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**Office fédéral de l'énergie OFEN**

# INTEGRATED MULTIFUNCTIONAL GLAZING FOR DYNAMICAL DAYLIGHTING

## Midyear report 2011



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### ABSTRACT

In this project, a novel integrated concept and the development of advanced glazing for dynamical daylighting are studied. The novel glazing will combine the functions of daylighting, glare protection, overheating protection in summer and thermal insulation in winter. Novel micro-structures shall provide redirection of the incident solar radiation, thus providing for chosen angles projection of daylight deep into the room in the same manner as an anidolic mirror-based system, as well as glare protection. The solar gains will be reduced for chosen angles (e.g. for given incidence angles in summer at noon). Recently developed solar protection coatings ("M-coatings") shall provide the optimized spectral properties of the transmitted sunlight: maximized visible transmission for daylighting and carefully dosed energetic transmission for overheating protection in summer. The solar protection coatings simultaneously provide the necessary low thermal emittance in combination with a double glazing in order to ensure thermal insulation in winter. Technological progress will include the improvement of micro-structures by selective deposition of micro-mirrors, easier fabrication of micro-structures by sol-gel techniques and the powerful combination of solar protection "M-coatings" and micro-structures.

In the first half of 2011, the software tools have been extended with a thin film calculations module and further used to asses the performance of structured glazing. An angular selective structure with a strong seasonal behaviour was designed.

In the laboratory, the first prototype mould and the second more advanced mould were realised using electrical discharge machining. Using a replication technique in UV curing polymer, custom microstructured samples were realised. These sample were then selectively coated in an evaporation process. The samples were then characterised using different imaging techniques.

The optical set-up for the measures of planar transmission distribution was completed. It provides a fully automated measurement of planar transmission distribution with a high dynamic range and a custom software. The first sample were measured using this setup and demonstrated the principle of integrated mirrors .

## Project Goals

In this project a novel integrated concept and the development of advanced glazing for dynamical daylighting are studied. The novel glazing will combine several functions:

- Daylighting: redirection of incident radiation and projection of daylight deep into the room, thus reducing electrical lighting needs.
- Glare protection/visual comfort: angular dependent solar transmission to achieve the most effective blocking for the elevated angles of direct solar radiation during summer.
- Overheating protection in summer: The glazing should avoid overheating of the building in summer, but provide sufficient natural daylighting and acceptable solar gains in winter.
- Thermal insulation in winter: Double-glazing and the low emissivity properties of the used thin film coating provide thermal insulation in winter.

**APPROACH:**

- **Study existing products and architectural requirements**.
- **Obtain further simulation results**.
- **Fabricate novel micro-structures.**
- **Show that it is possible to partially coat the micro-structures.**
- **Measure the resulting coated micro-structure.**

## Accomplished work and results.

### 1. Study of existing products and architectural requirements for this novel glazing.

Professor Peter Oelhafen was interviewed about the architectural habits concerning glazing. Further literature review was done in the area of energy efficient architecture. All this work brought us to the conclusion that the pursued advanced fenestration system should be cheap and targets particular situations. It makes most sense in case of highly glassed façades, daytime occupied spaces and lighting needs more than 5m from the window. This type of complex fenestration system (CFS) is therefore better suited for high rise office buildings then individual personal houses. For glazing in public transportation a CFS could also be interesting but the varying orientation of the glazing would require an further research.

An other conclusion of this study is that the influencing factors for the choice of a glazing are the g value and aesthetic aspects. The g value is then often calculated over a whole year or season. In the most advanced case, the g value is calculated for both the heating and the cooling season. During the heating season, a high g value is preferred, while during the cooling season a low g value is preferred.

### 2. Simulation results

The simulation tool was extended with the ability to model thin films. Transmission and reflection coefficients in systems with thin films are directly influenced by thickness of the thin films and the wavelength of light. Snell law and Fresnel coefficients are not sufficient any more. To be able to model CFS including thin films these calculations were added and verified with a stack of 4 layers alternating low and high refractive indexes to compose an anti-reflective coating (*Figure 1*). Additionally, in order to obtain 3 dimensional BTDF the algorithm was modified to accurately compute a 3D path in a 2D system. Because of the extruded property of the designs, the intersections can be computed in two dimensions while the interactions (reflection, refraction) are computed in three dimensions.

The optimisation of such a stack of layers is complex. In tools such as TFCalc this can be done easily using algorithmic methods. In the case of complex geometries with multiple facets and orientation of the coated area, the incoming angle can be changed after multiple reflections. Analytical methods are not available in this case. We propose to introduce a genetic algorithm to search for the optimal solution in an evolutionary manner.

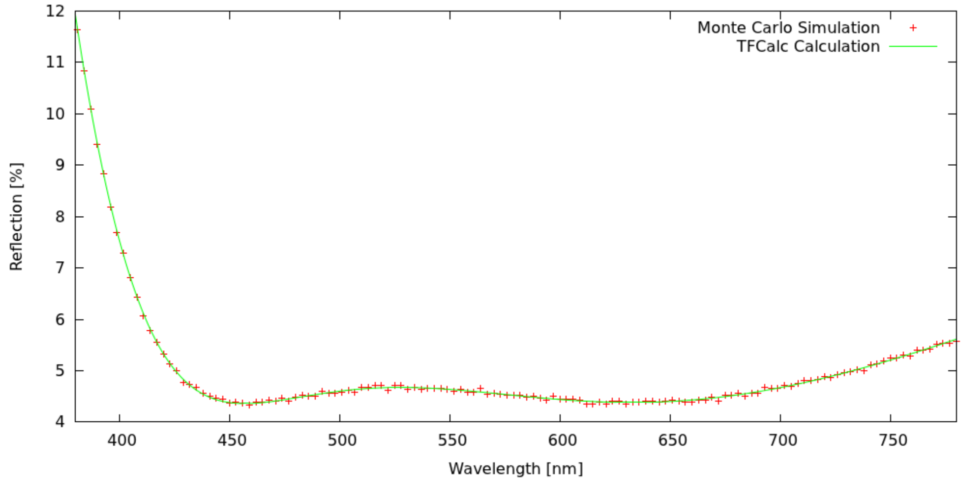



*Figure 1 : Comparison of the spectral reflectance between TFCalc simulation and Monte Carlo Simulation.*

So far, only the daylighting aspect was optimised and the seasonal behaviour was not fully realised. In a new design, a strong angular dependent behaviour is achieved: for incidences between 50° and 60° the transmission is cut down gradually from 80% to 10%.

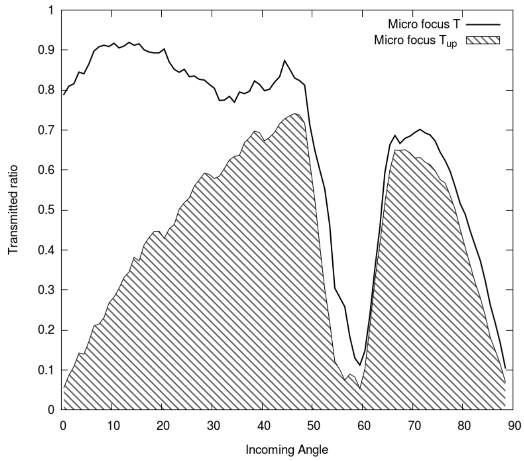
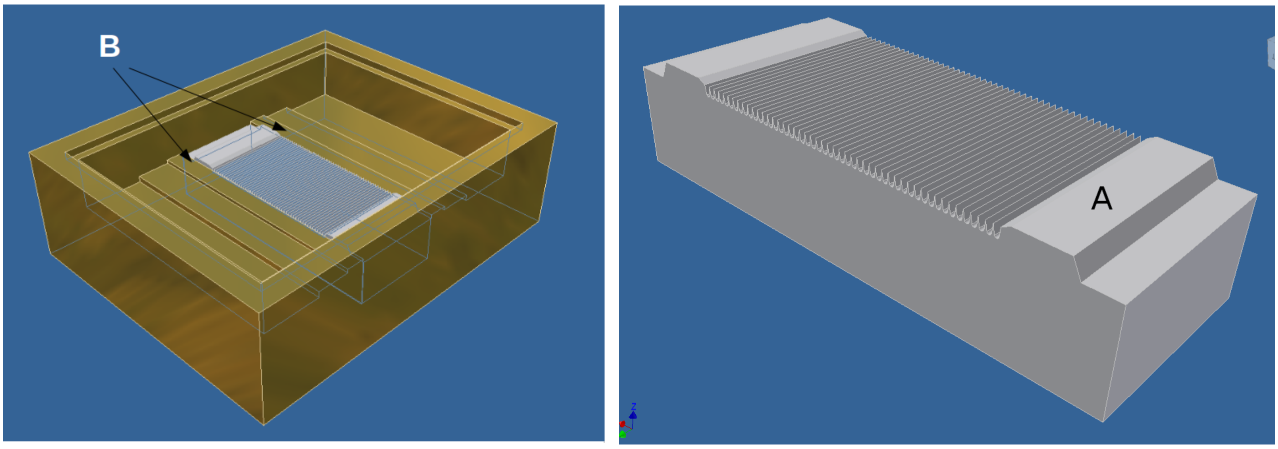



*Figure 2 : Transmission and upwards transmission depending on incoming angle.*

### 3. Fabrication of micro-structures

The first mould was fabricated by electrical discharge machining on site with the collaboration of the mechanical department of the physics institute. Because of the round shape of the wire, sharp corners can not be realized at concave angles. Therefore the mould has round corners at the bottom of the grooves and sharp edges at the top (see *Figure 3b*). The shape of this mould is an ideal final shape, and it will be referred to as father. To reproduce the shape of the father, a negative can be used as mould for the substrate, the negative will be named mother. This intermediate step makes it possible to chose a material well suited for moulding of the final material: a UV curing resin developed at the LTC. Polydimethylsiloxane (PDMS) is a silicon based organic polymer and is known to work well as a mould for most resins and has been tested at LTC.

The first trials for PDMS mould fabrication were done at CMi and a satisfying, simple stamp like mother was obtained. Once the trial revealed successful, a more refined mould had to be designed to align the structures perpendicularly to the glass substrate. This second generation mould shown in *Figure 3a* also had to be designed to be able to fill the sawtooth shape after coating. To do so, the resin structure must have two reference surfaces on each side of the structural region (A in the figure). These reference surfaces must by higher than the structure, they define the final thickness of the system. The design of this mould takes into account that excess resin must escape the mould (B in the figure).




*a)* *b)*

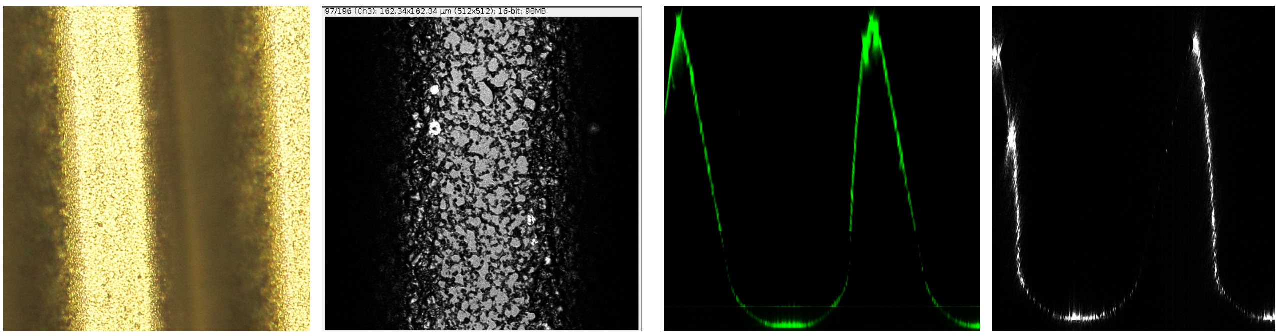
*Figure 3 a) view of the father mould and b) : detail of swappable structure mould.*

A replication setup available at LTC was used to produce samples from the mother mould. The substrate, resin and mould are placed on a piston, the piston pushes against a sapphire glass above witch a UV lamp is switched on for 3 minutes to cure the resin.

## 4. Coating of micro and macro structures by physical vapour deposition (PVD)

Some of the structures obtained with the first mould were also coated with an aluminium layer using the angular setup for evaporation. The resulting samples were effectively facet selectively coated and showed angular dependent behaviour when illuminated with a collimated beam.

Images obtained by optical microscopy of the transparent mother mould (*Figure 4a*) show how the roughness created by the wire erosion process transferred perfectly to the PDMS. This roughness also transfers perfectly to the resin structure (*Figure 4b*). It is a sign of good replication and demonstrates the fidelity of this method. However, this roughness creates very diffusing surfaces that will have to be eliminated in the future. Because confocal microscopy gives greater resolution than traditional optical microscopy and allows to create 3D profiles, it was selected for complimentary characterisation.



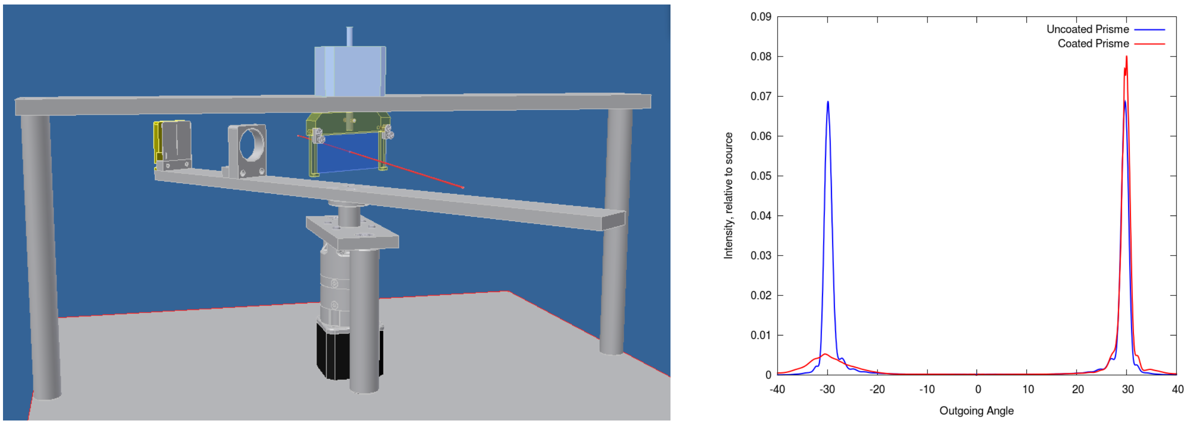
*a)* *b)* *c)* *d)*

*Figure 4 a) optical microscope view of roughness on PDMS replication. b) Confocal microscope image of the surface texture for a replicated structure in resin. c) confocal microscope image showing the profile of an uncoated replicated sample. d) Confocal microscope image of a coated microstructure.*

Confocal microscopy is an optical imaging technique using point illumination with a laser and a spatial pinhole to increase optical resolution and contrast. This point by point acquisition enables the reconstruction of three-dimensional structures. This particular aspect is very interesting to study the profile of created microstructures. Images were obtained at the BioImaging and Optics Platform (BIOP) using a LSM 710 Zeiss confocal microscope. The two samples are microstructures of the first generations and it was possible to observe the shape of the structure (*Figure 4c*). The selective coatings appears clearly on *Figure 4d* : one face is bright and clear, the other on is almost invisible. The brightness of the peak is partially an artefact due to light scattering and the brighter bottom is due to higher reflectivity. This method requires a water immersed objective and it was observed that water swells the resin and destroys the structures.

**5. Measurements.**

For a precision goniometer we required an angle selective sensor, an accurate measure of the signal provided by the sensor, a data acquisition method to read this measure on a computer and a set of motors with a computer driven control for automated measure. For the sensor a focusing lens and a slit select only perpendicular light coming from the sample. Behind the slit, a photo diode with an amplifier converts light into voltage. These elements and two stepper motors were assembled as shown in *Figure 5a*. To measure accurately even very small signals and eliminate the surrounding noise, a lock-in amplifier was used. A lock-in amplifier uses a reference to distinguish signal from noise, integrates signal over time and amplifies it if necessary. Thanks to the work of Mario Geiger, a digital lock-in was developed using only a pre-amplifier and a sound card. The line in of a sound card has two channels and can read voltages between 0 and 1 V at 92KHz. Using one channel for the signal and one for the reference we have synchronised signals that can be used in a digital lock-in software.




*a)* *b)*

*Figure 5 a) CAD drawing of the measurement setup as it has been built. b) Measurement of a coated and uncoated prism using the given setup.*

This digital lock-in amplifier was then integrated to a program that simultaneously controls 2 stepper motors to rotate the sample and the sensor. The motors are driven by a controller card to witch the program sends its orders. A calibration step aligns the two motor axis with the zero reference before measuring BSDF in the plane. Angular resolution of less than one degree has been reached. This setup was used to measure transmission in coated and uncoated prismatic films. For validation of the measure, the transmission of a clear glass sample was measured depending on incoming angle. A coated and uncoated 3M prism was measured using this setup and the angular dependant behaviour was demonstrated (*Figure 5b*).

## Mid-Term Evaluation 2011

There are five main objectives to this project: a study of the state of the art, a simulation aspect, the fabrication and deposition task, and finally measurement of optical properties. All of these have been approached and most of them successfully reached.

1. **Architectural integration:** Progress was made and needs have been further identified.
2. **Simulations:** Thin films calculations and accurate three dimensional calculations were added.
3. **Micro-structure fabrication:** First metal moulds were produced and replicated.
4. **Coating:** Selective Coatings were successfully realised on custom microstructures. Only few samples could be produced because the laboratory move had to be moved to an other building.
5. **Measurements:** The set-up was fully automation and first measurements were carried out. Only few samples could be measured because the laboratory move had to be moved to an other building.

## Outlook for End of 2011

Because the laboratory is in the process of being moved, before any work can be continued, all the equipment used in the laboratory has to be installed if it is not already done, restarted and recalibrated.

1. **Architectural integration:** More architects will be contacted to further understand their needs.
2. **Simulations:** Genetic algorithms will be introduced for optimisation.
3. **Micro-structure fabrication:** The moulds have to be mirror polished to reduce diffusion. Further miniaturisation has to be studied.
4. **Coating:** Deeper studies on the effect of the deposition angle will be done using the confocal microscopy. A solution to the swelling problem has to be found.
5. **Measurements:** The methodology and protocol for the measurement has to be completed to give quantitative results.

## Invited presentations 2011

A. Schüler, *Nanocomposite thin films for solar energy applications*, invited lecture, January 26, 2011, Centre de Recherche Européenne CREE de St-Gobain, Cavaillon, France.

A. Schüler, *Nanocomposite optical coatings for solar energy applications*, invited lecture, February 11, 2011, St-Gobain Recherche SGR, Paris, France

A. Schüler, *Nanocomposite coatings for solar energy conversion*: Large opportunities for small structures, invited lecture, May 19, 2011, Eidgenössische Technische Hochschule Zürich ETHZ

## Industry Contacts

- Partnership with SWISSINSO: technology transfer of magnetron sputtering and research on novel coatings for innovative solar collector glazing
- Collaboration with GLAS TRÖSCH for production of prototype glazing by industrial scale magnetron sputtering
- ASULAB (SWATCH GROUP) donated equipment for vacuum deposition of thin films, suitable for multilayer deposition

## International Collaboration

- Pietro Altermatt, University of Hanover and Institut für Solarenergieforschung Hameln (ISFH)

## National Collaborations

- Collaboration with Prof. Peter Oelhafen and Roland Steiner's research group at the Institute of Physics, University of Basel.
- PV laboratory at the University of Neuchâtel.

**ON CAMPUS:**

- Research group of Dr. Yves Leterrier in Professor Jan-Anders E. Månson's laboratory LTC for structure replication.
- Access to lithographic techniques and etching for micro-structuring at EPFL-CMi
- Access to electron microscopes and to the facilities of TEM sample preparation at the Interdepartmental Center of Electron Microscopy EPFL-CIME
- Prof. Libero Zuppiroli's research group (LOMM at EPFL) provides access to their new ellipsometer
- Collaboration with Dr. Rosendo Sanjines and Henry Jotterand, Laboratory of Thin Films Physics, Prof. Laszlo Forro, Institute of Complex Matter Physics, EPFL. Experiments on magnetron sputtering and X-ray diffraction analysis.
- Synergy with Dr. Jerôme Kaempf of LESO-PB who has the competences for macro scale modelling and rendering.