PHOTON MANAGEMENT WITH LUMINESCENT MATERIALS

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1 INTRODUCTION

Photon management aims for higher efficiencies by making a better use of the full solar spectrum. The underlying idea is to split or modify the solar spectrum before the photons are absorbed in a solar cell. In this paper we investigate the concept of fluorescent concentrators, which allow for spectral splitting and concentration without the need for tracking systems. We also present an advanced upconversion design, which combines upconversion, spectral and geometric concentration with the help of fluorescent concentrators, and spectral management with photonic structures.

2 FLUORESCENT CONCENTRATORS

Fluorescent concentrators are a concept to concentrate both direct and diffuse radiation without using tracking systems [1]. In such concentrators, dye molecules in a matrix absorb radiation and emit light with a longer wavelength. Total internal reflection traps most of the emitted light, so that the light is guided to the edges, where it is utilized by solar cells. There has been considerable progress recently in the development of fluorescent concentrators. High efficiencies have been achieved [2, 3] and the fundamental problem of escape cone losses could be solved with the application of photonic structures [3]. Considerable progress has also been made in their understanding and theoretical description, e.g. [4, 5]. Based on these achievements, the different approaches that lead to progress should be combined and larger systems with high efficiencies should be developed to make this concept commercially attractive.
A stack of different fluorescent concentrators to use the full solar spectrum, spectrally matched solar cells and photonic structures, which increases the fraction of light guided to the edges of the concentrator, are the key features of advanced system designs (Figure 1).

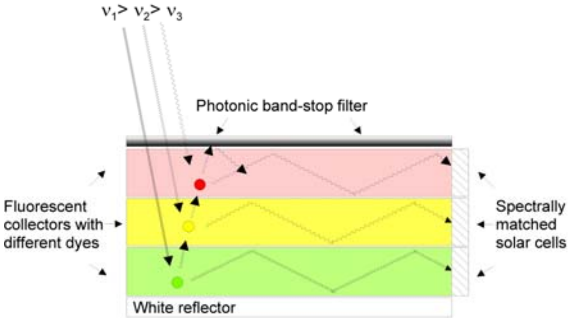

Figure 1: *An advanced fluorescent concentrator system design. The full spectrum can be used with a stack of fluorescent collectors with different dyes. The escape cone of total internal reflection is a principal efficiency-limiting problem. At least 26% of the light is lost. A photonic structure helps to minimize these losses. The photonic structure acts as a bandstop reflection filter. It allows light in the absorption range of the dyes to enter the concentrator, but reflects light in the emission range.*

We realized a fluorescent concentrator system with 6.7% efficiency by the combination of two materials and the use of GaInP solar cells at all four edges. A larger system (5 x 10 cm^2) with only one attached GaInP solar cell had an efficiency of 2.6%. A photonic structure increases this efficiency to 3.1%, which corresponds to a relative increase of 20% (Figure2). This fluorescent concentrator system featured a concentration ratio of 20x and produced 3.7 times more energy than that of the GaInP solar cell by itself. To combine all features, a system with dimensions of 5x5 cm^2 with two materials and spectrally matched GaInP and GaAs solar cells is currently being developed. A system with one GaInP solar cell attached to one edge shows 3.7% efficiency and a system with one GaAs solar cell achieves 4.6%. When these two systems are stacked, the combined efficiency reaches 5.6%. With the addition of more solar cells to the edges and with the photonic structure, the efficiency is expected to exceed 7%.
The production of one-dimensional photonic structures is still quite costly. We also investigate the possible alternative of three-dimensional photonic structures. They could be produced with a dip-coating utilizing self-organization [6]. This process could be also applied on large area concentrators. At the moment, the positive effect of the reduction of the escape cone losses is compensated by unwanted scattering losses. However, a positive effect is likely to be achieved with ongoing progress in the deposition technique.

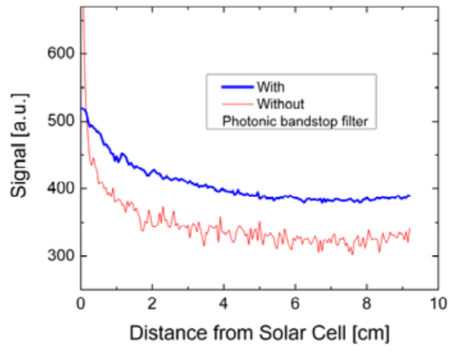

Figure 2: *Line scans of a fluorescent concentrator system, with and without a photonic structure on top. The fluorescent concentrator was 5 cm x 10 cm² wide and 5 mm thick. The material was PMMA doped with BA241. One 50 mm x 5 mm GaInP solar cell was attached to one edge. Over most of the concentrator area the collection efficiency is increased, resulting in an efficiency enhancement of the system by 20 % relative.*

3 UPCONVERSION

Frequency upconversion of sub-bandgap light is a promising approach to overcome the fundamental problem of sub-bandgap losses. The theoretical efficiency limit is pushed from close to 30% up to 40.2% for a silicon solar cell with an upconverter illuminated by non-concentrated light [7].

Rare earth-based materials are very suitable as upconverters. The major problem of rare earth-based upconverters like erbium-doped $NaYF_4$ is the weak and narrow absorption range of the rare earth dopant. To overcome this inherent constraint, Strümpel et al. proposed to combine the upconverter with a fluorescent material [8]. The fluorescent material should absorb photons with wavelengths between the bandgap of the solar cell and the absorption range of the upconverter and emit in the narrow absorption range of the upconverting material. The upconverter then converts these photons to photons with energies above the bandgap of silicon. Because the photon density in the upconverter absorption range is increased, we call this process 'spectral concentration'. This approach increases the upconversion efficiency significantly by two mechanisms: first, more potentially upconvertible light is absorbed. Secondly, the photon density in the absorption range of the upconverter is increased. As upconversion is a nonlinear process, the efficiency of the upconverter increases with increasing intensity of the incoming radiation.

Unfortunately, the luminescent materials that can used for spectral concentration, such as PbSe quantum dots, also absorb the radiation emitted from the upconverter. Thus, upconverter and fluorescent material have to be separated from each other in order to prevent the upconverted radiation from being absorbed by the fluorescent material. We therefore propose an advanced upconverter system design as depicted in Figure 3.

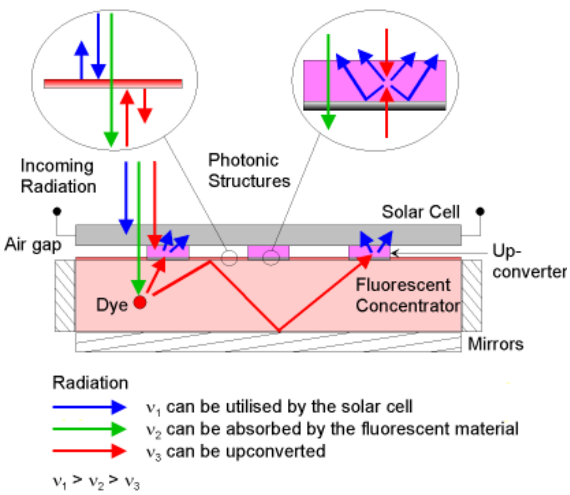

***Figure 3**: An advanced upconversion system. By the use of a luminescent material, a larger spectral range is up-converted. Because of the non-linear characteristic of the upconverter, efficiency increases due to additional geometric concentration.*

The fluorescent material is incorporated separately in a transparent matrix material to form a fluorescent concentrator. The upconverting material is located between this fluorescent concentrator and the bifacial solar cell. If the upconverting material does not cover the complete back of the solar cell, we achieve an additional geometric concentration in addition to the spectral concentration. The fluorescent concentrator collects the infrared radiation from the entire area and concentrates it to the smaller upconverter area. This additionally increases the photon flux irradiating the upconverter. As previously mentioned, due to the non-linearity of the upconversion this additionally increases the efficiency of the upconversion. Selectively reflective photonic structures at the interface between fluorescent concentrator and upconverter prevent the upconverted light from re-entering the concentrator, so the problem of unwanted absorption can be solved. A second type of selective mirrors could increase the collection efficiency of the fluorescent concentrator, by reflecting the light that is emitted by the fluorescent material. Additionally, these structures could serve as an effective back mirror for the radiation, which can be utilized by the solar cell. The latter is very important since the solar cell must have a bifacial layout to be able to use the upconverted radiation. Under the condition that we need at least two photons to create a free electron hole pair in the solar cell, the upper limit for the extra current from an erbium based system is 3.8 mA/cm^2 (detailed calculation in paper currently in press).

4 SUMMARY

We have shown that there is considerable progress in the development of efficient fluorescent concentrator systems. Their main features are material combinations, spectrally matched solar cells, and photonic structures. We also presented a concept that has the potential to increase upconversion efficiency considerably.

5 ACKNOWLEDGEMENTS

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