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Integrated multifunctional glazing for dynamical daylighting

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L'auteur de ce rapport porte seul la responsabilité de son contenu et de ses conclusions.

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. Technological progress includes the fabrication and improvement of micro-structures by selective deposition of micro-mirrors.

An advanced set of software tools using an original algorithmic approach was developed specifically for this research. It was used for the development of a novel complex fenestration system combining an original 2D profile and thin films. A structure offering both redirection of light for daylighting and seasonal blocking of direct radiation for dynamic thermal control was found. Direct and diffuse solar gains were evaluated using radiometric data from meteonorm. Radiance was used to render daylighting in offices and compute illuminance levels. This design was patented and presented at both international and national conferences and workshops.

An advanced mould corresponding to this design with feature periods of 200 micron was used in a 5 step process to create initial samples. The structure was replicated to create a soft mould for the nano lithography imprinting of polymers. The resulting polymeric structures were coated with aluminum thin films and embedded to create micro-mirrors. Critical steps in the fabrication process were identified and solutions were studied. An optical set-up was conceived and built for the optical characterization of samples. Samples surfaces and profiles were also studied using optical and contact profilometry, confocal microscopy, SEM and 3D SEM.

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:

1. - Daylighting: redirection of incident radiation and projection of daylight deep into the room, thus reducing electrical lighting needs.
2. - Glare protection/visual comfort: angular dependent solar transmission to achieve the most effective blocking for the elevated angles of direct solar radiation during summer.
3. - 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.
4. - Thermal insulation in winter: Double-glazing and the low emissivity properties of the used thin film coating provide thermal insulation in winter.

Novel microstructures with embedded micro mirrors can provide redirect 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 incidence angles in summer at noon). Recently developed solar protection coatings ("M-coatings") will provide the optimized spectral properties of the transmitted sunlight: maximized visible transmission for daylighting and carefully dosed energetic transmission for overheating protection in summer. Technological progress will include the improvement of microstructures by selective deposition of micro-mirrors, fabrication of novel microstructures and the powerful combination solar protection "M" coatings and microstructures. To reach this combination of objectives, we can rely on the changing elevation of the sun over the seasons. This principles are illustrated in figure 1.

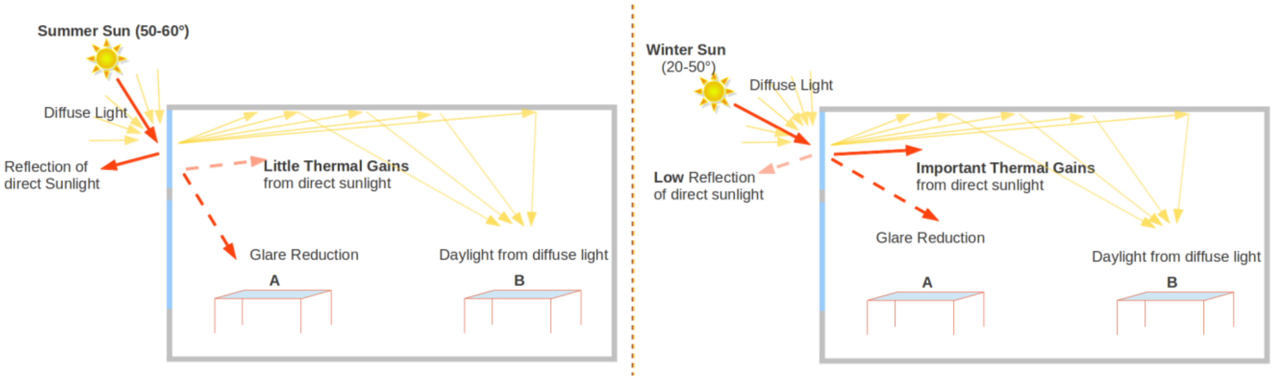


Figure 1: Working principle of the pursued complex fenestration system.

APPROACH:

- Study existing products and architectural requirements and set corresponding specifications for quantification of performances.
- Simulate novel designs reaching the defined objectives and characterize their performances.
- Fabricate novel micro-structures.
- Partially coat the micro-structures and embed them.
- Measure the resulting coated micro-structure's optical behavior.

Accomplished work and results.

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

Because this research aims at producing an integrated element for architecture, it is important to understand the needs and the existing solutions in this domain. Preventing glare is a common problem, usually solved by the use of blinds. Designers have optimized blind shapes to combine protection with comfortable light levels. The large amount of available solutions proves the interest for blinds that protect from glare but preserve a comfortable level of illumination.

The *retrolux*© blinds by *RETROSolar*© might well be the most advanced blinds with such aims (*Figure 2 a*). On a macroscopic scale, they are a very good example of what we wish to accomplish on a microscopic scale. The number of projects for offices and public building integrating such blinds reveal the growing interest for complex fenestration systems (CFSs). Another approach uses static glazing with special angular properties. Laser cut panel acrylic panels, for example, use total internal refraction to redirect light upwards. Again, such panels are used in public buildings (schools, museums) and offices (*Figure 2 b*). They are partially transparent and often placed in the upper third of the window. A second example of static systems is the *Lumitop*© glazing by *St-Gobain*© (*Figure 2 c*).

(a) (b) (c)

Figure 2: Examples of existing products and application domains. a) Retrolux© blinds b) Lasercut Panels in classroom c) Lumitop© example and principle.

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. For glazing in public transportation a CFS could also be interesting but the varying orientation of the glazing would require further research. 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. For seasonal thermal control, the defining values are 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. This is generally represented by a single g value. For accurate characterization of a CFS with the described goals, the annual evolution of thermal contribution should be considered.

One important conclusion is that the considered problematic differs depending on the type of building, the orientation of façades, the type of architectural element, the latitude on earth. The second important conclusion is that few products offer simultaneous daylighting and thermal control. Also truly transparent devices do not currently exist in spite of the demand. Another conclusion of this study is that the influencing factors for the choice of a glazing generally are the g value and aesthetic aspects. The g value is a single value representing the proportion of transmitted radiation. This single value is not sufficient when developing CFSs with strong seasonal dynamics. During the heating season, a high g value is preferred, while during the cooling season a low g value is preferred. Or the transmittance can be computed hourly over the year.

2. Simulation results

Ray-tracing software is often used to calculate the Bidirectional Scattering Distribution Function (BSDF) of complex fenestration systems (CFS) but no dedicated tool was found for the modeling of complex fenestration systems combining geometry and material-dependent designs and integrating thin films. Also no tool included the window specific performance studies. Initially, a combination of existing software was used but this showed insufficient and a custom tool had to be developed.

Combination of Existing tools

The combination of a CAD software (Auto CAD), two ray tracing software (Photopia and Radiance) and a graphical user interface for the visualization of results was selected regarding the following criteria and objectives:

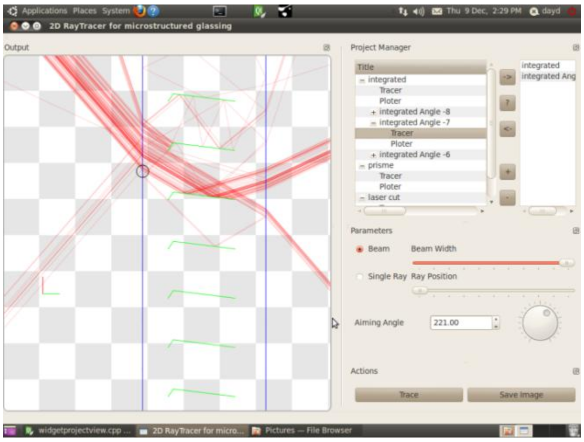
1. **The ability to easily design multiple 3D structures** was needed and this function is not available in every ray tracing software. When it is, design tools are very specific (for lens design for example) and it is not always easy to obtain multiple models suiting our needs. However, most software provide us with the possibility to import the design form a CAD (computer aided design) tool such as AutoCAD, Solid Works or Rhino. Furthermore, scripting is possible in most CAD programs so we can easily generate the desired geometries. Since an AutoCAD license is available on campus and because AutoCAD offers multiple scripting abilities (AutoLisp and Visual Basic Application) it was an obvious choice for the design of the studied systems.
2. **The possibility to model the scattering of light** passing through the CFS. The system should be characterized by the angular distribution of transmitted light depending on the incoming angle. Generally, we want to describe the bidirectional scattering distribution function (BSDF): both in transmission (BTDF) and reflection (BRDF) for multiple skies and sun positions.
3. **Simulate the resulting effect in a standard office.** For the daylighting evaluation, we are seeking the illuminance in a plane and the daylighting factors (DLF). This part can be done independently, using a previously calculated BSDF in a more architectural, rendering oriented software such as Radiance (backward ray tracing). Some energetic characterization is also required.
4. **An efficient, rapid and user-friendly execution of these various steps**, required scripting abilities in the chosen software. The various tools can then be called from a common graphical interface that will be developed in QT, a cross-platform application framework extending standard C++ with a useful set of objects and rapid graphical user interface development.

Using these criteria and budget limitations (some licenses are sold for over 10.000 dollars), a search for available software was conducted. Regarding this comparative study, Photopia was chosen for BSDF calculation and daylighting evaluation. This choice was made mainly because there was some in situ experience for the usage of this tool for the illuminance characterization of daylighting systems and because the person of contact at LTI Optics is very helpful and understanding of academic requirements. Furthermore, Photopia offers solution for the daylighting evaluation and there is no need to use a 3rd software for this part. They provide a very good solution for rapid results and to get a feeling for what will give the best result. If the same study was to be done today it is important to mention the completion of the Radiance set of tools with a module for the computation of BSDF in complex fenestration systems. The genBSDF method was introduced and validated in 2011. This once again shows how relevant and actual this research on CFS is and its importance to the architectural and daylighting community.

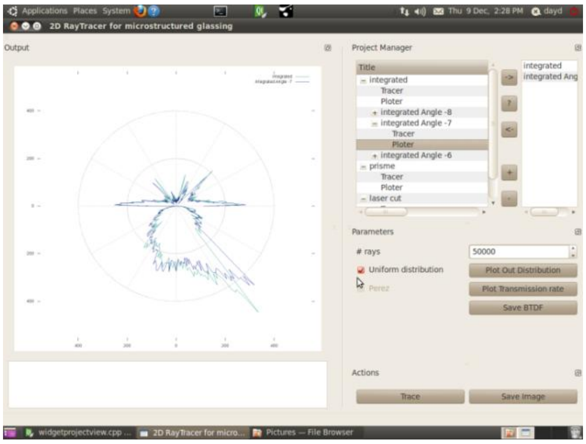
The first step was then to implement a script to generate the geometries in AutoCAD. This was done in AutoLisp, an extension to AutoCAD allowing us to write Lisp scripts using the AutoCAD commands and some math. The resulting scrip takes the following parameters: spacing, depth, width and shape of micro mirrors and window dimensions. It generates a 3D drawing in AutoCAD and saves it as a DXF or DWG drawing that can then be imported in Photopia. The layers in this drawing have the appropriate names to be identified as materials in Photopia. The second step was then to write a script in Photopia to import the drawings, add a light source, position it correctly (elevation and azimuth) and then set the analysis parameters to generate the BTDF. This was done in Photopia's own script language. The outputs are available as graphs and numerically in a text file. The initial results for flat embedded mirrors obtained with Photopia were encouraging: the modeled glazing system is redirecting 32.5% of transmitted light upwards.

2D profile optimisation

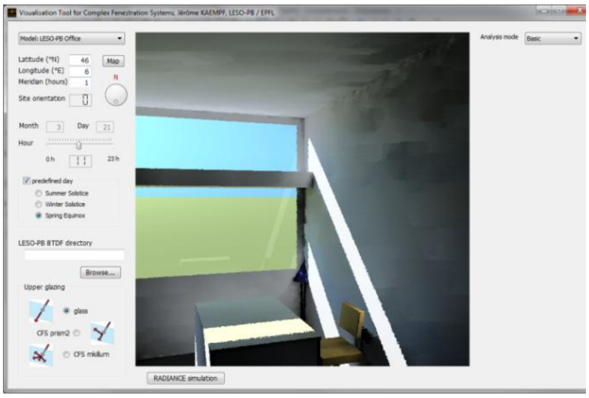
Because of its limitation and slow execution, this compilation of tools was abandoned and custom software was developed for the ray tracing. Using numerical modeling on a microscopic scale, we can define what influence the different parameters of the structure have on the performance. It is not only important to design a structure with geometrical goals such as "redirect light upwards" or "block a certain range of angles" but also to understand quantitative architectural goals like daylight factor and glare. For a rapid assessment, a custom 2D tracing tool was developed. Most daylighting and shading devices have 2D profiles (blinds, lumitop, prismatic sheets...) and 2D ray tracing allows to visualize the path of light depending on angle and position (*figure 3a*), it calculates transmission factors and distributions depending on the incoming angle. The graphical interface makes it possible to directly compare multiple designs, vary parameters individually and rapidly identify their effect (*figure 3b*). This algorithm ignores the third dimension but produces a good approximation of the transmission distribution. This first approximation of the three dimensional transmission distribution was used in radiance for rendering of an office with a clear glass and a micro-structured glazing. It allowed a visualization in time of the effect of such a glazing (*figure 3 c & d*).



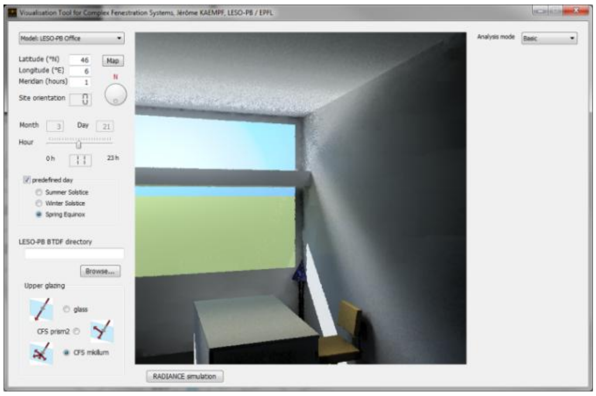
a) Ray tracing for custom embedded mirrors



b)Angular distribution comparison of transmittance as computed by Monte Carlo 2D tracing.



c) Radiance simulation of an office with clear window, clear sky.



d) Radiance simulation with embedded micro mirrors using the calculated BTDFs.

Figure 3: Various outputs of the ray tracing software

Accurate 3D and Thin film modelling

The simulation tool was then 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 4*). The optimization 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 and Monte Carlo methods have to be used. We also proposed to introduce a genetic algorithm to search for the optimal solution in an evolutionary manner.

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. This elegant algorithmic solution provides both accuracy and speed of execution. The working principle is illustrated in figure 5.

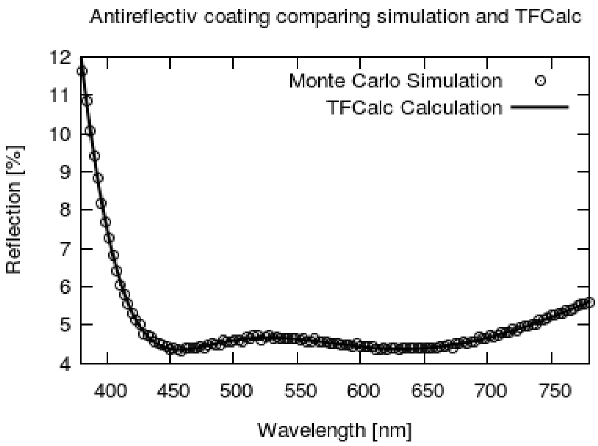


Figure 4 Comparison of the spectral reflectance between TFCalc simulation and Monte Carlo Simulation

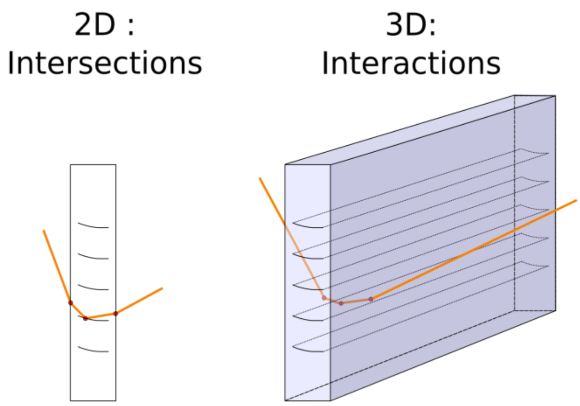


Figure 5 working principle of the mixed dimensionality approach.

Genetic alogrithm

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 optimize. 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 generations 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 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 thicknesses 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 6* shows the best reflection spectra for generations 1, 6 and 10 when all 4 thicknesses 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.

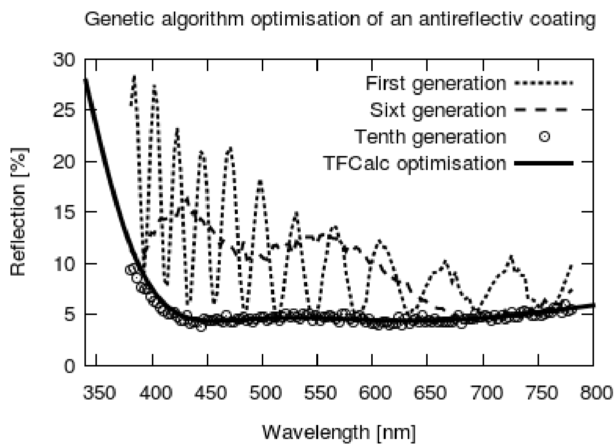
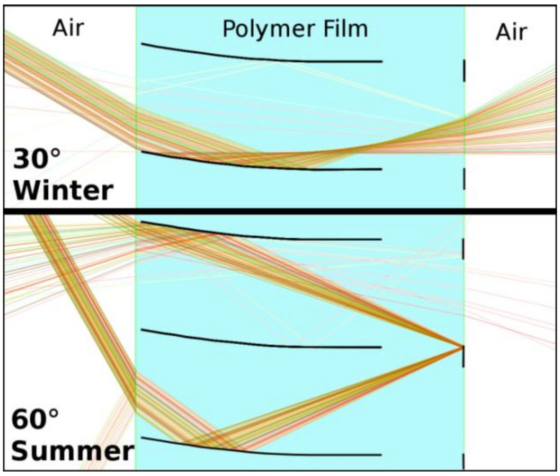


Figure 6: Convergence of a population towards an optimized 4 layer anti-reflective coating using a genetic algorithm and ray tracing.

Developing a novel geometry.

So far, only the daylighting target was reached with embedded micro mirrors and the seasonal behavior was not fully realized. In a new design, a strong angular dependent behavior is achieved: for incidences between 50° and 60° the transmission is cut down gradually from 80% to 10%. This new design uses a parabolic embedded mirror to fulfill the objectives defined above. The key concept of this new design is the focusing of light from an angular interval by a first component onto a second component as illustrated in *figure 7a*. 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 (*figure 7a*).



a) Ray path as simulated through the proposed CFS for typical summer and winter elevations of the sun

b)Simulated transmittance for embedded parabolic mirrors depending on the incoming angle.

Figure 7: Ray tracing and transmission distribution as computed by Monte Carlo ray tracing simulation.

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 7b.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, direct 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.

Characterisation of thermal and daylighting performance

To assess the performance of the developed complex fenestration systems following the metrics identified earlier, the software is used to create the characteristic bidirectional transmittance distribution functions (BTDF) of a CFS. Thermal gains are then estimated by combining the BSDF with meteonorm radiometric data. To obtain a good result, diffuse and direct radiation are treated separately and a common representation of space has to be used. For direct radiation the transmittance is computed for hourly solar positions and combined with the corresponding dirrect irradiance given in the climatic data. For diffuse radiation, the hemisphere is divided into patches following Tregenza's subdivision of the sky and for each patch an hourly irradiance is calculated using the climatic data and a Perez (R. Perez et Al. All-Weather model for sky luminance distribution – preliminary configuration and validation, Solar Energy Vol 50. 1993) representation of the sky. The mean transmittance for each patch is computed with the ray tracing and combined with hourly values of the sky. 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. The resulting gains are compared to incoming irradiance in Figure 9.

Figure 8: Rendering of a typical office at noon during a summer day with a microstructured glass

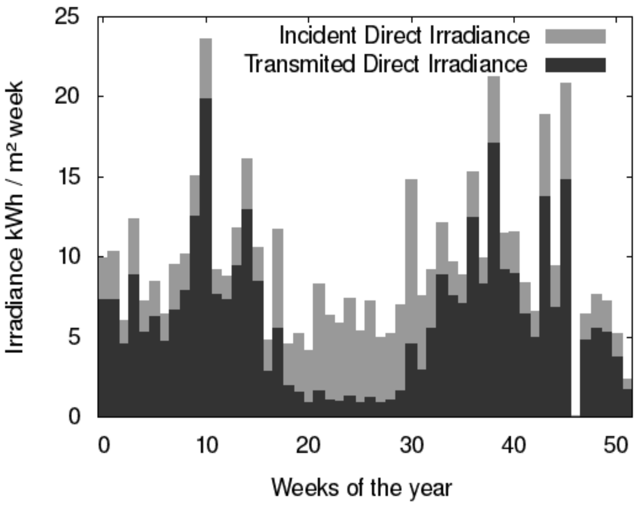


Figure 9: Simulated transmitted irradiance per surface area for a microstructured glass over the year compared to incident direct irradiance.

This new design based on a parabolic embedded mirror was also studied further regarding daylight and glare. Glare on the work plane was analyzed using the Unified Glare Rating (UGR) or the Daylight Glare Index (GDI). Illuminance values (in lux) on the workspace in a typical office were studied over the year. Illuminance should be above 300 lux for common office work. To obtain these results, the BTDF calculated from the ray tracing was used in combination with Radiance. This work was based on a software developed by Jerôme Kaempf at LESO. The reference coordinates and time had to be carefully alignment to obtain accurate 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 8.

Tools developed by German Molina Larrain in Chile (sunlite) were integrated for the study of annual illuminance values. The collaboration with German Molina Larrain is bilateral and will be presented at the next Radiance Workshop. The 2D ray tracing developed here revealed itself as a powerful alternative to the time expensive genBSDF used in Radiance. Further interest came from Austria with the intent to use such simulations for the optimization of busbar profiles for enhanced light trapping in solar cells.

3.Fabrication of micro-structures

Existing structures are scarce and limited to specific applications. For example, arrays of lenses, called lenticular sheets are used for advertising (to show 2 different images depending on the viewing angle or 3D images). Arrays of 45° pyramids, called prismatic films or glasses, are used for solar protection in buildings on a macroscopic scale and as brightness enhancement films in portable devices on the microscopic scale. In this project, aims and specifications are different and the required structure was defined by the simulations.

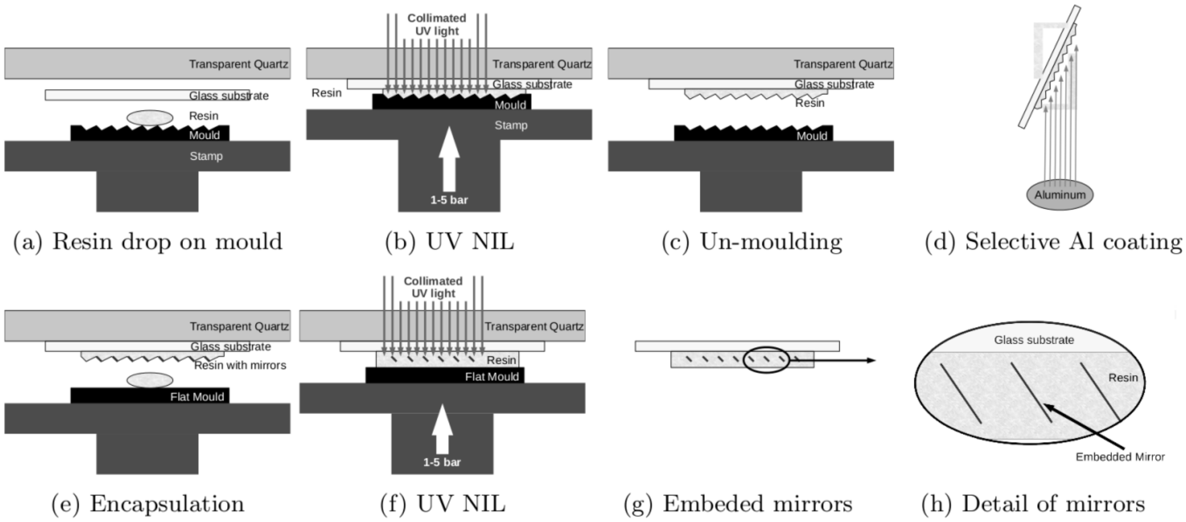


Figure 10: Encapsulation process for micro-mirrors fabricated by imprint lithography replication.

To obtain integrated mirrors, the chosen approach is illustrated in figure 9, a jigsaw like structure is first fabricated by replication, and then selected surfaces are coated. The sample is tilted and only facets exposed to the evaporation source are coated. The structure is then filled to obtain a flat surface with encapsulated mirrors. Since variable structures are desired, a flexible process is needed. The materials used need to be easily molded to be able to produce the high aspect ratio saw-shaped surface and refill the gaps after the coating deposition. The process also needs to be easily reproducible to test the various coating parameters on the same shape. Finally, the fabrication methods have to be suitable for up-scaling to industrial processes.

Mould Fabrication and replication

The first mould was fabricated by electrical discharge machining with the collaboration of the mechanical department of the physics institute on EPFL campus. Because of the round shape of the wire, sharp corners cannot 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 13*). 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 choose a material well suited for molding of the final material: a UV curing resin developed at the LTC. For the mother mould, Polydimethylsiloxane (PDMS), silicon based organic polymer that is known to work well as a mould for most resins and has been tested at LTC was used.

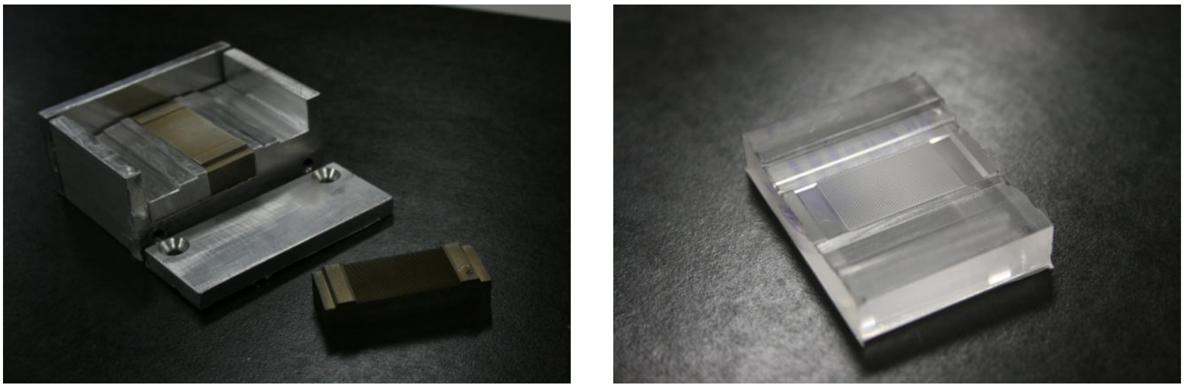


Figure 11: a) Photograph of the father mould and the two inserts b) Photograph of a PDMS mother mould.

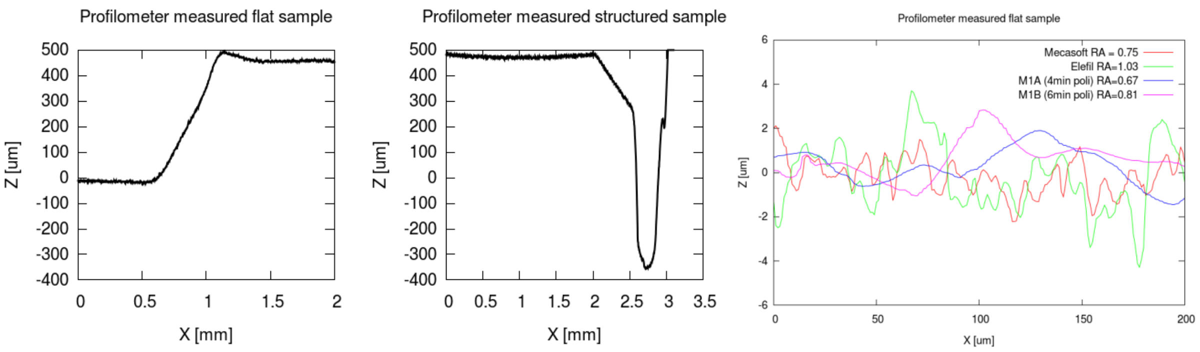
The first trials for PDMS mould fabrication were done at CMi and a satisfying, simple stamp like mother was obtained. Once the trial revealed successful, a more refined mould had to be designed to align the structures perpendicularly to the glass substrate. This second generation mould shown in *Figure 11a* also had to be designed to be able to fill the saw tooth shape after coating. To do so, the resin structure must have two reference surfaces on each side of the structural region. 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. Such an advanced mould was fabricated in two parts: an aluminum case and interchangeable inserts fabricated by electrical discharge machining. PDMS mother moulds were produced (*Figure 11b*). These moulds were then used to create structured and flat surfaces on glass substrates using an UV polymerizing resin.

For the replication of custom Micro structures, an on-campus collaboration was established with the “Laboratoire de technologie des composites et polymères“ (LTC) at EPFL. The research group led by Y. Leterrier develops a replication process for nano structures using a resin and UV polymerization. A replication setup available at LTC was used to produce samples from the mother PDMS mould. A drop of resin is deposited on the mould, a treated glass placed on top of the mould and pressure up to 5 bars is applied. A UV lamp is then turned on for 3 minutes of polymerization. Once the resin is hardened, the glass is removed from the mould and the surface of this transparent resin retains the mould's shape. A good adhesion between substrate and material was sometimes hard to reach. But an optimization of the process parameters and a suitable choice of the used resin resulted in satisfying samples.

Characterization

Some samples were completely coated with aluminum and analyzed with a UBM profilometer (*Figure 12)*. The flat area of the flat sample was used to characterize 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 behavior 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 12b* indicates that the resin was not completely cured and that it was distorted during unmolding. 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 and the 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. Profile from electro-polished surfaces are shown in *figure 12c,* the remaining roughness has a larger scale and is probably due to movements of the wire during the cutting process.



a) b) c)

Figure 12: Optical profilometer characterization of first replicated samples. a) the right border of the flat sample b) the left boarder and first microstructure of the structured sample. c) Laser profilometer measurements of surface roughness for polished and unpolished flat surfaces. The polished surfaces show less small scale variation but larger wavelike variations remain.

Further miniaturisation and reduction of surface roughness

The glazing we propose should be transparent to satisfy user comfort and aesthetic requirements. To make the embedded mirrors invisible to the human eye, they should be as small as possible but staying in a range were geometrical optics are predominant over diffraction and interferences. This means dimensions just below one hundred micrometers. To get closer to this objective and realize structures with the design introduced earlier, a second generation of mould was ordered from professionals in the field of electro machining. A mould with parabolic surfaces, increased spatial resolution, smaller size and lower surface roughness realized by electrical discharge machining with a 50 micron diameter 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. To reach lower dimensions, stainless steel could no longer be used because of internal stress in the material. The cut shape would bend due to those tensions and for this reason, tungsten carbide was used. The resulting mould overlapped with the design is shown in *figure 13*.

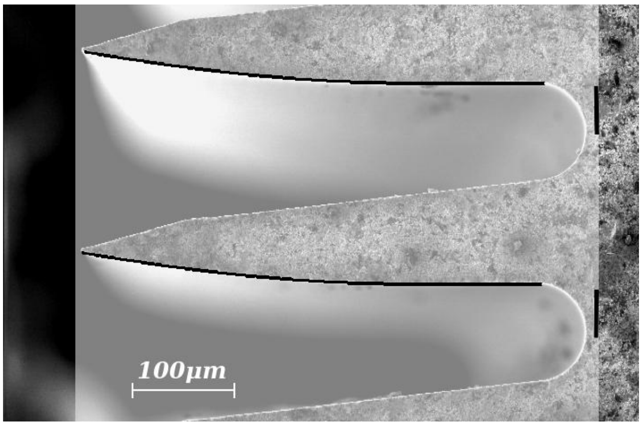


Figure13: Overlapped image of the parabolic design and a SEM micrograph of the EDM mould. The dark lines represent mirrors, and the uniform gray area is the polimeric material they are embedded in.

Despite the more advanced technology and change of material, some roughness remains after EDM and reflected light is still scattered. Because the used material is no longer stainless steel but tungsten carbide, electro polishing cannot be used. 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 create 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 optimization of spin speed and time as well as resists viscosity. This solution did not apply to provide sufficiently smooth and regular surfaces. Light is focused by the parabolic mirror only if it's surface is smooth enough for specular reflection. Regarding this objective, the EDM technique reached its limits and other techniques have to be studied. Interference lithography and engraving of soft materials followed by electroplating are considered.

Conventional lithography is not adapted to the fabrication of the type of structures required for the realization 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 realized with this technique.

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.

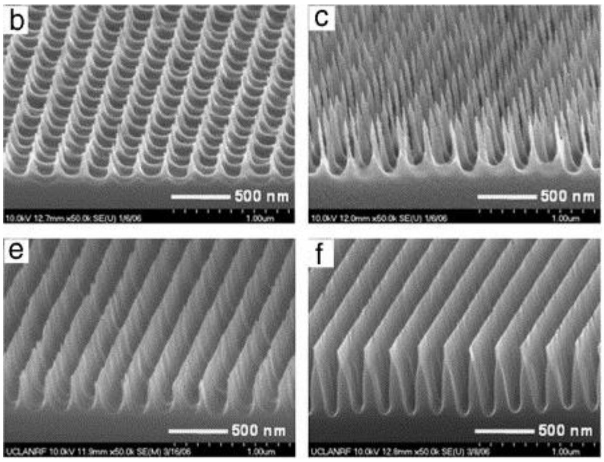


Figure 14a: Results of interference lithography as published by: Chang-Hwan Choi et Al (Cell interaction with three-dimensional sharp-tip nano-topography, Biomaterials 2007)

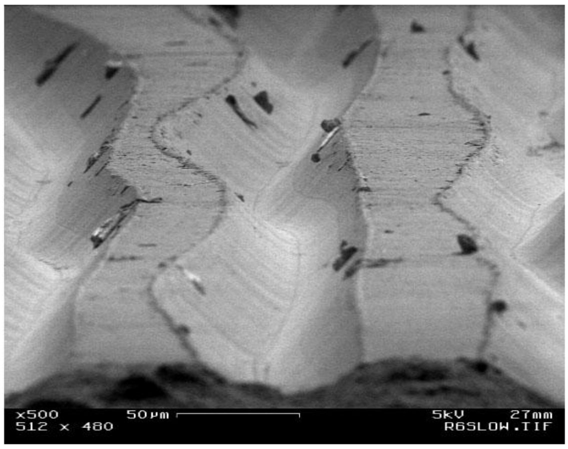


Figure 14b: SEM image of a vinyl (used) surface. As performed by Chris Supranowitz.

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

In order to be able to deposit a coating only on a selected part of the structure, the material is evaporated at a given angle (*figure 10d*). Therefore, the first necessary element is a device to hold the samples at a give angle. It was designed to fit a Balzer PVD machine and built with LESO's mechanical engineer, Pierre Loesch (*figure 15 a*).

a) CAD drawing of the tilting sample holders. Individual sample may be tilted at different angles.

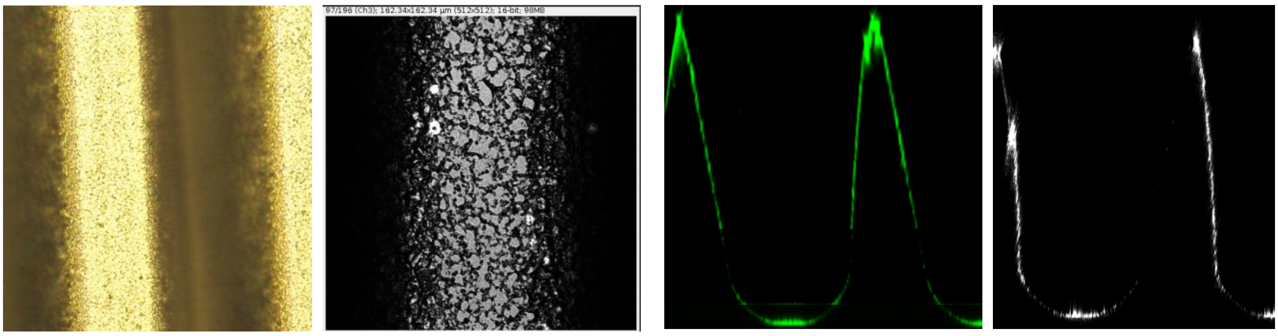
b) 45° prism ready to be coated

c) Coated prism: Partial coating can be observed, one facet is mirrored, the other one still "bends" light and shifts the image like an original, clear prism

Figure 15: Setup for facet selective coating of structured surfaces using tilting sample holder.

A macroscopic acrylic 45° prism was ordered from Colt to demonstrate that it is possible to coat only exposed surfaces. Also, various micro-prisms were ordered from 3M. Those prisms are flexible, have a period between 13 and 50 µm and are made of a stack of polymers. First attempts were made to coat the 45° micro-prisms from 3M. The first evaporation was too long and the plastic suffered from the heat. Optimized parameters yielded a rapid (less than 10 seconds) and stress free process. A macroscopic 45° prism was coated to demonstrate that it is possible to coat only exposed surfaces (*figure 15b*). The first visual check confirmed that only one side of the prism was coated: normally those prisms duplicate objects into left and right displaced images. The coated prism shows only one image through the uncoated facet, the coated facet reflects an image (*figure 15c*).

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



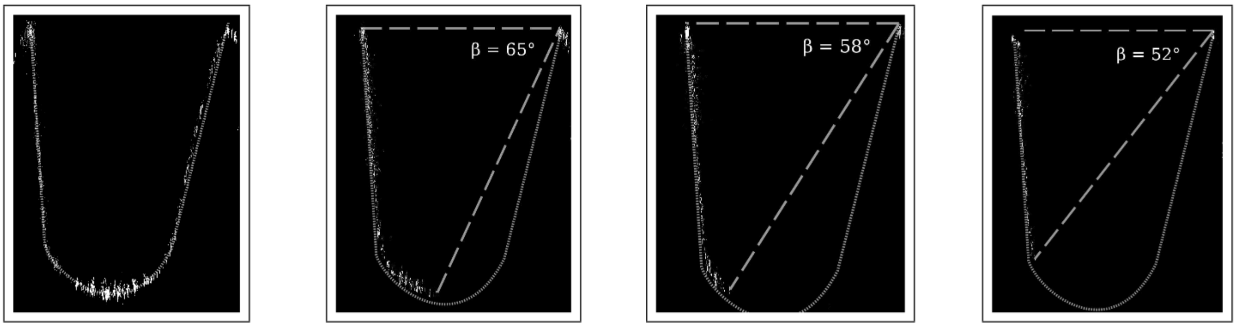
a) b) c) d)

Figure 16 a) optical microscope view of roughness on the surface of a PDMS mould. 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.

Images obtained by optical microscopy of the transparent mother mould (*figure 16a*) 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 16b*). 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 characterization

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 16c*). The selective coatings appears clearly on *figure 16d* : one face is bright and clear, the other on is almost invisible. The brightness of the peak is partially an artifact 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.

Structured samples obtained with the second mould were coated with an aluminum layer using the angular setup for evaporation. Confocal microscopy was once again used to create 3D profiles, and characterize how the angular deposition affected the coating location. The image processing software *Fiji* was used to measure angles on the resulting images (*Figure 17*). 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 measured at the same location.



(a) Sample tilt angle: 90° (b) Sample tilt angle: 55° (c) Sample tilt angle: 50° (d) Sample tilt angle: 45°

Figure 17: Angular dependent coating.

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

Table 2 Incident angle and observed deposition angle.

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

The parabolic shaped structures were also partially coated. Due to a higher aspect ratio the tuning of the right angle was not straight forward. This tuning was made harder by the problems encountered during the embedding phase. Embedding of mirrors was straight forward so far but with the higher aspect ratio of the new mould embedding problem arouse and two new challenges are faced. During embedding and probably due to resin shrinkage, voids appear at the very bottom of the structures. They disappeared after optimization of the curing parameters and slowing down the polymerization. However, it was observed that bubbles can be formed overnight due to ageing processes in the resin during the first days. The second challenge is that interfaces do not disappear completely when a resin structure is filled with the same material. The interface creates certain diffusion and strongly reduces overall transparency. This can be explained by index mismatching and by the strong roughness of the interface. Reducing roughness should dramatically decrease this effect.

For the fabrication of the design found by simulation, parabolic mirrors need to be deposited but also the backside mirrors for the blocking of a selected angular range. The materials and set-up was prepared for the coating of these 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 behavior. 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 aluminum 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 cannot be electro-polished because only aluminum was found suitable for the thin cuts. Conventional techniques used in lithographic processes for the production of chrome masks will be applied.

To obtain a proper relative positioning of the mirrors, either replication of the structure or deposition of the stripes has to be done in alignment. It is easier to align the structure with a substrate that already has mirror stripes. For the replication of the structures, the previously adopted process is used but an extra alignment step was added. 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.

5. Measurements.

The designs of the structures and coatings are based on simulations, their accuracy has to be verified. Also it should be possible to check if the produced sample corresponds to what was designed. Comparing simulations and measures can give those answers. Therefore, a set-up for the measurement of transmitted planar distribution depending on the incident angle was conceived. The requirements for such a measurement are accurate control of angles and a broad dynamic range for the signal acquirement. Because of the large number of measured angles, an automated setup is required. The angular accuracy should be lower than 0.1° and the range for the measurement should be at least 3 orders of magnitude.

For precise positioning, two main options exist: DC motors with an encoder and stepper motors with a reference position. The later combined with reduction gearing offer very precise, repeatable positioning and an easy computer interfaced control. For low level signal acquirement and dynamic range, the ideal solution is a Lock-in Amplifier.

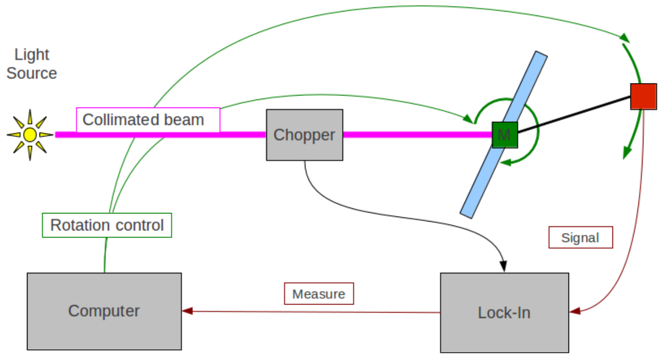
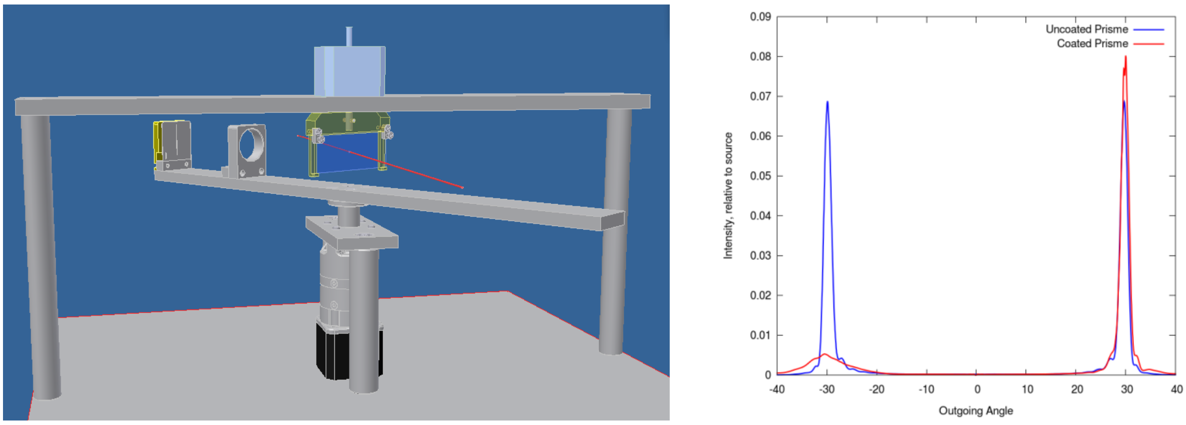


Fig 18: Goniophotometric measurement set-up principle

For a precision goniometer we required an angle selective sensor, an accurate measurement of the signal provided by the sensor, a data acquisition method to read this measurement 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 18 &19a*. 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 amplifier 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 synchronized signals that can be used in a digital lock-in software.

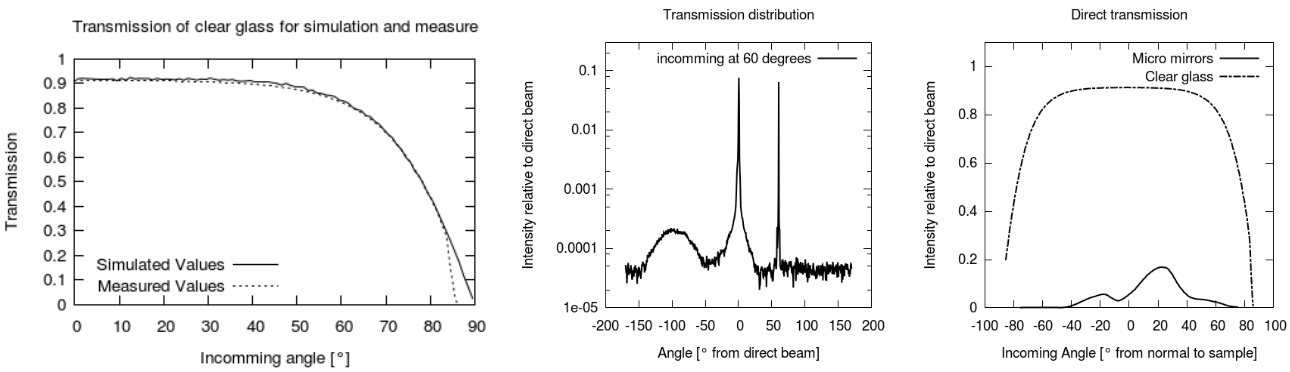
This digital lock-in amplifier was then integrated to a program that simultaneously controls 2 stepper motors to rotate the sample and the sensor. The motors are driven by a controller card to which the program sends its orders. A calibration step aligns the two motor axes with the zero reference before measuring the BSDF in the plane. Angular resolution of less than one degree has been reached. This setup was used to measure transmission in a coated and uncoated 3M prism and the angular dependant behavior was demonstrated (*figure 19b*). For validation of the measure, the transmission of a clear glass sample was measured depending on incoming angle. 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.



a) *b)*

Figure 19a) CAD drawing of the measurement setup as it has been built. b) Measurement of a coated and uncoated prism using the given setup.

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 20a*). 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 20: 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 behavior was characterized (*figure 20b*). The direct transmission is strongest at about 20° when the incident beam is refracted inside the sample, parallel to the structures (*figure 20c*). The direct transmission is minimal at incidences above 40° when the structures redirect 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.

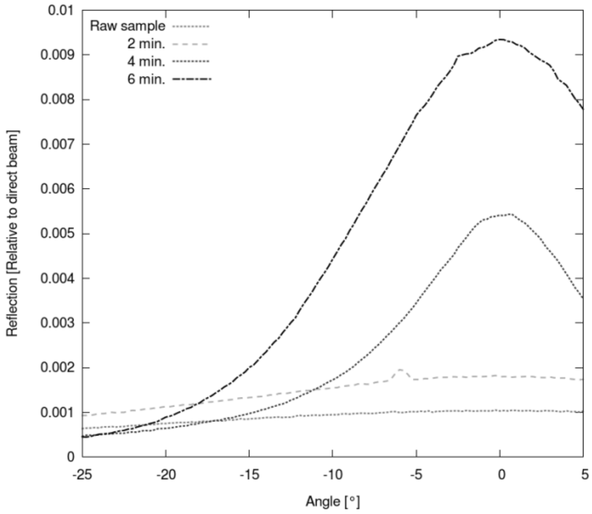


Figure 21 Scattering distribution on surfaces with different electro polishing times.

The precision photo-goniometer was also used to characterized 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 section 3.B, the macroscopic roughness was measured with a laser profilometer.

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 aluminum coating and the partly successful embedding of the microstructures

Project evaluation

There are five main objectives to this project: a study of the state of the art and the architectural requirements, a simulation aspect, the fabrication of microstructures, the deposition of coatings on selected facets of these structures, and finally the measurement of optical properties. All of these have been approached and were reached to a large extent.

1. **Architectural integration:**

1.1. It seems that an easy to integrate and location specific glazing offering a combination of daylighting and thermal control is of interest to architects but does not currently exist.

1.2. Numerous discussions were held with architects and engineers during the span of this project.

1.3. Glare, illuminance on the workspace and solar gains over the year were defined to be the relevant characteristics to be studied.

1.4. Potential architectural partners were contacted and a partnership for future work is in place.

2. **Simulations:**

2.1. A framework for computer simulation was defined, suitable software tools were identified and the concept of redirection by embedded micro-mirrors rapidly tested.

2.2. A better adapted, fast 2D ray tracing tools was developed to study the shape of the existing systems and optimising parameters.

2.3. Additional tools were developed and they helped defining the shape of the first, most simple integrated mirrors. Architectural simulations showed clear glare elimination and daylighting capabilities.

2.4. Thin films calculations, accurate three dimensional calculations and genetic algorithm optimization were added.

2.5. The appropriate tools and methods were identified to evaluate the architectural linked characteristics and a novel design was found and patented

3. **Micro-structure fabrication**:

3.1. The possible methods for prototyping were defined.

3.2. A feasible, scalable method for production of micro structured transparent sheets was identified.

3.3. Advanced metal moulds were produced and replicated. Electro polishing was tested as a polishing method. Moulds with periods as low as 200 um were realized.

3.4. Surface roughness was reduced further but is still to high for appropriate functioning.

3.5. Alternate fabrication methods are being studied-.

4. **Coating:**

4.1. The device for angular selective coating was prepared and both micro and macroscopic existing structures were coated.

4.2. Selective Coatings were successfully realized on custom microstructures. Only few samples could be produced because the laboratory move had to be moved to another building.

4.3. The coating location was observed and the correspondence between deposition angle and effective coating location characterized

4.4. The coatings were further studied and it was found that they increase surface scattering.

4.5. The coating of thin periodic reflective stripes was prepared and an alignment setup fabricated

5. **Measurements**:

5.1. The requirements for the measure of precise angle dependent transmission and reflection distribution were defined.

5.2. First manual measurements were carried out and confirmed selective coating for microscopic structures.

5.3. The set-up was fully automated and verified. Measurements of integrated mirrors were carried out and the concept validated.

5.4. The measurement was used to quantify improvements by polishing and to characterize and compare different surfaces.

5.5. Profilometer measurements of surface roughness were realized

5.6. Spectral capabilities were added to the setup.

In the course of this project, advanced simulation tools and a measurement apparatus were successfully created. A scalable fabrication process was identified for the fabrication of embedded micro mirrors. An advanced design was found with the simulation tools. The proposed solution combines daylighting, glare protection, seasonal thermal control and transparency. The thermal and daylighting performance of the proposed design have been simulated. Each step in the production of embedded mirrors was revisited to realize 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 finally perfect embedding of the mirrors to make other interfaces disappear.

The remaining technical challenges were identified: fabrication of a mould with mirror polished surface and high aspect ratio and perfect embedding of the mirrors to make other interfaces disappear. Solutions to these challenges were studied.

The present work was presented at the Cisbat conference in 2011, at an international conference in 2012 (SPIE, San Diego) and in to a network of concerned people in Switzerland (Brenet status seminar). It will be presented at the Cisbat conference in 2013. A patent was submitted for the novel design and a paper on the simulation aspect of this work is under preparation. The work was also presented to three major industrial partners: BASF, Dow Chemical and Nitto Denko. BASF has showed significant interest and is willing to participate in future work on the topic. Amongst the numerous architect interested by this solution, contact has been made with the engineering bureau of Mr Conti who is also motivated to participate in future work.

It is worth mentioning that during the span of this project, the whole laboratory had to be moved and all equipment relative to this project had to be dismantled and set up to run again.

Outlook for a subsequent follow-up project.

1. **Architectural integration:** Use the collaboration with Conti to do a case study.
2. **Simulations:** Add scattering for better comparison between simulation and measure.
3. **Micro-structure fabrication:** Create smooth surfaces on the mould, to achieve this, attempt the engraving of a soft material with LIGA fabricated stylus. Options in case of failure are lithography and interference lithography.
4. **Coating:** coat a substrate with thin periodic reflective stripes and align them with the structures.
5. **Measurements:** measure a complete microstructure.

Invited Talks

A. Schüler, Advanced nanostructured coatings for solar energy conversion: Large opportunities for small structures, CISBAT 2009, International Scientific Conference, 2-3 September 2009

A. Schüler, Optische Nanokomposit-Beschichtungen für Solarenergie-Anwendungen und Gebäudeintegration von Solarenergie-Systemen, Innovationsgruppe Plusenergiehaus, ETH Zürich, September 16th, 2009

A. Schüler, Solar Buildings: From Nano to Urban Scale, Solar Summits Freiburg, Oct 2009

A. Schüler, Advanced nanostructured coatings for innovative solar façade glazing, SwissINSO Open House at EPFL, November 3rd, 2009

A. Schüler, Nanostructured inorganic thin films in solar energy conversion, Part I: Vacuum deposited selective absorber coatings, invited keynote lecture, Winter College on Optics and Energy, February 8-19, 2010, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

A. Schüler, Nanostructured inorganic thin films in solar energy conversion, Part II: Sol-gel coatings for solar thermal and photovoltaic applications, invited keynote lecture, Winter College on Optics and Energy, February 8-19, 2010, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

A. Schüler, Innovatives Architekturglas für aktive Solarfassaden: Neue Möglichkeiten für gebäudeintegrierte Solarthermie und Photovoltaik, invited plenary talk, 3. Energie-Apéro des Energie-Clusters Schweiz, Bern, March 2nd 2010

A. Schüler, Optical and electronic properties of carbon- and nitrogen- based nanostructured inorganic thin films, invited keynote lecture, International Conference on Metallurgical Coatings and Thin Films ICMCTF 2010, April 26-30, San Diego, USA

A. Paone, A. Schüler, Semiconductor-metal transition in vanadium dioxide based thin films: towards “smart” solar energy materials, invited plenary talk, From Solid State to BioPhysics V, June 12-19 2010, Cavtat, Croatia

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

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

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

A. Schüler, Couches minces optiques composées de matériaux nanocomposites pour applications dans le domaine de l’énergie solaire, colloque: “Nanotechnologies: une autre vision sur les énergies”, entretiens Jacques Cartier, November 19th, 2012,INSA de Lyon, France

Publications with presentations at conferences

Kostro A., Scartezzini J.-L., Schüler, A.M. T*owards microstructured glazing for daylighting and thermal control*, poster presentation, EPFL, CISBAT, Sept 2011.

Kostro, A. , Geiger, M., Jolissaint, N., Lazo, M.A.G., Scartezzini, J.-L., Leterrier, Y., Schüler, A.M. , *Embedded microstructures for daylighting and seasonal thermal control,* oral presentation, Proceedings of SPIE - The International Society for Optical Engineering, Volume 8485, 2012.

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

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
- Contact and partnership with BASF Switzerland, Basel
- First contact with Dow-Chemical
- Contact with Nitto Denko, visit to research offices in Ibaraki, Osaka, Japan in February 2013
- Solar control SA

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-CIMEProf. 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. 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