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THE STUDY OF ABSORPTION PROPERTIES OF BROADBAND METAMATERIAL PERFECT ABSORBER INTEGRATED LOSSY ELEMENTS

SUMMARY OF DOCTORAL THESIS IN MATERIALS SCIENCE

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INTRODUCTION

1. The urgency of the thesis

In 2008, Landy et al. proposed the perfect absorber based on metamaterial (MPAs: Metamaterials Perfect Absorbers) with thin dimensions, easy fabrication, low cost, and easy-to-control absorption properties through structural parameters [6]. Since then, MPA has been rapidly implemented theoretically and experimentally from the MHz frequency domain to the optical domain [7] [8] with many potential applications.

The catch research trends in the world, the Institute of Material Science, Graduate University of Sciences and Technology, and Vietnam Academy of Science and Technology first implemented research about metamaterial in Vietnam. After that, this research direction has expanded to the Hanoi National University of Education, Vinh University, Thai Nguyen University of Science, Hanoi University of Science and Technology, Hanoi University of Mining and Geology, and VinUni University. The studies aimed to achieve high absorbance with structural optimization, the ability of absorber over multiple frequency bands, and less sensitivity to changes in incidence angle and polarization angle [9]. In addition, MPAs have been extended to materials with elastic properties [10] and two-dimensional isotropic absorption [11] to further enhance the practical applicability of MPAs. However, because the nature of the metamaterial depends on the resonance structure, leading to the frequency range of the absorber is narrow, but the broadband properties are required in different applications in the civilian and military, such as photovoltaic (PV), optical detection, and stealth technologies [12].

Some of the methods for extending the absorption bandwidth of BMPAs proposed include horizontal arrangement multi-resonance structures [13] or vertical arrangement multi-resonance structures [14] according to the polarization of the incoming wave, structures using lossy components [15], plasmonic nanocomposites [16], dielectric resonance structures [17], or using phase change materials [18].

The research results about MPA on domestic can be mentioned that Dr. Do Thanh Viet successfully defended his thesis on the study of narrow band absorption I-shaped, disc, and ring-structured MPAs and the multi-peak and the broadband of high absorption achieved by manipulating the resonators in only one layer of MM, in 2015. However, the proposed MPAs only operated in the GHz frequency region [19]. In 2018, Dr. Dang Hong Luu presented the results that combine the theory and simulation to design multi-peak MPA operating in the THz frequency region [20]. In 2020, Dr. Dinh Hong Tiep reported the research results about broadband metamaterial absorbers by integrating polymer in metal resonator structures [21]. However, the research only implemented in the frequency range from 4 to 22 GHz. In 2022, Dr. Tran Van Huynh proposed and demonstrated the ability to control the two-dimensional isotropic absorption properties of MPA integrating graphene operating in the THz frequency region by combining electrical resonance and magnetic resonance or hybridization of magnetic resonances. So far, domestic studies of the broadband MPA have only been carried out at the GHz frequency regions, while the THz ones only have narrowband or multi-peak MPA studies. As such, extending the absorption bandwidth of MPA in both the GHz and THz frequency regions is currently a fascinating research topic aimed at shielding applications and the absorption and transformation of electromagnetic wave energy.

Therefore, the PhD student chose the theme "***The study of absorption properties of broadband metamaterial perfect absorber integrated lossy elements***" with a completely different approach from the previous theses. Specifically, the thesis designs and fabricates resistor-integrated BMPAs to increase the impedance of the resonant surface operating in the GHz frequency region. In addition, the thesis proposes designs that simulate water-based BMPA structures to increase dielectric layer loss, operating in both the GHz and THz frequency regions. The proposed BMPAs achieved absorption over 90% in a wide frequency range, less sensitivity to the incident, and polarization angles. The designs had a lightweight, easy-to-fabricate, simple structure.

2. Research objectives of the thesis

The thesis develops and finalizes the theoretical basis of MPA in general and BMPA in particular. We focuse on solving the problem of expanding the absorption bandwidth of MPA.

The design and optimization of the resistance-integrated and water-based BMPA structures in the GHz and THz frequency regions.

Mastering the process, fabrication technology, and quality measurement of BMPAs operating in the GHz frequency region.

3. The main contents of the thesis

The thesis builds a physical model and investigates the influence of structural parameters and materials on the properties of the BMPAs integrated lumped resistors and based water, operating in the GHz and THz frequency regions.

We design BMPAs integrated lumped resistors operating in C, X, and Ku bands. From there, we built the fabrication process and measured the absorption of the BMPA operating in the GHz frequency region.

CHAPTER 1. OVERVIEW

1.1. General overview of metamaterial

Metamaterials (MMs) are composed of “pseudo-atoms” which are electromagnetic resonance structures that are many times smaller in size than the operating wavelength [30]. When electromagnetic waves flux to the material, they interact with the constituent micro-components, producing an electromagnetic induction moment and directly affecting the permittivity and magnetic permeability of the MM.

When electromagnetic waves project to the material, they interact with the constituent micro-components, producing an electromagnetic induction moment and directly affecting the permittivity and magnetic permeability of the MM. Thus, it is possible to control the electromagnetic properties of MM by changing the parameters of the constituent components of the material, leading to several effects such as inversion of Snell's law, reverse Doppler effect, and so on. Over the past two decades, MMs have indeed had significant potential in many fields and have attracted research interest from scientists.

1.2. Classification of MPAs

1.2.1. Anisotropic metamaterial perfect absorber

The unit cell of the anisotropic MPAs usually has three layers of metal-dielectric-metal. The idea of MPA is based on the principle of impedance matching to suppress the reflected component when electromagnetic waves incident the surface. For most anisotropic MPAs, absolute absorption based on magnetic resonance can reach near-perfect absorption when the virtual part of the refractive index is enhanced at the resonant frequencies [29].

1.2.2. Isotropic metamaterial perfect absorber

The disadvantage of the anisotropic structures is that MPAs absorb only when the wave travels to the MPA surface in a single direction, which limits the applicability of MPAs in practice. Thus, the isotropic MPA structures are studied both theoretically and empirically. The absorption mechanism of the isotropic structure relies on the “interaction” of electrical resonance and magnetic resonance or uses the hybridization effect with the “interaction” of two magnetic resonances [37,39].

1.3. Physic mechanisms of absorption

1.3.1. Interference theory

Interference theory is one of the methods for calculating the absorption of MPA, which is based on the effect of interference suppression between the incoming wave components and reflected by the material.

1.3.2. Resonance and Impedance matching

Impedance matching occurs at one or several frequencies at $\varepsilon = \mu$. Therefore, it is possible to control the permittivity and magnetic permeability component by investigating the shape and size of the structure to achieve equilibrium [29]. At that time, the reflectivity R = 0, and the electromagnetic wave completely passes through the metasurface between the air and the material environment, and the near-perfect absorption is achieved at the electromagnetic resonance frequencies.

After passing through the contact between the environment and the material by the impedance matching principle, the electromagnetic energy dissipated inside the material depends on the electrical and magnetic components and is represented by Poynting theory.

Around the resonant frequencies, the unit cell structure produces a larger lossy environment, including Ohmic and dielectric losses. Thus, electromagnetic waves can be trapped and dissipated as soon as they pass inside the MPA structure.

1.3.3. Overlap of electrical and magnetic resonances

Interacting with electromagnetic waves, magnetic and electrical resonances can occur at different frequencies in the MM structure. The resonant frequencies depend on the geometric parameters of the structure, so it is possible to adjust each frequency so that they overlap each other. When resonance overlap occurs, the absorption is enhanced. This mechanism has been analyzed in several recent studies applied to isotropic MPA structures [39], [41] - [43].

1.3.4. Magnetic resonance hybridization

MPAs based on electrical resonance have absorption dependent on the incident angle. Thus, the hybridization mechanism using two magnetic resonances is proposed [37].

1.4. The recent research directions on MPA

In this thesis, we focus on designing BMPAs with an anisotropic structure.

1.4.1. Optimizing structure and improving absorption properties

One of the research trends of MPA is the simplification of resonant structures to ease fabrication while still achieving high absorption suitable for the specific application.

1.4.2. Minimizing the structure

Researchers have proposed different methods to increase the effective electrical length compared to the working wavelength. Therefore, resonances at lower frequencies can be stimulated.

1.4.3. Operating in different frequency ranges

Besides structural optimization, MPAs have been studied in frequency ranges ranging from microwave[46] to infrared [47] or optical frequencies[48].

1.4.4. Incident and polarization independent

Metamaterial absorbers often have a symmetrical structure, so the absorption properties are independent of the polarization angle. However, electromagnetic waves that project to the surface at different angles of incidence often make it difficult for MPA structures to maintain the impedance matching conditions, leading to reduced absorption. Therefore, it is required to design MPAs that are not sensitive to changes in angle of incidence and angle of polarization.

1.4.5. Broadening the absorption bandwidth of metamaterial absorbers

In many practical applications, broadband absorption is required. Therefore, broadband absorbers attract more than research interest.

1.5. Broadband MPA

The absorption properties of BMPA can be controlled by the temperature [58] [59], electric field [60], magnetic field [61], and polar voltage [62] based on integrating components (or materials) into the structures of the MPA.

1.5.1. Mechanisms of broadband perfect absorption

Physical mechanical supporting broadband MPAs include horizontal and vertical stacking of resonators, reduction of the Q-quality factor, dielectric tailoring, and resonator material tailoring [52].

1.5.2. Applications of BMPAs

BMPA has been studied for more than 15 years with many wide applications in many fields such as energy harvesting, photodetection and so on.

1.6. Conclusion chapter

Chapter 1 focuses on the development history, classification, and recent research on MPA. In addition, chapter 1 also emphasizes the broadband absorption mechanisms of BMPA and some of the outstanding applications of BMPA.

CHAPTER 2. RESEARCH METHODS

The thesis combines semi-theoretical computational research, modeling by simulation, and experimental fabrication. The methods have been widely used by the international research community, inherited, and developed by the research team at the Institute Materials Science, Graduate University of Sciences and Technology, and Vietnam Academy of Science and Technology.

2.1. Research methods of MPA

2.1.1. Theory caculation

According to theory, a fundamental change in the material structure and composition will lead to fundamental changes in the properties of the MMs. Electromagnetic waves can propagate in the medium of a material with a double negative refractive index with the *k*-wave vector opposite to the energy flow vector, so the first calculation to determine the proposed structure has achieved both negative magnetism and negative electromagnetism. However, direct measurement or simulation of these parameters has many obstacles. Chen et al. [93] introduced how to calculate the reflection and transmission function based on the refractive index *n* and the normalized impedance *Z*. From this, the electromagnetic properties of the underlying MPAs are determined

2.1.2. Equivalent circuit theory

The equivalent circuit is a simple and effective solution to solve the impedance coordination problem by designing a suitable resistor and conductor element model in a metal-dielectric-metal structure. The MPA structures often use precious metals such as copper (Cu), silver (Ag), and gold (Au), so the value of resistance is negligible and can be ignored. It is possible to determine the resonant frequency of MPAs [62] based on the LC circuit model.

2.1.3. Computer simulation

CST Microwave Studio software is used to simulate the electromagnetic properties of MPA. In CST, this method can used on the time domain (T) or the frequency domain (F). The frequency domain (F) method is more suitable for structures with a periodic nature, such as MPA or the polarized converter.

2.1.4. Experimental method

Photography is used in materials science and technology to fabricate small dimensions of material, electronic micromechanical components (MEMS). The disadvantage of photography is that the light is diffracted, so it is impossible to focus the light beam down to small sizes, so it is impossible to fabricate nano-particles.

2.2. The fabrication process of MPA operated in GHz region

The fabrication process includes four main steps:

Step 1: Expose to light

Step 2: Apply developer

Step 3: Etching

Step 4: Remove remaining photoresist

2.3. Measurement system

In the GHz frequency region, the measurement uses a vector network analysis system. The sample system is set in a GHz wave absorption chamber, two horn antennas used to transmit the signal through the sample. To measure the parameters of MPA samples operating in the GHz frequency band, use the Rohde and Schwarz ZNB20 vector network analysis system.

2.4. Conclusion chapter

Chapter 2 presents MPA research methods including semi-theoretical computational methods, simulations based on CST software, equivalent circuit modeling, and experimental fabrication. The research methods are accurate and reliable and are widely used by the community of researchers.

CHAPTER 3

THE DESIGN AND FABRICATION BROADBAND ABSORBER METAMATERIAL IN GHz FREQUENCY REGION INTERGRATED RESISTORS

The multi-resonance (2D) or multi-resonance (3D) structures were found to be highly feasible through simulating but with considerable difficulty in fabrication. MPAs using lumped resistors to create the high-impedance surface have proven to be an easy method to extend the absorption frequency ranges.

3.1. Design proposal

MPA structures using ring, circle, and square discs have a relatively narrow bandwidth. The absorption decreases, and the absorption frequency range becomes narrower when the incident angles increase. Multi-band absorbers can use CRRs having different radiuses or a combination of circular disks and CRR structures.

If the proposed design changes into the asymmetry structure, as the example in Figure 3.3, the design can be optimized to become an electromagnetic wave polarized converter or the poor absorption metamaterial.

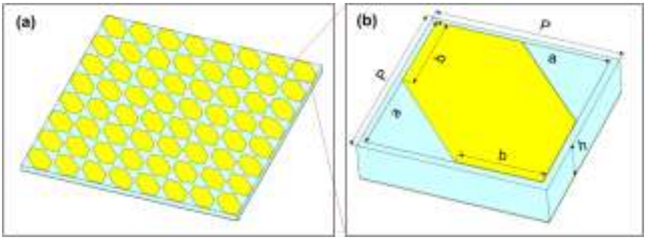

Fig 3.4. Polarized converter (a) Top view and (b) 3D mode of unit cell [102].

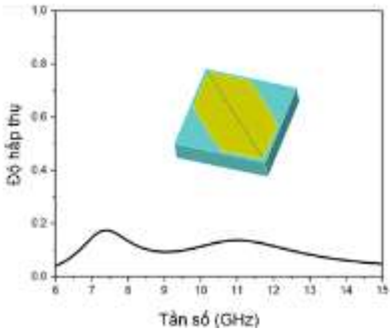

Fig 3.8. The absorption of BMPA shown in Fig 3.4.

The physics models of the BMPA proposed next in chapter 3 of the thesis will have a completely symmetrical structure so as not to depend on the polarization angle, having integrated the least number of resistors (4 resistors). The designs are optimized in order to achieve high absorption in the wide frequency ranges for *S*, *C*, *X*, and *Ku* band applications.

3.2. The design of BMPA integrated lumped resistors for X-band applications

In this part, we proposed a simple design of single layer broadband BMPA based on a split circle ring (SCR) loaded with four lumped resistors for X-band applications (8-12 GHz)

Figure 3.19 shows the results of this investigation at normal incidence under transverse electric (TE) polarization. It can be seen that the BMPA without lumped resistors provides two absorption peaks at 8.5 GHz and 12.5 GHz with an absorption intensity of 26.1% and 93.9%, respectively. The BMPA structure with four lumped resistors exhibits a broadband absorption performance with absorptivity >90% in the broader frequency range from 7.8 GHz to 12.6 GHz

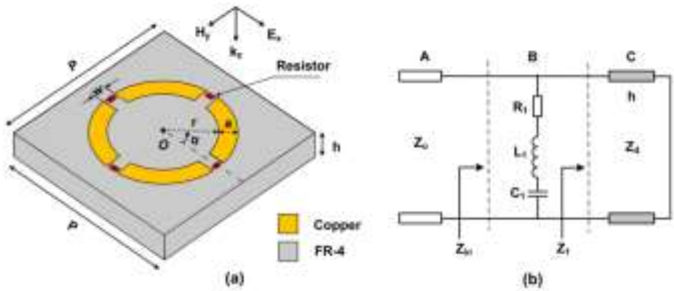

Fig 3.14. Schematic of unit cell of the proposed MMA (a) 3D-view and (b) its equivalent circuit model [109]L

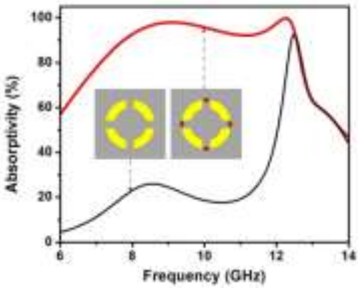

Fig 3.19. Absorption spectra of the designed MMA structures with and without lumped resistors under normal incidence for TE polarization[109].

At the operating frequency band, the impedance matching between the free space and the BMPA should occur in order to obtain a near perfect absorption. The calculated normalized input impedance coincides with the simulated one. Moreover, the imaginary and the real part of the normalized input impedance are nearly 0 and 1, respectively, in the resonant frequency range.

The result in the figure 3.22 shows that the absorption spectra of the BMPA are dependent on the incident angle. Moreover, BMPA has an insensitive polarization characteristic due to symetry of structure.

To gain insights into the absorption mechanism, the distributions of electric and surface current of the proposed BMPA are simulated under the TE polarization at the two resonant frequencies of 9.1 GHz and 12.2 GHz in the XOY plane under normal incidence.

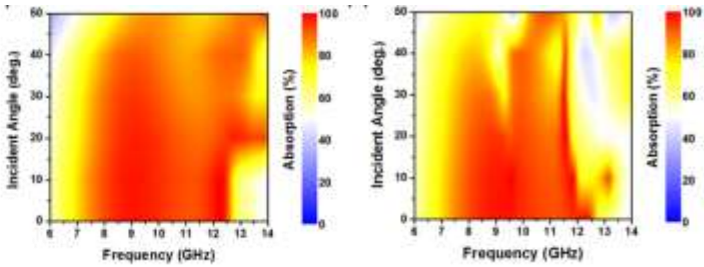

Fig 3.22. Absorption spectra of the proposed BMPA as a function of the incident angle of TE (a) and and of TM polarizations (b) [109].

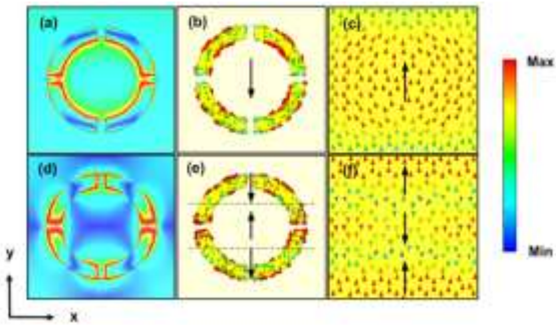

Fig 3.23. [(a) and (d)] Distributions of electric field, [(b) and (e)] the top surface current, and [(c) and (f)] bottom surface current at various resonant frequencies of 9.1 GHz and 12.2 GHz [109].

Finally, the absorption performance of the proposed BMPA is compared with the other reported BMPAs based on lumped resistors. It can be seen that the proposed BMPA is a moderate structure, meaning it is not superior in all aspects; nevertheless, it is characterized by a simple structure and small thickness with a relatively high bandwidth per lumped resistor.

3.3. The design of BMPAs integrated lumped resistors for S- and C –band, C- and X-band applications

From the design of the polarized converter operating in the S- and C bands [117], we adjust the resonator shape to a wheel shape so that the design is symmetrical and has the function of an absorber. To extend the absorption frequency range, we integrated resistors, as shown in Figure 3.25, in order to increase the surface impedance and reduce the *Q*-factor.

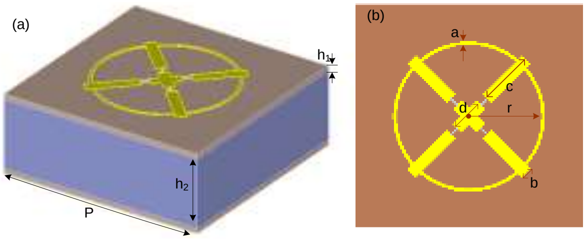

Fig 3.25. Proposed BMPA for S- and C-bands.

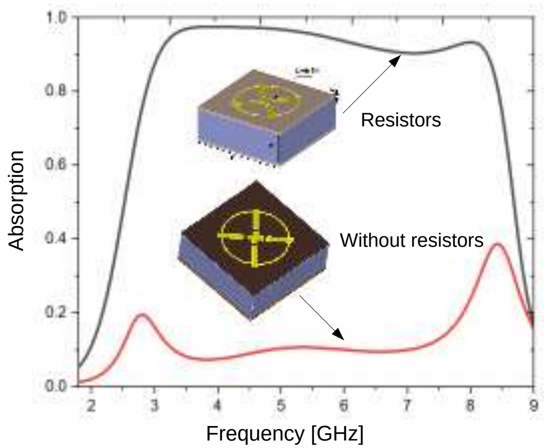

Fig 3.27. Absorption of BMPA with resistors and without resistor.

The absorption spectrum of BMPA for TE polarization and TM polarization is coincident if the incident angle is perpendicular to the structural surface or $\theta = 0^0$. On the other hand, it can be seen that the MPA that does not integrate a resistor has two absorption peaks at a frequency of

2.8 GHz and 8.4 GHz with an absorption of 20% and 39.9%, respectively. The BMPA structure uses four resistors and has an absorption of over 90% in a wide frequency range from 3 GHz to 8.3 GHz, showing the role of the lumped resistors in enhancing the absorbency of BMPA.

The effect of the incident angle on the absorption spectrum of BMPA was also investigated. The results show that the absorption maintains approximately 80% for angles up to 40° with TE polarization, and the absorption spectrum splits into many distinct bands as the angle of incidence increases with TM polarization.

For C-band and X-band applications, we proposed 2D metamaterial structure with lumped resistors. The dielectric layer consists of two identical FR-4 layer separated by an airgap, as shown in Fig 3.31.

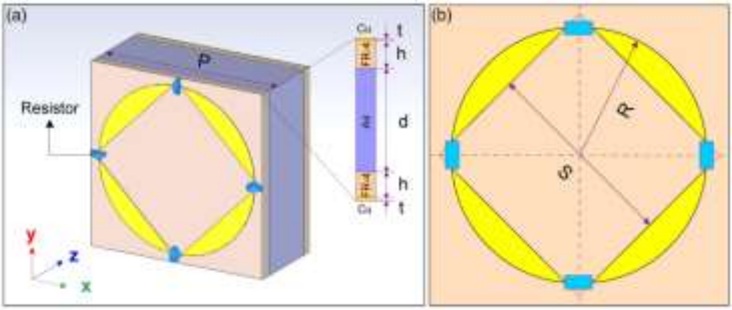

Fig 3.25. Schematic drawings of the designed unit cell with geometric: a) 3D view and b) top view [118].

The BMPA structure without chip resistors shows a very poor absorption performance in the band from 2 to 20 GHz. The absorption band of the proposed MMA with chip resistors exhibits two distinct resonance absorption peaks at 4.5 and 11.4 GHz and entirely covers the X and C bands from 4 to 12 GHz.

Furthermore, simulation results for various oblique incidences of TE and TM polarization waves. This result confirms a high absorption level is still retained with a wide oblique incident angle, which is extremely interesting for a broadband absorber. The proposed BMPA exhibits a polarization-insensitive property because of its symmetry structure.

The electric field distribution at different resonant frequencies of 4.5, 11.4, and 17.2 GHz is investigated. The direction of surface current on the top layer and bottom layer is antiparallel to each other at the lower resonant frequency of 4.5 GHz, indicating that the perfect absorption at this resonant frequency is originated from the magnetic resonance. In contrast, at the resonant frequency of 11.4 GHz, the top and bottom surface currents are in the parallel direction and electric resonance is excited at this resonant frequency. However, at the higher frequency of 17.2 GHz, the top and bottom surface currents are separated into three distinct regions, with antiparallel currents in adjacent regions, forming three current loops between the top and bottom layers [120].

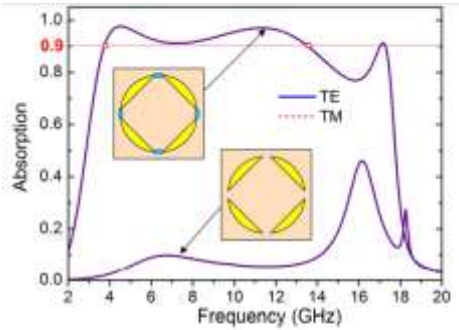

Fig 3.32. Absorption spectra of the designed MMA with and without chip resistors for TE and TM polarizations under normal incidence [118].

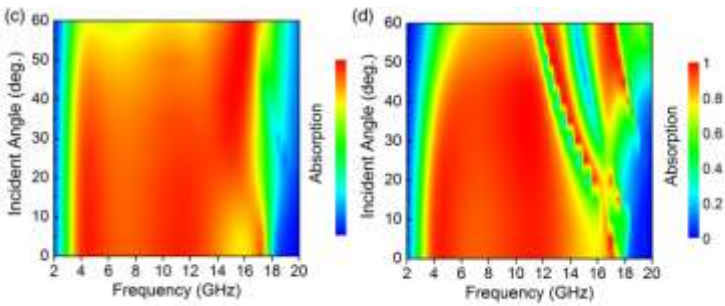

Fig 3.33. Absorption spectra of the proposed MMA with various incident angles of (c) TE polarization and (d) TM polarization [118].

To verify the simulation results, an MMA prototype was fabricated for experimentation. The structural parameters of the fabrication sample are fixed the same as the simulated model. The sample was patterned on an FR-4 substrate with the same properties as in the design using the standard photolithography process. The inset photo of figures 3.39 (a) and 3.39 (b) b a shows a fabricated unit cell of the BMPA and the schematic of the test setup for reflection measurement of the fabricated absorber sample

A vector network analyzer (Rohde and Schwarz ZNB20) together with two identical linearly polarized standard-gain horn antennas as transmitter and receiver was used to measure the reflection coefficient.

The measured result confirms that the bandwidth with an absorption rate higher than 88% of the MMA entirely covers the C and X bands for both TE and TM polarizations. The measured absorption intensity is slightly poorer than the simulated one due to the imperfection in the SUT fabrication and measurement. Even though the total thickness of the proposed BMPA is of a moderate value, the proposed BMPA is characterized by the most lightweight design due to the thinnest thickness without an airgap. Moreover, the proposed BMPA has the highest RAB per number of lumped resistors, demonstrating that it is the most efficient design with the using of the lumped resistor to broaden the absorption bandwidth.

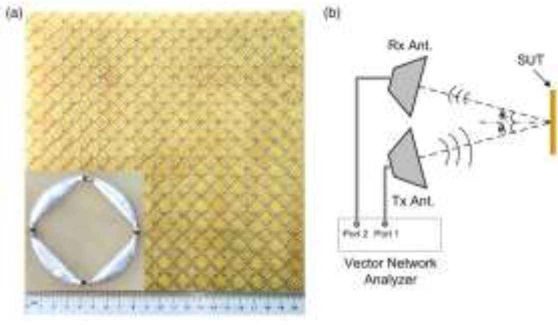

Fig 3.39. a) Fabricated MMA and b) schematic illustration of the measurement setup [117].

3.4. The design of BMPA integrated lumped resistors for X- and Ku-band applications

The proposed design in 3.2 for X-band applications has a relative bandwidth of 47% and insensitive angles [109]. Therefore, we proposed a design of BMPA that has the structure as shown in Fig 3.35 for X- and Ku-band applications [123]. We investigated the effect of structure parameters on the absorption of BMPA.

Figure 3.43 (a) shows that the BMPA works in the frequency range of 8–18 GHz covering the entire X- and Ku-bands with an absorption efficiency higher than 90%. the relative bandwidth (RBW) of the proposed MA can reach to 76.92%, indicating that the designed MA achieves the ultra-broadband absorption properties.

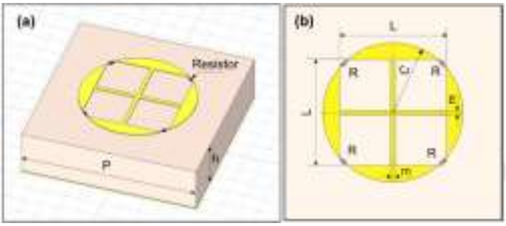

Fig 3.35. Schematic of the proposed BMPA: (a) 3D-view and (b) top view of a unit cell [123].

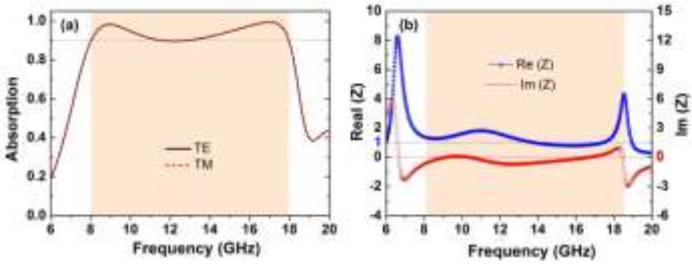

Fig 3.43. (a) Absorption spectra and (b) the normalized impedance of the proposed BMPA under normal incidence[123].

The absorption mechanism of the proposed MA can be explained by the impedance matching between the MA structure and the free space, as shown in Figure 3.37b.

To further investigate the physical mechanism, we have simulated the electric field and surface current distributions of the proposed BMPA at the resonant frequencies of 8.9 GHz and 17.1 GHz in the XOY plane. Moreover, the dependence of the absorptivity on the frequency and the incident angles in the range of 0-50^o for both TE and TM polarizations is implemented. It can be seen that for both polarizations, the absorptivity of the proposed MA decreases with increasing the incident angle. However, the proposed absorber can maintain the high absorption intensity above 70% with increasing the incident angle up to 50º. It indicates that the proposed BMPA has a good broadband absorption performance for a wide incident angle for both TE and TM polarizations.

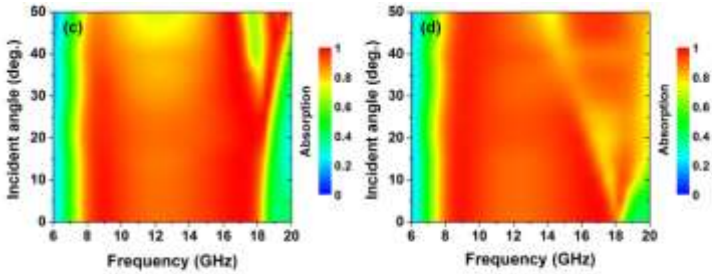

Fig 3.45. Absorption spectra and the corresponding absorption maps of the proposed MA with different incident angles for (c) TE and (d) TM polarizations, respectively[123]

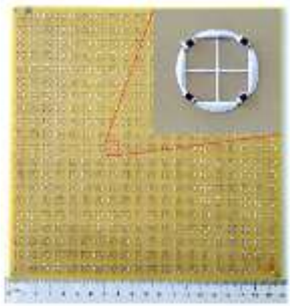

Fig 3.47. The image of the fabricated sample and its enlarged view[123].

To verify the performance of the designed BMPA, device fabrication was using the conventional photolithography process. The measurement data are collected in the range of 6-18 GHz. It can be observed that the experimental results are in good agreement with the simulation results. The measured absorptivity keeps higher than 80% in the range of 8-18 GHz with incident angle up to 40º for both TE and TM polarizations. It confirms that the designed BMPA is a wide incident angle insensitivity.

Finally, we have compared the performance of the proposed BMPA with other recently reported broadband BMPAs designed based on lumped resistors. The results show that the proposed design has a simple structure with the smallest thickness and moderate periodicity and excellent performance characterized by the highest relative bandwidth per layer as well as per lumped resistor, simultaneously.

3.4. Conclusion chapter

Chapter 3 presents simulated results of BMPAs integrated lumped resistors in the GHz frequency region. The BMPA samples were fabricated by photolithography method in the laboratory of the Material Science Institute, Graduate University of Science and Technology. The measured results are in good agreement with the simulation results. The research results are published in ISI journals, the list of the publications related to the thesis includes papers 1, 2, and 3.

CHAPTER 4
THE DESIGN OF BROADBAND METAMATERIA PERFECT ABSORBER BASED ON WATER IN GHz AND THz FREQUENCY REGIONS

BMPA integrates water, with dielectrics dispersed over a wide frequency range, opening up a simple way but has the potential to achieve broadband absorption that is insensitive to both the angle of incidence and the angle of polarization. This method is considered new now for PhD students in the same field of BMPA design. Thus, in this chapter, the PhD student proposes to design a water-based BMPA that operates in the GHz (5-38.5 GHz) and THz (0.6-10 THz) frequency range [133].

4.1. Electromagnetic properties of water

4.2. Water-based BMPA in GHz frequency region

Water is a cheap material and is available in nature. In addition, water has because water has a large and frequency dispersive permittivity, so the loss is relatively high. Based on these advantages, the water is proposed in designing the MPAs. Figure 4.2 introduces the water-integrated BMPA model operating in the GHz frequency region.

Figure 4.4 shows that absorption efficiency reaches approximately 90% in the wide frequency range from 5 to 38.5 GHz for both TE and TM polarization. The design achieves high absorption due to impedance matching between BMPA and free space. In addition, the BMPA has a broadband absorption spectrum because the dielectric of the water disperses in a wide frequency range.

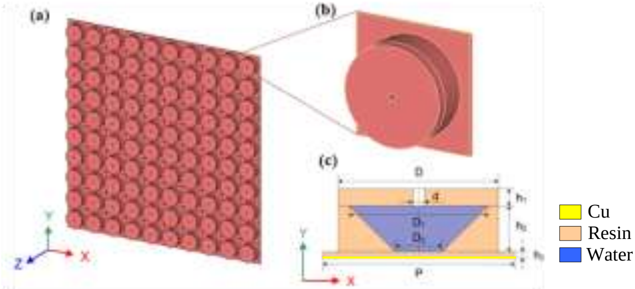

Fig 4.2. Schematic of the water_based BMPA operated in GHz region.

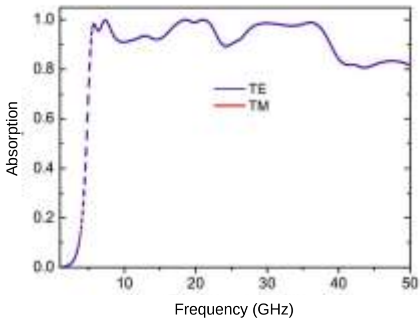

Fig 4.4. Absorption of proposed BMPA.

When the impedance of BMPA and impedance of free space are matched, the absorption of BMPA is maximum.

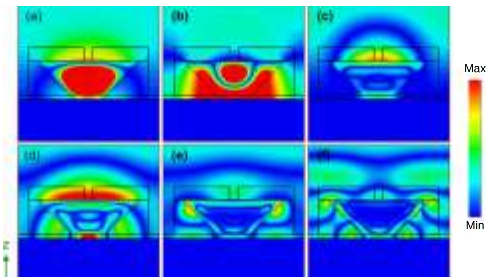

Fig 4.7. Distribution of magnetic field H at various frequencies (a) 5.8 GHz, (b) 7.3 GHz, (c) 18.6 GHz, (d) 21.21 GHz, (e) 29.1 GHz, (f) 36 GHz.

To further investigate the physical mechanism of BMPA, we simulated the distribution of magnetic field in a unit cell at resonant frequencies in the XOY plane, as presented in Fig 4.7. The absorption performance of BMPA at different angles is studied. The results in Figure 4.11 show that BMPA has wide incidence angle. For TE mode, the absorption performance reaches around 80% from 5 to 18 GHz with the incidence angle up to 50^o and appears distint spectral peaks. However, the absorption maintains over 90% from 18 GHz to 38.5 GHz. For TM mode, the absorption achieves over 90% with the incidence angle up to 70^o from 18 to 38.5 GHz.

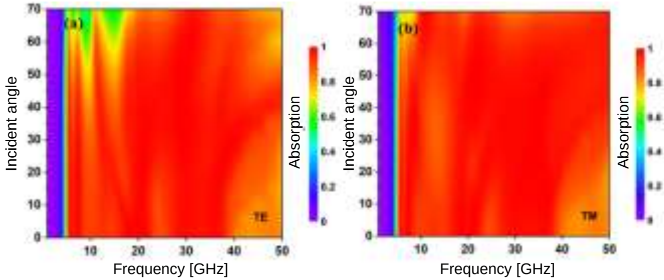

Fig 4.11. The absorption spectrum of BMPA with different angles.

4.3. Water-based BMPA for THz frequency range

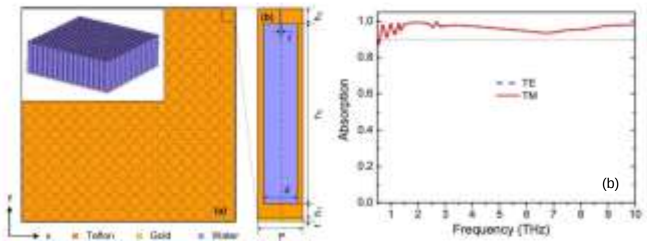

Fig 4.15. (a) Schematic of the designed water-based absorber and và (b) the absorption of BMPA at normal incidence for TE and TM modes[134].

In this part, we report water-based BMPA for THz frequency range [134]. The designed absorber is formed by arranging these unit cells in the x- and y-directions with a period of *P*, as shown in Fig 4.15. The proposed structure achieves the absorption performance of over 90% in the ultra-wideband from 0.6 to 10 THz.

We have investigated the distribution of electric and magnetic fields in a unit cell of the proposed absorber in the XOY plane at various frequencies 1 THz, 2.7 THz, 4.8 THz, and 8.5 THz and the results are shown in Figs. 4.21 and 4.22, respectively.

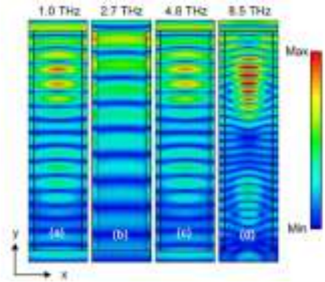

Fig 4.21. The distribution of electric field at various frequencies (a), 1.0 THz, (b), 2.7 THz, (c), 4.8 THz and (d) 8.5 THz [134].

Considering the losses on the layers of the BMPA structure, the loss is mainly in the water layer, while the losses in the Teflon and the gold layers are negligible.

In practical applications, electromagnetic waves illuminate the surface of the absorber in various directions. Therefore, the absorption performance of the absorber at different angles is studied. Form obtained results, it can be concluded that the proposed design achieves the high absorption performance with large incident angles for both TE and TM modes.

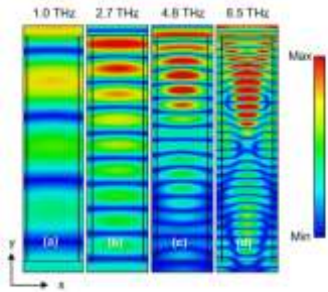

Fig 4.21. The distribution of magnetic field at various frequencies (a), 1.0 THz, (b), 2.7 THz, (c), 4.8 THz and (d) 8.5 THz [134].

A simple design of the water-based broadband terahertz metamaterial absorber was proposed and numerically studied. The proposed absorber consists of a periodic array of a cylindrical water resonator encapsulated in the cuboid container and backed with a copper plate. The designed absorber structure achieved an absorption efficiency above 0.9 in the wide frequency range from 0.6 to 10 THz. Moreover, the absorber maintained a high absorption performance of over 0.9 with a wide variation of incident angle up to 40^o for TE mode and 70^o for TM mode.

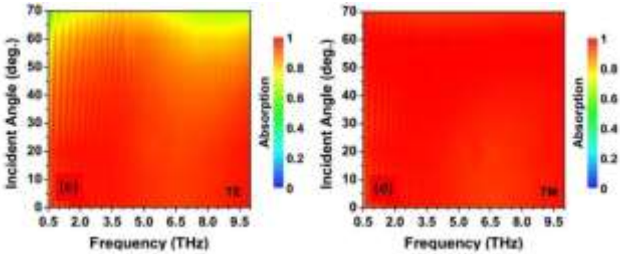

Fig 4.24. The absorption spectra of the absorber with different polarization angles for (c) TE mode and (d) TM mode [133].

4.4. Conclusion chapter

We built the model and studied the absorption properties of water-based BMPA operating in the GHz and THz frequency regions by simulation method. The proposed BMPA models have high absorption in a broadband frequency range, working with a wide angle of incidence. The research results include 01 paper in a domestic specialized journal under the category of the National Research Institute, in the "List of the publications related to the thesis" is number 4. 01 research results in the GHz frequency band are submitted for publication in the SCI-E journal.

CONCLUSIONS

The thesis "*The study of absorption properties of broadband metamaterial perfect absorber integrated lossy elements* " was carried out at the Institute of Materials Science, Graduate University of Sciences and Technology, and Vietnam Academy of Science and Technology. The main results related to BMPA have been published, including 03 papers in the SCI-E and 01 paper in a domestic journal. The thesis has contributions to the study of MMs in general and BMPAs in particular, including:

The thesis builds a physical model and investigates the influence of structural parameters and materials on the properties of the BMPAs integrated lumped resistors operating in the GHz frequency regions.

We design BMPAs integrated lumped resistors operating in C, X, and Ku bands. From there, we built the fabrication process and measured the absorption of the BMPA operating in the GHz frequency region.

1. The thesis proposed physical modeling, simulation, and optimization of structural parameters of BMPA integrating resistors for applications in the GHz region. After that, we have fabricated successfully BMPA samples integrating lumped resistors operating in the GHz frequency range such as S-band(2-4GHz), C-band (4-8GHz), X-band (8-12 GHz), and Ku-band (12-18 GHz), and proposed the BMPA fabrication process in the GHz frequency region. The results demonstrate that integrating resistors into the resonant structure of MPA is an easy method to extend the absorption bandwidth of MPA. BMPAs with lumped resistors have an absorption performance of over 90% at resonant peaks compared to about 30% of BMPA without resistors.

2. The thesis proposed an optimal physical model, simulation, and survey of the structural parameters of the water-based BMPA, operating in the frequency range GHz (5-38.5 THz) and THz (0.6-10 THz). The study results show that proposed BMPA structures are simple and easy to expand the absorption bandwidth because water has a large and frequency dispersive permittivity with relatively high dielectric loss.

NEW CONTRIBUTIONS OF THE THESIS

i) Integrating lossy elements (resistors and water) in the structure of the broadband metamaterial perfect absorber operated in GHz and THz frequency regions.

ii) Valuating the effects of structure parameters, incident angle, and polarization angle on the operation of BMPA in GHz and THz frequency regions.

LIST OF THE PUBLICATIONS RELATED TO THE THESIS

1. Thu N. T. K, Minh T. N., Quang H. N., Nghia C. T., Tuyen D. L., Khuyen X. B., Tung. S. B, Lam C. T., Lam V. D., Hoa N. T. Q, 2021, Simple design of efficient broadband multifunctional polarization converter for X-band application, *Sci. Rep*,11, 2032.

2. Thu N. T. K, Nghia C. T, Hieu N. N., Tuyen D. L., Khuyen X. B., Lam C. T., Hoa N. T. Q., 2021, Simple Design of a Wideband and Wide-Angle Insensitive Metamaterial Absorber Using Lumped Resistors for X- and Ku-Bands, *IEEE Photon. J.*, 13 (3), 1-10.

3. Tung. P. D., **Thu N. T. K**., Hieu N. N., Tuyen D. L., Khuyen X. B., Lam V. D., Lam C. T Hoa N. T. Q., 2021, Lightweight, Ultra-Wideband, and polarization-Insensitive Metamaterial Absorber Using a Multilayer Dielectric Structure for C- and X-Band Applications, *Phys Status Solidi B Basic Res*, 258, 2100175.

4. Thu N. T. K, Minh T. N., Quang H. N., Tam N. T. M., Thuong H. T. H., My P. T., Lam V. D., 2023, A simple design of water-based broadband metamaterial absorber for THz, *Comm. Phys*, 33 (1), 93-102.