

Design of a Simple Three-layer Broadband Optical Absorber with a Hollow Cylindrical Resonator for Optical Sensing Applications

Yong Du,¹ Yu-Chen Tsai,² Hsiao-Chi Hsu,² Wei-Min Chi,^{3,4*} and Cheng-Fu Yang^{2,5**}

¹School of Ocean Information Engineering, Jimei University, Xiamen 361021, China

²Department of Chemical and Materials Engineering, National University of Kaohsiung, Kaohsiung 811, Taiwan

³Elite Engineers College, Dongguan University of Technology, Dongguan 523808, China

⁴Lunghwa University of Science and Technology, Department of Electronic Engineering, Taoyuan City 333, Taiwan

⁵Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan

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Simple three-layer broadband optical absorbers have attracted considerable attention because of their potential applications in solar-energy harvesting, thermal emitters, and high-performance optical sensing systems. In particular, broadband absorbers can significantly enhance light–matter interaction, making them promising candidates for improving the performance of optical sensors and ultraviolet photodetectors. In this study, a simple three-layer optical absorber composed of a W ground plane, an Al₂O₃ dielectric spacer, and a top W square resonator containing a centrally hollow cylindrical cavity was designed and analyzed using the finite element method implemented in COMSOL Multiphysics. The effects of structural parameters, including the thicknesses of the W and Al₂O₃ layers, the dimensions of the top resonator, and the radius of the hollow cylindrical cavity, were systematically investigated to optimize the broadband absorption performance. In addition, optical impedance, electric field distribution, magnetic field distribution, and angular absorption characteristics under both transverse electric and transverse magnetic polarizations were analyzed to clarify the underlying absorption mechanisms. The optimized absorber exhibits absorptivity exceeding 90% over the wavelength range of 200–1760 nm, together with excellent angular stability under oblique incidence. Owing to its simple structure, broadband absorption capability, and robust optical performance, the proposed design is a promising candidate not only for solar-energy harvesting but also for broadband optical sensors, ultraviolet photodetectors, and other integrated optoelectronic sensing devices.

1. Introduction

The rapid development of renewable energy technologies, infrared camouflage, thermal photovoltaics, and solar-energy harvesting has significantly increased the demand for high-performance optical absorbers capable of efficiently capturing electromagnetic waves over

*Corresponding author: e-mail: jcewm@gm.lhu.edu.tw

**Corresponding author: e-mail: cfyang@nuk.edu.tw

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broad spectral ranges.^(1–4) Compared with conventional coatings, metamaterial-based optical absorbers provide superior absorption performance through impedance matching, localized surface plasmon resonance, Fabry–Pérot cavity resonance, and magnetic resonance mechanisms. These unique electromagnetic characteristics enable the realization of near-unity absorption while maintaining compact dimensions and design flexibility. Consequently, broadband optical absorbers have attracted considerable attention for applications in solar energy conversion, photothermal systems, thermal emitters, infrared stealth technology, and energy-efficient optoelectronic devices.^(1–5) Recent studies have demonstrated that carefully engineered multilayer or planar metamaterial structures can simultaneously achieve wide operating bandwidth, polarization insensitivity, and excellent incident-angle tolerance. Our previous studies have also demonstrated that planar metamaterial absorbers can achieve broadband optical sensing performance from the visible to infrared regions through optimized multilayer structures, providing an effective approach for next-generation energy harvesting and optical sensing devices.^(6–8)

Recent studies have further demonstrated broadband absorber designs extending from the ultraviolet and visible regions to the near-infrared and infrared ranges.^(9–13) Importantly, the experimental fabrication and optical characterization of multilayer absorbers have demonstrated good agreement between the measured and simulated absorption spectra, supporting the practical feasibility of simulation-guided broadband absorber design.⁽⁹⁾ These advances provide an important experimental basis for the development of broadband absorbers for optical sensing and energy-harvesting applications. Aside from energy applications, broadband optical absorbers have become increasingly important in optical sensing systems because they significantly enhance light–matter interaction and improve the sensitivity of photodetectors and optical sensors.^(3,4,14) Efficient absorption increases the number of generated carriers, thereby improving responsivity, detectivity, signal-to-noise ratio, and overall sensing performance. In particular, ultraviolet (UV) photodetectors require high optical response in the deep-ultraviolet and near-ultraviolet spectral regions for applications such as environmental monitoring, flame detection, space communications, and biological analysis.^(14–16) Such devices have found widespread applications in environmental monitoring, flame detection, space communications, biological analysis, industrial inspection, and military warning systems.^(14–16) Therefore, designing broadband optical absorbers with high absorption efficiency extending from the ultraviolet to the near-infrared region has become an important research topic. Recent investigations have further shown that integrating metamaterial absorbers with semiconductor photodetectors can effectively improve optical coupling efficiency and device performance. These advances demonstrate the significant potential of optical absorbers in next-generation multifunctional sensing platforms.^(6,14,15)

Various numerical methods have been employed to investigate the electromagnetic behavior of optical absorbers before fabrication. Among them, the finite-difference time-domain (FDTD) method is one of the most widely adopted techniques because it directly solves Maxwell's equations in the time domain and provides accurate broadband electromagnetic responses.⁽¹¹⁾ Another commonly used approach is the finite element method (FEM), which offers excellent numerical accuracy for complex multilayer geometries and arbitrary boundary conditions.

Commercial software packages based on FEM, such as COMSOL Multiphysics, have become powerful design tools for optimizing optical absorbers because they allow efficient multiphysics coupling and flexible geometric parameterization.^(17–19) Other frequently used electromagnetic simulation software programs include ANSYS Lumerical FDTD Solutions, CST Studio Suite, ANSYS HFSS, and MEEP, each providing different advantages for specific optical and electromagnetic applications. Among these simulation platforms, COMSOL Multiphysics is particularly suitable for multilayer metamaterial optimization because it enables the precise evaluation of electric field distributions, magnetic field distributions, impedance matching, absorption spectra, and resonance mechanisms. Therefore, COMSOL Multiphysics is adopted in this study to optimize the proposed absorber structure.

In this work, a simple three-layer broadband optical absorber is proposed to achieve absorptivity exceeding 0.9 over an ultrawide wavelength range from 200 to 1760 nm. The proposed structure consists of a tungsten (W) continuous metallic substrate, an intermediate aluminum oxide (Al_2O_3) dielectric layer, and a top W square resonator containing a centrally hollow cylindrical cavity. Compared with previously reported multilayer metamaterial absorbers, the proposed design exhibits a much simpler configuration while maintaining excellent broadband absorption characteristics. Using COMSOL Multiphysics based on the finite element method, we systematically investigated the effects of the thicknesses of the W substrate and Al_2O_3 dielectric layer, together with the geometric parameters of the top W resonator, including its side length and the diameter of the hollow cylindrical cavity. The optimized absorber exhibits excellent broadband absorption covering the ultraviolet, visible, and near-infrared spectral regions, making it a promising candidate for broadband optical sensing, ultraviolet photodetection, solar-energy harvesting, and integrated optoelectronic devices.^(6–14)

2. Experimental Procedure

The proposed geometry was selected by considering broadband absorption, structural simplicity, and fabrication feasibility. A three-layer metal–dielectric–metal configuration was adopted because the top metallic resonator, dielectric spacer, and metallic ground plane can provide the essential electric and magnetic resonances required for effective impedance matching, while avoiding the increased fabrication complexity and accumulated dimensional tolerances associated with multilayer structures. W was selected as the metallic material because its relatively high optical loss over a broad spectral range facilitates electromagnetic energy dissipation, while its high melting point and good thermal stability are advantageous for practical optical and energy-related applications. In addition, W is compatible with conventional thin-film deposition and semiconductor fabrication processes. For the top resonator, a square geometry was adopted because of its structural simplicity and in-plane symmetry, which are beneficial for stable optical responses and straightforward fabrication. The central hollow cylindrical cavity introduces an additional inner metal–dielectric boundary and modifies the effective resonant current path, thereby enhancing the localized electric field confinement and coupling with the dielectric spacer. This mechanism is consistent with the field distributions discussed in Fig. 1, where electric field enhancement occurs around the resonator edges and the inner cavity surface,

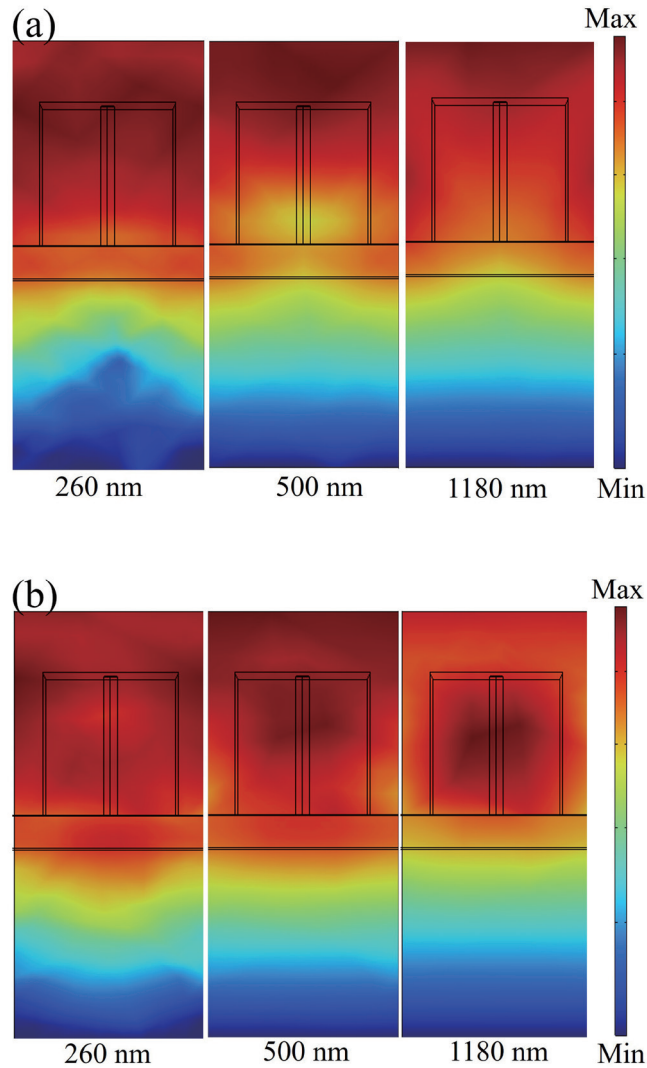


Fig. 1. (Color online) Intensity distributions of (a) electric and (b) magnetic fields at 260, 500, and 1180 nm for the final absorber configuration with $h_1 = 300$ nm, $h_2 = 50$ nm, $h_3 = 110$ nm, $w = 200$ nm, and $r = 10$ nm.

while magnetic field confinement is mainly observed within the Al_2O_3 spacer. Therefore, the proposed $\text{W}/\text{Al}_2\text{O}_3/\text{W}$ square resonator with a central hollow cavity was selected as a practical configuration that balances broadband absorption performance, physical simplicity, and fabrication feasibility.

Figure 2 illustrates the proposed optical absorber structure. This proposed structure consists of a simple three-layer configuration comprising a continuous W ground plane with a thickness of h_1 , an Al_2O_3 dielectric spacer with a thickness of h_2 , and a top W periodic square resonator array with a thickness of h_3 . Each square resonator incorporates a centrally hollow cylindrical cavity, which is designed to enhance broadband light absorption through optimized electromagnetic resonance and impedance matching. The absorber is constructed on the basis of

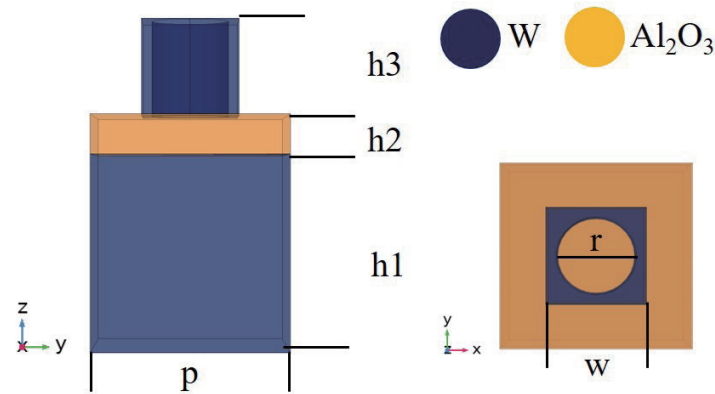


Fig. 2. (Color online) Structure of the investigated optical absorber.

a periodic square unit cell with a fixed lateral period (p) of 300 nm to ensure structural periodicity. The thicknesses of the bottom $h1$ W ground plane and the $h2$ Al_2O_3 dielectric spacer are set to 300 and 35 nm, respectively, while the height of the top $h3$ W resonator is fixed at 210 nm. The side length w of the top square resonator is initially set to 200 nm, and the radius (r) of the centrally hollow cylindrical cavity is initially fixed at 10 nm. To systematically evaluate the optical performance, a comprehensive parametric study was conducted over a broad wavelength range from 200 to 3000 nm, covering the ultraviolet, visible, and near-infrared regions.

The periodicity (p) was fixed at 300 nm throughout the simulations. The thickness of the $h1$ W ground layer was varied from 50 to 300 nm with a step size of 50 nm to ensure the sufficient suppression of optical transmission. The thickness of the $h2$ Al_2O_3 dielectric spacer was swept from 10 to 110 nm in 10 nm increments to investigate its influence on optical cavity effects and phase modulation. Furthermore, the thickness of the top W resonator ($h3$) was varied from 110 to 210 nm with a step size of 10 nm to examine its effects on light confinement and plasmonic resonance enhancement. The width (w) of the $h3$ W cube was swept from 100 to 200 nm in 10 nm increments, while the radius (r) of the central cylindrical hole was varied from 10 to 70 nm with a step size of 10 nm to evaluate their combined effect on broadband absorption performance. The optical response of the proposed absorber was investigated using COMSOL Multiphysics (version 6.0). The electromagnetic field distributions were calculated by solving Maxwell's equations with FEM. The discretized model consists of 90,680 mesh vertices, 17745 tetrahedral elements, 1834 triangular boundary elements, 288 edge elements, and 32 vertex elements, resulting in a total of 17785 finite elements and providing a high-resolution spatial representation of the proposed structure.

The mesh quality was carefully evaluated, yielding a minimum element quality of 0.1679 and an average element quality of 0.6465, which indicate a stable and reliable mesh for electromagnetic simulations. Furthermore, the element volume ratio was 1.97×10^{-5} and the total mesh volume was $6.03 \times 10^7 \text{ nm}^3$. To ensure numerical reliability, mesh convergence was examined by progressively refining the computational mesh and comparing the resulting absorption spectra. The mesh was considered sufficiently converged when further refinement

produced no appreciable change in the calculated absorption spectrum. The final mesh contained 17785 finite elements with an average element quality of 0.6465, providing a suitable balance between numerical accuracy and computational cost. In addition, sensitivity to the principal geometrical parameters was systematically investigated by varying h_1 , h_2 , h_3 , w , and r , as presented in Fig. 3. These parametric results demonstrate the dependence of the broadband absorption response on the structural dimensions and provide the basis for selecting the optimized geometry.

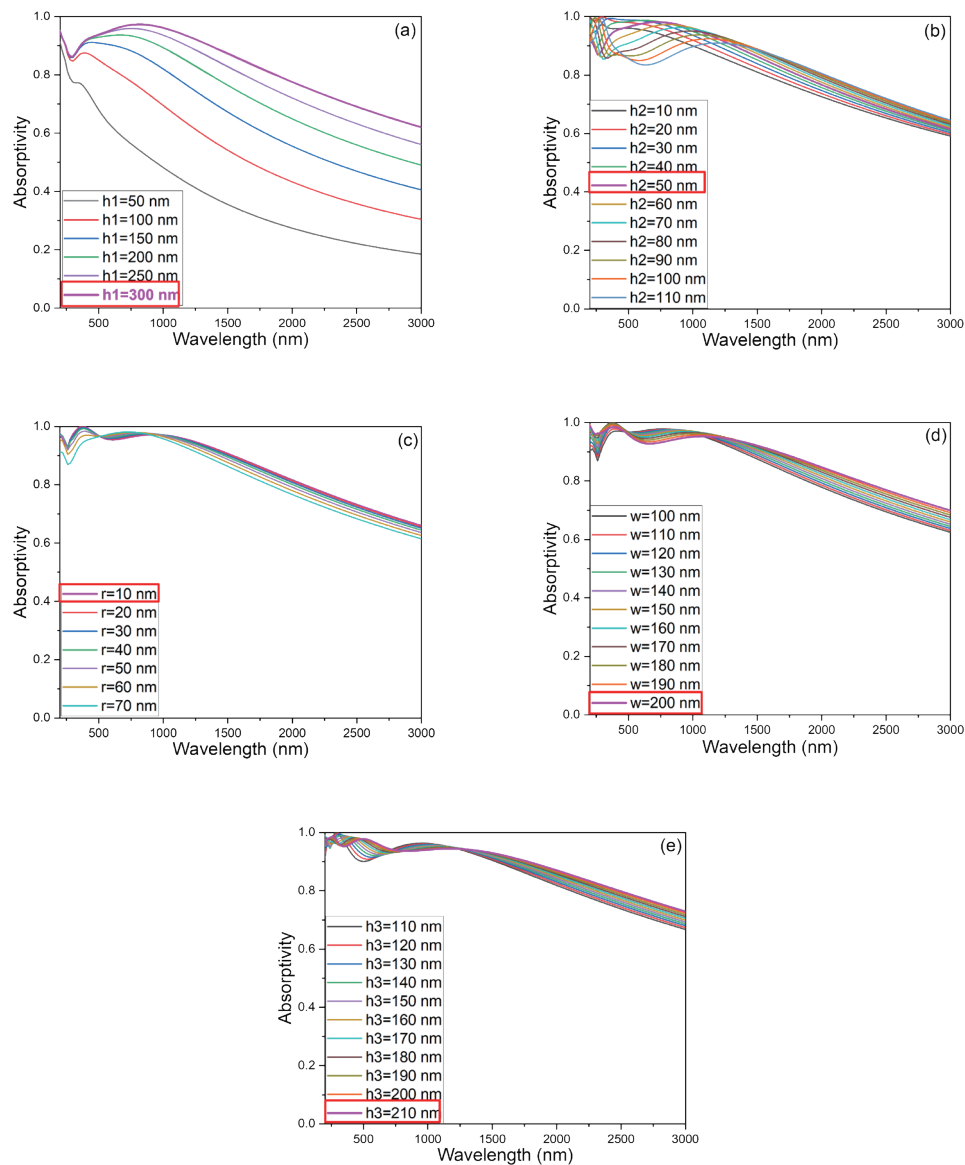


Fig. 3. (Color online) Effects of different structure parameters on absorption characteristics of the designed absorber: (a) thickness of h_1 layer, (b) thickness of h_2 layer, (c) r of central hollow cylinder, (d) width of top h_3 W resonator, and (e) thickness of h_3 layer.

Although the present study focuses on numerical design and optimization, the proposed absorber can be fabricated using established semiconductor and thin-film fabrication processes. In our previous study, a multilayer optical absorber was successfully fabricated by physical vapor deposition, and its measured absorption spectrum showed good agreement with the COMSOL simulation results.⁽⁹⁾ This previous experimental validation demonstrates the practical reliability of the numerical design approach. For the present W/Al₂O₃/W structure, the continuous W and Al₂O₃ layers can be deposited using conventional thin-film deposition techniques, while the top W resonator and hollow cylindrical cavity can be defined using standard lithography and etching processes. In practical fabrication, deviations in layer thickness and lateral dimensions may cause slight shifts in resonance wavelength and absorption bandwidth; therefore, fabrication tolerance should be carefully controlled.

The fabrication of the central hollow cylindrical cavity with a designed radius of approximately 10 nm represents the major practical challenge of the proposed structure. For prototype fabrication, high-resolution electron-beam lithography or focused-ion-beam patterning followed by appropriate dry etching can be employed to define such nanoscale features. Dimensional deviations in cavity radius, resonator width, and layer thickness, as well as surface roughness introduced during deposition and etching, may slightly shift or broaden the resonant absorption features because of changes in local electromagnetic confinement. Therefore, the careful control of pattern dimensions and surface morphology is required. For large-area integration, direct electron-beam or focused-ion-beam processing is less attractive because of its relatively low throughput; nanoimprint lithography using a high-resolution master pattern followed by thin-film deposition and etching provides a more scalable fabrication route. Future experimental work will further quantify these fabrication tolerance and surface roughness effects.

For practical deployment, thermal stability, mechanical flexibility, and compatibility with semiconductor platforms should also be considered. The W/Al₂O₃/W material system is compatible with established thin-film deposition and semiconductor processing techniques, facilitating potential integration with photodetectors and other optoelectronic devices. However, thermal stress may modify material properties and interfacial conditions, potentially shifting the resonant absorption characteristics. Mechanical deformation may similarly alter the resonator dimensions and periodicity; therefore, the present rigid configuration is more suitable for planar semiconductor platforms than for flexible devices. Also, future work will evaluate temperature-dependent optical performance, mechanical deformation effects, and device-level integration to establish the long-term reliability of the proposed absorber under practical operating conditions.

3. Results and Discussion

First, the effect of the thickness of the bottom h_1 W ground layer on the absorption performance was investigated. Increasing the thickness of the W ground layer progressively improves the overall absorptivity, as illustrated in Fig. 3(a). The most pronounced improvement occurs near 400 nm. In this region, the absorption valley becomes shallower with increasing h_1 , leading to higher absorptivity. In addition, the high-absorption bandwidth over the 400–3000

nm wavelength range gradually broadens as the W layer becomes thicker, indicating improved broadband absorption performance. This behavior can be attributed to the enhanced blocking of electromagnetic transmission by the thicker metallic ground layer, which increases the interaction time of the incident light within the absorber and promotes stronger impedance matching and resonant energy dissipation. Once the W layer reaches a sufficient thickness, nearly all transmitted light is effectively suppressed, allowing the incident electromagnetic energy to be more efficiently confined and dissipated within the absorber. Therefore, $h_1 = 300$ nm was selected as the optimal thickness for the subsequent simulations.

Next, the effect of the h_2 Al_2O_3 dielectric spacer on the absorption performance was investigated. Figure 3(b) demonstrates the strong dependence of the absorption spectrum on the Al_2O_3 spacer thickness. This parameter controls the optical cavity resonance and phase matching between the top resonator and the bottom W ground layer. When the h_2 layer is relatively thin, the absorptivity in the 200–500 nm wavelength range is notably enhanced. However, the absorptivity decreases below 90% at longer wavelengths, falling below this threshold at approximately 1000 nm, which limits the broadband absorption performance. In contrast, increasing the spacer thickness shifts the resonance toward longer wavelengths, resulting in a pronounced absorption valley in the 500–1000 nm region where the absorptivity is significantly lower than 90%. For $h_2 = 40, 50$, and 60 nm, although a narrow wavelength range below 500 nm exhibits absorptivity slightly below 90%, this deficiency can be effectively compensated by the subsequent optimization of the top resonant structure. Among these three cases, $h_2 = 50$ nm provides the most balanced performance, maintaining relatively high absorptivity across the entire spectrum while exhibiting superior absorption characteristics below 800 nm with only a shallow absorption dip. Therefore, $h_2 = 50$ nm was selected as the optimal dielectric spacer thickness for the subsequent structural optimization.

To further verify the necessity of the central hollow cylindrical cavity, an additional reference simulation was performed for $r = 0$ nm, corresponding to a solid square W resonator without the cavity. The $r = 0$ structure did not exhibit a broadband wavelength region with absorptivity exceeding 0.9, whereas introducing the hollow cavity with $r = 10$ nm produced the desired broadband high-absorption response. Because the no-cavity case did not satisfy the high-absorption criterion, its absorption spectrum was not included in Fig. 3(c) to maintain the clarity of the parametric comparison. Note also that the monotonic trend observed for $r = 10$ –70 nm cannot be directly extrapolated to $r = 0$, because eliminating the cavity removes the inner metal–dielectric interface and changes the electromagnetic resonance configuration of the top W resonator. Physically, the hollow cavity introduces an additional metal–dielectric boundary that modifies the local electromagnetic field distribution and effective resonant current path. The inner cavity surface provides additional sites for electric field localization, thereby strengthening the coupling between localized resonances and the underlying metal–dielectric cavity. This behavior is consistent with the electric field distributions in Fig. 1, where pronounced field enhancement is observed around the inner surface of the hollow cavity. The resulting resonant coupling improves effective impedance matching with free space, suppresses optical reflection, and consequently broadens the high-absorption wavelength region. Therefore, the $r=10$ nm cavity was retained because it provides a clear broadband absorption advantage over the no-

cavity configuration and confirms the functional role of the hollow cylindrical cavity in the proposed absorber. Reducing the cavity radius enhances the short-wavelength absorptivity [Fig. 3(c)]. In particular, a smaller r produces a shallower absorption valley below 500 nm and consequently broadens the wavelength range with absorptivity exceeding 90%.

The effects of the width (w) of the top $h3$ W resonator on the absorption characteristics were investigated, and the corresponding results are presented in Fig. 3(d). As the width of the $h3$ layer increases, the broadband absorption performance is significantly improved. When $w \geq 130$ nm, the absorptivity remains above 90% over a broad wavelength range from approximately 200 to 1500 nm, indicating the formation of an efficient broadband absorption regime. Furthermore, Fig. 3(d) shows that the absorption peak located near 800 nm gradually shifts toward longer wavelengths as w increases, accompanied by a notable broadening of the absorption bandwidth. This redshift can be attributed to the increased effective resonant cavity size and the extended optical path length within the top W resonator, which strengthens the localized electromagnetic resonance at longer wavelengths. The enlarged resonator also enhances the coupling between adjacent resonant modes, resulting in a broader high-absorptivity bandwidth. Among the investigated structures, $w = 200$ nm provides the widest absorption bandwidth while maintaining absorptivity above 90% across most of the ultraviolet, visible, and near-infrared regions. Therefore, $w = 200$ nm was selected as the optimal design parameter for the proposed absorber.

Finally, the effects of the $h3$ layer thickness on the absorption characteristics were systematically investigated, and the corresponding results are presented in Fig. 3(e). Reducing the $h3$ thickness significantly broadens the absorption bandwidth [Fig. 3(e)]. This improvement results from better impedance matching with free space and stronger coupling among the localized electromagnetic resonances. A thinner $h3$ layer also reduces excessive optical losses associated with the metallic resonator while preserving sufficient plasmonic coupling, thereby improving the overlap of multiple resonance modes and resulting in enhanced broadband absorption. Consequently, a thinner top W resonator facilitates the more efficient confinement and dissipation of incident electromagnetic energy over a wider wavelength range. Moreover, all investigated structures exhibit absorptivity exceeding 90% continuously from 200 nm onward, demonstrating excellent broadband absorption performance regardless of the $h3$ thickness. Among the investigated designs, the absorber with an $h3$ thickness of 110 nm achieves the broadest high-absorption bandwidth while maintaining near-unity absorption across most of the ultraviolet, visible, and near-infrared regions. Therefore, an $h3$ thickness of 110 nm was selected as the optimal design parameter for the subsequent investigations.

The structural parameters were optimized using a sequential one-factor-at-a-time (OFAT) procedure, in which one geometrical parameter was varied while the remaining parameters were fixed, and the selected value was subsequently used in the evaluation of the next parameter. This approach enables the individual influence of each structural parameter on the absorption spectrum to be clearly identified while avoiding the substantially increased computational cost associated with a full multidimensional parameter sweep. After completing the sequential optimization, the final absorber configuration was defined using $h1=300$ nm, $h2=50$ nm, $r=10$ nm, $w = 200$ nm, and $h3 = 110$ nm. The broadband absorption spectrum and all subsequent analyses, including the optical impedance, electric and magnetic field distributions, and angular

responses under TE and TM polarizations, were evaluated using this complete final parameter set. Therefore, the reported absorptivity exceeding 90% over the wavelength range of 200–1760 nm represents the response of the final combined structure rather than a result assembled from separate parameter sweeps. Nevertheless, because possible interactions among the geometrical parameters were not exhaustively evaluated, the selected configuration should be regarded as a practical optimized design obtained through sequential parameter analysis rather than a mathematically proven global optimum. A comprehensive multidimensional optimization and parameter-interaction analysis may be considered in future work.

Note that, except for $h_2 = 50$ nm, the selected values of $h_1 = 300$ nm, $r = 10$ nm, $w = 200$ nm, and $h_3 = 110$ nm occur at the boundaries of the investigated ranges. Therefore, these values should be regarded as the best-performing design values within the present parameter ranges rather than mathematically proven local optima. Their selection also considers physical and fabrication constraints. For h_1 , increasing the W ground-plane thickness beyond the level required to suppress transmission is expected to provide diminishing optical benefit. A cavity radius below 10 nm would substantially increase fabrication difficulty, whereas further increasing w is constrained by the fixed unit-cell period of $p = 300$ nm and the required separation between adjacent resonators. Similarly, further reduction of h_3 may affect resonator integrity and fabrication tolerance. Therefore, the selected parameters provide a practical compromise between broadband absorption performance and structural feasibility. A broader multidimensional optimization may be considered in future work to investigate possible global optima outside the present parameter ranges.

Figure 4(a) presents the absorption spectrum of the final absorber configuration with $h_1 = 300$ nm, $h_2 = 50$ nm, $r = 10$ nm, $w = 200$ nm, and $h_3 = 110$ nm. The final structure maintains an absorptivity exceeding 0.9 continuously from 200 to approximately 1760 nm with an average absorptivity of 0.944, corresponding to a high-absorption bandwidth of approximately 1560 nm.

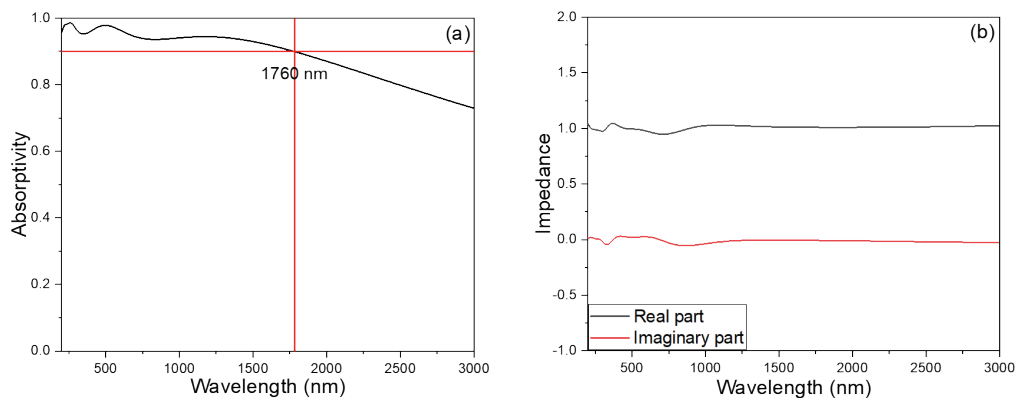


Fig. 4. (Color online) (a) Absorption spectrum of the final absorber configuration and (b) corresponding normalized optical impedance. The structural parameters are $h_1 = 300$ nm, $h_2 = 50$ nm, $h_3 = 110$ nm, $w = 200$ nm, and $r = 10$ nm.

Beyond approximately 1760 nm, the absorptivity gradually decreases below 0.9, indicating the long-wavelength limit of the broadband high-absorption region. This behavior can be understood together with the normalized optical impedance shown in Fig. 4(b). Within the principal high-absorption region, the real part of the normalized impedance remains relatively close to unity and the imaginary part remains close to zero, indicating favorable impedance matching between the absorber and free space and consequently suppressed optical reflection. At longer wavelengths, the gradual deviation from the ideal impedance-matching condition, together with weaker electromagnetic resonance, increases reflection and reduces the absorptivity. Therefore, the 200–1760 nm bandwidth reported in this study is directly derived from the absorption spectrum of the complete final parameter set and is consistent with the corresponding impedance characteristics. To evaluate the impedance-matching characteristics of the proposed absorber, the effective optical impedance was retrieved from the simulated scattering parameters (S_{11} and S_{21}) using the equivalent electromagnetic parameters of the structure as below.

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

For a reciprocal and symmetric structure, $S_{11} = S_{22}$ and $S_{12} = S_{21}$, allowing the impedance to be directly calculated from the simulated S_{11} and S_{21} values. The appropriate sign of the square root was selected to satisfy the passive-medium condition, $Re(z) > 0$. When the real part of the normalized impedance approaches unity and the imaginary part approaches zero, the impedance mismatch between the absorber and free space is minimized, resulting in suppressed reflection and enhanced electromagnetic energy absorption. In this study, the wavelength-dependent permittivity and permeability of each material were obtained from the built-in optical material database in COMSOL Multiphysics. Consequently, the retrieved impedance accurately reflects the intrinsic electromagnetic response of the proposed absorber.

Figure 4(b) presents the wavelength-dependent normalized optical impedance of the proposed absorber. As shown, the real part of the normalized impedance remains close to unity over a broad wavelength range from 200 to 3000 nm, while the imaginary part remains close to zero throughout most of this spectral region. These results indicate excellent impedance matching between the absorber and free space, thereby effectively suppressing reflection and promoting the efficient absorption of the incident electromagnetic waves. Although the imaginary part gradually shifts to slightly negative values beyond approximately 2500 nm, the deviation remains relatively small even as the wavelength approaches 3000 nm. This slight impedance mismatch has only a limited effect on the absorption performance, allowing the absorber to maintain a high absorptivity of approximately 0.8 at 3000 nm. The excellent impedance-matching characteristics over such a wide spectral range confirm that the proposed structure efficiently couples the incident electromagnetic energy into the absorber, which is the primary reason for its outstanding broadband absorption performance extending from the ultraviolet to the near-infrared region.

The decrease in absorptivity beyond approximately 1760 nm can be attributed to the gradual deterioration of impedance matching and weaker electromagnetic resonance at longer wavelengths. In particular, the deviation of the normalized impedance from the free-space condition becomes more evident toward 3000 nm, resulting in increased reflection and a decrease in absorptivity to approximately 0.8. Therefore, although the proposed absorber retains useful absorption in the longer-wavelength region, its present configuration is primarily optimized for the ultraviolet, visible, and near-infrared regions. This limitation may reduce its effectiveness for thermal-emission and infrared-camouflage applications requiring near-unity absorption over a broader infrared range. Further optimization of the resonator dimensions, dielectric thickness, or additional infrared resonant elements would be required to extend the high-absorption bandwidth toward longer wavelengths. The impedance analysis further suggests that the broadband absorption originates from efficient impedance matching, while the underlying resonance mechanisms responsible for energy confinement are further analyzed through the electric and magnetic field distributions in the following section.

As shown in Fig. 3(e), the optimized absorber exhibits three representative absorption peaks at approximately 260, 500, and 1180 nm. These wavelengths were selected to investigate the spatial distributions of the electric and magnetic fields, thereby elucidating the underlying broadband absorption mechanisms. The corresponding electric and magnetic field distributions are presented in Figs. 1(a) and 1(b), respectively. At all three wavelengths, the electromagnetic fields are primarily concentrated within the top W resonator and gradually decay toward the Al_2O_3 spacer and the bottom W ground plane. This top-to-bottom attenuation indicates that the incident electromagnetic energy is efficiently confined and progressively dissipated inside the absorber rather than being reflected back into free space. Pronounced electric field enhancement occurs around the resonator edges and the inner surface of the hollow cavity. This distribution indicates the strong localization of the incident electromagnetic waves. On the other hand, the magnetic field is mainly confined within the Al_2O_3 dielectric spacer, suggesting the excitation of magnetic resonance between the top resonator and the bottom metallic layer. The coexistence of localized electric field enhancement and magnetic resonance effectively improves impedance matching with free space and strengthens electromagnetic energy confinement. Consequently, the proposed structure achieves efficient light trapping and broadband absorption over the ultraviolet, visible, and near-infrared spectral regions.

The angular dependence of the proposed optical absorber was evaluated under both transverse electric (TE) and transverse magnetic (TM) polarizations for incident angles ranging from 0 to 90°, as shown in Figs. 5(a) and 5(b). Under TE polarization, the absorber maintains an absorptivity exceeding 90% over the wavelength range of 200–1760 nm for incident angles up to 45°, demonstrating excellent angular stability. Under TM polarization, absorptivity remains above 90% within the same wavelength range for incident angles up to 30°. Note that the angular absorption characteristics in Fig. 5 are presented as continuous wavelength–incident-angle color maps; therefore, the approximate angular limits of 45° for TE polarization and 30° for TM polarization were determined from the color distribution corresponding to the $A > 0.9$ criterion rather than from an abrupt physical boundary. The absorption response varies continuously with both wavelength and incident angle, and the color scale provides the corresponding quantitative

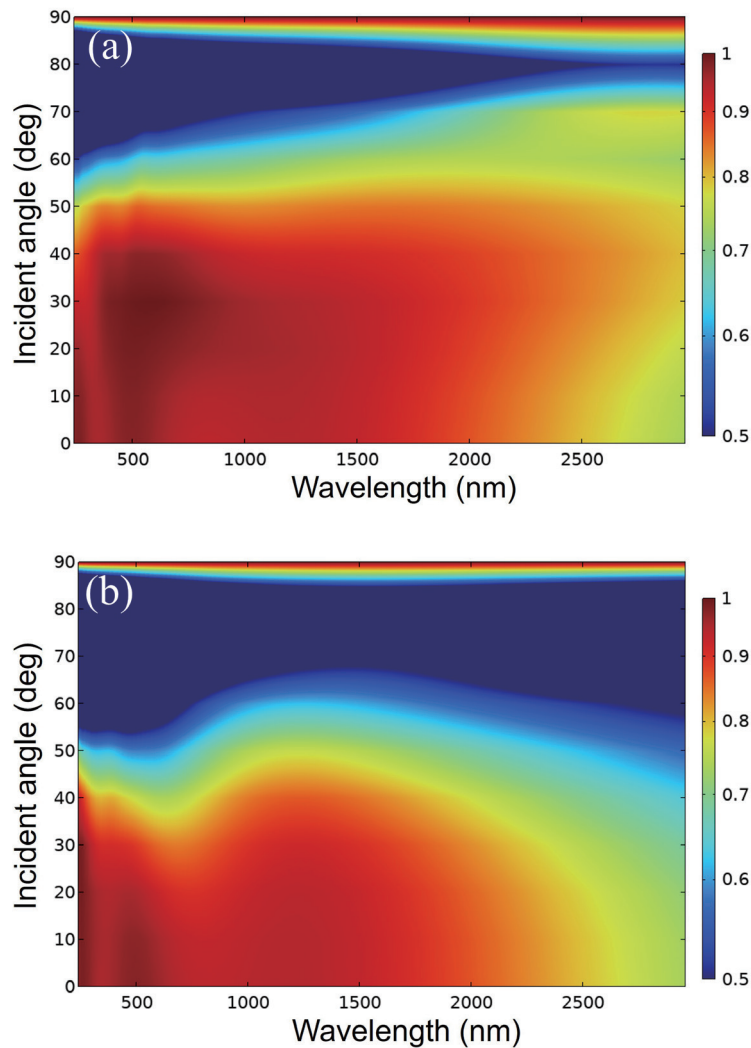


Fig. 5. (Color online) Angular absorption distributions under (a) TE and (b) TM polarizations for the final absorber configuration with $h_1 = 300$ nm, $h_2 = 50$ nm, $h_3 = 110$ nm, $w = 200$ nm, and $r = 10$ nm. The color scale represents the absorptivity used to identify the $A > 0.9$ high-absorption region.

absorptivity for identifying the high-absorption region. At larger incident angles, the absorption performance gradually decreases. This reduction originates mainly from deteriorated impedance matching between the absorber and free space, which increases optical reflection. Nevertheless, the proposed structure still exhibits relatively high absorption at larger incident angles, indicating good tolerance to oblique incidence. The superior angular performance can be attributed to the optimized multilayer configuration and the strong electromagnetic coupling between the top W resonator, the Al_2O_3 dielectric spacer, and the bottom W ground plane, which effectively preserves the resonance conditions over a wide range of incident angles. These results demonstrate that the proposed absorber is not only broadband but also exhibits excellent polarization and angular robustness, making it a promising candidate for practical optical

sensing, photodetection, and solar-energy harvesting applications where light is typically incident from multiple directions.

From an application perspective, the broadband absorption characteristics of the proposed structure are beneficial for both photodetection and solar-energy harvesting. The optimized absorber maintains an absorptivity above 90% over the wavelength range of 200–1760 nm, indicating the efficient utilization of incident photons across the ultraviolet, visible, and near-infrared regions. For a photodetector, the external responsivity can be expressed approximately as $R = \eta q \lambda / (hc)$, where R is the responsivity, η is the external quantum efficiency, q is the elementary charge, λ is the incident wavelength, h is Planck's constant, and c is the speed of light in vacuum. For example, under the ideal assumption that carrier collection efficiency and other electrical properties remain unchanged, increasing optical absorption from 70 to 90% would correspond to an approximately 28.6% increase in absorbed photon flux and, consequently, similar theoretical increases in photocurrent and responsivity. This value represents an optical upper-bound estimate rather than experimentally demonstrated device enhancement. If carrier collection efficiency remains unchanged, enhanced optical absorption increases the number of photogenerated carriers and can therefore proportionally improve the photocurrent and responsivity. Similarly, detectivity D^* may be improved through increased responsivity when the detector noise remains approximately unchanged. For photovoltaic applications, enhanced absorption can increase the short-circuit current density J_{sc} by increasing the absorbed photon flux and may consequently improve power conversion efficiency. However, the actual improvements in R , D^* , J_{sc} , and conversion efficiency also depend on carrier recombination, collection efficiency, electrical losses, and device architecture. Therefore, the >90% broadband absorptivity obtained in this study should be regarded as an optical performance basis for potential device enhancement rather than a direct prediction of device level efficiency.

Table 1 shows comparison of the proposed absorber with the representative broadband optical absorbers reported in recent studies. Although some multilayer and nanopatterned structures achieve wider absorption bandwidths or larger angular tolerance, they generally require

Table 1
Comparison of the proposed absorber with representative broadband optical absorbers.

Absorber	Structure/complexity	High-absorption wavelength range	Bandwidth	Angular tolerance	Fabrication complexity
Yang <i>et al.</i> ⁽⁹⁾	Eight-layer planar structure	350–1970 nm (average $A = 96.76\%$)**	1620 nm	—	Moderate
Zhou <i>et al.</i> ⁽¹⁰⁾	Four-layer, X-cavity patterned structure	400–2500 nm	2100 nm	~50°	Moderate–high
Nakti <i>et al.</i> ⁽¹¹⁾	Multimaterial double-grating structure	Broadband VIS–NIR	—	Wide-angle	High
Hakim <i>et al.</i> ⁽¹²⁾	Metamaterial-based broadband absorber	Broadband optical absorption	—	Wide-angle response	Moderate–high
Nanopatterned CHRR absorber ⁽¹³⁾	Three-material/layer concentric hexagonal resonator	380–2500 nm	2120 nm	~70°	High
This work	Three-layer W/Al ₂ O ₃ /W + single hollow resonator	200–1760 nm ($A > 90\%$)	1560 nm	TE: 45°; TM: 30°	Moderate

additional material layers or more complex nanoscale resonator geometries. In comparison, the present absorber consists of only three functional layers (W/Al₂O₃/W) and a single hollow-cavity resonator geometry, while maintaining absorptivity above 90% over the wavelength range of 200–1760 nm, corresponding to a 1560 nm bandwidth. It also maintains >90% absorption up to 45° for TE and 30° for TM polarization. Therefore, the main advantage of the proposed design is not the maximum bandwidth or angular tolerance alone, but its favorable balance among broadband absorption, structural simplicity, and fabrication feasibility.

4. Conclusions

In this study, a simple three-layer broadband optical absorber consisting of a W ground plane, an Al₂O₃ dielectric spacer, and a top W square resonator with a centrally hollow cylindrical cavity was successfully designed and optimized using COMSOL Multiphysics based on the finite element method. A systematic parametric investigation demonstrated that the thicknesses of the W and Al₂O₃ layers, together with the dimensions of the top resonator and the hollow cavity, play key roles in determining the broadband absorption performance. The optimized structure achieved absorptivity exceeding 90% over the wavelength range of 200–1760 nm, covering the ultraviolet, visible, and near-infrared spectral regions. The impedance analysis confirmed excellent impedance matching with free space over a broad wavelength range, while the electric and magnetic field distributions revealed that the outstanding absorption performance originates from the combined effects of localized electric field enhancement, magnetic resonance, and efficient electromagnetic energy confinement within the multilayer structure. Furthermore, the proposed absorber exhibited excellent angular stability, maintaining absorptivity above 90% for incident angles up to 45° under TE polarization and 30° under TM polarization, indicating its robustness under oblique illumination conditions. Compared with previously reported broadband absorbers, the proposed design provides a much simpler structural configuration while maintaining excellent broadband optical performance, making it attractive for practical fabrication and large-area integration. Because the proposed absorber efficiently enhances light–matter interaction over an ultrawide spectral range, it can serve as an effective optical absorption layer for various sensor technologies, including ultraviolet photodetectors, broadband optical sensors, photonic sensing platforms, environmental monitoring sensors, and integrated optoelectronic sensing devices. In addition, its broadband absorption and angular stability indicate strong potential for solar-energy harvesting and optical sensing applications, whereas further long-wavelength optimization is required for thermal-emission and infrared-camouflage applications. The proposed absorber is particularly suitable for integration with semiconductor-based optical sensors because its broadband and high absorptivity can significantly improve light utilization efficiency, thereby enhancing sensor responsivity, detectivity, and signal-to-noise ratio over a wide spectral range.

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