

Article

An Ultra-Wideband Metamaterial Absorber Ranging from Near-Infrared to Mid-Infrared

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Abstract: This study focused on designing an ultra-wideband metamaterial absorber, consisting of layers of Mn (manganese) and MoO₃ (molybdenum trioxide) arranged in a planar interleaving pattern, with a matrix square-shaped Ti (titanium) on the top MoO₃ layer. Key features of this research included the novel use of Mn and MoO₃ in a planar interleaving configuration for designing an ultra-wideband absorber, which was rarely explored in previous studies. MoO₃ thin film served as the fundamental material, leveraging its favorable optical properties and absorption capabilities in the infrared spectrum. Alternating layers of Mn and MoO₃ were adjusted in thickness and order to optimize absorptivity across desired wavelength ranges. Another feature is that the Mn and MoO₃ materials in the investigated absorber had a planar structure, which simplified the manufacturing of the absorber. Furthermore, the topmost layer of square-shaped Ti was strategically placed to enhance the absorber's bandwidth and efficiency. When the investigated absorber lacked a Ti layer, its absorptivity and bandwidth significantly decreased. This structural design leveraged the optical properties of Mn, MoO₃, and Ti to significantly expand the absorption range across an ultra-wideband spectrum. When the Ti height was 280 nm, the investigated absorber exhibited a bandwidth with absorptivity greater than 0.9, spanning from the near-infrared (0.80 μ m) to the mid-infrared (9.07 μ m). The average absorptivity in this range was 0.950 with a maximum absorptivity of 0.989. Additionally, three absorption peaks were observed at 1010, 2510, and 6580 nm. This broad absorption capability makes it suitable for a variety of optical applications, ranging from near-infrared to mid-infrared wavelengths, including thermal imaging and optical sensing.

Keywords: ultra-wideband metamaterial absorber; near-infrared; mid-infrared; Mn and MoO₃; square-shaped Ti



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1. Introduction

Since Landy et al. introduced a metamaterial-based perfect absorber with nearly 100% absorption in 2008, research into perfect absorbers has significantly expanded [1]. Metamaterials are specially engineered materials characterized by their unique periodic structures with unit cells smaller than the wavelength of the electromagnetic waves they interact with. These materials allow for precise control over their electromagnetic properties through various methods of structural engineering. By meticulously optimizing their geometry, designing the unit cells, and arranging them in specific patterns, engineers can tailor the metamaterials' response to electromagnetic fields, achieving effects that are not possible with natural materials. This exploration now spans an ultra-broadband range with high absorptivity across a diverse array of spectral regions, including visible

wavelengths [2], near-infrared [3], terahertz [4], and radio frequency and microwave ranges [5]. By leveraging advanced metamaterials, it is possible to design absorbers that not only cover these broad spectral ranges but also integrate the characteristics of both multi-wavelength resonant absorbers and ultra-wideband visible absorbers [6]. This capability enhances performance and versatility, enabling more efficient and adaptable absorption technologies across various applications. The advancements have led to diverse applications and innovations across multiple fields, reflecting the growing importance and versatility of perfect absorbers in modern technology.

Near-infrared (NIR, 0.75–1.4 μm) and mid-infrared (MIR, 1.4–8 μm) absorbers play crucial roles in various application areas. NIR absorbers are valuable for imaging and diagnosing biological tissues because NIR light can penetrate tissues and provide useful imaging information. Consequently, they can be used in various medical applications [7]. MIR absorbers are widely used in Fourier-transform infrared (FTIR) spectroscopy to identify and analyze the molecular structures of chemical substances [8,9]. They are also applicable in environmental monitoring, where they help detect gases and pollutants in the air, such as methane and carbon monoxide. The ability to detect and image short-wave infrared (SWIR) light is crucial for a range of important applications, including biological imaging, autonomous navigation, and surveillance [10]. In biological imaging, SWIR light can penetrate deeper into tissues and provide high-resolution images, which is valuable for medical diagnostics and research [11]. For autonomous navigation, SWIR sensors enhance visibility in various environmental conditions, improving the reliability and safety of self-driving vehicles [12,13]. In surveillance, SWIR imaging enables effective monitoring and detection in low-light or obscured conditions, significantly enhancing security and situational awareness [14].

In the past, Zhang et al. investigated an IR-perfect absorber structure based on a GaAs/Au/SiO₂ metamaterial using numerical simulations. They incorporated gold split-ring resonators embedded within the GaAs layer. Under plane wave excitation with polarization perpendicular to the split-ring resonators' opening direction, absorption exceeded 99% at 1360 nm [15]. Murata et al. utilized rhenium(I) complexes to explore and develop stable absorbers for the NIR region [16]. Their research focused on enhancing the performance and stability of these materials, aiming to improve their efficiency in applications requiring NIR absorption. Hasan et al. employed a CMOS-compatible Mo-AlN-Mo platform to develop a metamaterial-based absorber for the MIR spectrum [17]. Their work underscores the significant and diverse applications of NIR and MIR absorbers. However, it is evident that the materials used in the development of these NIR and MIR absorbers are often difficult to obtain or challenging to manufacture. In response, this study aims to create a metamaterial-based absorber featuring a simple structure that is easy to produce and capable of operating across both the NIR and MIR spectra. This approach seeks to address the limitations of current materials by offering a more accessible and versatile solution for a range of applications.

In the past, various metal-oxide materials were utilized in optical devices. For instance, MnO₂ is a well-studied three-dimensional (3D) transition metal oxide known for its advantages in ultrafast optics, including superior electron transfer capability, a porous structure, a narrow bandgap, a large specific surface area, and a broad range of light absorption [18]. In this study, MoO₃ (molybdenum trioxide) was used as the metal-oxide material to investigate an ultra-wideband metamaterial absorber ranging from near-infrared to mid-infrared. The first significant innovation of this study is the design of an ultra-broadband absorber using Mn (manganese) and MoO₃ in an interleaved structure, with the primary absorption range extending from near-infrared to far-infrared regions. Designing an ultra-broadband absorber using Mn and MoO₃ in an interleaved structure offers the following advantages:

- (1) **Wideband absorption:** The material properties of Mn and MoO₃ allow for effective absorption of electromagnetic waves across a very broad wavelength range. Mn performs well in the visible and near-infrared ranges, while MoO₃ excels in the longer

infrared wavelengths. Combining these materials enables ultra-broadband absorption from visible to mid-infrared regions.

- (2) Excellent optical properties: Both Mn and MoO₃ exhibit unique optical characteristics, such as high refractive indices and low losses, which make them highly effective in absorber design. Their combination can optimize light absorptivity while minimizing reflection and scattering losses.
- (3) High tunability: The optical properties of Mn and MoO₃ can be adjusted by varying their thickness, arrangement, and other fabrication parameters. This flexibility allows for the design to be tailored to meet different application needs and wavelength ranges.
- (4) Thermal and chemical stability: MoO₃, as an oxide material, offers good thermal and chemical stability, maintaining its structure and performance even in high-temperature environments. Mn also exhibits strong thermal stability, making this absorber suitable for harsh conditions.
- (5) Versatility: This material combination is not only effective for light absorption but also has potential applications in light detection, optical sensors, and solar cells, among other uses, providing significant versatility.
- (6) Cost-effectiveness: Both Mn and MoO₃ are relatively inexpensive and readily available materials. Thus, using them for manufacturing ultra-broadband absorbers can be more cost-effective compared to more expensive alternatives.
- (7) Ease of fabrication: The design of the first through eighth layers in this study uses only Mn and MoO₃ materials arranged in a planar interleaved structure, simplifying the manufacturing process.

The main challenge of this material design lies in optimizing the arrangement and structure of Mn and MoO₃ to maximize absorptivity while minimizing reflection and other losses. With careful design, it is possible to achieve a highly efficient, stable, and broad-spectrum electromagnetic wave absorber. The second key feature of this research is the novel application of Mn and MoO₃ in a planar interleaving configuration to design an ultra-wideband absorber, a concept that was rarely explored in previous studies. In this approach, the MoO₃ thin film serves as the fundamental material, taking advantage of its favorable optical properties and absorption capabilities in the infrared spectrum. The alternating layers of Mn and MoO₃ can be adjusted in thickness and arrangement to optimize absorptivity across the desired wavelength ranges. Additionally, the planar structure of Mn and MoO₃ materials simplifies the manufacturing process of the absorber.

Titanium (Ti) exhibits excellent optical properties in both the near-infrared and far-infrared ranges, which significantly enhances the absorptive performance of the structure. In this optical absorber design, the matrix of square-shaped Ti serves the following key functions:

- (1) Square-shaped Ti can act as an optical material to enhance light absorption. Its main role is to improve the absorber's performance across various wavelengths, from NIR to MIR, particularly in the ultraviolet–visible to near-infrared range. Ti can increase the material's absorption efficiency, helping achieve broader spectral absorption.
- (2) Square-shaped Ti can function as an optical enhancement layer by increasing the optical path length within the material. This is achieved by altering the light's propagation path, which improves the material's absorptivity for specific wavelengths.
- (3) The addition of square-shaped Ti helps extend the material's spectral absorption range, enhancing its performance across different infrared spectra and thus increasing the optical absorber's versatility and application range.

The third characteristic of this study is that as the height of the matrix square-shaped Ti structures increases from 200 nm to 280 nm, there is a redshift in the relative absorption peak, accompanied by an increase in absorptivity. The underlying theories explaining these observations will be discussed in this paper.

2. Structure of the Investigated Bidirectional Switching Functionality Absorber

Designing an optical absorber that operates efficiently across the near-infrared to far-infrared spectrum requires meticulous and precise engineering to ensure optimal light capture throughout this broad range. In the past, many software was used to simulate the properties of the designed optical devices, for example, time-dependent density functional theory (TDDFT) [19]. To achieve this, we employed COMSOL Multiphysics® (version 6.0), a sophisticated finite element analysis software, to conduct detailed simulations. This tool allowed us to model the absorber's performance accurately and iteratively refine its design. The structure used in this research is depicted in Figure 1a, with each layer's parameters clearly defined. The dielectric layers were composed exclusively of MoO_3 , while the metal layers were entirely Mn. These materials were chosen for their well-established deposition techniques and cost-effectiveness, which are advantageous for designing optical absorbers with high absorptivity across a broad spectrum. The absorber structure consists of alternating layers of Mn and MoO_3 arranged in a planar interleaving pattern. Specifically, the layers are stacked in the sequence Mn (h1)/ MoO_3 (h2)/Mn (h3)/ MoO_3 (h4)/Mn (h5)/ MoO_3 (h6)/Mn (h7)/ MoO_3 (h8)/Ti (h9), from bottom to top. In sequence from bottom to top, the thicknesses of each layer were 310 nm/160 nm/15 nm/190 nm/5 nm/210 nm/5 nm/170 nm/280 nm.

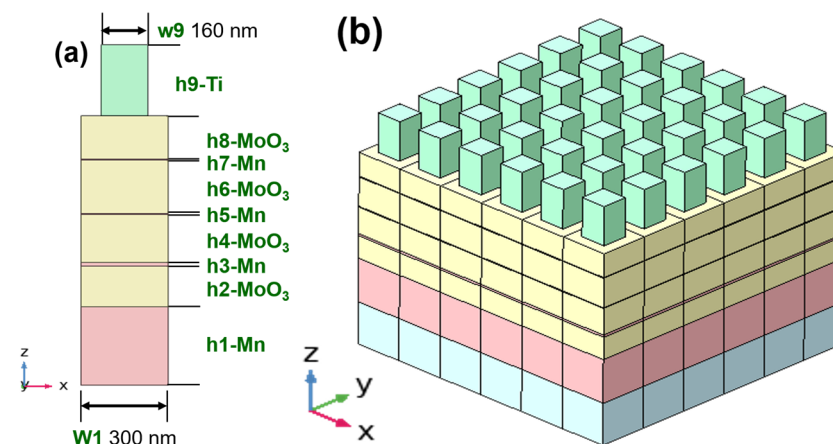


Figure 1. The structure of the investigated ultra-wideband metamaterial absorber. (a) Side view and (b) 3D structure. Green: Ti; yellow: MoO_3 ; and pink: Mn.

Figure 1a displays the single structure used for analysis. Figure 1b illustrates the matrix-like structure of the investigated absorber, which consists of a grid of square-shaped Ti patterns on the top MoO_3 layer. When designing a super-wideband absorber, the key parameters include reflectance, transmittance, absorbance, electromagnetic response, material properties, and geometric parameters. By considering these factors comprehensively, the design of the metamaterial absorber can be optimized to achieve optimal optical performance. The choice of specific layer thicknesses is typically based on several key factors, including optical path length, interference effects, and the optical properties of materials. During the optimization process, parameters such as reflectance, transmittance, and absorbance are often considered. As for the choice of square unit shapes, this decision not only simplifies modeling but also has the following advantages:

- (1) Symmetry: Square structures generally exhibit good symmetry, which aids in simplifying analysis and enhancing absorption performance.
- (2) Uniformity: Square units provide more uniform characteristics in all directions, contributing to consistent absorption across a wide frequency range.
- (3) Design flexibility: The square unit design allows for easier integration with other shapes, facilitating the creation of more complex structures to optimize performance over specific wavelength ranges.

The cross-sectional shape of the matrix square-shaped Ti significantly impacts the overall performance of the structure. It directly influences light scattering, resonance, and absorption mechanisms. Different cross-sectional shapes can lead to varying local electromagnetic field distributions, which, in turn, affect absorption efficiency. Notably, the h1 to h8 layers form continuous planes, and adjustments to the distance between the matrix squares of the h9 Ti in the top layer regulate the spacing between adjacent Ti squares. However, other parameters were optimized iteratively by systematically adjusting h1 to h9 and w1 and w9, while keeping the original parameters shown in Figure 1a unchanged, to determine their optimal values. The absorber under investigation featured a mesh structure with the following specifications: 23,464 grid nodes, a maximum grid length of 1.5 nm, and a minimum grid length of 0.75 nm. The mesh comprised 14,100 triangular elements, 127,747 tetrahedral elements, 980 edge finite elements, and 52 endpoint elements. The average element quality was 0.6467, with a minimum quality of 0.07237. The total grid area was $1.571 \times 10^8 \text{ nm}^2$, and the element-to-volume ratio was 1.527×10^{-4} , ensuring the accuracy and reliability of the simulation results.

3. Results and Discussion

Historically, metal-organic frameworks (MOFs) have been employed in the development of ultra-wideband metamaterial absorbers due to their remarkable properties, such as high porosity, extensive specific surface area, and a wide range of functionalities and structural variations [20–22]. However, the complexity of manufacturing MOFs presents a significant challenge, making them less practical compared to planar matrix structures. Consequently, this research primarily adopts planar configurations, leveraging their ease of fabrication while still aiming to achieve optimal performance in metamaterial absorption. This decision highlights a trade-off between advanced material properties and practical manufacturability, underscoring the importance of balancing innovation with feasibility in materials design. When the thickness of the h1 Mn layer ranges from 230 to 310 nm, Figure 2 shows how these variations affect absorptivity across different wavelengths from 400 to 10,000 nm, with thickness values in 10 nm intervals. The results indicate that the h1 Mn layer thickness has little impact on absorptivity; overall, it remains high and largely independent of wavelength within this range. Notably, two primary wavelengths with high absorptivity are identified: 2000 nm and 6000 nm. A closer look at the yellow region around 2000 nm shows that a thickness of 310 nm yields optimal absorptivity.

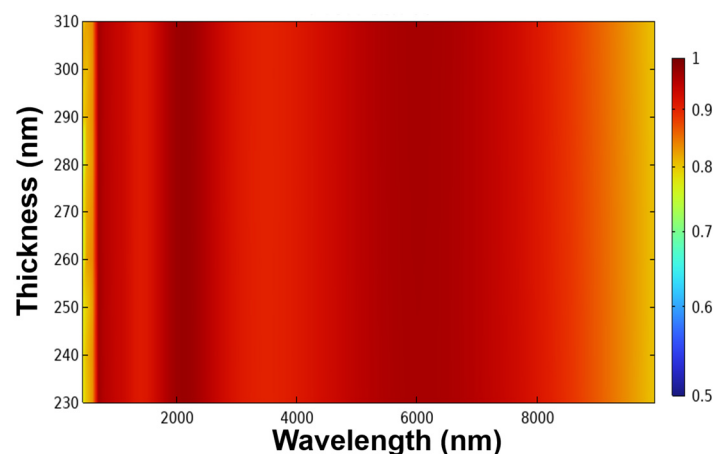


Figure 2. Effect of the various thicknesses of the h1 Mn layer on the absorptivity under different simulation wavelengths.

The color variations shown in the analysis diagram behind Figure 2 depict the changes in absorptivity as a function of light wavelength and different material thicknesses. The absorptivity can be referenced using the color scale on the right side of Figure 2, where blue indicates an absorptivity of 0.5 (50%). As the color shifts toward red, red signifies absorptivity

greater than 0.9 (90%), while dark red indicates an absorptivity approaching 1 (100%), denoting perfect absorption. In Figure 2, when the thickness of Mn increases from 230 nm to 310 nm, a dark red line appears around a wavelength of approximately 2000 nm, indicating that the absorber has a high absorptivity at this wavelength. Subsequent results related to light wavelength and the thickness of individual material layers convey a similar meaning, where different colored regions or the extension of lines represent variations in absorptivity. It is important to note that the h1 Mn layer is positioned at the bottom of the structure. The primary source of absorption in this configuration is the Surface Plasmon Resonance (SPR). SPR refers to the coherent oscillation of free electrons at the surface of a metal when excited by incident light, typically at specific wavelengths. This phenomenon occurs at the interface between a conductor and a dielectric, resulting in a significant enhancement of the electromagnetic field. This topic will be further discussed in a later section.

Variations in the h1 Mn layer thickness have minimal impact on overall absorptivity, which will be discussed further in later sections. The h2 MoO₃ layer thickness was adjusted from 160 to 240 nm in 10 nm increments, with wavelength scans ranging from 400 to 10,000 nm (a consistent range for all scans). Similar to the h1 Mn layer results, the absorptivity with different h2 MoO₃ thicknesses showed no significant differences across this range, so these findings are not detailed here. The optimal thickness for the h2 MoO₃ layer was determined to be 160 nm. The main reason is that when the h2 MoO₃ layer is 160 nm thick the absorptivity exceeds 0.9 across the range from 0.8 to over 9 μm . Figure 3 shows the relationship between absorptivity and the thickness of the Mn layer (h3), varying from 5 nm to 45 nm in 5 nm increments. At 5 nm, two low absorptivity regions appear around 1200 nm and 1800 nm. As the thickness increases to about 15 nm, these regions merge, raising overall absorptivity. When the thickness reaches approximately 18 nm, a new low absorptivity region appears around 1500 nm and further increases in thickness lead to a significant decline in absorptivity. Furthermore, as the Mn layer thickness increases from 15 to 45 nm, a significant decline in absorptivity is observed, decreasing from approximately 0.9 to around 0.75 within the 8800 to 10,000 nm range. This trend highlights the importance of Mn layer thickness in optimizing absorber performance. Conversely, reducing the Mn layer thickness decreases absorptivity around 4000 nm, but there is an increase in the 2000 nm range. For designing a NIR and MIR ultra-wideband absorber, a thickness of 15 nm for the Mn layer was selected as the optimal value.

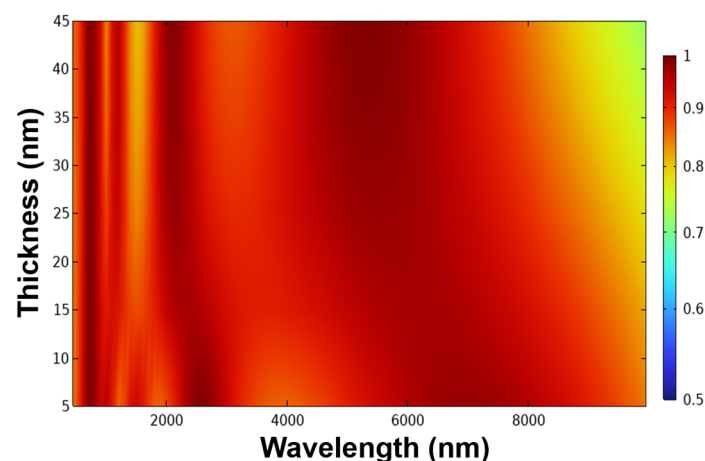


Figure 3. Effect of the thickness of the h3 Mn layer on the absorptivity under different simulation wavelengths.

We then conducted a parameter scan analysis on the h4 MoO₃ layer, varying its thickness from 150 nm to 230 nm in 10 nm increments, as shown in Figure 4. The results reveal that absorptivity significantly increased around 10,000 nm as the thickness increased from 150 nm to 230 nm. Conversely, at 1000 nm, absorptivity decreased with greater thickness. Additionally, absorptivity at 400 nm gradually declined as thickness decreased. Figure 4

shows that the overall sensitivity of absorptivity to the thickness of the h4 MoO₃ layer is relatively low. To achieve high absorptivity across the NIR to MIR range, we chose an optimal thickness of 190 nm for the h4 MoO₃ layer. This intermediate thickness ensures effective performance across the desired spectrum, enhancing its utility in practical applications.

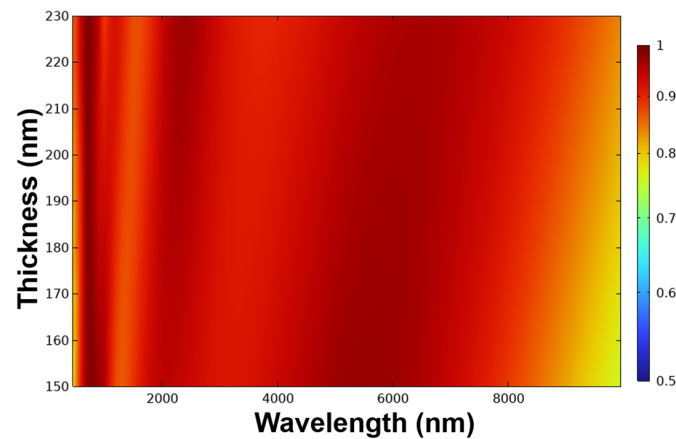


Figure 4. Effect of the thickness of the h4 MoO₃ layer on the absorptivity under different simulation wavelengths.

Figure 5a shows how varying the h5 Mn layer thickness affects absorptivity across different wavelength ranges. Thickness was adjusted from 5 to 45 nm in 5 nm increments. As the thickness increases, absorptivity significantly decreases in the 6000–10,000 nm range, with similar reductions observed at 1000 nm and 2000 nm. In the design of NIR and MIR absorbers, we observe a significant decrease in absorptivity, dropping from approximately 0.92 to around 0.55 within the 6000–10,000 nm range as the thickness of the Mn layer increases from 10 to 45 nm. This reduction in absorptivity suggests again that the thickness of the Mn layer plays a critical role in the absorber's performance, potentially affecting its efficiency in specific applications. Understanding this relationship is essential for optimizing the design of absorbers for desired spectral ranges. The overall absorptivity is much more sensitive to changes in the h5 Mn layer thickness than in the h1 Mn layer. As the Mn film thickness increases from 5 nm, absorptivity in the 6000–10,000 nm range significantly decreases. This reduction is likely due to changes in surface impedance from increased thickness, affecting light coupling and penetration depth, which reduces absorptivity. Additionally, while SPR can lead to strong absorption by metals within specific wavelength ranges, the film thickness significantly influences the excitation conditions and resonance frequency of SPR.

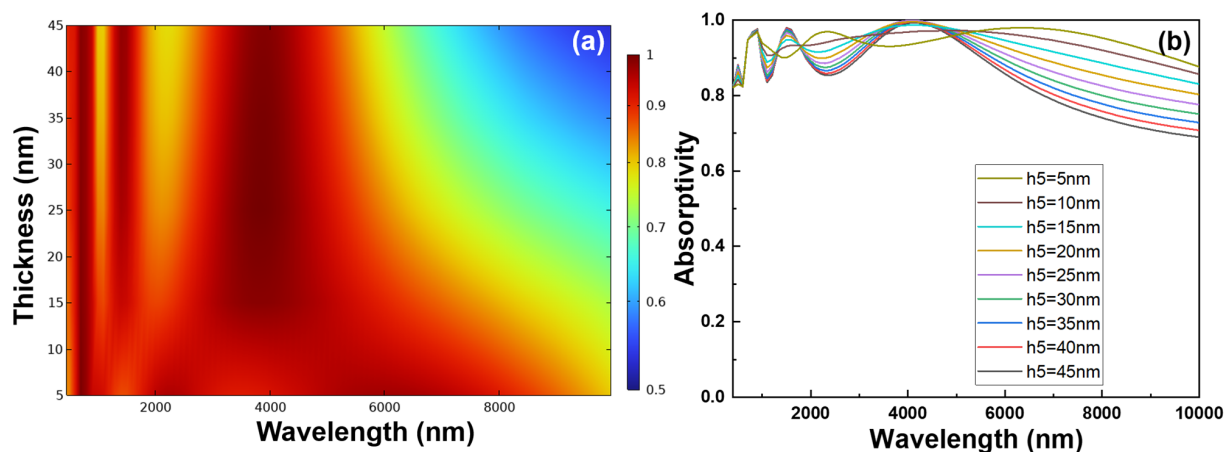


Figure 5. Effect of the thickness of the h5 Mn layer on (a) the absorptivity under different simulation wavelengths and (b) the absorption spectra under different thicknesses of the h1 Mn layer.

As the film thickness increases, the position and intensity of the SPR peak may shift or even disappear. Another contributing factor could be changes in the optical constants of the material. The refractive index and extinction coefficient of the metal are critical parameters that determine its optical properties. As the film thickness increases, alterations in these optical constants can affect the absorptivity. Figure 5b shows the absorptivity spectra for various thicknesses of the h5 Mn layer. The data clearly indicate that increasing the thickness of the h5 Mn layer does not significantly alter the wavelength of the absorption peaks. This suggests that changes in layer thickness do not affect the SPR absorption peak values. Therefore, the observed decrease in absorptivity is likely due to factors other than SPR, as discussed previously. Increasing thickness may alter the surface equivalent dielectric constant, affecting absorption characteristics at specific wavelengths. Thus, a minimum thickness of 5 nm is recommended to optimize absorber performance while maintaining desirable SPR characteristics.

We conducted a parameter scan on the h6 MoO₃ layer thickness, ranging from 140 to 220 nm in 10 nm increments. Results showed that as thickness decreased, absorptivity at wavelengths below 2000 nm and above 8000 nm also decreased. The maximum thickness of 220 nm was not chosen due to a drop in absorptivity around 4000 nm, similar to the h4 MoO₃ layer findings. Therefore, we selected h6 = 210 nm for further analysis. Figure 6a illustrates the absorptivity variations for the h7 Mn layer, with thicknesses ranging from 5 to 45 nm in 5 nm increments. The data show that as the h7 Mn layer thickness increases from 5 nm, absorptivity generally decreases at multiple wavelengths. Figure 6b presents the absorptivity spectra for different thicknesses, revealing a notable absorption peak around 6500 nm at 5 nm thickness. As thickness increases to 10 nm, this peak becomes less pronounced. These results highlight the critical influence of h7 Mn layer thickness on absorption in the NIR and MIR ranges, with an optimal thickness of 5 nm identified for maximizing absorptivity. This thickness achieves a strong absorption peak and high overall absorptivity, essential for effective NIR and MIR performance.

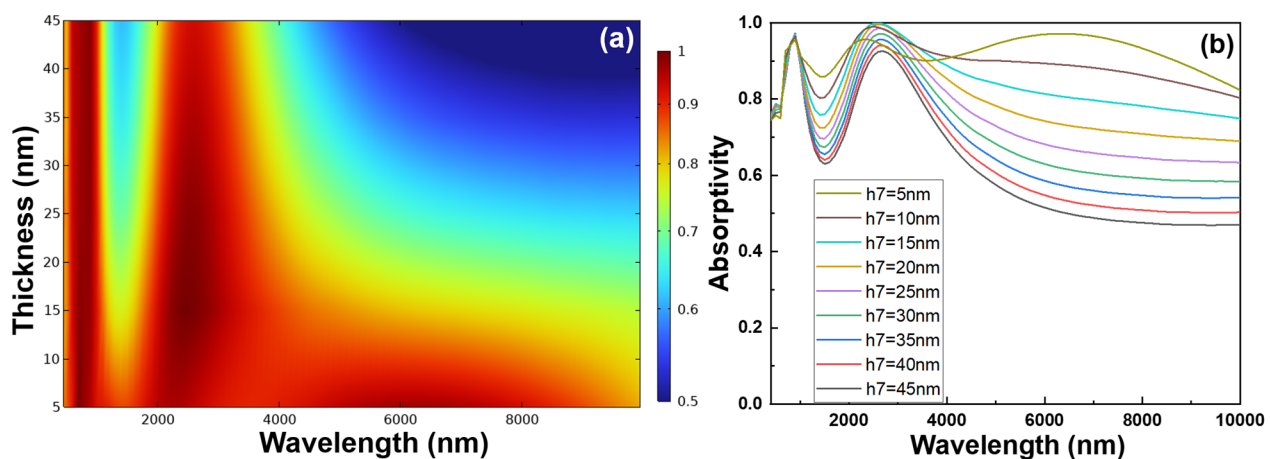


Figure 6. Effect of the thickness of the h7 Mn layer on (a) the absorptivity under different simulation wavelengths and (b) the absorption spectra under different thicknesses of the h7 Mn layer.

Next, we analyzed the h8 MoO₃ layer parameters over a wavelength range of 400 to 10,000 nm, testing thicknesses from 160 to 240 nm in 10 nm increments. We found that absorptivity at 1800 nm decreased with increased thickness, while absorptivity at 10,000 nm increased. To enhance absorptivity at 2000 nm, we selected a thickness of 170 nm. Although the optimal thickness for absorption at 400 nm was between 190 and 210 nm, the effect was more pronounced at 1000 nm, consistent with findings for the h4 MoO₃ layer, which are not detailed here. Finally, we analyzed the h9 Ti layer over a wavelength range of 400 to 10,000 nm. Ti's excellent optical properties in both NIR and MIR enhance the absorptive performance of square-shaped Ti structures. Thickness varied from 200 to 280 nm in 10 nm increments. As height increased from 200 nm to 280 nm, we observed a redshift

in the absorption peak and improved absorptivity (see Figure 7). Changing the height from 280 nm to 200 nm altered the bandwidth from near-infrared (0.80 μm) to far-infrared (9.07 μm) and from red light (0.66 μm) to far-infrared (8.25 μm). However, the absorption peak around 1.6 μm diminished significantly with decreasing thickness, indicating that the optical properties of Ti structures are sensitive to height changes, enhancing light interactions at specific wavelengths.

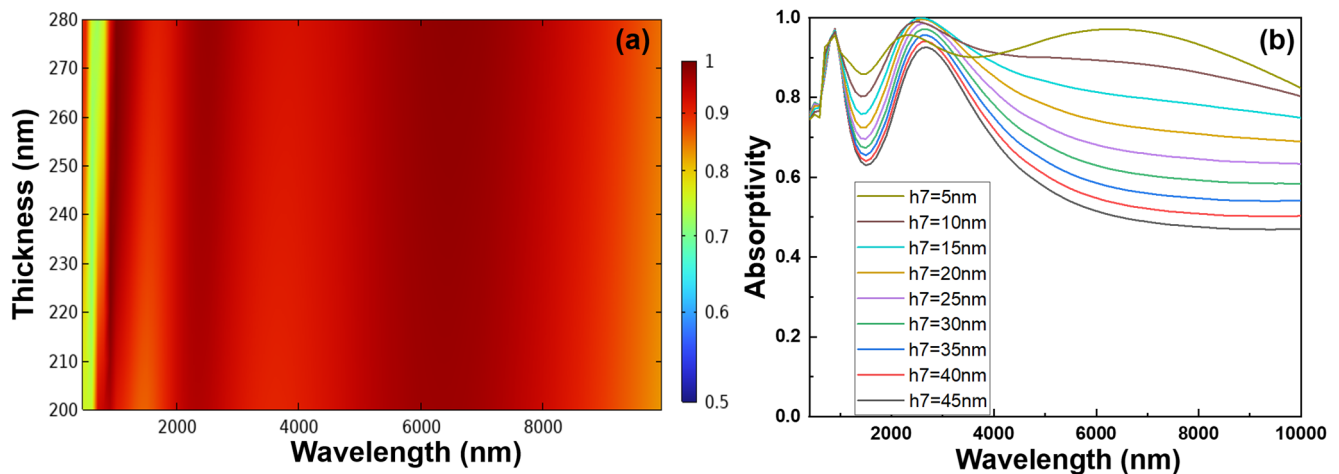


Figure 7. Effect of the thickness of the h9 square-shaped Ti layer changed from 200 nm to 280 nm on (a) the absorptivity under different simulation wavelengths and (b) the absorption spectra under different thicknesses of the h9 Ti layer.

However, increasing the height of the square-shaped Ti structures to 290 nm results in a significant decrease in near-infrared absorption. This decline is due to the complex interplay between geometric dimensions and optical resonance effects. The redshift up to 280 nm suggests that the resonant wavelength shifts to longer wavelengths, enhancing absorption in that range, likely due to changes in optical path length and resonance conditions. Both the parameter scan (Figure 7a) and the absorptivity comparison graphs (Figure 7b) indicate that a thickness of 280 nm provides optimal absorption. Specifically, at a wavelength of 1000 nm, the absorption rate at a thickness of 280 nm is significantly higher than at other thicknesses. While this thickness does not provide the best absorption at 400 nm, it has a more pronounced effect at 1000 nm. The drop in absorption at 290 nm may be due to a shift from optimal resonance conditions, where the structures no longer effectively interact with light. Increased height might also lead to greater scattering losses or changes in the material's optical properties, reducing absorption efficiency. These findings emphasize the need to carefully optimize the geometric parameters of nanostructures to achieve desired optical properties.

Optical impedance is a complex quantity, typically represented as $Z = R + iX$, where R is the real part representing resistance and X is the imaginary part representing reactance. When the real part R approaches 1, it indicates that the system's absorptive properties are close to an ideal impedance matching condition, allowing light energy to effectively enter or pass through the system. This usually means that the system can efficiently absorb light energy with minimal reflection. When the real part R deviates significantly from 1, it suggests that the system's absorptive properties are far from ideal impedance matching. This can result in increased reflection and reduced absorption efficiency. If the imaginary part X is close to 0, it indicates that the system primarily exhibits resistive properties rather than reactive properties. This means that light energy is mainly absorbed rather than stored within the system. Conversely, when the imaginary part X deviates significantly from 0, it indicates that the system has strong reactive properties. This may suggest processes such as the storage or release of light energy, like resonance phenomena or delay effects. In optical systems, the real and imaginary parts of the optical impedance correspond to the absorption and storage characteristics of light energy, respectively. Therefore, changes in these values are important indicators of the system's optical behavior.

When the real part of the optical impedance is close to 1, it indicates that the material's refractive index is close to that of free space (vacuum). This typically means that the material has a low reflectivity, allowing most of the incident light to enter the material. If the material also has absorptive properties, more light energy will be absorbed, resulting in higher optical absorptivity. Conversely, when the real part of the optical impedance deviates significantly from 1, it indicates a significant difference between the material's refractive index and that of free space. This usually leads to higher reflectivity, reducing the proportion of incident light that enters the material and thus potentially decreasing the optical absorptivity. If the refractive index is much greater than 1, the reflection becomes more pronounced; if it is much less than 1, it may also result in reflection or other complex optical behaviors. When the imaginary part of the optical impedance is close to 0, the material exhibits low optical losses, meaning it has weak absorption of light. This indicates that the material is a good transmitter of light, allowing incident light to pass through with minimal absorption, resulting in low optical absorptivity. On the other hand, when the imaginary part of the optical impedance deviates significantly from 0, it indicates that the material has higher absorptive characteristics. The larger the imaginary part, the higher the optical absorptivity. This generally corresponds to increased optical losses within the material, where more light energy is converted into other forms, such as heat, thereby increasing the optical absorptivity. Both the real and imaginary parts of optical impedance influence optical absorptivity. The real part primarily affects the reflection and refraction characteristics of light, while the imaginary part is directly related to the material's absorption properties. These components together determine the efficiency with which a material absorbs and transmits light.

Figure 8a shows the relationship between impedance and wavelength. Around the wavelength of 3500 nm, it is evident that the real part of the impedance deviates slightly from 1, while the imaginary part deviates somewhat from 0. This corresponds to the absorption trough in Figure 8 (i.e., the wavelength range where absorptivity drops to around 0.9). As previously mentioned, when the real part of the optical impedance deviates from 1, it indicates a significant difference between the refractive index of the material and that of free space. This typically results in higher reflectivity, reducing the proportion of incident light entering the material, and thereby potentially decreasing light absorptivity. Additionally, when the wavelength exceeds 8200 nm, although the imaginary part of the impedance does not significantly deviate from 0, the real part clearly deviates from 1. This suggests that the optical properties of the material at these wavelengths differ more markedly from those of free space, further affecting the behavior of light propagation. In particular, when the refractive index of the material significantly differs from that of free space, the reflection of light at the material interface is enhanced, causing more light to be reflected rather than absorbed.

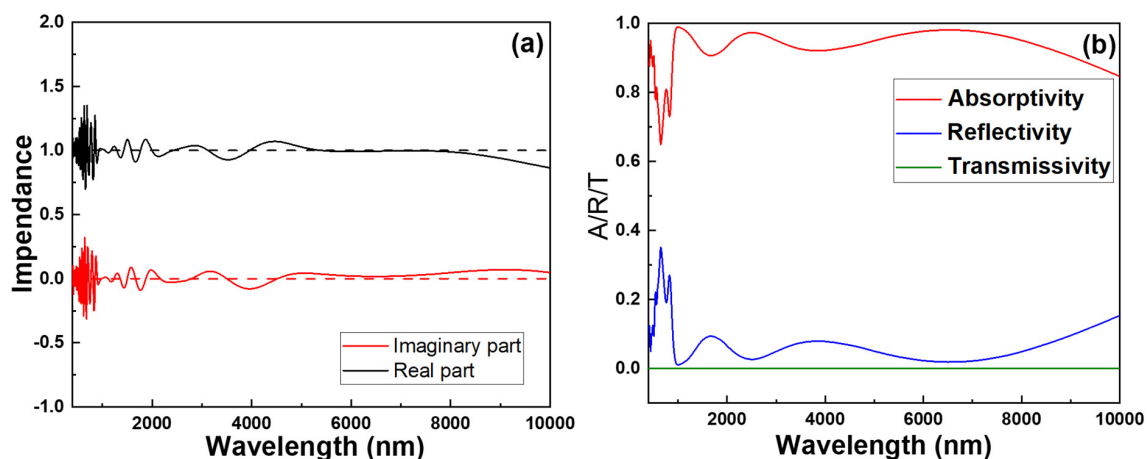


Figure 8. Variations of (a) optical impedance and (b) absorptivity, reflectivity, and transmissivity spectra for the designed absorber in the range of 400–10,000 nm.

Figure 8b further corroborates these observations, showing a significant decrease in absorptivity and a notable increase in reflectivity around the wavelength of 3500 nm. This indicates that at this wavelength, the optical impedance matching between the material and free space decreases, resulting in more light being reflected rather than absorbed. Similarly, when the wavelength exceeds 8200 nm, absorptivity decreases further, while reflectivity increases more prominently. This further supports the previous observations that the mismatch in optical impedance leads to increased reflectivity and decreased absorptivity. Additionally, as shown in Figure 9b, the model's absorptivity (A), reflectivity (R), and transmissivity (T) adhere to the energy conservation equation $A + R + T = 1$. It can be observed that the transmittance is approximately zero ($T \approx 0$) due to the thickness of the model, which prevents light from penetrating through to the bottom. Therefore, it can be written as $R + A = 1$.

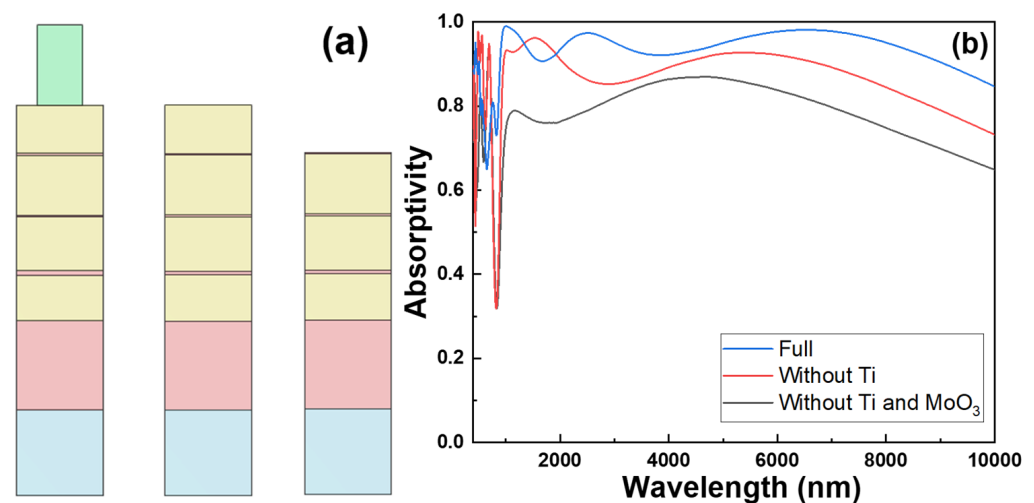


Figure 9. (a) Structure and (b) absorption spectra of the different absorbers in the range of 400–10,000 nm.

To demonstrate the significance of the h8 MoO₃ layer and the matrix square-shaped Ti, we compared the absorption spectra of three configurations: the original absorber design, the original absorber without the matrix square-shaped Ti layer, and the original absorber without both the h8 MoO₃ layer and the matrix square-shaped Ti layer, as shown in Figure 9a. The results of this comparison of the absorption spectra are presented in Figure 9b. When the investigated absorber lacked the matrix square-shaped Ti layer, its absorptivity and bandwidth significantly decreased. When the h8 MoO₃ layer and the matrix square-shaped Ti layer were both removed, the decrease in absorptivity was more pronounced. Overlaying the matrix square-shaped Ti on the MnO₃ layer significantly enhanced absorptivity in the range of 0.80 μm to 9.07 μm . This enhancement is likely attributed to the following physical phenomena:

- (1) The matrix square-shaped Ti induced SPR, especially when their size and shape are optimized. This can generate a strong local electromagnetic field in the NIR and MIR regions, enhancing light absorption.
- (2) The structure formed by the matrix square-shaped Ti on the MnO₃ layer could induce optical resonance. For instance, the size and arrangement of the matrix square-shaped Ti may cause light waves to resonate within these structures, leading to increased absorption in specific wavelength ranges.
- (3) The introduction of the matrix square-shaped Ti may alter the scattering behavior of light, enabling more effective scattering and trapping of light within the Mn-MnO₃ structure, thereby improving absorption efficiency.
- (4) The surface of the matrix square-shaped Ti can create localized electromagnetic fields, increasing the electric field intensity of incident light and thereby enhancing absorption in the MnO₃ layer. This effect is commonly observed in nanoscale structures. This result will be demonstrated in the subsequent analysis of the absorptivity distribution

of Transverse Magnetic (TM)–polarized light at normal incidence and various oblique angles, and this will be further demonstrated later.

- (5) The difference in refractive indices between Ti and MnO_3 can affect light propagation within the structure. When the matrix square-shaped Ti is overlaid on the MnO_3 layer, they may alter the dielectric constant and light propagation modes of the overall structure, thus enhancing light absorption.

When the top MnO_3 layer was removed, the absorptivity and bandwidth of the investigated absorber also significantly decreased. This result is primarily due to the absence of the MnO_3 layer, which alters the light absorption characteristics. The decrease in absorptivity may be related to the following mechanisms:

- (1) The MnO_3 layer might have provided an anti-reflective effect. Anti-reflective coatings typically work by altering the angles of incidence and reflection, thereby reducing light reflection and increasing the amount of light transmitted and absorbed. The MnO_3 layer could have created specific interference effects within the 0.80 μm to 9.07 μm wavelength range, allowing incident light to more effectively enter the material and be absorbed. When the MnO_3 layer is removed, this interference effect disappears, leading to reduced light absorption.
- (2) The presence of the MnO_3 layer may have adjusted the optical band gap of the overall structure. Anti-reflective layers are often designed to enhance the optical performance of materials within specific wavelength ranges. If the optical band gap and refractive index of the MnO_3 layer were such that incident light within the 0.80 μm to 9.07 μm range was effectively absorbed, removing the MnO_3 layer would eliminate this effect, resulting in decreased absorptivity.
- (3) The MnO_3 layer might have modified the surface or interface states of the material, which could impact light absorption characteristics. If the MnO_3 layer improved the optical properties of the surface or interface—such as reducing reflection or altering interface energy levels—removing the layer would eliminate these enhancements, leading to a decrease in absorptivity.

The investigated ultra-wideband optical absorber is a material or structure engineered to absorb light over a broad spectrum within the NIR and MIR wavelength ranges. Figure 10 illustrates the results of the analysis for electric fields, as depicted in Figure 10a, and magnetic fields, as shown in Figure 10b, across wavelengths of 1000, 2500, and 6500 nm. The electric field intensity distribution results shown in Figure 10a reveal that the overall absorptivity of the structure was relatively low at wavelengths of 1000, 2500, and 6500 nm. Furthermore, as the wavelength increased from 1000 nm to 6500 nm, there was a noticeable decrease in absorptivity throughout the entire structure. The depth of high absorptivity shifts from the topmost h9 Ti layer to halfway through the h1 Mn layer at 1000 nm, and decreases to the h2 MoO_3 layer at 6500 nm. Additionally, the magnetic field intensity distribution results depicted in Figure 10b show that, regardless of whether the wavelength is 1000, 2500, or 6500 nm, there is very high absorptivity from the top h9 layer down to halfway through the h1 Mn layer. This confirms that the thickness of the h1 Mn layer has minimal impact on absorptivity, as previously mentioned. Moreover, it reaffirms that the primary reason for achieving high absorptivity in this structure across the NIR (0.80 μm) to MIR (9.07 μm) range is indeed due to SPR.

The evolution of absorption performance for the ultra-wideband NIR and MIR meta-material absorber was assessed across a range of incident angles from 0° to 90° , under both TE and TM polarizations, as illustrated in Figure 11. The results, presented in Figure 11, reveal a significant difference in absorption performance between TE and TM polarizations. The simulation results illustrated in Figure 11 reveal how absorptivity varies with different incident angles and wavelengths. Specifically, as shown in Figure 11a, for TE polarization, the absorber demonstrated high absorptivity across a wavelength range from approximately 400 to 3000 nm, provided the incident angle was less than 40° . In contrast, when the incident angle or wavelength deviated from these ranges, there was a notable decrease in absorptivity under TE polarization. This indicates that when the TE polarization is used, there is a

strong dependency of the absorber's performance on both the wavelength and the angle of incidence within the specified conditions. Figure 11b presents the results of illuminating the system with TM-polarized light at various oblique incidence angles and normal directions. The data indicate that, when TM-polarized light is employed, high absorptivity is observed predominantly at incidence angles greater than 60° across the 400–10,000 nm wavelength range. In some instances, this high absorptivity is achieved at angles exceeding 70° . This observation explains why TE-polarized light generally does not exhibit high absorptivity over most angles and wavelengths. Despite this, the overall system maintains high absorptivity across a broader wavelength range of $0.8\ \mu\text{m}$ to $9.07\ \mu\text{m}$. These findings underscore that the high absorptivity in this system is primarily driven by TM-polarized light, reinforcing its pivotal role in enhancing the system's performance. These results highlight how polarization can dramatically influence the absorber's effectiveness, with each polarization affecting the absorption characteristics differently across various incident angles.

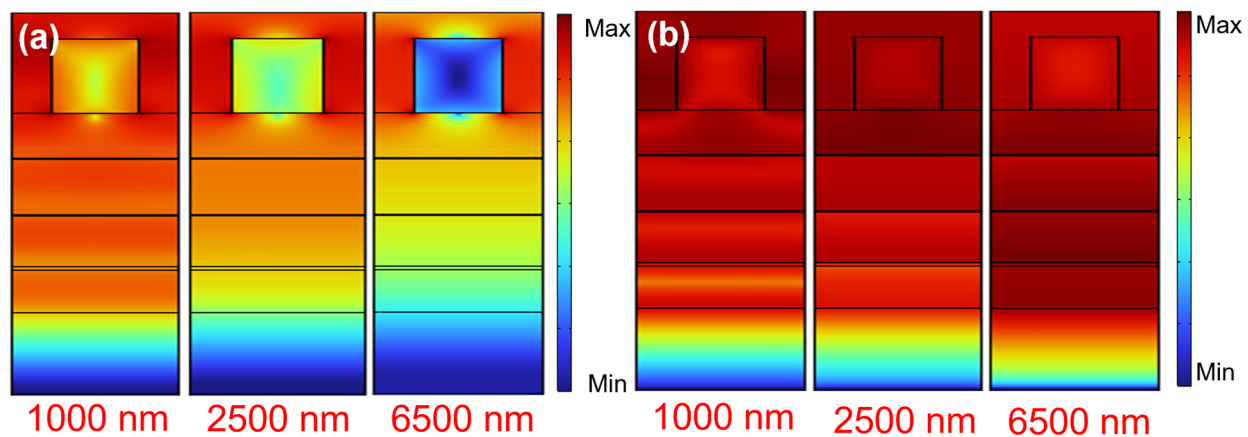


Figure 10. Distributions of (a) the electric field intensity and (b) the magnetic field intensity, with different normal incident wavelengths.

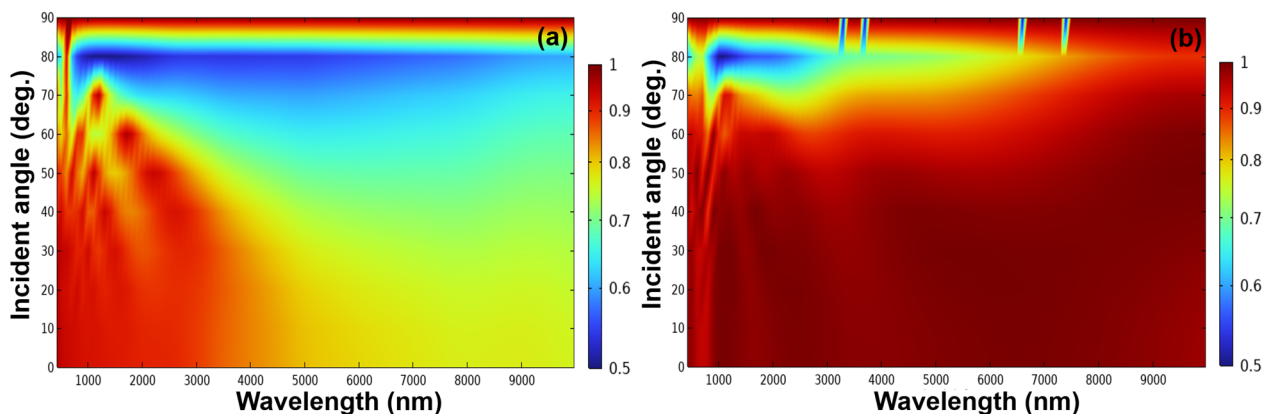


Figure 11. Absorptivity distribution of the investigated ultra-wideband NIR and MIR metamaterial absorber for the (a) TE-polarized light and (b) TM-polarized light with various oblique incidence angles and normal direction.

4. Conclusions

The simulation results demonstrated the investigated ultra-broadband absorber having high absorptivity across the NIR ($0.80\ \mu\text{m}$) to MIR ($9.07\ \mu\text{m}$) spectrum. The design featured eight alternating planar layers of Mn and MoO_3 (Mn was the bottommost h1 layer), capped with a matrix square-shaped Ti layer. This study revealed that the optimal thicknesses for each layer, from bottom to top, are as follows: h1 Mn = 310 nm, h2 MoO_3 = 160 nm, h3 Mn = 15 nm, h4 MoO_3 = 190 nm, h5 Mn = 5 nm, h6 MoO_3 = 210 nm, h7 Mn = 5 nm, h8 MoO_3 = 170 nm, and h9 Ti = 280 nm. Although variations in Mn layer thicknesses had

minimal effect on the resonance peak wavelength, they significantly influenced the overall absorptivity. Notably, a 5 nm thick h7 Mn layer created an additional absorption peak at a wavelength of 6500 nm. Changes in each MoO₃ layer thickness had a relatively minor impact on the absorber's overall efficiency. The removal of the topmost h9 Ti layer, or both the h8 MoO₃ and h9 Ti layers, resulted in a substantial reduction in both absorptivity and bandwidth. The analysis results indicate that the primary absorption mechanism is surface plasmon resonance, which effectively absorbs TM-polarized light. In contrast, TE-polarized light exhibits very low absorption across both the NIR and MIR ranges.

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