

Design and Electromagnetic Analysis of an Ultra-broadband Six-layer Planar Optical Absorber

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In this study, we present the design and numerical investigation of a six-layer planar optical absorber with ultra-broadband absorption characteristics. The proposed structure consists of alternating metallic and dielectric multilayer thin films, enabling efficient electromagnetic energy dissipation over a wide spectral range from 300 to 4000 nm. Finite element simulations using COMSOL Multiphysics (version 6.0) were performed to evaluate the optical response, including reflectance, transmittance, and absorptivity, based on the energy conservation relation $A = 1 - R - T$. The results show that the absorber achieves absorptivity exceeding 0.9 across a broad wavelength range, demonstrating strong robustness against structural variations. The broadband absorption behavior is associated with electromagnetic coupling and energy attenuation within the multilayer structure. Electric and magnetic field distributions at representative wavelengths of 320, 540, and 1920 nm reveal progressive field attenuation through the stacked layers, suggesting wavelength-dependent electromagnetic interactions and material losses. These characteristics contribute to the broadband optical response and provide useful design considerations for optical sensing and energy absorption applications. From a sensing perspective, such non-cavity-based absorption behavior provides improved spectral stability and consistent response across wavelengths, which is advantageous for broadband optical sensing applications. The fully planar configuration offers potential advantages in fabrication simplicity and structural scalability. Although experimental validation remains necessary, the simulated broadband absorption characteristics suggest possible applications in optical sensing, infrared detection, and solar energy harvesting systems.

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1. Introduction

The rapid advancement of photonic and optoelectronic technologies has significantly increased the demand for high-performance optical absorbers capable of efficiently capturing electromagnetic energy across a broad spectral range.^(1,2) Optical absorbers play a crucial role in a wide variety of applications, including solar energy harvesting, thermal emission control, infrared imaging, and sensing systems.⁽³⁾ In particular, the development of ultra-broadband absorbers has attracted considerable attention owing to their ability to maintain high absorptivity over extended wavelength regions.⁽⁴⁾ Recent studies have demonstrated that metamaterial-based absorbers can achieve near-unity absorption through engineered electromagnetic responses such as impedance matching, localized surface plasmon resonance (LSPR), and Fabry–Pérot (FP) cavity effects.^(5,6) Many high-performance designs rely on complex nanofabrication processes, which increase manufacturing cost and limit scalability.^(7,8)

In addition to energy-related applications, optical absorbers have become increasingly important in modern optical sensing systems. In photodetectors and optical sensors, absorber structures directly affect the efficiency of photon-to-electrical signal conversion by controlling light–matter interaction within the sensing layer.⁽⁹⁾ High absorptivity enhances the generation of charge carriers, thereby improving sensitivity, signal-to-noise ratio, and detection accuracy.^(9,10) For broadband sensing applications, such as environmental monitoring, biomedical diagnostics, and infrared detection, absorbers must maintain stable performance across a wide spectral range.⁽⁹⁾ Furthermore, the integration of absorber structures with sensing platforms enables enhanced spectral selectivity and tunability, allowing sensors to target specific wavelength bands. From a sensing perspective, the absorber can be regarded as a functional interface that transforms incident optical signals into measurable electrical or thermal responses, thereby bridging electromagnetic wave propagation and sensor output. Therefore, the design of broadband and structurally robust absorbers is essential for advancing next-generation optical sensing technologies.^(9,10)

To address these challenges, multilayer thin-film absorbers have emerged as a promising alternative to nanostructured metamaterials. Compared with complex nanostructures, planar multilayer configurations offer advantages such as easier fabrication, better reproducibility, and compatibility with large-area deposition techniques.^(1,8) These structures typically consist of alternating metal and dielectric layers, forming metal–insulator–metal (MIM) or extended multilayer configurations. Through the appropriate selection of material properties and layer thicknesses, it is possible to achieve strong light confinement and efficient absorption via multiple physical mechanisms, including impedance matching, interference effects, and resonant energy dissipation.^(5,6) The results of previous studies have shown that dielectric stacking layers can serve as antireflection coatings, effectively reducing surface reflection and improving energy coupling into the absorber. At the same time, metallic layers provide loss mechanisms that convert electromagnetic energy into heat, thereby enhancing overall absorption efficiency. Despite these advantages, achieving ultra-broadband absorption while maintaining structural simplicity remains a key challenge, particularly in the long-wavelength region where absorption tends to degrade.

From a modeling and design perspective, numerical simulation plays a critical role in understanding and optimizing absorber performance. Finite element method (FEM)-based tools, such as COMSOL Multiphysics, enable the accurate analysis of electromagnetic field distribution, power dissipation, and spectral response within multilayer structures.⁽²⁾ By systematically varying structural parameters, such as layer thickness and material composition, the relationship between physical mechanisms and optical performance can be established. In particular, impedance matching between the absorber and free space is widely recognized as a key condition for minimizing reflection and maximizing absorption.⁽⁵⁾ Recent findings indicate that impedance matching alone is not sufficient to guarantee high absorptivity across all wavelengths, especially in the long-wavelength regime. Instead, absorption performance is governed by a combination of factors, including resonance effects, material loss characteristics, and internal field distribution. Therefore, a comprehensive design approach that integrates electromagnetic analysis, material selection, and structural optimization is necessary to achieve stable ultra-broadband absorption.

In this study, we propose and systematically investigate a six-layer planar optical absorber consisting of alternating metallic and dielectric thin films by finite element simulations. The developed structure consists of alternating metallic and dielectric layers, designed to achieve ultra-broadband absorption over a wide wavelength range from the visible to the infrared region. The principal contribution of this work lies in the systematic characterization of layer-dependent absorption behavior in a six-layer Fe/SiO₂/Ti/TiO₂/Al₂O₃/MgF₂ structure. Unlike studies focusing primarily on maximizing absorptivity through thickness optimization, the present investigation examines the relationships among absorption bandwidth, optical impedance, electromagnetic field distribution, and wavelength-dependent energy dissipation. Particular attention is given to the long-wavelength region, where absorption degradation occurs despite favorable impedance matching. These findings provide additional physical insight into broadband absorption behavior and practical design considerations for planar optical absorbers.

2. Methodology

We employed COMSOL Multiphysics to simulate and optimize a planar optical absorber by FEM for accurate electromagnetic analysis. A structured workflow was adopted to ensure reliable results. On the basis of the absorber design, a 2D or 3D model was constructed, defining layer geometry, thickness, and spatial dimensions, with an air domain added above to represent realistic conditions. Each layer (metal, dielectric, or semiconductor) was assigned optical constants (n and k) taken from literature and experimental data. To analyze wave propagation and absorption from 300–4000 nm, input and output ports were defined. The unit cell of the investigated absorber, as shown in Fig. 1, consists of six layers: H1 Fe (100 nm), H2 SiO₂ (20 nm), H3 Ti (400 nm), H4 TiO₂ (240 nm), H5 Al₂O₃ (110 nm), and H6 MgF₂ (200 nm). The constituent materials were selected for their complementary optical properties, wavelength-dependent dispersion characteristics, material availability, and potential fabrication compatibility. Fe and Ti were employed as lossy metallic layers because their complex refractive indices enable electromagnetic energy dissipation over a broad spectral range. Their availability and established

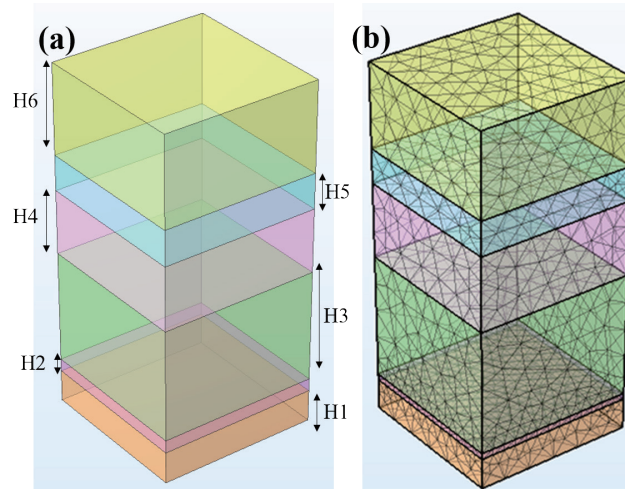


Fig. 1. (Color online) (a) Original side view and (b) mesh model of the investigated absorber.

thin-film deposition processes also make them practical material candidates. SiO_2 and Al_2O_3 provide relatively low optical loss and dielectric spacing, while TiO_2 offers a higher refractive index for controlling optical interference and electromagnetic coupling. The different refractive indices and spectral dispersion characteristics of these dielectric materials contribute to wavelength-dependent optical responses within the multilayer structure. MgF_2 was selected as a low-refractive-index layer to reduce surface reflection and improve optical coupling. In addition, the thermal characteristics and compatibility of these materials with conventional thin-film deposition techniques suggest potential fabrication advantages. However, material cost, thermal stability, and manufacturing feasibility were considered qualitatively and require further experimental evaluation.

The input port introduced incident plane waves, while the output port measured transmission. Reflectance was also calculated to determine absorption using $A(\lambda) = 1 - R(\lambda) - T(\lambda)$, where $A(\lambda)$ represents absorptivity, $R(\lambda)$ is reflectance (the portion of incident light reflected by the structure), and $T(\lambda)$ is transmittance (the portion transmitted through the structure). This relation ensures the energy conservation of the incident wave. Because the structure is periodic, Floquet periodic boundary conditions were applied to simulate an infinite array. This method captures interactions between unit cells while reducing computational cost. Finally, the model was meshed to discretize the geometry. Finer meshes were applied at metal–dielectric interfaces to accurately resolve strong field gradients and LSPR effects. Mesh convergence was confirmed by refining the mesh until absorption results stabilized.

Following the construction of the structural model, the geometry was discretized into finite elements through a meshing procedure, as shown in Fig. 1(b). The finite element mesh used in this study consists of 2468 mesh nodes, with a maximum element size of 90 nm and a minimum element size of 1.8 nm, ensuring adequate resolution for capturing fine geometric and electromagnetic features. A curvature factor of 0.6 was applied to accurately represent curved boundaries and interfaces within the multilayer structure. The discretized domain comprises

12151 tetrahedral elements, supplemented by 2822 triangular boundary elements, 328 edge elements, and 32 vertex elements, forming a comprehensive finite element representation of the computational domain. In terms of mesh quality, the minimum element quality is 0.224, while the average element quality reaches 0.6417, indicating an overall acceptable and stable mesh suitable for numerical simulation. The element volume ratio is 0.009394, reflecting a well-controlled distribution of element sizes across the structure. The total mesh volume is $3.68 \times 10^8 \text{ nm}^3$. These results confirm that the mesh is sufficiently refined to resolve localized electromagnetic field variations, particularly in regions with high field gradients. The established mesh provides a reliable and accurate foundation for subsequent finite element simulations, ensuring the precise evaluation of key optical responses, including reflectance, transmittance, and absorptivity spectra.

3. Simulation Results and Discussion

This multilayer structure integrates both metallic and dielectric components to achieve broadband optical absorption and enhanced electromagnetic field confinement across the visible-to-infrared spectrum. The thicknesses of the H1 Fe and H2 SiO₂ layers were systematically varied to evaluate their effect on optical performance. As shown in Fig. 2(a), the H1 layer thickness was adjusted from 100 to 180 nm, while the H2 layer thickness (not shown here) was varied from 20 to 100 nm, both with increments of 20 nm. The results reveal that variations in the thicknesses of the H1 and H2 layers negligibly affect the overall absorption spectrum and absorptivity. In all tested configurations, the absorptivity consistently exceeded 90% across a wide wavelength range of 300–3360 nm, indicating the high robustness of the absorber design against thickness fluctuations in these layers. This behavior suggests that the primary absorption mechanism is not dominated by the H1 and H2 layers, but rather by other layers within the structure that more strongly affect impedance matching and localized surface plasmon resonance. On the basis of these findings, the minimum tested thicknesses, 100 nm for the H1 layer and 20 nm for the H2 layer, were selected as the optimal configuration. These minimum investigated thicknesses of 100 nm for H1 and 20 nm for H2 were therefore selected to maintain broadband absorption while reducing the total structural thickness. The thicknesses of the H3 Ti and H4 TiO₂ layers were systematically varied to investigate their effect on optical performance.

As illustrated in Figs. 2(b) and 2(c), increasing the thickness of either the Ti or TiO₂ layer produces a minimal change in absorptivity for wavelengths below approximately 2000 nm. In this shorter wavelength region, the absorptivity remains nearly invariant, indicating that the absorption mechanism is relatively insensitive to thickness variations of these layers. However, for wavelengths exceeding approximately 2000 nm, a clear dependence emerges: the absorptivity increases with the thicknesses of both the Ti and TiO₂ layers. This enhancement becomes more pronounced at longer wavelengths, suggesting improved impedance matching and stronger electromagnetic field confinement within the structure in the infrared regime. Specifically, when the H3 (Ti) layer thickness is increased from 320 to 400 nm, the effective absorption bandwidth (defined as absorptivity > 0.900) expands from 300–3140 to 300–3360 nm. Similarly,

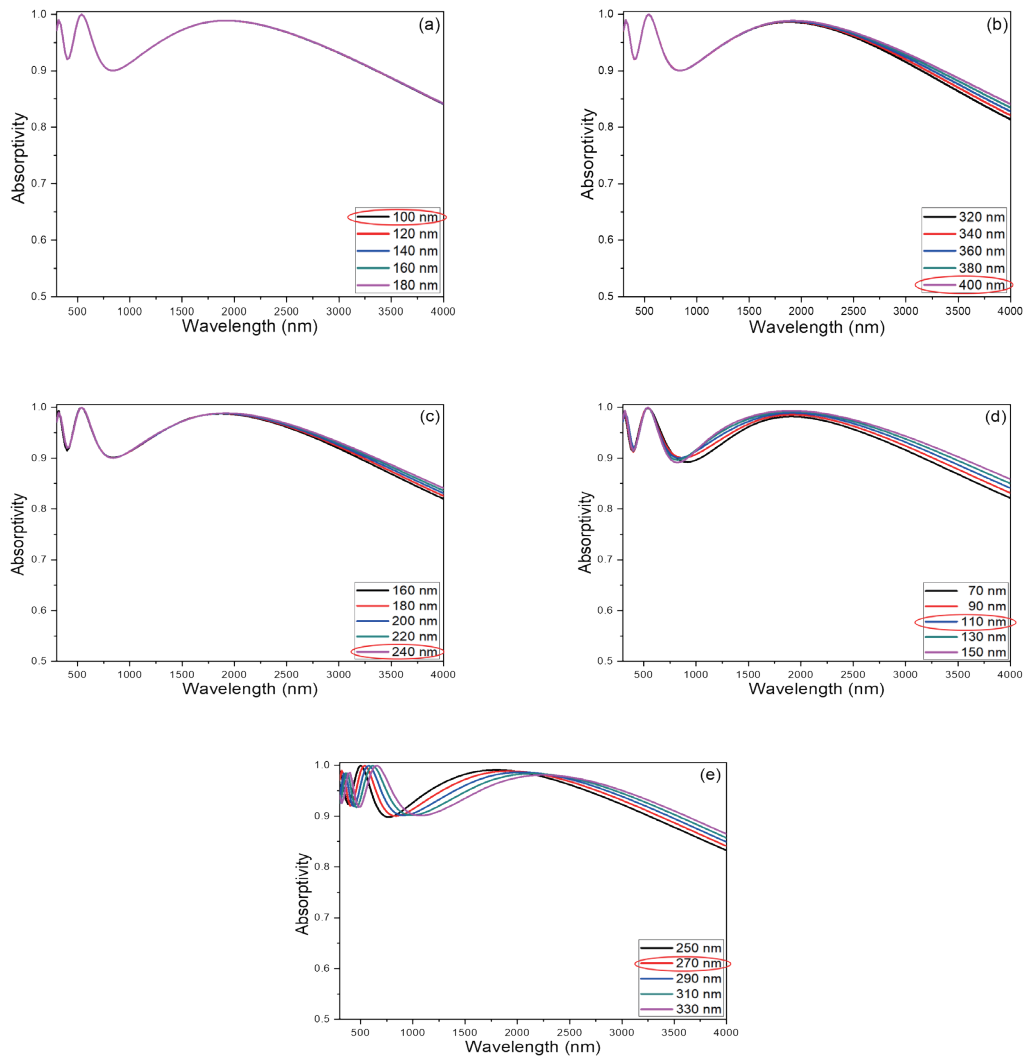


Fig. 2. (Color online) Effects of different thicknesses of (a) H1 Fe, (b) H3 Ti, (c) H4 TiO₂, (d) H5 Al₂O₃, and (e) H6 MgF₂ layers on absorption characteristics of the investigated absorbers.

increasing the H4 (TiO₂) layer thickness from 160 to 240 nm extends the bandwidth from 300–3160 to 300–3360 nm. Despite this notable bandwidth enhancement, the average absorptivity within the >0.900 range shows only a marginal improvement, increasing slightly from 95.2 to 95.3%. This behavior indicates that the H3 and H4 layers play a more significant role in tuning long-wavelength absorption rather than enhancing peak absorptivity.

The observed trend can be attributed to the increased optical path length and improved coupling of incident electromagnetic waves into the structure, which strengthens absorption in the infrared region. From a design perspective, these results highlight a trade-off between bandwidth extension and structural thickness, where thicker layers improve long-wavelength performance while offering only limited gains in overall absorption efficiency. Finally, the effect

of the H6 MgF_2 layer thickness on the absorption spectra was investigated by varying the thickness from 250 to 330 nm in increments of 20 nm. The results show that increasing the H6 layer thickness leads to a clear redshift in the overall absorption spectrum. The effective absorption bandwidth (absorptivity > 0.9) expands from 300–3220 nm at 250 nm to 300–3600 nm at 330 nm. This redshift can be attributed to the increased optical path length and phase accumulation within the multilayer structure. As a low-refractive-index dielectric, the MgF_2 layer acts as an antireflection and impedance-transition layer, improving electromagnetic wave coupling at longer wavelengths and shifting the response toward the infrared region.

Enhanced light–matter interaction at metal–dielectric interfaces supports stronger LSPR effects, contributing to broadband energy dissipation. However, the average absorptivity within the high-absorption bandwidth does not increase monotonically. An optimal condition occurs at a thickness of 270 nm, where the average absorptivity reaches 95.3%. Beyond this thickness, although the bandwidth continues to expand, the average absorption slightly decreases, indicating a trade-off between bandwidth and efficiency. This suggests that excessive dielectric thickness may weaken field confinement or reduce effective coupling. Overall, the MgF_2 layer thickness serves as a key parameter for tuning and optimizing broadband absorption performance. The optimization procedure was based on systematic parametric sweeps of individual layer thicknesses within predefined ranges. The selection criteria included broadband absorptivity, effective absorption bandwidth, and structural thickness. Because the investigated material combination exhibited favorable optical performance, alternative material combinations and global optimization algorithms were not considered. Therefore, the selected structural parameters should be regarded as a favorable design within the investigated parameter ranges rather than a globally optimized solution.

Figure 3(a) illustrates the optical impedance characteristics of the proposed multilayer absorber under optimized structural conditions. The black and red curves represent the real and imaginary parts of the normalized impedance, respectively. In general, when the real part approaches unity and the imaginary part approaches zero, the structure achieves near-perfect impedance matching with free space, thereby minimizing reflection and promoting efficient

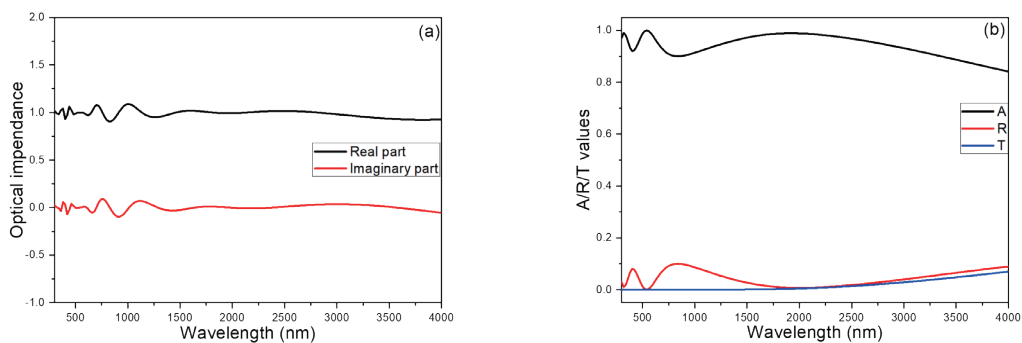


Fig. 3. (Color online) (a) Optical impedance and (b) optical absorption, reflection, and transmission characteristics of the investigated absorber.

energy coupling into the absorber. From the results, it is observed that the impedance matching condition is well maintained over a broad wavelength range. In particular, even when the wavelength extends to approximately 4000 nm, the real part of the impedance remains close to 1 while the imaginary part remains near 0. This behavior indicates that impedance mismatch is not the dominant factor responsible for the degradation of absorptivity at longer wavelengths (beyond approximately 3300 nm). In other words, although the impedance condition still satisfies near-ideal matching, the absorption performance begins to decline, suggesting the presence of other governing mechanisms. A more detailed analysis can be obtained by examining the reflection and transmission spectra. As shown in Fig. 3(b), when the wavelength exceeds approximately 2500 nm, both reflectance and transmittance increase simultaneously.

This phenomenon directly leads to the observed reduction in absorptivity, since the incident energy is no longer effectively dissipated within the structure. In conventional multilayer absorbers, metallic layers typically act as reflective backplanes, enhancing absorption by preventing transmission and promoting multiple internal reflections. However, in the present multilayer configuration, the optical response at longer wavelengths deviates from this behavior. Specifically, the multilayer structure exhibits a partial antireflection effect in the long-wavelength region ($\lambda > 2500$ nm). Instead of being confined and absorbed, a portion of the incident light is reflected without sufficient interaction with lossy materials, while another portion propagates through the structure, leading to a concurrent rise in both reflection and transmission. This indicates that the internal resonant and plasmonic loss mechanisms become less effective at longer wavelengths, reducing the overall energy dissipation capability. Therefore, the decrease in absorptivity in the long-wavelength regime is primarily attributed to the simultaneous increase in reflection and transmission, rather than to impedance mismatch.

This finding highlights that, although impedance matching is a necessary condition for achieving high absorption, it is not sufficient on its own. The overall performance of ultra-broadband absorbers must also consider wavelength-dependent resonant behavior, material loss characteristics, and structural design to ensure sustained light confinement and dissipation across the entire spectral range. An important finding is that favorable optical impedance matching does not necessarily guarantee high absorptivity over the entire investigated spectrum. Although the normalized impedance remains close to the ideal matching condition at longer wavelengths, the simultaneous increase in reflectance and transmittance reduces the effective electromagnetic energy dissipation. This observation highlights the importance of evaluating both impedance matching and internal energy-loss characteristics when optimizing broadband multilayer absorbers. Therefore, the proposed design provides useful insight into the physical limitations of broadband absorption beyond conventional structural thickness optimization.

Figures 4(a) and 4(b) illustrate the electric and magnetic field distributions at representative wavelengths of 320, 540, and 1920 nm, respectively. The field intensities generally decrease from the upper region toward the lower layers, indicating progressive electromagnetic attenuation within the multilayer structure. This behavior suggests that the incident electromagnetic energy interacts with the metallic and dielectric layers, where material absorption and interfacial electromagnetic coupling contribute to the broadband optical response. Although field enhancement near metal–dielectric interfaces may be associated with

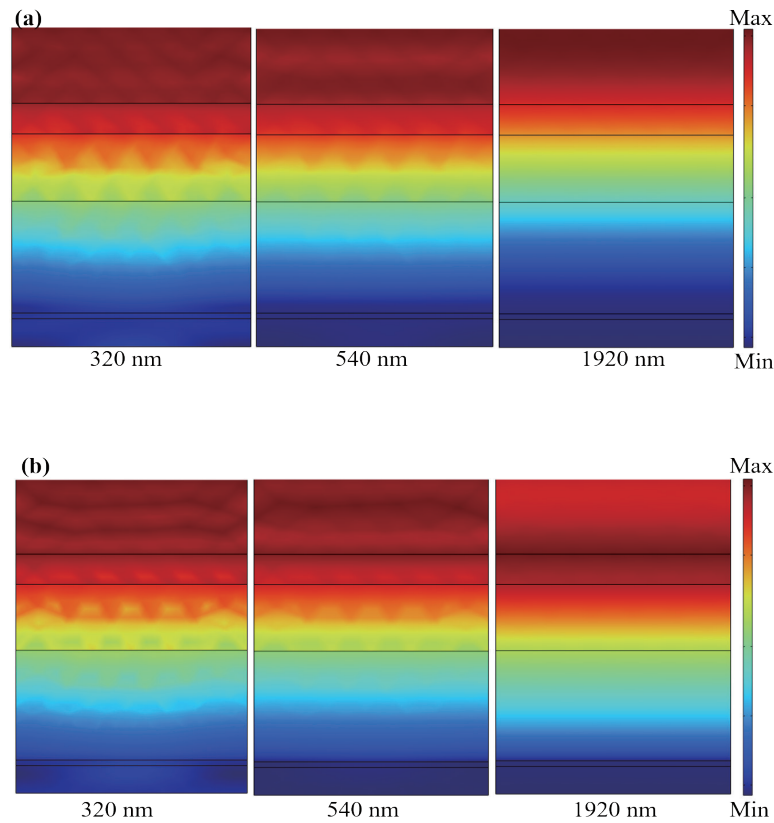


Fig. 4. (Color online) Distributions of the (a) electric and (b) magnetic field intensities of the absorptivity at different wavelengths.

plasmonic effects, the present field distributions alone cannot conclusively establish LSPR as the dominant absorption mechanism. Therefore, the broadband absorption is more appropriately interpreted in terms of wavelength-dependent electromagnetic coupling, material losses, and multilayer interference effects. In addition, our simulation results (not shown here) indicate that a Fe layer thicker than 80 nm is required to achieve near-total reflection. Therefore, a thickness of 100 nm was selected as the optimal design parameter to ensure complete reflectivity and stable optical confinement. This reflective metallic layer effectively suppresses transmission and reinforces the overall absorption by redirecting residual electromagnetic energy back into the upper absorbing layers, thereby enhancing the overall energy utilization within the structure. The combined effects of LSPR-induced localized field enhancement and the reflective function of the Fe layer enable efficient broadband absorption without relying on conventional cavity resonance mechanisms.

Figure 5 presents the simulated solar absorption efficiency under the AM1.5 illumination condition. The results show that the average absorptivities in the wavelength ranges of 300–400, 400–700, 700–1400, 1400–3000, and 3000–4000 nm are 95.2, 96.5, 91.6, 94.6, and 88.1%, respectively. The overall average absorptivity across the entire spectral range from 300 to 4000 nm reaches 94.6%, indicating excellent broadband absorption performance. The absorber

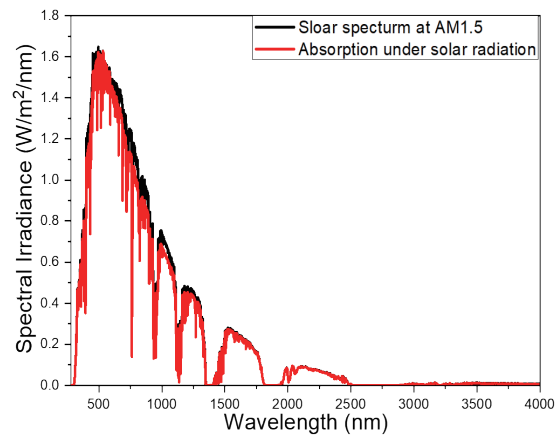


Fig. 5. (Color online) Absorption spectrum of the designed absorber.

Table 1
Optical characteristics of the proposed and previously reported broadband optical absorbers.

Study	Structure	Wavelength range (nm)	Average absorptivity	Validation
Ref. 11	TiN/SiO ₂ multilayer	300–2500	93.5% (3 cells)	Numerical
Ref. 12	Eight-layer planar films	350–1970 (approx.)	96.76%	Experimental and numerical
Ref. 13	Six-layer planar films	300–2500	98.51% (calculated)	Experimental and numerical
Present work	Fe/SiO ₂ /Ti/TiO ₂ /Al ₂ O ₃ /MgF ₂	300–4000	94.6%	Numerical

Note: The reported wavelength ranges and average absorptivities are based on different evaluation intervals and may not be directly comparable. Literature values should be examined against the original articles before submission.

exhibits high efficiency across the UV, visible, and near-infrared regions, which correspond to the major portion of solar energy in the AM1.5 spectrum. The slightly reduced absorptivity in the 3000–4000 nm range is attributed to weaker material loss and less effective light–matter interaction at longer wavelengths. The high absorption in the UV–visible region (300–700 nm) is mainly associated with strong LSPR at metal–dielectric interfaces, while the broadband response in the near-infrared region is maintained through impedance matching and gradual energy dissipation within the multilayer structure. Note that the present results are based entirely on numerical simulations, and the predicted optical performance has not yet been experimentally verified. Therefore, the practical absorption efficiency, fabrication tolerance, and sensing applicability require further experimental investigation. Future work will involve thin-film fabrication and optical characterization to validate the simulated absorption characteristics.

To further evaluate the performance of the proposed absorber, its optical characteristics were compared with those of previously reported broadband absorbers, as summarized in Table 1. Although several reported structures achieve higher average absorptivity, their investigated wavelength ranges, structural configurations, and validation methods differ. The proposed six-layer absorber achieves an average absorptivity of 94.6% over the wavelength range of 300–4000 nm, demonstrating broadband optical performance within a fully planar configuration. Therefore, the main contribution is not superior absorption efficiency alone but the combined investigation of broadband absorption, layer-dependent spectral characteristics, and electromagnetic energy dissipation. Since the reported absorption averages were evaluated over different wavelength intervals, direct numerical comparisons should be interpreted with caution.

4. Conclusions

In this study, we designed and numerically investigated a six-layer fully planar optical absorber using the finite element method. The proposed structure demonstrated ultra-broadband absorption performance over the wavelength range of 300–4000 nm, with an average absorptivity of 94.6% under AM1.5 conditions. The results of electromagnetic field analysis indicated progressive field attenuation within the multilayer structure, suggesting that broadband absorption is associated with material losses, interfacial electromagnetic coupling, and multilayer optical interactions. Although the field distributions provided insight into electromagnetic energy propagation, further quantitative analyses of power-loss density and localized field enhancement are required to conclusively identify the contribution of specific plasmonic resonance mechanisms. Parametric analysis results revealed that structural parameters, particularly the dielectric layer thickness, play a critical role in tuning spectral response and bandwidth. The selected design provided a favorable balance between broadband absorption and absorption efficiency within the investigated parameter ranges, while the simulation results indicated relatively low sensitivity to certain layer-thickness variations. Furthermore, the fully planar configuration may offer potential advantages in fabrication simplicity and scalability, although these characteristics have not yet been experimentally verified. The main contribution is the identification of layer-dependent spectral responses and the clarification of the relationship between optical impedance matching and actual energy dissipation. In particular, the long-wavelength absorption degradation demonstrated that favorable impedance matching alone is insufficient to maintain high absorptivity. These findings provide practical guidance for optimizing broadband planar absorbers while balancing absorption bandwidth, structural thickness, and optical performance.

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