High Solar Concentration Using Diffractive Optics

F. Languy[1], C. Lenaerts, S. Habraken
HOLOLAB, Physics Dept, Univ. de Liège (Belgium)
[1] flanguy@ulg.ac.be

0. Objective

Solar concentrators using lenses suffer from chromatic aberration which is unfavourable for multijonction solar cells. One can think about doublets but unfortunately they are too heavy and expensive to be used.
So the aim of our research is to find an alternative to doublets in order to improve -at low cost- the efficiency of solar concentrators.

1. Theory : ideal diffractive lens

Equating OPL's until the desired focal point, we find the ideal profile.

Fig. 1: monolayer diffractive lens

Each zone introduces a 2π phase shift without discontinuity for the designed wavelength λ_o so that the scalar diffraction efficiency $\eta(\lambda_o)$ is 100%. The efficiency at the 1st order is given by

$$\eta_1 = \left| \frac{\sin[\pi(\alpha-1)]}{\pi(\alpha-1)} \right|^2$$

where α depends on the wavelength :

$$\alpha(\lambda) = \frac{|n(\lambda)-1|\, d}{\lambda} \quad ; \quad d = \frac{\lambda_0}{n_1(\lambda_0)-1}$$

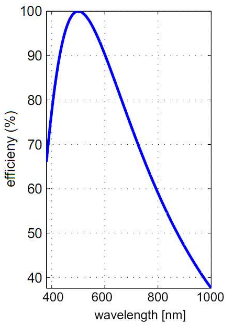

Fig. 2: diffraction efficiency for PMMA

Unfortunately the efficiency drops rapidly by illuminating the lens with another wavelength than λ_o [see Fig. 2]
Adding layers of other material could reduce the wavelength dependence :

$$\alpha(\lambda) = \sum_i \frac{[n_i(\lambda) - n_{i+1}(\lambda)]\, d_i}{\lambda}$$

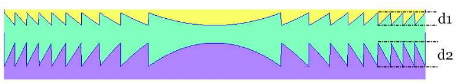

Fig. 3: multilayer diffractive lens

Not only the efficiency depends on the wavelength but also the focal length :

$$f(\lambda) = f(\lambda_0)\frac{\lambda_0}{\lambda}$$

so that the Abbe number V_d=-3.45 is independent of the material used.

The use of a diffractive lens and a refractive one could thus easily lead to an achromatic system over a wide wavelength range.

2. Non sequential ray-tracing (ASAP ®)

First of all, we have to note that ASAP traces only geometric rays so that we need to check the energy.

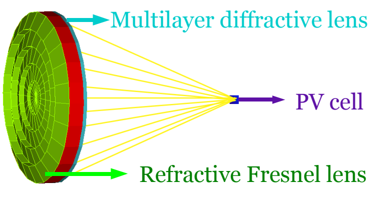

Fig. 4: system under analysis

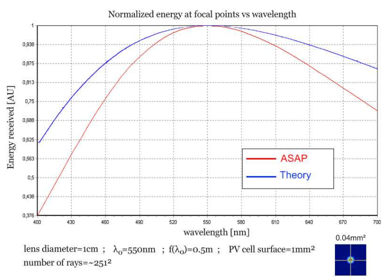

Fig. 5: energy violation

We used the option that propagates gaussian beams based on scalar waves.

At the designed wavelength, theory and results agree but at other wavelengths we observe a violation of the energy conservation [see Fig. 5]. Moreover, if we try to simulate a multilayer diffractive lens ASAP doesn't achieve to propagate the gaussian beams.

3. Optimization on solar spectrum

With two layers (or more) we can easily reach 100% efficiency for two chosen wavelengths. The thicknesses d1 and d2 [see Fig. 3] allowing to get 100% efficiency (this mean α=1) are determined by

$$\left. \begin{aligned} \alpha(\lambda_1) = 1 = \frac{n_1(\lambda_1)-1}{\lambda_1} d_1 + \frac{n_2(\lambda_1)-1}{\lambda_1} d_2 \\ \alpha(\lambda_2) = 1 = \frac{n_1(\lambda_2)-1}{\lambda_2} d_1 + \frac{n_2(\lambda_2)-1}{\lambda_2} d_2 \end{aligned} \right| \text{ 2 equations and 2 unknows}$$

We can then integrate the energy coming from the sun and transmitted at the first diffraction order and optimize the energy transmitted by moving the maxima (= changing d1 and d2)

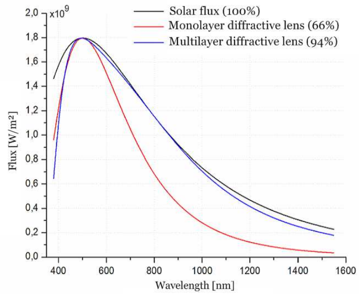

Fig. 6: flux at first order compared with solar flux

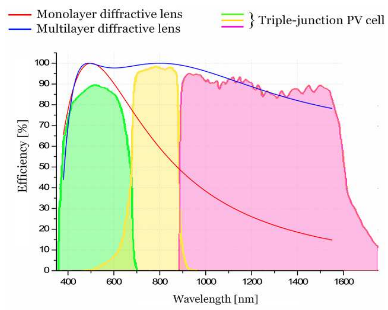

Fig. 7: 1st order diffraction efficiency compared with a triple junction PV cell

4. Rigorous coupled wave analysis

Based on Maxwell's equations, RCWA is a powerful numerical tool to deal with diffraction gratings.
Although our software is limited by a periodic structure because of a decomposition of the permittivity in Fourier series, thanks to RCWA we are able to determine which part of energy will be diffracted in each order of diffraction.
This allow us

- to check the validity of scalar theory [see Fig. 8];
- to check the importance of the thickness between layers;
- to investigate the consequence of an angle of incidence other than zero [see Fig. 9].

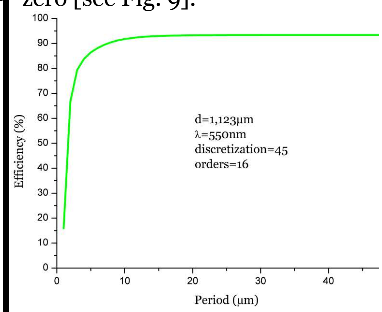

Fig. 8: period dependence

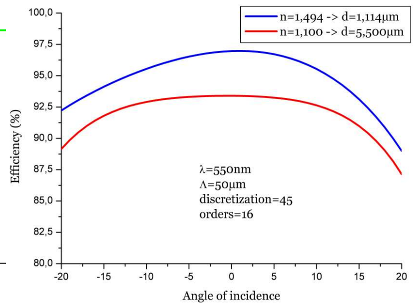

Fig. 9: evolution of the efficiency with the angle of incidence

Note that with a higher number of orders (>45) the efficiency increases by about 2% but simulations require expensive time calculation.

5. Conclusions and further research

Hybrid lenses represent a serious alternative to refractive doublets: they are thiner, lighter and so should be cheaper if made by mass production.

In the next months we will implement our RCWA programme so that it will be able to take count of the chromatic dispersion.
In the same time, ASAP simulations should be performed using another option (INTERFACE DIFFRACT) planed for diffractive surfaces.

In January 2009 the industrial phase should begin.