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RAPID COMMUNICATION

Flexible luminescent waveguiding photovoltaics exhibiting strong scattering effects from the dye aggregation

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Abstract
Luminescent solar concentrators have received renewed interest because they can harvest solar radiation without the need for expensive tacking systems. In this work, highly efficient luminescent waveguiding photovoltaic devices exhibiting mechanical flexibility and solar concentration ability have been prepared by integrating Si solar cells with soft polydimethylsiloxane (PDMS) waveguides. We observed that segregated dyes in the PDMS waveguides induce strong scattering effects in the long-wavelength range. The scattered photons were transported effectively to the solar cells, leading to high power conversion efficiencies (*PCE*s). A single module exhibited a remarkable power conversion efficiency of 4.62±0.02%. After stacking two waveguides, we achieved *PCE*s as high as 5.23±0.01%, with a projected *PCE* approaching 12%.
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Introduction

Photovoltaic (PV) technology is a promising approach toward supplying renewable energy and overcoming any potential worldwide energy crises. Wide acceptance of solar energy, however, has not occurred because of their high cost originated from the materials, the fabrication processes, and other soft expenses (installation, racking, permitting, etc.) [1]. One beneficial approach toward decreasing PV costs is to use solar concentrator systems to harvest more solar radiation over the limited area of a solar cell. Among the various types of PV concentrators, luminescent solar concentrators (LSCs) [2-8] have received renewed interest because they can harvest solar radiation without the need for expensive tacking systems. Typical LSCs feature a planar waveguide in which dye molecules

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are dispersed to enhance the light absorption ability. After the thin plate receives direct and/or diffuse sunlight, the dyes converted the photonic energy to red-shifted photons; the emission is guided toward the solar cells attached to the sidewalls of the waveguide. As a result, sunlight is concentrated effectively in such a device configuration because the top surface area of the waveguide is usually much larger than that of the solar cells [2,7]. Weber and Lambe introduced the concept of LSCs in 1976 [2]; currently, the record efficiency has reached 7.1% for a device featuring four highly efficient GaAs solar cells attached to the edges of the concentrators [4].

The efficiencies of LSCs remain limited by several factors, including the limited absorption range, reabsorption of the luminophores, surface losses, and energy dissipation as heat during the red-shifting process [7,9–14]. Many approaches have been reported to overcome these obstacles and improve the efficiencies. For example, stacking dual waveguides containing different dyes has been suggested as a means to harvest broad band solar irradiation [15]. Patterning of the dye layer is also an effective method for minimizing reabsorption losses and increasing emission efficiencies [16,17]. Furthermore, selection and/or design of appropriate dyes is an important aspect of optimizing the performance of LSCs; for example, the harnessing of near-infrared (NIR) luminophores can aid the absorption of the NIR portion of the solar spectrum [18,19]. More recently, nanocluster phosphors exhibiting massive Stokes shifts have been adopted to harvest ultraviolet light selectively and decrease reabsorption losses simultaneously [20]. Moreover, the principle of aggregation-induced emission has been also used to design new fluorophores; their quantum efficiencies remain high in the solid state, thereby overcoming the problem of concentration quenching, regardless of whether the luminophores are dispersed in the polymer matrix or deposited as thin films [21]. Accordingly, it appears that further explorations of the fundamental properties of luminescent molecules will have great impact on our ability to prepare higher-efficiency LSCs.

It is generally agreed that LSCs should complement Si cells, rather than become a competitive technology [22]. They have capability to be used in areas that obtain mostly diffuse light, where the efficiency of Si panels would drop significantly. Furthermore, the greater flexibility of LSCs, in terms of both color and shape, would potentially improve the esthetic appeal of solar cells, meaning that they could be positioned directly in a wider array of public areas. Nevertheless, the rigid substrates [e.g., poly(methyl methacrylate) (PMMA), high-density glass] adopted as waveguide components in conventional LSCs might complicate their fabrication and limit their applicable potentials. Previously, we reported high-performance flexible waveguiding photovoltaics (FWPVs) [23] that display outstanding flexibility because they use soft polydimethylsiloxane (PDMS) as the waveguide [24–26]. The flexible module, which is equipped with a flexible bottom scattering reflector (BSR), can effectively concentrate diffuse light and direct the energy toward the cells. Moreover, other optical microstructures (e.g., microlenses) can be integrated readily into the waveguides to enhance their performance. In this present study, we incorporated organic dyes into a PDMS light guide to develop flexible luminescent waveguiding photovoltaics (FLWPVs, Figure 1). We have observed that segregated dyes in the PDMS waveguides induce strong scattering effects in the long-wavelength range. Surprisingly, the scattered photons are also transported effectively to the solar cells, leading to high power conversion efficiencies (*PCE*s). An FLWPV featuring a BSR delivered a *PCE* of $4.62 \pm 0.02\%$. After stacking two waveguides, we achieved *PCE*s as high as $5.23 \pm 0.01\%$, with a projected *PCE* approaching 12%. To the best of our knowledge, this efficiency is the highest ever reported for an LSC incorporating monocrystalline Si (m-Si) as its solar cells. We anticipate that this new scattering scheme might pave the way toward LSCs exhibiting even better performance.

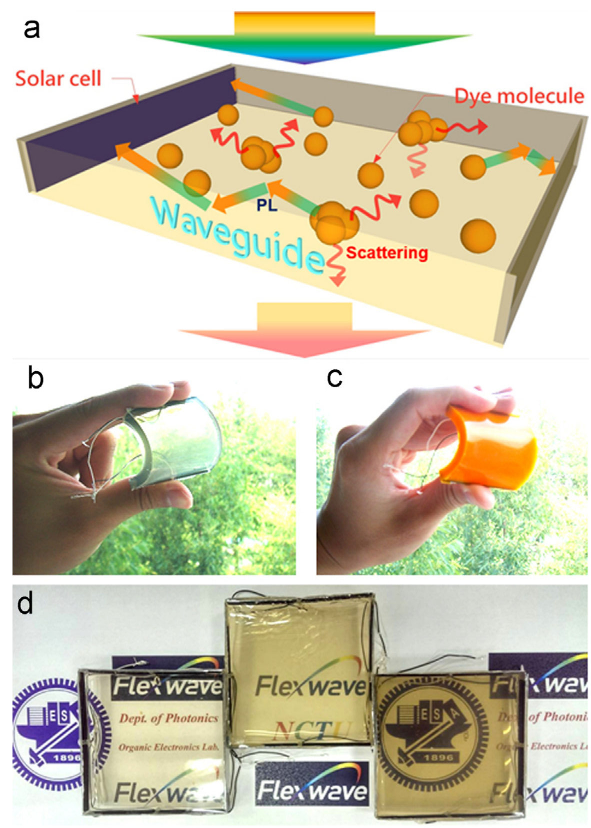

Figure 1 (a) Schematic representation of a FLWPV. The incident photons were absorbed and re-emitted, at a Stokes-shifted wavelength, by the dye molecules; the luminescence and scattering were guided to the solar cells through total internal reflection in the waveguide. Scattering also occurred as a result of dye aggregation. (b) and (c) Photographs of FLWPV-2 modules doped with (b) C440 and (c) DSF. For the transparent module in (b), a high transparency could be obtained while retaining a *PCE* of approximately 1%. (d) Photograph of C440-doped transparent modules of various transparencies; from left to right, the concentrations of C440 were 87.12, 174.24, and 348.48 mg/L, respectively.

Material and methods

Figure 1a provides a schematic representation of the FLWPV module investigated in this study. We prepared the modules according to the integral molding method that we described previously [23]. The dimensions of the waveguide were fixed at 5.0 cm × 5.0 cm × 0.5 cm; we attached either two or four m-Si cells to the PDMS waveguide. For simplification, we name the modules incorporating four and two solar cells at the sidewalls

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