Enhanced efficiency of the luminescent solar concentrator fabricated with an aqueous layer

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A novel method for preparing a luminescent solar concentrator (LSC) with fluorescent aqueous layer sandwiched between two pieces of flat glass is developed. By this method, an aqueous layer concentrator with a size of 78×78×7 (mm) is fabricated. After coupled with silicon solar cell, the concentrator shows a power conversion efficiency of 3.9%, about 30% higher than that of the same sized laminated glass concentrator employing the same dyes. Furthermore, the measured efficiency almost reaches the calculated limit of the aqueous layer LSC. This kind of aqueous layer LSC offers a potential application in the building-integrated photovoltaics.

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Since Weber and Lambe demonstrated the concept of luminescent solar concentrators (LSCs) in the late 1970s, LSCs have been proposed as one approach to reduce the cost of photovoltaic devices[1]. The basic design of a LSC consists of a transparent matrix in which organic or inorganic luminescent materials are dispersed. Solar light shining on the front surface of a LSC is 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 small photovoltaic (PV) cells attached to the side edge of the concentrator[2,3]. Compared with the traditional optical solar concentrators, LSCs are able to accept both direct and diffuse light without tracking system. Due to that LSCs only absorb the ultraviolet (UV) and visible light matching the absorption of the luminescent materials, the long-wave radiation can pass the device and reduce the thermal effect, and thus makes the cooling system unnecessary. Also, because the expensive silicon solar cell panel is replaced by the cheap transparent matrix and commercial luminescent materials, the cost of the PV system can be reduced significantly. After decades of research and development, LSCs have shown great potential in the application for building-integrated photovoltaics (BIPV).

Up to now, the most common fabrication method of LSCs is incorporating the fluorescent dye into transparent matrix (polymers or glass) or preparing fluorescent thin films on the transparent medium[4−9]. For example, a power conversion efficiency (PCE) of 2.4% was reported by Maggioni *et al.*[10] for a thin film LSC after coupled with the GaAs cell and a bottom white diffuser. Slooff *et al.*[11] reported the highest PCE of 7.1% for LSC, which was fabricated by incorporating two kinds of dyes into polymethylmethacrylate (PMMA), and coupled with the GaAs cells. Using the same method, Desmet *et al.*[12] recently presented a LSC with a PCE of 4.2% after coupled with the monocrystalline silicon solar cells. However, LSCs prepared by these methods are prone to wear and aging because of the lack of protection. In order to solve the problem, we proposed to laminate the luminescent ethylene-vinyl acetate (EVA) copolymer layer between two pieces of ultrawhite glass[13]. This sandwich structure protects the fluorescent layer from mechanical scratch and air contamination and increases the stability of LSCs significantly. However, the residual dusts and bubbles in the waveguide medium are difficult to be removed completely, which leads to the loss of transmission light and decrease of the PCE. Furthermore, uniform dispersion of luminescent materials in the polymer medium is also hard to obtain and often consumes large amounts of organic solvent, increasing the costs as well as causing the environmental contamination. Therefore, a facile and environmentally friendly procedure for the preparation of LSCs with high stability and efficiency is desired. Mansour[14] studied the optical efficiency of aqueous concentrators with a rectangular glass tank containing dye dissolved in liquid polymer. They found that the aqueous concentrators were as efficient as those with solid matrices, and their efficiencies were enhanced under diffuse light illumination. Another representative aqueous concentrator was investigated by sealing PbS quantum dots solutions into quartz panels with a size of 45×12×4 (mm)[15]. Normally, for LSC fabricated with this facile process, the optical waveguide transmission efficiencies are comparable to traditional LSCs. From the synthetic and industrial perspective, the development of large-size device with high transmission efficiency and proper protection comes to be a major target.

In this letter, we report a simple fabrication method of aqueous layer LSC by syringing fluorescent solution into the space between the two pieces of flat glass of 78×78 (mm). The maintenance is very convenient for the replacement of fluorescent solution, benefiting the sustainable recycle of LSC devices. Furthermore, the dusts and bubbles in the waveguide medium can be easily removed and thus the optical waveguide transmission efficiency is enhanced. By comparing with results from the home-written simulation software[16], the measured PCE of the LSC fabricated by this method almost reaches the calculation limit of the aqueous layer LSC.

The aqueous layer LSC device was fabricated by syringing fluorescent solution into the space between two pieces of flat glass. The schematic of the fabricating process is shown in Fig. 1. Two pieces of ultrawhite glass with a size of 78×78×3 (mm) were cleaned with deionized water and alcohol and then fixed using UV adhesives with 1 mm gap left between them. Four pieces of commercial silicon solar cell (78×7 (mm)) with an efficiency of 17% were attached to the four side edges of the sandwich-structured concentrator using UV adhesives. The silicon cells used were fixed on circuit boards to protect the cells from breaking. Fluorescent dyes of Lumogen Red 305 and Yellow 083 (BASF) were dissolved into cyclohexane (Sinopharm Chemical Reagent Co., Ltd) with a mass ratio of 2:1 and a concentration of 0.1 wt% Red 305. After ultrasonic dispersion, the mixed fluorescent dye solution was injected into the gap with a syringe and the pinhole was subsequently sealed with glass glue. For comparison, the traditional laminated glass concentrator was fabricated by laminating an EVA layer with the same mixed dyes between two pieces of ultrawhite glass[13]. Absorption spectra were measured at room temperature with a Shimadzu DUV-3700 UV–visible spectrophotometer. Luminescent spectrum measurements were carried out on a Jobin Yvon LUOROLOG-3-TAU spectrometer with excitation wavelengths of 440 and 500 nm for Yellow 083 and Red 305, respectively. Refractive index of the fluorescent solution was measured using an Abbe refractometer (WAY-2S) operated at room temperature. I-V curves of the fabricated LSCs were recorded by Keithley 2400 Source Meter under AM 1.5 illumination using a Solar Simulator (Oriel Sol 3A). The control experiment was performed from two parts: the efficiency of the blank device filled with pure cyclohexane and the efficiency that comes from stray light.

The Yellow 083 and Red 305 dyes, especially the latter, are widely used in LSCs because the emission of Red 305 ranges from 580 to 800 nm and matches well with the absorption of silicon solar cell[17,18]. Their fluorescent quantum yields are approximately 98% (Red 305) and 91% (Yellow 083)[6]. Figure 2 shows the absorption and emission spectra of Red 305 and Yellow 083. It can be seen that the effective absorption region of Red 305 (from 400 to 600 nm) covers the low absorption range of Yellow 083. Therefore, the mixing of Red 305 and Yellow 083 can enhance the absorption capacity of fluorescent solution within the visible part of the solar spectrum efficiently[19].

The photograph of the blank device without the fluorescent solution is shown in Fig. 3(a). It can be seen that the blank device exhibits a high transparency not only in the center of the flat glass but also at the edge. The syringing process of the fluorescent solution is shown in Fig. 3(b). Using a syringe, the fluorescent solution can be easily injected into the space between the two pieces of flat glass within a short time. This quick and facile process is easy to operate and prevents the dusts from entering the gap. Furthermore, the fluorescent solution can fill the entire gap between the two pieces of flat glass and thus exhaust the bubbles completely, which ensures a high transmission efficiency of optical waveguide. Figure 3(c) shows the as-prepared aqueous layer LSC before the four solar cells were attached. The scenery behind the device is barely visible, which is attributed to the effective absorption of the aqueous layer in the visible region. Compared with the traditional LSC fabricated by incorporating fluorescent dyes into transparent matrix or depositing thin films on transparent medium, the prepared aqueous layer LSC can protect the fluorescent layer effectively with the sandwich structure while keeping a high transmission efficiency of optical waveguide.

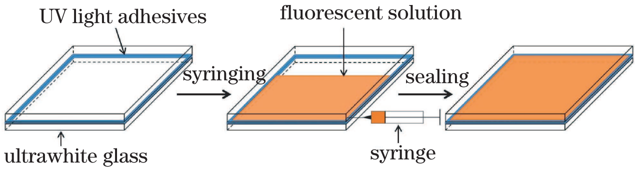

Fig. 1. Schematic of fabricating process of the aqueous layer LSC device.

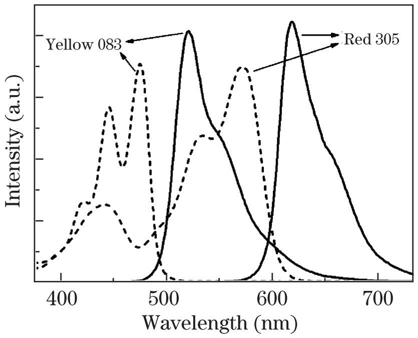

Fig. 2. Absorption and emission spectra of the fluorescent dyes Red 305 and Yellow 083.

I-V curves of the fabricated LSCs measured under AM 1.5 illumination are shown in Fig. 4. It can be seen that the prepared aqueous layer LSC has a PCE of 3.9%, about 30% higher than that of the traditional laminated glass LSC. The high efficiency of the aqueous layer LSC can be attributed to its low optical transmission loss because the defects such as dusts or bubbles are exhausted almost completely[20,21]. Up to now, the highest experimental LSC efficiency for c-Si PVs was reported to be 4.2% by Desmet *et al.*[12] on a 50×50 (mm) stacked dual waveguide with a geometric gain (the ratio of the total waveguide surface area to the total PV cell surface area) of 2.5. In our work, the prepared aqueous layer LSC exhibits a PCE close to the reported device and has a relatively large size of 78×78 (mm) with a geometric gain of 2.8.

In previous study, our group developed a simulation software to calculate the PCE limit of the LSC with different sizes of the optical waveguide, solar cells, and numbers of layer[16]. According to the simulation results, the PCE of LSCs depends on many factors, such as the light collection efficiency of waveguide, transmission efficiency of light in the waveguide, optical properties of

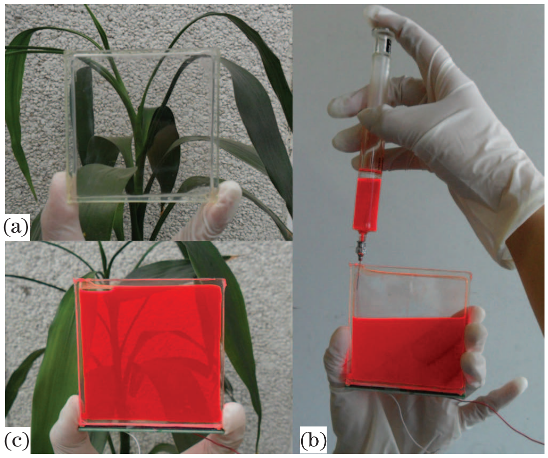

Fig. 3. Photographs of (a) the blank device, (b) the syringing process of fluorescent solution, (c) and the as-prepared aqueous layer LSC before the remaining three solar cells were attached.

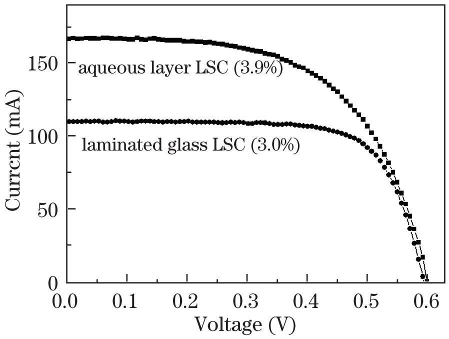

Fig. 4. I-V curves of the fabricated LSCs measured under AM 1.5 illumination.

the luminescent material, voltage coefficient, and the fill factor of the solar cell. Among these factors, transmission loss is a critical factor limiting the scale-up of LSCs because it could lead to consecutive leakage and exponential decay of the guided light over the long pathway of waveguide. Using the software, we calculated the theoretical efficiency of the aqueous layer LSC and the laminated glass LSC. The theoretical efficiency of a LSC can be expressed as

$$\eta = \eta_{\mathrm{L}} \cdot \eta_{\mathrm{C}} \cdot \eta_{\mathrm{S}}, \tag{1}$$

where η is the PCE of the LSC, η_{L}, η_{C}, and η_{S} are the luminescent efficiency, the transmission efficiency of the waveguide, and the efficiency of solar cell, respectively. With an explicit description, the equation can be expressed as

$$\eta = N \cdot \eta_{\mathrm{f}} \cdot n_{\mathrm{t}} \cdot \eta_{\mathrm{t}} \cdot \eta_{\mathrm{PE}} \cdot E_{\mathrm{g}} \cdot V \cdot F \cdot e/Q, \tag{2}$$

where N is the absorbed photon number of the luminescent material, η_{f} is the quantum efficiency of the luminescent material, n_{t} is the light collection efficiency of the waveguide, and η_{t} is the transmission efficiency of light in the waveguide. η_{PE}, E_{g}, V, and F are the quantum efficiency, energy gap, voltage coefficient, and the fill factor of the solar cell, respectively. Q is the optical power of the light source. The parameters of η_{f}, η_{PE}, E_{g}, V, and F were obtained through the experimental measurement and the results were listed in Table 1. The collection efficiency of waveguide n_{t} is calculated by the equation

$$n_{\mathrm{t}} = 1 - 2\frac{2\pi \cdot (1-\cos\theta_0)}{4\pi} = \cos\theta_0 = \sqrt{1-\frac{1}{n_1^2}}, \tag{3}$$

where θ_0 is the critical angle of total reflection and n_1 the refractive index of the matrix. For the fluorescent solution and EVA, their refractive indices are 1.43 and 1.50, respectively, the corresponding n_{t} are thus calculated to be 0.72 and 0.75, respectively. The absorbed photon number N was integrated to be 7.95×10^{20} from the absorption spectrum of the dyes and solar spectrum. For the aqueous layer LSC and laminated glass LSC, the transmission efficiency η_{t} was computed to be 0.945 and 0.936, respectively, from the size of optical waveguide, refractive indices, and absorption coefficient of glass and matrix. The final calculation results are shown in Table 1. It can be seen that the calculated efficiency limit of the aqueous layer LSC and laminated glass LSC are 3.42% and 4.20%, respectively. In comparison, after subtracting the efficiency of a control device, the PCE of the aqueous layer LSC (3.4%) almost reaches the calculation limit (3.42%), while that of the laminated glass LSC is much lower than the calculation limit. The results demonstrate that the fabricated aqueous layer LSC has a very low optical transmission loss which makes it possible to develop a large sized, high efficient LSC. Furthermore, the preparation method is simple and the fluorescent solution in the interlayer is easy to be replaced and the transparency of the LSC can be easily adjusted. The sandwich-structured aqueous layer LSC has a potential application in BIPV.

In conclusion, a sandwiched aqueous layer LSC with a size of 78×78×7 (mm) is fabricated by a simple preparation method. Compared with the same sized laminated glass LSC, the aqueous layer LSC has a higher PCE, almost reaching the calculation limit of aqueous layer LSC. The reason is attributed to the very low optical transmission loss of the fabricated aqueous layer LSC. With

Table 1. Calculation and Experimental Results of the Aqueous Layer LSC and Laminated Glass LSC

	Aqueous Layer LSC	Laminated Glass LSC
N	7.95×10^{20}	7.95×10^{20}
n_{t}	0.72	0.75
η_{t}	0.945	0.936
η_{f}	0.98	0.98
η_{PE}	1	1
E_{g} (V)	1.12	1.12
V	0.536	0.536
F	0.60	0.72
η (Theoretical)	3.42 %	4.20 %
η^a (Experimental)	3.9 %	3.0 %
η^b (Control Experiment)	0.5 %	–

[a]Efficiency of the aqueous layer LSC; [b]Efficiency measured in the control experiment.

further modification, it is possible to develop a large sized and high efficient LSC device, which has a potential application in BIPV.

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