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Highly efficient luminescent solar concentrators employing commercially available luminescent phosphors

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ABSTRACT

Luminescent solar concentrators (LSC) have great potential for providing solar energy at a competitive cost. They are simple devices employing a luminescent material embedded in a transparent sheet with solar cells attached on the edges. The luminescent material absorbs short wavelength solar radiation and emits red-shifted light. The emission is then guided towards the sheet edges, where the concentrated light is absorbed by the solar cell to produce electricity. The commercialization of luminescent solar concentrators has been stunted by an ongoing search for an adequate luminescent species that, among other things, is UV stable and inexpensive. While luminescent phosphors exhibit these characteristics, as well as other desirable qualities, their use in LSCs has received limited attention because they are highly scattering. Here, we demonstrate that luminescent solar concentrators can effectively employ scattering luminescent phosphors in the form of films. Monte Carlo simulations are used to investigate the optimum film location (top or bottom of the LSC) and concentration of phosphor within the film. The results show that when a film with a high phosphor concentration is placed at the bottom of the LSC, escape cone losses are lower than when the film is placed at the top, which increases light concentration within LSC. Four LSCs fabricated with commercially available materials, including the luminescent phosphor, are tested at varying incident angles using a full spectrum solar simulator. Moderate flux gains are achieved with efficiencies ranging from ~1.6 to 8.6%, depending on the angle of incidence and aspect ratio (AR). These results demonstrate the potential of luminescent phosphors for LSC applications.

1. Introduction

Luminescent solar concentrators (LSC) are a promising alternative to expensive solar technologies such as focusing optics, heliostats, and traditional solar panels [1–7]. LSCs passively collect sunlight from large surface areas and concentrate it onto small strips of photovoltaics (PV) via waveguiding. Internal reflection is enhanced through the addition of a luminescent species, which improves the probability that light will remain within the LSC, even for angles less than the critical angle for total internal reflection (TIR). By concentrating sunlight, and red-shifting the solar spectrum via luminescence, more power can be generated per square meter of solar cell and with enhanced conversion efficiencies [8]. In this way, LSCs can provide inexpensive solar power. This is possible for both direct and diffuse light, without the need for solar tracking. Additionally, if the LSC waveguide shows strong absorption of ultraviolet light (UV), solar cell degradation can be reduced through limited UV exposure.

Although knowledge of luminescence dates back to the tenth century Asia, there is abundant modern day research in this area owing to its role in biomedical imaging, lamps, displays, light emitting diodes (LED), and LSCs [9,10]. The ideal luminescent species for LSC applications should exhibit a number of properties, including: absorption of wavelengths where the solar cell response is poor; emission at wavelengths where the solar cell response is optimal; no overlap between the absorption and emission bands; a quantum efficiency (QE) of 100%; quenching not sensitive to temperature or species concentration; compatibility with polymers for easy dispersion; inexpensive fabrication; UV stability with a lifetime comparable to a solar panel; and being environmentally friendly and non-toxic [5,6,11–13].

Currently, two predominant types of luminescent species are employed in LSCs, namely luminescent dyes and quantum dots (QD). In general, luminescent dyes suffer from self-absorption losses and/or have narrow absorption bandwidths, but are relatively inexpensive and widely available [6,14]. Conversely, broadband absorption, tunable through material choice and size distribution, has been demonstrated with QDs, but they are expensive and far less common [15]. Lastly, both dyes and QDs have poor UV stability. Consequently, they are ill-suited for outdoor use and this has stood as a significant barrier to the

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commercialization of LSCs.

An alternative to both luminescent dyes and QDs are the luminescent phosphors. Luminescent phosphors satisfy many of the desired properties including tunable absorption and emission spectra, minimal self-overlap, high QE, excellent chemical compatibility, low cost and excellent UV stability, all achieved with innocuous materials [15]. Nonetheless, effectively utilizing phosphors in LSCs is challenging because they are highly scattering, which can increase both non-emissive absorption and escape cone losses (light refracted out of the top surface of the LSC). For this reason, there have been very few investigations into the performance of LCS utilizing phosphors. In previous literature reports, phosphors were incorporated through homogenous dispersion [16] within the entire LSC, or used in films [13,17] applied to a clear sheet. Films of various phosphor concentration (C_p) have been placed at both the top [17] and bottom [13] of the LSC, but the optimum film location, and concentration of phosphor within the film, remains unclear.

The objective of this paper is to investigate the use of LSCs employing luminescent phosphor films. First, Monte Carlo simulations are used to better understand which location of the phosphor film within the LSC is favorable: the top or bottom of the LSC. This insight is then used to guide the fabrication of LSCs employing a phosphor film. Fabricated devices are tested using a full spectrum solar simulator equipped with a xenon lamp. To illustrate the potential for future commercialization of LSCs employing luminescent phosphors, we utilize a widely available LED phosphor, embedded in a highly transparent, UV stable, commercially available silicone matrix.

2. Monte Carlo simulations of LSCs employing phosphor films

Monte Carlo simulations have proven to be a useful and accurate tool for analyzing the performance of LSCs. Traditionally, absorption by discretely absorbing luminescent species such as quantum dots (QD) or luminescent phosphors dispersed in a matrix is addressed with effective absorption and scattering coefficients, or Mie theory [13,18–21]. However, effective properties ignore the discrete nature of the interaction of light with individual phosphor particles, while Mie theory requires knowledge of properties often not readily available for the phosphors particles including, but not limited to, the index of refraction and absorption coefficient as function of wavelength. To address these limitations, in our previous work we developed a method combining Monte Carlo simulations and simple experiments to simplify the characterization of radiation transport in media with scattering luminescent phosphors [22]. A more in-depth discussion of the drawbacks of alternative methods, as well as an extensive investigation of the method can be found in Ref. [22]. In summary, this approach was developed for phosphor particles dispersed in an absorbing host matrix, and is applicable when the spacing between particles, and average particle size, is much larger than the wavelengths of light. The description of the interaction of light with particles is simplified using a particle extinction coefficient (Γ) to determine when light reaches a particle, which is a function of the phosphor concentration. Once at a particle, the probability of absorption, P_A, then determines if light is absorbed or scattered.

Our previous work has shown that this method provides the ability to accurately simulate radiation transport in a medium containing luminescent phosphor particles and significantly reduces the number of parameters required for simulation. Here, we utilize this method to simulate LSCs employing a phosphor film, as shown in Fig. 1. As previously discussed, phosphor films have been employed as an alternative to QD or luminescent dyes [13,17]; however, the optimal location, top or bottom of the LSC, has not been investigated. To elucidate which is the favorable option, Monte Carlo simulations were carried out for three LSCs of varying aspect ratio *($AR = L/H$)* with 1 mm thick phosphor films of varying Γ's.

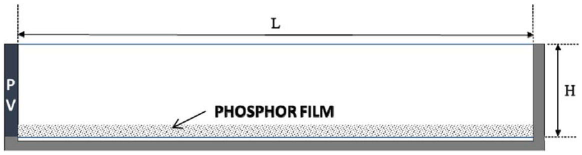

Fig. 1. Diagram of an LSC employing a phosphor film modeled using Monte Carlo simulations. Solar cells cover one edge and the remaining edges are specular reflectors with 95% efficiency. L is LSC length, and H is LSC height. In the simulations, the film was placed at the top (not shown) or bottom of the LSC, as shown in this figure. The LSC height and film thickness were held constant at 5 and 1 mm, respectively; a gap of 100 µm was considered between the phosphor film and the bottom reflector.

The chosen dimensions of the LSC and phosphor film are influenced by three main factors: aspect ratio, matrix material, and fabrication. LSCs of the same aspect ratio ($AR = L/H$) will have similar performance. However, for a given length, the greater the height of the LSC (H in Fig. 1), the larger the solar cells required at the edge. Thus, keeping the LSC height minimized reduces the associated cost of solar cells. Second, the assumed matrix material used here (silicone) has non-negligible absorption of visible light. Thus, smaller lengths and heights decrease the average pathlength of light within the LSC, reducing losses due to absorption by the matrix. This is also true for the phosphor film, which is assumed to be fabricated with the same matrix material. Thus, less light will be lost to the film when it is thinner. Lastly, the fabrication of the LSC and phosphor film place practical limits on their size. The chosen LSC height matches that of available small-scale solar cells. For the thickness of the film, the thinner the film, the greater the phosphor concentration required to achieve a desired Γ and the more difficult it becomes to ensure an even desired film thickness and resistance to tearing. Additionally, the goal is to use simple fabrication techniques to prepare the films to minimize the complexity and cost of fabricating each LSC. Prior laboratory experience showed that films on the order of 1 mm provide a good balance between all of the associated factors.

For these reasons, within the Monte Carlo simulations, the phosphor film was given a height of 1 mm, while the LSC height was held constant at 7 mm. As previously mentioned, this matches the height of the commercially available small-scale photovoltaics used in the fabrication and testing of LSCs discussed in Sections 3 and 4. This thickness of the phosphor film is consistent with the thickness of the phosphor films used there. At one edge of the LSC, a solar cell with optical and conversion properties corresponding to those of a monocrystalline silicon (c-Si) was considered. All additional edges, except where the solar cells were considered to be positioned, were assumed covered with specularly reflecting mirrors with 95% efficiency. The imperfect contact between the bottom reflector and the LSC was modeled as a sub-millimeter gap (100 µm), and through additional simulations, was found to be beneficial because it reduces losses associated with imperfect mirror reflection. The spectral absorption coefficient and index of refraction of Sylgard 184, a UV stable silicone polymer, was used to predict absorption by the matrix. Absorption by the solar cell was accounted for using the external quantum efficiency (EQE) of a c-Si solar cell. All reflections from the solar cell's surface were considered diffuse as a consequence of solar cell surface texturing. Direct-normal insolation of light entering the LSC was used and was assumed to have the spectral distribution of a full-spectrum xenon lamp traditionally used in solar cell characterization which was used in the experimental testing of devices discussed in Section 4. Exhaustive details of these input parameters, as well as additional parameters used to produce the simulation results presented in this paper, are provided as Supplemental information.

A green phosphor, available from Phosphortech.com, was chosen as the luminescent phosphor. This phosphor was chosen because it is readily available, comprised of innocuous materials, has a characterized quantum efficiency (QE), and is the least expensive option available from Phosphortech with a QE above 70%. Fig. 2 shows the