Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 119 (2015) 452–460
SOLAR ENERGY
www.elsevier.com/locate/solener

A fast and effective procedure for the optical efficiency determination of luminescent solar concentrators

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Received 22 December 2014; accepted 24 May 2015

Communicated by: Associate Editor Antoine Bittar

Abstract

We introduce a new method for the prompt and effective evaluation of the optical efficiency of different sets of luminescent solar concentrators (LSC) based on dye-doped poly(methyl methacrylate) thin films. The procedure founded on the realization of a home-build apparatus (PeryRoom), which allowed for a fast and reliable measurement of the generated photocurrents profiting of the use of a photodiods system. The photocurrents were analyzed by means of a simple model inspired by the work of Goetzberger and Greube (1977) and rationalized in terms of different dye characteristics and film thickness. The procedure was eventually validated by comparing the optical efficiencies measured by using a Si-based photovoltaic module. Overall, the present results support the use of PeryRoom for the optimization of the current state-of-art LSC systems.

Keywords: Fluorescent dyes; Poly(methyl methacrylate) thin films; Luminescent solar concentrators; Photodiods; Optical efficiency

1. Introduction

In the scene of renewable energies, photovoltaic (PV) has always had a predominant role due to the extraordinary power with which the sun irradiates the earth and for the possibility to bring the energy producing systems directly in the built environment. Anyway, beside the enormous progress experienced by PV technology in the past decades, the price of PV generated power is still too high to assure to sun energy a predominant role in the energy market share (van Sark, 2013; Sawin, 2014).

Sunlight concentration is one of the most promising paths toward the reduction of PV energy costs. This is achieved by limiting the amount of active material needed to convert the same amount of solar energy, since the latter is the predominant factor in the final cost (Rabady, 2014; Rabady and Andrawes, 2014; Swanson, 2000).

Over classical optical concentrators, which are based on geometrical optics and make use of lenses and mirrors, luminescent solar concentrators (LSC) show advantages like light weight (Swanson, 2000), higher theoretical concentration factors (Bronstein et al., 2013; Yablonovitch, 1980; Smestad et al., 1990), ability to work well with diffuse light (Sanguineti et al., 2013; Bailey et al., 2007) and no need of sun tracking (Madhugiri and Karale, 2012;

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http://dx.doi.org/10.1016/j.solener.2015.05.031
0038-092X/

Tiwari and Mishra, 2012) or cooling apparatuses (Madhugiri and Karale, 2012).

Nowadays, the research of high efficiencies for PV devices based on LSC technology has made great development (Sanguineti et al., 2013; Debije and Verbunt, 2012; Meinardi et al., 2014; Flores Daorta et al., 2014; Benjamin et al., 2014; Desmet et al., 2012; Goldschmidt et al., 2009; Slooff et al., 2008; Currie et al., 2008). A LSC usually consists in a transparent glass or polymer slab doped with a fluorescent dye that can absorb the solar spectrum (Debije and Verbunt, 2012). If the refractive index of the host is higher than the one of the outer environment, then part of the emitted photons remain trapped inside the device by means of total internal reflection (TIR) and can be collected at the edges to produce electric power with a PV cell.

Measurement of the LSC efficiencies are usually performed by attaching PV modules to the concentrating system and irradiating it with a light source that emulates the solar conditions (Goldschmidt et al., 2009; Slooff et al., 2008; Dienel et al., 2010). While this approach is effective to evaluate the ultimate LSC performances, it can be costly and time consuming when trying to optimize all single components such as dyes and polymer characteristics or alternative designs. Moreover, this approach has created a lot of confusion in the literature data (Debije and Verbunt, 2012), since many research groups make use of different and not always directly comparable conditions and experimental setups on their pursue to the best performing LSC system. The use of different exposed areas, back reflectors and/or mirrors on the edges as well as the evaluation of the efficiencies using different parameters make the comparison of different LSC setups quite difficult. More than that, sometimes LSCs are evaluated with parameters referred to other solar generating systems like photon-per-electron efficiencies or fill factors which are meaningless in this specific case since the LSC itself is not an energy generating device but achieves light concentration only (Debije and Verbunt, 2012).

In our opinion, this approach is counterproductive as it complicates the comparison of LSCs data from different laboratories. Moreover, the laboratory research in LSC technology should be aimed at the optimization of the single parameters which affect the overall LSC performances, so that they can be optimized and implemented together in a functional and less expensive system (Desmet et al., 2012; Geetha et al., 2004; Earp et al., 2011).

In this work, we propose an easy procedure for the determination of the optical efficiency of different sets of LSCs based on dye-doped poly(methyl methacrylate) thin films, in order to rapidly identify the best working conditions for each system. More specifically, the relations between dye concentration and the light output from the LSC systems are investigated by using a home build setup profiting on the fast response time of photodiods and rationalized in terms of a simple model based on the different dyes characteristics.

2. Experimental

2.1. Materials

Poly(methyl methacrylate) (PMMA, Aldrich, Mw = 350,000 g/mol, acid number <1 mg KOH/g), Rhodamine B (fluorescence grade, Sigma–Aldrich) and Lumogen Red F350 (BASF) were used as received with no further purification. N,N′-bis-(1′-phenylethyl)-perylene-3,4,9,10-tetracarboxidiimide was synthetized from perylene-3,4,9,10-tetracarboxidianydride and 1-phenylethylamine following a literature procedure (Pucci et al., 2010).

2.2. Preparation of polymer films for optical studies

Different dye/PMMA thin films were prepared by drop casting, i.e. pouring 0.8 mL chloroform solution containing 30 mg of the polymer and the proper amount of dye to obtain concentrations in the range 0.05–2.2 wt.% over a 76 × 25 × 0.8 mm microscope slide (Carlo Erba). The glass slides were cleaned with chloroform and immerged in 6 M HCl for at least 12 h, then they were rinsed with water, acetone and isopropanol and dried for 8 h at 120 °C. Solvent evaporation was performed on a warm hot plate (about 30 °C) and in a closed environment. The thickness of the films was measured to be 20 ± 5 μm.

2.3. Preparation of polymer films for PeryRoom and LSC studies

Dye/PMMA thin films were prepared by drop casting, i.e. pouring 0.9 mL chloroform solution containing a variable amount of polymer and a proper quantity of dye to obtain concentrations in the range 0.05–2.2 wt.% on 35 × 50 mm area over a glass, previously cleaned as described before. Solvent evaporation was performed on a warm hot plate (about 30 °C) and in a closed environment. The film thickness was measured to be 18 ± 5 μm, 24 ± 5 μm and 43 ± 5 μm for the films prepared using 20.0, 30.5 and 61.0 mg of PMMA, respectively. The PMMA films were easily removed with a spatula after immersion in water so that they can be stored for successive measurements and comparison by attaching them on 50 × 50 × 3 mm optically pure glass substrate (Edmund Optics Ltd BOROFLOAT window 50 × 50 TS) with a high-purity silicone oil with a refractive index comparable to PMMA and glass (i.e., poly(methylphenyl siloxane), 710 fluid, Aldrich, refractive index $n = 1.5365$). Absorption and emission properties of such devices showed negligible differences with the freshly prepared ones.

2.4. Apparatus and methods

The thickness of the films was measured with a Starrett micrometer.