A High-temperature Near-perfect Solar Selective Absorber Combining Tungsten Nanohole and Nanoshuriken Arrays

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Abstract

A solar selective absorber is a key component that directly influences the photothermal efficiency in high-temperature solar energy harvesting. In the present work, a solar selective absorber combining tungsten nanohole and nano shuriken arrays was proposed and studied. Firstly, the geometry of the absorber was optimized, obtaining a near-perfect absorber. Then, evaluation of the near-perfect absorber indicated that it can achieve near unit spectral absorptance within 0.28-1.25 μm and obtain a solar absorptance of 0.9457, thus achieving a photothermal efficiency of 91.52% at 1273 K under 1000 suns. Then, analysis of its absorbing mechanisms revealed that the high solar absorptance is contributed by the impedance matching, and the coupling effects of the cavity resonance, surface plasmon polaritons, magnetic polaritons, and local surface plasmon resonance. In addition, a study on the effects of the geometric parameters indicated that the absorber performance is insensitive to the changes in geometric parameters when the changes are within fabrication uncertainties. Finally, the effects of the polarization angle and incident angle were examined, indicating that the near-perfect absorber exhibits high insensitivities to wide-angle incidence and all-angle polarization. These results indicate the near-perfect absorber is promising for high-temperature solar energy harvesting.

Keywords: High-temperature solar energy harvesting; Solar selective absorber; Nanohole and nano shuriken; Selective absorption; Photothermal efficiency.

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1. Introduction

Nuclear fusion in the sun emits inexhaustible and pollution-free solar energy. Solar energy utilization is a promising approach to solving problems such as the energy crisis,^[1] environmental pollution,^[2] and global warming.^[3] Solar power generation technologies mainly include photovoltaics,^[4] concentrating solar power (CSP),^[5,6] thermophotovoltaics,^[7] etc.

In operation, CSP and thermophotovoltaics first convert solar energy to thermal energy through solar selective absorbers and then convert the thermal energy to electricity.^[8-10] For the typical commercial CSP, it absorbs solar irradiation at below 838 K and drives a low-efficiency (~40%) Rankine cycle.^[11] To improve its efficiency, a molten-tin CSP that produces tin at above 1573 K and drives a cascade cycle has been proposed by De Angelis *et al.*^[12], Wilk *et al.*^[13] and Amy *et al.*^[14] The typical thermophotovoltaic system absorbs solar irradiation by an absorber and emits radiation to a photovoltaic

cell by an emitter, where the operating temperature can achieve 1000-1500 K.^[15,16]

During the photothermal processes in the CSP and the thermophotovoltaics, the absorbers will absorb solar irradiation and emit infrared radiation to the environment intensively at extremely high temperatures.^[17] To achieve high photothermal efficiency (η), the solar selective absorber should exhibit near unit total solar absorptance and near zero emittance within the infrared spectrum.^[18] In addition, the solar selective absorber should be able to withstand high temperatures.^[19]

Due to the interband transition, the tungsten (W) can achieve relatively high spectral absorptivity of 0.30-0.56 when the wavelength (λ) is within 0.25-1.59 μm and small spectral emittance of < 0.1 with the λ beyond 2 μm .^[20] Additionally, the melting point of tungsten is around 3673 K, which is much higher than the operating temperature of the absorber. Hence, tungsten is a perfect alternative material for the absorber, and some absorbers have been proposed based on tungsten in the literature.

The first group of studies focused on multilayer absorbers. For example, Tian *et al.*^[21] experimentally investigated a

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SiO₂/Al₂O₃/W/Al₂O₃/W multilayer absorber, obtaining the total solar absorptance (α_{tot}) of 0.881 and the η of 82.5% under 373 K and one sun (*i.e.* 1.0 kW·m⁻²). Niranjana *et al.*^[22] fabricated a W/WAlSiN/SiON/SiO₂ multilayer absorber, which can achieve the α_{tot} of 0.955 and the η of 89.5% at 773 K and 100 suns. Wu *et al.*^[23] proposed a SiO₂/W multilayer absorber with square holes, obtaining the average α_{λ} of 0.986 within 0.26–1.58 μm and the η of 90.32% under 373 K and one sun. Dan *et al.*^[24] designed a W/WAlN/WAlON/Al₂O₃ multilayer absorber and achieved a high α_{tot} of 0.934 and a low emittance of 0.11 at 773 K. Aikifa *et al.*^[25] designed a SiO₂/SiC-W/W three-layer structure, and the SiC-W layer includes three SiC sublayers containing random tungsten nanoclusters in different concentrations. And this design can obtain the α_{tot} of 0.9545 and the emittance of 0.2 at 1050 K.

The next group of studies focused on developing 1D, 2D, and 3D gratings. For example, Zhang *et al.*^[26] designed a SiO₂/W/SiO₂ 1D grating on a tungsten film, achieving the average α_{λ} of 0.960 within 0.3–1.2 μm . Yeng *et al.*^[27] proposed a tungsten absorber with a cylindrical hole array, achieving the η of around 72% under 1000 K and 500 suns. Wang *et al.*^[28] designed a 2D tungsten grating, achieving the α_{tot} of 0.88 and the η of around 86% under 373 K and one sun. Liang *et al.*^[29] designed an absorber that consists of a tungsten square hole array filled by SiO₂, achieving the α_{tot} of 0.946 and the η of 93.4% at 373 K and one sun. Wang *et al.*^[30] deposited a truncated pyramid array on an MgF₂/W basis, achieving the α_{λ} of > 0.9 within the solar spectrum and the η of 78% at 373 K and one sun. Tian *et al.*^[31] designed an Al₂O₃ pyramid array containing random tungsten nanoparticles on a W/Al₂O₃/W basis, achieving the α_{tot} of 0.941 and the emittance of 0.06 at 773 K. Lin *et al.*^[32] constructed a 3D woodpile-like tungsten emitter, achieving the average α_{λ} of above 0.8 within 1.5–1.9 μm . Song *et al.*^[33] numerically investigated an absorber with a W/SiO₂/W nano cuboid array on a tungsten basis, and the results showed that the average α_{λ} of 0.953 is obtained within 0.6–1.8 μm . Sakurai *et al.*^[34] embedded a tungsten nanosphere array in a dielectric layer, achieving the α_{tot} of 0.896 and the η of 85.3% at 1000 K and 86.3 suns. Hou *et al.*^[35] designed an absorber that consists of a cylindrical SiO₂ array coated by tungsten and Al₂O₃, which can achieve the α_{tot} of above 0.95 and keep stable under 1300 K. Ye *et al.*^[36] proposed an absorber using a nanosphere-nano cuboid array, obtaining the α_{tot} of 0.9535 and the η of 87.56% under 1000 K and 100 suns. Xu *et al.*^[37] fabricated an absorber that employs a tungsten nanodisc array on a SiO₂/W basis, and the average α_{λ} is 0.90 within 0.5–1.75 μm . Chang *et al.*^[38] fabricated an absorber that employs tungsten nanodiscs with different sizes on an Al₂O₃/W basis, finding it can keep stable under 1473 K.

To sum up, although many selective solar absorbers have been proposed, their performance has not reached the ideal. Therefore, as pointed out in different references,^[39–41] it is a formidable but significant task to design a polarization-independent, wide-angle, high-photothermal-efficiency selective solar absorber with a relatively simple structure. This

work proposed a solar selective absorber by combining simple tungsten nanohole and nano shuriken arrays for high-temperature (>1273 K) solar energy harvesting. Firstly, the geometric parameters of the proposed absorber were optimized to obtain near-perfect performance based on the finite element method and orthogonal experimental design. Then, a 3D full-wave simulation was used to reveal the absorbing mechanisms of the absorber. In addition, the effects of the geometric parameters on the performance were also analyzed. Finally, the sensitivities of the proposed absorber to polarization and incidence angles were further tested.

2. Design of the solar selective absorber

The solar absorption of the tungsten-based solar absorber can be enhanced by designing its nanostructures through producing and tuning plasmonic modes such as cavity resonances (CRs), surface plasmon polaritons (SPPs), magnetic polaritons (MPs), and localized surface plasmon resonance (LSPR).^[40,41] CR refers to the electric field enhancement caused by interference effects within the cavity, and the light is absorbed via multiple reflections in the cavity. SPPs refer to plasma oscillations of free electrons resonantly excited by incident light at a metal-dielectric interface, and the SPPs also propagate along the surface with evanescent electromagnetic fields. MPs refer to the magnetic enhancement provoked by a metal-dielectric-metal structure, and the circulating current caused by it will lead to the dissipation of electromagnetic energy due to ohmic dissipation.^[37] LSPR refers to the collective oscillation of conduction band electrons at the interface of metallic structures whose sizes are comparable to or smaller than the wavelength of incident light.

To enhance the solar absorption in high-temperature (>1273 K) solar energy harvesting (see Fig. 1a), a solar selective absorber combining tungsten nanohole and nano shuriken arrays (see Fig. 1b) was designed by producing and tuning these plasmonic modes reasonably. In the design process, firstly, a tungsten layer with a regular octagonal nanohole array (layer 2, see Figs. 1c, e) was designed on a bottom tungsten layer (layer 1) to produce CRs. Then, a tungsten nano shuriken array (layer 4, see Figs. 1b, d) was designed to produce SPPs and LSPRs. Each nano shuriken can be regarded as a combination of two mutually perpendicular rhombic prisms (see Fig. 1d). In addition, there is also a layer of dielectric (layer 3, see Fig. 1c) between the nano shuriken array and the nanoholes to form a metal-dielectric-metal structure for producing MPs. Moreover, the nanoholes and the nano shurikens were covered by SiO₂ for preventing tungsten from grain growth,^[42] and the SiO₂ covering around every nano shuriken was designed to be a cuboid (see Fig. 1d). Finally, a top SiO₂ layer (layer 5) was coated above the nano shurikens for preventing the tungsten from being oxidized.

This designed absorber can be fabricated expediently in the following ways. Firstly, a 650-nm tungsten film is deposited on a clean substrate by magnetron sputtering. Then, an E-beam

Fig. 1 (a) Sketch of a concentrating solar collector, (b) Sketch of the solar selective absorber, (c) A unit cell of the absorber, (d) Top view of a nano shuriken, (e) Top view of a unit cell.

resist is spin-coated on the film and baked. Then, electron beam lithography is used to fabricate octagonal holes on the E-beam resist, which is used as the etching mask when the octagonal tungsten nanoholes are etched by Inductively Coupled Plasma (ICP) etching. Then, electron beam evaporation is used to fill the nanoholes with SiO₂ and deposit a 30-nm SiO₂ film (layer 3) on it. Then, a 120-nm tungsten film is deposited on layer 3 by the magnetron sputtering. Then, the 120-nm tungsten film is etched to obtain nano shurikens by the ICP etching. Then, a 180-nm SiO₂ film is deposited on layer 3 by electron beam evaporation. Finally, the 180-nm SiO₂ film is etched to obtain the SiO₂ covering around every nano shuriken. The roughness values of the magnetron sputtering, electron beam evaporation, electron beam lithography, and ICP etching can reach <5 nm,^[43] <10 nm,^[44] <5 nm,^[45] and <10 nm,^[46] respectively.

The geometric parameters of the proposed absorber mainly include the length of the period (p) of the array, the thickness of the layer 1 (h_1), the excircle diameter (d), and the height (h_2) of the regular octagonal nanohole, the height of the dielectric layer 3 (h_3), the height (h_4) of the tungsten nano shuriken, the long axis (c) and the short axis (d) of the rhombus cross-section of the rhombic prism, the diagonal length (l) of a square cross-section of the SiO₂ cuboid surrounding the nano shuriken, and the thickness of the layer 5 (h_5). These parameters would be optimized and their effects on the performance would be discussed.

3. Numerical model for the radiation transport and absorption

When solar radiation irradiates the absorber, the electromagnetic waves would interact with the nanohole and nano shuriken arrays, and a part of the radiation would be

absorbed. The radiation transport and absorption processes in the absorber were simulated by solving Maxwell's equations (see Eq. (1)) through the finite element method.^[47]

Due to the periodic characteristics of the absorber structure (see Fig. 1b), only a unit cell (see Fig. 1c) is necessary for simulating the radiation transport and absorption processes. Meanwhile, Floquet periodicity boundary conditions described by Eq. (2) and Eq. (3) can be employed on the left and right boundaries, and front and back boundaries of the unit cell, respectively. On the upper surface of the unit cell, a port condition was used to allow the electromagnetic waves to enter the absorber. On the bottom surface, a port condition was employed to count the transmitted radiation. To enhance the solar absorption as much as possible, layer 1 is designed to be 150 nm to ensure that no radiation would transmit the absorber and reach the bottom surface.

$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2 \epsilon_r \mathbf{E} = 0 \quad (1)$$

$$\mathbf{E}_{\text{dst}} = \mathbf{E}_{\text{src}} e^{-ik_F(\mathbf{r}_{\text{dst}} - \mathbf{r}_{\text{src}})} \quad (2)$$

$$\mathbf{H}_{\text{dst}} = \mathbf{H}_{\text{src}} e^{-ik_F(\mathbf{r}_{\text{dst}} - \mathbf{r}_{\text{src}})} \quad (3)$$

where $\mathbf{E}$ and $\mathbf{H}$ are electric and magnetic fields, respectively; k_0 is the wave number; ϵ_r is the dielectric function, which is calculated by $\epsilon_r = (n - ik)^2$; n and k are complex refractive indexes; $\mathbf{r}_{\text{dst}}$ and $\mathbf{r}_{\text{src}}$ are positions of destination boundary and source boundary, respectively; the dst and src in the subscripts refer to destination and source, respectively; $\mathbf{k}_F$ is the k -vector of Floquet periodicity.

In the simulation, the wavelength-dependent refractive indexes of tungsten and SiO₂ were considered, as shown in Fig. 2.^[48,49] It is worth noting that the melting point of SiO₂ (~2000 K) and tungsten (~3700 K) are much higher than the operating conditions of thermophotovoltaics and CSP (the maximum is ~1573 K) and the thermal expansion coefficients of these two materials are relatively small, so the refractive indexes of the

materials of the absorber vary very little with temperature. Therefore, the effects of temperature on the refractive indexes can be ignored.^[50]

Fig. 2 The refractive indexes of tungsten and SiO₂.

Since the thickness of layer 1 ($h_1 = 150$ nm) exceeds the penetration depth of incident radiation, the spectral transmittance (τ_λ) equals zero.^[51] The relation between the spectral absorptance (α_λ) and the spectral reflectance (ρ_λ) can be expressed as Eqs. (4)-(5).^[29,52]

$$\alpha_\lambda = 1 - \rho_\lambda \quad (4)$$

$$\rho_\lambda = |S_{11}|^2 \quad (5)$$

where S_{11} is the scattering matrix coefficient of the reflection.

The S_{11} can also be used to analyze the effective impedance z_λ (see Eq. (6)) for further understanding of the absorption characteristics.^[53] After considering Eqs. (4)-(6) together, the spectral absorptance (α_λ) can be expressed as an equation of the real part ($Re(z)$) and imaginary part ($Im(z)$) of z_λ in Eq. (7).^[54]

$$z_\lambda = \frac{\sqrt{(1+S_{11})^2 - S_{21}^2}}{\sqrt{(1-S_{11})^2 - S_{21}^2}} \quad (6)$$

$$\alpha_\lambda = \frac{4Re(z)}{[1+Re(z)]^2 + [Im(z)]^2} \quad (7)$$

The total solar absorptance of the absorber for the AM1.5 solar spectrum (α_{tot}) can be expressed as Eq. (8)^[31,55], and the total emittance (ε_{tot}) of the absorber under the temperature of T can be expressed as Eq. (9).^[56] It should be noted that the α_{tot} of the absorber should be the average of the absorptances of TE polarized wave (*i.e.* the electric field is in the y direction in Fig. 1b) and TM polarized wave (*i.e.* the magnetic field is in the y direction in Fig. 1b). However, due to the symmetric structure of the absorber, the TE and TM polarized waves are totally equivalent under normal incidence. Therefore, only the TM polarized wave is necessary while evaluating the α_{tot} under normal incidence using Eq. (8). The performance of the absorber can also be evaluated by its photothermal efficiency (η). After considering the radiative heat loss but ignoring the

convective and conductive heat losses, the η can be estimated using Eq. (10).^[57]

$$\alpha_{tot} = \frac{\int_{0.28\mu m}^{4\mu m} \alpha_\lambda I_{AM1.5}(\lambda) d\lambda}{\int_{0.28\mu m}^{4\mu m} I_{AM1.5}(\lambda) d\lambda} \quad (8)$$

$$\varepsilon_{tot} = \frac{\int_{0.28\mu m}^{50\mu m} I_B(\lambda, T) \alpha_\lambda d\lambda}{\int_{0.28\mu m}^{50\mu m} I_B(\lambda, T) d\lambda} \quad (9)$$

$$\eta = \alpha_{tot} - \varepsilon_{tot} \frac{\sigma(T_{abs}^4 - T_{amb}^4)}{C \cdot I_s} \quad (10)$$

where $I_{AM1.5}(\lambda)$ is the spectral solar irradiance under the atmosphere of AM1.5;^[58] T_{abs} and T_{amb} are the temperatures of the absorber and ambient, respectively; σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$; I_s is AM1.5 solar irradiance, which is equal to $1 \text{ kW} \cdot \text{m}^{-2}$ (*i.e.* one sun); C is the solar concentration ratio; $I_B(\lambda, T)$ is the spectral irradiance of the blackbody radiation, which is obtained by Planck's law,^[56] as shown in Eq.(11).

$$I_B(\lambda, T) = \frac{c_1 \lambda^{-5}}{e^{\frac{c_2}{\lambda T}} - 1} \quad (11)$$

where $c_1 = 3.7419 \times 10^{-16} \text{ W} \cdot \text{m}^2$ and $c_2 = 1.4388 \times 10^{-2} \text{ m} \cdot \text{K}$.

4. Grid independence check and model validation

A grid independence check was carried out to ensure that the simulation results would not be affected by the number of grids, and the proposed absorber with the parameters of $h_1 = 150$ nm, $h_2 = 500$ nm, $h_3 = 30$ nm, $h_4 = 120$ nm, $h_5 = 60$ nm, $d = 366$ nm, $p = 450$ nm, $c = 260$ nm, $b = 140$ nm, and $l = 300$ nm, was taken as an example to show the checking process. Several tetrahedral grid systems with different grid numbers were generated, and the TM polarized wave was normally irradiated on the absorber. The total solar absorptance (α_{tot}) was selected as the checking criterion, and the α_{tot} values under different grid systems were compared as shown in Table 1. It can be found in Table 1 that the α_{tot} changes from 0.9457 to 0.9456 when the grid number increases from 156,184 to 506,179, where the net deviation is just 0.0001. These results indicate that 156,184 grids should be enough for this absorber case. Similar grid checks have also been conducted for other cases.

Table 1. Grid independence check.

Grid system	Grid number	Total solar absorptance α_{tot}
1	9,708	0.9467
2	29,817	0.9462
3	49,178	0.9462
4	88,297	0.9459
5	156,184	0.9457
6	506,179	0.9456

To verify the FEM model, the spectral absorptance (α_λ) of an absorber that employs a nanodisk array on a SiO₂/W basis (see Fig. 3) was simulated by the current FEM model. After the simulation, the present results were compared with Han *et al.*'s data obtained through finite-different time-domain (FDTD) simulation,^[37] as shown in Fig. 3.

It can be found that the present curve agrees very well with Han *et al.*'s curve within a wide wavelength range of 2.002 μm ($\lambda = 0.498\text{--}2.5\ \mu\text{m}$), and the deviation is smaller than 0.019. When $\lambda < 0.498\ \mu\text{m}$, the variation trends of the two curves are similar although deviation exists, which can be explained by the slight differences in optical properties and model settings. The above comparison indicates that the current FEM model is reliable.

Fig. 3 Comparison of present FEM results and Han *et al.*'s FDTD data [37].

5. Results and discussion

In this section, firstly, the proposed absorber was optimized to obtain a near-perfect absorber, and its performance was analyzed. Then, mechanisms for selective absorption in the near-perfect absorber were revealed and discussed. Then, the effects of the geometric parameters on the absorber performance were discussed. Finally, the effects of polarization angle and incident angle were studied.

5.1 Near-perfect solar selective absorber

The ideal solar selective absorber should be able to achieve the highest photothermal efficiency (η) under its absorber temperature (T_{abs}) and the concentration ratio (C). To realize this purpose, the ideal absorber should achieve the spectral absorptance (α_λ) of 1.0 when the wavelength is below the truncation wavelength (λ_{tru}) for absorbing the solar irradiance as much as possible. Meanwhile, when the wavelength is beyond λ_{tru} , the α_λ should be zero for reducing the radiant heat loss.

Considering Eq. (10), the truncation wavelength (λ_{tru}) under different absorber temperatures (T_{abs}) and concentration ratios (C) can be obtained as shown in Table 2. It can be observed in Table 2 that the truncation wavelengths under the typical concentration ratio of 1000 are between 1.76–1.8 μm when T_{abs} changes from 1273 K to 1573 K. These results indicate that the α_λ should be designed to decrease quickly from around 1.0 to around 0 at near 1.76–1.8 μm while

designing a solar selective absorber working at above 1273 K and around 1000 suns.

Table 2. The truncation wavelengths (λ_{tru}) under several high temperatures and the typical concentration ratio.

Concentration ratio	Absorber temperature	Ambient temperature	Truncation wavelength
C / suns	T_{abs} / K	T_{amb} / K	λ_{tru} / μm
1000	1273	300	1.794
1000	1373	300	1.791
1000	1473	300	1.776
1000	1573	300	1.761

Based on the above-suggested range of the truncation wavelength, the structures of the proposed absorber were optimized through multiple orthogonal experiments. In the optimization, the objective function η_m was defined as Eq. (12).

$$\eta_m = (\eta_{1273} + \eta_{1373} + \eta_{1473} + \eta_{1573})/4 \quad (12)$$

where η_{1273} , η_{1373} , η_{1473} , and η_{1573} are the photothermal efficiencies of the absorber when the absorber temperatures are 1273 K, 1373 K, 1473 K, and 1573 K, respectively, under $C = 1000$ and $T_{\text{amb}} = 300$ K.

After the optimization, a near-perfect optimal absorber with the parameters of $h_1 = 150$ nm, $h_2 = 500$ nm, $h_3 = 30$ nm, $h_4 = 120$ nm, $h_5 = 60$ nm, $d = 366$ nm, $p = 450$ nm, $c = 260$ nm, $b = 140$ nm, and $l = 300$ nm was obtained. The spectral absorptance (α_λ) of the optimal absorber under a normally incident TM polarized wave is shown in Fig. 4. It can be seen in Fig. 4 that α_λ drops sharply within 1.7–2.1 μm , which is close to the suggested range of the truncation wavelength of the ideal absorber. Moreover, as can be seen in Fig. 4, the optimal absorber can achieve the α_λ of above 0.8 within 0.28–1.7 μm , and especially when $\lambda = 0.28\text{--}1.25\ \mu\text{m}$, the α_λ almost reaches 1.0. Fig. 4 also shows the absorbed solar spectral irradiance of the optimal absorber under the AM1.5 solar spectrum. It can be seen in Fig. 4 that the spectral irradiance

Fig. 4 Spectral absorption characteristics of the optimal absorber under normally incident TM polarized wave and AM1.5 solar spectrum.

within 0.28 μm -1.8 μm is almost completely absorbed. Due to the above good absorption performance, the total solar absorptance (α_{tot}) of 0.9457 is achieved by the optimal absorber.

In order to clearly demonstrate the photothermal conversion performance of the near-perfect absorber, Table 3 shows the total solar absorptance (α_{tot}), the total emittance (ε_{tot}), and the photothermal efficiency (η) of the optimal absorber and the ideal absorber under several typical temperatures and concentration ratios.

As shown in Table 3, when $C = 5$ -50 suns and $T_{\text{abs}} = 373$ K-673 K, the photothermal efficiency (η) of the optimal absorber reaches 93.74%-94.18%, which indicates that the spectral selectivity of this absorber is excellent. In addition, when $C = 1000$ suns and $T_{\text{abs}} = 1273$ K-1573 K, the total solar absorptance (α_{tot}) of the optimal absorber (0.9457) is just 0.0059-0.098 lower than that of the ideal absorber. Meanwhile, the total emittance (ε_{tot}) of the optimal absorber is within 0.2056-0.3228, which is just 0.0227-0.0321 higher than that of the ideal absorber. Furthermore, the optimal absorber can achieve the η of 83.38%-91.52% which is just 1.33%-1.70% lower than that of the ideal absorber. It can be concluded from Table 3 that the performance of the optimal absorber is quite close to that of the ideal absorber. Therefore, this optimal absorber can be regarded as a near-perfect absorber. More performance evaluations indicated that the near-perfect absorber can achieve the low ε_{tot} of 0.0491-0.3228, the high η of 94.52%-83.38% when $C = 1000$ suns, and the T_{abs} is in the wide range of 673 K-1573 K.

In addition, the performance of the near-perfect absorber was compared with that of some absorbers reported previously in Table 3. When $T_{\text{abs}} = 1000$ K and $C = 86.3$ suns, the η of the present near-perfect absorber is 87.16% which is 1.86% larger than the 85.3% of an absorber based on tungsten nanosphere

arrays.^[34] Moreover, when $T_{\text{abs}} = 1000$ K and $C = 100$ suns, the η of the near-perfect absorber is 88.17% which is 0.55% higher than the 87.62% of an absorber constructed by tungsten nanosphere-nano cuboid arrays.^[36] Furthermore, when $T_{\text{abs}} = 1050$ K and $C = 100$ suns, the near-perfect absorber achieves the η of 85.81% which is 3.13% higher than the 82.68% of a SiO_2/SiC -W/W three-layer absorber.^[25] These results indicate that the near-perfect absorber can achieve better performance than some existing absorbers.

5.2 Mechanisms of the near-perfect selective performance

To understand the mechanisms of the near-perfect selective performance, the energy transport and absorption of the TM polarized wave in the absorber were simulated under normal incidence, and the absorption characteristics were analyzed as follows.

Firstly, the contributions of different layers to the spectral absorptance (α_{λ}) of the optimal absorber are shown in Fig. 5. It can be seen in Fig. 5 that layer 2 and layer 4 are the main

Fig. 5 Contributions of different layers to the spectral absorptance.

Table 3. Performance of different absorbers under typical temperatures and concentration ratios.

Absorber	C / suns	T_{abs} / K	T_{amb} / K	α_{tot}	ε_{tot}	η
Present	5	373	300	0.9457	0.0310	94.18%
Present	10	473	300	0.9457	0.0350	93.48%
Present	20	573	300	0.9457	0.0405	93.43%
Present	50	673	300	0.9457	0.0491	93.74%
Ideal	1000	1273	300	0.9555	0.1813	92.85%
Present	1000	1273	300	0.9457	0.2056	91.52%
Ideal	1000	1373	300	0.9552	0.2214	91.07%
Present	1000	1373	300	0.9457	0.2441	89.67%
Ideal	1000	1473	300	0.9538	0.2564	88.54%
Present	1000	1473	300	0.9457	0.2834	87.02%
Ideal	1000	1573	300	0.9516	0.2907	85.08%
Present	1000	1573	300	0.9457	0.3228	83.38%
Present	86.3	1000	0	0.9457	0.1129	87.16%
Ref.[34]	86.3	1000	0	0.8960	0.0660	85.30%
Present	100	1000	0	0.9457	0.1129	88.17%
Ref.[36]	100	1000	0	0.9535	0.1375	87.62%
Present	100	1050	300	0.9457	0.1280	85.81%
Ref.[25]	100	1050	300	0.9545	0.2000	82.68%

contributors to the high α_λ of the near-perfect absorber when $\lambda = 0.28\text{--}1.7\ \mu\text{m}$. When the λ varies from $1.7\ \mu\text{m}$ to $2.1\ \mu\text{m}$, the contributions of layer 2 and layer 4 decrease quickly, leading to the decreasing α_λ of the absorber. Meanwhile, it is seen that layer 1 also contributes a little α_λ when $\lambda < 0.7\ \mu\text{m}$.

Fig. 6 Comparison of several structures.

Meanwhile, to further explore the effects of layer 2, layer 3, and layer 4 on the absorption performance, a comparison of α_λ among the near-perfect absorber, and the absorbers without layer 3, layer 2, or layer 4 is shown in Fig. 6. As seen in Fig. 6, the α_λ of the absorber without layer 3 is similar with that of the near-perfect absorber when $\lambda = 0.28\text{--}1.1\ \mu\text{m}$. However, when $\lambda = 1.1\text{--}2.1\ \mu\text{m}$, the α_λ of the absorber without layer 3 is obviously lower than that of the near-perfect absorber. This enhancement in α_λ within $\lambda = 1.1\text{--}2.1\ \mu\text{m}$ should be attributed to the metal-dielectric-metal structure of the layer 2-layer 3-layer-4. It can also be seen from Fig. 6 that the α_λ of the absorber without layer 2 or layer 4 is relatively low when $\lambda = 0.28\text{--}1.3\ \mu\text{m}$, which indicates that both the nano shuriken and the nanohole are important for enhancing the α_λ .

Fig. 7 The real part $Re(z)$ and imaginary part $Im(z)$ of the effective impedance (z_λ) of the near-perfect absorber.

Then, to further explain the absorption mechanisms of the near-perfect absorber, the relation between the effective impedance (z_λ) of the absorber and the α_λ is analyzed. According to Eq. (7), when the effective impedance is matched to the impedance of the free space (*i.e.* $Re(z) = 1, Im(z) = 0$), the absorber will be able to achieve high α_λ . It can be seen in Fig. 7 that the $Re(z)$ and $Im(z)$ of the near-perfect absorber are close to 1 and 0, respectively when $\lambda = 0.28\text{--}1.30\ \mu\text{m}$, which is consistent with the extremely high α_λ (0.9540–0.9997) in this band, as shown in Fig. 4. When the λ increases to be greater than $1.7\ \mu\text{m}$, the $Re(z)$ and $Im(z)$ of the near-perfect absorber deviate from the impedance of the free space quickly, resulting in the sharp decrease in the α_λ (see Fig. 4).

Then, in order to have a deeper understanding of the dissipation mechanisms of electromagnetic waves in the optimal near-perfect absorber, Fig. 8 visualizes the transport and absorption of the light in the absorber under normally incident TM polarized wave. Detailed analyses of the results in Fig. 8 are as follows.

Firstly, according to Zhao *et al.*^[59] and Heinzel *et al.*^[60] both TE and TM polarized waves can excite SPPs in 2D gratings. Under normally incident TM polarized wave, SPPs can be excited along the x direction if the dispersion relation in Eq. (13)^[59] is satisfied.

$$\frac{2\pi}{\lambda} \sqrt{\frac{\epsilon_{r,1}\epsilon_{r,2}}{\epsilon_{r,1} + \epsilon_{r,2}}} = \left| \frac{2\pi \cdot m}{p} \right|, m = \pm 1, \pm 2, \pm 3, \dots \quad (13)$$

where λ is the wavelength of the incident TM polarized wave in a vacuum; m is the order of the diffracted wave; $\epsilon_{r,1}$ and $\epsilon_{r,2}$ are the complex dielectric functions of the SiO_2 and tungsten, respectively.

To analyze the SPPs excited by the 2D nano shuriken grating, only the real parts of $\epsilon_{r,1}$ and $\epsilon_{r,2}$ are necessary to be considered in Eq. (13) as typically done by Zhao *et al.*^[59] When $m = 1$, through solving Eq. (13), the λ corresponding to the first-order SPPs can be predicted to be $0.54\ \mu\text{m}$. Fig. 8a and Fig. 8b show the distributions of the $|H|$ and $|E|$ around the nano shuriken in the xz plane when $\lambda = 0.54\ \mu\text{m}$, respectively. It can be observed in Fig. 8a that strong $|H|$ appears at the upper surface of the nano shuriken, and strong $|E|$ occurs at the edges of the nano shuriken in Fig. 8b. These phenomena indicate that SPPs are excited at the upper surface of the nano shuriken when $\lambda = 0.54\ \mu\text{m}$.

Then, it can be observed in Fig. 8a that strong $|H|$ also occurs within the dielectric layer 3 because of the magnetic polaritons (MPs), resulting in the strong $|E|$ at the edges of the nano shuriken in Fig. 8b. It is also seen in Fig. 8a that the $|H|$ in layer 3 increases obviously with increasing λ when $\lambda = 0.54\text{--}1.2\ \mu\text{m}$, which indicates that the MPs are more effective in enhancing the absorption at relatively large wavelength.

Then, because the xy plane at $z = 740\ \text{nm}$ is in the middle of the nano shuriken, it is quite suitable to illustrate the absorption characteristics of the nano shuriken, and the $|E|$ distribution in this plane is illustrated in Fig. 8c. It can be observed in Fig. 8c that strong $|E|$ regions located at the

Fig. 8 Distributions of the magnitude of the electric field ($|E|$) and the magnitude of the magnetic field ($|H|$) under normally incident TM polarized wave, where the white arrows are the Poynting vectors. (a) $|H|$ in the xz plane with $y = 225$ nm; (b) $|E|$ in the xz plane with $y = 225$ nm; (c) $|E|$ in the xy plane with $z = 740$ nm; (d) $|E|$ in the yz plane with $x = 0$.

vertexes of the nano shuriken, which are introduced by the localized surface plasmon resonance (LSPR). It can also be found in Fig. 8c that the maximum $|E|$ reaches $72.8 \text{ kV} \cdot \text{m}^{-1}$, $87.0 \text{ kV} \cdot \text{m}^{-1}$, $104.2 \text{ kV} \cdot \text{m}^{-1}$, $160.1 \text{ kV} \cdot \text{m}^{-1}$ when λ is 0.54, 0.7, 0.9, and $1.2 \mu\text{m}$, respectively, indicating that the LSPR is more effective in enhancing the absorption at larger wavelength.

It can be seen from Fig. 8d that the magnitude of the electric field ($|E|$) is strong at the center of the nanohole, indicating that the cavity resonances (CRs) are begotten in the

nanohole. Moreover, it is seen in Fig. 8d that the $|E|$ in the nanohole decreases gradually when λ increases from $0.54 \mu\text{m}$ to $1.2 \mu\text{m}$, which indicates that the CR in the nanohole is more effective in enhancing the absorption at a relatively small wavelength.

To sum up, the CRs in the nanohole and the SPPs above the nano shuriken are more effective in enhancing the absorption within the visible region, and the LSPR and MPs in the nano shuriken are more effective in enhancing the

absorption within the near-infrared region. By combining the SPPs, CRs, LSPR, and MPs in the near-perfect absorber, the near-perfect solar absorptance is achieved. Considering the Poynting vectors within the near-perfect absorber, the transport and absorption of the electromagnetic wave can be visually observed. It can be seen in Fig. 8 that some Poynting vectors are bent towards the nano shuriken due to the SPPs, LSPR, and MPs around the nano shuriken, and Poynting vectors get into the wall of the nanohole after the effects of CRs. The electromagnetic waves that enter the tungsten nano shuriken and cavity wall are finally absorbed because of ohmic dissipation in the metal.

5.3 Geometric effects on spectral absorption at normal incidence

Although the optimal geometric parameters have been determined by multiple orthogonal experiments, the effects of the geometric parameters of layer 2, layer 3, and layer 4 on the spectral absorptance (α_λ) are still unclear. Hence, in this section, the effects of geometric parameters were further analyzed under normally incident TM polarized wave. In the analysis, when one structural parameter was studied, the other structural parameters were consistent with the optimal parameters.

5.3.1 Effects of the geometric parameters of layer 2

The parameters related to layer 2 are the period (p), the excircle diameter of the nanohole (d), and the height of the nanohole (h_2). Effects of the three parameters on the α_λ are shown in Fig. 9a, Fig. 9b, and Fig. 9c, respectively.

It can be observed in Fig. 9a that the α_λ increases slightly as the period p decrease when $\lambda > 1.3 \mu\text{m}$, and the α_λ in Fig. 9b increases slightly with the increasing d when $\lambda > 1.1 \mu\text{m}$. This is because the decrease in p and the increase in d can help the electromagnetic wave to enter the nanohole, thus enhancing the intensities of CRs and SPPs. As can be seen from Fig. 9c, h_2 influences slightly the α_λ when λ is around $0.5 \mu\text{m}$, however, it has little effect on the α_λ under other wavelengths. This is

because the size of the nanohole is close to the λ when λ is around $0.5 \mu\text{m}$, introducing relatively stronger effects on the CRs inside the nanohole.

5.3.2 Effects of the geometric parameters of layer 3

The only geometric parameter of layer 3 is its height (h_3), and its effects on the spectral absorptance (α_λ) of the absorber are shown in Fig. 10. As seen in Fig. 10, the h_3 influences the spectral absorptance mildly due to the variations of the MPs produced in layer 3. Moreover, it can be found in Fig. 10 that the spectral absorptance varies irregularly with the increasing h_3 at the same λ when $\lambda > 1.24 \mu\text{m}$, indicating that the increase in the h_3 does not necessarily enhance the spectral absorptance of the absorber.

5.3.3 Effects of the geometric parameters of layer 4

The parameters related to layer 4 are the diagonal length of a square cross-section of the SiO_2 cuboid surrounding the nano shuriken (l), the height of layer 4 (h_4), the c and b in Fig. 1c. Effects of these parameters on the α_λ are shown in Fig. 11a, Fig. 11b, Fig. 11c, and Fig. 11d, respectively.

It can be seen in Fig. 11a that the increase in l leads to a slight increase in the α_λ when $\lambda > 1.2 \mu\text{m}$. This is because the intensity of the LSPR within the dielectric surrounding the nano shuriken increases with increasing l . Moreover, it can be seen in Fig. 11b that the increase in h_4 also leads to a slight increase in the α_λ when $\lambda > 1.4 \mu\text{m}$. This is due to the increasing area of the side wall of the nano shuriken, where the LSPR can be excited.

As shown in Fig. 11c and Fig. 11d, the long axis c and the short axis b of the rhombus cross-section of the rhombic prism affect the α_λ of the absorber irregularly and slightly. This is because the c and b not only influence the LSPR and MPs around the nano shuriken but also affect the electromagnetic wave entering the nanohole. These interactional effects result in the irregular variation of the α_λ . Moreover, it can be found in Fig. 11c and Fig. 11d that the effects of both c and b on spectral absorptance are mild.

Fig. 9 Effects of the geometric parameters of layer 2 on the spectral absorptance of the absorber. (a) Effects of the period (p), (b) Effects of the excircle diameter of the nanohole (d); (c) Effects of the height of the nanohole (h_2).

Fig. 10 Effects of the height of layer 3 (h_3) on the spectral absorptance of the absorber.

To sum up, when a geometric parameter varies within a 20 nm range around its optimal value, its effects on absorptance will not be obvious. Considering the fact that the roughness of each object in the absorber can be lower than 5 nm or 10 nm when employing the manufacturing methods introduced in Section 2, it can be concluded that the spectral absorptance of the optimal absorber is insensitive to fabrication uncertainties.

5.4 Effects of polarization angle and incident angle

In the realistic solar absorber, sunlight irradiates the absorber under different polarization angles and incident angles, so a good absorber should be insensitive to these angles. In this section, the effects of the polarization angle (see φ in Fig. 1b) and incident angle (see θ in Fig. 1c) on the spectral absorptance (α_λ) of the current near-perfect absorber are analyzed under the typical wavelength range of $\lambda = 0.28\text{--}4.0$ μm , and the results are shown in Fig. 12 and Fig. 13.

Fig. 11 Effects of the geometric parameters of layer 4 on the spectral absorptance of the absorber. (a) Effects of the diagonal length (l) of a square cross-section of the SiO_2 cuboid surrounding the nano shuriken, (b) Effects of the height of layer 4 (h_4), (c) Effects of c , (d) Effects of b .

As shown in Fig. 12, when $\lambda = 0.28\text{--}4.0\ \mu\text{m}$, the spectral absorptance (α_λ) of the near-perfect absorber varies little with the polarization angle (ϕ) when ϕ increases from 0° to 90° . It implies that the near-perfect absorber is totally insensitive to polarization angle within the above typical λ range. This good polarization insensitivity can be explained by the symmetric structure of the absorber according to Mahmud *et al.*^[61]

Fig. 12 Spectral absorptance (α_λ) of the near-perfect absorber under different polarization angles (ϕ) at normal incidence.

Moreover, the α_λ of the near-perfect absorber at different incident angles are examined under TE and TM polarized waves, respectively, as illustrated in Fig. 13. As seen in Fig. 13a, under the TE polarized wave, the absorber can obtain the α_λ of 0.8–1.0 when $\lambda = 0.28\text{--}1.448\ \mu\text{m}$ and $\theta = 0\text{--}60^\circ$. Meanwhile, it can be found in Fig. 13c that the high total solar absorptance (α_{tot}) of 0.8635–0.9457 is also achieved. Moreover, as seen in Fig. 13b, under the TM polarized wave, the α_λ of 0.8–1.0 is achieved when $\lambda = 0.28\text{--}1.435\ \mu\text{m}$ and $\theta = 0\text{--}60^\circ$, and the corresponding α_{tot} of 0.9022–0.9457 is obtained. These results indicate that the optimal absorber is insensitive to the incident angle under both TE and TM polarized waves.

Fig. 13 Absorptance of the near-perfect absorber under different incident angles (θ). (a) α_λ of TE polarized wave, (b) α_λ of TM polarized wave, (c) α_{tot} of TE and polarized waves.

To sum up, the above results and discussion indicate that the near-perfect absorber exhibits high insensitivity to wide-angle incidence and all-angle polarization.

6. Conclusions

In this work, a solar absorber composed of tungsten nanohole and nano shuriken arrays is proposed and studied for high-temperature solar power. The following conclusions are obtained.

(1) A near-perfect selective solar absorber is obtained after optimizing the absorber structure. The optimal parameters are $h_1 = 150\ \text{nm}$, $h_2 = 500\ \text{nm}$, $h_3 = 30\ \text{nm}$, $h_4 = 120\ \text{nm}$, $h_5 = 60\ \text{nm}$, $d = 366\ \text{nm}$, $P = 450\ \text{nm}$, $c = 260\ \text{nm}$, $b = 140\ \text{nm}$, and $l = 300\ \text{nm}$.

(2) Performance comparisons indicate that the performance of the near-perfect absorber can be quite close to that of the ideal absorber and is better than that of three existing absorbers. It can achieve a high total solar absorptance of 0.9457, a low total emittance of 0.0491–0.3228, and a high photothermal efficiency of 94.52%–83.38% at 1000 suns and 673–1573 K.

(3) Analysis of the absorbing mechanisms indicates the high total solar absorptance of the near-perfect absorber should be ascribed to the impedance matching, and the coupling effects of CRs, SPPs, MPs, and LSPR.

(4) The optimal near-perfect absorber is found to exhibit high insensitivity to its geometric parameters, wide-angle incidence, and all-angle polarization, which is highly expected by the industry.

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Supporting information

Not Applicable.

Conflict of interest

There are no conflicts to declare.

Abbreviations

CSP	Concentrating Solar Power
CRs	Cavity Resonances
LSPR	Local Surface Plasmon Resonance
MPs	Magnetic Polaritons
SPPs	Surface Plasmon Polaritons

Nomenclature

b	short axis of the rhombus cross-section of the rhombic prism / nm
c	long axis of the rhombus cross-section of the rhombic prism / nm
c_1, c_2	Constants
d	diameter of excircle of the nano hole / nm
$ E $	magnitude of electric field / $V \cdot m^{-1}$
h_1	thickness of the layer 1 / nm
h_2	height of the layer 2 / nm
h_3	height of the dielectric / nm
h_4	thickness of the tungsten nanoshuriken / nm
h_5	height of the layer 5 / nm
$ H $	magnitude of magnetic field / $A \cdot m^{-1}$
I_s	AM1.5 solar irradiance, $1.0 \text{ kW} \cdot m^{-2}$ (one sun)
$I_{AM1.5}(\lambda)$	AM1.5 spectral solar irradiance / $W \cdot m^{-2} \cdot m^{-1}$
I_B	blackbody spectral emittance
k	k -vector or wave vector
k_F	k -vector of Floquet periodicity
k_0	wave number
k	imaginary part of the refractive index
l	diagonal length of the square cross section of the SiO_2 cuboid surrounding the nanoshuriken / nm
m	the order of the diffracted wave
n	real part of the refractive index
p	period of the nano hole / nm
r_{dst}	position of destination boundary
r_{src}	position of source boundary
S_{11}, S_{22}	scattering matrix coefficients
T_{amb}	ambient temperature / K
T_{abs}	absorber temperature / K
x, y, z	axes of the Cartesian coordinate system / nm
z_λ	effective impedance
α_{tot}	total solar absorptance

α_λ	spectral absorptance /emittance
ε_{tot}	total emittance
ε_r	dielectric function
η	photothermal efficiency / %
θ	incident angle / °
λ_{tru}	truncation wavelength / μm
λ	wavelength of the electromagnetic wave in vacuum / μm
τ_λ	spectral transmittance
φ	polarization angle / °
ρ_λ	spectral reflectance
σ	Stefan-Boltzmann constant

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