Design of Biomimetic Leaf-type Hierarchical Nanostructure for Enhancing the Solar Energy Harvesting of Ultra-thin Perovskite Solar Cells

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Abstract

Ultra-thin perovskite solar cell had the advantages of low cost, high efficiency and flexibility, which had significant potential in application. However, a severe optical loss was often observed in the ultra-thin perovskite solar cell due to the insufficient light absorption. In this study, inspired by the efficient light harvesting of hierarchical structure in leaf, a biomimetic leaf-type hierarchical nanostructure was introduced for designing highly efficient ultra-thin perovskite solar cell. In detail, three layers of hexagonal arrays of silica nanoparticles with different radius constructed the biomimetic leaf-type hierarchical structure. The biomimetic leaf-type hierarchical nanostructure was optimized by finite-difference time-domain method combined with particle swarm optimization algorithm to reduce the light reflection and increase the light absorption of the ultra-thin perovskite solar cell. The results indicated that biomimetic leaf-type hierarchical nanostructure could enhance the light absorption of ultra-thin perovskite solar cell by maximum 39% at the long wavelength. The photocurrent of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was 8.4% higher than that of perovskite solar cell without biomimetic

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leaf-type hierarchical nanostructure.

**Keywords**

Solar energy, perovskite solar cell, biomimetic, hierarchical nanostructure, radiative transfer, full spectrum

**Nomenclature**

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<th>Symbols</th>
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<tr>
<td>$\text{Abs}$</td>
<td>absorption</td>
<td>$\mu$ complex permeability</td>
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<tr>
<td>B</td>
<td>magnetic flux density, T</td>
<td>$\mathcal{E}$ complex permittivity</td>
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<tr>
<td>c</td>
<td>light speed, m/s</td>
<td>$\omega$ angular frequency</td>
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<tr>
<td>d</td>
<td>radius, nm</td>
<td>$\delta$ absolute error</td>
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<tr>
<td>D</td>
<td>electric displacement field, C/m$^2$</td>
<td>$\epsilon^{-}$ imaginary part of index</td>
</tr>
<tr>
<td>e</td>
<td>electron charge, C</td>
<td>$\lambda$ wavelength</td>
</tr>
<tr>
<td>E</td>
<td>electric field, V/m</td>
<td>$\text{FF}$ filling factor</td>
</tr>
<tr>
<td>h</td>
<td>Planck constant</td>
<td>$H$ magnetic field, A/m</td>
</tr>
<tr>
<td>I</td>
<td>solar radiance at AM=1.5</td>
<td>$\text{abs}$ absorption</td>
</tr>
<tr>
<td>J</td>
<td>Photocurrent, mA/cm$^2$</td>
<td>$l$ large particle</td>
</tr>
<tr>
<td>L</td>
<td>distance, m</td>
<td>$s$ small particle</td>
</tr>
<tr>
<td>P</td>
<td>absorbed energy per unit volume</td>
<td>$\text{eff}$ Effective</td>
</tr>
<tr>
<td>R</td>
<td>ratio</td>
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1 Introduction

Renewable energy is the promising way to solve the energy and environmental crisis.\cite{1-3} One type of renewable energy is solar energy,\cite{4-6} which have excellent future for natural environment protection,\cite{7-10} greenhouse gas emission reductions\cite{11-13} and air pollution alleviation.\cite{14-17} Among photothermal, photoelectricity and photochemistry,\cite{18-21} photovoltaics is environmentally friendly, whose installed capacity has increased dramatically in the past few years.\cite{22-24} Yet, the overheating of photovoltaics greatly reduces the efficiency and service life of the photovoltaics. For this reason, water and phase-change material (PCM) are usually used to cool PV panels. Nowadays, unlike above cooling method to decrease the temperature of PV cells, photovoltaics industry is moving towards ultra-thin, low-cost and flexible solar cells, which aimed at for consumer-oriented electronic products.\cite{25-28}

Perovskite solar cell has obtained tremendous interesting in the past years due to their excellent characteristics.\cite{29,30} The perovskite solar cell is flexible due to the reduced thickness, which has a promising market applicability.\cite{31,32} However, the reduction of the perovskite absorber layer thickness can reduce the optical path length of light, which in turn lead to unsaturated light absorption of perovskite solar cell.\cite{33-36} Therefore, poor power conversion efficiency of ultra-thin perovskite solar cell is usually observed due to the serious optical loss.\cite{37,38}

For the above-mentioned problem of insufficient light absorption of ultra-thin perovskite solar cell, photon management was prospective to enhance the optical path length and light absorption.\cite{39,40} Several approaches had been proposed to manipulate the incident sunlight, which essentially increased the light absorption by controlling the scattering and focusing of light.\cite{41-44} For example, ultra-thin textures such as grating, prism arrays, micro-lens, nanopillars, nanopyramids and nanoholes had been extensively investigated.\cite{45-51} These randomly textured surfaces and periodic photonic structures could be easily manufactured by wet etching, low-pressure deposition, and nanoimprint lithography techniques.\cite{52,53} Roozbeh et.al\cite{54} designed and analyzed the effects of ZnO nanorods and plasmonic nanoparticles on the performance on the
perovskite solar cell. Halo et al.\cite{55} conducted a ray tracing analysis of inverted pyramids to investigate different light-trapping schemes in thin crystalline silicon (c-Si) for solar cells. Raphael et al. reported that structuring perovskite layers with textures could improve the photocurrent of perovskite solar cell by about 5\%\cite{56}. Akshit et al.\cite{57} reported that micro lens arrays could improve the photocurrent of perovskite solar cell by about 6\%. Xu et al.\cite{58} reported that a combination of order and disorder nanopillar/nanohole arrays could improve the average light absorption by about 97\%. These ultra-thin textures could reduce the light reflection over broadband and improve the light absorption of perovskite solar cell.\cite{59} However, texturing would unavoidably enhance the surface area and defect density in the perovskite material, which in turn enhanced carrier recombination and eventually deteriorated the solar cell’s efficiency.\cite{60,61} Therefore, it was important to develop a useful photon management strategy which could protect the integrity of the perovskite absorber layer and did not increase the recombination and capture of charge carriers.\cite{62}

Recently, inspired by nature, such as butterflies,\cite{63} honeycomb\cite{64} and moth-eye,\cite{65} biomimetic nanophotonic structures have been developed to control the incident light for camouflage, antireflection and scattering.\cite{66,67} Leaf has the precise structure to harvest sunlight and efficiently conduct photosynthesis.\cite{68} Leaf usually has hierarchical structures, which manipulate the incoming sunlight to be absorbed in high efficiency.\cite{69} Leaf can capture and absorb incoming sunlight over broadband. Therefore, comprehending the photon management advantage of hierarchical structures observed in leaf, and imitating these hierarchical structures could offer precious instructions on designing and manufacturing nanophotonic structures for ultra-thin perovskite solar cell. In addition, the hierarchical nanostructure could keep the perovskite absorber layer from damage, which did not enhance the recombination and capture of charge carriers.

Literature survey indicated that the hierarchical structures of leaf harvest light efficiently, but the advantages of hierarchical structures was remained to be explored to improve the light absorption for ultra-thin perovskite solar cell. In this study, imitating the hierarchical structures observed in leaf, a biomimetic leaf-type hierarchical
nanostructure was introduced for designing highly efficient ultra-thin perovskite solar cell. The effects of the ratio, radius and filling factor of the biomimetic leaf-type hierarchical nanostructure on the light absorption and photocurrent of the perovskite solar cell were investigated. The particle swarm optimization algorithm was adopted to develop the full potential of the biomimetic leaf-type hierarchical nanostructure from the perspective of optics. The calculated analysis results could offer designing suggestions for enhancing light absorption and energy conversion efficiency of ultra-thin perovskite solar cell.

2 Methodology

2.1 Design of biomimetic leaf-type hierarchical nanostructure

The photon management of leaf is outstanding due to the unconventional hierarchical structures, which is provided for highly efficiently light harvesting. As shown in Fig 1(a), a typical C₃ leaf has a unique hierarchical structure, which composes of the following four-layer structures: upper epidermis layer, palisade cell layer, spongy mesophyll layer and lower epidermis layer.[⁷⁰] The epidermis layer has two unique optical properties: (1) the epidermis layer is transparent to visible light; (2) the shape of the epidermis is convex. These two optical properties enable the epidermis layer could collect the sunlight. The palisade cell layer promotes the sunlight to penetrate deep into the leaf. Leaf could manipulate and distribute the internal light to maximize the light absorption through regulating the geometry structure and packing density of the palisade cell. The spongy mesophyll layer could scatter downwards light back into the palisade cell due to the refractive index mismatch between cells and air, which could enhance the light absorption.
Based on the above photon management advantage of hierarchical structures observed in leaf, a biomimetic leaf-type hierarchical nanostructure was designed for enhancing the light absorption of ultra-thin perovskite solar cell. As shown in Fig. 1 (b), the biomimetic leaf-type hierarchical nanostructure was composed of three layers of hexagonal arrays of silica nanoparticles with different radius. The top layer of hexagonal arrays of silica nanoparticles with larger radius was mimicking the epidermis layer. The middle layer of hexagonal arrays of silica nanoparticles with smaller radius was mimicking the palisade cell layer. The bottom layer of hexagonal arrays of silica nanoparticles with smaller radius was mimicking the spongy mesophyll layer.

![Hierarchical structure of a typical C3 leaf; (b) Schematic diagram of a perovskite solar cell with biomimetic leaf-type hierarchical nanostructure.](image)

**Fig. 1** (a) Hierarchical structure of a typical C3 leaf; (b) Schematic diagram of a perovskite solar cell with biomimetic leaf-type hierarchical nanostructure.

**Fig. 2 (a)** presented the cross-section of an ultra-thin planar perovskite solar cell. An ultra-thin planar perovskite solar cell was composed of the following five-layer structures: a transparent conductive electrode layer, an electron transport layer, a perovskite absorber layer, a hole transport layer, and a metal conductive electrode layer.
**Fig. 2 (b)** presented the cross-section of an ultra-thin perovskite solar cell with biomimetic leaf-type hierarchical nanostructure. The radius of silica nanoparticle locating in the top layer was larger than those locating in the middle and bottom layer. The radius of silica nanoparticle locating in the middle layer was same as that locating in the bottom layer. The ratio ($R$) was adopted to define the ratio between the radius of the large silica nanoparticle and the radius of the small silica nanoparticle, which was calculated by a dimensionless factor ($R$):

$$R = \frac{d_l}{d_s}$$

(1)

The filling factor ($FF$) was adopted to define the distance between the two nanoparticles, which was calculated by a dimensionless factor ($FF$):

$$FF = \frac{L}{d_l}$$

(2)

where $d_l$ was the radius of the large silica nanoparticle locating on the top layer, $d_s$ was the radius of the small silica nanoparticle locating on the middle and bottom layer, and $L$ was the distance between the two nanoparticles.

Silica rarely absorbed solar energy with the wavelength range of 400~1000 nm, which is transparent to visible light.\textsuperscript{[71]} Therefore, the silica was used as the material of biomimetic leaf-type hierarchical nanostructure. Transparent conductive electrode layer should have excellent conductivity and transparence. Therefore, indium tin oxide (ITO) was adopted as the material of the transparent conductive electrode layer. Titanium
dioxide was applied into the electron transport layer. A typical methylammonium lead iodide (CH$_3$NH$_3$PbI$_3$) was applied into the perovskite absorber layer, and the thickness of the perovskite absorber layer was 250 nm. Spiro-OMeTAD was applied into the hole transport layer (HTM), and the thickness of the HTM was 150 nm. Ag was adopted into the back metal, and the thickness of the Ag was 80 nm. The biomimetic leaf-type hierarchical nanostructure was introduced and located on the ITO, which could be straightly incorporated onto the ITO layer by simple colloidal spin coating technology. In addition, the biomimetic leaf-type hierarchical nanostructure would keep the perovskite absorber layer from damage, which did not enhance the recombination and capture of charge carriers.

2.2 Mathematical calculation description

The Maxwell's equations can be adopted to compute the electromagnetic field distribution of the perovskite solar cell with biomimetic leaf-type hierarchical
nanostructure, which can compute the optical characteristic of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure. In this study, FDTD numerical solution was adopted to compute the Maxwell's equations.\cite{72,73}

\[
\nabla \times H = \frac{\partial D}{\partial t} \tag{3}
\]

\[
\nabla \times E = \frac{\partial B}{\partial t} \tag{4}
\]

\[D = \varepsilon E\] \tag{5}

\[B = \mu H\] \tag{6}

Where \(E\) was the electric field, \(H\) was the magnetic field, \(B\) was the magnetic flux density, \(D\) was the electric displacement field, \(\mu\) was the complex permeability, and \(\varepsilon\) was the complex permittivity.

After calculating the electromagnetic field distribution, the spectral absorptivity could be computed by: $^{[41,60]}

\[
Abs(\omega) = \int P_{abs}(\omega) dV \tag{7}
\]

The \(P_{abs}(\omega)\) was the absorbed energy by per unit volume with the normalization of the incident energy, which was expressed as:

\[
P_{abs}(\omega) = \frac{1}{2} \omega \varepsilon^' |E|^2 \tag{8}
\]

where \(\omega\) was the angular frequency and \(\varepsilon^'\) was the imaginary part of the complex
The photocurrent of the perovskite solar cell was calculated as follows:

\[ J_{ph} = e \int \frac{\lambda}{hc} A b e_{eff}(\lambda) I(\lambda) d\lambda \]  

(9)

where \( e \) was the electron charge, \( h \) was Planck constant, \( c \) was the light speed, and \( I(\lambda) \) was the solar spectral radiation power at AM=1.5.

The maximum potential of biomimetic leaf-type hierarchical nanostructure to improve the light absorption of perovskite solar cell was investigated. The biomimetic leaf-type hierarchical nanostructure was optimized by FDTD method combined with particle swarm optimization algorithm. Particle swarm optimization algorithm\(^{[74-76]}\) was an optimization calculation method, which imitated the bird’s predation.

### 3 Model validation

For the purpose of checking numerical calculation accurateness in this study, the numerical results calculated by FDTD method were compared with those calculated by transfer-matrix (TM) method and rigorous coupled-wave analysis (RCWA) method, respectively. The model validation had two parts. Exactly, the first part was that the reflectivity and absorptivity of the planar perovskite absorber layer calculated by FDTD method were compared with those calculated by transfer-matrix (TM) method. The second part was that the reflectivity of photovoltaic having nanostructures calculated by FDTD method was compared with those calculated by rigorous coupled-wave analysis (RCWA) method in Ref.\(^{[77]}\) The complex refractive index used in the
calculation was shown in Figs. 3 (a) and (b). Fig. 4 (a) presented the comparison of the planar perovskite absorber layer’s spectral absorptivity computed by FDTD method and TM method, respectively. As shown in this figure, the planar perovskite absorber layer’s spectral absorptivity computed by FDTD method matched well with that computed by TM method with the maximum absolute error ($\delta_{\text{max}} = |A_{\text{FDTD}} - A_{\text{transfer matrix}}|$) of 4%. Fig. 4 (b) presented the comparison of the planar perovskite absorber layer’s spectral reflectivity computed by FDTD method and TM method, respectively. As shown in this figure, the planar perovskite absorber layer’s spectral reflectivity computed by FDTD method matched well with that computed by TM method with the maximum absolute error ($\delta_{\text{max}} = |A_{\text{FDTD}} - A_{\text{transfer matrix}}|$) of 5%. In addition, the reflectivity of photovoltaic having nanostructures calculated by FDTD method was compared with those calculated by rigorous coupled-wave analysis (RCWA) method employed by University of Texas at Arlington, USA in Ref. [77]. As presented in Fig. 5, the spectral reflectivity of photovoltaic having nanostructures matched well with that obtained by University of Texas at Arlington, USA in Ref. [77].

![Figure 3](image1.png)

(a) Real part of refractive index  (b) Imaginary part of refractive index

**Fig. 3** (a) Real part of refractive index for SiO$_2$, ITO, TiO$_2$, perovskite, Sprio-OMeTAD; (b) Imaginary part of refractive index.
4 Results and discussions

4.1 Performance of perovskite solar cell with/without hierarchical nanostructure

The influence of biomimetic leaf-type hierarchical nanostructure on the light
absorption and photocurrent of perovskite solar cells was investigated. **Fig. 6** presented the photocurrent of perovskite solar cell without/with biomimetic leaf-type hierarchical nanostructure. As shown in the graph, the photocurrent of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure was 20.6 mA/cm$^2$, and the photocurrent of perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was 22.3 mA/cm$^2$. The photocurrent of perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was 8.4% higher than that of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure. This phenomenon is due to the reason that biomimetic leaf-type hierarchical nanostructure can enhance the effective light absorption of perovskite solar cell in the NIR wavelength range.

![Graph of Photocurrent of Perovskite Solar Cells](image)

**Fig. 6.** Photocurrent of perovskite solar cell without/with biomimetic leaf-type hierarchical nanostructure

**Fig. 7** presented the effective light absorption of perovskite solar cell with biomimetic leaf-type hierarchical nanostructure and the effective light absorption of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure. As shown
in the graph, the effective light absorption of perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was higher than that of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure in the 400–800 nm wavelength band. And the biomimetic leaf-type hierarchical nanostructure mainly enhanced the light absorption of perovskite solar cell at the long wavelength. For example, at λ=761 nm, the effective absorptivity of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was 92%, while the effective absorptivity of the perovskite solar cell without biomimetic leaf-type hierarchical nanostructure was 66%. Therefore, the effective light absorption for perovskite solar cell was improved by 39% at 761 nm, when the biomimetic leaf-type hierarchical nanostructure was adopted. Fig. 6 shown the parasitic absorptivity of perovskite solar cell with/without biomimetic leaf-type hierarchical nanostructure as well. The parasitic absorptivity of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure was lower than 10% in the 400–800 nm wavelength band, and the parasitic absorptivity of perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was lower than 10% in the 400–800 nm wavelength band as well. The biomimetic leaf-type hierarchical nanostructure did not improve parasitic absorptivity of the perovskite solar cell, which did not increase the possibility to decrease the photocurrent of perovskite solar cell.
In order to explain the light absorption difference between the perovskite solar cell without the biomimetic leaf-type hierarchical nanostructure and the perovskite solar cell with the biomimetic leaf-type hierarchical nanostructure, the mechanism of biomimetic leaf-type hierarchical nanostructure to enhance the light absorption of perovskite solar cell at long wavelength was investigated. Fig. 8 displayed the field of the absorption per unit volume ($P_{\text{abs}}$) of perovskite solar cell without the biomimetic leaf-type hierarchical nanostructure and perovskite solar cell with the biomimetic leaf-type hierarchical nanostructure at $\lambda=761$ nm, respectively. Fig. 8 (a) displayed the field of the absorption per unit volume ($P_{\text{abs}}$) of perovskite solar cell without the biomimetic leaf-type hierarchical nanostructure at $\lambda=761$ nm. As shown in the graph, the absorption of the solar energy of 761 nm was distributed in the entire perovskite absorber layer along the Z axis, and the perovskite absorber layer mainly absorbed the solar energy of 761 nm wavelength within a depth of 100 to 150 nm from the surface. The reason for this absorption distribution was that the perovskite absorber layer could not completely absorb incoming longer wavelength (761 nm) due to the low absorption coefficient of perovskite absorber layer at longer wavelength (761 nm). Therefore, the unabsorbed longer wavelength (761 nm) would reflected back and forth at the upper and lower surfaces of the perovskite layer, which would form Fabry Perot interference effect. Fig. 8 (b) displayed the field of the absorption per unit volume ($P_{\text{abs}}$) of perovskite solar cell with the biomimetic leaf-type hierarchical nanostructure at $\lambda=761$ nm. As shown in the graph, the absorption of the solar energy of 761 nm was scattered in different locations, when the biomimetic leaf-type hierarchical nanostructure was used. The biomimetic leaf-type hierarchical nanostructure could scatter the incident solar energy of 761 nm into distinct orientation, and the scattering light with distinct orientation would travel in the perovskite absorber layer along the X and Y axis directions. Therefore, the light absorption of solar energy of 761 nm was improved.
4.2 Effects of ratio \((R)\) on the performance of perovskite solar cell

The ratio \((R)\) was adopted to define the ratio between the diameter of the large silica nanoparticle and the diameter of the small silica nanoparticle. The influence of the ratio \((R)\) on the photocurrent and effective light absorption of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure were presented in Figs. 9 and 10, respectively. The photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure and perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the different ratio \((R)\) was displayed in Fig. 9. As shown in the graph, the photocurrents of perovskite solar cells without biomimetic leaf-type hierarchical nanostructure were 19.9 mA/cm\(^2\), 20.5 mA/cm\(^2\), 20.4 mA/cm\(^2\), 20.6 mA/cm\(^2\), 20.6 mA/cm\(^2\) and 20.8 mA/cm\(^2\). The photocurrents of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure of were 20 mA/cm\(^2\), 22.1 mA/cm\(^2\), 21.5 mA/cm\(^2\), 22.4 mA/cm\(^2\), 21.9 mA/cm\(^2\) and 22.1 mA/cm\(^2\) with the ratio \((R)\) of 1:1, 1:2, 1:3, 1:4, 1:5 and 1:6, respectively. The photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure was 0.5%, 7.8%, 5.4%, 8.7%, 6.3% and 6.3% higher than those of perovskite solar cells without biomimetic leaf-type hierarchical nanostructure. Therefore, biomimetic leaf-type hierarchical nanostructure with different ratio \((R)\) could improve the photocurrent of perovskite solar cells with different improvement.
The effective light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the different ratio ($R$) was displayed in Fig. 10. As shown in the graph, the light absorption of the biomimetic leaf-type hierarchical nanostructure with the ratio ($R$) of 1:1 was lower than that of the biomimetic leaf-type hierarchical nanostructure with the other ratio ($R$). Little difference in the light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the ratio of 1:2, 1:3, 1:4, 1:5 and 1:6 were observed in the short wavelength range of 400~700 nm. However, the obvious difference in the light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the ratio of 1:2, 1:3, 1:4, 1:5 and 1:6 were observed in the long wavelength range of 700~800 nm. The light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the ratio of 1:3 and 1:6 did not have obvious absorption peaks in the long wavelength range of 700~800 nm, while the light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the ratio of 1:2, 1:4 and 1:5 had absorption peaks in the long wavelength range of 700~800 nm. Therefore, the biomimetic leaf-type hierarchical nanostructure could enhance the light absorption of perovskite solar cells in the long wavelength range of 700~800 nm.
4.3 Effects of radius on the performance of perovskite solar cell

In this section, the ratio ($R$) between the radius of the large silica nanoparticle and the radius of the small silica nanoparticle was set to 1:4. The influence of the radius of the top layer of large nanoparticle on the photocurrent and effective light absorption of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure were displayed in Figs. 11 and 12, respectively. The photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the different radius was displayed in Fig. 11. As shown in the graph, the photocurrents of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure were 20.3 mA/cm$^2$, 21.6 mA/cm$^2$, 22.5 mA/cm$^2$, 21.4 mA/cm$^2$ and 21 mA/cm$^2$, while the radii of top layer of large nanoparticle were 0.104 μm, 0.204 μm, 0.304 μm, 0.404 μm, and 0.504 μm, respectively. The photocurrents of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with radius of 0.304 μm were 10.8%, 4.2%, 5.1%, and 7.1% higher than those with radii of 0.104 μm, 0.204 μm, 0.404 μm, and 0.504 μm, respectively.
phenomenon was induced due to the reason that biomimetic leaf-type hierarchical nanostructure with different radii had different enhancement capabilities for the effective spectral absorptivity of perovskite solar cells.

![Diagram](image)

(a) Different radii of nanostructure             (b) Effects of radius on photocurrent

**Fig. 11.** Effect of radius of biomimetic leaf-type hierarchical nanostructure on the photocurrent of perovskite solar cells

The effective light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the different radius of the top layer of large nanoparticle was displayed in **Fig. 12.** As shown in the graph, the trend of effective spectral absorptivity of with biomimetic leaf-type hierarchical nanostructure varied with the change of the radii. The trend of the effective light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure was the same in the 400~675 nm band with radii of 0.104 μm, 0.204 μm, 0.304 μm, 0.404 μm and 0.504 μm. However, the trend of the effective light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure was different in the 675~800 nm band with radii of 0.104 μm, 0.204 μm, 0.304 μm, 0.404 μm and 0.504 μm. The obvious difference was that the perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with radius of 0.304 μm had an effective light absorption peak at the λ=761 nm, while the
perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with radii of 0.104 μm, 0.204 μm, 0.404 μm and 0.504 μm did not have obvious effective light absorption peaks in the wavelength range of 675–800 nm.

**Fig. 12** Effect of radius of biomimetic leaf-type hierarchical nanostructure on the effective light absorption of perovskite solar cells

### 4.4 Effects of filling factor (FF) on performance of perovskite solar cell

In this section, the influence of the filling factor (FF) of the top layer of large nanoparticle on the photocurrent and effective light absorption of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure were displayed in **Figs. 13** and 14, respectively. The ratio (R) between the radius of the large silica nanoparticle and the radius of the small silica nanoparticle was set to 1:4. The radius of the top layer of large nanoparticle was set to 0.304 μm. The photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the different filling factor
(FF) was displayed in Fig. 13. As shown in the graph, the photocurrents of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure were 21.4 mA/cm², 21.7 mA/cm², 22.5 mA/cm², 21.5 mA/cm² and 20.9 mA/cm², while the filling factor (FF) of top layer of large nanoparticle were 1, 1.05, 1.15, 1.25 and 1.35, respectively. The photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1.15 were 5.1%, 3.7%, 4.7%, and 7.7% higher than those with filling factor (FF) of 1, 1.05, 1.25, and 1.35, respectively. This phenomenon was induced due to the reason that biomimetic leaf-type hierarchical nanostructure with different filling factor (FF) had different enhancement capabilities for the effective light absorption of perovskite solar cells.

![Diagram](image)

(a) Different filling factors of nanostructure  (b) Effects of filling factors on photocurrent

**Fig. 13** Effects of the filling factor (FF) of top layer of large nanoparticle on the photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure

The effective light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with the different filling factor (FF) of the top layer of large nanoparticle was displayed in Fig. 14. As shown in the graph, the light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure decreased with the increasing the filling factor (FF) within the wavelength range of 400~686 nm.
In the wavelength range of 686~800 nm, the trend of the effective light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1 was different from those with filling factor (FF) of 1.05, 1.15, 1.25 and 1.35. The obvious difference was that the perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1 had no effective light absorption peak, while the perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1.05, 1.15, 1.25 and 1.35 have obvious effective light absorption peaks in the wavelength range of 686~800 nm. The light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1.15 was higher than those with filling factor (FF) of 1.25 and 1.35 within the wavelength range of 400~686 nm. In addition, the light absorption of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1.15 was higher than those with filling factor (FF) of 1, 1.05, 1.25 and 1.35 within the wavelength range of 686~800 nm. Therefore, the biomimetic leaf-type hierarchical nanostructure with filling factor (FF) of 1.15 could enhance the light absorption and photocurrent greatly.

![Absorptivity vs Wavelength](image)

**Fig. 14** Effects of the filling factor (FF) of top layer of large nanoparticle on the effective spectral absorptivity of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure
5 Conclusions

A serious optical loss was often observed in the ultra-thin planar perovskite solar cell. In this study, a biomimetic leaf-type hierarchical nanostructure was introduced for reducing the optical loss and enhance the light absorption. The geometrical parameters (ratio, radius and filling factor) of the biomimetic leaf-type hierarchical nanostructure was crucial to enhance the light absorption of perovskite solar cell. The particle swarm optimization algorithm was adopted to develop the full potential of biomimetic leaf-type hierarchical nanostructure from the perspective of optics. The following conclusions could be drawn:

- The biomimetic leaf-type hierarchical nanostructure could scatter the incident light with long wavelength into distinct orientation and enhance their optical path length in the perovskite absorber layer to enhance the light absorption of the perovskite solar cell;
- The biomimetic leaf-type hierarchical nanostructure could enhance the light absorption of ultra-thin perovskite solar cell by maximum 39% at the long wavelength;
- The photocurrent of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was 8.4% higher than that of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure;
- The ratio, radius and filling factor of the biomimetic leaf-type hierarchical nanostructure mainly influenced the effective light absorption of the perovskite solar cell in the long wavelength band.

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Supporting Information

Not applicable

Conflict of interest

There are no conflicts to declare.

Reference


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