Analysis of Luminescent Solar Concentrator Performance Using a Ray Tracing Algorithm: Modelling, Optimization and Validation

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Abstract:

In this paper, the behaviour of a LSC doped with Near-Infrared Quantum Dots (NIR-QD) in an epoxy host material is modelled by a ray tracing algorithm under different iteration numbers. It is shown that by increasing the number of input rays in the system improving the accuracy of simulation and the QDs emission spectra. However, increasing the number of the rays has linearly increased simulation iterations, hence the simulation time. This challenge is overcome by optimizing the program by avoiding recalculations of parameters in the program which significantly reduces the volume of calculations; thus, simulation time. As a case in point, in a simulation run for 126000 rays, the simulation time was decreased from around 107 hours in the primary program to around only 3 hours in the optimized version. Furthermore, in the simulation for around 718000 rays, the optimized program achieved the simulation time of roughly 18 hours with higher accuracy . The ray-trace model predicted optical efficiency compared with references results to validate the model and found to be in an excellent agreement.

Keywords: Luminescent Solar Concentrator, Ray Tracing, Modelling, Quantum Dot, Emission, Absorption

1- Introduction:

Luminescent Solar Concentrators (LSCs) are known as efficient light collectors for solar energy and PV systems. PVs cells are not efficient in all ranges of wavelengths and different methods can be used to enhance the efficiency of the solar cells. Of these, the first method can be done by improving the electrical characteristics of photovoltaic (PV) cells and their structure; for instance, designing PV device with very narrow structure [1]. Although, this method is difficult and expensive, it has been resulted in fabricating new PV devices such as third generation PV cells including multi-junction, heterojunction and intermediate band gap solar cells. [2-4]
An alternative method to enhance the output efficiency of PV systems and improve the spectral response is use of luminescent materials which can be done by two techniques. The first one is doping luminescent material in the encapsulation layer such as dye-doped plastic Luminescent Down-Shifting (LDS) layer in order to red-shift the illuminated spectrum. The second is using luminescent material in a transparent host material and fabricate a light-guiding concentrator such as a planner LSC whose structure can be seen in Figure 1. [5] LSC has been proposed as an interesting strategy in order to concentrate and convert sunlight to a single wavelength, where PV cells have higher efficiency. The idea of using luminescent materials in order to enhance the spectral response of solar cells was first introduced in 1970s and first generations were based on dyes. [6-8]
The use of LSC in PV systems has some advantages. LSCs are spectrum converters to manage photons in which molecules of fluorescent absorb photons with small wavelengths and emit them in longer wavelengths where PV cell has relatively high efficiency. Then, the photons are concentrated to the PV cells by Total Internal Reflection (TIR). This not only increases the efficiency of the system, but also reduces the required PV area; accordingly, decreases the cost of the solar panel. Furthermore, both diffuse and direct light can be concentrated and converted by LSC; hence, they are a very suitable technology where diffuse solar radiation is dominant, such as in northern European countries where over 50% of light is diffuse. [9]. They are low-cost and can be designed and constructed in transparent small and large scale windows with different colours. It has been proven that using LSC in building can enhance visual comfort, day lighting and correlated colour temperature. [10] Moreover, the combination of different LSC sheets can be used in order to generate a near-white light source [11]. These features make them a preferred choice for use in Building Integration Photovoltaic (BIPV) systems and façades of buildings which brings us closer to the goal of constructing buildings with zero

carbon energy consumption and buildings which are able to cover their required energy by renewable energies [12-14]. This can help to achieve the goal of the European Parliament and the Council of the European Union enacted in 2009 on using renewable energy to reduce pollution and fossil energy consumption. [15], [16].

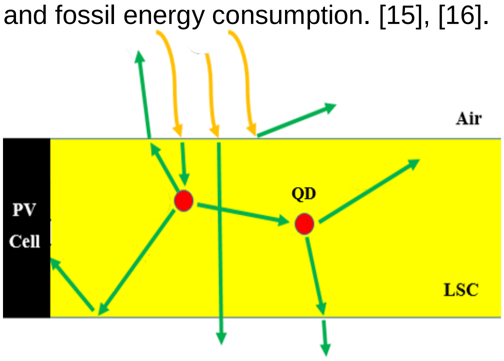

Figure 1: LSC device doped with QD in host material and PV cell installed on the edge

In this paper, the behaviour of a LSC including NIR-QD doped in an epoxy host material is modelled by a ray tracing algorithm. The program was optimized by reducing the amount of calculations in it so that the execution time of the program is decreased significantly. In the following; the basis of the ray tracing algorithm is explained and the model details are presented. Results were obtained and validated by comparing the results with the reference reported results.

2- Ray Tracing Basis and Modelling:

Monte Carlo ray tracing algorithm has a statistical nature and achieves the results by random sampling and solves the problems in an iteration loop. Generally, Monte Carlo method has been used in many applications in the fields of fluids, solids, optics and physics where the behaviour of the input parameters in problems are non-linear and have dramatic uncertainty. In other words, the inputs in these types of problems can be interpreted by probabilities and they cannot be solved by traditional methods [17-20].

Monte Carlo ray tracing algorithm can obtain the results by tracing a large number of photons which are generated based on the energy distribution of the input radiation light. The photons are irradiated to the modelled systems. Afterwards, in an iteration loop, the fate of each photon is calculated based on the probability of each event which may occur for that including reflection and refraction. If the ray is refracted to the LSC, it may be absorbed by host material (lost as heat) or absorbed and then emitted by QDs. Since the host material are transparent in the visible range of solar radiation, it is believed that the irradiated light is absorbed by the luminescent species. The absorption is calculated by the Beer Lambert law as shown in equation 1 [19, 21, 22]:

$$A = -\log_{10} T \qquad (1)$$

Where A is the Absorbance and T is the value of Transmittance of the material.

Monte Carlo ray tracing algorithm is based on the calculations in a “For” loop which is a time-consuming process. The number of the iterations in the loop is determined by the number of the photons irradiated to the LSC. Thus, increasing the number of the photons (in order to have more accurate results) leads to increase in the number of iterations and calculations; therefore, the simulation time.

In order to reduce the simulation time, the program’s process and algorithm is optimized by eliminating unnecessary re-duplications and re-calculations of the same parameters in different places or functions of the program. In the optimized version, the constants and the similar parameters are only calculated once in the pre-processing stage of the program before the main iteration “For” loop. By using this idea, the number of the calculations in each iteration of the “For” loop is decreased which reduces the execution time of each iteration and the overall simulation time.

3- Results and Discussions:

The result of ray tracer program with and without the optimized steps were compared with the reported results in [23]. The modelled LSC had the dimensions of 60 × 60 × 3 mm and the host material was epoxy with refraction index of 1.5. The quantum yield of the used NIR QD was 85%. The input solar spectrum used was a Direct Sun Light (AM 1.5) radiation and the detector was placed at one of the edges of the LSC. The emission and absorption spectra of the NIR QD LSC is shown in Figure 2. Table 1 shows the optical efficiency of the NIR QD LSC calculated by the ray tracer program and compared with the reference value. The program was first run for a total number of 126000 rays (iterations). The simulation time was around 107 hours. The value obtained for the optical efficiency by the model was 7.33%. The optical efficiency of reference LSC was 7.59%. Figure 3 shows the emission spectrum detected at the edge of the LSC by the model in comparison with the measured emission spectrum. As it can be seen from Figure 3, the emission spectrum obtained by the model is noisy due to the low number of input photons (iterations). Increasing the number of iterations is important in order to get more accurate results and smother spectrum; however, it increases the simulation time.

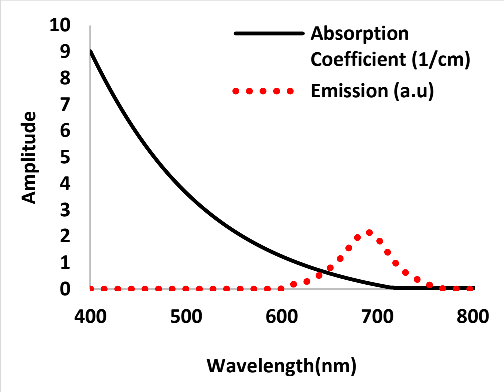

Figure 2: Absorption coefficient and emission spectra for NIR QD LSC [23]

The optimization steps to the ray tracer program was then important in order to reduce the time taken to run the model. The optimized program was run for the same number of iterations. It has been found that, the simulation time is reduced to around 3 hours and maintained the same optical efficiency. The program was run for higher number of iterations, 718000. The value of the optical efficiency was recorded 7.5% which was in a close match with the reference value, 7.59%. Figure 4 shows the emission spectrum obtained with iterations number of 718000 compared to reference emission spectrum. It appears that, the achieved and the reference results are in an excellent match.

Table 1: Comparison of the results obtained by ray tracer program (with and without the optimized steps) and reference [23]

	Ray tracer program	Ray tracer program (optimised)	Ray tracer program (optimised)
Iterations	126000	126000	718000
Optical Efficiency (In [23]: 7.59%)	7.33%	7.33%	7.50%
Simulation Time(s)	385462.5 (107 hours)	10821 (3 hours)	63772.1 (18 hours)

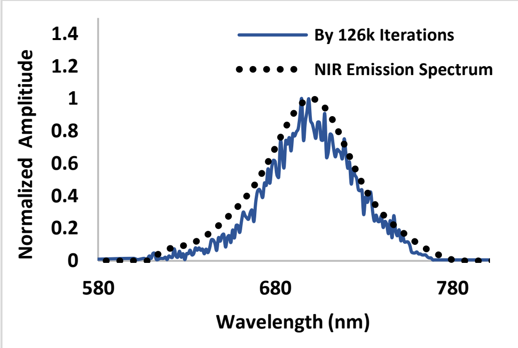

Figure 3: Comparison of the output spectra of the LSC under 126k rays and the emission spectrum of NIR QD

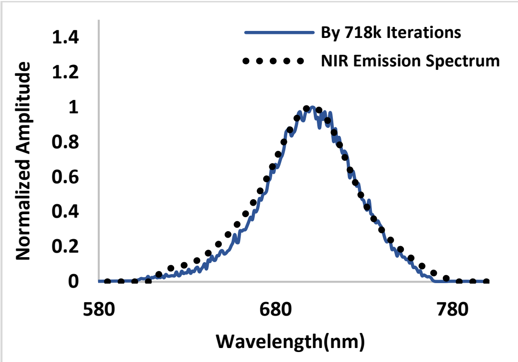

Figure 4: Comparison of the output spectra of the LSC under 718k rays and the emission spectrum of NIR QD

4- Conclusion:

In this paper, a Monte Carlo ray tracer program was used in order to model a NIR QD doped LSC. In the program, the output results were obtained by detecting the fate of each input ray in an iteration loop. It has been observed that, by increasing the number of the input rays, more accurate results could be achieved. This however increased the simulation time. In order to overcome this limitation, an optimization steps were taken in the ray tracer program. As a result, the speed of the program was increased significantly. For example, the simulation time for 126k rays was reduced from 107 to 3 hours. Moreover, by increasing the number of the rays, the output modelled results were more precise and in an excellent match with the reference results.

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