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Polymethylmethacrylate-based luminescent solar concentrators with bottom-mounted solar cells

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ABSTRACT

Luminescent solar concentrators offer an attractive approach to concentrate sunlight economically without tracking, but the narrow absorption band of luminescent materials hinders their further development. This paper describes bottom-mounted luminescent solar concentrators on dye-doped polymethylmethacrylate plates that absorb not only the waveguided light but also the transmitted sunlight and partial fluorescent light in the escape cone. A series of bottom-mounted luminescent solar concentrators with size of 78 mm × 78 mm × 7 mm were fabricated and their gain and power conversion efficiency were investigated. The transport process of the waveguided light and the relationship between the bottom-mounted cells were studied to optimize the performance of the device. The bottom-mounted luminescent solar concentrator with cell area coverage of 9% displayed a cell gain of 1.38, to our best knowledge, which is the highest value for dye-doped polymethylmethacrylate plate luminescent solar concentrators. Power conversion efficiency as high as 5.03% was obtained with cell area coverage of 27%. Furthermore, the bottom-mounted luminescent solar concentrator was found to have a lowest cost per watt of $1.89 with cell area coverage of 18%. These results suggested that the fabricated bottom-mounted luminescent solar concentrator may have a potential in low-cost building integrated photovoltaic application.

1. Introduction

Because of the increasing demand for energy and limited global fossil fuels storage, solar energy is attracting increasing attention due to its significant advantages. However, till now, the conversion of solar energy into electricity is not efficient enough and cost-competitive yet [1]. Solar power is still five to ten times more expensive than electricity generated from fossils [2]. To reach lower photovoltaic (PV) cost, several routes are being pursued. Le et al. developed thin-film solar cells with excellent opto-electrical properties, offering a potential for cost reduction by reducing material consumption [3]. Yu et al. summarized the advanced progress of organic solar cells, which can be considered as a potential strategy due to their low cost fabrication process [4]. Especially, PV concentrators are technically feasible to reduce PV cost by replacing the expensive cells with a cheaper solar radiation concentrating system [5]. Luminescent solar concentrator (LSC) as an alternative concentrator was first proposed since the late 1970s [6] and then the comprehensive theoretical and experimental work on LSC was carried out [7]. As shown in Fig. 1(a), a LSC consists of a waveguide layer in which luminescent materials are dispersed or casted. Solar light can be absorbed and re-emitted by the luminescent materials. Most of the emitted light is trapped in the waveguide by total internal reflection and transported to the side edges where PV cells are attached. The main purpose of LSCs is to cut the usage of expensive solar cells to reduce the cost of PV electricity generation. Compared with the traditional geometrical concentrators, which commonly use tracking and cooling systems [8], LSCs can accept both direct and diffuse light without the expensive tracking system [9] and the cooling systems are not required due to the long-wave radiation can transmit the device [10].

In the last decades, many efforts have been made to increase the power conversion efficiency (PCE) of the LSCs in different ways. Goldschmidt et al. [11] used photonic structure as a bandstop

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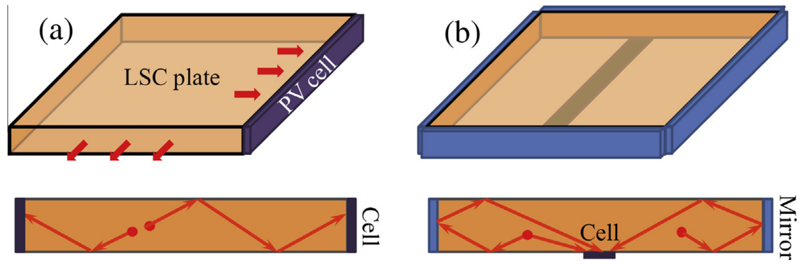

Fig. 1. Schematic of (a) the conventional LSC, and (b) bottom-mounted LSC.

reflection filter to reduce escape cone losses and increased the LSC efficiency by 20%. Peng et al. [12] applied fiber dye-sensitized solar cell in LSCs to maximize the utilization of incoming photons. Besides, many promising luminescent materials have also been developed for the application in LSC. Purcell-Milton and Gun'ko [13] introduced quantum dots which allow absorption to be tuned across the entire solar spectrum for incorporation in LSC devices. Bozdemir et al. [14] reported unimolecular energy gradients with strong absorption in the visible spectrum which can be used for highly efficient LSCs. Katsagounos et al. [15] used lanthanide complexes with enhanced luminescent emission in LSC technology and increased the cell efficiency by 28%. Griffini et al. [16] investigated organic molecular host/guest cocrystals to achieve high solubility of the luminescent species in the host matrix. Till now, the highest PCE of LSC is 7.1% achieved on a 50 mm × 50 mm × 5 mm waveguide in which expensive GaAs cells were used [17]. However, the corresponding performance-price ratio of LSC is still lower than that of the silicon PV modules due to the narrow absorption band of luminescent materials and self-absorption problem [18]. Mansour [19] studied the performance of three LSCs with different configurations and found that the bottom-mounted LSC exhibited the highest short-circuit current. It is shown that LSC with this bottom-mounted configuration (Fig. 1(b)) allows the solar cell absorb direct incident sunlight and reduce the transmission distance that photons have to travel in the waveguide, which may help to solve the narrow-absorption and self-absorption problem. Recently, Corrado et al. [20] reported the bottom-mounted PV design based on thin film LSCs and found that a cell area coverage of 14% yielded the lowest cost. Leow et al. [21] simulated the transport process of photons in the bottom-mounted thin film LSC using a Monte Carlo ray tracing model. The effects of the waveguide thickness, cell dimensions and panel layout on the power gain were studied. Although the performance and light transport process of bottom-mounted thin film LSC have been investigated, the influences of cell area coverage and position on the performances of bottom-mounted LSCs based on dye-doped plates remain unclear. Additionally, further studies on the relationship between the bottom-mounted cells and the real transport process of the waveguided light in LSC plate are necessary.

In this study, firstly, a conventional LSC composed of dye-doped polymethylmethacrylate (PMMA) plate and edge-mounted crystalline silicon solar cells was developed. Based on it, a series of bottom-mounted LSC plates were prepared and their performances were compared with that of the conventional LSC with edge-mounted PV cells. In order to find out the transport process of waveguided light in the LSC plate, the efficiency contribution from different region of LSC plate was studied. Besides, the influences of additive cells were studied to reveal the absorption of waveguided light for the bottom-mounted cells. The relationship between cell area coverage and LSC performances was also investigated for the optimization of the bottom-mounted LSC. Finally, the performance-price ratio of bottom-mounted LSCs was estimated for the purpose of potential in building integrated photovoltaic (BIPV) application.

2. Methodology

The fabrication process of LSCs mainly consists of two steps. First, dye-doped PMMA plates were prepared by in-situ polymerization method. Then, crystalline silicon solar cells were mounted to the as-prepared dye-doped PMMA plates, according to the configuration depicted in Fig. 1(a) and (b), respectively.

2.1. Fabrication of dye-doped PMMA plates

First, a solution with 5 wt% NaOH was added to the commercially available methylmethacrylate monomer (MMA, Sinopharm Chemical Reagent Co., Ltd.) with a volume ration of 1:10. After 2 h stirring with a speed of 600 rpm, NaOH solution was separated to remove the inhibitor of hydroquinone. A ratio of 5 wt% $CaCl_2$ (Sinopharm Chemical Reagent Co., Ltd.) was put into the extracted MMA for 24 h and filtered to remove the residual water. Then fluorescent dyes Lumogen Red 305 and Yellow 083 (BASF) were mixed in mass ratio of 2:1 and dissolved into the refined MMA with a concentration of 0.1 wt% for Lumogen Red 305. Subsequently, 0.1 wt% benzoyl peroxide (BPO, Sinopharm Chemical Reagent Co., Ltd.) was added to the mixture as the initiator for polymerization. The obtained mixture was heated at 80 °C in the oil-bath for 1 h pre-polymerization. The pre-polymer was cooled down and then poured into the glass moulds and heated at 50 °C for 24 h to complete the polymerization. After demoulding and cutting, the dye-doped PMMA plates with size of 78 mm × 78 mm × 7 mm were obtained.

2.2. Fabrication of LSCs

The bottom-mounted LSCs were prepared by attaching commercial monocrystalline silicon solar cell (Trina Solar Co., Ltd., with dimension of 78 mm × 7 mm) to the bottom of the plates with ultraviolet (UV) adhesives (XSSS Optical adhesive UV-3129, with refractive index of 1.49). For comparison purpose, the conventional LSC with edge-mounted PV cells was also prepared by attaching four pieces of same monocrystalline silicon solar cells to the four edges of the plates and connecting them in series. The measured efficiency of the used monocrystalline silicon solar cell under AM 1.5 illumination was 17.0% with short-circuit current of 204 mA, open-circuit voltage of 0.605 V and fill factor of 0.752. For the bottom-mounted LSCs, silver mirrors (>85% reflectance for visible light) were attached to the four waveguide edges with UV adhesives. A white reflector was added to the bottom side of LSC (separated by an air gap) to increase the energy output, which was made by spraying a cardboard sheet with white paint (Dulux).

2.3. Characterization

The current–voltage (I–V) curves of fabricated LSCs were recorded by Keithley 2400 Source Meter under AM 1.5 illumination using a solar simulator (Oriel Sol 3A). The masking experiment was carried out to obtain the relationship between the LSC plate area and