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Modelling and experimental analysis of the angular distribution of the emitted light from the edge of luminescent solar concentrators

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ABSTRACT

Luminescent solar concentrators (LSCs) have the potential to provide cheap solar electricity by significantly reducing the solar cell area. However, these devices are still at the research level and several aspects of their behaviour need investigation in order to improve efficiencies. Understanding how light is absorbed/emitted and concentrated to the edge of LSCs is required to design a high efficiency device as well as identifying and overcoming the various losses present. One strategy for investigating the photon absorption and transport in LSCs as well as pinpointing the sources of losses in these devices is to look at the luminescence escaping the LSC as a function of angle. This paper presents a new model that reveals the main features of the angular distribution of light escaping a LSC edge. We compare this model with experimental measurements and provide an assessment of non-ideal losses and identify which emission angles are affected most by these losses. We investigated experimentally the effects of the absorption profile of the chromophores and re-absorption on the photon flux travelling at different angles. The effect of back surface reflectors, commonly used to 'recycle lost photons', on the edge emission of LSCs has also been investigated in this work.

1. Introduction

Luminescent solar concentrators (LSCs) were proposed more than thirty-five years ago [1–3] as a concept that could provide low cost solar electricity. In LSCs a host material such as polymethyl methacrylate (PMMA), or glass is used with luminescent dyes [4–6], inorganic absorbers [7,8] or quantum dots [9–11] either embedded within the bulk material or deposited on the external surface of the substrate as a thin film. The chromophores (organic, inorganic, quantum dot) absorb incident light (direct and diffuse) over a large front surface area and emit at a longer wavelength in the form of luminescence. A large portion of the emitted light is then trapped in the LSC by total internal reflection (TIR) and is guided to the edge of the LSC where attached solar cells can convert the incident light to electricity. The LSC has the ability to concentrate the incident sunlight because of the large area difference between the front face of the LSC and the edge areas and offers advantages over geometric concentrators due to the ability to concentrate diffuse light at much lower fabrication costs.

The first stage of research of this technology started during the late 70's [2,3,12–14]. At the time of writing this paper, the highest published efficiency of LSCs was reported using four GaAs solar cells at the edges of the collector with a 7.1% solar power conversion efficiency [15]. It has been shown [16], however, that LSCs have the potential to reach efficiencies similar to the Shockley–Queisser (S–Q) limit [17], in particular, it has been shown that LSCs coupled to silicon solar cells could achieve a combined theoretical efficiency limit of 26.8% [16]. Despite their potential for generating low-cost solar power and entering the PV market, the principal challenge facing LSCs is associated with overcoming fundamental losses.

This observed disparity between experimental and theoretical efficiencies is due to losses that can be broadly classified in two categories, dye related losses and light transport losses. Dye related losses include a limitation in the absorption bandwidth of individual dyes, non-unity luminescence quantum yields, and stability issues over extended periods of sunlight exposure. Light transport losses are related with the transport of photons to the edge of the LSC and include re-absorption [18], which results from the partial overlap of the absorption and emission bands, and escape cone losses, which are unavoidable in a TIR arrangement. This loss is exacerbated if the luminescence quantum yield is less than unity.

To increase the optical efficiency of LSCs, mirrors and white scattering layers have been applied at the back of the substrate in order to reduce light lost from the bottom of the LSC [19–21].

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When applied with an air gap ensuring TIR is not disrupted and it can increase the absorption length of light.

One technique used to analyze absorption and photon transport in LSCs is to make angular measurements of the luminescence emission escaping the edge of LSCs [22–26]. In [22] the emitted luminescence intensity was measured as a function of detection angle for a LSC consisting of a thin luminescent film deposited on glass. In later works a cylindrical lens coupled to the LSC edge [23–25] was used to 'see' inside uniformly doped LSC polymer plates. Monte Carlo simulations of the photon flux exiting the LSC edge were also presented in these publications. In [26] thin film and bulk doped LSCs were studied. The edges were not coupled to a lens and a simple numerical model that qualitatively explains fringe-like patterns detected for spot illumination was presented.

To our knowledge, the effect of back surface specular mirrors and white scatterers on the angular dependence of the edge emission in LSCs has not been previously investigated. This study is important since these structures have the potential to increase the efficiency of LSC systems without introducing new losses and will certainly need to be incorporated in any commercial LSC systems. Therefore an understanding of their effect on the optical performance of LSCs is vital. We also present a new model that describes the luminescence emission exiting the LSC edge as a function of angle. Angular resolved measurements of bulk doped LSCs are also presented. The theoretical model is shown to reproduce the main characteristics of the angularly resolved measurements and can possibly be used in the future as a tool to identify the exact source of non-ideal losses in LSCs. In addition, an examination of the spectrum emitted at different angles has been carried out in order to experimentally illustrate the effect of re-absorption of rays with different path length within the collector.

2. Theory

In this section we shall develop expressions describing the luminescence emission exiting a LSC edge (the LSC is assumed to not be attached to any device i.e. mirrors, solar cells, etc.).

The first generation (i.e. re-absorption free) luminescence exiting the LSC, $\phi_{out,1}$, is directly proportional to:

$$\phi_{out,1}(\theta) \propto \xi(\theta)\{1 - \Gamma_1(\theta)\}, \tag{1}$$

where θ is the zenith angle of detection, $\xi(\theta)$ is an angular loss factor which quantifies non-ideal losses (i.e. losses other than due to re-absorption or non-unity luminescence quantum yield) and is assumed to depend on the angle of emission (and therefore the path length photons have travelled). Γ_1 is the angular re-absorption probability for light emitted with the first generation luminescence emission spectrum. It represents the probability that light emitted at an angle θ will be re-absorbed.

Assuming the azimuthal angle of emission detected is close to 90°, Γ_1 is given by

$$1 - \Gamma_1(\theta) = \int_{(\lambda_1)}^{(\lambda_2)} \frac{\int_0^L A_1(z) e^{-\frac{\alpha_{em}(\lambda)(L-y)}{\sin\theta}} dy}{\int_0^L A_1(z)\, dy} f_1(\lambda)\, d\lambda, \tag{2}$$

where z is the axis measuring the depth of the LSC, y is the axis along the length of the LSC, A_1 is the emission distribution of the LSC with depth for the first generation luminescence and λ_1 and λ_2 are the lower wavelength limit of absorption and the upper wavelength limit of emission respectively. This is described by the Beer–Lambert law and is defined by the absorption coefficient at the excitation wavelength α_{ex}. α_{em} is the absorption coefficient at the emission wavelength, L is the length of the LSC, f_1 is the first generation luminescence of the dye without re-absorption, normalised to a unit total emission probability, $\int f_1(\lambda)\, d\lambda = 1$ i.e. it is the distribution of the re-absorption free luminescence and λ is the emission wavelength.

For different positions within the LSC along the y axis, the emission that reaches the detector at a particular zenith angle θ (Fig. 1), corresponds to emission originating at a specific depth z.

Consider the LSC to be of thickness d. If only light passing through the centre of the detector facing edge (i.e. $z = d/2$) and only rays travelling in the plane of rotation of the detector (i.e. within a narrow solid angle i.e. ϕ close to $\pi/2$) is detected, the specific depth, z, within the LSC at which the light 'seen' by the detector originates, depends on a distance d_1. For light reaching the detector at zenith angles between 0° and 90° (Fig. 1), d_1 is given by:

$$d_1 = \frac{(L - y)}{\tan\theta} - \frac{d}{2}. \tag{3}$$

For emission from 90° to 180°, d_1 is similarly obtained:

$$d_1 = (L - y)\tan\left(\theta - \frac{\pi}{2}\right) - \frac{d}{2}. \tag{4}$$

Each layer in the stack shown in Fig. 1 represents one instance of total internal reflection. The depth of emission z depends on whether the number of stacks, k, is odd or even. If k is odd then:

$$z = (d_1 + d) - (k - 1)d. \tag{5}$$

If k is even:

$$Z = (d_1 + d) - (d_1 - \{k - 1\}d). \tag{6}$$

The total photon flux escaping a LSC, ϕ_{out}, is a summation over all the different generations of luminescence:

$$\phi_{out}(\theta) = \phi_{out,1}(\theta) + \phi_{out,2}(\theta) + \phi_{out,3}(\theta)\ldots \tag{7}$$

Since Γ_1 depends on A_1 which in turn is different for each generation of luminescence, each term in the infinite series needs to be calculated individually. However, in the case of uniform absorption across the LSC thickness (i.e. $A_1 = 1$), similar to [5,27], it can be shown that in the case of uniform absorption across the LSC thickness, the photon flux reaching the edge is directly proportional to the first generation transmission probability i.e. ϕ_{out} is also given by (1).

3. Materials and methods

Two molded PMMA based LSCs doped with different concentrations of BASF Lumogen F Red 305 dye (supplied by Teknova AS) were characterised. This dye has been developed to have a high luminescence quantum yield, a broad absorption spectrum and a good photo-stability [28,29]. Dye concentrations of 300 mg/l and

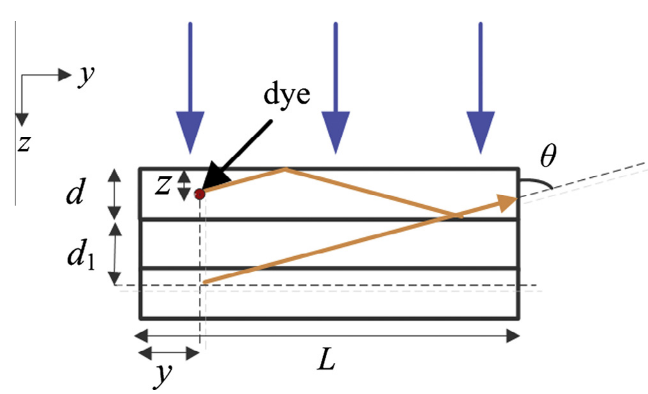

Fig. 1. The top stack is the side view of a LSC. TIR path length is equivalent to straight propagation in a stack of LSCs.