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Performance analysis of a large-area luminescent solar concentrator module

N. Aste [a], L.C. Tagliabue [a,*], C. Del Pero [a], D. Testa [b], R. Fusco [b]

[a] Architecture, Built Environment and Construction Engineering Department, Politecnico di Milano, Via Bonardi 9, 20133 Milano, Italy
[b] Eni S.p.A, Research Center for Non-Conventional Energies, ENI Donegani Institute, Via Fauser 4, 28100 Novara, Italy

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A B S T R A C T

Today Luminescent Solar Concentrators (LSCs) represent a very promising solar technology, especially the semi-transparent ones, suitable for building integration. These components can likely represent an effective way to produce renewable energy while preserving the transparency of the building envelope, by using a wide amount of surfaces which at the moment are neglected, such as windows, skylights, shading devices, etc. This paper describes the first operating measurements carried out on a new LSC prototype, monitored at the Photovoltaic (PV) Test Facility of the Politecnico di Milano. The photoluminescent composition of the ENI dye used for the spectrum converter dispersed in the LSC includes an acene compound and a benzothiadiazole compound. The preliminary results show a better energy performance ratio for the LSC in comparison with standard PV modules, and are representative of the first phase of a research work aimed at industrializing an innovative building integrated component with a large dissemination potential.

1. Introduction

Solar energy exploitation plays a key role in the sustainable development and energy efficiency of buildings [1]. The European goals to improve renewable energy and to reduce energy consumption and pollution [2] are strongly based on solar technology, which is one of the preferred ways used to construct “nearly zero-energy buildings” [3]. Although the Building Integrated Photovoltaic (BIPV) sector is constantly growing [4], the use of standard modules for building integration involves serious constraints: the most efficient components are opaque and have a standard shape, and, in addition, they need a high availability of direct solar irradiation.

When transparency and a more extensive use of diffuse radiation are required, LSCs components may be a good alternative to traditional PV [5]. However, their durability and technical-economic competitiveness must be ensured [6].

The first experiments on LSC can be found already in the late 1970s [7–9] when the total internal reflection (TIR) effect of specific dyes was discussed to implement solar components with reduced PV surface, in order to minimize the costs of the technology. Furthermore, the crucial issues of self-absorption, constraining size and shape of the components and different dyes and guest materials were studied [10–12]. Commercial dyes are now available and this paper describes a new component which uses a mix of two dyes (i.e. a commercial dye and a custom-produced dye), which improves the energy performance.

This paper describes, in section 2, the operating principles of the LSC analyzed, while in section 3 a characterization of the component in different configurations is carried out (i.e. a free plate and a plate equipped with a frame), based on LSCs specific parameters deduced by technical literature. During the research, the LSC prototype developed was assembled in a LSC module, which underwent an outdoor measurement campaign described and discussed in sections 4 and 5. The electrical performance results of the LSC module, compared with those of the traditional PV technologies, are reported in section 5. Section 6 summarizes the conclusions and the follow-up of the research activities on the LSC.

2. Operating principles of LSCs

This work concerns a specific LSC developed by the ENI Donegani Institute and tested at the Politecnico di Milano. The concept consists essentially in a semitransparent yellow plate with PV cells

* Corresponding author. Tel./fax: +39 02 2399 9469.
E-mail address: chiara.tagliabue@polimi.it (L.C. Tagliabue).

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on the edges. Dye molecules are dispersed into a square transparent plastic polymethylmethacrylate (PMMA) sheet and strips of single crystalline solar cells (Sc–Si) are glued to the four edges of the plate. The Sc–Si PV technology used was chosen due to its good efficiency as well as to technical-economic reasons.

Fig. 1 shows the operating scheme of the LSC. Fluorescent molecules act as spectrum converters: they absorb and emit photons with different frequencies. The photons emitted from a molecule of dye spread into the plate and, due to total internal reflection, are concentrated at the edges of the slab, where the photovoltaic cells are located. The silicon-based solar cells absorb and convert visible radiation and part of the infrared radiation [13] as discussed in section 4, according to the external quantum efficiency (EQE) curve plotted in Fig. 5. The features of the LSC panel allow a better exploitation of the cells by means of the spectrum conversion, shifting solar radiation to more favorable wavelengths and, in addition, reducing the self-absorption effect of the dyes.

Furthermore, the possibility to direct and concentrate solar radiation to the edges of the panel by total internal reflection (TIR) allows to minimize the PV surface [14].

The specific concentration of the dyes in the guest material, which is about 100 ppm, makes it possible for a 25% of the whole solar radiation incident on the aperture area (i.e. the front surface) of the LSC plate to be absorbed, while the remaining 75% passes through. Then, part of the absorbed radiation hits the solar cells at the edges, with a subsequent change of the spectrum and of the related energy content.

The solar radiation absorbed by the fluorescent molecules at frequency ν_1 is emitted at a lower frequency ν_2, at which it is subjected to a lower self-absorption by the other fluorescent molecules.

Therefore, the crucial self-absorption problem is minimized and the re-emitted radiation, guided by total internal reflection, is concentrated on the edges of the solar cells.

The LSC panel realized by ENI Donegani Institute uses a 50 × 50 cm PMMA plate, 6 mm thick, doped with two dyes: DTB (4,7-di(2-thienyl)benzo[c]1,2,5-thiadiazole) synthesized by ENI, and DPA (9,10-diphenylanthracene), a commercial dye (Patent Number(s): WO2011048458-A1; WO2011048458-A8).

The curves of absorption and photoluminescent intensity of emission related to the two dyes are shown in Fig. 2. It can be noted that the peaks of absorption of the DTB dye are located at 300 and 450 nm and the emission peak is at about 600 nm. The DPA dye has peaks of absorption around 350 and 400 nm and peaks of emission

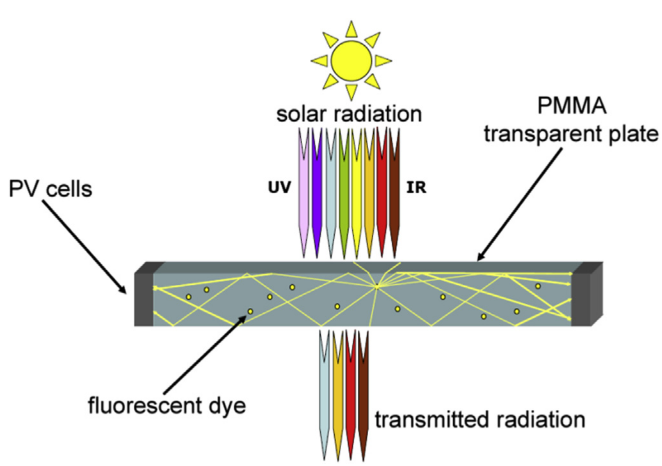

Fig. 1. Diagram of the incident photons and of the photons emitted by a dye molecules inside the LSC (source: ENI Donegani Institute).

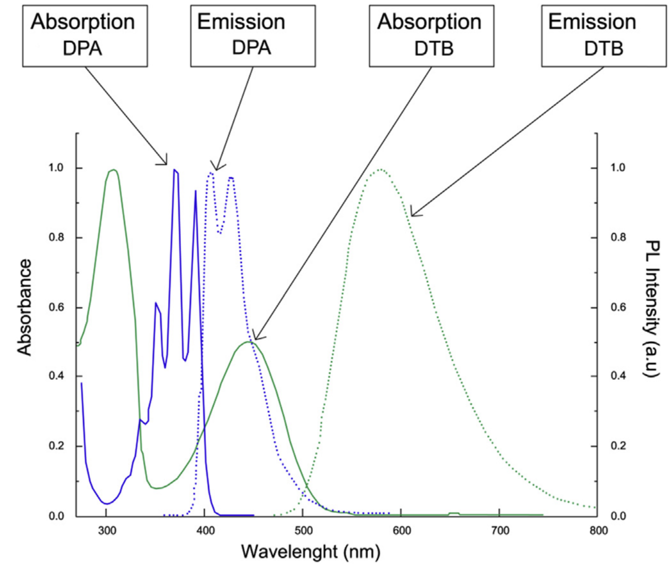

Fig. 2. Absorbance and emission spectra of DTB and DPA in PMMA; experimental measurements carried out at ENI Donegani Institute.

at 420 and 450 nm. Thus the dyes perform a shifting of the wavelength from the ultraviolet to the visible and infrared (IR) light, more favorable to PV devices with respect to the specific PV cells used.

The LSC panel is equipped with 88 monocrystalline PV cells, 22 × 7 mm each, in a combined series-parallel connection, assembled with silicone into the four edges of the plate (Fig. 3). The characteristics of the cells are listed in Table 1.

By assembling six 50 × 50 cm panels in a single metal frame, a 108.4 × 161.8 cm LSC module was realized, as shown in Fig. 4. The total nominal power of the 528 cells installed in the module amounts to 11.77 W_p.

3. LSC panel characterization

Primary experimental evaluations were carried out at ENI Donegani Institute to define the basic characterization of the LSC panel.

In order to calculate the electric gain and the efficiency of the LSC component, it is possible to refer to some specific parameters, as described hereafter.

First, the electric gain (γ_p) of a single cell of the LSC is defined as the ratio between the ideal output power of the cell [15,16] and that of a reference PV cell, according to the following equation [17], where quantities are referred to Standard Test Conditions (STC):

$$\gamma_p = \frac{I_{sc,LSC} V_{oc,LSC}}{I_{sc,REF} V_{oc,REF}} \tag{1}$$

where:

$I_{sc,LSC}$ is the short circuit current of the cell integrated in the LSC plate [A];
$V_{oc,LSC}$ is the open circuit voltage of the cell integrated in the LSC plate [V];
$I_{sc,REF}$ is the short circuit current of the reference PV cell [A];
$V_{oc,REF}$ is the open circuit voltage of the reference PV cell [V].

The reference cell is a PV cell with the same area and characteristics as the ones integrated in the LSC plate, and with the same tilt and azimuth angles of the LSC plate.