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Increasing the area of a white scattering background can increase the power output of a luminescent solar concentrator

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ABSTRACT

Luminescent solar concentrators (LSCs) have the potential of converting solar energy into electricity more cheaply than a standard photovoltaic (PV) panel. LSCs are thin plates of plastic or glass that contain fluorescent material throughout the plate or in a thin film adhered to the surface. The fluorescent material absorbs sunlight and its fluorescence is concentrated onto PV cells along the edges of an LSC using total internal reflection. Some light is able to pass through the LSC and does not reach the PV cells. A white diffusive scattering surface, or white background, is able to scatter this light back into the LSC for another chance of reaching the PV cells. The results of our experimental and theoretical research reveal that using white backgrounds larger than the area of the LSC can further increase its power output. Larger backgrounds produce more power, but with diminishing returns. An optimal air gap between the LSC and a larger white background is required to achieve maximum benefit. The size of this optimal air gap increases as the area of the white background increases. The predictions of our theoretical model agree with our experimental results for the relative performance of these larger white backgrounds with respect to their size and separation from the LSC. Our experimental results show an optimal air gap of 10.7 cm separating an LSC from a white background with an area 16 times larger than the LSC. In this configuration, the LSC produced 28% more power than the maximum power output of the LSC using a white background of the same area, and 54% more power than the LSC with no white background present.

1. Introduction

Luminescent solar concentrators (LSCs) absorb sunlight and convert it into fluorescence. An LSC acts as a waveguide, causing most of the fluorescence to be trapped by total internal reflection until it reaches the edges where it is absorbed by photovoltaic (PV) cells and converted into electricity. They are inexpensive, omni-directional concentrators typically made of thin plates of plastic or glass containing fluorescent material. Though they are not as efficient in converting sunlight into electricity as PV cells alone, their low cost compared to PV cells make them attractive as a concentrator for potentially lowering the cost per kW/hr of solar power (Assadi et al., 2016; Debije and Verbunt, 2012; Shanks et al., 2016).

Not all of the sunlight that is incident on an LSC ends up as photons concentrated onto the PV cells. The absorption spectra of fluorescent materials is strongly wavelength dependent and may be limited to a small part of the UV/visible/NIR spectrum. This limited absorption bandwidth hinders the amount of sunlight converted into electricity. The limited absorption bandwidth is actually an advantage in some applications, such as when LSCs are used in greenhouses (Corrado et al., 2016) or windows (Zhao et al., 2014). Increasing the optical density of an LSC increases its power output to an extent. Unfortunately, there is typically some overlap in the absorption and fluorescence spectra causing re-absorption losses that create a practical limit for an LSC's maximum concentrating ability (Debije and Verbunt, 2012; Wilson et al., 2010). Depending on the optical density of the material, some of the light passes through an LSC by either transmission of unabsorbed sunlight or through escape-cone losses of the fluorescence (Assadi et al., 2016; Debije and Verbunt, 2012; Hermann, 1982; Wilson et al., 2010).

An inexpensive reflective material underneath the LSC helps by sending this light back through the LSC for a second chance of absorption (Lifante et al., 1983; Roncali and Garnier, 1984). Typically, a diffusive scatterer works better than a mirror (Debije et al., 2009). Sunlight hitting an LSC at a small incident angle travels a short pathlength through the LSC making it less likely to be absorbed. On average, a diffusive scattering surface sends this transmitted light back into the LSC at larger incident angles, resulting in more internal reflection and longer pathlengths. This increases the light's chances of being absorbed

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more than if specular reflection off a mirrored background occurred. Except for small LSCs, a highly reflective, diffuse scattering surface separated from the bottom of an LSC by an air gap is better than making optical contact between the scattering material and the LSC (Debije et al., 2009). In the latter case, the scattering material can scatter the fluorescence trapped in the plate into angles that allow some of it to refract out of the plate.

Recent studies restricted their research to diffusive scattering surfaces, or white backgrounds, with the same area as the LSC. The backgrounds either were in direct contact with the LSC or spaced away from it by only a small air gap. Different small area elements around the white background were found to contribute different amounts to increasing the LSC's current (Debije et al., 2009). The enhancement ratio for current generated by an LSC with a white background versus the size of the LSC initially dropped as the LSC's area increased and then remained nearly constant (Wang et al., 2010). In this work, we explore the potential of a new, unique role for the white background by expanding it beyond its conventional configuration. We examine the benefits of using white backgrounds that are larger in area than the LSC, thereby partially capturing sunlight from a larger region. Experimental measurements and a computational model show how increasing the area of the diffusive white background and varying the air gap can dramatically increase the LSC's power output using inexpensive materials.

2. Experimental methods

The LSC used in these experiments was a 12.5 × 12.5 × 0.68 cm poly(methyl methacrylate) plate (index of refraction = 1.48) (Fig. 1) infused with the fluorophore Lumogen F Red 300 (BASF). The plate has an optical density of 2.76 at its absorption peak of 577 nm (Hyldahl et al., 2009). After cutting the plate, the edges were polished. PV cells (SolarMade) were cut and attached to all four edges using a clear optical adhesive (Norland 68T) such that they did not extend above or below the LSC's edges. The PV cells were electrically connected in parallel.

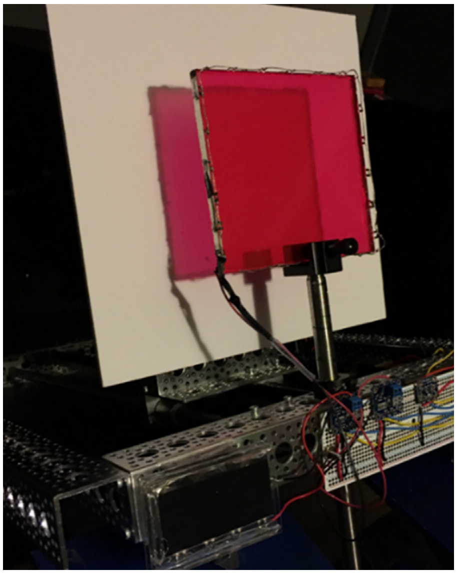

Fig. 1. Apparatus for varying the distance between the luminescent solar concentrator (LSC) and a white background. The LSC is held in a fixed position at normal incidence to the sun while the air gap is varied by mounting the white background to the linear translational stage. The white background shown is four times (4×) the area of the LSC and has regions that are shaded (red region, same size as 1× area) and unshaded (outer white frame) by the LSC. Current from a reference PV cell (bottom center) is used to correct for small variations in the sun's irradiance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Eight square white background plates of different areas were cut out of 5-mm thick foam poster board that had a white paper surface. The surface's reflectivity at 633 nm was 83% when compared to measurements from a plate of Spectralon (Labsphere) with a known reflectivity of 99% at 633 nm. The white paper surface acted as a Lambertian reflector when measured with a calibrated radiometer (International Light Technologies) over incident angles from 10° to 80°. The sides of the backgrounds had lengths of 12.5 cm (1× LSC area), 14.4 cm (1.33× LSC area), 16.1 cm (1.66× LSC area), 17.7 cm (2× LSC area), 21.7 cm (3× LSC area), 25.0 cm (4× LSC area), 35.4 cm (8× LSC area), and 50.0 cm (16× LSC area). The LSC was also tested with no white background such that light scattered off the distant environment could enter through the bottom of the LSC.

A programmable, microcontroller-based linear translational stage was designed and built in-house to hold the LSC and the white background being tested (Fig. 1). It varied the distance between the back surface of the LSC and the front surface of the white background, referred to as the air gap, from 0.7 to 19.0 cm. While the air gap was changed, the short circuit currents from the LSC and from the 6.7 × 3.2 cm reference PV cell mounted on the apparatus were measured simultaneously every ~3 ms for ~42 s. Approximately 14,000 data points per measurement were recorded, or one data point every ~13 µm. For each white background area, at least three consecutive measurements of the LSC's power output versus air gap were recorded and averaged to generate a final data curve (Fig. 2). The mean absolute deviation (MAD) averaged over an entire curve was 0.8 mW or less for all the curves. The measurements were done on a clear day between about 12:00 pm and 1:00 pm. The irradiance of sunlight was a stable (81 ± 2) mW/cm^2 as measured using a calibrated radiometer (International Light Technologies). The current measured from the reference cell was used to correct the data for variations (~2%) in the sun's intensity. Using a digital multimeter, the open circuit voltage of the LSC was measured at (0.50 ± 0.01) V across the full range of current values for all measurements. This agrees with the manufacturer's specification for the PV cells. The LSC's power output was calculated by multiplying the short circuit current by 0.50 V.

During each measurement, the white background was secured to the translational stage such that its surface was parallel and centered with respect to the surface of the LSC. The apparatus was then adjusted to set the LSC, white background, and reference cell surfaces at normal incidence to the sunlight. As the white background moved away from the LSC, the position of the LSC's shadow on the white background remained fixed, keeping a constant "shaded region" on the white background that is the same area as the LSC. The apparatus was designed to minimize the shadow created by the structure holding the LSC plate (Fig. 1). The C-Clamp holding the LSC caused the minimum air gap to be 0.7 cm rather than 0 cm. This was preferred over edge mounting of the LSC, which would have created a larger shadow on the white backgrounds.

3. Experimental results

3.1. Total white background

Experimental data showing how the LSC's power output changes with the size of the air gap using eight different white backgrounds are shown in Fig. 2. The LSC's power output using no white background is nearly constant with an average value of 406.7 mW and an average MAD of 0.3 mW over the time of the measurements. When any white background is placed behind the LSC with the smallest air gap (0.7 cm), the LSC's power output significantly increases compared to no white background being present. Using the 1× LSC area white background, the LSC's power output increases 16.2% from 406.7 mW to 473 mW. Increasing the white background's area to 1.33×, 1.66×, and 2× further increases the LSC's power output to 495, 505, and 508 mW, respectively. Any additional increase in the white background's area does not yield any more power with an air gap of 0.7 cm.