Solar Energy 139 (2016) 149–156

Contents lists available at ScienceDirect

Solar Energy

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

Design and optimization of spectral beamsplitter for hybrid thermoelectric-photovoltaic concentrated solar energy devices

Enok J.H. Skjølstrup, Thomas Søndergaard *

Department of Physics and Nanotechnology, Aalborg University, Skjernvej 4A, DK-9220 Aalborg East, Denmark

ARTICLE INFO

Article history:
Received 1 July 2016
Received in revised form 7 September 2016
Accepted 27 September 2016

Keywords:
TE-PV hybrid system
Beam-splitter
Dichroic mirror
Thin-film multilayer structures
Spectrum splitting
Conversion efficiency optimization

ABSTRACT

The design and optimization of a thin-film multilayer spectral beamsplitter for hybrid thermoelectric-photovoltaic (TE-PV) solar energy devices are considered. In the configuration being studied the concentrated solar radiation is either transmitted through the beamsplitter onto a thermoelectric generator, or reflected onto a photovoltaic cell. The role of the beamsplitter is to reflect (transmit) those parts of the solar spectrum that can be converted most efficiently in the PV cell (TE generator). Beamsplitters are designed for maximizing the output of the hybrid system taking into account the spectral efficiency of realistic solar cells based on amorphous or microcrystalline silicon, efficiencies of the thermoelectric generator of either 4% or 8%, and the AM1.5 solar spectrum. The beamsplitter is constructed using thin-film layers of SiO_2 and Si_3N_4 deposited on N-BK7 glass. The layer thicknesses are optimized for maximizing the efficiency of the hybrid system. The total achievable efficiency versus the number of layers used in the beamsplitter is studied considering from app. 20 to app. 200 layers. For an amorphous solar cell the relative increase in hybrid system efficiency above the single solar cell efficiency is 21.4%. Designs are made assuming that solar radiation is incident on the beamsplitter at an angle of 45°. However, the efficiency is found to only change slightly if the angle is varied from 35° to 55°. Finally, it is also found that efficient beamsplitters cannot be constructed for the reverse configuration with the TE and PV elements interchanged since efficient reflection of the long-wavelength radiation relevant for the TE generator is not possible without also having reflection of shorter-wavelength radiation that would be converted more efficiently in the PV cell.

1. Introduction

Spectrally selective beam splitting (SSBS) or filtering of radiation can be utilized in several different types of systems converting solar or other radiation into electricity (Imenes and Mills, 2004). In thermophotovoltaics it has for example been proposed to apply a filter between a source of heat radiation and a long-wavelength photovoltaic (PV) cell that only transmits thermal radiation in a narrow spectral window with high conversion efficiency in the PV cell (Bauer, 2011). Multilayer interference structures for SSBS are of interest for increasing the conversion efficiency in systems combining several PV cells being efficient at different wavelengths (see e.g. Antonini et al., 2015; Barnett et al., 2007). It is also possible to combine PV cells and other systems converting radiation into heat, which is then further converted into electricity in a regular power plant (DeSandre et al., 1985; Osborn et al., 1986; Chendo et al., 1987). Alternatively the PV cell can be combined with a thermoelectric (TE) generator, where radiation absorption leads to a temperature difference being exploited for thermoelectric generation of electricity (Goldsmid, 2010; Rowe, 2006; van Sark, 2011).

Theoretical studies of the TE-PV hybrid system has showed a potential for increasing the hybrid-system conversion efficiency beyond that of a single PV cell assuming ideal SSBS (Kraemer et al., 2008; Ju et al., 2012). However, while those papers discussed the optimum cutoff wavelengths of the assumed SSBS they did not consider how to actually make the beamsplitter (BS) and also not how close it is possible to get to ideal SSBS with a practical beamsplitter.

In this paper we will consider the design and optimization of a beamsplitter for SSBS in the TE-PV hybrid system illustrated in Fig. 1, where the PV cell (or solar cell) and TE generator are physically separated. Two configurations are shown where solar radiation is focused using either a lens (Fig. 1(a)) or a reflector arrangement (Fig. 1(b)). The angular distribution of light intensity onto the BS depends on the concentrator (lens or reflector). The angle of incidence will vary across the BS and is chosen to be 45°

* Corresponding author.
E-mail address: ts@nano.aau.dk (T. Søndergaard).

http://dx.doi.org/10.1016/j.solener.2016.09.036
0038-092X/

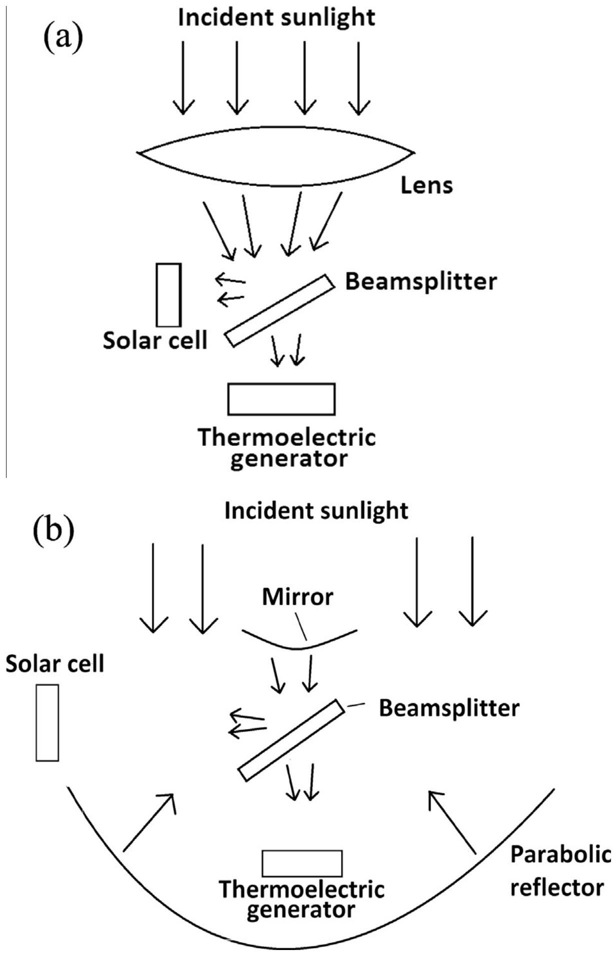

Fig. 1. Schematic of TE-PV hybrid systems showing splitting of concentrated solar radiation by a spectrally selective beamsplitter. Concentration of solar radiation by (a) a lens, or (b) a reflector arrangement.

in the center, and will deviate from this elsewhere. The BS will be optimized in this paper assuming that the incident angle is 45°, and then for an optimized structure we will consider the effect of the angular distribution on the efficiency. We will take into account how the efficiency of the hybrid system depends on the properties of the PV cell and the TE generator. As examples we will consider a microcrystalline (mc-Si) and an amorphous (a-Si) silicon PV cell. For the efficiency of the TE generator we choose 4% or 8% following Kraemer et al. (2008). We will calculate the efficiency of the optimized TE-PV hybrid system as a function of number of layers in the BS and compare with the case of using only a single PV cell.

For the BS we choose a multilayer thin-film geometry with alternating layers of SiO_2 and Si_3N_4 deposited on N-BK7 glass, which are common materials for fabricating thin-film multilayer mirrors and coatings. These materials have the advantage of practically negligible propagation losses for most of the solar spectrum except for some small losses in Si_3N_4 at the shorter wavelengths. Optical constants of the materials were obtained from (McIntosh, 2014; Palik, 1985; N-BK7 glass data, 2016). Obviously absorption in the BS must be kept low since otherwise it will become very hot in a concentrator system, and furthermore any radiation absorbed there will also be lost for conversion. For a given TE generator and PV cell, and a given solar radiation spectrum, the conversion efficiency is a function of all the layer thicknesses of the BS, which in this paper can vary from app. 20 to 200. Thus we need to optimize a function of a large number of variables.

The possibility of integrating the PV cell and TE generator into a single component has also been considered in several papers (Vorobiev et al., 2006; van Sark, 2011; Chávez-Urbiola et al., 2012; Deng et al., 2013; Fisac et al., 2014). In this case the radiation not being absorbed and converted in the PV cell will pass through the PV cell into the TE generator. This approach puts restrictions on the PV cell design, and it is for example not possible to have a back-reflector. Furthermore, the PV cell will be placed near or directly on the hot side of the TE generator. High temperatures tend to decrease the efficiency of PV cells, and especially for concentrated illumination it can be necessary to apply active cooling of the PV cell (Royne et al., 2005) to keep a high PV cell efficiency. The PV cell works best in a cold environment, and it is thus worth to consider hybrid systems where the PV cell and TE generator are physically separated. In addition this will allow using existing PV cells and TE generators, where these are individual components.

The paper is organized as follows. In Section 2 we describe the procedure for initial BS design and the further design optimization for maximum hybrid-system efficiency. We then study in detail the design and optimization of the BS for the cases of mc-Si and a-Si PV cells (Section 3), and finally we offer our conclusion (Section 4).

2. Procedure for design and optimization of beamsplitter

In this section the procedure for design and optimization of the BS will be described. This includes the description of an initial design of the BS in the form of a layered thin-film geometry, and then a procedure for iterative optimization of layer thicknesses for maximum total efficiency of the hybrid system.

2.1. Initial design of beamsplitter

The ideal reflectance spectrum of the BS is a step function with 100% reflectance for wavelengths where the conversion efficiency of the PV cell is more efficient than that of the TE generator, while the ideal transmittance must be 100% for other wavelengths where the TE generator is more efficient. As an initial design that approaches the ideal BS we choose to combine in series a number of blocks, where each block is a layered bandgap structure with large reflection at a certain wavelength interval. By combining blocks appropriately the resulting structure will be able to reflect with close to 100% reflectance the radiation within a much larger wavelength range than a single block would. A block consists of a certain number of unit cells, where a unit cell consists of a layer of Si_3N_4 and a layer of SiO_2.

The total layered structure is illustrated in Fig. 2 for the case of three unit cells in each block. The layered structure is deposited in practice on 1 mm of N-BK7 glass, and a layer of SiO_2 and a layer of

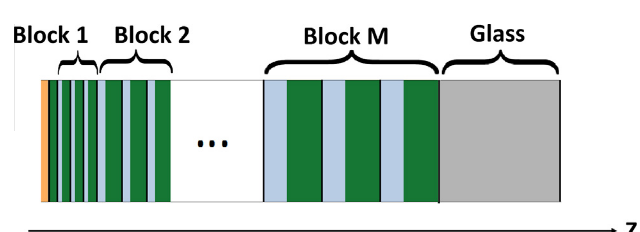

Fig. 2. Schematic of initial design. The first two layers from left represents MgF_2 (orange) and SiO_2 (dark green), respectively. This is followed by a number of blocks, where each block consists of a number of unit cells (3 in the schematic) with a layer of Si_3N_4 (light blue) and a layer of SiO_2. The layered structure is deposited on 1 mm of glass shown as the last layer to the right. Light is incident from the left. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)