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Omnidirectional and broadband light absorption enhancement in 2-D photonic-structured organic solar cells

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The effect of 2-D photonic-structures on omnidirectional and broadband light absorption enhancement in organic solar cells (OSCs) is analysed using a combination of theoretical simulation and experimental optimization. The photonic structures in the active layer, with a blend system of poly[4,8-bis[(2-ethylhexyl)oxy] benzo[1,2-b:4,5-bA] dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl) carbonyl]thieno[3,4-b]-thiophenediyl] :[6,6]-phenyl-C70-butyric-acid-methyl-ester (PTB7:PC70BM), were prepared by the nanoimprint method. It shows that the 2-D photonic structures enable not only broadband but also omnidirectional absorption enhancements in the PTB7:PC70BM-based OSCs over a broader angle range of the incident light, leading to >11 % increase in the power conversion efficiency, as compared to an optimal planar control cell. A weak angular dependency on light absorption is a unique feature of the photonic-structured OSCs, which is useful for different applications.

**Keywords:** Organic solar cell; photonic structure; light trapping; omnidirectional and broadband light absorption enhancement; nanoimprint; FDTD simulation;
Organic solar cells (OSCs) are a promising alternative photovoltaic technique to the conventional solar cells due to their mechanical flexibility and low-cost solution process fabrication capability for application in architectural surfaces, tension membrane, textiles and building facades etc., which are expected to use without a sunlight tracking system.\(^{1-5}\) Bulk heterojunction OSCs have enjoyed a dramatically development during the past decade, achieving power conversion efficiency \((PCE)\) of \(>10\%\).\(^{6-12}\) As an adopted convention, the reported \(PCE\) of the cells is measured typically under the normal incidence of light. However in actual applications, OSCs mostly receive sunlight at varying angles and the performance of the cells depends on the angle of the incident light.\(^{13-14}\) Therefore, light absorption in the cells at different angles of incidence and its impact on the performance of OSCs are important factors to be considered in the device design.\(^{15}\)

The absorption enhancement in OSCs under the normal incidence of light was realized by incorporating the dual-side photonic structures, e.g., using moth’s eye nanostructure (MEN) with a two-dimensional sub-wavelength structure.\(^{16}\) In the MEN-based OSCs, the first MEN structure was created by patterning the 100-nm thick ZnO electron-transporting layer (ETL). The 100-nm thick ZnO ETL was prepared by sol-gel approach using 2-step sintering process at temperatures of 140 \(^\circ\)C for 10 min and 150 \(^\circ\)C for 5 min in air. An external MEN structure (fabricated by UV curable resin), attached to the outside surface of the glass substrate forming dual-side nanostructures, was used to assist enhancing light absorption in the photonic-structured OSCs. It is shown that the combination of the dual-side nanostructures, e.g., a 100-nm thick patterned ZnO ETL (MEN pattern inside the cell) and a UV resin-based nanostructure attached to the outside surface of the glass substrate, contributes to a 20\% increase in light in-coupling efficiency, leading to a \(PCE\) of 9.33\%.\(^{16}\) The efficient light trapping in the photonic-patterned OSCs also was demonstrated using dual-sided deterministic aperiodic nanostructures (DANs).\(^{17}\) In the DAN-based photonic-structured
OSCs, the nanostructures were created on a 100-nm thick sol-gel-derived ZnO ETL. An external DAN-patterned ZnO light trapping layer was coated on the glass-side of the substrate. It is shown that a combination of a patterned ZnO ETL (inside cell) and an external DAN-patterned ZnO light trapping layer (outside cell) helps to enhance light harvesting, yielding 18% increase in the photocurrent of the nano-structured OSCs as compared to a control cell made with a 100-nm thick flat ZnO ETL. However, the absorption enhancement in photonic-structured OSCs under the periodic incidence of light as compared to that of a planar control cell has not yet been examined systemically.

After the sunrise and our days start, the angle of the incident light to the normal of the solar panel reduces, reaching to the normal incidence at noon, then the behaviour repeats in reverse in the afternoon till sunset. The performance of the solar cells varies quite substantially with the angle of the incident solar light. To unravel the unique feature of the enhanced absorption in photonic-structured OSCs under the oblique incidence of light as compared to that of a planar control cell, and also for a more accurate assessment of the cell performance in practical applications, it is important to take into consideration of light absorption in OSCs at different angles of incidence, which accounts for the variation in the intensity of the solar irradiation from sunrise to sunset throughout the day.\textsuperscript{2, 18-19} Suppression of the angle dependent light absorption using nanostructures has advantages for application in thin film solar cells.\textsuperscript{20-22} A more detailed investigation of the angular dependent absorption behaviour in OSCs is desired,\textsuperscript{23-25} particularly, the effect of angle of incidence on light absorption in 2-D photonic-structured OSCs with regard to the excitation of surface plasmon polaritons (SPPs), waveguide modes and light scattering effects in the active layer.

In this work, omnidirectional light absorption enhancement in 2-D photonic-structured OSCs is analysed using a combination of experimental optimization and finite-difference time-domain (FDTD) simulation. The incoming light at an incident angle $\theta$ from the normal
to the cell is considered in the simulation. Light absorption in 2-D photonic-structured OSCs and an optimal planar control cell is examined over a wide incident angle range from -45 deg to 45 deg with regard to the normal incidence. The angular dependent absorption profiles, obtained for both the photonic-structured OSCs and a planar control cell at different angles of the incident light, are analysed. For 2-D photonic-structured OSCs, having a structure period of 350 nm, with an average \( PCE \) of 7.74\% is obtained, which is >11\% higher than that of an optimal planar control OSC (6.94\%). Results show that there is only a slight variation in the short circuit current density \( (J_{SC}) \) of the 2-D photonic-structured OSCs, obtained over the range of the angle of the incident light from the normal to 45 deg. However, \( J_{SC} \) of a planar control cell is more sensitive to the angle of incidence and decreases much faster with increase in the angle of the incident light over the same wavelength range.

**Device fabrication**

Both types of OSCs have the same cell configuration of glass/indium tin oxide (ITO)/zinc oxide (ZnO) (10 nm)/PTB7:PC\(_{70}\)BM/ molybdenum oxide (MoO\(_3\)) (2 nm)/Ag (100 nm). The pre-patterned ITO/glass substrates, with a sheet resistance of 10 \( \Omega \)/square, were cleaned by ultrasonication sequentially with detergent, deionized water, acetone and isopropanol each for 20 min. A 10 nm thick ZnO electron extraction layer (EEL), using the solution of ZnO nanoparticles with a diameter around 5.0 nm in methanol, was first spin-coated on ITO/glass. A 90 nm thick PTB7:PC\(_{70}\)BM active layer was then formed on the surface of ZnO EEL by spin-coating the polymer blend solution at a rotation speed of 2000 rpm for 120 s inside the glove box, having oxygen and moisture levels <0.1 ppm. The PTB7:PC\(_{70}\)BM active layers with the desired 2-D photonic structures having a pitch size of 350 nm were created by nanoimprint method using a polydimethylsiloxane (PDMS) mould. The nanoimprinting process was performed at room temperature for 10 min. The height of the 2-D photonic structures in the active layer was modified by controlling the mould pressure.
during the imprinting process, and was adjusted by optimizing the performance of the photonic-structured OSCs. We found that the optimized height of the 2-D squares with different periodicities (250 nm, 350 nm, 500 nm) was around 30 nm. Therefore, as an approximation and a consistency for comparison between theoretical calculation and experimental optimization, the height of 30 nm was used in the calculation for the photonic-structured OSCs having pitch size ranging from 200 nm to 1000 nm. After the PDMS mould detached from the active layer, samples were then transferred to an adjacent vacuum evaporator, with a base pressure of $5.0 \times 10^{-5}$ Pa, for deposition of the MoO$_3$/Ag electrode. A shadow mask was used to define the top MoO$_3$/Ag electrode. OSCs thus made have an active device area of 0.09 cm$^2$.

**Angular-dependent absorption profiles in 2-D photonic-structured OSCs**

FDTD method was applied to calculate the electromagnetic field in each position of the device by rigorously solving the Maxwell's equations using commercial software Lumerical FDTD Solutions. A 2-nm thick MoO$_3$ interlayer was neglected in the calculation because it was too thin to induce any change in optical modes. The quadrilateral close-packed nanostructures with ellipse profile at the PTB7:PC$_{70}$BM/Ag interface in photonic-structured OSCs were considered in the calculation. The device was meshed by using the grid-based differential time-domain model. The time-dependent Maxwell's equations can be discretized using central-difference approximations to the space and time partial derivatives. The performance of the photonic-structured OSCs, with a structure height of 30 nm (optimized experimentally) having pitch size ranging from 200 nm to 1000 nm, was calculated.

It is known that the absorption behaviour in the 2-D photonic-structured OSCs is closely correlated to their nanostructures.$^{18,26-27}$ To better investigate the optical characteristics of the OSCs, the integrated absorbance and reflectance of the photonic-structured OSCs, formed by
a 2-D array of squares with pitch size ranging from 200 nm to 1000 nm, were analysed. The cross-sectional view of a typical 2-D photonic-structured OSC with an array of squares in the active layer is shown in Fig. 1(a). The performance of the photonic-structured OSCs, with a fixed structure height of 30 nm having pitch size ranging from 200 nm to 1000 nm, was calculated. For cells with different structure periodicities, the duty cycle, defined as the ratio of the structure size to the pitch size, used in the calculations is kept unchanged. The wavelength dependent absorption spectra calculated for the 2-D photonic-structured OSCs with different pitch sizes are plotted in Fig. 1(b).

The integrated absorptance, \( \bar{A} \), in the active layer and the integrated reflectance, \( \bar{R} \), of the OSCs can be calculated using the following equations:\(^{28-29}\)

\[
\bar{A} = \frac{\int A(\lambda) \cdot \Phi(\lambda) d\lambda}{\int \Phi(\lambda) d\lambda},
\]

\[
\bar{R} = \frac{\int R(\lambda) \cdot \Phi(\lambda) d\lambda}{\int \Phi(\lambda) d\lambda},
\]

where \( \Phi(\lambda) \) is the spectral irradiance of the sun light (in W/m\(^2\)-nm) incident on the device, in this work, AM1.5G solar irradiation with a power density of 100 mW/cm\(^2\) is used in the calculation. \( A(\lambda) \) is the wavelength dependent light absorption in the active layer, and \( R(\lambda) \) is the wavelength dependent reflection of the cell. \( \bar{A} \) and \( \bar{R} \) as a function of the structure periodicity, under the normal incidence of light, are plotted in Fig. 1(c). It can be seen in Fig 1(c) that \( \bar{A} \), integrated over the wavelength range from 380 nm to 780 nm, remains with an almost constant of 70% for the 2-D OSCs over the pitch size ranging from 200 nm to 350 nm, it decreases slightly with increase in the structure periodicity of the 2-D photonic structures, e.g., changes from 70.1% for a 2-D photonic-structured cell with a pitch size of 200 nm to 68.7% for the one with a pitch size of 1000 nm. The integrated reflectance \( \bar{R} \) increases from
17.7% for a 2-D photonic-structured OSC having a pitch size of 200 nm to 19% for the one with a period of 1000 nm. For an optimal planar control cell under the normal incidence, a lower $\bar{A}$ of 66.2% in the active layer is obtained, due to a higher integrated reflectance of the cell (20.3%).

To better understand the effect of absorption enhancement in the photonic-structured OSCs, an absorption enhancement factor is introduced, which is obtained by taking the ratios of the differences in absorption between the photonic-structured OSCs having different pitch sizes and an optimal planar control cell, as illustrated in the inset of Fig. 1(d), to the absorption, $A(\lambda)$, of a planar control cell, the dashed curve in Fig. 1(b). The absorption enhancement ratios, calculated for 2-D OSCs with different pitch sizes, as a function of the wavelength are plotted in Fig. 1(d). There is an obvious absorption improvement over a broad wavelength range from 440 nm to 680 nm, which is less dependent on the structure periodicity or pitch sizes of the photonic-structures in the cells. This indicates that the improvement in the absorption in this wavelength region is mainly due to light scattering and diffraction effects. The diffracted light can be coupled into different waveguide modes, resulting in enhanced optical path length and localized electric field. The location of the peaks appeared in the absorption enhancement factor curves over the long wavelength region from 700 nm to 800 nm varies with different structure periodicities, contributed by a combination of the waveguide modes and SPPs.30-31

To further investigate the performance of a planar control cell and the photonic-structured OSCs under the oblique illumination, the angular dependent absorption and reflection spectra as a function of the wavelength are calculated. The absorptance and reflectance of a planar control cell and the 2-D photonic-structured OSCs with different pitch sizes, calculated at different angles of the incident light from $-45$ deg and 45 deg with regard to the normal incidence are plotted in Fig. 2. The integrated absorptance and reflectance calculated for 2-D
photonic-structured OSCs with different pitch sizes are less sensitive to the angle of the incidence as compared to that obtained for a planar control cell.

The absorption spectra calculated for 2-D photonic-structured OSCs with a pitch size of 350 nm and a planar control cell at different angles of the incident light are shown in Fig. 3. It shows that there is a moderate decrease in the absorption of the 2-D photonic-structured OSC with increase in the angle of the incident light. However, the planar control cell experiences an obvious fast reduction in the absorption with increase in the angle of incidence of light.

Fig. 4(a) is a contour plot of the angular-dependent absorption in the active layer, calculated for the photonic-structured OSCs and a planar control cell over the wavelength range from 380 nm to 780 nm. The red regions in the contour plot, as seen in Fig. 4(a), correspond to the wavelength range where the high absorption in the photonic-structured OSCs takes place over the incident angle range from the normal (0 deg) to 45 deg. A contour map of the angular-dependent absorption in the active layer of a planar control cell over the same wavelength range is shown in Fig. 4(b). Compared to the results shown in Figs. 4(a) and 4(b), broadband absorption enhancement in the active layer of a 2-D photonic-structured OSC is clearly attained in the wavelength region from 380 nm to 780 nm. The absorption enhancement is closely associated with light trapping caused by a combination of light scattering, excitation of SPPs, waveguide modes and their mutual coupling.\textsuperscript{19, 32} Therefore, the enhanced light absorption in the photonic-structured OSCs under different angles of the incident light is achieved as compared to that of a planar control cell over a broad wavelength range.

**Performance of nanoimprinted photonic-structured OSCs**

Following the theoretical simulation, considering the cell structure having a high light absorbance in the active layer, as illustrated in Fig. 1 (c), and the process compatibility in the
nanoimprinting approach, PDMS mould with a pitch size of 350 nm was used for device fabrication. A series of 2-D photonic-structured OSCs, with a pitch-size of 350 nm, were characterized for analysing the angular dependent light absorption enhancement. The results are compared to that of an optimal planar control OSC.

The current density–voltage ($J$–$V$) characteristics measured for the 2-D photonic-structured OSCs and a planar control cell are shown in Fig. 5(a). The cell parameters and the corresponding statistical standard deviations obtained for the 2-D photonic-structured OSCs and a planar control cell are summarized in TABLE I. The results reveal that both types of the OSCs have the same open circuit voltage ($V_{OC}$) of 0.73 V. This implies that incorporation of the photonic structures does not change the $V_{OC}$ in the OSCs, which agrees with the previous report.$^{32}$ The $J_{SC}$ of 15.17 mA/cm$^2$ is obtained for 2-D photonic-structured OSCs, which is 7.6% higher than that of a structurally identical control planar cell (14.01 mA/cm$^2$). 2-D photonic-structured OSCs also possess a higher fill factor (FF), attaining an enhanced PCE of 7.74%, which is >11% higher than that of a planar control cell (6.94%). The insert in Fig. 5(a) is the AFM image measured for the surface of the OSCs with a MoO$_3$ (2 nm)/Ag (100 nm) top contact deposited on the imprinted photonic-structured PTB7:PC$_{70}$BM active layer, following the active layer morphology acting as a plasmonic element and the top electrode.

The incident photon to current efficiency (IPCE) spectra measured for the photonic-structured and an optimal planar OSC at the normal incidence are shown in Fig. 5(b). The corresponding IPCE enhancement factor, which is obtained by taking the ratio of the difference in IPCE spectra between a photonic-structured OSC and a planar control OSC to the IPCE spectrum of a planar control cell, the blue curve shown in Fig. 5(b). There is an obvious enhancement in the IPCE spectra of the photonic-structured OSCs over the visible light wavelength range from 460 nm to 700 nm, which agrees well with the FDTD simulation.
The absorption enhancement in the long wavelength region, predicted by the theoretical simulation, also is manifested by the IPCE measurements, contributed due to the waveguide modes, SPPs and their mutual coupling.\textsuperscript{32}

To unveil the origin of the performance enhancement in OSCs, the charge extraction probability, \(P(I, V_{\text{eff}})\), as a function of the effective voltage \(V_{\text{eff}}\) is analysed. \(I\) is the intensity of light, \(V_{\text{eff}} = V_0 - V_b\), where \(V_0\) is the built-in potential and \(V_b\) is the external bias, recorded for the photonic-structured OSCs and a planar cell under AM1.5G irradiation of 100 mW/cm\(^2\). At a given \(I\), the charge extraction efficiency \(P\) as a function of \(V_{\text{eff}}\) can be expressed as:\textsuperscript{33}

\[
P(I, V_{\text{eff}}) = \frac{J_{\text{ph}}(I, V_{\text{eff}})}{J_{\text{ph, sat}}(I)},
\]

where \(J_{\text{ph}} = J_l - J_d\), \(J_l\) and \(J_d\) are the photocurrent and dark current. \(J_{\text{ph, sat}}(I)\) in eq.(3) denotes the saturation photocurrent of the OSC at a given intensity of light. It was obtained by measuring \(J_{\text{ph}}\) of the OSCs approaching high \(V_{\text{eff}}\) of \(>1.0\) V. Under this condition, it is expected that the high effective internal electric field inside cell assists in the suppression of the charge recombination loss, thereby facilitating an efficient sweeping-out of the photo-generated charge carriers reaching to a saturated photocurrent \(J_{\text{ph, sat}}\). \(P - V_{\text{eff}}\) plots obtained for the photonic-structured OSCs and a planar control cell are shown in Fig. 6. It shows that \(P\) approaches unit at a high \(V_{\text{eff}}\), which corresponds to the complete extraction of the photo-generated charges.\textsuperscript{34} In this regime, recombination can be negligible. \(P\) decreases with reduction in \(V_{\text{eff}}\). The \(P - V_{\text{eff}}\) plots measured for the 2-D photonic-structured OSCs and a planar control cell overlap in the whole effective voltage range from short circuit to open circuit conditions, implying that both types of OSCs have similar charge extraction properties. The results in Fig. 6 suggest that the creation of the 2-D photonic-structure with a pitch size of 350 nm in the active layer does not affect the charge extraction probability in the OSCs.
The above discussion agrees with a previous study of 2-D photonic-structured OSCs, with an array of hexagonal-structures having a pitch size of 480 nm, in showing that the nanoimprinted photonic-structured OSCs possess the same charge collection efficiency as compared to that of an optimal planar control cell.\textsuperscript{32}

The diffracted light inside the photonic-structured OSCs has a profound impact on light absorption in the cells, caused by the distinct optical phenomena in the imprinted periodic 2-D grating active layer. The higher order diffracted light at an angle greater than the critical angles is totally reflected and trapped forming wave guide mode inside the photonic-structured OSCs. Our theoretical simulation reveals that light coupled into the waveguide mode in the 2-D grating active layer contributes to light absorption enhancement. The presence of the periodic metallic nano-structures at the active layer/metal interface also is favourable for light harvesting due to the coupling of the incident light into surface plasmon polaritons propagating at the active layer/metal electrode interface as well as guided modes in the active layer. The distributions of the electric field ($|E|$) calculated for a planar control OSC and the 2-D photonic-structured OSC (pitch size 500 nm, structure height 30 nm) at different wavelengths of 540 and 810 nm are plotted in Fig. 7. Figs. 7(a) and (b) show that the $|E|$ distribution in a planar control cell is localized near the vicinity of the organic/metal interface and quickly diminishes toward the Ag electrode. In the photonic-structured OSC, the $|E|$ field in the photonic-structured active layer is remarkably enhanced. The resonant optical modes of the $|E|$ field are trapped within the active layer, indicating that the absorption of the incident light can be enhanced. The distribution of the enhanced field in the active layer calculated for the wavelength of 540 nm, shown in Fig. 7 (c), is due to the waveguide modes, contributing to the absorption enhancement. The field enhancement at the long wavelength of 810 nm, as illustrated in Fig. 7 (d), is associated with the plasmonic resonance excited by the 2-D periodic nanostructured Ag rear electrode, harvesting the long wavelength light in the cell.
The performance of the photonic-structured OSCs and a planar control cell at the oblique incidence of light also was examined. IPCE spectra measured for a photonic-structured cell and a planar control cell at different angles of 0 (normal), 15, 30 and 45 degrees of the incident light are shown in Figs. 8(a) and 8(b). A moderate decrease in the IPCE spectrum with increase in the angle of the incident light in a 2-D photonic-structured OSC is observed. However, the planar control cell experiences a much faster reduction in IPCE with increase in the angle of the incident light. Compare to a planar control cell, the enhancement in IPCE of the photonic-structured OSCs occurs at the different angles of the incident light. The increase in the absorption in the photonic-structured OSCs is more prominent over the wavelength range from 450 nm to 680 nm, which agrees well with the results seen in the simulated absorption spectrum.

The $J_{SC}$ of different OSCs also was calibrated using the corresponding IPCE spectrum by the following equation:

$$J_{SC} = \int IPCE \times \frac{q\lambda}{hc} \Phi(\lambda)d\lambda,$$

where $q$ is elementary charge, $c$ is the speed of light, and $h$ is the Planck’s constant. Applying eq. (4), $J_{SC}$ values calibrated using the IPCE spectra measured for the photonic-structured OSCs and a planar control cell at different angles of the incident light are plotted in Fig. 9(a). It is clear that $J_{SC}$ of the photonic-structured OSCs has less dependence on the angle of the incident light, e.g., changes from 15.17 mA/cm$^2$ (at 0 deg) to 14.76 mA/cm$^2$ (at 45 deg), which is 97.3% of the $J_{SC}$ obtained at the normal incidence. $J_{SC}$ of a planar control cell has a more prominent dependence on the incidence angle. It decreases from 14.02 mA/cm$^2$ (0 deg) to 13.15 mA/cm$^2$ (45 deg), which is only 93.8% of the $J_{SC}$ obtained at the normal incidence, indicating a faster drop in the absorption of the flat cells with increase in the angle of the incident light.
The values of the integrated absorbance, calculated for the active layers in the photonic-structured OSCs and a planar control cell, are shown in Fig. 9(b). As the angle of the incident light increases from 0 deg (normal) to 45 deg, the absorbance in the active layer of a photonic-structured OSC changes slightly from 70.1% to 67.7%, remaining 96.6% of the absorbance obtained at the normal incidence. While for a planar control OSC, the integrated absorbance in the active layer attained at an oblique incident angle of 45 deg remains only 94% of the absorbance obtained at the normal incidence, e.g., a larger decrease in the absorbance from 66.2% to 62.2%. In addition to the broadband absorption enhancement, the photonic-structured OSCs also have the advantages in boosting light absorption at the oblique angle of incidence.

As shown in Fig. 9, the use of photonic-structures not only enables a high $J_{SC}$, but also greatly reduces the angular dependent absorption on the incident light. The behavior of such absorption enhancement is mainly due to the distinct optical phenomena in the OSCs containing 2-D periodic nanostructures. The unique feature of weak angular dependency on light absorption in photonic-structured OSCs is of great importance in practical application. With different angles of incidence of solar irradiation, more efficient light trapping can be maintained in the active layer of the photonic-structured OSCs. The incorporation of the periodical structures enables the effective light trapping for attaining simultaneous omnidirectional and broadband absorption enhancement in such OSCs.

Conclusions

In summary, omnidirectional and broadband light absorption enhancement in 2-D photonic-structured OSCs with a pitch size of 350 nm is demonstrated experimentally. The results reveal that increase in the $J_{SC}$ of 2-D photonic-structured OSCs at the different angles of the incidence of light benefits from the combined effects of light scattering, excitation of
SPPs, waveguide modes and their mutual coupling, caused by the photonic structures. An average $PCE$ of 7.74% is obtained for a PTB7:PC$_{70}$BM-based photonic-structured OSC, having a pitch height of 30 nm and a pitch size of 350 nm, which is 11.4% higher than that of an optimized planar control cell (6.94%).

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References


Fig. 1: (a) Schematic diagram showing the cross-sectional view of the photonic-structured cell, (b) absorption spectra calculated for a planar control cell and a set of photonic-structured OSCs with pitch size ranging from 200 nm to 1000 nm, (c) $\bar{A}$ and $\bar{R}$ of the photonic-structured OSCs as a function of the pitch size, the values of $\bar{A}$ and $\bar{R}$ calculated for a planar control cell are indicated for comparison, and (d) the absorption enhancement ratio as a function of wavelength calculated for different photonic-structured OSCs. Inset in Fig. 1(d): difference in absorption between the photonic-structured OSCs and a planar control cell.
Fig. 2: Integrated (a) absorptance and (b) reflectance calculated for a planar control and the 2-D photonic-structured OSCs with different pitch sizes at different angles of the incident light from -45 deg to +45 deg.

Fig. 3: The wavelength dependent absorption spectra calculated for (a) a 2-D photonic-structured OSC with a pitch size of 350 nm and (b) a planar control cell at different angles of the incident light.
Fig. 4: The contour maps of the angular-dependent absorption in the active layer, calculated for (a) a photonic-structured OSC with a pitch size of 350 nm and (b) a planar control cell over the wavelength range from 380 nm to 780 nm.

Fig. 5: (a) $J-V$ and (b) $IPCE$ characteristics measured for a photonic-structured OSC and a planar control cell at the normal incidence.
Fig. 6: $P-V_{eff}$ characteristics obtained for a 2-D photonic-structured OSC with a pitch size of 350 nm and a planar control cell.

Fig. 7: Distributions of the electric field ($|E|$) calculated for a planar control cell at different wavelengths of (a) 540 nm and (b) 810 nm, and the corresponding $|E|$ distributions calculated for the 2-D photonic-structured OSCs, with a pitch size of 500 nm, structure height 30 nm, at different wavelengths of (c) 540 nm and (d) 810 nm.
Fig. 8: IPCE spectra measured for (a) a 2-D photonic-structured OSC with a pitch size of 350 nm and (b) a planar control cell at different angles of 0 deg (normal), 15 deg, 30 deg, and 45 deg of the incident light.

Fig. 9: (a) The calibrated $J_{SC}$ and (b) the calculated $\bar{A}$ obtained for the photonic-structured OSCs and a planar control cell as a function of the angle of the incident light.
TABLE I: Summary of $V_{OC}$, $J_{SC}$, $FF$, $PCE$ and sheet resistance, $R_S$, obtained for the photonic-structured OSCs with a pitch size of 350 nm and a planar control cell.

<table>
<thead>
<tr>
<th>OSCs</th>
<th>$V_{OC}$ (V)</th>
<th>$J_{SC}$ (mA/cm$^2$)</th>
<th>$FF$ (%)</th>
<th>$PCE$ (%)</th>
<th>$R_S$ (Ω·cm$^2$)</th>
</tr>
</thead>
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<tr>
<td>Photonic-structured</td>
<td>0.73±0.01</td>
<td>15.17±0.20</td>
<td>70.0±1.2</td>
<td>7.74±0.20</td>
<td>3.7±0.5</td>
</tr>
<tr>
<td>Planar control</td>
<td>0.73±0.01</td>
<td>14.01±0.15</td>
<td>68.1±1.1</td>
<td>6.94±0.15</td>
<td>3.8±0.6</td>
</tr>
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TOC