



INTEGRATED MULTIFUNCTIONAL GLAZING FOR DYNAMICAL DAYLIGHTING

Annual report 2012

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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 2012, the software tools have been used to find an optimised structure offering both redirection of light for daylighting and seasonal blocking of direct radiation for dynamic thermal control. This design was patented and presented at an international conference. Direct and diffuse transmitted energy have then been evaluated using data from meteorology. Rendering using Radiance have been performed to evaluate the daylighting aspect.

A company was contracted to produce an advanced mould corresponding to this design using electrical discharge machining of tungsten carbide. The feature period was lowered to 200 micron using a 50 micron diameter wire for the cutting. This mould was then spin coated with resin to further smoother the surface. Interference lithography and soft material engraving were studied as solutions for the production of smooth moulds.

The mould was used to create microstructured samples of polymer. The sample were coated with aluminium and the resulting film studied. Some of the coated microstructures were covered with resin to embed the mirrors. The optical set-up was used to characterise the diffusivity due to the surface roughness and to evaluate the performance of embedded parabolic mirrors. The surface roughness was also measured using contact and laser profilometry.

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:

- **Set specifications for quantification of performances (for architectural requirements.)**
- **Obtain a corresponding design.**
- **Fabricate novel micro-structures.**
- **Partially coat the micro-structures and embed them.**
- **Measure the resulting coated micro-structure.**

Accomplished work and results.

1. Set specifications for quantification of performances

For daylighting, glare and illuminance on the work plane are the critical values. Glare can be estimated using the Unified Glare Rating (UGR) or the Daylight Glare Index (GDI) and illuminance is measured in lux and should be between 300 and 1000 depending on the task. For common office work, values between 300 and 500 lux are required. To assess these values for the developed complex fenestration systems, the software is used to create the characteristic bidirectional transmittance distribution functions (BTDF). First results using these BTDFs with a radiance based software showed good results.

For seasonal thermal control, the defining values is the thermal gains. For each square meter of window, a portion of the incoming radiation is transmitted and this energy heats up the space behind the window. To calculate an estimate of this value, diffuse and direct transmission factors are calculated with the ray tracing simulation tool and will be used in combination with meteorological radiometric data. To combine these data, a common representation of space has to be used. For direct radiation the solar position is used and for diffuse radiation, the hemisphere is divided into patches following Tregenza's subdivision of the sky.

2. Simulation results

A new design using a parabolic embedded mirror fulfilling the objectives defined above was found. The key of this new design is the focusing of light from an angular interval by a first component onto a second component. To focus incoming light, the first component of the system should be a parabolic surface. The parabola has to be drawn in order to focus light incoming from a given range of incident angles on a second reflecting surface, which is located on the inner side of the system. This second mirror reflects lights from the selected range back through the system. The ratio between the width of the first component and its periodicity will determine the range of angles for which the parabola redirects light. After reflection on a parabolic shape a parallel beams is distributed over a range of angles. This distribution of direct light is suited for daylighting.

The second component should be located close to the foci of the first component. The focus is achieved for angles corresponding to the summer elevation of the sun at the specified location (for example 60° in Lausanne). For this range the light is concentrated on the second surface and reflected. The resulting transmission depending on the incoming angle can be seen in *figure 1c*. The two components have to be arranged in a way to minimize further interactions and efficiently reflect light out of the system. To achieve clear view, di-

rect transmission without interaction for close to normal angles is maximized: the two elements have a minimal height and maximum overlap. Also, the first and last interfaces are parallel to avoid distorting the image. This novel design was submitted for patenting.

This new design based on a parabolic embedded mirror was the studied further. The range of incident angles for which the light transmittance is considerably reduced was studied and for the evaluation of the proposed system, glare and illuminance on the work plane were analysed. Glare can be estimated using the Unified Glare Rating (UGR) or the Daylight Glare Index (GDI) and illuminance is measured in lux and should be above 300 lux for common office work. The BTDF calculated from the ray tracing is directly used in Geronomo, a software developed by Jérôme Kaempf at LESO. After careful alignment of the reference coordinates and of time, this radiance simulation was used to compute illuminance levels and glare indices on the defined workspaces over the course of a day, month or year in different sky conditions. A rendering example can be seen in Figure 1.



Figure 1: Rendering of a typical office at noon during a summer day with a microstructured glass

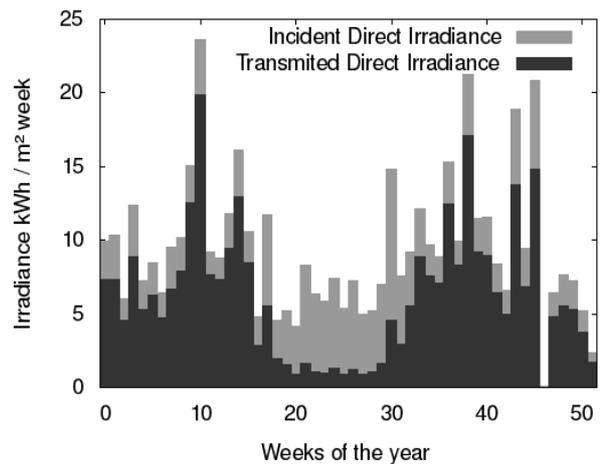


Figure 2: Simulated transmitted irradiance per surface area for a microstructured glass over the year compared to incident direct irradiance.

For seasonal thermal control, the defining values are the thermal gains. To calculate and estimate this value, diffuse and direct transmission factors are calculated with the ray tracing simulation tool and used in combination with radiometric data from meteonorm. The thermal gains due to direct and diffuse radiation were computed over the year and compared with other types of glazing. The designed glazing showed a transmittance of direct sunlight lower than 20% during the summer period and higher than 70% during the winter period. Results are shown in Figure 2.

3. Fabrication of micro-structures

A mould with parabolic surfaces, increased spatial resolution, smaller size and lower surface roughness realised by electrical discharge machining with a 50 micron wire was ordered from Derwa SA. This mould has a 200 micrometer period and an increased aspect ratio to increase the fraction of redirected light at low incoming angles. Some roughness remains after EDM and reflected light is still scattered. Attempts were made to use a thin film coating of a resin to smooth the surface and create a mirror polished surface. The resist is spun on a spin coater and before it hardens, surface tensions creates a smooth surface. On flat surfaces of EDM cut metal, results are concluding; however on structured surfaces, the layer is not very homogeneous and the process requires optimisation of spin speed and time as well as resist viscosity.

Because of the problems with surface roughness when using Electrical Discharge Machining, other techniques have been researched. As defined in the beginning of this project, conventional lithography is not adapted to the fabrication of the type of structures required for the realisation of the design. Interference lithography can be used to produce curved shapes with a thickness of several hundred micrometers on relatively large areas. Other laboratories working with this technique have been contacted to find a collaboration. However, regarding this technique it remains unsure if the resulting surface is acceptable for optical application. Because the design contains both a curved and a flat surface it has to be verified if the geometry can be realised with this technique.

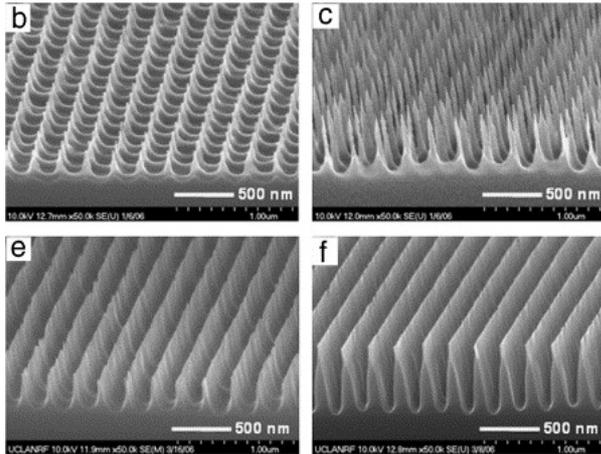


Figure 3a: Results of interference lithography as published by: Chang-Hwan Choi et Al (*Cell interaction with three-dimensional sharp-tip nano-topography, Biomaterials 2007*)

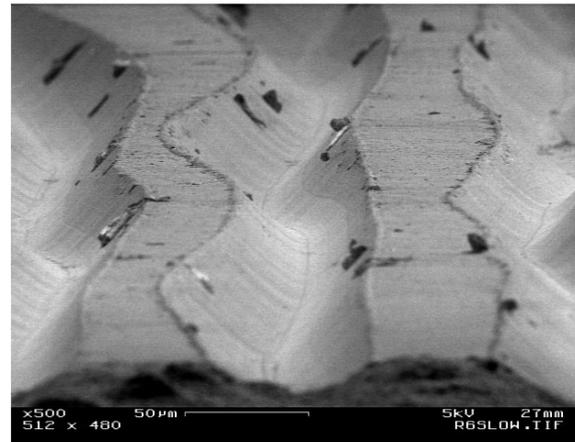


Figure 3b: SEM image of a vinyl (used) surface. As performed by Chris Supranowitz.

A second approach based on engraving was studied. The grooves on vinyl records have a width and depth between 50 and 100 microns, which is in the order of magnitude of the targeted structure. Also, the surface roughness is very low due to low noise requirements for record playback. In this technique, a soft lacquer (usually nitrocellulose) is engraved using a stylus oscillating at the frequency of the recorded sound. This master is then chemically coated with a thin conducting silver layer. An electro deposition step deposits a thicker nickel layer on the master. This Metallic mould can then be removed and used as a “stamper” to create replicas of the originally engraved grooves into vinyl. Using LIGA lithography, a stylus with the required shape and with smooth edges could be produced. This stylus would present as a nickel or silicon array of precisely shaped tips with smooth contours. They could be swept across a large surface of soft material to produce the desired array of grooves. For this approach materials have been selected and an industrial partner found for the production of the styli.

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

The coating of the structures is still done with aluminium and tilted samples. It was shown that the produced aluminium surface is more diffusing than the original surface. This might be explained by the fact that aluminium is corrosive in liquid state and when aluminium is deposited on the substrate it condenses from vapour to the solid state. Also, the latent heat brought to the substrate during the deposition of aluminium may have an impact on the surface topography. Finally surface tensions during the cooling of the aluminium layer may cause the surface roughness to increase.

With the embedding of the structures, some unexpected optical behaviours appeared. With an uncoated samples, the interface remains visible and in some geometries, light is diffracted. This is probably due to the index of refraction which must be different at the interfaces.

5. Substrate coating with periodic reflective stripes by lift off process.

No further coating was done on microstructures but the materials and set-up was prepared for the coating of the backside stripes. The backside stripes need to be precisely dimensioned and their edges well defined to obtain the angular selectivity and therefore the desired seasonal behaviour. To achieve this, two processes exist: lift off or etching. Lift off was identified as the preferred solution because of its ease of use and wide spread application in the nearby CMI laboratory. The required laboratory equipment and chemicals were purchased for this step. The last missing item is the mask, the mask ought to be a dark field (or positive) mask: the exposed areas will result in aluminium coated areas. Because the dimensions are relatively large, attempts have been made to use laser cutting for the fabrication of this mask. But the resulting mask has uneven edges and can not be electro-polished because only aluminium was found suitable for the thin cuts. Conventional techniques used in lithographic processes for the production of chrome masks will be applied.

6. Alignment and UV – NIL replication.

For the replication of the structures, the previously adopted process is used but an extra alignment step has to be added. This alignment is required for the correct relative positioning of the embedded mirror and the backside mirrors deposited on the substrate. For this alignment a device was designed to be placed under an optical microscope. This device allows respective placement of the mould and the substrate and subsequent UV exposition for the curing of the resin. For the UV source 3 UV leds with an intensity modulated power supply have been fitted on a cooling device. This light source provides enough power for the curing of the resin.

7. Measurements.

The precision photo-goniometer was used to characterised the diffusion of light by the surface roughness. Results show that electro polishing of the metallic mould improve the quality of the surface. The remaining diffusion is due to a macroscopic structure rather than to the surface roughness itself. This macroscopic structure is most probably due to the movement of the wire during the cutting process. This hypothesis was verified and, as shown in figure 4, the macroscopic roughness was measured with a laser profilometer.

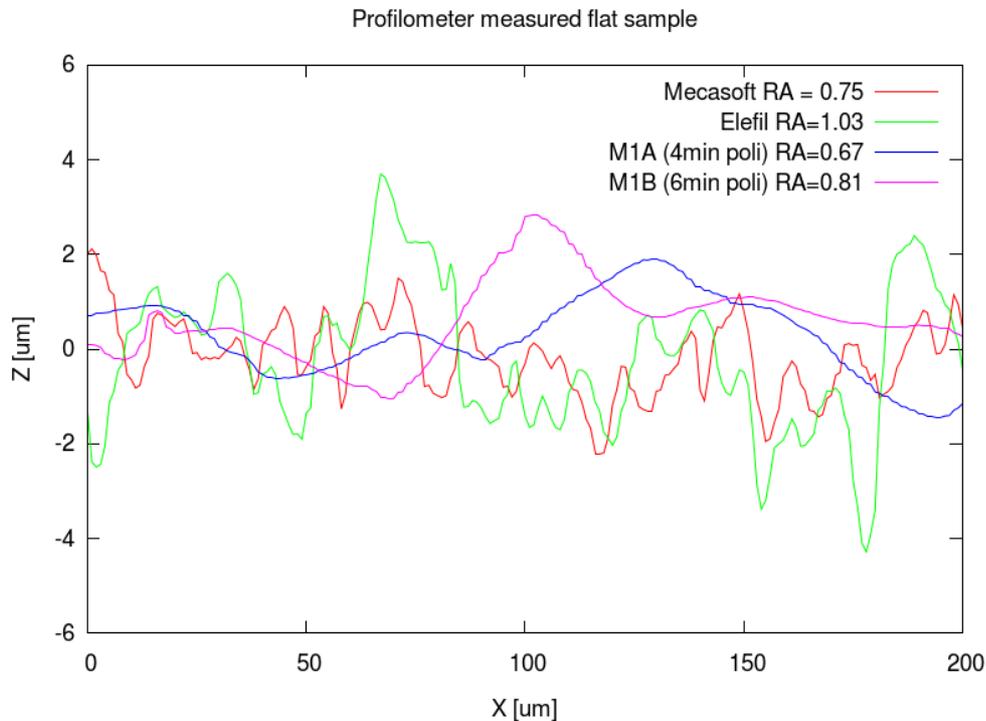


Figure 4: Laser profilometer measurements of surface roughness for polished and unpolished flat surfaces. The polished surfaces show less small scale variation but larger wavelike variations.

Embedded mirrors produced with the parabolic shaped mould were also measured but did not provide satisfactory results. This is most probably explained by the very diffusing aluminium coating and the partly successful embedding of the microstructures.

2012 Evaluation

The thermal and daylighting performance of the proposed design have been simulated. Each step in the production of embedded mirrors was revisited to realise the complete design: fabrication of a mould with mirror polished surface and high aspect ratio, deposition of thin periodic stripes of reflective mirror, alignment and replication of the structure into a UV curing resin, coating of polymer with a reflective material without altering the surface quality, and embedding the mirrors and make other interfaces disappear.

The present state of the art was presented at an international conference (SPIE, San Diego) and in to a network of concerned people in Switzerland (Brenet status seminar). A patent was submitted for the novel design. Three potential industrial partners were identified : BASF, Dow Chemical and Nitto Denko.

1. **Architectural integration:** Potential architectural partners were contacted
2. **Simulations:** the simulation tools were adapted to evaluate these characteristics and a novel design was found and patented
3. **Micro-structure fabrication: alternate** fabrication methods are being studied-.
4. **Coating:** the coating of thin periodic reflective stripes is prepared.
5. **Measurements:** profilometer measurements of surface roughness were realized

Outlook for end of project (April 2013)

1. **Architectural integration:** Establish the collaboration with an architecture firm and do a case study.
2. **Simulations:** Add scattering for better comparison between simulation and measure.
3. **Micro-structure fabrication:** Attempt the engraving of a soft material with LIGA stylus, find a partner willing to attempt the realisation of the structure with interference lithography.
4. **Coating:** coat a substrate with thin periodic reflective stripes.
5. **Measurements:** measure a complete microstructure.

Presentations 2012

A. Kostro, *Embedded microstructures for daylighting and seasonal thermal control*, oral presentation, August 13, 2012, SPIE Optics and Photonics Conference, San Diego.

A. Kostro, *Conception d'un vitrage micro-structuré pour l'éclairage naturel et le contrôle thermique saisonnier*, poster session with short oral presentation, September 13, 2012, BRENET Status Seminar, Zurich.

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
- First contact with BASF
- First contact with Dow-Chemical
- First contact with Nitto Denko

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 (LOMM at EPFL) provided 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. Jérôme 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