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Spectral splitting module geometry that utilizes light trapping

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ABSTRACT

In this paper, we present a novel geometry for a photovoltaic module. This novel geometry employs light trapping effects to split the solar spectrum onto two different kinds of solar cells. The two different kinds of solar cells utilize different parts of the solar spectrum most efficiently. The proposed structure is based on prisms. The different kinds of solar cells are attached to opposing surfaces of the prisms. To achieve spectral selectivity, either spectrally selective filters or the solar cells itself are used. After introducing the general concept, we discuss different possible realizations. The theoretical potential of the light trap is calculated using the concept of spectral efficiency. Based on experimental solar cell data, we calculate theoretically that conversion efficiencies exceeding 30% are possible with such a module using silicon and GaAs solar cells. First experiments show that the optical losses of the proposed geometry are as low as 2.1% relative.

1. Introduction

Presently, silicon is the dominant material for commercial solar cells and will most likely remain so for a considerable time. On the other hand, its highest documented efficiency has not been improved since 1991 [1]. This indicates that silicon solar cells are experimentally close to their efficiency limit although progress still occurs for products on the market.

In contrast, higher and still rising efficiencies are being achieved with III–V multi-junction solar cells. Because of their high costs, these solar cells are used either for application in space or for terrestrial use, under high concentration of sunlight.

The higher efficiencies are a result of the use of multiple junctions, and the inherent spectral splitting that occurs when high band-gap solar cells are stacked on top of the low band-gap solar cells: In such a configuration, each solar cell absorbs the part of the spectrum it uses most efficiently and transmits sub-band-gap photons to the subsequent solar cells. For large area solar panels multi-junction solutions exist with amorphous Si alone and amorphous plus microcrystalline Si but their efficiencies are well below that of crystalline Si [2].

The concepts mentioned so far rely on stacked junctions. One disadvantage of this approach is the requirement of equal current in the series connection of cells (current matching). This is, for example, not compatible with changes in the spectrum like they occur during the course of a day or a year. Another disadvantage of stacked solar cells is that the morphology limits the possible material combinations (lattice matching). An alternative is to split the solar spectrum by a spectrally selective element before the light arrives at the solar cells. This concept is very straightforward for concentrating systems and has been proposed long ago [3]. Recently it was revived and modernized by Barnett et al. [4]. A review of spectral splitting can be found in [5]. In Refs. [6–8] theoretical studies for different designs are presented, of which Refs. [6,8] deal with spectral splitting between photovoltaic and thermal system. Theoretical efficiency calculations based on experimental data are presented in [9]. Successful realizations of this concept were published in [10–12].

In a preceding paper, we describe a concept in which spectral splitting is realized by applying light trapping and spectrally selective filters. The concept consists of a light trap, based on using diffuse light in a transparent volume, to which different solar cells and spectrally selectively reflecting filters can be attached [13]. In this paper, we describe a new version of the light trap. The main feature of this new concept is that it does not rely on diffuse radiation. It has the advantage of permitting splitting of the solar spectrum into two parts without loss and a full acceptance angle of 180°.

In the first part of the paper we give an outline of the principle concept and present theoretical considerations on the concept's potential. This part is followed by preliminary experimental results and final conclusions.

2. Concept

2.1. The spectral splitting module geometry

We propose a structure in which parallel prisms made from a transparent material with a refractive index n form the module. To the opposing sides of each of these prisms, two different kinds

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of solar cells are attached. The overall structure is depicted in Fig. 1. The different kinds of solar cells are optimized for different parts of the solar spectrum and feature two different band-gap energies $E_{G,Low}$ and $E_{G,High}$. To profit from the different solar cell characteristics, at each side of the prism spectral selectivity must be achieved. At the side of the solar cell optimized for the lower energy part of the solar spectrum, this is best achieved with a spectrally selective photonic structure in front of the solar cell. This structure should reflect the high energy part of the solar spectrum, which can be used by the other solar cell, while the lower energy part must be transmitted with high optical efficiency. These characteristics are matched by a long (wavelengths) pass filter. At the side of the solar cell optimized for the high energy part selectivity could be achieved in two different ways: the first possibility is to use as well a spectrally selective photonic structure in front of the solar cell. At this position, the structure should transmit the high energy photons and reflect the low energy ones (short pass filter). The second option is to use the solar cell itself as a filter in combination with a good reflector behind the solar cell. The solar cell would transmit photons with energies below its band-gap, which are reflected by the reflector subsequently. The advantage is that in this configuration no optical filter is required, however, parasitic absorption processes in the rear reflector or free-carrier absorption will reduce the optical efficiency. It is worth noting that an air gap between solar cell and reflector will be helpful. Due to the air gap, lossless total internal reflection can occur inside the semiconductor, prior to the reflection on a metal or dielectric reflector, which is associated with losses.

The overall prism configuration ensures that all photons that are impinging on one kind of solar cell are reflected in case they can be used more efficiently by the other kind of solar cells. A sketch of the module geometry is shown in Fig. 1.

It is important to note that because of refraction at the sun facing surface of the prisms, the light impinges only from a certain angular range onto the solar cells, even if light impinges from all directions onto the module. This angular range from which the light impinges internally onto the solar cell corresponds to the escape cone of total internal reflection. Because of the change in direction at the tilted solar cell surface, the light being reflected from one solar cell either hits the opposing solar cell directly or hits the surface of the module in a rather shallow angle. In case of a sufficiently steep prism angle, the reflected light will be totally internally reflected at the sun-facing surface of the light trap such that the light reaches a solar cell of opposing kind in one of the neighbouring prisms (or the same prism).

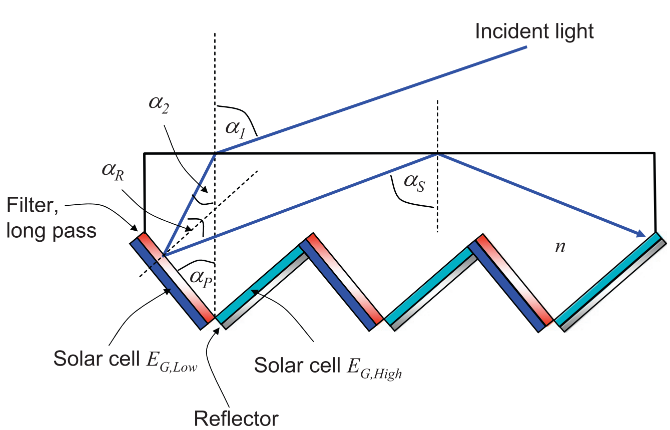

Fig. 1. Principle configuration of the proposed module structure. The module consists of parallel prisms to which solar cells with different band-gaps are attached. Spectrally selective elements ensure that each part of the spectrum is used in the kind of solar cell with the highest conversion efficiency for the specific spectral range. All light that impinges on the module is refracted and thus concentrated into an angular range that corresponds to the loss cone of total internal reflection. The angle of the prism α_P is designed such that light being reflected at one side of the prism is trapped by total internal reflection and hits a solar cell with a different band-gap subsequently.

On the other hand, it is beneficial when the angle of the prism α_P is as big as possible, to minimize the necessary solar cell area. Hence it is interesting to know, which is the biggest possible angle α_P for which total internal reflection occurs for all light being reflected the first time by a solar cell or photonic structure, independently from the angle of incidence α_1.

In the extreme case of shallow incidence, $\alpha_1 = 90^\circ$. In that case, after refraction at the front surface, the angle α_2 corresponds to the critical angle of total internal reflection. For the steepest possible angle of the prism, which still ensures total internal reflection, this ray is reflected onto itself. All other rays will be refracted in steeper angles while entering the module so that they hit the surface of the module after reflection in an even shallower angle, resulting in total internal reflection. From this consideration it can be concluded that the angle of the prism α_P should satisfy the condition

$$\alpha_P \leq 90^\circ - \text{arc sin}(1/n) = \text{arc cos}(1/n). \quad (1)$$

This simple structure has several advantages: Assuming perfect optical elements, spectral splitting can be achieved without any losses regardless of the angle of incidence onto the module. This feature is not common to many spectral splitting geometries and enables the use of the structure in conjunction with concentration but also as a flat plate module. Furthermore, the geometry is so simple that it could be combined with thin-film technologies and the solar cell could be deposited directly on the prism. In this case, spectral selectivity could be achieved by adapting (and extending) the antireflection coatings between solar cell and prism surface.

Furthermore, because the different kinds of solar cells are separated from each other there are no constraints from current- or lattice matching.

In Fig. 1, a flat plate-like section of material is shown on top of the actual prisms. This configuration was chosen to provide for a mechanical interconnection of the individual prisms. It does not affect the optical performance of the system. In principle the plate-like part should be as thin as possible, in order to avoid additional absorption losses in the surplus material.

2.2. Decreasing solar cell area and further extensions of the concept

The high band-gap solar cells will be operated under slight concentration conditions, as their area is smaller than the module area facing the sun and the range of the solar spectrum these cells can utilize is fully available to them. On the other hand, the low band-gap solar cell will see a reduced light intensity, because part of the spectrum is absorbed by the high band-gap solar cell. The overall solar cell area in the presented module exceeds the aperture area; therefore more solar cells are needed than for a common solar module with only one kind of solar cells. For $n = 1.5$ about 34% more solar cell area is necessary. Therefore, it is interesting to explore how the necessary solar cell area can be decreased by changing the geometry of the light trapping module.

One possibility to decrease the necessary solar cell area is to sacrifice the module's response at shallow angles of incidence. If α_1 equals the shallowest angle of incidence for which subsequent total internal reflection should occur, the angle α_S for which the light impinges on the front surface again must equal the critical angle of total internal reflection:

$$\alpha_S \geq \text{arc sin}(1/n). \quad (2)$$

From considerations on the angle sum of the triangles being formed by the various passes of the light and the surfaces of the