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3D-printed concentrator arrays for external light trapping on thin film solar cells

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ABSTRACT

After our recent demonstration of a 3D-printed external light trap on a small solar cell, we now consider its potential for large solar panels. An external light trap consists of a parabolic concentrator and a spacer that redirects the photons that are reflected by the solar cell back towards the solar cell. These retro-reflections enable higher absorptance and improved power conversion efficiency. Scaling a single external light trap such that it covers a large solar panel has disadvantages in terms of height and cost of the external light trap. These disadvantages can be overcome by deploying an array of concentrators as the top part of the external light trap. We present an optimization study of concentrator arrays for external light trapping. We fabricated 3D-printed external light traps with a square, hexagonal and circular compound parabolic concentrator to test their suitability for concentrator arrays. The 3D-printed traps were placed on top of an organic solar cell which resulted in a significant enhancement of the external quantum efficiency. The required transmittance of these concentrator arrays is calculated as a function of the parameters of both the concentrator and the solar cell. We compare the theoretical and experimentally determined optical performance of the different concentrators. Finally, the prospects of external light trapping are analyzed and we give guidelines for improvements of the external light trap design.

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1. Introduction

Thin solar cells benefit from low bulk recombination of excited charge carriers. Hence the performance of a thick solar cell generally improves by reducing its thickness provided that the absorptance stays constant. Therefore, large efforts have been made to obtain high absorptance in thin solar cells by modifications of the solar cell surface to obtain internal light trapping [1,2]. However, these internal cell modifications often have a negative impact on the material quality and the electrical performance of the solar cell. For example, by texturing the surface of crystalline silicon (c-Si) solar cells the surface recombination velocity increases due to the enlarged surface area [3,4]. For other cells like nanocrystalline silicon (nc-Si) the growth of a solar cell on top of a textured scattering surfaces is challenging [5–7] while for organic solar cells texturing is less effective [8]. It is thus challenging to realize the full theoretical potential of internal light trapping for most solar cells and there is a need for better light trapping methods [9]. We demonstrate an external light trapping method that can complement or even replace internal light trapping and which moreover can be directly applied on all solar cells.

Fig. 1 illustrates the concept of an external light trap: a concentrator focuses the sunlight through a small aperture before the light reaches the photovoltaic device. Most of the reflected (and radiatively emitted) light by the solar cell is reflected back to the solar cell by the reflective coating of the cage. Therefore, there is a higher probability for a photon to be absorbed. This photon recycling enables higher power conversion efficiency [10–14]. Moreover, external light trapping enables new photovoltaic devices that, for example, can facilitate spectrum splitting [15,16].

The theoretical energy conversion efficiency limit of external light trapping surpasses that of conventional internal light trapping [17,18,13]. This is mainly due to the improved electrical quality of...
thin solar cells and the potential recycling of radiative emission. Recently, we demonstrated a broadband absorption enhancement by applying one external light trap on a \( \sim 1 \text{ cm}^2 \) nanocrystalline silicon solar cell [14]. A light trap that covers a larger solar cell area can be made of a single tall concentrator, but this translates to high material costs and weight, and moreover it is aesthetically unattractive. The use of an array of small concentrators overcomes these disadvantages. We present an optimization study of the design of concentrator arrays suited for external light trapping. Furthermore, we compare the theoretical and experimental transmittance of a square, hexagonal and circular 3D-printed parabolic concentrator. Previously, a light trap incorporating a micro-lens array has been shown to be successful on an organic solar cell [19,20]. Here, a low cost fabrication method is presented that requires less fabrication steps and is industrially scalable.

To test the performance of the external light traps we use organic solar cells (OSC). For these cells there are currently no adequate light trapping methods. The absorptance of a thin OSC is relatively low. Although a thick OSC has a high absorptance, a thick cell design is not desirable: due to the high bulk recombination rate, the IQE decreases for a large number of reflections at the concentrator surface. At each reflection a small fraction of the light is reabsorbed by parasitic losses at the recombination center. We assume that the light is reflected back to the solar cell. A small fraction of the light can escape out of the cage.

**2. Experimental: design of the concentrator**

Metallic parabolic concentrators with a square and a hexagonal top shapes can be arranged in an array. Figs. 2a and d show a square concentrator that is composed of four parabolic segments. These square concentrators can be arranged in a square array as shown in Fig. 2g. In a similar way a hexagonal array can be made as shown in Fig. 2b, e and h. Circular concentrators cannot completely fill a plane. To overcome this filling problem the circular concentrators can be truncated at four sides to enable the formation of a square array as illustrated in Fig. 2c, f and i. In a similar way a hexagonal array of circular concentrators can be made. In between the neighboring concentrators there are sharp peaks which are fragile and challenging to fabricate.

The transmittance of the concentrator is a key-parameter for the performance of the external light trap. Incoming light that travels in a straight line towards the aperture of the concentrator is transmitted without being reflected by the concentrator. The main part of the light is reflected one or more times at the reflective concentrator surface before going through the aperture to enter the cage. The exact number of reflections depends on the geometry of the parabolic concentrator. At each reflection a small fraction of the light is absorbed by parasitic losses at the reflective surface of the concentrator. The averaged transmittance of a concentrator therefore decreases with increasing geometric concentration factor \( C \), where \( C \) is defined as the following area ratio:

\[
C = \frac{A_{\text{cell}}}{A_{\text{aperture}}}.
\]

To determine the optimal concentrator geometry we calculated the average transmittance of incoming light propagating parallel to the central axis of the concentrator. The transmittance of light originating from other angles depends on the parabolic shape of the concentrator [29]. Diffuse light is only partly transmitted by the concentrator. The maximum transmitted power \( P_{\text{trans}} \) of isotropically distributed diffuse light \( P_{\text{diff}} \) is \( P_{\text{trans}} = (1/C)P_{\text{diff}} \) [30]. Sun tracking will yield the best averaged transmittance of the concentrator as all rays of the direct sunlight will be transmitted through the aperture. However, external light trapping can be more cost effective without diurnal sun tracking which is possible: at low concentration factors \( C < 10 \times 1 \) a static concentrator can still accept the direct sunlight for around 8 h per day [31].

It is difficult to determine the transmittance of a hexagonal concentrator analytically and therefore we performed ray tracing. Fig. 3a shows three different rays at paraxial incidence with a different number of reflections at the concentrator surface. Depending on the origin, a ray hits the hexagonal concentrator a certain number of times. Fig. 3b indicates the number of reflections for a large number of rays. The average number of reflections for this concentrator with \( C = 15x \) is 1.43. From this ray tracing the transmittance is approximated by the average transmittance of all rays assuming a wavelength and angle-independent reflection coefficient of 95%.

Fig. 4 shows the calculated transmittance of the concentrators as a function of the concentration factor. The right inset depicts the average number of reflections at the concentrators before a ray is transmitted. For the circular and square concentrators this average converges to 1 and 2 reflection(s) respectively. Therefore, the transmittance of these concentrators converges to \( R \) and \( R^2 \) respectively. There is no convergence for the hexagonal concentrator.

Rounded ridges in between neighboring concentrators will inevitably form during fabrication due to, for example, limited fabrication accuracy and limited material strength. We assume that these limitations translate to ridges having a width \( \Delta \). The fraction of the total area covered by ridges \( f_{\text{ridge}} \) is shown in Fig. 5. Light
hitting a rounded ridge is not transmitted to the solar cell but is instead reflected to another direction which limits the transmittance to $f_{\text{ridge}}$. It can be seen that a hexagonal array has the lowest ridge fraction. The horizontal dimensions of an individual concentrator in an array should be roughly 200 times larger than the smallest ridge width that can be fabricated to realize a ridge loss below 1%. For the fabrication of a concentrator array, a trade-off has to be made between the ridge area fraction, the material consumption, the height of the array, and the transmittance.

To optimize the performance of the external light trap we use an optical statistical model to determine the key parameters for the performance [14]. We consider a bare solar cell with an absorptance $A_{sc}$ and a concentrator transmittance $T_c$. We assume the light to be scattered such that it is uniformly distributed and the escape probability is given by the area fraction of the aperture. According to the model, the total absorptance in the cell with an external light trap ($A_T$) is given by

$$A_T = T_c \left( 1 - R_{sc} \left( 1 - C^{-1}R_{cage} \right) A_{sc} \right).$$

where $R_{sc}$ and $R_{cage}$ are respectively the reflectance of the bare solar cell and the cage [14]. The external quantum efficiency (EQE)
of the cell with light trap $E_{\text{QE}_\text{trap}}$ is given by

$$E_{\text{QE}_\text{trap}} = A_T \cdot \text{IQE},$$

with IQE being the internal quantum efficiency of the cell.

With this statistical model we can derive the equivalent optical thickness of a solar cell with an external light trap. Therefore we introduce the optical path length enhancement factor ($\Pi_{\text{ext}}$) which indicates how many times a photon statistically passes the solar cell. In other words, the effective optical thickness is given by $\Pi_{\text{ext}}$ multiplied by the thickness of the cell. From absorption measurement with and without external light trap applied we can calculate the effective external path length enhancement factor according to

$$\Pi_{\text{ext}} = \frac{\log(1 - A_T)}{\log(1 - A_c)} = \frac{\log(1 - A_T)}{\log(R_{cage})}.\tag{3}$$

In the low absorbing limit ($T_c = R_{cage} = R_{sc} = 1$) the value of $\Pi_{\text{ext}}$ interestingly equals $C$. By substituting $A_T$ (from Eq. (1)) into Eq. (3) one finds that $\Pi_{\text{ext}}$ gradually drops to one with decrease of the cell reflectance [14].

This theoretical framework enables us to determine the critical design parameters of the external light trap. A reduction of the aperture (which is equivalent to an increase of the concentration factor) results in significantly enhanced light trapping as the escape probability becomes more restricted. However, at a certain aperture size the device performance will become most significantly limited by other parameters, see Eq. (1).

We calculated the achievable path length enhancement factor from the concentrator transmittance, the reflectance of the solar cell and the concentration factor of the external light trap. By reversing this procedure we determined the concentrator transmittance required for a desired path length enhancement factor.

Fig. 6a illustrates the concentrator transmittance at $C = 6 \times$ and $R_{cage} = 0.95$ required to obtain an effective path length enhancement factor of $1 \times$ to $4 \times$ as a function of the cell reflectance. When $\Pi_{\text{ext}} = 1$, the gain due to light trapping equals the transmittance losses. The net absorptance is reduced by the light trap when $\Pi_{\text{ext}} < 1$ as indicated by the red zone in the parameter space.

For solar cells with a high reflectance the external trap enables the highest degree of light trapping and efficiency improvement, even at a relatively low concentrator transmittance. On the other hand, for solar cells with a low reflectivity a relatively high concentrator transmittance is required for a significant performance boost.

External light trapping is thus of less direct interest for highly absorbing solar cells. In the end, however, external light trapping can enable more efficient solar cell designs. For example, the combination of a thin, non-textured solar cell of high electrical quality and a high optical quality external light trap that has the potential to outperform conventional light trapping methods [17,13].

Figs. 6b and c show the same scan of the parameter space at $C = 10 \times$ and $C = 20 \times$ which improves the light trapping. At a concentration factor of $20 \times$ and a cage reflectance of $R_{cage} = 0.95$ the escape loss via the aperture and the absorptance in the cage are both 5% per cycle. Interestingly, the loss at the concentrator is a one-time event, while the loss at the reflective cage accumulates for each recycle event. The absolute optical loss at the cage depends on the intensity of the (multiple times) reflected beam and is thus related to the reflectivity of the solar cell. The net optical absorptance loss is mainly determined by the dominant loss mechanism. Therefore, only diminishing returns are obtained upon a further increase of the concentration factor: the loss by the cage becomes dominant. For a further improvement it is rewarding to improve the reflectance of the cage as shown for $R_{cage} = 0.99$ in Fig. 6d. This reduction of the parasitic cage absorption can be realized by using a highly reflective white paint [32,33].

3. Results and discussion

Figs. 7 and 8 show the fabricated concentrators with a concentration factor of $C = 6x$. They were 3D-printed, chemically polished with acetone vapor and metalized [14]. The cage and the concentrators were coated with silver, which is also used in optical telescopes because of its high reflectance [34]. The flat, reflective bottom side of the concentrator forms the top of the cage which reflects the light back to the solar cell. The light traps were placed on top of an organic solar cell which is illustrated in Fig. 9a. The processing details of the solar cell are described in the supplemental.

The effectiveness of the light trap is largely determined by the concentrator transmittance, which in our experiment is limited by the reflectance of the sputter coated silver. Fig. 9b shows the reflectance of silver ($R_{\text{silver}}$) measured at normal incidence. Also shown is $R_{\text{silver}}^2$ which represents the two reflection at the corner areas of the square concentrator. Close to the plasma wavelength
are relatively high at different \( \lambda \), and the solar cell reflectance\( (R_{sc}) \) required to obtain the indicated path length enhancement\( (\Pi_{ext}) \), see Fig. 10[e] [14]. At short wavelengths\( (\lambda \leq 400 \text{ nm}) \) the external path length enhancement is less than 1 due to the relative low concentrator transmittance. At 400 nm the transmittance losses are roughly compensated by the gain due to light trapping. At 500 nm the cell reflectance is low, which slightly reduces the gain of light trapping and therefore \( \Pi_{ext} \) is \( \sim 1 \). In the long wavelength regime\( (\lambda \geq 600 \text{ nm}) \) the optical path length is effectively doubled.

The path length enhancements caused by the different concentrators do not all follow the exact trend. This is partly caused by the different optical paths of the light within the cage due to the different concentrator shapes. Furthermore, there are small variations in the smoothness and the reflectance of the bottom side of

Most of the light is absorbed in the poly(3-hexylthiophene-2,5-diyl) (P3HT); phenyl-C61-butyric acid methyl ester (PCBM) blended layer. At wavelengths of \( \sim 300 \text{ nm} \) PCBM absorbs strongly, while P3HT peaks at around 500 nm [36]. In the wavelength range 300–600 nm there is significant potential for recycling as the reflectance varies from 5% to 55%.

The EQE curves of the solar cell with the external light traps on top are shown in Fig. 10a–d. For each concentrator three EQE measurements were performed, their spread is indicated by the colored areas. The light trap was re-aligned for each measurement which translates to this spread of a few percent. For the hexagonal and the circular concentrators an improvement at almost all wavelengths longer than 380 nm is observed. The IQE and \( R_{sc} \) are relatively high at wavelengths around 400 and 620 nm, this combination translates to a high absolute gain of the EQE at these wavelengths. The EQE of the hexagonal light trap improved by 9%\( \Delta \text{abs} \) at 620 nm and by 69%\( \Delta \text{rel} \) at 660 nm. The circular concentrator shows the best performance below \( \sim 500 \text{ nm} \) because the absorptance loss in the silver of this concentrator is relatively small as there is only 1 reflection. The hexagonal and circular concentrators show the best performance: the implied short circuit current improved from 6.5 to 7.3 mA/cm².

From the difference in EQE of the cell with and without light trap the external path length enhancement factor was calculated using Eq. (3), see Fig. 10[e] [14]. At short wavelengths\( (\lambda \leq 400 \text{ nm}) \) the external path length enhancement is less than 1 due to the relative low concentrator transmittance. At 400 nm the transmittance losses are roughly compensated by the gain due to light trapping. At 500 nm the cell reflectance is low, which slightly reduces the gain of light trapping and therefore \( \Pi_{ext} \) is \( \sim 1 \). In the long wavelength regime\( (\lambda \geq 600 \text{ nm}) \) the optical path length is effectively doubled.

(\( \lambda \sim 310 \text{ nm} \)) the parasitic absorptance in the silver is extremely high, resulting in a low concentrator transmittance [35]. At longer wavelengths the silver reflectance gradually improves to 95%. Therefore, a significant transmittance difference is expected between the circular and the square concentrator between wavelengths of 325 and 500 nm.

In addition to the transmittance of the concentrator the reflectance of the solar cell affects the light trap performance. Fig. 9c shows the reflectance, absorptance, EQE and IQE of the organic solar cell.

Fig. 6. Overview of the relation between the path length enhancement factor of an external light trap, the concentrator transmittance\( (\Pi_{ext}) \), and the solar cell reflectance\( (R_{sc}) \) at several concentration factors. (a)-(d) The solid lines depict the\( \Pi_{ext} \) required to obtain the indicated path length enhancement\( (\Pi_{ext}) \) as a function of\( R_{sc} \) at different concentration values\( (C) \) and cage reflectance\( (R_{cage}) \). In the red area the cell performance is reduced in the presence of the light trap. The blue shaded area in (a) indicates the range in which our experiment is performed. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Fig. 7. Silver coated square, hexagonal and circular parabolic concentrators. For reference a 10 eurocent coin is shown on the right.

Fig. 8. A 3D-printed 2 × 2 square array of concentrators that can be used as a top part of an external light trap. The coin is shown as reference.
the concentrator (which forms the top reflector of the cage). Light is reflected only once in the circular concentrator, therefore it has a higher transmittance and a higher $\Pi_{\text{ext}}$ at short wavelengths than the square and hexagonal concentrators.

We made a fit to the experimental EQE data by inserting the parameters of the solar cell and the concentrator into our optical model (see dashed black lines in Fig. 10a–d). The formula for the fit is obtained by substituting Eq. (1) into Eq. (2) from which $\text{EQE}_{\text{External light trap}}(T_{\text{C}}, R_{\text{sc}}, C, R_{\text{cage}}, \text{IQE}, \lambda)$ is derived. The concentrator transmittance ($T_{\text{C}}$) was set as variable. There is an excellent agreement between the fitted curves and the experimental EQE data.
When the light trap is applied there is a range of angle of incidence (AOI) at the solar cell, while without the light trap the light comes in at normal incidence. In order to keep the optical model universal the IQE is assumed to be independent of the AOI and to be the same for the cell with and without external light trap. However, depending on the type of solar cell, this non-normal AOI can have several effects on the cell performance: an increased AOI can reduce the IQE especially at short wavelengths due to the relative high absorption in electrically dead top layers [37,27,14]. For this reason we presume that the experimental data at short wavelengths (λ < 350 nm) is a few percent lower than the fit.

The theoretical and measured average transmittance of the fabricated concentrators (C = 6 × 1) are listed in Table 1. At least 4% of the light is lost due to the absorptance in the concentrator. The theoretical transmittance of the concentrator is calculated at a reflectance of 95% at the concentrator surface. The transmittance of the square array is significantly lower than the single square concentrator due to the ridge fraction.

The theoretical and experimental values of \( \tilde{\eta} \) differ by a few percent for which we can indicate several causes. First, the 3D-printing process results in small contour errors with respect to the intended 3D-model. Secondly, the vapor smoothing of the concentrator does not lead to a perfectly smooth surface. These errors are expected to be most severe at the sharp corners of the square and hexagonal concentrators. Finally, in the optical model we assumed a normal angle of incidence at the reflective concentrator surface. However, this angle depends on the curvature of the concentrator leading to a spread in the angle of incidences at the solar cell.

4. Conclusions

We demonstrated that external light trapping is of interest for all solar cells as its effectiveness does not depend on the refractive index or texture of the solar cell and it is easy to apply. As the device is an add-on it guarantees that there is no negative impact on the electrical properties of the solar cell. We proposed several possible designs for an array of concentrators that can be integrated in an external light trap that covers a large solar cell area. The use of 3D-printed light traps with a square, hexagonal and circular parabolic concentrates resulted in a significantly improved EQE of an organic solar cell. Excellent agreement was found between the fit based on our model and the experimental data, which shows the predictive power of the model. Moreover, an effective path length enhancement factor larger than 2 is observed while the EQE improved by up to 69\%num, corresponding to an increase of the short circuit current of 13%. This indicates that external light trapping is an interesting alternative or supplement for internal light trapping.

To determine the critical design parameters of the light trap we calculated the achievable path length enhancement as a function of several parameters of the light trap and the solar cell. The transmittance loss in the concentrator has to be fully compensated by light trapping, and therefore a high concentrator transmittance is essential for a high device performance. For further optimization we indicated how the achievable concentrator transmittance depends on the concentration factor, fabrication accuracy, cage reflectivity, concentrator shape and concentrator size. Our theoretical analysis shows that a hexagonal array of circular concentrators has the best optical performance.

High fabrication accuracy is essential to realize a high transmittance and performance. Once a sufficiently high concentrator transmittance has been realized the concentration factor and the cage reflectance become more critical. We thus demonstrated how an external light trap made from an array of concentrators can effectively improve the efficiency of solar cells and we showed a clear pathway for further optimization.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.solmat.2015.03.002.

References


Table 1

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<tr>
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[33] Labsphere Website on spectralon® [online, cited January 29, 2015].


