PHOTONIC STRUCTURES FOR THE APPLICATION ON SOLAR CELLS

M. Peters[1], J. C. Goldschmidt[1], P. Löper[1], C.Ulbrich[2], T. Kirchartz[3], S. Fahr[4], B.Bläsi[1], S. W. Glunz[1], A. Gombert[1]

[1]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, D-79110 Freiburg, Germany
[2]Institute for Physical Electronics, Pfaffenwaldring 47, D-70569 Stuttgart, Germany
[3] Institute of Energy Research, Photovoltaics, Forschungszentrum Jülich, D-52425 Jülich, Germany
[4]Institute for condensed matter theory and solid state optics, Max-Wien-Platz 1, D-07743 Jena, Germany
Phone: +49 (0) 761 4588 5148 Fax: + 49 (0) 761 4588 9250 Email: marius.peters@ise.fhg.de

Motivation

Photonic structures can be used to increase the efficiency of solar cell systems in several ways. In this study we give examples of two systems that utilize either angular or spectral selectivity for the efficiency enhancement.

The development of the field of photonic crystals that started with the work of E. Yablonovitch and S. John in 1987 [1][2] led to optical elements with interesting spectral and angular characteristics. Photonic crystals are artificial materials with a spatially and periodically varied refractive index. In these materials the photons show phenomena similar to the ones of electrons in a semiconductor. Photonic crystals posses a photonic band gap, a region in the energy-regime where no photons can exist within the material. As photons with energies in the band gap can't enter the crystal and therefore have to be reflected, this band gap can be used to create spectral selective filters. Because the photonic crystals may show different structures depending on the direction of the incident light they also can be used to create angular selective filters.

An example of how spectral selective filters can be used for an efficiency enhancement is given by the advanced fluorescent concentrator concept. This concept has been presented in 2006 by Rau [3] and Goldschmidt [4]. Here the spectral selectivity of the filters is used to stem the main loss mechanism of the fluorescent concentrator.

The process of Ultralighttrapping is an example of how angular selectivity can be used for a very efficient pathlength enhancement. The concept can be found by Green [5].

Simulation of Filters

Two examples for filters are given here that both show an angular as well as a spectral selectivity. The first example is the rugate filter. The rugate filter consists of layers with different refractive indices that are arranged in a way that they approximate a sinusoidal development of the refractive index. The rugate filter shows a spectral selective reflectance with no harmonic sidebands. Simulations of this filter have been performed using the characteristic matrix approach.

The second example is the opal, a three dimensional photonic crystal. The opal consists of spheres with a diameter in the range of the wavelength of the considered light that are ordered in the hexagonal closest package. For the simulation of the three dimensional photonic crystals a codec of Philipp Lalanne that is based on the rigorous coupled wave analysis (RCWA) has been used [6].With this method the electromagnetic field is determined rigorously within an arbitrary periodic structure with a finite thickness. The result of the calculation can be used to obtain the optical properties of the filter under examination.

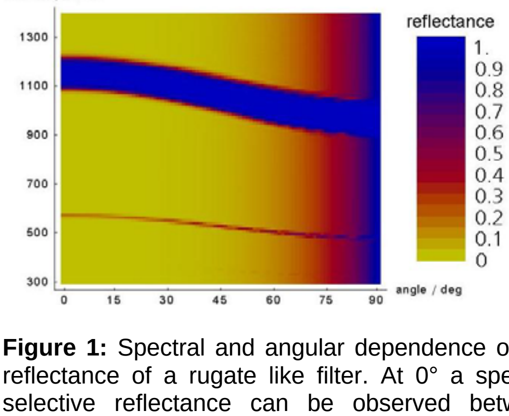

Figure 1: Spectral and angular dependence of the reflectance of a rugate like filter. At 0° a spectral selective reflectance can be observed between 1100nm and 1260nm that is blue shifted for higher polar angles.

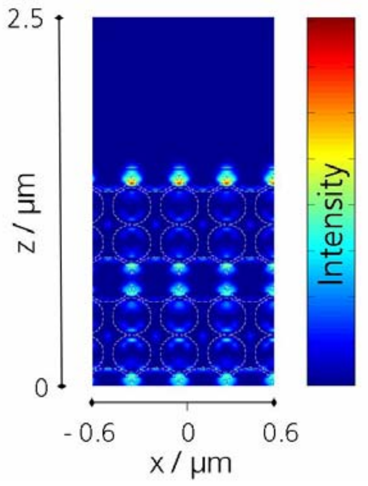

Figure 2: Result of the RCWA-simulation of a three dimensional photonic crystal. In the picture the intensity of the z-component of the electric field inside the crystal is shown. The optical properties are determined from all six components of the EM field.

Results

In a fluorescent concentrator light is absorbed and reemitted with a Stokes-shifted wavelength. The reemitted light is transported to the rims of the concentrator by total internal reflection. Light that is emitted into an angular region where no total internal reflection occurs, the loss cone, is lost for the concentrator. This mechanism leads to losses of about 40% of all the light in the concentrator. The loss mechanism can be stemmed by the use of a spectral selective filter. The demand on this filter is a high transmittance in the absorption range of the dye and a high reflectance in its emission range. In that way the light that the fluorescent concentrator absorbs can enter the system but cannot leave it anymore after the Stokes-shift. The demanded characteristic can be fulfilled by a rugate filter. A filter has been specially designed for one of our fluorescent concentrator system and an enhancement of more than 20% in the efficiency was obtained. The opal shows a similar spectral characteristic. Compared to the rugate filter, the use of opals has the advantage that it acts like a grating and may be used to redistribute light into angles where it is transported to the rims of the concentrator more efficiently.

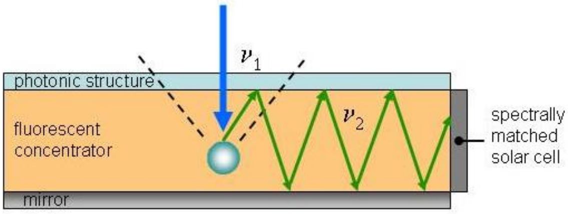

Figure 3: The advanced fluorescent concentrator concept. Light within the loss cone is kept in the concentrator by a spectral selective filter. An enhancement in the efficiency of more than 20% was obtained

A system with a scattering device and an angular selective filter can be used for a very efficient lighttrapping. Light that enters the system is redistributed into all angles. A part of this light is now already trapped in the system because of total internal reflection. Light that leaves the system through the loss cone is again redistributed into the full half space because of Snell's law. An angular selective filter that shows a high transmittance only in a certain angular range will keep again a part of the light in the system. The pathlength enhancement for this system is given by

$$s = \frac{4n^2}{\sin(\alpha)^2}$$

[5] where α is the acceptance angle of the filter and n is the refractive index of the material used. If the acceptance angle of the filter is confined to the appearance angle of the sun, the pathlength enhancement reaches a value of 2.2E6 for silicon with $n = 3.5$. A system like that recommends precise tracking.

In figure 1 the angular selectivity of a rugate like filter is shown. This filter was designed in a way that the light in the region of low absorption of silicon was trapped. We have performed calculations of the theoretical efficiency of a silicon solar cell whereon such a filter was applied. A maximum enhancement in the theoretical efficiency from 25.4% to 26% was shown. A further optimization of the system is possible [7].

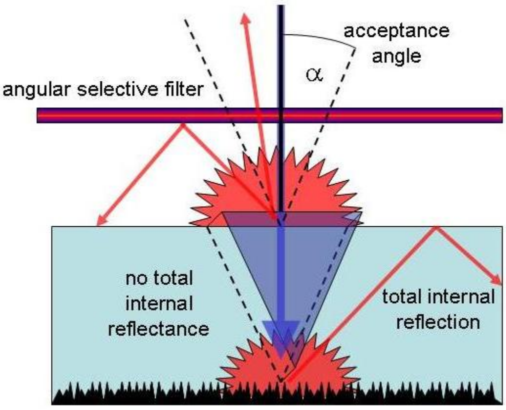

Figure 4: Concept of Ultralighttrapping. Light is scattered at the rear end of the system. All light in the loss cone is again distributed into the full half space. Only the part of light that is after refraction on the front side emitted into the acceptance range of the filter can leave the system.

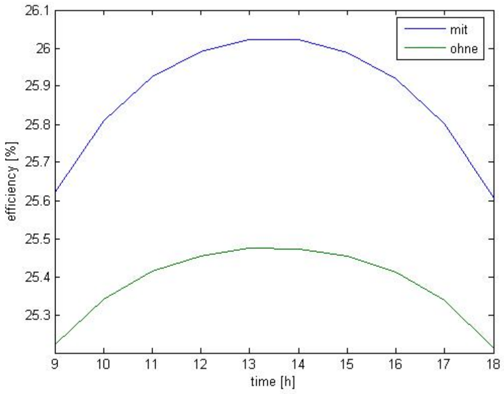

Figure 5: Calculation of the theoretical efficiency of a silicon solar cell with and without the filter shown in figure 1 without tracking. On the x-axes the time of day is shown. The result shown is for a non-tracked system. The maximum efficiency occurs at 13:30 and is increased by the filter from 25.4% to 26%

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