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Ray-trace Modelling of Quantum Dot Solar Concentrators

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Performance of single plate luminescent solar concentrators containing different luminescent species.

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Abstract

Ray-trace modelling has been used to investigate the performance of luminescent solar concentrator (LSC) plates containing high quantum yield (QY) NIR emitting quantum dots (qd). Optical efficiencies and spectrally enhanced concentration ratios are compared to those of LSC plates containing green and orange emitting qds. Concentration ratios 2-5 times higher are predicted with the NIR emitting qds, partly due to the broader absorption range but more significantly due to lower re-absorption losses. The performance of the NIR plate is found to be similar to that predicted for a plate containing a single red Coumarin dye. For each luminescent species, the predicted optical efficiencies are higher for diffuse incidence than for direct incidence, as a higher fraction of the diffuse incident spectrum is within the absorption range.

1) Introduction

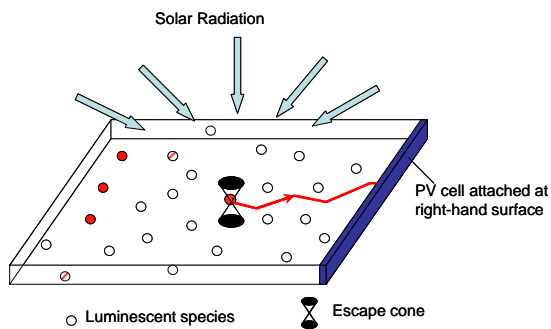


Figure 1. Luminescent solar concentrator with PV attached at one edge.

Luminescent solar concentrators (LSCs) [1, 2] are non-imaging concentrators which do not require solar tracking and concentrate both direct and diffuse light. Currently developed LSCs consist of a flat polymer plate doped with a luminescent dye or other luminescent species such as qds [3]. As incident light passes through the plate, photons are absorbed by the dye/qds. Subsequently, photons are emitted

isotropically (Figure 1) by the dye molecules/qds. The refractive index of the plate is larger than that of the surrounding air, resulting in much of the emitted light being trapped by total internal reflection and transmitted to one edge, where a photovoltaic (PV) cell is attached.

To date, LSCs containing qds have not attained as high concentration ratios as with luminescent dyes. This is due to large re-absorption losses arising from the spectral overlap between qd emission and absorption spectra. In this paper, re-absorption losses are quantified, for different qd types (visible and NIR emitting). Optical efficiencies and concentration ratios are determined for both direct and diffuse incident light.

2) Ray-trace model and input parameters.

Monte-Carlo ray-trace modelling can be used effectively to determine optical efficiency (η_{opt}) values of LSC devices [4-11]. The η_{opt} value is defined as the fraction of photons incident on the top surface which is transmitted to the PV cell. In the model, a photon is represented by a ray, and each ray is traced through the LSC until it is lost from the system or is transmitted to the PV cell. The loss mechanisms considered in the model are escape cone losses, matrix attenuation losses, quantum yield (QY) losses, external mirror reflection losses, and losses due to initial reflection from the top surface. The geometric gain, G_{geom} , is defined as the area of the top surface divided by the area of the PV cell. The photon concentration ratio, C_{ph} , is given by $C_{\text{ph}} = G_{\text{geom}} \times \eta_{\text{opt}}$. Using C_{ph} , the spectrum of light incident on the PV cell, and the cell spectral response the overall spectrally enhanced concentration ratio (C) is determined. A measured matrix material attenuation spectrum [12] and external mirror reflection coefficient have been used in the model to predict realistic possible concentration ratios for plates

containing qds with high QY of 85%. The refractive index of the material was assumed to be 1.5.

Green, orange and NIR emitting qds were modelled in a 60x60x3 mm LSC. Firstly, the doping concentration of each type was varied to find the optimum concentration. The optimum absorption spectra are shown in Figure 2. The AM 1.5 direct and diffuse spectra used as input are shown in Figure 3, along with the measured matrix material attenuation spectrum and the mc-Si cell spectral response.

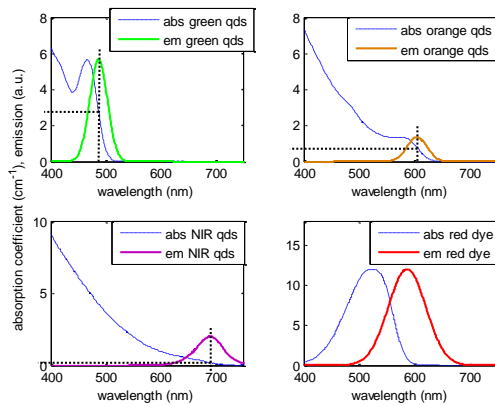


Figure 2. Absorption and emission spectra of three qd types and a red luminescent dye. Green qds: CdSe/ZnS, emission wavelength 488nm, Nanoco technologies. Orange qds: CdSe/ZnS, emission wavelength 605nm Evident technologies. NIR qds: CdSe multi-shell coating CdS/CdZnS/ZnS, emission wavelength of 690 nm, fabricated at Utrecht University. Red dye: Bayer Fluorescent Red Coumarin dye.

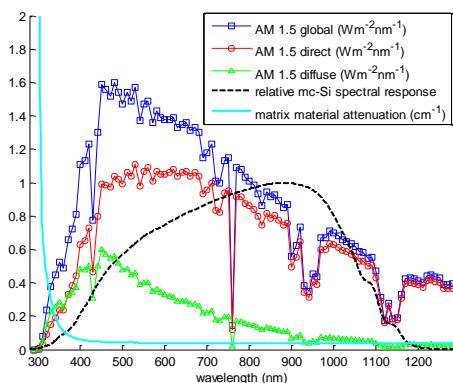


Figure 3. AM 1.5 global, direct and diffuse spectra; along with the attached mc-Si PV cell relative spectral response and the measured attenuation spectra of the LSC plate matrix material (Epoxy resin).

3) Results

The optical efficiency (η_{opt}) of the plate containing NIR emitting qds is predicted to be twice that of the plate containing orange emitting qds - i.e. 7.59% compared to 3.71%, respectively (see Table 1). This is partly due to the broader absorption spectrum - 30.0% of incident light is absorbed by the NIR plate compared to 24.9% by the orange plate. If re-absorption losses were equal in the NIR and orange plates, η_{opt} would be proportional to the percentage of incident photons absorbed. As this is not the case, it indicates that re-absorption losses must be significantly lower in the NIR plate compared to the orange (and green) plate. Re-absorption losses comprise of both escape cone losses and QY losses. Both plates are assumed to have the same qd QY (85%). An analysis of the predicted loss mechanisms in the orange plate shows that 68.9% of rays initially absorbed by a qd are lost in the escape cone or lost due to the qd QY. For the NIR plate, 54.8% of absorbed rays are lost in the escape cone or lost due to the qd QY. Examining the cross-section shape of the (optimum) absorption spectra (Figure 2), it is seen that the NIR qd absorption coefficient at the emission peak wavelength is significantly lower than the orange qd absorption coefficient at the emission peak, and hence the lower re-absorption losses. η_{opt} and C were calculated (see Table 2) using the diffuse incident spectrum shown in Figure 3, assuming an isotropic angle of incidence on the plate top surface. Again, the higher η_{opt} for the NIR plate, compared to the orange (and green) plate, is partly due to the increase in the percentage of incident photons absorbed but more significantly due to lower re-absorption losses. For each qd type, the predicted η_{opt} and C are higher for diffuse incidence, as a higher fraction of the incident spectrum is within the absorption range. For comparison, η_{opt} and C are predicted for a plate containing a Coumarin red dye (QY=95%). The dye absorption and emission spectra are shown in Figure 2. For these plate dimensions (60x60x3 mm), η_{opt} obtained with the NIR qds is only slightly lower than that predicted for the red dye (13.2% compared to 13.4% under diffuse light, respectively). C is higher for the NIR qds than for the red dye, however, as the mc-Si cell is more efficient at the

longer wavelengths where the NIR qds emit.

	% Photons absorbed	η_{opt} (%)	C
Green qds (QY=0.85)	14.4	1.63	0.28
Orange qds (QY=0.85)	24.9	3.71	0.86
NIR qds (QY=0.85)	30.0	7.59	1.96
Red dye (QY=0.95)	24.7	8.36	1.89

Table 1. Predicted optical efficiencies (η_{opt}) and spectrally enhanced concentration ratios (C) for 60x60x3 mm LSCs under AM 1.5 direct incidence.

	% Photons absorbed	η_{opt} (%)	C
Green qds (QY=0.85)	31.2	4.46	0.94
Orange qds (QY=0.85)	43.7	7.46	1.89
NIR qds (QY=0.85)	49.6	13.2	3.91
Red dye (QY=0.95)	37.5	13.4	3.51

Table 2. Predicted optical efficiencies (η_{opt}) and spectrally enhanced concentration ratios (C) for 60x60x3 mm LSCs under AM 1.5 diffuse incidence.

Increasing the LSC size, C was calculated for plates containing each luminescent species (Figures 4 and 5). C for the NIR qd plate increases significantly for larger plate sizes and is similar (+/- 10%) to that of the red dye plate. The increase in C for larger orange and green plates is limited by the larger re-absorption losses.

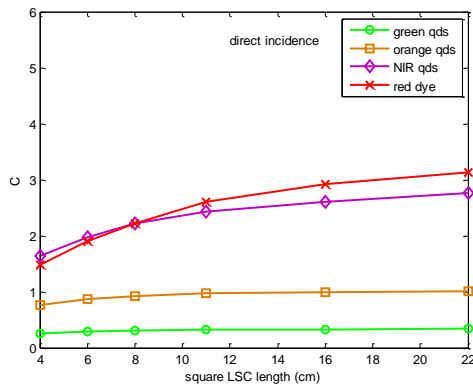


Figure 4. Predicted spectrally enhanced concentration ratios (C) for square LSCs of increasing size under direct incidence

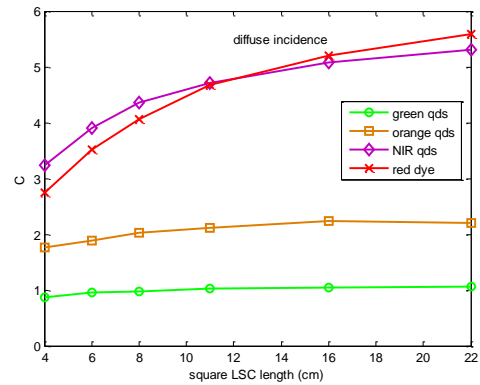


Figure 4. Predicted spectrally enhanced concentration ratios (C) for square LSCs of increasing size under diffuse incidence.

Conclusion

Ray-trace modelling has been used to investigate the performance of LSC plates containing high quantum yield (QY) NIR emitting qds. The results show NIR plates can achieve much higher efficiencies than has currently been achieved [13] in fabricated devices incorporating visible emitting qds. The higher efficiencies are due partly to the broader absorption spectrum but more significantly due to the lower re-absorption losses arising from the cross-section shape of the NIR qd absorption spectrum.

In general, the predicted η_{opt} and C are higher for diffuse incidence, as a higher fraction of the incident spectrum is within the absorption range of each qd type. For example, for the 60x60x3 mm NIR plate, C is predicted to be 1.96 and 3.91 under direct and diffuse incidence, respectively, which highlights the potential of LSCs as practical devices in the cloudy Northern European climate.

As previous studies have indicated [11,13], concentration ratios for uniformly doped single plate LSCs, containing commercially available visible emitting qds, are too low to result in commercially viable LSC devices. However, the results presented here indicate that employing *NIR emitting* qds will achieve much higher concentration ratios because of the lower re-absorption losses. Predicted concentration ratios employing these particular NIR qds are similar (+/-10%) to those predicted for a red dye, and are 2-5 times higher than those predicted for the green and orange emitting qds.

Acknowledgments

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