Solar Energy Materials & Solar Cells 136 (2015) 120–126

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

High-efficiency spectrum splitting for solar photovoltaics

Alexander Dorodnyy [a,*], Valery Shklover [b], Leonid Braginsky [b,c], Christian Hafner [a], Juerg Leuthold [a]

[a] Institute of Electromagnetic Fields, ETH Zurich, 8092 Zurich, Switzerland
[b] Laboratory of Crystallography, ETH Zurich, 8093 Zurich, Switzerland
[c] Institute of Semiconductor Physics, Novosibirsk State University, 630090 Novosibirsk, Russia

ARTICLE INFO

Article history:
Received 26 September 2014
Received in revised form
10 December 2014
Accepted 4 January 2015
Available online 24 January 2015

Keywords:
Spectrum splitting
Linear solar tracking
Numerical optimization
Concentrated light conversion

ABSTRACT

A linear solar-tracking spectrum-splitting scheme for solar photovoltaics is investigated. The investigation is made by means of a numerical optimization and an analytical approach to predict conversion efficiency based on available experimental data. For a simple spectrum splitting scheme, a high conversion efficiency limit of 43% without and 48% with solar concentration is predicted for two single junction solar cells. It is also shown that efficiencies of at least 37% and 41% are to be expected if state of the art cells are used. The investigation was performed using a Fourier Modal Method electromagnetic solver based on the scattering matrix formalism combined with a numerical optimizer utilizing the Evolution Strategy.

1. Introduction

Spectrum splitting is an essential way to enhance the efficiency of solar cells. A single junction cell can efficiently convert light to electricity only for a small part of the spectrum above the band gap. For an efficient conversion of the whole solar spectrum, one must find a way to split it into several frequency intervals and convert them in cells with appropriate band gaps. A good way to realize spectrum splitting is by building different junctions that are physically split. This avoids lattice or current matching problems of conventional (tandem) multi-junction solar cells. It brings as well a possibility of independent fabrication of each cell resulting in a simpler and possibly cheaper fabrication.

The idea of the spectrum splitting appeared about six decades ago and has shown promising theoretical efficiencies [1]. For the spectrum splitting, prisms [2–4], dichroic mirrors [5,6], holograms [7,8], and diffractive optical elements [9,10] were exploited (when talking about the "spectrum splitting" we always imply schemes that include spectrally selective elements other than absorptive media of solar cells themselves as it is done in standard multi-junction designs). In recent years an experimentally obtained efficiency of 34.3% was reported for splitting the spectrum between one tandem and two single-junction cells [5], 38.5% for splitting between two tandem cells [3] and 42.7% for splitting between two tandem and one single junction cells [2]. For these spectrum splitting designs it is still difficult to compete with more conventional multi-junction solar cells that already reach efficiencies above 40% with three junctions [11–13], and above 44% with four junctions [14]. Nevertheless – as stated above - the spectrum splitting approach has its advantages and smart schemes with cheap single junction cells might lead to more cost-efficient solutions. In order to analyze the potential of the spectrum splitting with numerical simulations and optimizations, we focus on the simplest scheme with only two cells, although it is clear that more complicated schemes will lead to higher efficiencies but also to higher costs.

The spectrum can be split between two photovoltaic cells, for example, by means of a single dichroic optical element which can be placed between the two cells or can be incorporated into one of the cells. This makes fabrication easier than that of double-junction cells because cells for spectrum splitting can be fabricated separately each with the most suitable technique. This also eliminates the problem of lattice matching in tandem cells. Spectrum splitting schemes can use separate electrical connections for each of the cells (each cell or set of identical cells is used in this case as a separate power source) which also excludes the problem of the current matching. Such schemes were already investigated for different material combinations and designs by several groups [1,6,15] and efficiencies above 25–30% were predicted.

In this article, we suggest a spectrum splitting scheme based on two types of single junction cells arranged in a linear solar tracking array. The structure was chosen in such a way that it can be used with or without a solar concentrator while tracking the sun around

* Corresponding author. Tel.: +41 44 632 57 22.
E-mail address: dorodnya@ethz.ch (A. Dorodnyy).

http://dx.doi.org/10.1016/j.solmat.2015.01.005
0927-0248/

one axis. Simulation results show that two-axis solar tracking is also possible if higher solar concentration values are to be used. The efficiency of the proposed scheme was first optimized using the detailed balance limit [16]. Then an analysis based on state of the art experimental achievements was performed in order to estimate a realistic achievable efficiency. We use modern simulation and optimization tools, and perform also an extensive angular dependence analysis of the spectrum splitting scheme. The suggested new arrangement is efficient for both concentrated and non-concentrated irradiation, light-weight and does not include any heavy prism elements. In our simulations we utilize the Fourier Modal Method [17,18] based on the scattering matrix approach [19] for optical calculations and the Evolution Strategy for the numerical optimization [20,21]. This approach allows us to combine an efficient calculation method for bulky structures with a robust optimizer that can deal with many optimization parameters.

The organization of the article is as follows. The design concept is described in Section 2. In Section 3 we introduce the analytical approach to estimate a realistically achievable efficiency. In Section 4 a selective photonic coating (dichroic mirror incorporated into the cell structure) for spectrum splitting is optimized and the efficiency estimations for direct sun light are made. Section 5 contains an analysis of the angular dependence of the performance and subsequent calculations for diffused and concentrated light conversion efficiencies.

2. Spectrum splitting scheme

The efficiency of a conventional single-junction cell cannot go beyond the Shockley-Queisser limit [16]. This limit is relatively low (around 33% without light concentration) because the solar spectrum is too wide to be efficiently converted by a solar cell with only one junction. Photons with energies below the band gap cannot be converted and are wasted while a huge part of the photons above the band gap will be converted inefficiently due to the thermalization loss [22]. An optical splitting of the spectrum between several photovoltaic cells with proper band gap values leads to a better spectrum management and higher conversion efficiencies. Since the complexity of the spectrum splitting structures is growing rapidly with the number N of junctions while the benefit from each subsequent junction is decreasing [23], we focus on the simplest case ($N=2$) and analyze the efficiency that a pair of two single-junction cells can reach. Such a scheme has a minimal cost increase compared to a single-junction cell and a maximum possible benefit from the additional junction.

The concept of the proposed scheme is shown in Fig. 1. It includes two types of single-junction cells arranged in a linear array. The first cell is tilted by an angle of 45° towards the incident light, while the second one is illuminated from a direction normal to its surface by the light reflected from the first cell, i.e. no direct sun light hits the second cell. The cells of different kinds have separate electrical connections and are used as separate power sources to avoid current or voltage matching. In other words there are two subsets of cells giving two different currents/voltages that need to have separate dc-ac converters to give the power to the grid. One of the big benefits of this is that changes in illumination conditions do not affect the performance to the extent as in multi-junction cells. In case of the multi-junction cells a drop of photogeneration in one sub-cell affects performance of all the sub-cells while with the separate cells - as in our design - the issue is avoided.

Because of the tilting, the surface of the first cell is larger than the second cell by a factor of $\sqrt{2}$. Furthermore, this cell needs a special design to split the light between two cells, i.e. to reflect a part of the spectrum for feeding the second cell. In our design the first cell has a lower band gap than the second one. There are

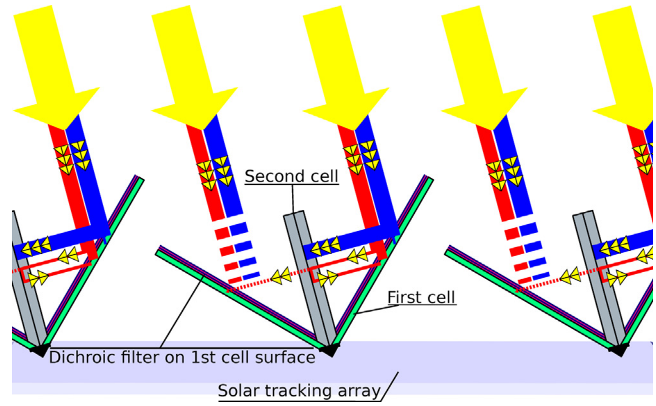

Fig. 1. Concept of the spectrum splitting scheme. An array of solar receivers is tracking the sun around one axis, perpendicular to the plane shown here. Within each receiver the solar spectrum is split between the first (lower band gap) and the second (higher band gap) cells by means of a dichroic filter incorporated in each of the first cells (on the picture: yellow arrows – sun light, red – low frequency, blue – high frequency). The second cells can be made transparent to decrease material consumption.

several reasons to do so, for example, the price for the first cell should be lower because of the size factor $\sqrt{2}$. Thus, the first cell should be based on Si as this is cheap and available a plenty and has a rather low band gap. Other reasons include the possibility of making a transparent second cell – which could be illuminated from both sides (from Fig. 1 one can intuitively see how such an approach could be implemented). This might additionally reduce the costs and increased the efficiency under a light concentration.

The low frequency light is mostly absorbed in the first cell. Though, because of design imperfections a portion of the low frequency light might be reflected from the selective photonic surface. That light however is not entirely lost because it should not be absorbed by the second cell. As illustrated in Fig. 1, it will either be directed back to the first cell after passing twice through the second cell and being reflected from a back contact or it will propagate through the transparent second cell and illuminate the first cell mounted on the other side of the second one.

To define an optimal combination of band gap values for our scheme we plot the dependence of the detailed balance limit efficiency of a two solar cell system as a function of the band gaps, see Fig. 2. The calculations were performed based on the standard direct solar spectrum ASTM G173-03. This is a terrestrial spectrum for the air mass coefficient of 1.5. We later on refer to it as AM1.5 spectrum for brevity. The maximal achievable efficiency is 45.3% for abrupt (when all of the photons below the splitting energy go towards the low band gap cell and all of the photons with higher energies towards the high band gap cell) spectrum splitting with a 0.9 eV band gap for the first cell and a 1.6 eV band gap for the second cell. Note that the deconcentration factor of $\sqrt{2}$ for the first cell is taken into account (without the deconcentration the efficiency limit would be 45.6%). Furthermore, the design with two second cells, mounted back to back is assumed.

We chose crystalline silicon as band gap material of the first cell, i.e., a material with a band gap of 1.1 eV instead of the optimal band gap of 0.9 eV. This reduces the maximum achievable efficiency to 44.1%. As a consequence, also the optimal band gap of the second cell is shifted from 1.6 eV to 1.8 eV. We therefore search for a material with a band gap close to 1.8 eV. AlGaAs has a band gap that can vary between 1.42 eV (for GaAs) and 2.16 eV (for AlAs). Thus, an AlGaAs cell composition can be adjusted for an optimal performance of the second cell. With this choice of materials the silicon cell could contribute 18.2% and the AlGaAs cell 25.9%, which adds up to 44.1%. Note that the efficiencies here are calculated for the case of an abrupt splitting of the spectrum between the cells and not for the calculated later optimized design.