyzer (VNA). The experimental results exhibit good agreement with the simulations, with only minor deviations due to fabrication tolerances.

***3.2.2. Optimization of the MPC structure for C-, X-, and Ku-band applications***

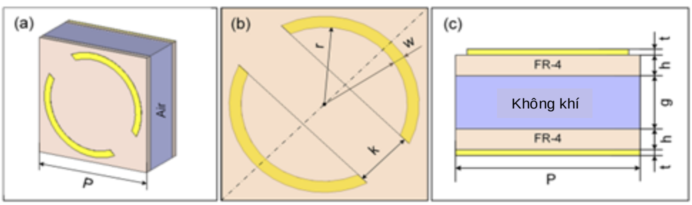


**Figure 3.20.** *Schematic of the proposed MPC*

The proposed MPC structure is designed for applications in the C-band (4–8 GHz), X-band (8–12 GHz), and Ku-band (12–18 GHz). The structure was analyzed using both simulation and experimental methods, as shown in Figure 3.20.

Simulation results indicate that the MPC achieves PCR above 93% in the frequency range of 4.0 to 14 GHz, as depicted in Figure 3.21(b). The relative bandwidth (RBW) reaches 111.1%.

Analysis of the reflection coefficients in the uv-coordinate system demonstrates that an incident y-polarized electromagnetic wave is reflected as an x-polarized wave, with the reflected wave undergoing a 90° phase shift relative to the incident wave.

An investigation of the electric field, magnetic field, and surface current distribution on the metallic resonator layer at four resonance frequencies reveals the underlying physical mechanisms: At 4.35 GHz and 7.42 GHz, the surface currents on the top resonator layer are parallel and opposite to those on the bottom metallic layer, indicating that these resonance frequencies originate from magnetic resonance. At 12.39 GHz and 13.87 GHz, the resonance is primarily due to electric resonance effects.

A study of the incident wave angle on MPC performance shows that as the angle varies from 0° to 50°, the polarization conversion efficiency remains above 90% for incident angles up to 10° and above 80% for angles less than 30°.

The experimental measurements were compared with simulation results, showing good agreement between the two. This validates the reliability of the simulation approach.

### *3.2.3. Design of MPC structure operating in the THz frequency range*

In this study, an MPC structure designed for THz frequency applications has been proposed (Figure 3.31). The PCR of the proposed structure reaches nearly 100% at the resonance frequencies and remains above 93% over the frequency range of 1.6 THz to 5.8 THz, achieving a relative bandwidth of 113.5%.

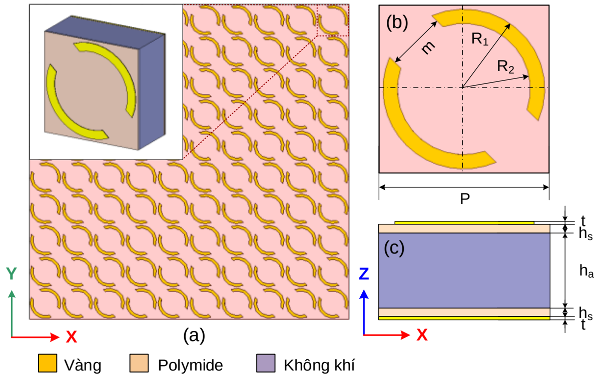


**Figure 3.31**. *illustrates the unit cell structure of the THz MPC, showing (a) a 3D view, (b) the top view, and (c) the side view.*

Additionally, the surface current distributions at four resonance frequencies indicate that: The resonance frequencies 1.74 THz and 3.13 THz are generated by magnetic resonance. The resonance frequencies 5.1 THz and 5.7 THz originate from electric resonance. These resonances play a crucial role in achieving high PCR across a broad frequency range. Furthermore, the PCR above 93% when the incident angle varies from 0° to 10° within the 1.6 THz – 5.8 THz range and above 80% when the incident angle varies from 0° to 30°.

**3.3. Chapter conclusion 3**

Chapter 3 presents the design of a MA integrating $VO_2$ phase-change material operating in the THz frequency range. The proposed structure features a simple design and the ability to switch between reflection and absorption modes by controlling the phase transition of $VO_2$ from the dielectric state to the metallic state. When $VO_2$ is in the metallic phase, the MA achieves an absorption rate greater than 90% over a broad bandwidth from 1.29 to 3.26 THz. Additionally, the MA demonstrates tunability in absorption efficiency by varying the conductivity of $VO_2$.

Furthermore, this dissertation introduces the design of MPC for applications in the S, C, X, Ku, and THz bands. All proposed designs exhibit high conversion efficiency exceeding 90% across a wide frequency range. Additionally, the MPCs designed for the S-C bands and the C-X-Ku bands were selected for experimental fabrication. The experimental results show good agreement with simulation data, confirming the reliability of the simulation-based research approach.

# CHAPTER 4. DESIGN AND OPTIMIZATION OF MULTIFUNCTIONAL METAMATERIAL STRUCTURES FOR ELECTROMAGNETIC WAVE ABSORPTION AND POLARIZATION CONVERSION

## 4.1. Design and optimization of MFM structures for metamaterial absorption and polarization conversion in the GHz frequency range

### *4.1.1. Design of a water-Integrated MFM structure for electromagnetic wave absorption and polarization conversion*

A water-integrated MFM structure capable of switching between absorption and polarization conversion modes in the GHz frequency range is proposed.

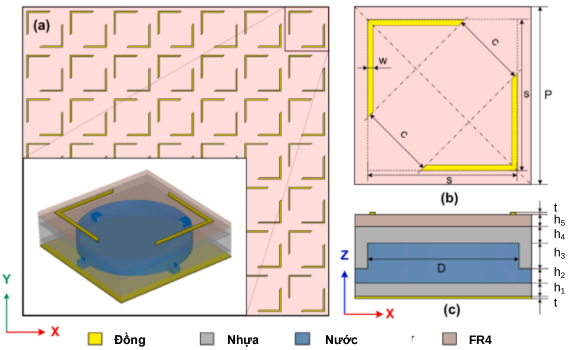


**Figure 4.3.** *Unit cell of the proposed MFM: (a) 3D view, (b) top-down view, (c) cross-sectional view.*

In the absence of water, the MFM operates as a cross-polarization converter with PCR exceeding 90% over a wide bandwidth from 4.38 to 11.9 GHz, achieving a relative bandwidth of 92.4%. When integrated with water, the MFM functions as an absorber with an absorption rate greater than 90% in the frequency range of 16.4 to 24 GHz, yielding an RBW of 38%.

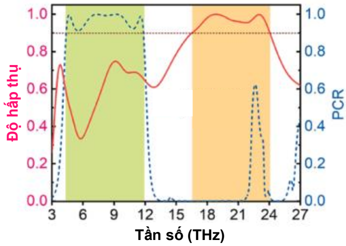


**Figure 4.4.** *Absorption efficiency and polarization conversion efficiency corresponding to the MFM with and without water integration*

#### *4.1.2. Investigation of MFM properties in absorption mode*

When the MFM is integrated with water, four absorption peaks are observed within the frequency range of 3–27 GHz at 3.8 GHz, 9 GHz, 18.82 GHz, and 23.15 GHz, corresponding to absorption rates of 73%, 75%, 70%, 100%, and 100%, respectively.

To explain the absorption mechanism of the material, the effective impedance Z(ω) of the MFM is calculated based on the effective medium interference theory. The calculated input impedance Z(ω) shows that its real and imaginary parts are close to 1 and 0, respectively, within the frequency range of 16.5–24 GHz. This confirms good impedance matching between the proposed MFM structure and the surrounding medium over a wide bandwidth.

The power loss density of the incident wave at two frequencies, 18.8 GHz and 23 GHz, indicates that at 18.8 GHz, power loss occurs at both the upper and lower surfaces of the cylindrical water layer. At 23 GHz, power loss primarily occurs at the interface between the upper surface of the water layer and the water container.

The investigation of the incident angle's effect on the absorption efficiency of the structure reveals that the proposed design maintains an absorption efficiency above 80% for both TE and TM modes when the incident angle increases up to 35°. Furthermore, the proposed structure remains stable under different polarization angles.

***4.1.3. Investigation of MFM properties in polarization conversion mode***

When electromagnetic waves are incident at angles ranging from 0° to 60°, the operational bandwidth of the proposed MFM structure is reduced in both TE and TM modes. However, the MFM structure maintains a polarization conversion efficiency above 80% in two frequency bands: from 4.38 GHz to 6.3 GHz and from 6.7 GHz to 11 GHz, even when the incidence angle reaches up to 40°.

Additionally, the reflection coefficients $r_{uv}$và $r_{vu}$, and $r_{uu}$ và $r_{vv}$ are nearly zero within the frequency range of 4.38–11.9 GHz. The phase difference Δφ: $180^o - 35^o \le \Delta\varphi \le 180^o + 35^o$ remains within a stable range in this frequency band. These results confirm that the MFM exhibits linear cross-polarization conversion over a broad frequency range.

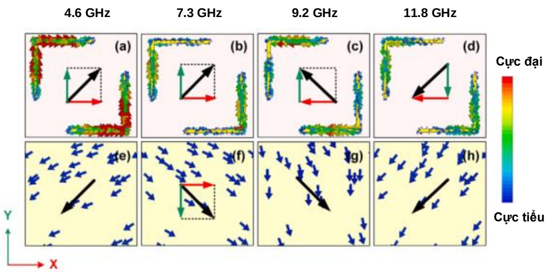


**Figure 4.12.** *Surface Current Distribution on the Top Metal Layer (a - d) and the Bottom Metal Layer (e - h) of the MFM at Resonant Frequencies*

To understand the physical mechanism of polarization conversion, we investigated and analyzed the surface current distribution at four resonant frequencies: 4.6 GHz, 7.3 GHz, 9.2 GHz, and 11.8 GHz.

***4.1.4. Investigation of the influence of material parameters and structural dimensions on MFM performance***

The water-integrated MFM is largely unaffected by variations in the plastic material's loss tangent and dielectric constant. As the structural parameter P increases from 0.6 to 1.4, both absorption and polarization conversion spectra shift to lower frequencies, while relative bandwidth remains nearly unchanged. This confirms the feasibility of tuning the operating frequency through structural adjustments.

The experimental characterization of the fabricated sample was compared with the simulation results, showing a good agreement between numerical simulations and experimental measurements.

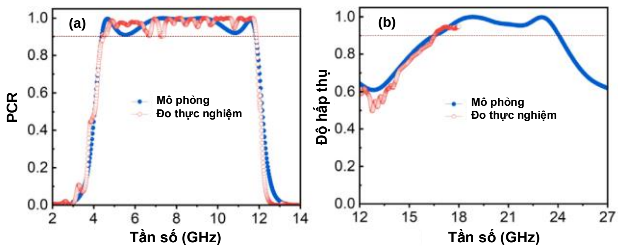


**Figure 4.15.** Simulated and measured results of (a) polarization conversion efficiency and (b) absorption efficiency.

Finally, we compared our research results with recently published reports, demonstrating that the proposed structure can operate over a wide frequency band with dual functionalities, including both absorption and polarization conversion. Compared to similar MFM structures in the literature, the proposed MFM exhibits a narrower operational bandwidth in absorption mode but achieves a broader bandwidth in polarization conversion mode.

**4.2. Design and optimization of an electromagnetic wave absorbing and polarization-converting MFM structure operating in the**

**THz frequency range**

### *4.2.1. Design of an absorbing and polarization-converting MFM structure based on phase-change material $VO_2$*

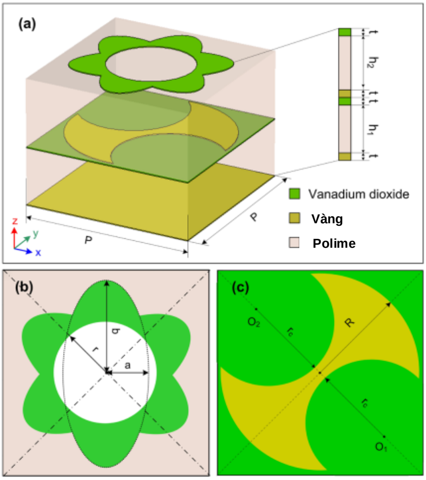


**Figure 4.18.** *Unit cell structure of the metamaterial (MMs): (a) 3D view, top-down view of (b) the resonator plate for absorption mode and (c) the resonator plate for polarization conversion mode.*

Based on the research on MMs integrated with phase-change material $VO_2$, as presented in Chapter 3, we have designed and optimized an absorbing and polarization-converting MFM structure incorporating $VO_2$, operating in the THz frequency range. Simulation results demonstrate that the proposed MFM structure can switch its function from broadband absorption to broadband cross-polarization conversion within the same frequency band by adjusting the state of $VO_2$ from an insulating phase to a metallic phase.

### *4.2.2. Investigation of the absorption properties of $VO_2$-integrated MFM*

When $VO_2$ is in a fully metallic state with a conductivity of $\sigma = 2\times10^5$ S/m, the $VO_2$ layer prevents wave transmission, thereby achieving total absorption, as shown in Figure 4.17. The structure exhibits a broadband absorption response with an efficiency exceeding 90% in the frequency range of 1.36 – 3.38 THz.

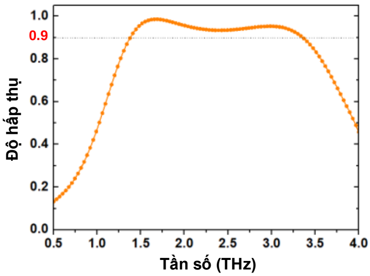


**Figure 4.17.** *Absorption efficiency of the proposed MFM structure.*

The proposed MFM structure exhibits high absorption efficiency over a wide incident angle range of up to 50° for both TE- and TM-polarized electromagnetic waves. In the TE polarization, absorption gradually decreases as the incident angle increases but remains above 80% for angles up to 50°. In the TM polarization, absorption increases with the incident angle, and the absorption spectrum extends to higher frequencies when the incident angle exceeds 30°.

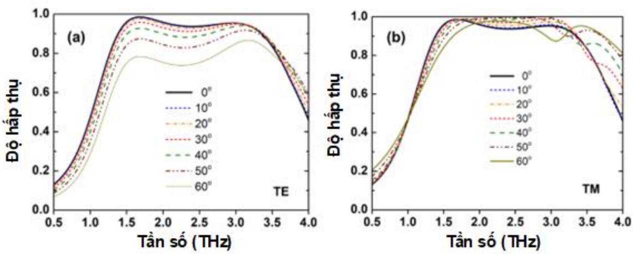


**Figure 4.18.** *Dependence of absorption on the incidence angle.*

***4.2.3.*** **Investigation of the electromagnetic wave polarization conversion properties of $VO_2$-integrated MFM**

When $VO_2$ is in the dielectric phase with σ = 200 S/m, the MFM achieves a polarization conversion ratio (PCR) above 90% over a broad frequency range from 1.04 to 3.75 THz, with a RBW of 113%.

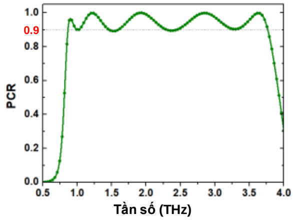


**Figure 4.22.** *Absorption efficiency and polarization conversion efficiency*

The designed structure exhibits stable polarization conversion efficiency for large incident angles ranging from 0° to 50° for both TE and TM polarizations.

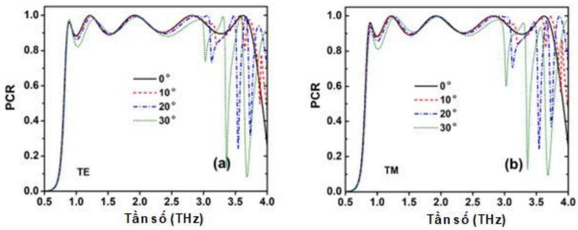


**Figure 4.25.** *Dependence of PCR on the Incident Angle for the Proposed MFM in Polarization Conversion Mode: (a, c) TE Mode and (b, d) TM Mode*

The surface current distribution on the upper and lower gold layers was analyzed at five resonance frequencies. Strong magnetic resonance contributes to the resonance frequencies at 1.91 THz, 2.83 THz, and 3.63 THz. In contrast, the resonance at 0.89 THz primarily results from electric resonance. Meanwhile, the resonance at 1.22 THz is a combination of both magnetic and electric resonances.

***4.2.4. Investigation of the influence of structural parameters and material layers on absorption and polarization conversion properties***

To optimize the design and achieve the highest absorption and polarization conversion efficiency, the parameters of the proposed structure were thoroughly examined.

Additionally, the absorption spectrum remained unchanged when the gold layer was removed, confirming that the $VO_2$ metallic film effectively blocks electromagnetic waves. In contrast, the gold substrate played a crucial role in preventing wave transmission, thereby enhancing the reflected waves when the metamaterial operates in polarization conversion mode.

Finally, a comparison between the proposed MFM and recent studies demonstrated that the proposed structure offers a novel approach for designing high-performance metamaterials and enabling multifunctional metasurfaces for THz-frequency applications.

### 4.3. Chapter conclusion 4

Using simulation methods, this dissertation has developed models and investigated the absorption and polarization conversion properties of water-integrated MFM operating in the GHz frequency range and $VO_2$-integrated MFM operating in the THz frequency range. The proposed MFM structures demonstrate high performance in both absorption and polarization conversion modes, with a wide operational bandwidth and minimal dependence on the incidence angle and polarization angle.

## CONCLUSION AND RECOMMENDATIONS

### 1. Conclusion

The main results of the dissertation include:

1. The absorption mechanism of the MA utilizing a circular disk structure with square perforations, integrated with phase-change material $VO_2$, operating in the THz frequency range, has been elucidated. The high-efficiency broadband absorption spectrum is achieved based on the principle of impedance matching between the material and the surrounding medium. When $VO_2$ is in the dielectric phase, the MA reflects electromagnetic waves. In the metallic phase, the MA absorbs electromagnetic waves with an absorption efficiency exceeding 90% over a broad frequency range of 1.29 –

3.26 THz.

2. The polarization conversion mechanism of MPC based on slotted ring resonator structures operating in the GHz and the THz frequency range has been elucidated. Specifically, the MPC operating in the S and C bands achieves a PCR of over 90% within the frequency range of 2–8.45 GHz. The MPC operating in the C, X, and Ku bands exhibits a PCR of over 93% within the frequency range of 4.0–14 GHz. The MPC operating in the THz frequency range demonstrates a PCR exceeding 93% from 1.6 THz to 5.8 THz. Additionally, MPC prototypes for the S, C bands and the C, X, Ku bands have been successfully fabricated, and electromagnetic characterization of the fabricated samples shows good agreement between simulation and experimental results.

3. The absorption and polarization conversion mechanisms, and the successful fabrication of a water-integrated MFM capable of switching between two modes for operation in the GHz frequency range have been clarified. When water is present, the proposed MFM operates in absorption mode with an absorption efficiency exceeding 90% in the wide frequency range from 16.4 to 24 GHz, and with over 80% absorption efficiency in both TE and TM modes up to an incidence angle of 35°. When water is absent, the proposed MFM operates in cross-polarization conversion mode with a PCR above 90% in the wide frequency range from 4.38 GHz to 11.9 GHz, achieving a bandwidth ratio of 92.4%.

4. The absorption and polarization conversion mechanisms of the MFM structure integrated with $VO_2$ phase-change material, capable of switching between absorption and polarization conversion modes for electromagnetic wave operation in the THz frequency range, have been clarified. When $VO_2$ is in the metallic phase, the proposed MFM structure operates in absorption mode with an absorption efficiency exceeding 90% in the frequency range of 1.36–3.38 THz, with a bandwidth ratio of 85%. When

$VO_2$ is in the dielectric phase, the proposed MFM structure operates in cross-polarization conversion mode with a PCR above 90% in the wide frequency range of 1.04–3.75 THz, achieving a bandwidth ratio of 113%.

## 2. Ecommendations

Based on the research results presented, the dissertation proposes several recommendations to further expand and improve the research content as follows:

Continue to improve the MFM structure to operate in higher frequency ranges, such as the infrared and visible light regions.

Investigate the ability to control the properties of MFM through external stimuli such as electric fields, magnetic fields, or optical fields, thereby opening up potential for practical applications.

## LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATIO

1. **Nguyen Thi Minh**, Nguyen Thi Kim Thu, Phan Duy Tung, Le Dac Tuyen, Vu Dinh Lam, Nguyen Thi Quynh Hoa, & Kim Jung Mu. (2022). Ultra-wideband and lightweight electromagnetic polarization converter based on multiresonant metasurface. *IEEE Access*, *10*, 92097-92104.

2. **Nguyen Thi Minh**, Phan Huu Lam, Vu Dinh Lam, Nguyen Thi Quynh Hoa, & Kim Jung Mu. (2022). Ultra-wideband and high-efficiency cross-polarization conversion using a double split ring shaped metasurface for C, X, and Ku-band applications. *AIP Advances*, *12*(11).

3. **Nguyen Thi Minh**, Vu Dinh Lam, Nguyen Thi Quynh Hoa, & Kim Jung Mu. (2022). Reconfigurable broadband metasurfaces with nearly perfect absorption and high efficiency polarization conversion in THz range. *Scientific Reports*, *12*(1), 18779.

4. **Nguyen Thi Minh**, Nguyen Thi Kim Thu, Nguyen Thi Hong Van, Nguyen Thi Minh Tam, Ho Thi Huyen Thương, Phan Duy Tung, Vu Dinh Lam & Nguyen Thi Quynh Hoa. (2022). Metal-dielectric phase transition of VO2 assisted broadband and high-efficiency bifunctional metasurface in the terahertz frequency. *Vietnam Journal of Science and Technology 60 (5).*

5. **Nguyen Thi Minh**, Phan Huu Lam, Nguyen Hong Quang, Cao Thanh Nghia, Luong Ngoc Minh, Nguyen Thi Kim Thu, Nguyen Thi Minh Tam, Ho Thi Huyen Thuong & Nguyen Thi Quynh Hoa. (2023). A simple design of broadband cross-polarization converter for the THz frequency range. *Vinh University Journal of Science*, *52*.

6. Nguyen Thi Quynh Hoa, Phan Huu Lam, **Nguyen Thi Minh**, Nguyen Ngoc Hieu, Le Dac Tuyen, Bui Xuan Khuyen, Vu Dinh Lam & Kim Jung Mu. (2024). Switchable bi-functional water-based metasurface for high efficiency and wideband polarization conversion and absorption. *Optical Materials*, 115682.