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Light trapping, a new approach to spectrum splitting

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ABSTRACT

In this paper, a novel type of light trap is introduced. It enables photovoltaic conversion with separate solar cells optimized for different frequency bands, which are covered by spectrally selective mirrors. Sunlight is coupled into a transparent medium and converted to diffuse radiation by randomization. It is well known that under these conditions light intensity is enhanced by a factor of $2n^2$ inside the medium. The unidirectional radiation at the aperture is however only n^2. Two types of light trap are presented. The first one employs concentrated radiation incident on a small volume light trap. It is shown that efficiency depends on the ratio (solar cell area)/(input area). A more detailed analysis shows that under regular conditions part of the light is absorbed directly after entering the trap which results in higher efficiencies. We show that a trapping efficiency above 90% is obtainable.

The second type of trap is based on a photonic structure covering the surface of the medium. It has high angular selectivity and broad spectral transmission. An analysis of efficiency and loss mechanisms is presented. If both types of trap are combined even higher efficiency is possible. Consequences for solar cell technology are investigated. It is further shown that the light trapping principle can also be applied to large area stationary modules.

1. Introduction

1.1. Background

The efficiency of a solar cell consisting of a single semiconductor material is limited theoretically to about 40% [1]. In order to reach higher efficiency, the solar spectrum has to be subdivided and converted by different solar cells with optimized band gaps. The best approach at present is to use multijunction cells stacked above each other such that the top cell converts the shortest wavelength fraction while being transparent to the longer wavelengths that are in turn converted by other solar cells lower in the stack. In concentrating systems, those multijunction cells consist of monolithically grown III–V compounds. Thin film double or triple junction cells have so far only been realized in amorphous-microcrystalline cells but efficiencies are moderate. The multijunction approach has so far yielded the highest efficiencies but has some limitations. To achieve high efficiencies for these cells, the lattice match conditions have to be regarded. Currently, new technologies like lattice mismatched and metamorphic cells [2] are developed though that alters this limitation. Furthermore, between cells tunnel diodes have to be inserted because the cells have opposite polarity. Very stringent is the requirement that all cells have to produce equal current because the stack represents a series connection. When the spectral conditions of irradiation change current match is negatively affected. If separate individual solar cells could be used to convert the frequency bands more freedom of design and potentially higher efficiency could be expected. A well-known idea to achieve spectrum splitting for separate solar cells is the fluorescent concentrator [3].

Another very old concept to achieve this type of spectrum splitting is to use dichroic mirrors in a concentrating system that focus different parts of the solar spectrum onto separate solar cells [4]. This concept has been getting renewed attention recently [5].

In this paper, a new method is described that permits to use separate solar cells side by side without the restrictions mentioned.

1.2. The basic concept

The light trapping concept presented here has the following properties:

- A transparent volume of the trap filled with diffuse radiation.
- Solar radiation enters the trap through an input area bordering air.
- The radiation is randomized either at entering the trap or by scattering centres or by lambertian reflectors within the trap.

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- Separate solar cells with different band gaps are optically coupled to the trap.
- The surfaces of these solar cells are covered with band-pass mirrors that transmit a specific wavelength range and reflect all other light.
- Surfaces not covered by solar cells are highly reflective.

In the first part of this paper, we describe the basic principle and its application to concentrating systems. Two versions of light traps will be considered. The first is very straightforward and can be applied to existing systems; the second relies on photonic structures requiring more advanced technology.

While these concepts are designed for concentrating systems, we will show in the following part how light trapping can also be applied to non-concentrating, stationary modules.

The mechanism of the light trap is based on the thermodynamic theory of Yablonovitch [6]. Randomized light within a slab of transparent material of irregular shape and of refractive index n is enhanced in its intensity with respect to the intensity outside in air by a factor of n^2. In his paper, Yablonovitch gives a factor $2n^2$ but he defines light intensity as being bidirectional. Radiation that illuminates the surface of a solar cell is however unidirectional. Therefore, we restrict ourselves to an enhancement by n^2 due to diffuse radiation and total internal reflection. The optically coupled solar cells are exposed to this increased intensity. At the input aperture, there is a drop of intensity by n^2 vs. air. In an idealized approach, the input aperture is considered without surface (Fresnel) reflection. If necessary, this can be included but surface reflection can be minimized by antireflection measures.

We will first consider the situation with fully diffuse light within the trap and then demonstrate that the direction of the incoming light is important and that by its consideration calculated efficiencies are higher.

2. Concentration by geometric optics

2.1. The basic principle

Fig. 1 shows the first approach to the principle of light trapping. Light is first concentrated in the usual manner by lenses or other optical means. The light trap has small openings corresponding to the focal point of the concentrating optics. The remainder of the surface is reflective. A similar concept for light confinement in bulk solar cells has been described by Luque [7,8] using micro CPCs, whereas the trap described here is fully transparent. At the bottom of the trap, there are solar cells and mirrors which may be diffuse reflectors. It has to be emphasized that diffusion of the light is essential to the concept. Exactly where the diffusion is accomplished is not important. As Yablonovitch pointed out, a diffusing surface at one point of the trap in combination with multiple reflections results in a nearly isotropic characteristic, even if the characteristic of the diffuse reflector is not lambertian itself [6].

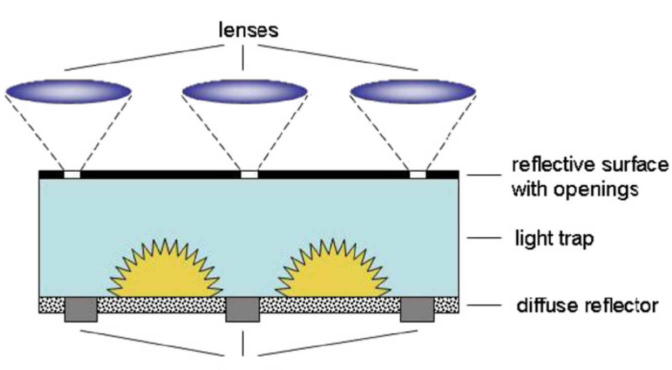

Fig. 1. Principle of a light trap. Light is concentrated by lenses or other optical means. The concentrated beam enters the light trap through a small aperture. Inside the trap the light is diffused. Solar cells with optical mirrors are optically coupled to the trap. The optical mirrors reflect all light the solar cell in question cannot use. The trap surface is reflective everywhere apart from the apertures and the solar cells. By that means light is spectrally selective concentrated onto different cells.

In a light trap with more than one solar cell, the solar cells are always combined with a band-pass mirror at the trap interface that is transparent for the light which is best used by each solar cell and reflective for all other light. As this is always the case, the mirrors were not separately included in the figures. Solar cells in the figures have always to be seen combined with band-pass mirrors or rear mirrors as described in Fig. 11.

We now estimate the efficiency of the light trap. In an idealized approach, we assume the radiation to have an isotropic characteristic and be fully uniform within the trap, the mirrors to be perfectly reflective and the solar cells to be perfectly absorbing, while there is no absorption in the trap itself. In this paper, light intensities are generally defined as being unidirectional. Let I_{int} be the internal radiation intensity, then the loss through the input aperture A_{i} is $I_{\text{int}}A_{\text{i}}/n^2$ (the input area A_{i} is normally somewhat larger than the illuminated area because of tolerances in focussing). The radiation absorbed by the solar cells with area A_{s} is $I_{\text{int}}A_{\text{s}}$. The trapping efficiency η_{trap} is now obtained simply by setting up the energy balance within the trap:

$$\eta_{\text{trap}} = \frac{I_{\text{int}}A_{\text{s}}}{I_{\text{int}}A_{\text{s}} + I_{\text{int}}(A_{\text{i}}/n^2)}$$

and

$$\eta_{\text{trap}} = \frac{1}{1 + (A_{\text{i}}/A_{\text{s}}n^2)} = \frac{1}{1 + (1/Fn^2)} \tag{1}$$

From Eq. (1), we see that efficiency depends on the ratio $F = A_{\text{s}}/A_{\text{i}}$. That means we can control efficiency by adjusting this ratio. In Fig. 2, efficiency is plotted vs. this ratio for $n = 1.5$ and 2.0. For example, for equal area and $n = 1.5$, $A_{\text{s}}/A_{\text{i}} = 1$: $\eta_{\text{trap}} = 0.69$ and for $A_{\text{s}}/A_{\text{i}} = 2$: $\eta_{\text{trap}} = 0.82$. In practice, this means that if we want to achieve high trapping efficiency, we have to concentrate the light first and then deconcentrate it in the light trap. It should also be kept in mind that Eq. (1) applies to every fraction of the solar spectrum separately. Therefore, the total area of solar cells is the product of the number of spectral subdivisions and the area of the solar cells. In other words if, for instance the spectrum is split into three parts, the total cell area is $3A_{\text{s}}$ (assuming equal area solar cells).

We can also estimate the radiation intensity in the light trap. Qualitatively we can state that the light intensity I_{int} should drop with increasing $A_{\text{s}}/A_{\text{i}}$ and efficiency should rise because emission through A_{i} is lowered. If I_{inc} is the concentrated radiation impinging on A_{i}, then without solar cells (for $A_{\text{s}} = 0$) $I_{\text{inc}} = I_{\text{int0}}/n^2$. I_{inc} is the concentrated radiation averaged over the entire input area. When solar cells with area A_{s} are added we obtain

$$\frac{A_{\text{i}}I_{\text{int}}}{n^2} + A_{\text{s}}I_{\text{int}} = A_{\text{i}}I_{\text{inc}} = A_{\text{i}}\frac{I_{\text{int0}}}{n^2}$$

$$\frac{I_{\text{int}}}{I_{\text{int0}}} = \frac{1}{1 + n^2(A_{\text{s}}/A_{\text{i}})} \tag{2}$$

or

$$\frac{I_{\text{int}}}{I_{\text{inc}}} = \frac{1}{(1/n^2) + (A_{\text{s}}/A_{\text{i}})} = \frac{1}{(1/n^2) + F} \tag{3}$$

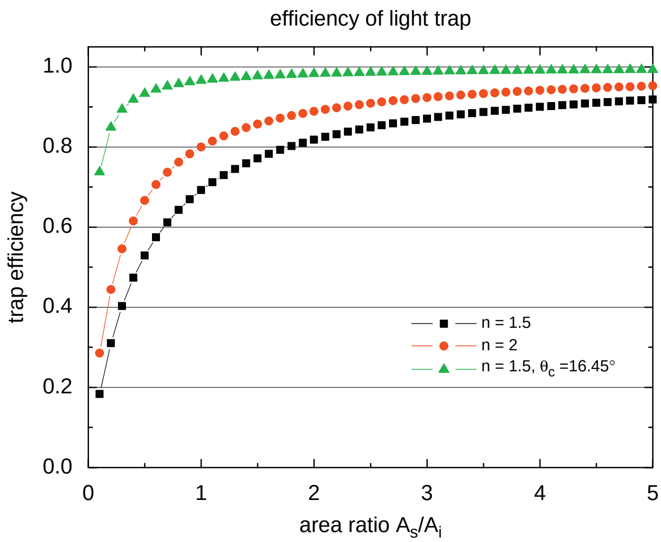

Fig. 2. Trapping efficiency vs. A_s/A_i for two values of the refractive index. The top curve is for the combination of the light trap with a photonic structure in a concentrating system as described in Section 3.3. The angular selective structure restricts the angular acceptance range to an angle of 16.45°. For high area ratios high efficiencies are reached.

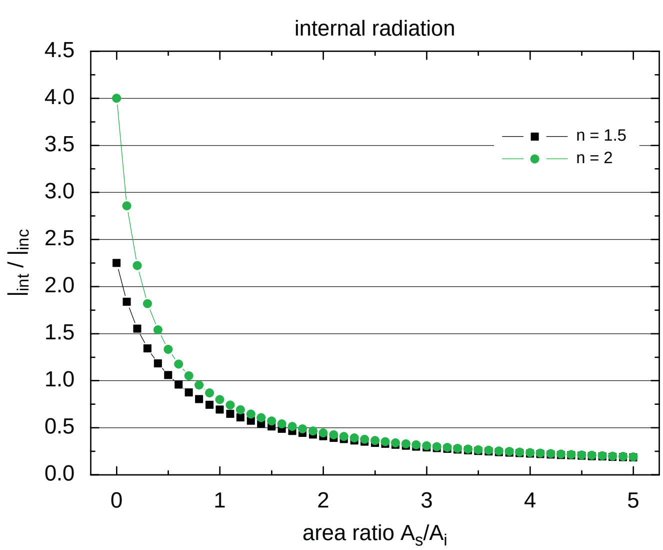

Fig. 3. Internal radiation density vs. area ratio for two different refractive indices of the trap $n = 1.5$ and 2. For larger ratios of A_s to A_i, the refractive index of the trap has less and less influence on the ratio I_{int}/I_{inc}.

The internal radiation density is shown in Fig. 3 against area ratio A_s/A_i. It shows that the refractive index becomes less important at larger area ratios.

2.2. Optimization of the geometric concentration light trap

The light trap sketched in Fig. 1 has the same area as the concentrating elements. There is no reason for the light trap to be so large. On the contrary, imperfect mirrors cause losses. This leads us to the design shown in Fig. 4.

In final consequence, we end up with a light trap that is entirely covered by solar cells (with exception of the input opening). As an example see Fig. 5. The light trap is a cube with A_i

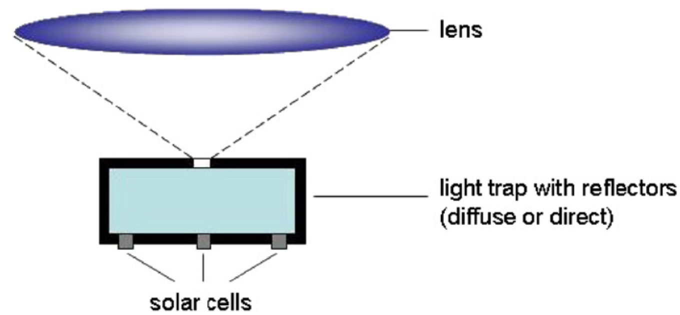

Fig. 4. Reduced area light trap. The area of the light trap may be chosen smaller than the area of light incidence. In the figure, the area of incidence is the lens area. A smaller light trap is advantageous when considering losses caused by imperfect reflections.

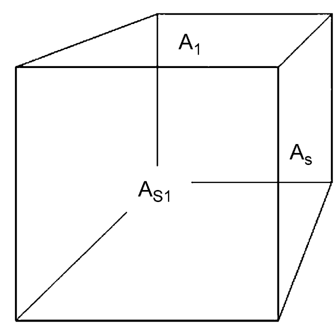

Fig. 5. Reduced size light trap. All sides A_s apart from the top A_1 are covered with solar cells. The length of a side of the cube being a, the solar cell area is $5a^2$. In this case the entire top face is the input with an area of a^2. Assuming a splitting of the light into three parts, we get $F = 5/3$ and $\eta_{trap} = 0.79$.

being the input and A_{S1}, A_{S2}, etc. being the solar cell areas. A small light trap has also other advantages:

- Absorption losses within the trap are minimized.
- Assuming perfect diffusivity, the light intensity is more uniform.
- Because of the small volume it is possible to use an expensive, highly refractive material for the trap.

The entire solar cell area of the cube in Fig. 5 is $5a^2$ with a as the dimension of the cube. If the solar spectrum is split into three parts, $A_s/A_i = 5/3$ and $\eta_{trap} = 0.79$. So even with very small light traps high efficiency can be achieved.

Similar concepts to the one given above have been proposed by Luque et al. [9] or Ortabasi [10]. In the concept of Luque a light confining cavity resembling an integrating sphere is used to reflect back the photons reflected by the solar cell. This system has already been examined closely [11,12] and high efficiencies have been predicted [8,13]. Ortabasi proposed to use a cavity into which the sunlight is concentrated. The cavity is covered on the inside with different solar cells and diffuse mirrors. In our terms, these systems would be described with a refractive index of the light trap of $n = 1$.

2.3. The effect of initial absorption

After understanding the basic principle of the light trap system, we are now able to consider initial absorption. Consider a light trap as in Fig. 5, with all the walls but A_i covered with one type of perfectly absorbing solar cells. The trapping efficiency should be $\eta_{trap} = 100\%$, as all the incoming light is absorbed by solar cells. However, this result is not given by Eq. (1). The conclusion is that we have to take the direction of the radiation into account, as the light is not randomized immediately. Light is absorbed by the solar cells already before it is randomized and fills the trap. We call this absorption "initial absorption". After the initial absorption, the light is randomized. The intensity of the diffuse light inside the trap in equilibrium with I_{inc} is denoted I_{int}. We know from [5] that the diffuse radiation with the intensity I_{int} impinging from the inside of the trap onto the surface which is coupled out equals I_{int}/n^2. The rest is totally internally reflected. However, this loss and the internal reflection can only occur for the light which actually reaches the surface again. Therefore, the intensity of the light from which the loss has to be calculated is reduced by the initial absorption.

We define an effective reflection coefficient R_{trap} as the fraction of light that actually reaches the incoupling surface after a "round trip" through the trap. The absorption $(1-R_{trap})$ includes light absorbed after multiple reflections and all light absorbed before the reflected light arrives again at the incoupling surface. As in Section 2.1, R_{trap} applies to each frequency band separately. R_{trap} depends on the geometry of the trap and the degree of spectrum splitting. It is advantageous if the bottom of the trap is diffusely reflecting (besides being absorbing for part of the spectrum) because then more light will be reflected to the vertical sides and have a chance to be absorbed. The efficiency of this light trap will now be calculated.

The relevant quantities are defined in Fig. 6. I_{inc} is the incident radiation and the incident energy is $E_{inc} = I_{inc}A_i$. It is assumed that the light traverses the trap surface without loss but is diffused when entering the trap. The energy reflected back towards the surface is

$$E_R = I_{inc}R_{trap}A_i \tag{4}$$

Eq. (4) can be seen as a definition of R_{trap} (according to the above definition of R_{trap}, it refers to the input area and not cell areas).

The energy absorbed by the solar cells is

$$E_{abs} = I_{inc}(1 - R_{trap})A_i + I_{int}A_s \tag{5}$$

The energy emitted by the trap is

$$E_{esc} = \frac{I_{int}A_i}{n^2}$$

Setting up the energy balance and solving for I_{int}

$$\begin{aligned} E_{inc} &= I_{inc}A_i = E_{esc} + E_{abs} \\ &= \frac{I_{int}A_i}{n^2} + I_{inc}(1 - R_{trap})A_i + I_{int}A_s \end{aligned} \tag{6}$$

$$I_{int} = \frac{I_{inc}R_{trap}}{(1/n^2) + F} \tag{7}$$

where $F = A_s/A_i$.

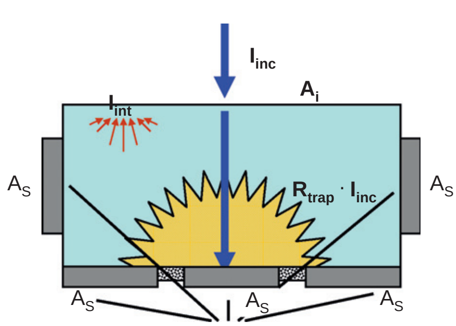

Fig. 6. Definition of quantities used in calculation of efficiency. I_{inc} is the incident intensity outside the trap. It enters the trap through an incident area A_i. In the trap, a fraction of the light is initially absorbed by solar cells with an area A_s. The rest is reflected, so that the reflected intensity is $R_{trap}I_{inc}$. R_{trap} denotes the effective reflection of the trap. The intensity of the diffuse light inside the trap that is in equilibrium with I_{inc} is called I_{int}.

Then

$$E_{esc} = \frac{I_{int}A_i}{n^2} = \frac{I_{inc}R_{trap}A_i}{1 + n^2F}$$

and

$$\begin{aligned} \eta_{tot} &= \frac{E_{inc} - E_{esc}}{E_{inc}} = \frac{I_{inc}A_i - (I_{inc}R_{trap}A_i)/(1 + n^2F)}{I_{inc}A_i} \\ &= 1 - \frac{R_{trap}}{1 + n^2F} \end{aligned} \tag{8}$$

We now check the validity of these relations.

When $R_{trap} = 0$, then $I_{int} = 0$ and $\eta_{tot} = 1$. In this case, all radiation is absorbed in the trap as was postulated above.

When $R_{trap} = 1$, then $\eta_{tot} = \eta_{trap}$; this is the case in which all incident light in the trap is diffuse as was assumed in Eq. (1). Normally, $R_{trap} = 1$ implies fully reflecting walls which also requires $\eta_{trap} = 0$. It is obvious that immediate conversion of the incoming radiation to diffuse radiation in a trap with partly absorbing walls can only be realized with scattering centres inside the trap. Therefore, the initial considerations in Section 2.2 are useful for understanding the light trap but do not fully describe the light trapping mechanism.

If we compare Eq. (6) with Eq. (3), we see that it differs by the factor R_{trap} as we expect from the the definition of R_{trap}.

In Fig. 7, η_{tot} is plotted vs. F for different values of R_{trap} and $n = 1.5$. This figure shows the strong influence of R_{trap} on the efficiency. The dashed lower curve in Fig. 7 ($R = 1$) represents the fully diffuse case that was also presented in Fig. 2. It is significantly below the curves with lower R.

3. The photonic light trap

3.1. The principle of the photonic light trap

In this section, the second concept for light trapping is described. This concept uses a photonic structure with a distinct angular selectivity in combination with a scattering reflector.

Photonic structures have recently been considered for improvement of thermophotovoltaic conversion [14]. Among the

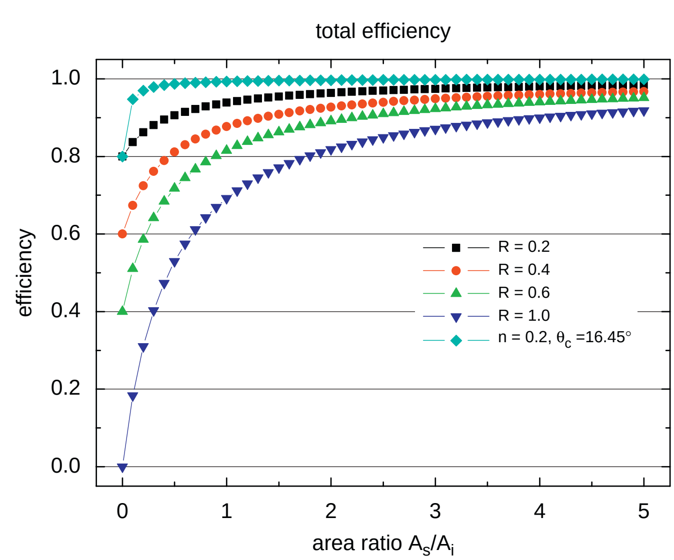

Fig. 7. Total efficiency including internal absorption of first pass of light for different values of trap reflectivity vs. coverage factor $F = A_s/A_i$. The lower dashed curve is the case without consideration of primary absorption; the top curve is with photonic structure at the input (see Fig. 8). The angular selective structure restricts the angular acceptance range to an angle of 16.45°.

photonic crystals, optical elements with unique optical properties [15] exhibiting spectral and angular selectivity can be found.

In Fig. 8, the principle of a light trap with an angular selective filter is sketched. A transparent light trap with refractive index n is covered with the photonic structure. The optimum photonic structure for this purpose has the following properties:

- Broad spectral bandwidth to transmit all or most of the solar spectrum for an angular range close to perpendicular incidence.
- Narrow angular selectivity to reflect all light that impinges on the filter under an angle greater a critical angle Θ_c.

With these properties, a light trap can function as a concentrator without other optical components. As in the preceding sections, the photonic concentrating trap can only accept direct radiation and has to track the sun. Light that impinges on the trap under perpendicular incidence can traverse the filter and enter the trap. The light is than scattered into a certain angular characteristic that is assumed to be lambertian in the following. This is realized by the application of diffuse reflectors and multiple reflections [6]. Furthermore, we assume a critical angle of $\Theta_c = 1^\circ$ which is compatible with the angle subtended by the sun of $\Theta_c = 0.27^\circ$ and with the tracking accuracy of present trackers [16].

The opening angle of the acceptance is modified by refraction upon entry into the light trap. In that way, the angular range Θ_c under which light can leave the trap and the filter is confined to a very narrow escape cone characterized by Θ_{int}. Rays outside this cone are reflected either by total internal reflection inside the trap or at the filter.

This concept has already been applied to the increase of the path length of light in solar cells [17]. The solar cells are optimized for spectral selectivity and are covered with spectrally selective mirrors.

The optical properties of the photonic light trap are now analyzed. For an idealized treatment, we first assume perfect transmission of the light trap, perfect reflectivity of the mirrored surfaces, uniformity of diffuse radiation and perfect absorption of the solar cells. The concept is for large area devices. For the clarity of the presentation, we therefore neglect the edge surfaces in our calculations.

The internal escape cone angle is

$$\Theta_{int} = \arcsin\left(\frac{\sin\Theta_c}{n}\right) \tag{9}$$

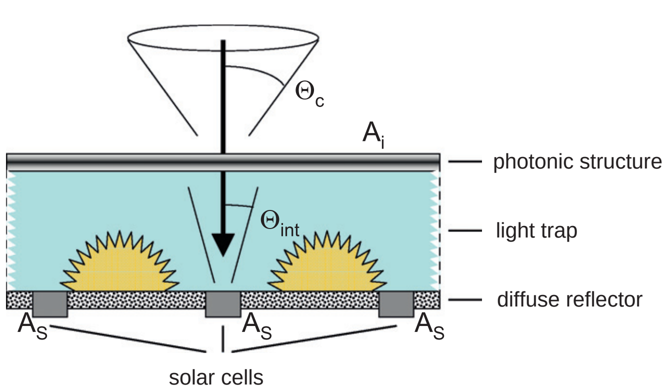

Fig. 8. Principle of light trap with angular selective photonic structure. The photonic structure has a critical acceptance angle Θ_c. Light that is scattered after diffusion into an angle greater than Θ_c is trapped. The solar cells are optimized for spectral selectivity and are covered with spectrally selective mirrors.

The escaping intensity is

$$I_{esc} = A_i \int_0^{2\pi}\int_0^{\Theta_{int}} B_{int}\cos(\vartheta)\sin(\vartheta)\,d\vartheta\,d\phi = \pi B_{int} \tag{10}$$

where A_i is the entire surface area of the trap and B_{int} is the internal radiation density per steradian. We now relate B_{int} to the internal unidirectional radiation intensity at the boundaries of the light trap:

$$I_{int} = \int_0^{2\pi}\int_0^{\pi/2} B_{int}\cos(\vartheta)\sin(\vartheta)\,d\vartheta\,d\vartheta\phi = \pi B_{int} \tag{11}$$

Therefore,

$$I_{esc} = A_i I_{int}\sin\left(\arcsin\left(\frac{\sin\Theta_c}{n}\right)\right)^2 = \frac{A_i I_{int}}{n^2}\sin(\Theta_c)^2 \tag{12}$$

The light absorbed by the solar cells is $I_{int}A_s$. Now we can calculate the efficiency of the photonic light trap by setting up the energy balance between incoming radiation and light absorbed by solar cells and light reemitted from the surface:

$$I_{inc}A_i = \frac{A_i I_{int}}{n^2}\sin(\Theta_c)^2 + I_{int}A_s \tag{13}$$

Solving for I_{int},

$$I_{int} = \frac{I_{inc}}{(\sin(\Theta_c)^2/n^2) + F} \tag{14}$$

with $F = A_s/A_i$.

The trapping efficiency is

$$\eta_{trap} = \frac{I_{int}A_s}{I_{inc}A_i} = \frac{1}{(\sin(\theta_c)^2/n^2F) + 1} \tag{15}$$

The efficiency depends strongly on the acceptance angle (Fig. 9).

The concentration is

$$C = \frac{I_{int}}{I_{inc}} = \frac{1}{(\sin(\Theta_c)^2/n^2) + F} \tag{16}$$

High concentration can only be reached with small acceptance angles.

$1/F$ can be interpreted as the geometric concentration (presently known angular selective filters do not yet show a spectrally independent characteristic. The development of structures

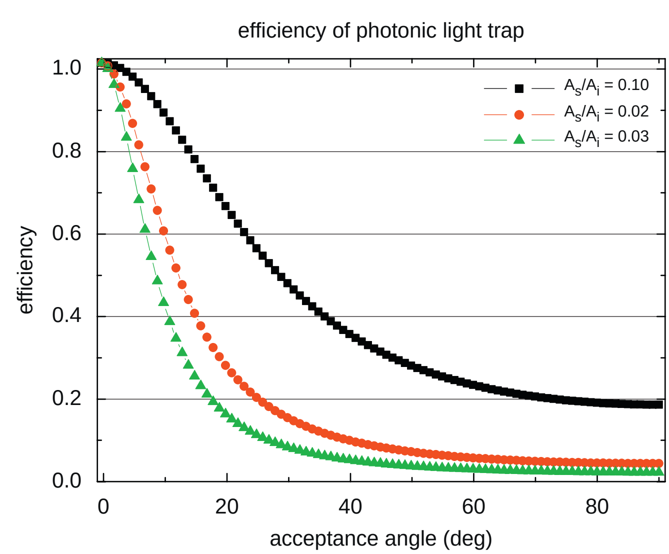

Fig. 9. Efficiency of photonic trap vs. opening angle Θ_c by restricting the acceptance angle of the photonic structure, the efficiency of the light trap is increased significantly. The maximum possible restriction is to the appearance angle of the sun of 0.27°.

with an adjusted angular characteristic is probably the most difficult part of this concept).

3.2. More realistic systems

The photonic trap does not require optical elements for concentration. Concentration occurs inside the trap. This type of trap therefore has to have a large area which means that reflection losses and absorption play a crucial role. Also, the solar cells may not be fully absorbing. All these factors will now be considered.

If the reflecting areas have a reflection factor R, then the amount of light lost is

$$E_{\mathrm{refl}} = A_{\mathrm{i}} I_{\mathrm{int}} (1-R)(1-F)$$

There will also be absorption in the volume. The amount of light lost in a trap with thickness W and absorption coefficient α is

$$E_{\mathrm{abs}} = \iint \alpha B_{\mathrm{int}}\, \mathrm{d}V\, \mathrm{d}\Omega = \int_0^{2\pi}\int_0^{\pi} \alpha B_{\mathrm{int}} W A_{\mathrm{i}} \sin\vartheta\, \mathrm{d}\vartheta\, \mathrm{d}\phi = 4 I_{\mathrm{int}} \alpha W A_{\mathrm{i}}$$

In the case of volume absorption, we have to take the bidirectional intensity $2I_{\mathrm{int}}$.

If the solar cell absorption is $\eta_{\mathrm{abs,cell}}$, then the light absorbed by the cell is

$$E_{\mathrm{abs,cell}} = I_{\mathrm{int}} \eta_{\mathrm{abs,cell}} A_{\mathrm{s}}$$

Again we can equate the gains and the losses:

$$I_{\mathrm{inc}} A_{\mathrm{i}} = \frac{A_{\mathrm{i}} I_{\mathrm{int}}}{n^2} \sin(\Theta_{\mathrm{c}})^2 + I_{\mathrm{int}} A_{\mathrm{s}} \eta_{\mathrm{abs,cell}} + A_{\mathrm{i}} I_{\mathrm{int}} (1-R)(1-F) + 4 I_{\mathrm{int}} \alpha W A_{\mathrm{i}}$$

In analogy to Eqs. (12)–(14), this results in the trapping efficiency:

$$\eta_{\mathrm{trap}} = \frac{\eta_{\mathrm{abs,cell}} F}{(\sin(\Theta_{\mathrm{c}})^2/n^2) + \eta_{\mathrm{abs,cell}} F + (1-R)(1-F) + 4\alpha W} \quad (17)$$

3.3. Combination of geometric concentration and photonic light trap

Optimal efficiency is obtained by combining both concepts described so far. In Section 2, we have implicitly assumed that the light entering the trap is coming from the full half space as it would at very high concentration. In reality, the light arriving at the trap from a concentrating lens has a limited opening angle. In Fig. 10, the situation in a real system (Flatcon) [18] is shown true to scale (the situation considered here is not compatible with secondaries).

In this case, the opening angle is $\Theta_{\mathrm{c}} = 16.45^{\circ}$. If a photonic structure with this acceptance angle is placed on the surface of the trap no light will be lost. On the other hand, light coming from the inside of the trap can only escape within the same angle modified by refraction. Inserting this value into Eq. (14), we obtain the upper curve in Fig. 2. Efficiency for this structure is very high. This combination has several advantages:

- The light trap is very small, so the losses due to absorption and reflective surfaces are negligible.
- Solar cell area can be of the same size as the input area, so efficiency is much higher.
- The surface area of the trap is small, so the cost of the photonic structure is tolerable.

The combination light trap probably cannot have a diffusing entry aperture. Randomization of the light can be achieved by diffusing reflectors or forward scattering centres close to the surface.

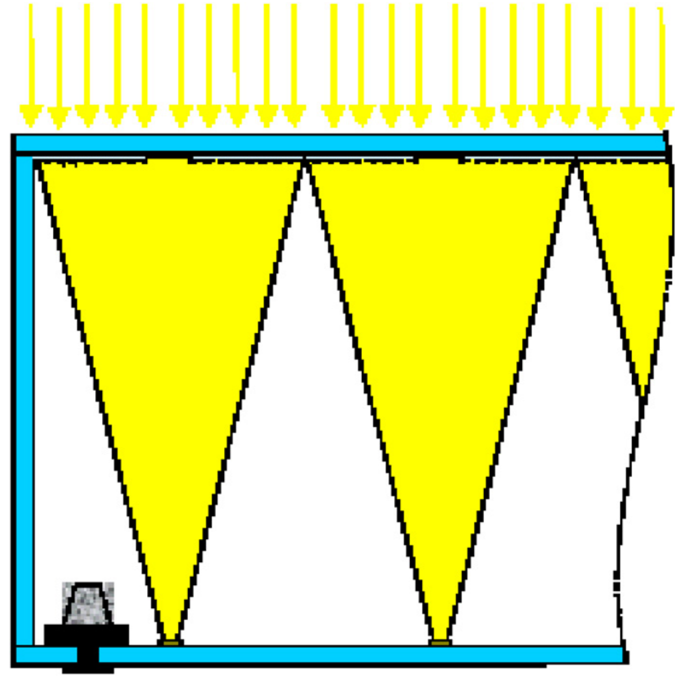

Fig. 10. Cross-section of a Flatcon concentrating system. Light is concentrated by Fresnel lenses onto highly efficient solar cells. The opening angle here is $\Theta_{\mathrm{c}} = 16.45^{\circ}$. Typical concentrations reached are in the order of 500.

The photonic system can also be analyzed with inclusion of initial absorption (Section 2.3). In order to calculate its efficiency, we modify Eq. (6) by inserting Eq. (14):

$$\eta_{\mathrm{tot}} = 1 - R_{\mathrm{trap}} \left(1 - \frac{1}{(\sin(\theta_{\mathrm{c}})^2/n^2 F) + 1}\right) \quad (18)$$

The upper curve in Fig. 7 is the efficiency for a reflection of $R = 0.5$. Even in this case, the light trap is practically lossless.

4. Solar cell technology for light trapping

The advantage of light trapping is that solar cells of different band gaps can be placed side by side at the light trap. This offers several advantages:

- The solar cells can consist of different semiconductor materials.
- They do not have to be grown monolithically with very small lattice mismatch.
- More abundant materials can be used.
- No tunnel diodes between the cells are needed.

On the other hand, light trapping is not 100% efficient. Furthermore, the solar cells have to be equipped with selective mirrors.

The selective reflection can be simplified if it is taken into account that semiconductors are transparent for sub-band-gap light. This light can be reflected by a mirror at the back of the solar cell. In Fig. 11, this is outlined for an example with three different solar cells. The largest gap cell only has a mirror at the rear of the cell. The middle cell has a mirror for the long wavelengths and an edge filter for the short wavelengths. It should be noted that the edge mirror only has to have a sharp cut off reflection but can extend far into the ultraviolet. Such mirrors are easier to realize than band reflecting mirrors. The low gap cell finally only has an edge mirror for the shorter wavelengths.

Another advantage for solar cells in conjunction with light traps is that since the cells are only thin, single semiconductor cells, wrap through technology can be used for contacts. In this way, shading of the front side by contacts is avoided.

Considering the selective mirrors, they do not have to be absolutely perfect regarding reflectivity and wavelength sensitivity. Reflected rays have a chance to be returned to the solar cell albeit at lower efficiency. High-energy photons absorbed by a lower gap cell are not lost but only converted at lower efficiency.

5. Stationary modules

So far only light traps for concentrating systems were analyzed. They permit high concentration although deconcentration by a factor of two or three is advantageous for high trapping efficiency. These systems are best suited for climates with high direct radiation intensity.

It is desirable to use the light trapping principle also for moderate climates with a high fraction of diffuse radiation. How this can be accomplished will be described now. In this paper, only stationary modules are considered. Low concentration or linear tracking systems might also be possible but will not be included here. In a first approach, the transparent superstrate of the module serves as the light trap (Fig. 12). In this case, the input aperture A_i is the entire module area. The surface of the module is structured to diffuse the light. If we consider a division of the solar spectrum by two (which is most feasible for stationary systems), the geometry of Fig. 12 results. ($A_s = A_i/2$) The lateral dimension of the solar cells should be of the order of the superstrate thickness or smaller. Otherwise the assumption of uniform light distribution breaks down.

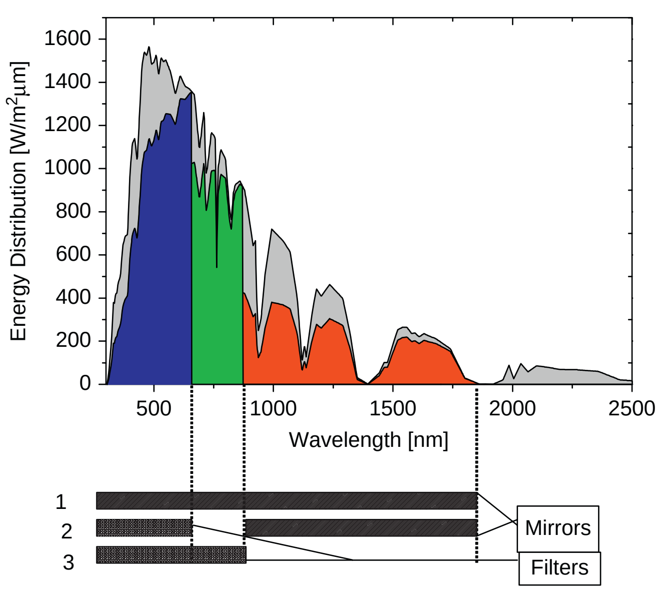

Fig. 11. Solar spectrum and spectral range of selective and regular mirrors for three stages 1–3. The first solar cell absorbs light with a wavelength lower than 700 nm. Higher wavelengths are transmitted and are reflected by a mirror. The second cell absorbs light with a wavelength smaller than 900 nm. To it a filter is attached that reflects light with a wavelength smaller than 700 nm. The mirror on the backside reflects the transmitted light. The third solar cell absorbs light with a wavelength smaller than 1800 nm. To it a filter is attached that reflects all light with a wavelength lower than 900 nm. By that means a spectrum splitting is realized. The shaded areas are schematic and only give losses due to band-gap energy.

The ratio $A_s/A_i = F$ is $F = 0.5$ and $R = 0.5$. From Eq. (6), we derive a trapping efficiency of $\eta_{tot} = 0.765$. This type of light trap can be improved by equipping the solar cells with a rough surface. There are however limits to this. Unlike the outer surface which is transmissive and will only randomize the incident radiation, a rough absorbing surface will lead to non-uniformity of the diffuse radiation. On the other hand, even a very modest structuring of the solar cell surface will improve efficiency noticeably. If the surface area is increased by a factor of 1.5, $F = 0.75$, then $\eta_{tot} = 0.814$. Better efficiency is possible with more complex geometries.

Some of them are outlined here: again deconcentration is employed. The solar cell area has to be larger than the module aperture. Many geometries can be imagined to accomplish this. Fig. 13 shows two examples namely saw tooth and parallel bars.

These geometries are particularly well adapted to thin film solar cells. Some aspects of the first two geometries will now be discussed.

Saw tooth: If the apex angle of the saw tooth is 45°, then thin film cells could be evaporated from the two sides as shown by the arrows in Fig. 13. The total efficiency is estimated as follows: $A_s/A_i = 2^{1/2} = 1.41$. R can be estimated to be about $R = 0.4$, then $\eta_{tot} = 0.9$.

Bars: For the bar $A_s/A_i = 3/2 = 1.5$, R could be exactly calculated for instance by ray tracing but is only estimated here. It is about $R = 0.25$. Then efficiency $\eta_{tot} = 0.943$. For manufacturing purposes, many bars could be placed side by side in a deposition chamber, rotated after deposition and again deposited. Finally, they could be placed in a module with the open side up. Here, just as for the saw tooth the usual thin film technologies for series connection could be used and contact could be made at the end of the bar. The structuring of the solar cell surface could of course also be applied to the geometries just mentioned.

6. Estimate of achievable conversion efficiency

6.1. Solar cell efficiency

We first consider solar cell efficiency and then look at influences of the optical system.

Starting with the thermodynamic limit, we know that efficiency increases significantly with the number of solar cells i.e. the degree of spectrum splitting. Table 1 gives the thermodynamic limit of efficiency vs. number of cells [19].

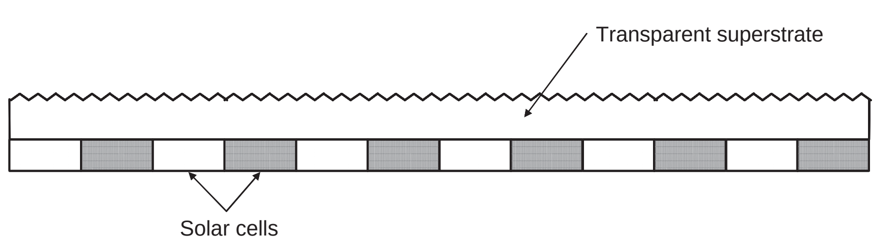

Fig. 12. Flat panel module with half-spectrum solar cells. The solar cells can either be small squares or, more practically, elongated strips. In the figure, two kinds of solar cells are shown, splitting the spectrum into two parts. Selective mirrors or reflectors as in Fig. 11 are not shown.

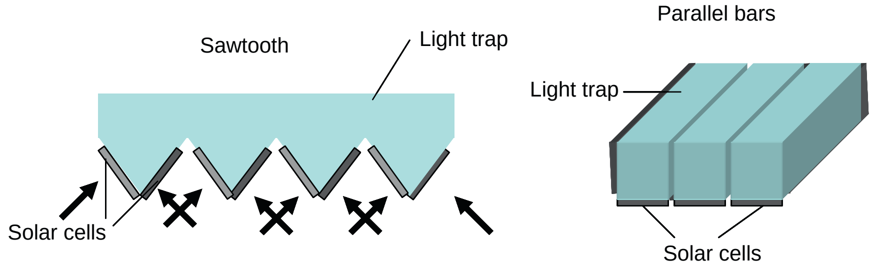

Fig. 13. Two versions of deconcentration in a flat plate module: (a) saw tooth and (b) parallel bars.

Table 1
Dependence of thermodynamic efficiency limit vs. number of cells

Number of cells	1	2	3	4	5
Efficiency	41.1	54.6	61.9	65.6	67.9

We see that these efficiencies are very high. The biggest increase occurs when going from one cell to two cells. Those ultimate efficiencies can of course not be reached in practice.

Barnett [5] estimates for a similar system practical efficiency by using derating factors. Higher band-gap cells are less derated than those with lower band gap. They estimate that for six junctions in four optical bins $\eta = 53.5\%$ can be achieved. Best experimental result so far is for three junctions in three optical bands $\eta = 42.8\%$, estimated from separate cell measurements under the conditions of their system.

With our light trap similar results can be anticipated. In order to limit the complication on the electrical side, it is suggested here that for high efficiency dual junction devices should be used for each optical band.

6.2. *Efficiency of light trap for concentrators*

As outlined in Sections 2 and 3, trapping efficiency can be very high if optimal geometrical and optical conditions are chosen, in particular if the light trap is combined with a photonic structure. Thus, the ultimate efficiency of the system light trap-solar cells can be very close to the values given above.

At this time, it is very difficult to estimate more realistic efficiencies. The following factors have to be considered:

(a) Absorption within the trap. This effect can be kept small because highly transparent materials are available and the trap can be made very small.
(b) The absorption of solar cells may be less than 100%.
(c) Efficiency of selective mirrors. Required are no parasitic absorption and good spectral selectivity as well as good reflectivity at all incidence angles.
(d) The requirement to create diffuse radiation is difficult to reconcile with selective mirrors and photonic structures. If this is not possible non-selective lambertian mirrors will have to be included. They should have very high reflectivity.

The overall system efficiency is further influenced by the efficiency of the optical concentration system as in conventional systems.

6.3. *Efficiency of the photonic structure light trap*

The photonic structure light trap as described in Section 3 is large area and does not need optical components. Concentration occurs within the trap. That means very high light intensity within the trap. Some loss factors are very severe:

(a) Absorption within the trap. When using very highly transparent material absorption could be tolerable.
(b) Reflectivity of mirrors. If high concentration is desired, a large fraction of the rear surface of the trap is covered by reflectors. Reflectivity has to be extremely good to enable high efficiency.
(c) Reflectivity of the photonic structure outside the escape cone. We assume total internal reflection but this has not yet been demonstrated (photonic structures can be as good as total internal reflection in principle).
(d) Efficiency of selective mirrors and absorption of solar cells have already been discussed in the previous paragraph.

6.4. *Stationary flat panel modules*

For the light trapping flat plate modules described in Section 5 the same solar cell efficiencies as discussed in Section 6.1 can be anticipated if optimal solar cells are used. Dependent on the geometry, lower efficiency of the light trap has to be taken into account. Optimal solar cells, however, may be too expensive for this application. Thin film cells are less costly and could be deposited onto the light traps. Amorphous Si is probably not capable of higher efficiency as the past development has shown. Better prospects are connected with micromorph films consisting of amorphous and microcrystalline films. Their efficiency is expected to be higher if used separately and not in a stacked cell. Even more efficiency can be foreseen for chalcogenides. The theoretical efficiency for two gaps has been estimated to be $\eta = 36.6\%$ [20]. In practice, $\eta = 20\%$ can be expected for a two gap system. Compared with concentrating systems flat plates have higher yield because they also utilise diffuse light.

7. Conclusions

The light trapping principle, based on diffuse radiation inside a transparent matrix, has been shown to offer many interesting aspects. It can be used for concentrating, tracking systems but also for stationary modules. The possibility to employ solar cells consisting of different materials and band gaps offers a much wider design space and holds hope to achieve higher conversion efficiency. The present paper presents mainly the basic principle and fundamental theory. Much experimental work is probably required to explore the practical applicability of this concept. Initial experiments are under way.

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