

Sandwich-Multilayer-Film Perfect Absorber Spanning the Entire Visible Spectrum

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Abstract

High-efficiency perfect absorption, spanning the entire visible region, plays an increasingly significant role in applications such as solar energy harvesting, photodetection, and thermal radiation management. However, the complexity and manufacturing difficulty of the currently proposed structures hinder large-scale application. In this work, we propose a broadband perfect absorber based on a tungsten–silicon nitride–tungsten (W-Si₃N₄-W) sandwich multilayer film. We combine the unique broadband absorption capability and high-temperature stability of material W with the low-loss characteristic of material Si₃N₄. By optimizing the geometrical parameters of the structure, we successfully achieved an average absorption efficiency exceeding 94% across a wide wavelength ranging from 500 nm to 900 nm. This work paves the way for developing high-performance, stable, and broadband absorption devices.

Keywords: broadband perfect absorber; Tungsten; visible light; Fabry–Pérot cavity

1. Introduction

Broadband perfect absorbers (BPAs) are essential optical devices designed to achieve near-total absorption of incident light across a specific wavelength range while minimizing both reflection and transmission. By converting electromagnetic energy into other forms, such as heat or electricity, BPAs play a crucial role in applications including photovoltaics [1–3], thermal imaging [4–6], thermal emitters [7,8] photothermal conversion [9–11], and photodetection [12,13]. An ideal BPA should exhibit broad spectral response, high absorption efficiency, low angular dependence, and excellent environmental stability. Conventional perfect absorbers, which primarily rely on plasmonic materials and nanostructures, have shown exceptional performance in narrowband absorption. However, their practical application is often limited by the high cost of noble metals and inherently narrow bandwidth. The emergence of metamaterial-based perfect absorbers offers a promising alternative. In 2008, Landy et al. [14] experimentally demonstrated near-unity absorption at a single microwave frequency using a metal–insulator–metal (MIM) resonator, inspiring subsequent efforts to develop broadband perfect absorbers using metasurfaces and metamaterials. Since then, absorbers covering ultraviolet (UV) [15], visible [16,17], infrared (IR) [18–21], and terahertz (THz) [22–24] regimes have been reported. For example, Qian et al. [25] realized visible-range broadband absorption using metal–dielectric nanocolumn arrays. Many of these designs employ resonance mechanisms, such as multi-mode



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coupling and Mie resonances, to extend the absorption bandwidth. Xiao et al. [26], for instance, developed a multifunctional absorber operating from UV to mid-IR through the interplay of multiple resonant modes. Nevertheless, such absorbers often suffer from large structural dimensions and complex fabrication processes, typically involving expensive techniques, i.e., electron-beam lithography and reactive ion etching. These factors impede mass production, especially for cost-sensitive applications. Therefore, there is a growing need for thin-film absorbers with simpler geometries and more economical fabrication routes to facilitate scalable production.

Recently, multilayer thin-film absorbers have attracted attention. A six-layer structure using MgF_2 and Cr was shown to achieve ultrabroadband absorption [27]. An Al- SiO_2 multilayer achieved perfect absorption in the visible to near-infrared range [28]. Lai et al. [29] optimized the $\text{Al}_2\text{O}_3/\text{TiO}_2\text{-TiON-C}/\text{Al}_2\text{O}_3/\text{TiO}_2\text{-TiON-C}$ multilayer structure and surface roughness treatment, enabling this high-brightness color solar selective absorption coating to achieve both high visible light reflectivity and high solar absorption efficiency. Lai et al. [30] investigated how surface roughness of $\text{Al}_2\text{O}_3/\text{Ti}/\text{Al}_2\text{O}_3$ solar absorption coatings influences optical performance and angular stability, ensuring consistent color and brightness across wide viewing angles for seamless architectural integration. These findings demonstrate that multilayer film structures with surface roughness possess significant application potential in building-integrated solar thermal systems, and the feasibility of this proposed structure for architectural applications warrants further investigation. However, such designs usually require at least four layers, increasing fabrication complexity, cost, and the demand for high precision. Hence, simpler and more cost-effective routes towards broadband perfect absorption remain highly desirable. In this work, we theoretically design and experimentally fabricate a broadband perfect absorber based on a metal-insulator-metal (MIM) absorber composed of tungsten (W) and silicon nitride (Si_3N_4). The structure supports Fabry-Pérot resonance, which enhances localized optical fields. The W material offers optical properties comparable to those of noble metals, along with superior chemical and thermal stability, while the Si_3N_4 film serves as a low-loss dielectric that allows for precise thickness control and optimized field distribution. Experimental results demonstrate even better absorption performance than initially predicted. The W- Si_3N_4 -W sandwich multilayer film provides an effective platform for high-performance, highly stable, and broadband perfect absorption.

2. Materials and Methods

Prepared substrates: K9 glass ($\Phi 60$ mm, Beijing Zhongnuo Advanced Materials Technology Co., Ltd., Beijing, China), used for substrates, is ultrasonically cleaned sequentially with deionized water, acetone, and alcohol for 15 min to remove surface contaminants such as metal impurities and inorganic residues. The cleaned substrates are baked in an oven at 90°C for 40 min to ensure complete dryness.

Fabricating W- Si_3N_4 -W sandwich multilayer film: The 150 nm tungsten (W) film is first deposited using a JGP560 magnetron sputtering system (Shenyang Scientific Instrument Co., Ltd., Chinese Academy of Sciences, Shenyang, China). The working pressure is set as 1.8 Pa, the sputtering power as 130 Watt and the flow rate of Ar as 40.5 sccm, yielding a deposition rate of 48.3 nm/min. Subsequently, an 80 nm silicon nitride (Si_3N_4) layer is deposited by a plasma-enhanced chemical vapor deposition (PECVD) system at a pressure of 600 mTorr, a temperature of 100°C , and argon flow rate of 272 sccm. Finally, a 5 nm W capping layer is deposited on the Si_3N_4 surface under the same sputtering conditions as the initial 150 nm W film. A schematic of the fabrication process is provided in Figure 1.

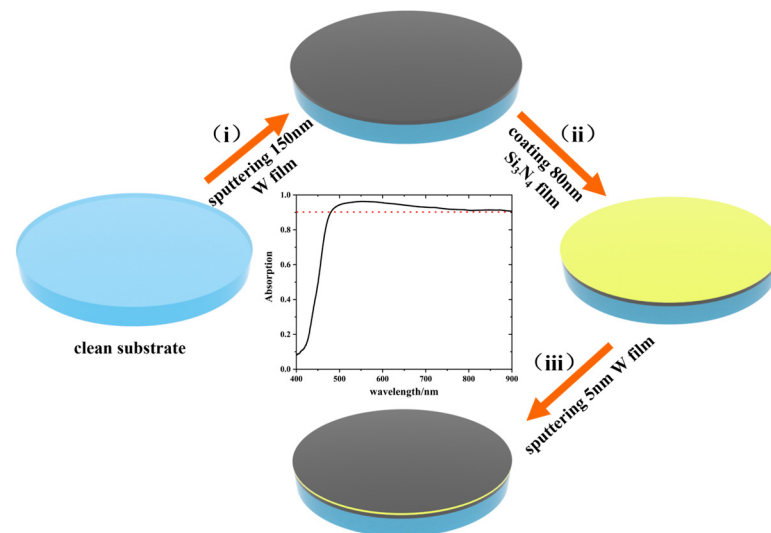


Figure 1. Experimental procedure for preparing W-Si₃N₄-W multilayer film structures. The inset shows the absorptance spectrum of the prepared structure, where the black solid line represents the measured absorptance and the red dashed line indicates the 90% absorptance baseline, highlighting that the average absorptance of the prepared structure remains above 90%.

3. Results and Discussion

The W film, as a highly lossy material, offers a promising route to achieving broadband absorption. Figure 2a presents the complex refractive index of W, which features a large imaginary part exceeding 3 throughout the visible spectrum, along with a smoothly varying and moderately dispersive real part. This optical profile favors effective impedance matching with the surrounding medium. Recently, W-based absorbers have attracted increasing attention. Several W-containing metamaterial and multilayer absorbers have been reported for broadband absorption. For instance, Li et al. [31] successfully developed a spectrally selective emitter based on a silicon nanodisk array on W substrate, where the high melting points of silicon and tungsten materials ensure the safe operation of the emitter at high temperatures. Kumar et al. [32] designed a three-layer metamaterial absorber composed of a periodic W crossing surface layer, a silicon dioxide dielectric layer, and a W metal bottom layer, achieving an average absorption rate of 99% in the 400–750 nm range. The Si₃N₄ film, represented by the blue curve for the real refractive index (n) in Figure 2a, is employed as the dielectric spacer. It shows high transparency across the operating wavelength range, as indicated by its near-zero extinction coefficient, together with negligible dispersion. Such low-loss characteristics are essential for forming a well-defined Fabry–Pérot resonance. Figure 2b illustrates the absorption performance of a standalone W layer, showing the reflection and transmission spectra for 100 nm and 150 nm thickness W films. In the proposed absorber, the bottom W layer serves as a reflective mirror that effectively suppresses transmission. By calculating the skin depth of W within the target wavelength range and optimizing the film thickness, a 150 nm W film is found to exhibit near-zero transmittance ($T(\lambda) \approx 0$). As a result, the absorption of the structure can be approximated as $A(\lambda) = 1 - R(\lambda)$. Moreover, the 150 nm W film displays a high and spectral flat absorption profile, offering a stable baseline performance. This strong and broadband intrinsic absorption stems directly from the large extinction coefficient of W shown in Figure 2a, confirming the suitability of W as an efficient broadband absorbing material. It should be noted that the calculated absorption spectrum in Figure 2b corresponds to an ideal smooth W film using bulk optical constants. Surface roughness, inter-grain voids and roughness-induced scattering in the experimentally sputtered W films are not included in the simplified model.

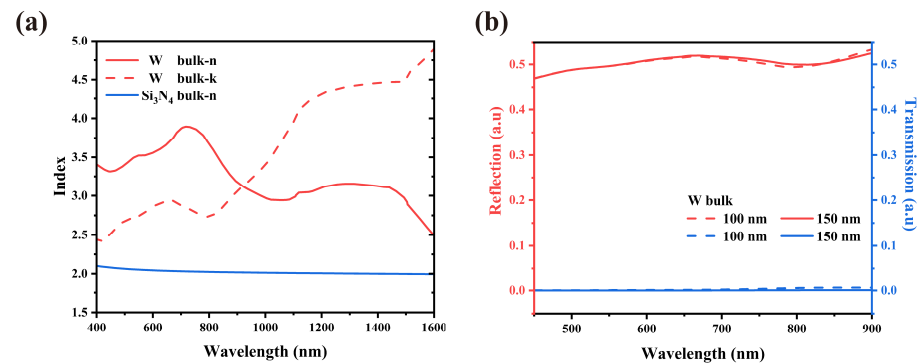


Figure 2. (a) Plots of the real (solid red line) and imaginary (dashed red line) parts of the complex refractive index of bulk W, and the real part (solid blue line) of the refractive index of bulk Si₃N₄, both versus wavelength. (b) Calculated reflection (R) and transmission (T) spectra for W layers with thicknesses of 100 nm and 150 nm.

The sputtering power significantly affects the surface morphology, roughness, and absorption performance of the W films. Figure 3a shows the absorption spectra of 150 nm W films deposited with different sputtering powers (50 W, 90 W, 130 W, and 150 W). Experimentally, the film sputtered at 130 W exhibits the highest absorption, exceeding 70% across a broad spectral range. To understand the influence of sputtering power on absorption, atomic force microscopy (AFM) is employed to characterize the surface morphology of the W films. Figure 3b–e present the AFM images of films deposited at 50 W, 90 W, 130 W, and 150 W, respectively. The root-mean-square (RMS) roughness values measured by AFM are 4.35 nm, 3.01 nm, 2.66 nm, and 4.57 nm at the respective sputtering powers. W films grown by magnetron sputtering typically exhibit a columnar grain structure with interstitial voids, which can be considered as low-refractive-index regions. When the surface roughness is lower (e.g., RMS $\approx$ 2.66 nm at 130 W), the film exhibits high uniformity in thickness and morphology. In this case, incident light can undergo constructive interference within the composite film structure, comprising both the columnar crystals and the gaps, effectively forming an anti-reflection layer that reduces surface reflection and enhances absorption. In contrast, when the roughness is too high (e.g., RMS = 4.57 nm at 150 W), excessive surface irregularities disrupt the phase coherence required for constructive interference leading to increased scattering and reflection. On the other hand, a higher roughness (e.g., RMS = 3.01 nm or below) may provide sufficient scattering centers or localized field enhancement to support strong light–matter interactions. The absorption behavior cannot be explained solely by the RMS roughness value. Although the 130 W sample has a slightly lower RMS roughness than the 90 W sample, the surface morphology is more uniform and may provide a better balance between reduced reflection, suppressed excessive scattering loss, and enhanced light trapping.

The absorption performance of different structural configurations, i.e., pure metal (M), metal–insulator (MI) structures and metal–insulator–metal (MIM) structures, is evaluated across the target wavelength range, as shown in Figure 4. Figures 4a and 4b present a comparison between the theoretical and experimental absorption spectra, respectively. The standalone 150 nm W film showed limited absorption, approximately 50% in simulations, due to intrinsic material losses. Coating an 80 nm Si₃N₄ dielectric layer on top to form a metal–insulator (MI) structure significantly enhanced the absorption, yielding an average of 85% between 530 nm and 900 nm, with a peak value of 95.5% at 765 nm. This improvement is attributed to the Fabry–Pérot cavity resonance, which enhances light trapping within the dielectric spacer. Further depositing a 5 nm W capping layer to construct the MIM sandwich absorber led to near-perfect absorption, aided by improved impedance matching with free space. The MIM absorber maintains over 80% absorption from 600 nm to 900 nm,

reaching a peak of 98% at 878 nm. Experimentally, the 150 nm W film alone achieved over 70% absorption across 470–900 nm. With the introduction of the 80 nm Si₃N₄ layer, absorption exceeded 80% in the same range. The MIM sandwich multilayer film further boosted the performance, surpassing 90% absorption from 480 nm to 900 nm. Figure 4c–e display optical images of the single-layer W film (M), bilayer W-Si₃N₄ film (MI), and trilayer W-Si₃N₄-W (MIM) absorber, respectively, illustrating the progressive sample morphology. The compared results demonstrate that the experimental absorption spectrum is superior to that of simulations. This high absorption efficiency is primarily attributed to the Fabry–Perot resonance effect, effective impedance matching, the inhibitory effect of the thick tungsten layer on light transmission, and the inherent ohmic loss of tungsten material. The non-ideal surface morphology of the sputtered thin films may be one of the reasons for the discrepancy between simulation results and experimental measurements. The W-Si₃N₄-W absorber exhibits high absorption across the visible spectrum, achieving an average exceeding 94% between 500 and 900 nm, with a minimum above 90%.

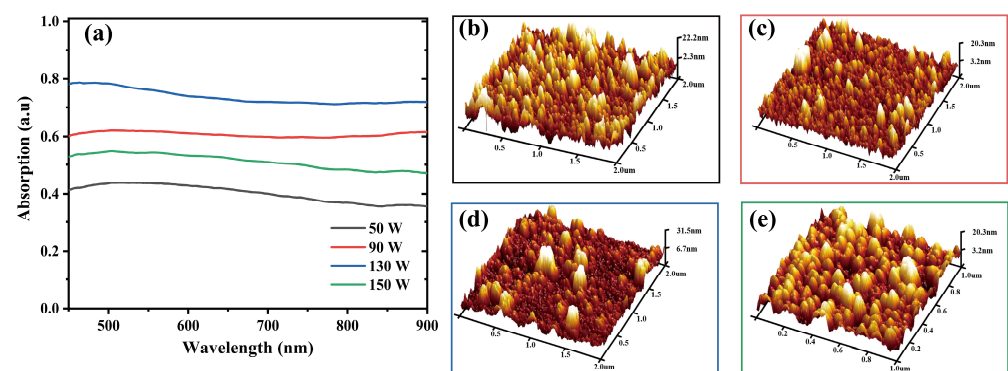


Figure 3. Effect of sputtering power on the optical properties of 150 nm W films. (a) Absorption of 150 nm W films as a function of sputtering power. (b–e) AFM topography images of the films deposited at (b) 50 W, (c) 90 W, (d) 130 W, and (e) 150 W. In the AFM images, the color contrast represents the relative surface height, with brighter regions corresponding to higher surface features and darker regions corresponding to lower regions; the height scale is indicated in each image.

Figure 5 shows the absorption characteristics of the W-Si₃N₄-W sandwich multilayer film at different incident angles. The results demonstrate that the absorption rate exhibits only slight fluctuation with the incident angle, maintaining over 80% absorption across a broad angular range of 0° to 50°, demonstrating its angle-insensitive characteristic. We show the absorption performance of sandwich absorbers with different stacked structures in the visible wavelength range in Table 1. These results confirm the effectiveness of the proposed design, providing a reliable platform for applications such as solar energy harvesting and photodetection.

Table 1. Comparative analysis of proposed unit cell and previous proposals.

Ref.	Number of Layers	Materials	Average Absorption (%)	Range (nm)
[33]	Four	Cu, Si ₃ N ₄	80%	400–700
[34]	Three	TiN, SiO ₂	87%	400–800
[35]	Three	W, SiO ₂	91.24%	389.34–697.19
[36]	Three	Ag, SiO ₂	80%	400–700
[37]	Three	Au, SiO ₂	83%	370–880
[38]	Three	Al, GaAs	80.74%	375–750
[39]	Four	Cr, SiO ₂	95%	400–1000
This work	Three	W, Si ₃ N ₄	94%	500–900

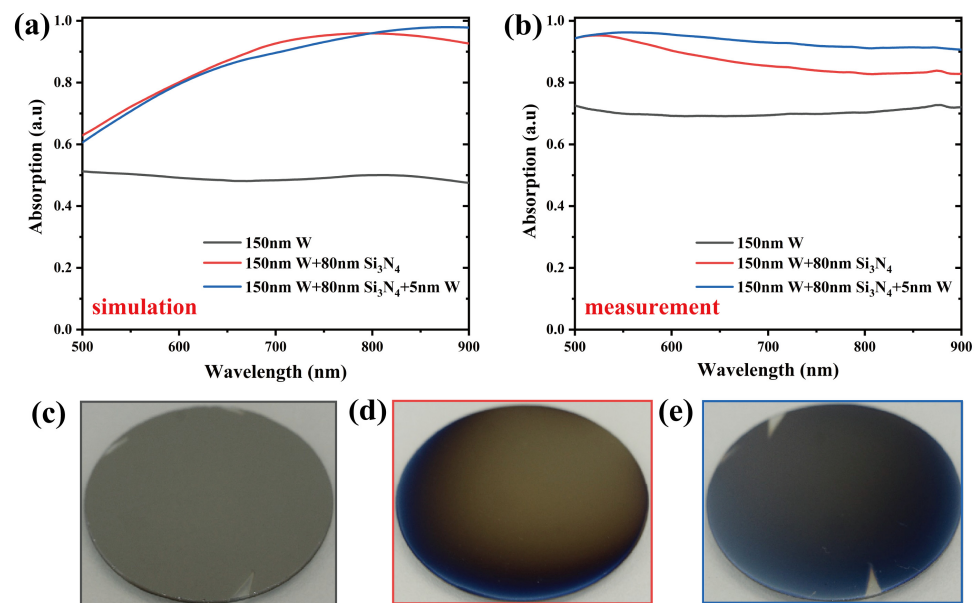


Figure 4. Comparison of simulated (a) and measured (b) absorption spectra for the W monolayer, W-Si₃N₄ bilayer, and W-Si₃N₄-W tri-layer. (c–e) Optical images of the respective samples.

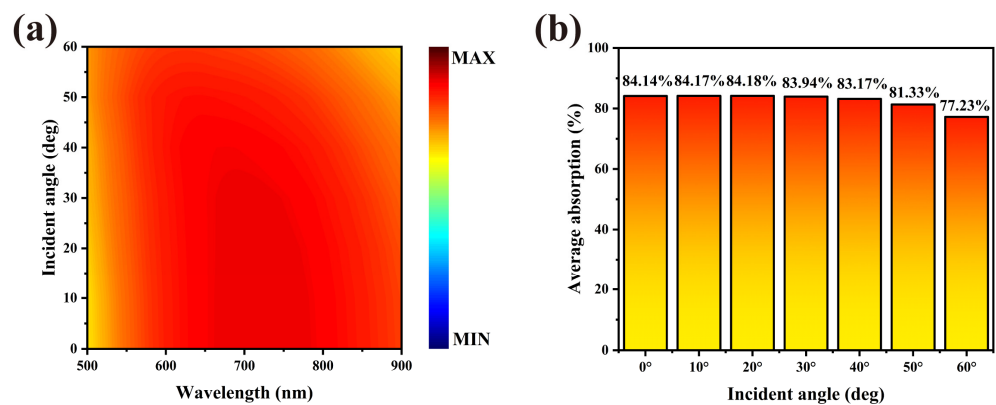


Figure 5. (a) Absorbance spectra under varying angles of incidence. (b) Average absorption rate from various angles.

To analyze the physical mechanisms underlying perfect absorption, we conduct a macroscopic analysis using impedance matching theory. When the impedance of free space matches that of the designed nanostructures, the absorption efficiency reaches its peak and the structure is regarded as a perfect absorber. It is generally assumed that the real part of the free-space impedance is 1 and the imaginary part is 0, whilst the impedance of the structure can be calculated using S parameters, as shown in the following formula [40]:

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

where S_{11} and S_{21} represent the scattering matrix coefficients for the reflection and transmission, respectively, considering the light normal incident with TM polarization. In the proposed MIM thin-film absorber, $T(\lambda) \approx 0$; therefore, $S_{21} \approx 0$. The real and imaginary parts of S_{11} parameters can be generated with COMSOL Multiphysics 6.1 software and substituted into Equation (1) yielding the critical impedance matching conditions. Since the 150 nm bottom W layer is optically thick, the transmission of the MIM absorber is nearly zero. Therefore, the absorption can be approximately expressed as $A \approx 1 - R$. To clarify

the broadband correlation between impedance matching and absorption performance, the simulated absorptance $A(\lambda)$ was plotted together with the retrieved normalized effective impedance, as shown in Figure 6a. The retrieved effective impedance shows that the real part of the impedance approaches unity and the imaginary part remains close to zero in the high-absorption wavelength range, indicating that the effective impedance of the absorber is close to that of free space; this result demonstrates that the wavelength range achieves near-perfect absorption. The effective resonance is necessary to modulate light field within the structure. The broadband perfect absorption achieved by the W-Si₃N₄-W sandwich multilayer film arises from the synergistic interplay of multi-reflection interference within a high-loss cavity and a low-Q Fabry–Pérot resonance. As illustrated in Figure 6b, incident light is partially reflected (r_1) and transmitted (t_1) at the top W–air interface. The transmitted component undergoes multiple reflections within the dielectric spacer, eventually exiting the cavity as wave t_2 with a phase shift of $\exp(-i2\beta)$. By carefully optimizing the thicknesses of the dielectric and top metal layers, the phase and amplitude of t_2 can be tailored to destructively interfere with r_1 . This results in near-perfect impedance matching with free space, effectively suppressing reflection and trapping light inside the structure to excite Fabry–Pérot resonance.

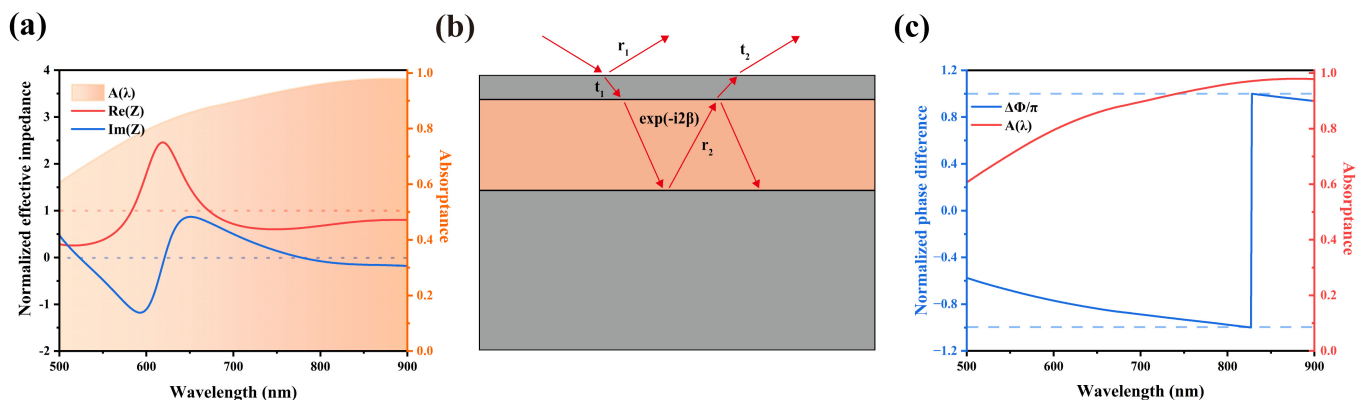


Figure 6. The physical mechanism of a perfect absorber and physical mechanism of the proposed W-Si₃N₄-W multilayer-film absorber. (a) The normalized impedance and absorptance of the MIM absorber. The shaded region represents the simulated absorptance $A(\lambda)$. The red and blue curves represent $\text{Re}(Z)$ and $\text{Im}(Z)$, respectively. The dashed horizontal lines indicate the ideal impedance matching conditions $\text{Re}(Z/Z_0) = 1$ and $\text{Im}(Z/Z_0) = 0$. (b) Schematic of the multi-reflection interference model governing the absorption mechanism. (c) Phase-difference analysis of the W-Si₃N₄-W absorber. The blue curve represents the normalized phase difference $\Delta\Phi/\pi$ between the directly reflected wave r_1 and the cavity-leakage wave t_2 , while the red curve represents the absorptance $A(\lambda)$. The dashed horizontal lines indicate the destructive-interference condition $\Delta\Phi/\pi = \pm 1$.

To further verify the Fabry–Pérot-type cavity mechanism, a phase analysis was performed based on the multiple-reflection interference model. As illustrated in Figure 6b, the total reflected wave can be regarded as

$$r_{\text{total}} = r_1 + t_2 \quad (2)$$

Here, r_1 represents the direct reflection wave, while t_2 represents the effective leakage wave from the Fabry–Pérot-type cavity. The phase difference between the directly reflected wave and the cavity-leakage wave is defined as

$$\Delta\Phi = \arg(r_1) - \arg(t_2) \quad (3)$$

For reflection cancelation, r_1 and t_2 should be approximately out of phase, satisfying the destructive-interference condition

$$\Delta\phi \approx (2m + 1)\pi \quad (4)$$

where m is an integer. Accordingly, the normalized phase difference should approach $\Delta\phi/\pi \approx \pm 1$. As shown in Figure 6c, the normalized phase difference $\Delta\phi/\pi$ remains close to -1 or $+1$ in the high-absorption wavelength region, indicating that the two reflected components are nearly out of phase. This destructive interference effectively suppresses the total reflection. Since the transmission is negligible, the suppressed reflection directly leads to enhanced absorption.

The magnetic-field distributions at representative wavelengths of 500 nm, 700 nm, and 878 nm further confirm the broadband validity of the proposed mechanism, as shown in Figure 7a–c. At all selected wavelengths, the magnetic field is mainly confined within the Si_3N_4 spacer and near the W/ Si_3N_4 interfaces, indicating that the incident electromagnetic energy is effectively coupled into the cavity region over the broadband absorption range. This resonance does not form symmetric standing waves for energy storage, as in conventional cavities. Instead, it significantly enhances the localized field intensity through coherent interference. The localized electromagnetic field is enhanced through coherent multiple-reflection interference and is subsequently dissipated through the intrinsic ohmic loss of the W layers.

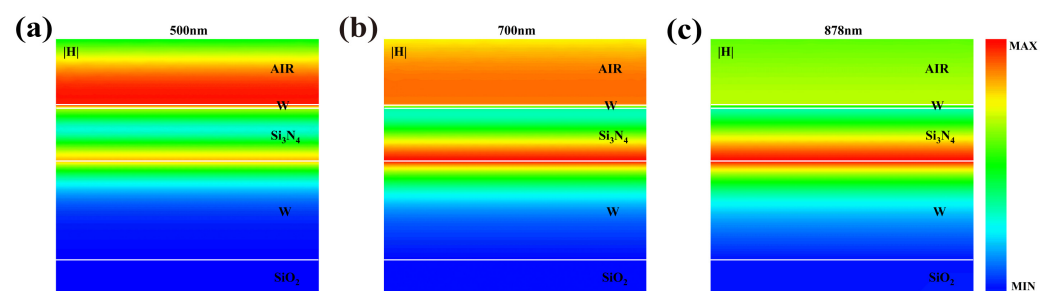


Figure 7. Simulated magnetic-field distributions of the W-Si₃N₄-W absorber at representative wavelengths of (a) 500 nm, (b) 700 nm, and (c) 878 nm.

Therefore, the near-perfect broadband absorption across 500–900 nm mainly originates from the combined effects of the optically thick bottom W layer blocking transmission, the Si₃N₄ spacer supporting Fabry–Pérot-type multiple-reflection interference, the ultrathin top W layer improving impedance matching and assisting reflection cancelation, and the intrinsic ohmic dissipation in the W layers.

4. Conclusions

We have theoretically designed and experimentally fabricated a simple W-Si₃N₄-W sandwich multilayer film that achieves near-perfect broadband absorption across the visible spectrum. Experimentally, the absorber exhibits an average absorption exceeding 94% between 500 and 900 nm. This high-performance absorption stems from the synergistic effects of Fabry–Pérot resonance, effective impedance matching and the intrinsic loss characteristics of tungsten. Notably, the proposed structure is wafer-scale compatible and can be fabricated using straightforward thin-film deposition techniques. The W-Si₃N₄-W sandwich absorber presents a highly promising platform for next-generation broadband absorption devices, with potential applications in solar energy harvesting, optical sensing, and integrated photonic systems.

Author Contributions: X.Z. and H.L.: Conceptualization, Methodology, and Writing. Y.H.: Data Curation and Investigation. L.L.: Visualization. J.Z.: Supervision, Reviewing, and Editing. X.Z. and H.L. contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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