ADVANCED FLUORESCENT CONCENTRATORS

J. C. Goldschmidt, S. W. Glunz, A. Gombert, G. Willeke
Fraunhofer Institute for Solar Energy Systems
Heidenhofstr. 2, 79110 Freiburg, Germany
Phone: +49 (0) 761 4588 5475 Fax: + 49 (0) 761 4588 9250 Email: jan.christoph.goldschmidt@ise.fhg.de

ABSTRACT: We present an advanced concept for fluorescent concentrator systems, which aims for higher efficiencies by utilization of the full solar spectrum. Key features are spectrally matched solar cells, new materials and a photonic structure, which increases the fraction of light guided to the rims of the concentrator. We introduce a new method for material characterization and show first experimental results of fluorescent concentrator solar cell systems. A system with GaInP solar cells at the rims of a fluorescent concentrator and a silicon solar cell at the bottom had an efficiency as high as 17.7%, whereas the fluorescent concentrator system significantly increased total system efficiency. The application of a Rugate filter with a reflection band in the emission range of the fluorescent dye increased the internal light guiding efficiency of the concentrator by 11%.
Keywords: Novel Concepts, Fluorescent Concentrators, Photon Management

1 INTRODUCTION

In a fluorescent concentrator dyes in a matrix absorb radiation and emit light with a longer wavelength. Most of the emitted light is internally totally reflected and therefore trapped and guided to the rims of the concentrator. This concentrated light can be efficiently utilized by solar cells. One important advantage of the fluorescent concentrator is the ability to concentrate both direct and diffuse radiation. Additionally, there is no need for a tracking system. This gives the concept high application relevance for conditions like in central Europe with extensive periods of low illumination intensities and a high fraction of diffuse radiation. The concept of fluorescent concentrators was investigated intensively in the early Eighties [1]. Research in those days aimed for cost saving by replacing expensive solar cells with eventually cheap fluorescent material. However, several problems led to reduced research interest. The used organic dyes had only relatively narrow absorption bands and although high quantum efficiencies of the absorption and reemission process above 95% could be achieved in the visible range of the spectrum, quantum efficiencies remained at 50% and lower in the infrared. Furthermore, the dyes which were sensitive in the infrared were unstable under long-term illumination. Reabsorption of the emitted light due to overlapping absorption and emission spectra further reduced efficiencies [2]. A principal problem was the escape cone of the internal reflection, which caused losses of at least 30%. Moreover, availability of efficient solar cells of which the spectral response matched the emission spectra of the dyes was limited.

2 ADVANCED FLUOERESCENT CONCENTRATORS – THE CONCEPT

After 20 years of progress in the development of solar cells and fluorescent dyes and with some new ideas we and other groups e.g. [3] are currently reinvestigating the potential of fluorescent concentrators. We favor an advanced concept (Figure 1), which aims for higher efficiencies by utilization of the full solar spectrum.

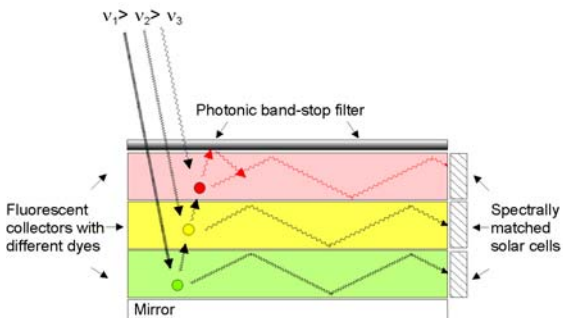

Figure 1: The advanced fluorescent collector concept. Dyes in a matrix absorb radiation of a specific spectral range and emit light with a longer wavelength. The light is guided by internal reflection to the rims of the concentrator, where it is utilized by spectral matched solar cells. The full spectrum can be used with a stack of fluorescent collectors with different dyes. The stack configuration allows for “recycling” of emitted photons that are lost in one collector but can be absorbed in another which is sensitive for lower energy photons. A photonic structure helps to minimize losses due to the escape cone of internal reflection, but does not affect the incoming light in the usable wavelength range.

One important feature is the use of a photonic structure to reduce the losses due to the escape cone of the total internal reflection. The application of photonic structures in the context of fluorescent concentrators was first proposed in [4]. The photonic structure acts as a bandstop reflection filter. It allows light in the absorption range of the dyes to enter the collectors, but reflects light in the emission range. Therefore a larger amount of light is trapped in the collector and guided to the solar cells at the rims. Additionally we take advantage of the availability of solar cells on different materials (see Figure 2). With a stack of fluorescent concentrators, each with a different dye, different parts of the solar spectrum can be converted by the matched solar cells at the rims. Therefore a broad spectrum of light can be utilized with high efficiencies.

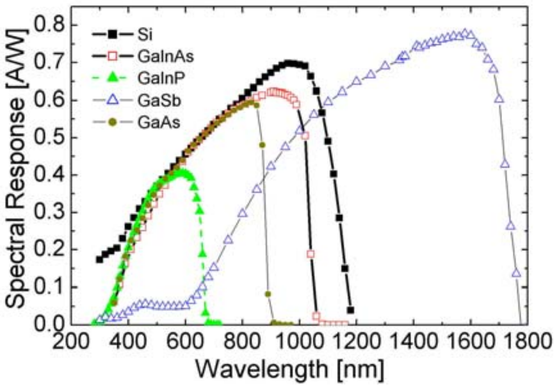

Figure 2: Spectral response of solar cells on different materials produced at Fraunhofer ISE. The full solar spectrum can be converted with high efficiencies.

The stack design with the matched solar cells at the rims provides a high degree of freedom for cell interconnection. This is a clear advantage over tandem cell concepts with the need for tunnel diodes and current limitation problems.

3 MATERIAL CHARACTERIZATION

Several parameters determine the ability of the fluorescent concentrator to guide light to its rims, such as the quantum efficiency of the dyes, the optical properties of the matrix material, the surface quality, and the geometrical dimensions of the collector plate. Measurements of the absorption spectra and the photoluminescence are not sufficient to assess this ability. EQE measurements of a system consisting of a fluorescent collector with a solar cell attached to one of its rims give information about the fraction of light guided to the rims of the collector, if the external quantum efficiency of the used solar cell is known. However, the obtained results are very sensitive to the optical coupling of solar cell and fluorescent concentrator, and therefore bear significant uncertainties. Moreover, this method would require different solar cell designs to study the effect of thickness variations on the ability to guide light to the rims of the concentrator.

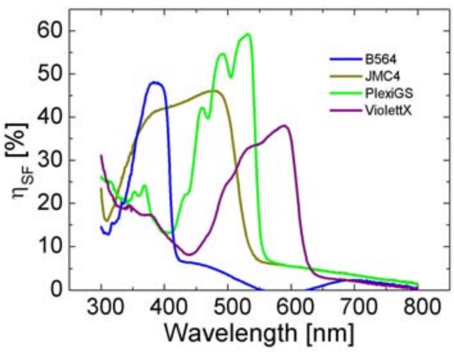

Figure 3: The fraction of light which is guided to the rims η_{SF} for four fluorescent concentrators out of different materials. Samples were 3 mm thick, and had a size of 2x2 cm^2.

We therefore developed a method to assess this ability with three measurements using a photo-spectrometer and an integrating sphere. At first, normal transmission *T* and reflection *R* measurements are performed. As the sample is outside the integrating sphere during those measurements, light, which leaves the fluorescent concentrator at the rims, is not detected. The third measurement is performed with the sample mounted in the center of the integrating sphere. This measurement yields one minus the total absorption *Abs* of the sample. From this the fraction of light which is guided to the rims, η_{SF} can be calculated with

$$\eta_{SF} = (1 - Abs) - T - R.$$

For comparison of different materials the lateral dimensions of the samples must be the same, as η_{SF} depends on the size. The measured values are only a lower limit, as light couples out more efficiently at a concentrator solar cell interface than at the concentrator air interface. Still, the method is a fast and easy way to assess and compare the ability to guide light to the rims of the concentrator produced from different materials. Figure 3 shows the result of a representative set of materials, using organic dyes. Apparently, there are no materials available with a high η_{SF} above 650 nm.

4 FLUORESCENT CONCENTRATORS WITH SILICON BOTTOM CELLS

In order to convert the IR-radiation, a promising option is to use a Si bottom cell instead of an extra fluorescent concentrator (Figure 4). As obvious from Figure 5 transmission of typical materials for fluorescent concentrators is high in the region in which the spectral response of a silicon solar cell is high, as well. This permits a system design with the silicon solar cells under the collector plate. Since the spectral response of GaInP solar cells matches the photoluminescence of most dyes (Figure 6), this material is the obvious choice for the solar cells at the rims. The typical open circuit voltage of a GaInP solar cell is in the region above 1300 mV. This compares to an open circuit voltage of a typical silicon solar cell of about 660 mV. That is, assuming the same fill factor, nearly twice the energy can be utilized if a photon is converted by the GaInP solar cell instead of the silicon solar cell.

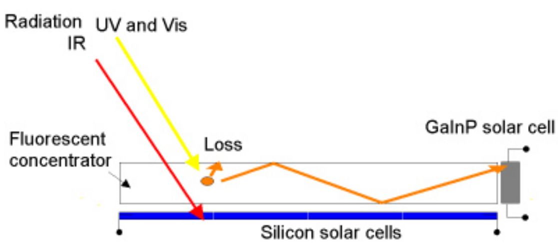

Figure 4: Concept of fluorescent concentrator with Si bottom-cells.

We realized this setup tentatively with one 2x2 cm^2 back-contact silicon solar cell and four 2x2 cm^2 GaInP solar cells. The GaInP solar cells were optically coupled to the rims of the fluorescent concentrator (3 mm

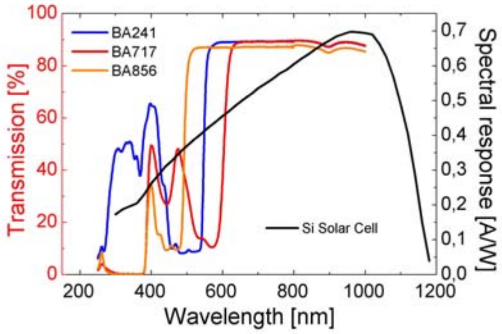

Figure 5: Transmission of three different materials for fluorescent concentrators and the spectral response of a silicon solar cell. The drop in the transmission indicates the absorption ranges of the dyes in the fluorescent concentrator. The dyes use a wavelength range from 400 to 600 nm. The concentrators have a high transmission in the region where the spectral response of the silicon solar cell is high, which makes the use of a silicon solar cell as bottom cell possible.

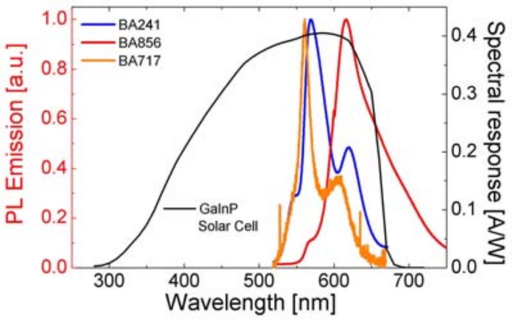

Figure 6: Photoluminescence emission of three different materials for fluorescent concentrators (the same as in figure 5) and the spectral response of a GaInP solar cell. The emission spectra peak in the region of the highest spectral response of the GaInP solar cell, so high conversion efficiencies could be achieved.

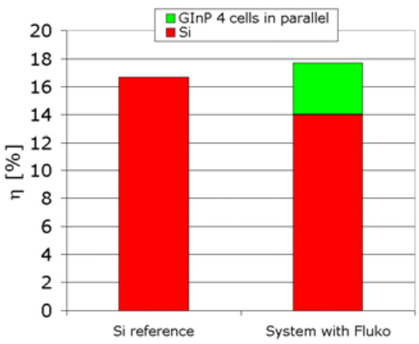

Figure 7: Comparison between a simple silicon solar cell and a system consisting out of the same silicon solar cell under a fluorescent concentrator and a parallel interconnection of 4 GaInP solar-cells at the rims of the fluorescent concentrator.

thick) and the remaining cell area was covered with black material. The silicon solar cell was placed under the fluorescent concentrator, with an air gap between cell and concentrator. Without the concentrator the silicon solar cell had an efficiency of 16.7%. Under the fluorescent concentrator the efficiency dropped to 14.0%. The parallel interconnection of the four GaInP solar cells had an efficiency of 3.7% in reference to the 4 cm^2 area of the fluorescent concentrator (Figure 7). Therefore the total system efficiency was 17.7%, which is significantly higher than the silicon solar cell alone. We expect much higher efficiencies with optimized GaInP solar cells with the correct geometric dimensions.

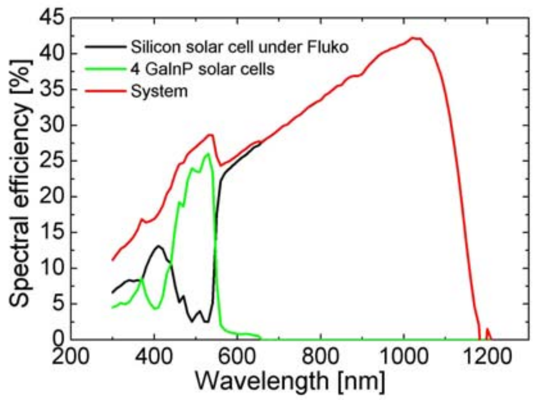

Figure 8: Spectral efficiencies of the silicon solar cell under the fluorescent concentrator, and of the parallel interconnection of 4 GaInP solar cells at the rims of the fluorescent concentrator. It can be seen clearly how the fluorescent concentrator system increases the efficiency in the region of 400 to 500 nm.

5 PHOTONIC STRUCTURE

All emitted light hitting the surface with an angle greater than the critical angle α_c is totally internally reflected, with $sin(\alpha_c) = 1/n$ and n the refractive index of the matrix material. Integration over the loss cone gives a fraction $F = (1-n^{-2})^{1/2}$ that is trapped in the collector [5]. For Plexiglas with $n=1.47$ this results in a trapped fraction of around 73%. The loss of around 27% occurs after every reabsorption and reemission process, so in fact losses due to the loss cone of internal reflection are considerably higher than 27%. Therefore a photonic structure which reflects all light in the emission range of the dye but has high transmission in the absorption range of the dye should significantly increase the collection efficiency of the concentrators.

A possible realization of such a photonic structure is a so-called Rugate filter. It features a continuously varying refractive index profile in contrast to the discrete structure of normal bragg reflectors. This results in the suppression of side loops, which would cause unwanted reflection and loss of usable radiation.

Figure 9 shows the reflection spectrum of a first Rugate filter produced at Fraunhofer IST by chemical vapor deposition. The figure also shows the absorption and photoluminescence spectrum of the fluorescent concentrator the filter was designed for. The reflection band of the filter very nicely fits the emission peak of the

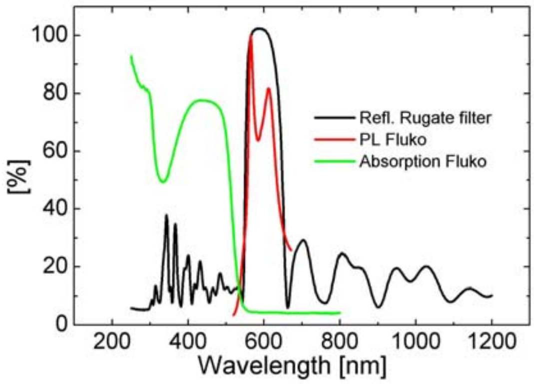

Figure 9: Reflection of Rugate structure, absorption and photoluminescence of the fluorescent concentrator the filter was designed for. The reflection band fits the emission very well, but there is some unwanted reflection in the absorption range of the fluorescent concentrator.

dye in the concentrator. However, there is still some unwanted reflection in the absorption range of the dye. In order to test the effect of the structure on the efficiency of the fluorescent concentrator we built a system out of a 2x2cm² fluorescent concentrator and one GaInP solar cell attached to one of its rims. Figure 10 shows a comparison of the efficiencies of the system in reference to the 2x2cm² area of the fluorescent concentrator with and without the filter for both with and without optical coupling of the solar cell to the fluorescent concentrator. In both cases, there was no significant net increase of the efficiency when the filter was applied to the fluorescent, due to the unwanted reflection in the absorption range of the dye. Weighted with the AM1.5-spectrum and the absorption spectrum of the fluorescent concentrator the losses due to this reflection are 10% of the light being otherwise absorbed by the fluorescent concentrator. That is, as the efficiency remained unchanged, the filter increased the internal light guiding efficiency after the light has been absorbed at least by 11%. The big differences between the cases with and without optical coupling underline the importance of a good optical coupling.

6 OUTLOOK

To increase the fraction of the spectrum that can be utilized with fluorescent concentrators, new dyes that are stable and have high conversion efficiencies in the UV and IR part of the spectrum are needed. Quantum structures, such as luminescent nanocrystals of CdSe [6] could be applicable for this purpose. Purposely built solar cells should significantly improve the efficiency of the systems with fluorescent concentrators and solar cells in comparison to the first test systems, presented in this paper. Growing experience in manufacturing the Rugate structures should result in a significantly positive effect of the structures on system efficiency.

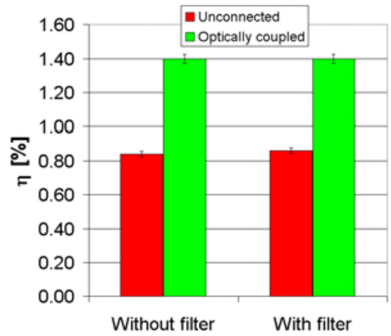

Figure 10: Comparison of the efficiency of a system of a fluorscent concentrator with a solar cell at one rim with and without the Rugate filter. No significant increase in efficiency was achieved. We investigated the effect with and without optical coupling of the solar cell and the concentrator. The optical coupling increased efficiencies significantly.

7 SUMMARY

We presented an advanced concept for a fluorescent concentrator system which aims for higher efficiencies by utilization of the full solar spectrum. Key features are the use of spectral matched solar cells, new materials and a photonic structure which increases the fraction of light guided to the rims. We introduced a quick method to determine this fraction for different fluorescent concentrator materials with photo-spectrometer measurements. First experiments showed efficiencies as high as 17.7% for systems with GaInP solar cells at the rims of a fluorescent concentrator and a silicon solar-cell at the bottom. Through application of the fluorescent concentrator a significant increase in the system efficiency was achieved. The application of a photonic structure which has a reflection band in the emission range of the fluorescent dye increased the internal light guiding efficiency of the concentrator by 11%.

8 ACKNOWLEDGEMENTS

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