Solar Energy Materials and Solar Cells 167 (2017) 133–139

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

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

Compensation of self-absorption losses in luminescent solar concentrators by increasing luminophore concentration

Zachar Krumer[a], Wilfried G.J.H.M. van Sark[b,*], Ruud E.I. Schropp[c], Celso de Mello Donegá[a]

[a] Condensed Matter and Interfaces, Debye Institute for NanoMaterials Science, Utrecht University, P.O. Box 80000, 3508TA Utrecht, The Netherlands
[b] Copernicus Institute, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[c] Eindhoven University of Technology, Department of Applied Physics, Plasma and Materials Processing, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

ARTICLE INFO

Keywords:
Luminescent solar concentrators
Self-absorption
Lumogen Red
Lumogen Orange
Saturation
Solar cells

ABSTRACT

Self-absorption in luminophores is considered a major obstacle on the way towards efficient luminescent solar concentrators (LSCs). It is commonly expected that upon increasing luminophore concentration in an LSC the absorption of the luminophores increases as well and therefore self-absorption losses will have higher impact on the performance of the device. In this work we construct a fully functioning liquid phase LSC where the luminophore concentration can be altered without changing other conditions in the experimental set-up. We step-wise enlarge the concentration of the luminophores Lumogen Red 305 and Lumogen Orange 240, while monitoring the electrical output and self-absorption effects. Contrary to common belief, self-absorption does not increasingly limit the performance of LSCs when the luminophore concentration increases.

1. Introduction

Luminescent solar concentrators (LSCs) are photovoltaic devices whose goal is to reduce the necessary amount of active photovoltaic elements per Watt of delivered power by means of concentration [1]. The LSC device is essentially a thin transparent plate, within which luminescent species (luminophores) are dispersed (Fig. 1). Solar radiation enters the LSC through the large top surface and is absorbed by the luminophores. Subsequently the luminophores emit at a longer wavelength and into a different direction. A large fraction of the isotropically emitted light hits the inner surface of the transparent plate in the regime of total internal reflection and is therefore trapped inside the transparent plate. The trapped light is waveguided to the edges of the plate, where solar cells are attached and conversion into electricity takes place. Concentration arises from the projection of light entering through the large top surface onto the small solar cell surface, which makes it possible to harvest much more light per unit of semiconductor material. Unlike conventional geometric concentrators, this concentrator concept does not require bulky tracking devices and allows greater freedom when it comes to form, which makes it well suited for building integration of low-concentration photovoltaics [2–5].

Similarly to geometric concentrators, LSCs are not only characterized by their power conversion efficiency η_{LSC}, which is the ratio of the electric power output P_{LSC} and the incident radiative power Φ_{in}:

$$\eta_{LSC} = \frac{P_{LSC}}{\Phi_{in}} \tag{1}$$

which is a number that is smaller than the power conversion efficiencies of the solar cells involved. The actual concentration strength is given by the optical concentration factor C and compares the radiative power Φ_{LSC} incident on the solar cell attached to the edge of the LSC to the radiative power that is incident on the bare solar cell Φ_{SC}:

$$C = \frac{\Phi_{LSC}}{\Phi_{SC}} \tag{2}$$

Mainly the following loss mechanisms cause the performance of LCSs to be as yet rather low: non-radiative dissipation of the absorbed radiative energy by the luminescent species, the escape losses, i.e. the emission of light outside the waveguiding mode and the incomplete absorption of the incident light by the luminescence species. In addition to those there is also the issue of self-absorption. The emitted light can be re-absorbed by the luminescent species itself, which recycles photons including those that were already in waveguiding mode before self-absorption occurred. In this way photons are exposed to some of the loss mechanisms repeatedly and thus their effect is amplified.

A partial approach to solving the challenges has been offered by BASF with their Lumogen series [6,7]. The high luminescence quantum efficiency (95%), the ratio between the emitted and absorbed photons, of these perylene derivatives is one of the reasons that record LSC efficiencies were achieved with these dyes [8,9]. On the practical side

---

* Corresponding author.
E-mail address: w.g.j.h.m.vansark@uu.nl (W.G.J.H.M. van Sark).

http://dx.doi.org/10.1016/j.solmat.2017.04.010
Received 13 July 2016; Received in revised form 3 April 2017; Accepted 6 April 2017

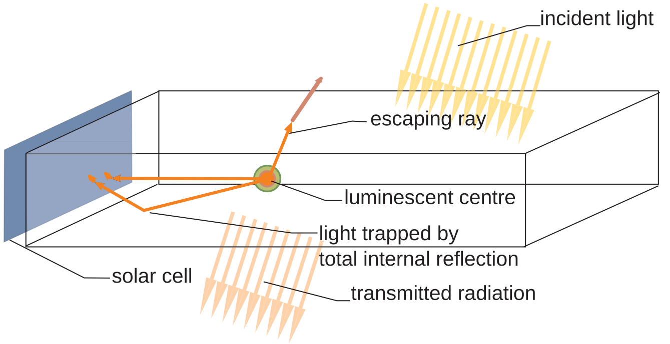

Fig. 1. Schematic representation of the working principle of a luminescent solar concentrator.

these dyes can be easily dispersed into PMMA [6] and passed long-term outdoor tests [10,11]. In fact Lumogen Red 305 is considered as the "working horse" of the LSC concept [12].

Organic dyes usually have narrow absorption bands when compared to semiconductor nanocrystals, which is why these have been receiving much attention in quantum dot LSCs [13,14]. In Lumogen Red 305 this can be overcome by enlarging the concentration of the dye, which increases absorption in the UV-region, as the law of Beer-Lambert predicts. This causes a gain in photon flux into the system and may lead in turn to a higher device output. However, the increase of overall absorption by enlargement of dye concentration simultaneously leads to an increase of self-absorption. These effects compete in reaching high device performance. In this work the concentration of Lumogen Red 305 is changed such that highest performance is reached, while monitoring the impact of self-absorption. Because of the competing effects we expect an optimal concentration for which the performance attains its maximum. We employ a *liquid* phase device, which allows the luminophore concentration to be easily and reliably changed, while keeping all other experimental parameters constant, such as coupling between the solar cell and the LSC, the quality of the transparent medium.

Because of the increase of the performance increasing effect (absorption) and the performance decreasing effects (self-absorption) with dye concentration an optimal concentration is expected at which the performance attains its maximum. The goal of this work is to critically evaluate the effects of luminophore concentration on the performance of LSCs.

2. Materials and methods

The monitoring of LSC performance and effects of self- absorption at various concentrations was carried out in two experiments: operation of a fully functional liquid phase prototype (Section 2.2) and spectroscopy at variable optical path lengths (Section 2.3). In both experiments the luminophore concentration was changed in a controlled way, such that data from both experiments was retrieved for the same range of luminophore concentrations. The scope of the work was widened by applying the procedure also to Lumogen Orange 240.

2.1. Luminophore solution

The commercially available BASF dyes Lumogen Red 305 (LR305) and Lumogen Orange 240 (LO240) were used to prepare a first highly concentrated stock-solution. The total mass of 120.8 mg LR305 was diluted in 10 ml toluene, while 7.8 mg LO240 was diluted in 10 ml acetone. Both solutions were used for the liquid phase prototype. The LR305 solution was diluted 12 times to obtain a second stock-solution for the spectroscopy at variable path lengths. The second solution was used to record the optical properties in standard cuvettes that are commonly used for absorption and luminescence spectroscopy (Section 2.3). The internal volume of these is 12 times smaller than the internal volume of the model LSC device, while the volume of the syringe used to add the stock solution to the measured solution was the same. Therefore the 12-fold dilution of the first stock solution for the second stock solution ensured that the luminophore concentrations were varied over the same range in both experiments. The absorption spectra of the individual concentrations were recorded using a Perkin-Elmer Lambda 950 spectrometer.

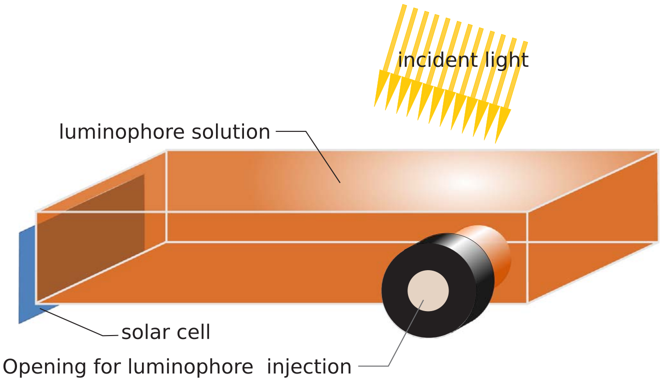

Fig. 2. Schematic representation of the liquid phase LSC system.

2.2. Model LSC device

The LSC was made from a custom-built quartz cuvette (Hellma Analytics) with the internal dimensions 100 mm × 35 mm × 10 mm. This cuvette is screw capped but the injection and removal of fluid is possible through the septum using a syringe (Fig. 2). Commercially available polycrystalline solar cells (14.56% (for Lumogen Red 305) and 15.13% (for Lumogen Orange 240) power conversion efficiency [15]) were used. Contacts were soldered to the back- and front side of the solar cell. For mechanical stability the cell was glued using a 3–5 mm thick layer of non-acidic silicone glue (Bison - transparent silicone sealant - Bi3311) on a glass substrate. The cell was covered with black absorber paper, which contained a window, such that the 35 mm × 10 mm facet of the cuvette could be placed in firm contact with the cell, while the remaining solar cell area was blocked from receiving light (Fig. 3). The cell was characterized by recording the current-voltage curves in the dark and under AM1.5 illumination, which yielded its efficiency. The efficiency measurements were carried out using class AAA [16] dual beam WACOM solar simulator [17]. It includes two light sources: a 1000-Watt Xenon lamp for the UV and visible part of the solar spectrum (below 700 nm) and a 300-Watt halogen lamp for the infrared part. The spectral mismatch is < 3% in the short wavelength ranges of interest here [18]. The current-voltage measurements were performed on a Keithley 238 High Current measure unit to characterize the bare solar cell, the LSC with pure solvent and the LSC with a luminophore solution at different concentrations. The cuvette was glued onto the solar cell using the adhesive MY-146, purchased from Mypolymers, which is refractive index matched to quartz (1.461 at 589 nm) [19]. The polymer was cured for a few seconds using a UV-lamp. Upon curing some air-bubbles appeared, which reduced the quality of optical coupling. The prototype with

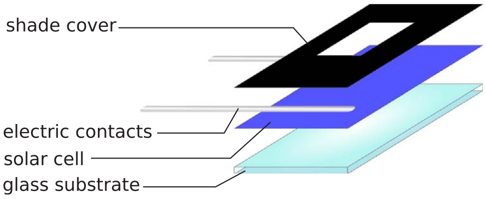

Fig. 3. Solar cell preparation for the liquid phase LSC device.