

Supplementary Information for

**Single-Layer Double-Sided Ultrawideband Near-Perfect
Absorber Based on Biomimetic Metamaterial with
Manufacturing Scalability, Flexible Transferability, and
Environmental Stability**

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S1. Structural tolerance of the metamaterial absorber

The influence of the structural parameters on the absorption performance of the metamaterial absorber was systematically investigated. Supplementary Figure S1 illustrates the simulated absorption spectra as a function of the polystyrene (PS) microsphere diameter and the chromium (Cr) layer thickness. It can be observed that the proposed metamaterial absorber maintains high absorption over a broad spectral range within a wide parameter window. Specifically, variations in the PS microsphere diameter lead to only minor changes in the absorption spectra for both front-side and back-side illumination. Similarly, the absorption performance remains robust when the thickness of the Cr layer is varied over a relatively large range. These results indicate that the metamaterial absorber exhibits strong structural tolerance, which significantly relaxes fabrication constraints. Such robustness is particularly advantageous for experimental realization and large-scale manufacturing, where inevitable process-induced variations are difficult to avoid.

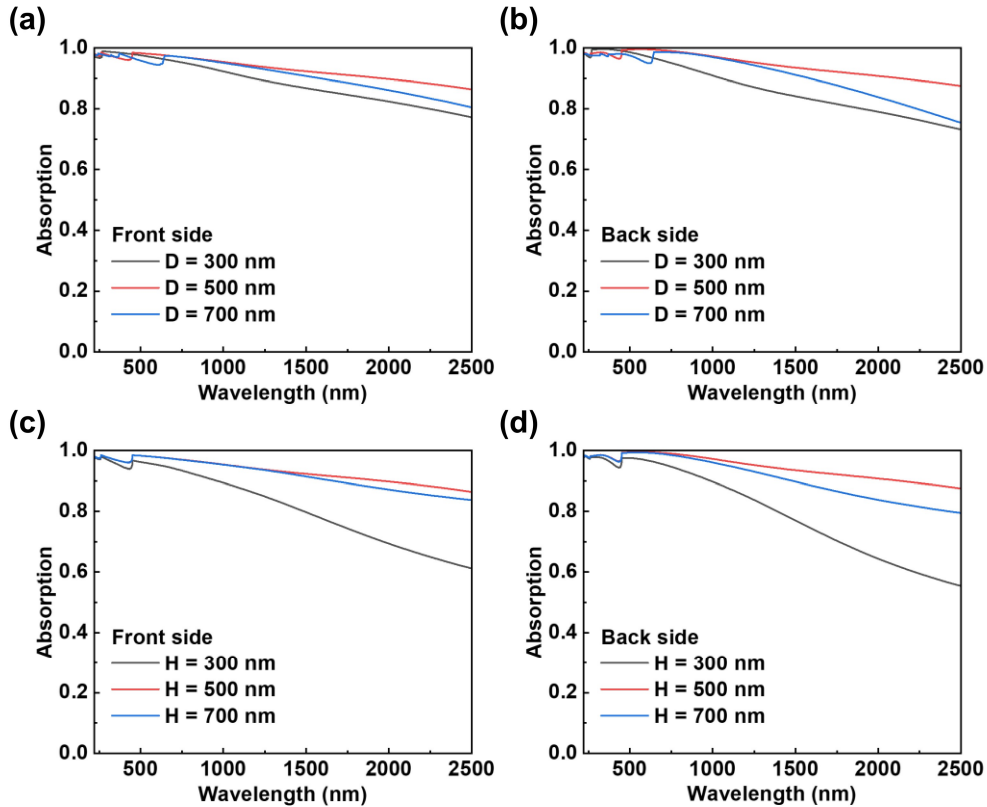


Figure S1. (a) Simulated absorption spectra of the metamaterial absorber under front-side and (b) back-side illumination, respectively, for different diameters D of the polystyrene microspheres. (c) Simulated absorption spectra under front-side and (d) back-side illumination, respectively, for different chromium layer thicknesses H .

S2. Calculation of solar-weighted absorption

The solar-weighted absorption of the metamaterial absorber was calculated to quantitatively evaluate its overall light-harvesting capability under realistic solar illumination conditions. The solar-weighted absorption A_{solar} is defined as the ratio of the absorbed solar energy to the total incident solar energy within a specified wavelength range, and is expressed as:

$$A_{\text{solar}} = \frac{\int_{\lambda_1}^{\lambda_2} A(\lambda) I_{\text{sun}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\text{sun}}(\lambda) d\lambda} \quad (\text{S1})$$

where $A(\lambda)$ denotes the wavelength-dependent absorptance of the device, with values ranging from 0 to 1, and $I_{\text{sun}}(\lambda)$ represents the solar spectral irradiance under standard AM1.5 conditions ($\text{W m}^{-2} \text{nm}^{-1}$).

The integration was performed over the wavelength range from 280 to 2500 nm, covering the primary spectral region of terrestrial solar radiation. The absorption spectra used in the calculation were obtained from experimental measurements. Based on these data, both the absorbed solar energy and the corresponding optical loss within the solar spectrum were quantitatively evaluated.

S3. Contribution of Intrinsic Chromium Loss and Surface Structure to Broadband Absorption

To clarify the respective roles of intrinsic chromium loss and structural effects in broadband absorption, the optical constants of the sputtered Cr film were first characterized and used to simulate a planar Cr film without surface structuring. Figure S2a shows the measured refractive index (n) and extinction coefficient (k) of Cr, revealing strong intrinsic optical loss across the UV–NIR range.

Using the measured optical constants, a 1000-nm-thick planar Cr film was simulated to ensure negligible transmission. As shown in Figure S2b, the planar film exhibits an average absorptance of only 68.1% over 220–2500 nm. Although the large extinction coefficient enables strong optical dissipation, it simultaneously causes pronounced impedance mismatch at the air/Cr interface, resulting in substantial reflection and

limited overall absorption.

In contrast, the biomimetic DS-BMA achieves >93% average absorptance over the same spectral range. Its hierarchical micro/nanostructure provides a gradual effective refractive-index transition that suppresses reflection, while the complementary protrusion–cavity geometry enhances optical confinement and broadband resonant coupling. Therefore, the near-perfect absorption originates from the synergistic effect of Cr intrinsic loss and biomimetic structural modulation, which together maximize light absorption and minimize reflection losses.

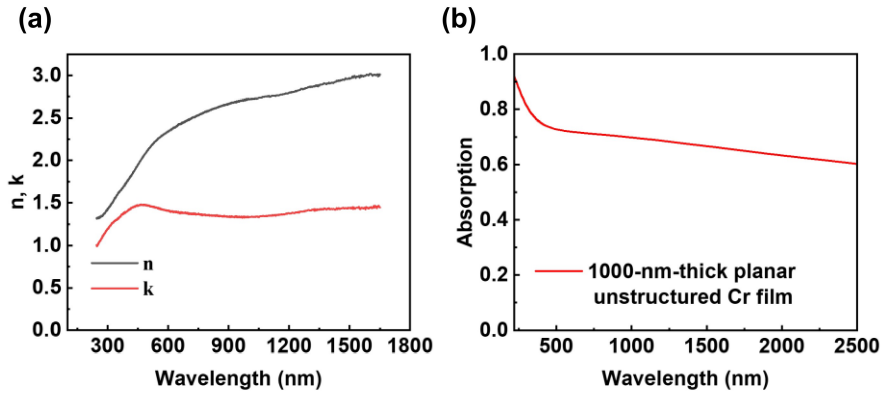


Figure S2. (a) Measured refractive index (n) and extinction coefficient (k) of the sputtered chromium film used in this work. (b) Simulated absorption spectra of a 1000-nm-thick planar chromium film and the proposed DS-BMA over the wavelength range of 220–2500 nm.

S4. Equivalent LC Circuit Interpretation of Magnetic Polariton Resonances

To provide an intuitive physical interpretation of the magnetic polariton (MP) resonances responsible for the broadband absorption, an equivalent LC circuit model is introduced (Figure S3). This model is employed solely as a qualitative tool to illustrate the physical roles of current loops and capacitive regions in the structure, rather than as a rigorous circuit representation of the electromagnetic response.

In this interpretation, the circulating displacement currents flowing along the curved chromium sidewalls form an effective inductive path, which is denoted as L . The existence of this inductive response reflects the formation of magnetic polariton modes supported by the metallic geometry, and it remains essentially unchanged under front- and back-side illumination. The effective capacitance originates from two main

geometrical features. The first contribution arises from the nanoscale air gaps between adjacent structural units, which generate strong electric-field confinement and are denoted as C_{gap} . The second contribution is associated with the air-filled hemispherical cavity regions, denoted as C_{cav} , where electromagnetic energy is stored through localized electric fields. At long wavelengths (e.g., 2500 nm), electromagnetic simulations reveal that the magnetic polariton modes extend deeper into the structure, leading to enhanced field localization in the cavity regions. Under this condition, the cavity-related capacitance (C_{cav}) provides the dominant contribution to the overall capacitive response, while the gap-related capacitance (C_{gap}) remains present and contributes to the broadening of the absorption bandwidth. The resonance behavior can be qualitatively described by the relation $\lambda \propto \sqrt{L(C_{\text{gap}} + C_{\text{cav}})}$. For backside illumination, the same inductive current path along the chromium sidewalls is preserved, whereas the dominant capacitive contribution originates from the hemispherical cavities on the lower surface. This complementary capacitive response under opposite illumination directions enables efficient excitation of magnetic polariton modes from both sides, thereby supporting robust double-sided broadband absorption.

Overall, the equivalent LC circuit illustration provides a physically intuitive picture of how the structural geometry facilitates magnetic polariton excitation and broadband absorption, consistent with the electromagnetic field distributions presented in the main text.

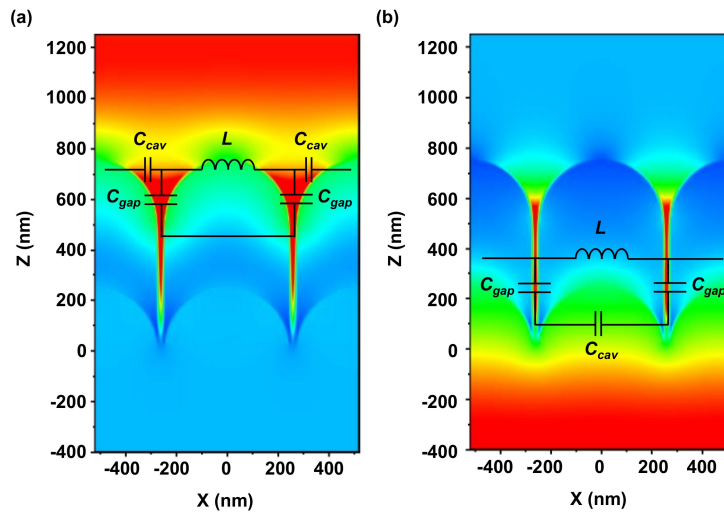


Figure S3. (a) Schematic diagrams of the equivalent LC circuit for the front and (b) back sides of the magnetic polariton resonance.

S5. Statistical Distribution of Experimental Nanogap Sizes

To quantitatively evaluate the experimental nanogap characteristics and their statistical uniformity, four representative SEM images of the fabricated absorber were analyzed using a MATLAB-based image-processing workflow. As illustrated in Supplementary Figure S4, the SEM images were first converted into processed binary maps to clearly distinguish the structural regions and inter-column nanogaps. Based on the extracted binary images, the local nanogap widths were quantitatively calculated and statistically analyzed over multiple sampling locations.

The resulting histogram reveals a relatively concentrated gap-size distribution centered at approximately 20 nm, with moderate variations around the mean value. This statistical result is in good agreement with the representative nanogap dimension adopted in the simulations and further supports the reasonable uniformity and controllability of the self-formed nanoscale gaps produced by the fabrication process.

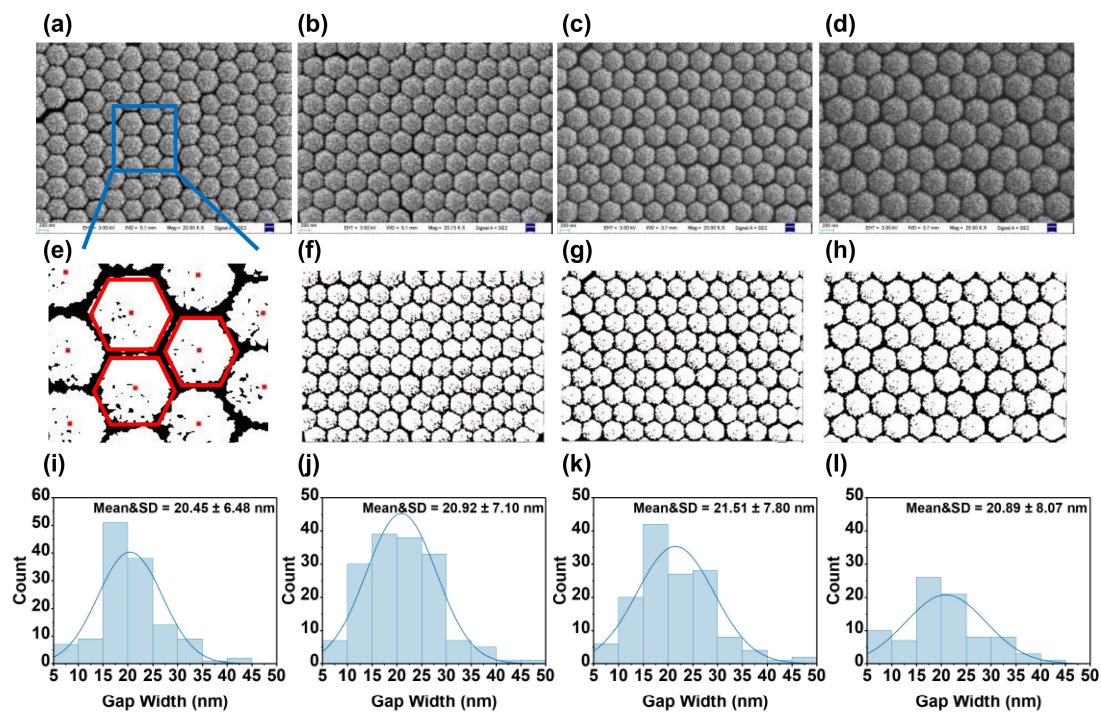


Figure S4. (a-d) Representative SEM images of the fabricated absorber. (e-h) MATLAB-processed binary maps converted from the SEM images for nanogap extraction, where (e) presents the enlarged processed region and (f-h) show the complete binary images. (i-l) Histograms of the extracted nanogap-width distributions from the corresponding SEM images, showing a concentrated distribution centered at approximately 20 nm.

S6. Polarization and angle insensitivity

The optical response of the metamaterial absorber was systematically investigated using the finite-difference time-domain (FDTD) method, with particular emphasis on its polarization and angular dependence. The simulated absorption spectra under different polarization states and incidence angles are presented in Supplementary Figure S5. For linearly polarized incident light, the absorber exhibits excellent polarization insensitivity. As the polarization angle varies continuously from 0° to 90° , the absorption spectra remain nearly unchanged for both front-side and back-side illumination, indicating a high degree of polarization-independent behavior. The angular performance of the absorber was further examined by varying the incident angle from 0° to 60° . Remarkably, the metamaterial maintains an average absorption exceeding 80% over this wide angular range. This pronounced angle insensitivity demonstrates the strong capability of the absorber to efficiently capture light under oblique incidence, which is highly desirable for practical applications such as wide-angle solar energy harvesting, omnidirectional photodetection, and all-weather photothermal conversion.

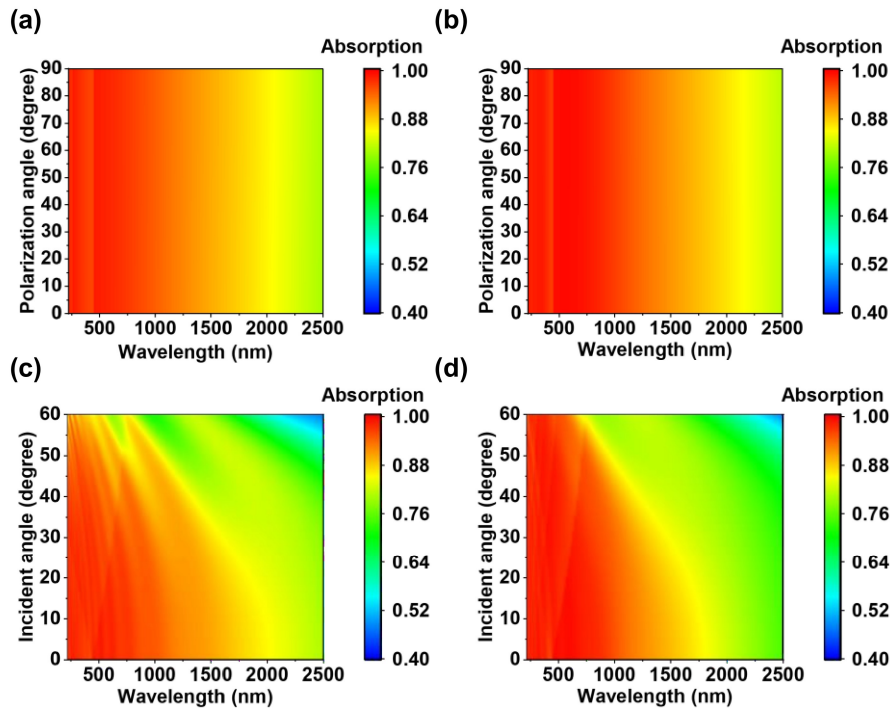


Figure S5. (a) Simulated absorption spectra of the metamaterial absorber under front-side and (b) back-side illumination, respectively, for different polarization angles of linearly polarized light. (c) Simulated absorption spectra under front-side and (d) back-side illumination, respectively, for different incident angles of linearly polarized light.

S7. Experimental details of sample fabrication

At an appropriate concentration of the polystyrene microsphere suspension, the microspheres spontaneously self-assemble at the air–water interface to form a monolayer with long-range periodic order. When illuminated with white light, this ordered array exhibits vivid structural colors arising from grating diffraction effects, as shown in Supplementary Figure S6a. Therefore, during the fabrication process, the appearance of uniform and bright structural colors was used as a qualitative indicator of good periodicity and monolayer coverage of the microsphere array.

Subsequently, the samples coated with a chromium layer were placed in a CAD heating tube and subjected to high-temperature treatment to thermally decompose the polystyrene microspheres, as schematically illustrated in Supplementary Figure S6b. The leftmost sample in Supplementary Figure S6c corresponds to the initial monolayer microsphere array. After annealing at 400 °C for 2 h, the microspheres were completely decomposed, and no visible residues were observed on the silicon substrate, confirming the effective removal of the polystyrene template.

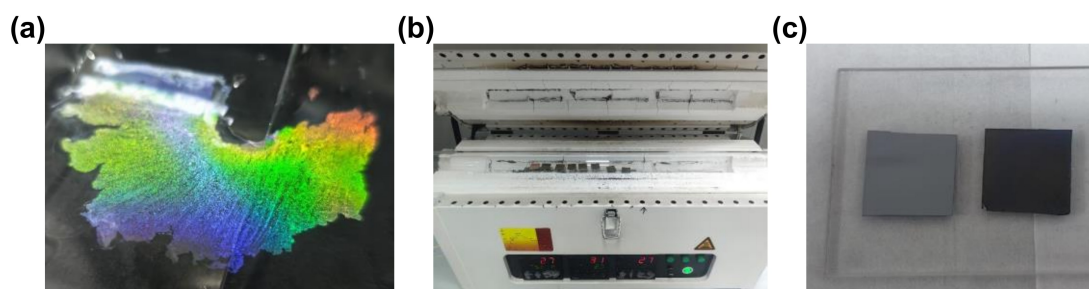


Figure S6. (a) Schematic illustration of the monolayer polystyrene microsphere film formed at the air–water interface. (b) Schematic illustration of the CAD heating tube used for thermal treatment. (c) Photograph of the experimental sample after annealing.

S8. Optical Influence of the PET Encapsulation Layer

To clarify the optical influence of the PET adhesive tape used for flexible transfer and encapsulation, additional FDTD simulations were performed for a PET film and the PET-encapsulated DS-BMA structure.

Figure S7a shows the simulated absorption spectrum of a 60 μm PET film. The PET film exhibits low absorption across most of the 220–2500 nm spectral range. Figure S7b shows the simulated absorption spectra of the PET-encapsulated DS-BMA under front-side and back-side illumination. The encapsulated structure maintains broadband high absorption over the 220–2500 nm wavelength range, with only minor spectral variations compared with the freestanding structure, indicating a limited optical contribution from the PET encapsulation layer.

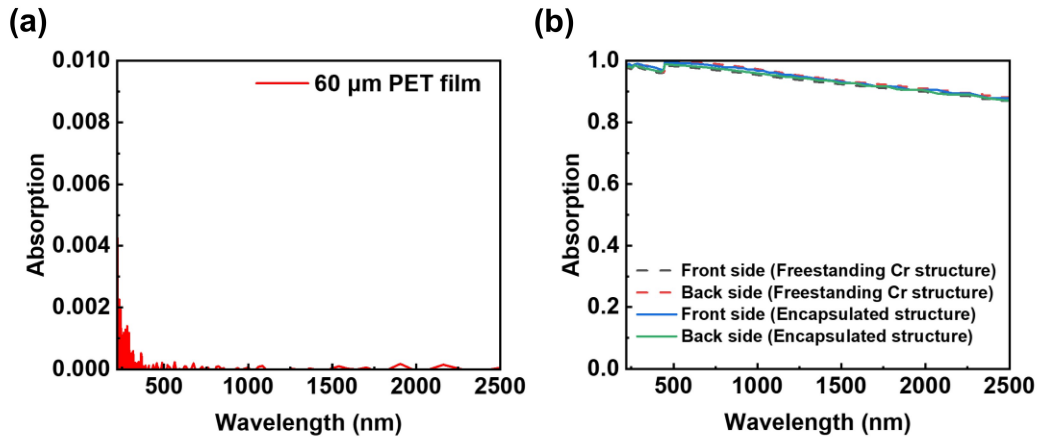


Figure S7. (a) Simulated absorption spectrum of a 60 μm PET film. (b) Simulated absorption spectra of the PET-encapsulated DS-BMA under front-side and back-side illumination.

S9. SEM characterization of the samples

Supplementary Figure S8a shows the surface morphology of a 500 nm-thick chromium (Cr) film deposited by physical vapor deposition using 400 nm polystyrene microspheres as the template. The scanning electron microscopy (SEM) image reveals that the periodic arrangement of the microsphere array is faithfully preserved, resulting in a uniform and well-ordered surface morphology. Supplementary Figure S8b presents a Cr film fabricated under identical deposition conditions but using 500 nm microspheres as the template. Cross-sectional SEM imaging, obtained by tilting the sample stage, clearly resolves the thickness of the Cr layer as well as its conformal coverage over the microsphere array, confirming the uniformity and structural consistency of the deposited film. Supplementary Figure S8c shows the SEM image of the back side of the Cr film after being detached from the substrate using a tape-transfer method. This image provides additional insight into the interfacial structure between the film and the substrate, which is important for evaluating film adhesion and structural integrity.



Figure S8. (a) Cross-sectional SEM image of a 500 nm-thick Cr film deposited using 400 nm polystyrene microspheres as the mask. (b) Cross-sectional SEM image of a 500 nm-thick Cr film deposited using 500 nm polystyrene microspheres as the mask. (c) SEM image of the back side of the sample after tape transfer.

S10. Experimental absorption spectra with different chromium thicknesses

The effect of chromium layer thickness on the absorption performance of the metamaterial absorber was experimentally investigated. Supplementary Figure S9 presents the measured absorption spectra under front-side and back-side illumination, respectively, for different Cr thicknesses. It can be seen that the absorber maintains high absorption over a broad spectral range across a wide range of Cr thicknesses. This result further confirms the strong fabrication tolerance of the proposed metamaterial design, which is beneficial for experimental implementation and scalable manufacturing without stringent control over film thickness.

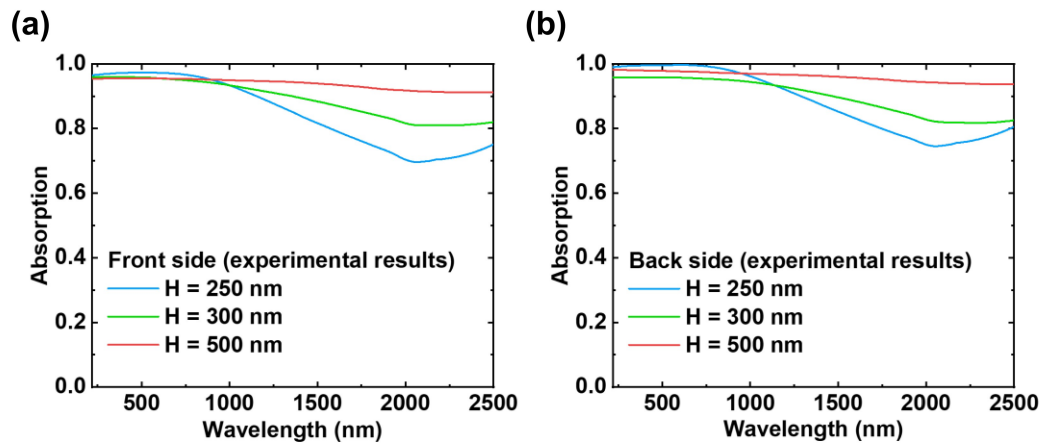


Figure S9. (a) Experimental absorption spectra of the metamaterial absorber under front-side illumination for different chromium layer thicknesses. (b) Experimental absorption spectra under back-side illumination for different chromium layer thicknesses.

S11. Performance comparison of representative broadband absorbers

The table summarizes the key performance metrics of representative broadband absorbers reported in recent literature, including the operational wavelength bandwidth, average absorption within the solar spectral range, total structure thickness, material composition, fabrication methods, and functional characteristics such as transferability and double-sided absorption. The performance of the metamaterial absorber presented in this work is included for direct comparison.

Table S1 Absorption performance of other broadband absorbing materials

Bandwidth (nm)	Average Absorption	Structure Thickness (nm)	Specific Structure	Fabrication methods	Transferable	Double-sided Absorption
Ren ¹ 200-5000	0.93	1700	Ti/SiO ₂ /Ti convex structure	Nano-imprint lithography, Wet etching, Magnetron sputtering	No	No
Ren ² 300-2500	0.91	675	Al/SiO ₂ /Ti concave structure	Nano-imprint lithography, Magnetron sputtering	No	No
Yang ³ 300-3000	0.98	1365	Cu/HMVF/MMVF/LMVF/Al ₂ O ₃ nano-cone structure	Colloidal lithography, Magnetron sputtering	No	No
Li ⁴ 250-25000	>0.9	2000	Hierarchical coral-structured TiN	Cu ²⁺ ion etching, Two-step Boehmite treatment, Dip-coating, Atomic layer deposition	No	No
Liao ⁵ 250-1000	0.95	1830	Au/rGO honeycomb aperture array	Template-assisted assembly, Magnetron sputtering	No	No
Zhang ⁶ 200-800	0.9	530	Au nanocluste, SiO ₂ /Au film	Self-assembly, Magnetron sputtering	No	No
Shi ⁷ 300-1300	0.89	125	Mo(Au)-SiO ₂ -Al with tangent nanoscale ball-cap structure	Nanoparticle self-assembly, Magnetron sputtering	No	No
Shen ⁸ 400-800	Front side: 0.9 Back side: 0.89	1050	Tapered dielectric nanostructure coated with Cr film	Nanoimprint lithography, E-beam evaporation	No	Yes
Our work 220-2500	Front side :0.93 Back side: 0.96	750	Complementary Cr nanorod arrays	Colloidal self-assembly, Magnetron sputtering	Yes	Yes

S12. Mid-Infrared Emissivity Analysis and Temperature Calibration

In this work, a FLIR ONE Pro thermal camera operating in the wavelength range of 7.5–14 μm was employed. The infrared camera provides only discrete emissivity presets (0.95, 0.80, 0.60, and 0.30). Since the experimentally determined emissivities are closest to 0.95, measurements were performed using the 0.95 setting, followed by FTIR-based radiometric correction. The thermal radiation (L) received by the infrared camera can be expressed as:

$$L = \int_{\lambda_1}^{\lambda_2} [\varepsilon_\lambda B_\lambda(T) + (1 - \varepsilon_\lambda) B_\lambda(T_{\text{refl}})] d\lambda \quad (\text{S2})$$

where ε_λ is the spectral emissivity, $B_\lambda(T)$ is the spectral radiance given by Planck's law, T is the actual sample temperature, and T_{refl} is the reflected apparent temperature, which was set to 25 $^\circ\text{C}$.

The camera calculates the apparent temperature T_{cam} by assuming a fixed emissivity $\varepsilon_{\text{set}} = 0.95$:

$$L_{\text{cam}} = \int_{\lambda_1}^{\lambda_2} [\varepsilon_{\text{set}} B_\lambda(T_{\text{cam}}) + (1 - \varepsilon_{\text{set}}) B_\lambda(T_{\text{refl}})] d\lambda \quad (\text{S3})$$

However, it remains unclear whether the metasurface possesses a similar emissivity. Therefore, emissivity correction is required to obtain the actual surface temperature. For convenience, an effective emissivity over the camera operating band is defined as:

$$\varepsilon_{\text{eff}}(T) = \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda B_\lambda(T) d\lambda}{\int_{\lambda_1}^{\lambda_2} B_\lambda(T) d\lambda} \quad (\text{S4})$$

Because the effective emissivity defined in Equation (S5) is obtained through Planck-weighted integration, it is theoretically temperature dependent. To verify the validity of using a fixed effective emissivity, $\varepsilon_{\text{eff}}(T)$ was calculated using the measured FTIR spectra over the experimental temperature range (25–95 $^\circ\text{C}$). According to Kirchhoff's law of thermal radiation, the spectral emissivity is equal to the spectral absorptivity (A_λ):

$$\varepsilon_\lambda = A_\lambda \quad (\text{S5})$$

Figure S10a shows the experimentally measured mid-infrared absorptance spectra of the encapsulated sample within the operating wavelength range of the infrared camera (7.5–14 μm). Using the experimentally measured FTIR spectra and Planck-weighted integration over the camera detection band, the effective emissivities were determined to be **0.923** for the front side and **0.891** for the back side of the encapsulated device, respectively, within the 7.5–14 μm band. Meanwhile, the experimental absorptance spectrum of the untransferred sample (Figure S10b) yields a lower effective emissivity of approximately **0.60**. As shown in Figure S10c, both the front- and back-side effective emissivities exhibit only negligible variations (<1%) within this temperature interval. Therefore, the effective emissivity can be reasonably approximated as temperature-independent in the present radiometric temperature-correction analysis.

Then, the actual surface temperature is obtained by equating the measured radiation to the camera-estimated radiation:

$$\varepsilon_{\text{eff}} \int_{\lambda_1}^{\lambda_2} B_{\lambda}(T) d\lambda = \varepsilon_{\text{set}} \int_{\lambda_1}^{\lambda_2} B_{\lambda}(T_{\text{cam}}) d\lambda + (\varepsilon_{\text{eff}} - \varepsilon_{\text{set}}) \int_{\lambda_1}^{\lambda_2} B_{\lambda}(T_{\text{refl}}) d\lambda \quad (\text{S6})$$

Using the experimentally determined effective emissivity of approximately 0.60, numerical calculation shows that the apparent temperature of the untransferred sample measured by the thermal camera is 50.1 $^{\circ}\text{C}$, corresponding to an actual surface temperature of approximately 66.5 $^{\circ}\text{C}$.

For the encapsulated device, the experimentally determined emissivities are much closer to the camera setting ($\varepsilon_{\text{set}} = 0.95$). Consequently, only minor radiometric corrections are required. After correction, the steady-state temperatures under one-sun illumination are 76.2 $^{\circ}\text{C}$ for front-side illumination and 73.3 $^{\circ}\text{C}$ for back-side illumination. The relatively small temperature difference further confirms the nearly symmetric photothermal conversion performance of the double-sided absorber after encapsulation.

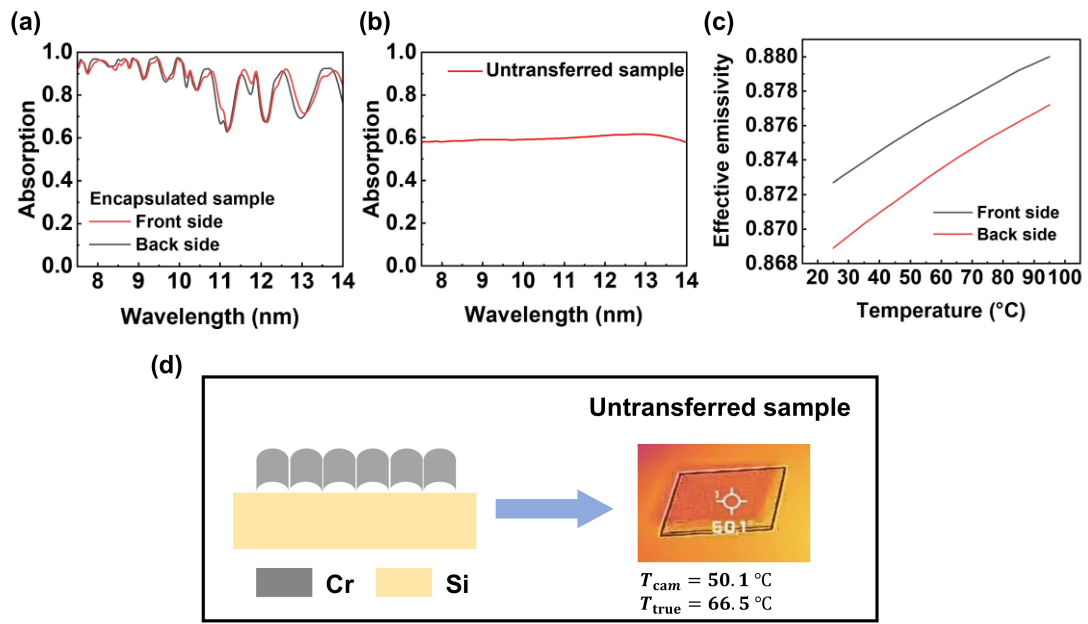


Figure S10. (a) Experimental mid-infrared absorption spectrum of the encapsulated sample in the 7.5–14 μm range. (b) Experimental mid-infrared absorption spectrum of the untransferred sample in the 7.5–14 μm range. (c) Temperature dependence of the effective emissivity calculated using Equation. (d) The thermal image of the sample taken by an infrared thermal imager shows a temperature of 50.1 $^{\circ}\text{C}$. Based on the experimental absorption spectrum and radiometric correction, the actual temperature is estimated to be approximately 66.5 $^{\circ}\text{C}$.

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