### Modelling the Performance of Fluorescent Solar Collectors

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# 1. Introduction

Fluorescent solar collector (FSC) (also known as fluorescent solar concentrator) bears the promise to reduce the size of solar cells in solar systems and thereby reduce the overall cost [1-3]. A typical FSC consists of a transparent sheet doped with fluorescent dyes. Save for one edge coupled with a solar cell, the remained edges and the bottom surface of this sheet are usually covered with mirrors. Photon flux (including both direct and diffuse radiation) incident onto the front surface of the FSC can be absorbed by the dyes inside the collector. The excited dyes will re-emit photons at higher wavelength with a lower energy. The photons trapped in the collector can be finally collected by the solar cell mounted at the edge by total internal reflection.

Although the theoretical energy conversion efficiency of a silicon solar cell with a FSC is believed to reach 90% of the maximum efficiency of an ideal silicon solar given by the Shockley-Queisser detailed balance limit [4], the practical efficiencies are significantly lower due to several loss mechanisms, and further study is needed to understand these losses in detail and build up a more realistic model. Following previous approaches [5-7], this work will present a modified model based on Weber and Lambe's theory [1], which will take the non-ideal coupling between the collector and the solar cell mounted at the edge into consideration.

#### 2. Model Description

The structure of the collector considered in this model is shown in Figure 1. Except for the edge mounted solar cell, the other three edges are assumed to be covered with mirrors. The bottom surface of the collector is not coupled with mirror. An air gap is assumed to exist between the collector and the solar cell, and this is the real situation when the edge fluorescence is detected by an optical fibre in the experiments. The optical index (PMMA, n=1.5) of the collector is higher than air (n=1), so there will be an escape cone (Fig.1, cone 1 and cone 3) at the edge. Only photons emitted in these two cones can be collected by the solar cell, if there is not any reabsorption. Photons emitted in the other two cones (Fig.1, Cone 2, 4) are considered as loss.



Figure 1. Collector structure and escape cones.  $\theta_c$  is the critical angle for total internal reflection.

The fluorescence photon collection efficiency of the collector, defined to be the number of photons collected by the solar cell divided by the number of photons emitted by the dye inside the collector. In Weber and Lambe's theory, the collection efficiency only counts the first generation photons [5]. However, their theory could be employed to calculate the reabsorption probability [7]. Assuming the fluorescent photons emitted to be isotropic and using the Beer-Lambert Law, the spectral reabsorption probabilities  $r(\lambda)$  are given bv

$$\{1 - r(\lambda)\}_{WL} = \frac{1}{4\pi(1 - P)}$$

$$\int_{0}^{\pi} d\phi \int_{\theta_{c}}^{\pi - \theta_{c}} \frac{\sin\theta\sin\phi}{\alpha_{e}(\lambda)L}$$

$$\{1 - \exp\left[\frac{-2\alpha_{e}(\lambda)L}{\sin\theta\sin\phi}\right] \} \sin\theta d\theta$$

$$\{1 - r(\lambda)\}_{MWL} = \frac{1}{2P\alpha_{e}(\lambda)L}$$

$$\int_{0}^{\theta_{c}} \left\{1 - \exp\left[-\frac{2\alpha_{e}(\lambda)L}{\cos\theta}\right] \right\} \cos\theta\sin\theta d\theta$$

$$(2)$$

where  $\{1 - r(\lambda)\}_{WL}$  is the spectral reabsorption probability for Weber and Lambe's theory,  $\{1 - r(\lambda)\}_{WWL}$  is for

Modified Weber and Lambe's theory,  $P = 1 - \cos \theta_c$  is the fraction of photons emitted inside cone 1 and cone 3 or cone 2 and cone 4,  $\theta_c$  is the critical angle for total internal reflection,  $\alpha_e(\lambda)$  is the attenuation coefficient at the emission wavelength, and *L* is the length of the collector. Figure 2 compares the numerical calculation results of the two spectral reabsorption probabilities.



Figure 2. Comparison of reabsorpiton probabilities calculated from Weber and Lambe's theory (dashed line) and Modified Weber and Lambe's theory (solid line).

Figure 2 shows that the spectral reabsorption probability for Weber and Lambe's theory is higher than that for Modified Weber and Lambe's theory. The apparent reason is that the photons considered to be collected in Weber and Lambe's theory propagate a longer pathlength before reaching the edge mounted solar cell.

### 3. Collector Characterisation Method

The reabsorption loss, the main loss of the collector, is evaluated by scaling the edge fluorescence to the first generation fluorescence, which is free from reabsorption. In experiments, the first generation fluorescence is the measured top fluorescence with a low dye concentration [7].

The probability that photons of the whole fluorescent emission spectrum will be reabsorbed is

$$R = \int r(\lambda) f_1(\lambda) d\lambda \tag{3}$$

where  $f_1(\lambda)$  is the normalised first gerenation fluorescence which satisfies the equation:

$$\int f_1(\lambda) d\lambda = 1 \tag{4}$$

The reabsorption probability can be evaluated from the first generation fluorescence and the edge fluorescence by using the equation:

$$1 - r(\lambda) = \frac{\hat{f}_e(\lambda)}{f_1(\lambda)}$$
(5)

where  $\hat{f}_e(\lambda)$  is a normalised edge fluorescence, which is equal to the first generation fluorescence at the long wavelength range, where the absorbance is low. The edge fluorescence is fitted to the first generation fluorescence in this long wavelength range.

# 4. Experimental

The collector samples were made of glass substrates (20×20×1mm) spin-coated with dye (BASF Lumogen F Red 300, Perylene) diluted in PMMA (MICRO CHEM 950 PMMA C 10). The spin-coating process lasts for 3 minutes at 1000 RPM [7].

For absorbance measurments, a halogen lamp was used as the excitation source to illuminate the top surface of the collector samples. The transmitted light was detected by a detector connected with a Bentham spectrometer (equipmed with a TM300 monochromator). For high dye concentration collector samples, the detector was a PMT tube (Hamamatsu R446), while for low concentration ones, the detector was a calibrated silicon detector (dh\_Si, Bentham Instruments Ltd).

The excitation source for top fluorescence was a metal halide lamp, the collector samples were excited at 440 nm by an connected optical fibre with the monochromator. An optical fiber connected with the Benthem spectrometer, fixed normal to the surface of the collector samples, was used to detect the top fluorescence. The excitation optical fiber was fixed 60° to the detection direction.

The edge fluorescence was measured by an Avantes spectrometer (AvaSpec-2048, grating UA(200-1100 nm), slit-25  $\mu$ m based on the symmetrical Czerny-Tuner design with a 2048 pixel CCD dector array). The top surface of the collector samples were uniformly illuminated by a Xenon lamp approximating AM1.5 spectrum with a 10 nm band pass filter at 440 nm. The edge fluorescence was detected from one edge by an optical fiber with a convergent lens and then conducted to the Avantes spectrometer. The remaining edges were coupled to a highly reflecting film (3M Vikuiti Enhanced Specular Reflector) with specular reflectance over 98% across the visible spectrum.

### 5. Results and Analysis



Figure 3. Normalised absorption, normalised first generation fluorescence (f1) and fitted edge fluorescence.

In Fig. 3, the first generation fluorescence was normalised from the top fluorescence of the collector sample with dye concentration of 40 mg/L by using Eq. (4). The edge fluorescence of the collector samples with dye concentration of 40 mg/L, 60mg/L, 400mg/L and 600 mg/L were fitted to the normalised first generation fluorescence in the wavelength range from 650 nm to 850 nm, where the absorbance of all the collector samples were below 0.0012.

Fig. 3 shows that higher dye concentration collector samples have larger reabsorption probability in the wavelengh interval where the absorption overlaps with the fluorescence. It is seen that, in the long wavelength range, the edge fluorescence of all the samples fits well with the first generation fluorescence.



Figure 4. Experimental reabsorption probability of different dye concentration collector samples compared with theory.

By using Eq. (5), the experimental spectral reabsorption probability of different dye concentration collector samples can be obtained and they were compared with Weber and Lambe's theory and Modified Weber and Lambe's theory in Fig. 4.

In Fig. 4,  $\alpha_{eff}$  is an effective absorption coefficient. The collector samples were assumed to be homogeneous since the optical index of the PMMA films were similar to that of the glass substrates. Then the effective absorption coefficient is given by:

$$\alpha_{eff} = \alpha_{film} \frac{d_{film}}{d_{film} + d_{glass}}$$
(6)

where  $\alpha_{film}$  is the true absorption coefficient of the PMMA film diluted with dye,  $d_{film}$  is the thickness of the PMMA film and  $d_{glass}$  is the thickness of the glass substrate.

Fig. 4 shows that the experimental reabsorption probability fits well with the Modified Weber and Lambe's theory.

### 6. Conclusions

This paper presents a model which takes into consideration the non-ideal coupling between the collector edge and the solar cell. In accordance with the edge fluorescence detection approach in the experiments, an air gap is assumed to exist between the collector edge and the solar cell, thus only photons emitted in the escape cones (Cone 1 and 3) could be collected by the solar cell or observed as edge fluorescence. This Modified Weber and Lambe's theory fits well with experimental results, and could be used to analyse the spectrum of the photons emitted out of the collector edges. Based on this analysis, it will be possible to infer the photon flux emitted by the collector onto a fully coupled solar cell which is not easy to measure experimentally.

### 7. Acknowledgements

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# 8. References

[1] W.H. Weber, J. Lambe, Luminescent greenhouse collector for solar radiation, Appl. Opt., 15 (1976) 2299-2300.

[2] J.A. Levitt, W.H. Weber, Materials for luminescent greenhouse solar collectors, Appl. Opt., 16 (1977) 2684-2689.

[3] A. Goetzberger, W. Greube, Solar energy conversion with fluorescent collectors, Applied Physics A: Materials Science & amp; Processing, 14 (1977) 123-139.

[4] T. Markvart, Detailed balance method for ideal single-stage fluorescent collectors, Journal of Applied Physics, 99 (2006) 026101.

[5] J.S. Batchelder, A.H. Zewail, T. Cole, Luminescent solar concentrators. 1: Theory of operation and techniques for performance evaluation, Appl. Opt., 18 (1979) 3090-3110.

[6] J.S. Batchelder, A.H. Zewail, T. Cole, Luminescent solar concentrators. 2: Experimental and theoretical analysis of their possible efficiencies, Appl. Opt., 20 (1981) 3733-3754.

[7] P. Kittidachachan, L. Danos, T.J.J. Meyer, N. Alderman, T. Markvart, Photon Collection Efficiency of Fluorescent Solar Collectors, CHIMIA International Journal for Chemistry, 61 (2007) 780-786.