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INTEGRATED MULTIFUNCTIONAL GLAZING FOR DYNAMICAL DAYLIGHTING

Annual 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 2011, the software tools have been extended with thin film calculations and genetic algorithm optimisation modules. They were then 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 and filled with resin to integrated the mirrors. The samples were then characterised using different imaging techniques.

The optical set-up for the measures of planar transmission distribution was completed and tested. 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. Discussion with architects was pursued during the Cisbat conference amongst other occasions. 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.

2. Simulation results

The simulation tool was extended with the ability to model thin films and optimise designs using a genetic algorithm. Transmission and reflection coefficients in systems with thin films are directly influenced by thickness of the thin films and the wavelength of light. 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 1a*). 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.

Using a genetic algorithm, a fitness function can be defined using the computed BTDF and target anything from low transmission, maximum redirection to specific spectral properties. The algorithm will generate random designs using the specified bounds for the parameters we want to optimise. These multiple designs are like individuals in a population. The best individuals regarding the fitness function are kept while the worse are omitted (survival of the fittest). The fittest individuals generate offspring following the genetic laws of crossover and mutation. This way, generation after generation, the populations evolves into a better one. The algorithm stops after a chosen number of generation or once the fitness converges.

This algorithm was tested on an anti-reflective coating. The coating was defined, simulated and optimized for minimum reflection in the visible range with a classical software for thin film design (TFCalc). It is a 4 layer coating on a glass substrate with alternate low and high refraction indices as shown in *Table 1*. The thickness of the 4 layers were successfully randomized and the Genetic algorithm was then used to find them. With one and two unknown parameters, the optimum is reached after only 2 generations. With 3 randomized parameters, the optimum is reached after 6 generations. *Figure 1b* shows the best reflection spectra for generations 1, 6 and 10 when all 4 layers are randomized.

Material	Sol-Gel TiO_2	MgF_2	Sol-Gel TiO_2	MgF_2
n	2.2	1.38	2.2	1.38
Thickness [nm]	17.66	50.52	25.00	122.47

Table 1 : Anti-reflective multi layer coating as optimised with TFCalc.

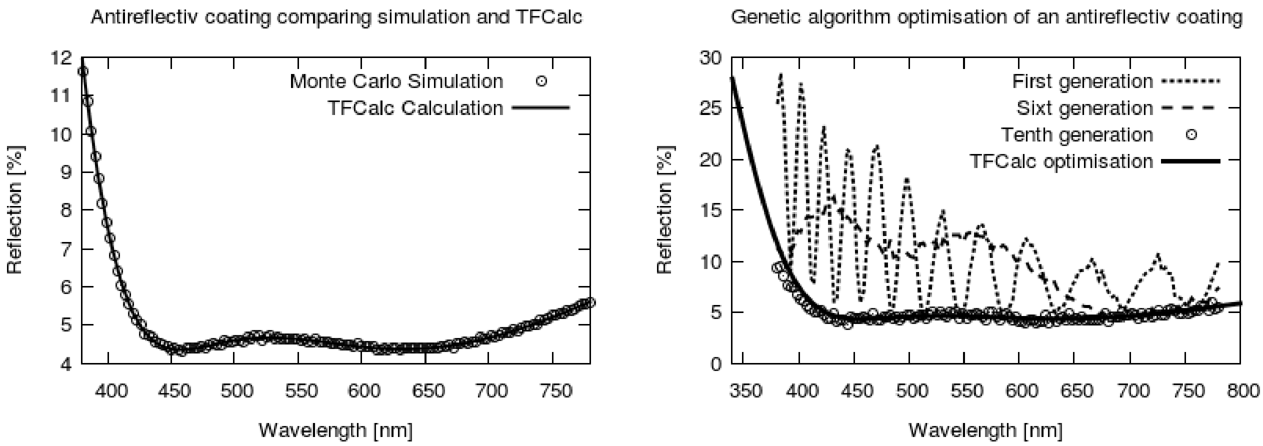


Figure 1 : a) Comparison of the spectral reflectance between TFCalc simulation and Monte Carlo Simulation b) Convergence of a population towards an optimised 4 layer anti-reflective coating using a genetic algorithm and ray tracing.

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 angles of incidence between 50° and 60° the transmission is cut down gradually from 80% to 10%. These new designs can now be modified and simulated with interferometric coating for the optimisation of spectral behaviour.

3. Fabrication of micro-structures

The first trials for PDMS mould fabrication were done at CMi and a satisfying mother mould was obtained. An advanced mould was designed to hold different insert fabricated by electrical discharge machining. PDMS mother moulds were produced (*Figure 2*). These moulds were then used to create structured and flat surfaces on glass substrates using an UV polymerizing resin.

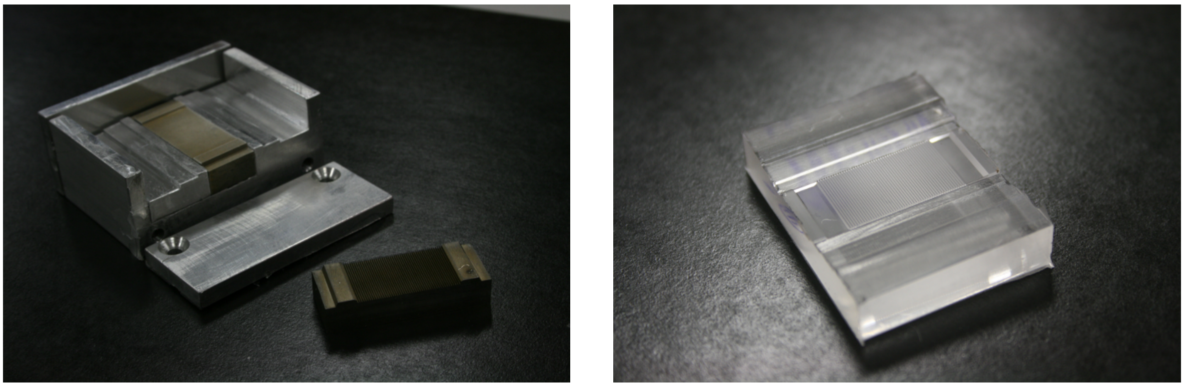
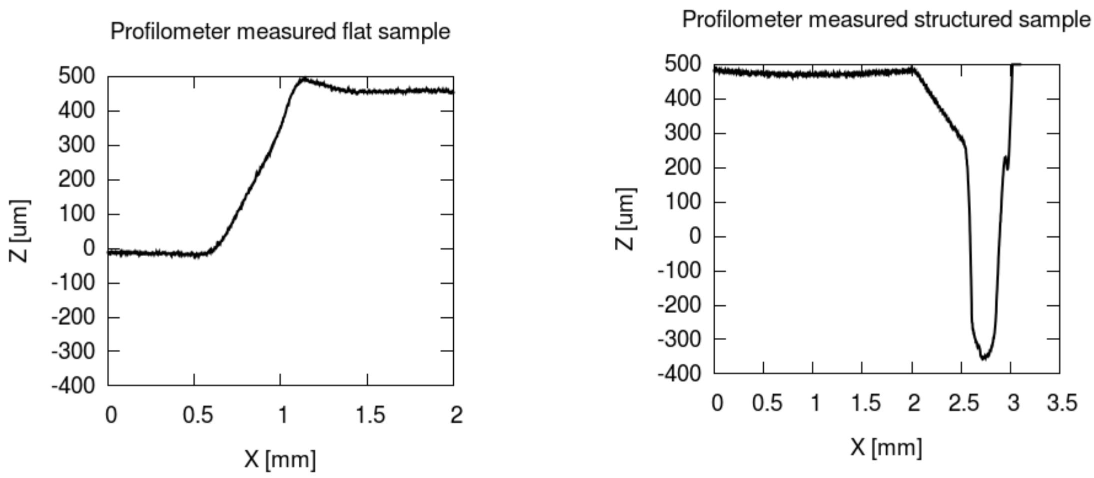


Figure 2: a) Photograph of the father mould and the two inserts b) Photograph of the PDMS mother moulds.

Some samples were completely coated with aluminium and analysed with a UBM profilometer (*Figure 3*). The flat area of the flat sample was used to characterise the surface roughness and the arithmetic average of the roughness (*Ra)* was measured at 1.48 um. This surface roughness is responsible for the diffusing behaviour of the sample. The structured sample could only be measured until the first peak of the first structure. At this point the signal was lost and the measurement interrupted. Both profiles were started on the border of the sample, on the reference surface for the filling of the structure. This surface is the area were the resin is thickest and the irregular, uneven profile shown in *figure 3b* indicates that the resin was not completely cured and that it was distorted during unmoulding. Longer UV exposure time solves this problem.

To eliminate the surface roughness of metallic mould inserts, a treatment in an ultrasonic bath with diamond micro particles was attempted but this technique was not successful. Electro polishing however yielded promising results. The test mould was electro polished during 2 minutes only and the flat surfaces cut with electrical discharge machining already showed a specular reflection of objects. The spikes of the father mould are conserved in this process and it seems to be the solution of choice to create mirror polished surfaces on the microstructures without wearing the spikes.

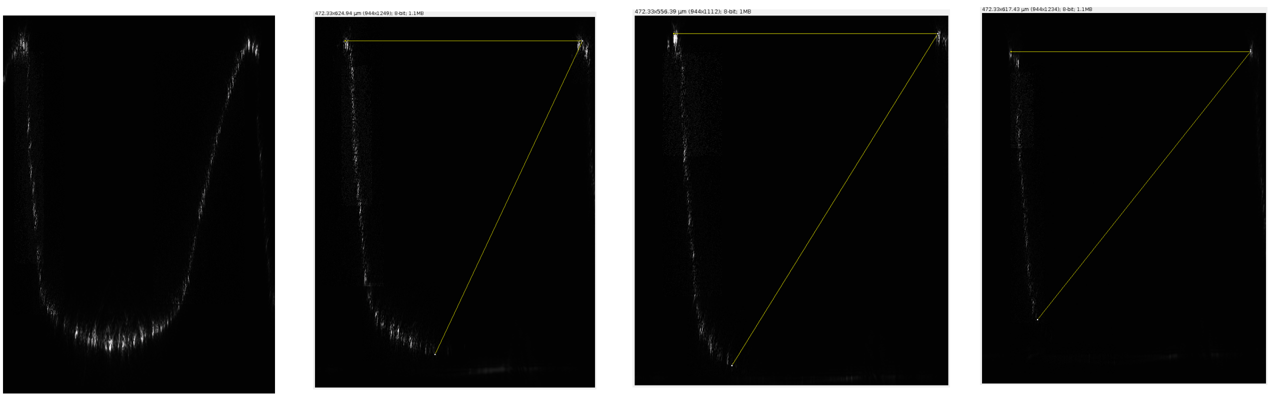


a) *b)*

Figure 3 a) the right border of the flat sample b) the left boarder and first microstrucutre of the structured sample.

4. Coating of microstructures by physical vapour deposition (PVD)

Structured samples obtained with the second mould were coated with an aluminium layer using the angular setup for evaporation. Confocal microscopy was once again used to create 3D profiles, and characterise how the angular deposition affected the coating location. The image processing software *Fiji* was used to measure angles on the resulting images (*Figure 4*). As shown in *table 2*, the angle of incidence directly influences the deposition region. However the relation does not seem to be linear, this is most likely due to the fact that the angle of deposition varies within 3° on a single sample and that samples were not necessarily measure at the same location.



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

Figure 4 a) 90° evaporation b) 55° evaporation c) 50° evaporation d) 45° evaporation.

Angle of incidence	90°	55°	50°	45°
Observed angle	90°	65°	58°	52°

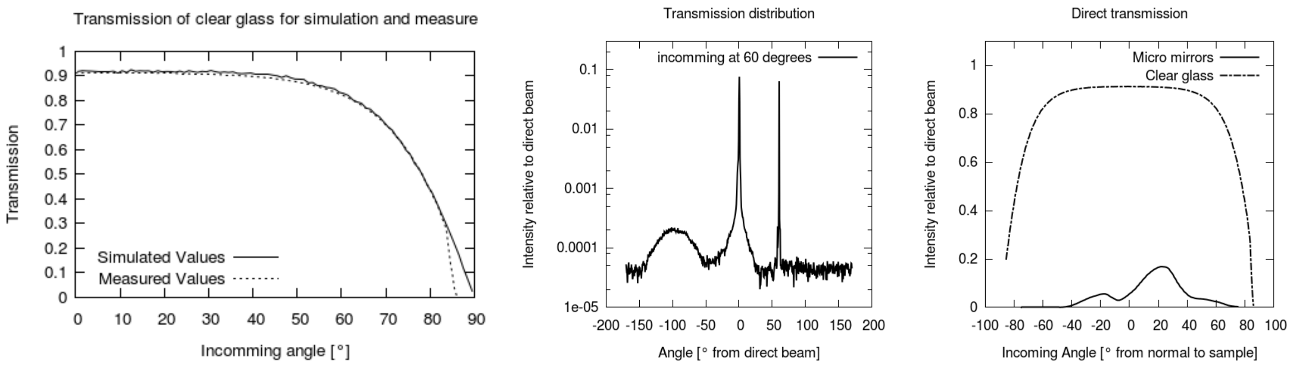
Table 2 Incident angle and observed deposition angle.

5. Measurements.

A precision photo-goniometer was developed and built. This 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.

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 which 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. For validation of the measure, the transmission of a clear glass sample was measured depending on incoming angle. The transmission is accurately measured until 83° incidence. For greater angles, the beam becomes to big on the sample.

It was tested for repeatability and after replacing the power supply with one independent from the mains voltage fluctuation, variations lower than 0.1% were measured. The quantitative output of the photo-goniometer was tested with the transmission of a simple glass substrate under changing incoming angles (*Figure 5a*). The linearity of the sensor was tested by comparison with an absolute calibrated spectrometer. It was confirmed that the used silicon photo diode has a specific spectral response with a peak at about 900nm. This will have to be kept in mind when the setup is adapted for spectral measures using a monochromator.



a) *b)* *c)*

Figure 5 a) Comparing measured and simulated transmission depending on incoming angle in a clear glass. b) Angular transmission for a 60° incoming beam c) Direct transmission depending on the incoming angle for a integrated mirror sample and a clear glass sample.

The coated samples with integrated mirrors were measured using this setup and despite the very strong diffusion due to surface roughness, the angular dependent behaviour was characterised (*Figure 5b*). The direct transmission is strongest at about 20° when the incident beam is refracted inside the sample, parallel to the structures (*Figure 5c*). The direct transmission is minimum at incidences above 40° when the structures redirects most of the light. The low values compared to a clear glass are due to the diffusing surface and to the fact that a large part of light is redirected thus not measured in the direct transmission.

2011 Evaluation

The laboratory was successfully moved and all equipment relative to this project is running again. 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 despite the moving of the laboratory.

1. **Architectural integration:** Discussion has been pursued.
2. **Simulations:** Thin films calculations, accurate three dimensional calculations and genetic algorithm optimisation were added.
3. **Micro-structure fabrication:** Advanced metal moulds were produced and replicated. Electro polishing was tested as a polishing method. Three times smaller moulds can be realised with the same technique.
4. **Coating:** Selective Coatings were successfully realised on custom microstructures. The coating location was observed.
5. **Measurements:** The set-up was fully automated and verified. Measurements of integrated mirrors were carried out and the concept validated.

Outlook for 2012

All tools for this project are now ready and validated, they now have to be used to produce results.

1. **Architectural integration:** Specifications for the quantifications of performance and needs depending on the building type will be set.
2. **Simulations:** The simulation tool will be used to refine designs and add spectral behaviour.
3. **Micro-structure fabrication:** The polishing has to be studied further and optimal parameters need to be found. Further miniaturisation has to be studied.
4. **Coating:** More samples will be produced and the special mask for coating will be designed and produced.
5. **Measurements:** The setup will be adapted to use a monochromator and give spectral measurements.

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
- Discussion with several providers 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 Roland Steiner and Prof. Peter Oelhafen, Institute of Physics, University of Basel.
- PV-Lab at IMT Neuchâtel (EPFL).

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.
- Access to profilometry at Tribology and Interface Chemistry Group with M.E.R Dr. Stefano Mischler