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Losses in luminescent solar concentrators unveiled

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ABSTRACT

A novel experimental method is presented to determine the optical efficiency and the loss channels of a luminescent solar concentrator (LSC). Despite strong promise, LSCs have not yet reached their full potential due to various mechanisms affecting the device's optical efficiency. Among those loss channels, escape cone and non-unity quantum yield losses are generally the most dominant. To further advance the field of LSCs, it is vital to understand the impact of each independently. So far, researchers have only characterized the total loss in LSCs. Here, an experimental method is proposed to separate the contribution from each individual loss channel. The experimental apparatus is the same as used for quantum yield measurements of fluorophores in solid samples. Therefore, the setup is commonly available to research groups already involved in LSC research. The accuracy of this method is demonstrated by comparing the experimental results with Monte-Carlo ray tracing. Our experimental method can have a strong impact on LSC research as it offers a means to unveil the loss channels of LSCs in addition to the optical efficiency.

1. Introduction

Luminescent solar concentrators (LSCs) offer an encouraging means to include solar energy to the built environment; they concentrate sunlight without the need for expensive tracking equipment and their design makes them suitable as windows. LSCs are composed of a transparent matrix material, generally a slab of poly(methyl methacrylate) (PMMA), which is doped with fluorophores to absorb the incoming sunlight. The absorbed energy is then emitted at a longer wavelength and, given the emission falls outside of the escape cone, trapped through total internal reflection within the slab of PMMA. Light that is guided towards the sides of the slab is converted into electricity by solar cells. The share of photons concentrated towards the sides of the LSC is denoted the optical efficiency of the device.

Though invented in the late 70s [1,2], LSCs still exhibit limited efficiencies mainly due to two loss channels: (1) photons emitted by a fluorophore within the *escape cone* and lost through the front and back surfaces of the LSC, and (2) photons absorbed by a fluorophore and lost due to a *non-unity quantum yield*. Both loss channels are further aggravated by re-absorption which is due to the overlap of the absorption and emission spectra of the fluorophore. Additionally, fluorophores such as organic dye molecules often have a narrow absorption band which results in a large share of the solar spectrum not being absorbed at all. To enhance the efficiency of LSCs, it is crucial to determine which loss channel deteriorates the performance of the LSC. While the wavelength band absorbed by the fluorophore can be determined with absorption measurements, it is less straightforward to experimentally investigate the extent to which escape cone and quantum yield losses degrade the performance of the LSC.

Different methods have been proposed to experimentally measure the optical efficiency of a LSC. The side surface emission of a LSC can be collected via an aperture in an integrating sphere while the illuminated front surface remains outside the integrating sphere [3–7]. If the whole sample is placed within the integrating sphere, one can determine the optical efficiency by selectively blocking the side surface emission using a black tape or marker [8–13]. Side surface emissions can also be measured using a fiber with a cosine corrector as a probe that is held against the respective side surface [14]. However, none of these proposed methods reveal the fate of the lost photons; whether they are lost due to a non-unity quantum yield or escape cone losses. In this work we present, to the best of our knowledge, for the very first time a method to experimentally determine and distinguish these two important loss channels for LSCs. This will allow researchers to better understand the limitations of their designs and to more effectively improve LSC efficiency for building-integrated photovoltaics.

Bragg mirrors or aligned fluorophores are means to enhance the trapping efficiency within a LSC [15–17]. Our method can determine the reduction in escape cone losses achieved by such a

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prototype LSC. It was also proposed to link and align different fluorophores to enhance the trapping efficiency and separate the absorption and emission process [6,17–19]. In addition to quantifying the reduction in escape cone losses, our method is also able to measure the potential change in non-unity quantum yield losses; the linking of fluorophores could deteriorate or even improve the quantum yield of the involved fluorophores. Previous methods are only able to determine the total loss which in some cases remains constant, e.g. when the reduction in escape cone losses and the change in non-unity quantum yield losses cancel each other out.

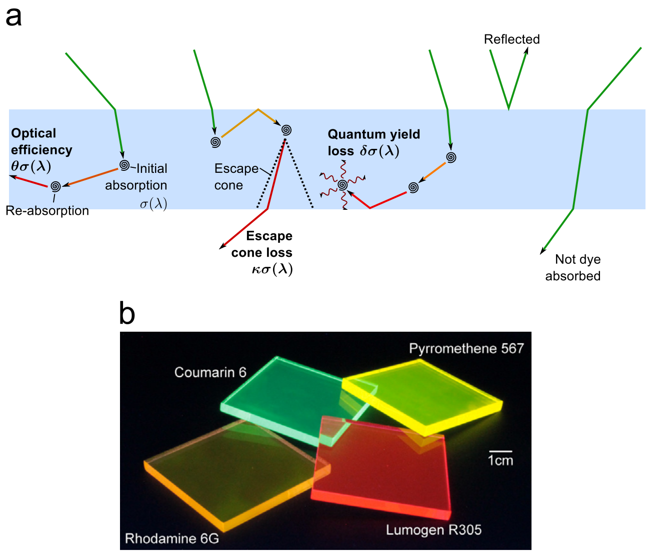

Fig. 1. (a) Fate of photons our experimental model is able to distinguish. After the initial absorption, a photon is either concentrated to a side surface with probability θ, lost via the escape cone with probability κ, or lost due to a non-unity quantum yield with probability δ. To take into account the initial absorption, the three probabilities have to be multiplied with $\sigma(\lambda)$, the probability that an incoming photon is absorbed. (b) LSCs doped with different dye molecules under UV illumination. The LSCs at the front are doped with Rhodamine 6G (left) and Lumogen R305 (right) and at the back with Coumarin 6 (left) and Pyrromethene 567 (right).

The photon paths within a LSC, which our experimental method is able to distinguish between, are shown in Fig. 1(a). An incoming photon is either reflected off the top surface, not dye absorbed, or absorbed by a fluorophore. After the initial absorption, the photon is either concentrated to the side surfaces, lost via the escape cone, or lost due to a non-unity quantum yield. LSCs fabricated for this study are doped with four different dye molecules which are shown in Fig. 1(b). Optical measurements are compared to Monte-Carlo ray tracing simulations which show very good agreement.

2. Theory

In this section, the theoretical background and the experimental setup of our novel experimental method to determine the efficiency and loss channels of a LSC are presented. The experimental method is based on the most common approach to determine the quantum yield of fluorophores incorporated in solid samples such as a slab of PMMA [20]. A monochromatic light source illuminates an integrating sphere that is connected to a spectrometer via a fiber cable. As shown in Fig. 2, five different configurations are necessary of which the first three are the same as used for quantum yield measurements [20].

In the first configuration (I) no LSC sits within the integrating sphere and only the incoming monochromatic light source is measured. For the second configuration (II) the LSC is placed within the integrating sphere and the incoming beam misses the LSC initially; thus only light scattered off the surface of the integrating sphere is absorbed by the LSC. The third configuration (III) is similar to the second one but the incoming beam now directly impinges on the LSC. For the remaining two configurations, (IV) and (V), the side surfaces of the LSC are blackened with a black

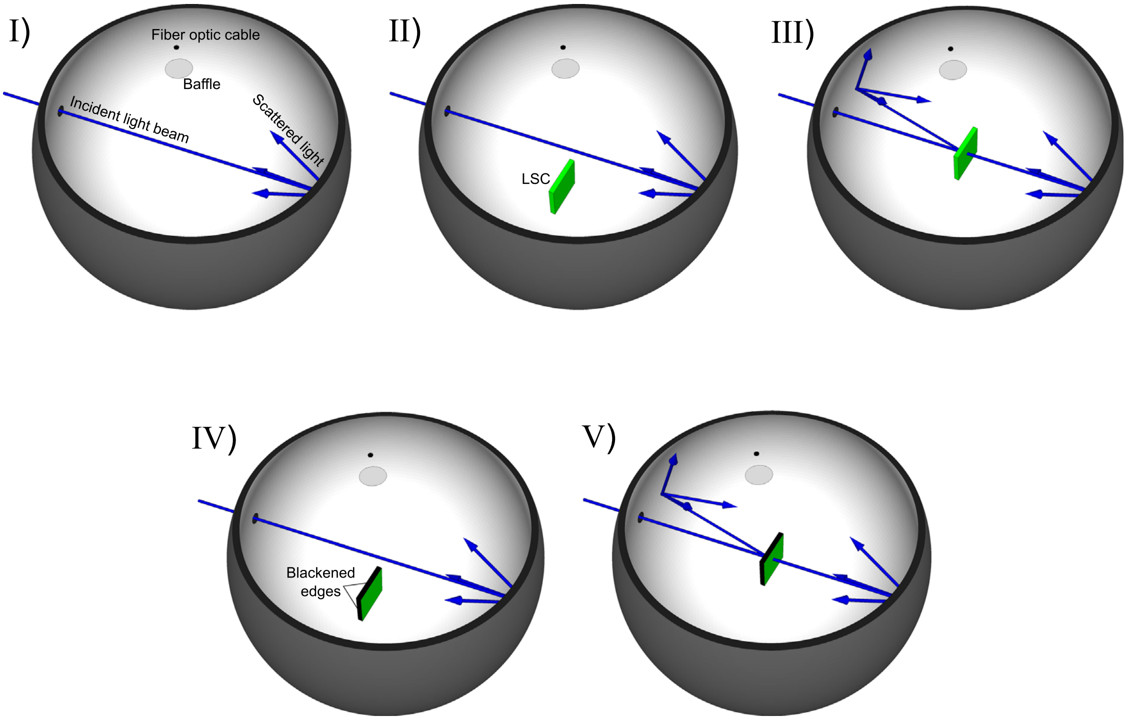

Fig. 2. The five configurations necessary to determine the internal optical efficiency and loss channels of a LSC: (I) the integrating sphere is empty; (II) the LSC is placed inside the sphere but not in the incident beam path; (III) the incident light beam directly impinges on the LSC; (IV) same as configuration (II) but the side surfaces are blackened; (V) same as configuration (III) but the side surfaces are blackened.