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## **TOWARDS MICROSTRUCTURED GLAZING FOR DAYLIGHTING AND THERMAL CONTROL**

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Glass is a central element to modern architecture and can cover up to 100% of a building façade. The main purpose of large glazed areas is to create bright, comfortable and healthy spaces. It was shown that increasing natural light in offices reduces sickness but high visual transmittance ( $\tau_v$ ) and excessive energetic transmittance ( $\tau_e$ ) can have opposite consequences: a high  $\tau_v$  can cause glare and visual discomfort for occupants while a high  $\tau_e$  induces overheating which has to be balanced with air conditioning in summer. The energetic and daylight performances of a fenestration system are central and important issues for architects and the right compromise between good lighting levels, electrical savings, solar gains in winter and overheating in summer is not easy to find. Over the past decades, progress was made and some solutions to these problems were found. Various types of blinds and shadings have been introduced to prevent glare, achieve a good daylight factor even far from the window and permit to adapt to conditions all along the year. Sun protection glazings on the other side are static systems with a selective coating to limit the transmitted part of the solar spectrum: traditionally a step function with maximum values in the visible range and minimal values in the infra-red and ultraviolet range cuts down excessive solar gains. Recent research show that the transmitted spectrum can be refined and applying a 'M' shaped transmittance distribution, a ratio of  $\tau_e / \tau_v = 0.33$  can theoretically be reached [1]. A market study on complex fenestration systems integrating daylighting functions and thermal control shows that apart from blinds and coatings which can be found in many variations, few products exist. Cutting edge elements such as laser cut panel, prismatic sheets and other micro-structures were studied. The study showed that there is no existing static complex fenestration system (CFS) combining the advantages for both daylight and energetic aspects with a seasonal behaviour. We are investigating a novel micro structure combining functions of daylighting, glare protection, overheating protection in summer and thermal insulation in winter. The optical performances of envisaged structures were evaluated with a simple two dimensional ray tracing program developed specially for the study of laminar structures. This tool permits to optimize parameters and search for new solutions.

**Reference****Laboratoires**

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# TOWARDS MICROSTRUCTURED GLAZING FOR DAYLIGHTING AND THERMAL CONTROL

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## ABSTRACT

Glass is a central element to modern architecture and can cover up to 100% of a building façade. The main purpose of large glazed areas is to create bright, comfortable and healthy spaces. It was shown that increasing natural light in offices reduces sickness but high visual transmittance ( $\tau_v$ ) and excessive energetic transmittance ( $\tau_e$ ) can have opposite consequences: a high  $\tau_v$  can cause glare and visual discomfort for occupants while a high  $\tau_e$  induces overheating which has to be balanced with air conditioning in summer. The energetic and daylighting performances of a fenestration system are central and important issues for architects and the right compromise between good lighting levels, electrical savings, solar gains in winter and overheating in summer is not easy to find.

Over the past decades, progress was made and some solutions to these problems were found. Various types of blinds and shadings have been introduced to prevent glare, achieve a good daylight factor even far from the window and permit to adapt to conditions all along the year. Sun protection glazings on the other side are static systems with a selective coating to limit the transmitted part of the solar spectrum: traditionally a step function with maximum values in the visible range and minimal values in the infra-red and ultraviolet range cuts down excessive solar gains. Recent research show that the transmitted spectrum can be refined and applying a 'M' shaped transmittance distribution, a ratio of  $\tau_e / \tau_v = 0.33$  can theoretically be reached [1]. A market study on complex fenestration systems integrating daylighting functions and thermal control shows that apart from blinds and coatings which can be found in many variations, few products exist. Cutting edge elements such as laser cut panel, prismatic sheets and other micro-structures were studied. The study showed that there is no existing static complex fenestration system (CFS) combining the advantages for both daylight and energetic aspects with a seasonal behaviour.

We are investigating a novel micro structure combining functions of daylighting, glare protection, overheating protection in summer and thermal insulation in winter. The optical performances of envisaged structures were evaluated with a simple two dimensional ray tracing program developed specially for the study of laminar structures. This tool permits to optimize parameters and search for new solutions.

## INTRODUCTION

To provide modular daylighting, solar gains and solar protection, the traditional Venetian blinds, roller shades and screens have been introduced long ago. It is clear that a smart management of available energy is interesting: good lighting levels are comfortable, prevent 'sick building syndrome' [2] and lower the energy bill due to electrical lighting [3]. A good exploitation of solar radiation can reduce heating costs in winter and cooling loads in summer.

In the first part of this study, some of the most recent innovations with such goals are reviewed.

The development of new solutions requires modelling tools, ray tracing software are often used to calculate the Bidirectional Scattering Distribution Function (BSDF) of complex fenestration systems [4]. To the best of our knowledge, no dedicated tool or model exists for the characterisation of complex fenestration systems that are geometry and material dependent. Existing commercial tools provide complete and time consuming 3D characterisation, the resulting outputs are complex and make it hard to compare several solutions. In the second part of the present study, a simple and efficient ray tracing tool will be presented. Using this tool, a complex solution combining daylighting, solar gains and solar protection is pursued. This study presents preliminary results regarding the daylighting aspect.

#### RECENT INNOVATIONS FOR BETTER DAYLIGHTING AND SOLAR CONTROL

This section will introduce existing concepts and products for complex fenestration systems. It focuses on elements of the dimension of common windows and does not include large architectural elements such as light shelves, large integrated anidolic systems, light tunnels, heliostats and solar tubes.

Over the years, the profile and functionality of blinds and shadings was fine tuned to prevent glare and protect from overheating while keeping a sufficient daylight level and good energetic performance. Engineers have optimised blind shapes: *Retrolux* blinds by *RETROSolar* are an example of very interesting geometry (see figure 1a). At high incidence most rays are reflected outwards, while the more horizontal rays are partially redirected towards the ceiling and deep into the room. Recently, split blinds with different inclination angles have been introduced and the upper and lower part of the blinds can be separately controlled. Automated control for blinds was introduced to optimize the position of shadings and adapt to changing conditions all along a day.



*Figure 1: Photographs and schematic illustrations of existing products and application. a) Retrolux blinds [5] b) Solartran Lasercut Panels in a classroom [6] c) Lumitop [7].*

Another approach uses static glazing with special angular properties. Laser cut acrylic panels, for example, use total internal refraction to redirect light upwards when it is incoming with a certain angle. The *Lumitop* glazing by *St-Gobain* (see figure 1c) traps light into banana shaped elements and guides it upwards. The *Serraglaze* sheets take advantage of the same concept and seek the same goals as laser cut panels but with a different fabrication scheme and slight different geometry (mainly differing by its smaller scale). Prismatic structures and holographic optical elements use geometric shapes and the index of refraction difference between air and glass or some acrylic to select rays from a certain angle.

For advanced thermal properties of transparent glazing, thin film coatings were introduced. For solar control, an interferometric coating composed of a succession of thin films “selects” a range of the spectrum for transmission. For low emissivity, a coating reduces heat losses through the window. Such coatings reduce lighting and cooling cost [8] but they don't have a seasonal behaviour, do not redirect light and can create too low light levels in winter.

### **Limitations of existing static solutions**

Some CFSs are only partially transparent or distort the view and are thus often placed in the upper third of the window only in order to preserve a clear view in the bottom part. Others have the inconvenience that they only work for specific angles and therefore have to be mounted on tracking systems. It has been observed that the only existing product combining the advantages for both daylight and energetic aspects with a seasonal behaviour still are dynamic blinds systems with complex geometry. There is a strong interest for CFSs and they are used in public buildings and offices (see *figure 1b*), but comparatively to the simplest blinds, they remain pricey. Beside the growing coated glazing market, split blinds are introduced in new buildings. They provide a dynamic control at a relatively low cost and a simple system to separately control daylight, view and thermal contributions. It would be ideal to have a static glazing achieving similar performances, with no mechanical parts subject to wear. Such a system does not exist.

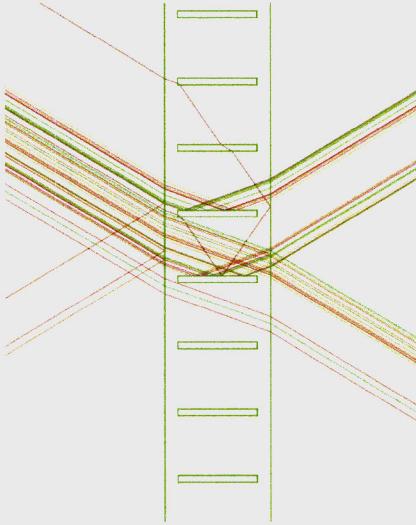
### **RAY TRACING TOOLS**

In order to investigate more complex systems, and because existing tools did not provide satisfaction, a custom ray tracing tool is developed. The goals are to make it simple to design new shapes and parameterize them; change and compare the effects of parameters; assess the propagation of light through the system rapidly and visually; compare multiple different systems regarding different criteria and finally produce usable BSDFs for rendering of daylighting in rooms with tools such as *Radiance*. Most blinds, redirecting glazings and structured systems are 2D profiles projected into the third dimension. A two dimensional approach was selected to simplify computation, programming and output. Neglecting the third dimension is exact in the plane that is perpendicular to the system and contains the normal vectors of all surfaces. Considering only variations of the elevation angle  $\theta$  with a constant azimuth angle  $\phi$  is sufficient to roughly and rapidly characterise systems.

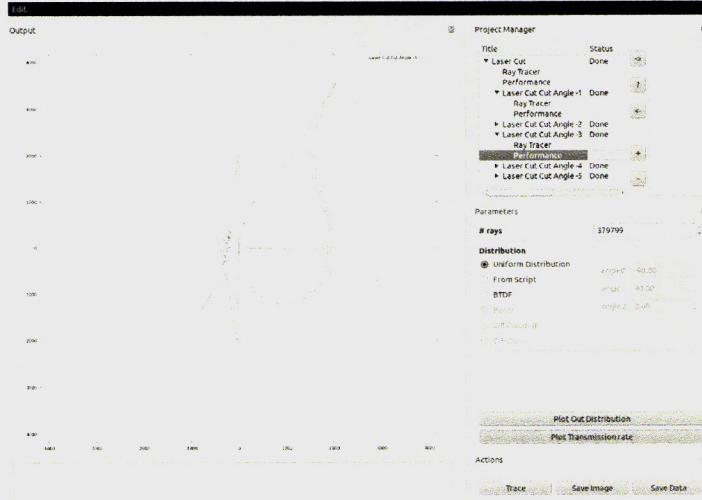
### **Assessment of performances**

The live visualisation of rays through the system at different incoming angles (see *figure 2*) give valuable indications about relevant parameters and approximate values. To get a quantification of the performance of a system, the ray tracing is performed for given incoming elevation angles  $\theta_{in}$  on the outer side off the CFS. The intensity distribution of  $\theta_{out}$  (transmitted and reflected) can then directly be displayed as a polar plot (see *figure 3*). The information given by this polar plot is not always sufficient since the incoming distribution in natural conditions is not uniform and changes with season, location and weather. For these reasons the transmission depending on the incoming angle is interesting and displayed in a second plot. But this ratio does not give sufficient information about daylighting and glare protection, we introduce the transmitted upward ratio indicating the proportion of light that is transmitted upward (see *figure 5*). This representation is useful to assess behaviours dependent both on the solar elevation and the transmitted angle (potential daylight or glare contributing part). Because the amount of information is relatively limited in both representations, it is possible to compare two designs, eventually three. The angular distribution of outgoing angles

depending on incoming angles can also be exported as a angular matrix (BSDF) for other analysis or use in a program such as *Radiance*.



*Figure 2: Simulated ray trajectories illustrating the Lasercut Panel principle.*

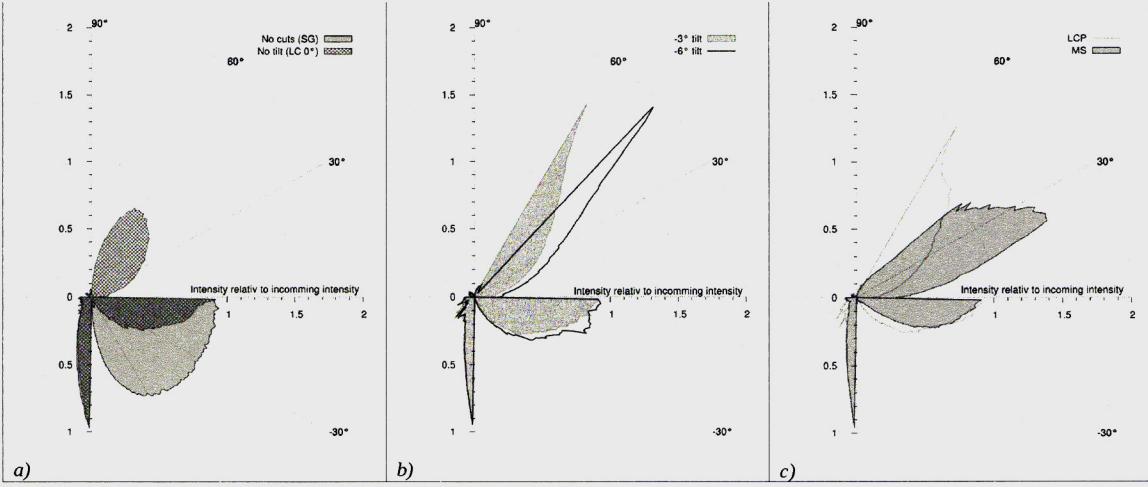


*Figure 3: Screen-shot of the developed graphical Interface with a polar plot of output angle distribution for a laser cut panel with  $-90^\circ < \theta_{in} < 90^\circ$ .*

To complete the model and fully describe the desired systems, several improvements are in process and partially implemented. In order to be able to use selective coatings in the model, thin films will be introduced with wavelength dependent indices of refraction for more precision in interferometry and reflection / refraction. Diffuse reflection will be introduced to model diffusing interfaces and mirrors. The third dimension will be introduced to model the azimuth dependent behaviour. The characterisation will include plots for  $\tau_e$  and  $\tau_v$ .

## RESULTS

On million rays being computed in less than a minute, the software allows rapid assessment of the designs. This section presents some results for optimisation of tilt angle in laser cut panels, then for optimisation of cut period. In the simulations, the CFS is vertical and rays are traced from left to right, uniformly distributed with  $0^\circ < \theta_{in} < 90^\circ$  where  $\theta_{in}$  is the elevation from the horizon. *Figure 4a* shows how a laser cut panel (LC) and a clear glass (SG) transmit and reflect light. The SG transmits better towards the normal and reflects grazing light. The Laser cut panel partially redirects the light and creates a peak in the upper quadrant; this peak is due to the air-glass interval in the panel where light hitting with angles higher than  $41^\circ$  is reflected. As expected and shown in *figure 4b*, the tilt angle of the cuts directly influences the direction of the peak in the distribution of light. The steep step in the intensity (at  $60^\circ$  for example for the  $-3^\circ$  tilted laser cut panel) is due to the inclination of the cuts, incoming rays are refracted at the air-glass interface into the panel: for  $67^\circ < \theta_{in} < 90^\circ$ , the first transmission cone is very narrow:  $40^\circ \pm 2^\circ$ . Due to the reflection at the cut, this angle is shifted by twice the tilt angle:  $28^\circ \pm 2^\circ$  for a  $6^\circ$  cut and light hits the exit interface with a much smaller angle than the initial transmitted angle. In this interval the transmission cone is much smaller:  $41^\circ$ - $49^\circ$  instead of  $67^\circ$ - $90^\circ$  for direct transmission. The effect is a directional transmission at preferred angles where light is concentrated, and the overall transmission can also be slightly increased by this effect (*see table 1*).



**Figure 4:** Polar plot of outgoing intensity distribution for  $0^\circ < \theta_{in} < 90^\circ$ . a) Clear glass (SG) and Laser cut panel (LC) . b) Laser cut panel at different tilt angles. c) Optimised Laser cut panel (LCP) and Microstructure (MS).

	SG	LC 0°	LC 1°	LC 2°	LC 3°	LC 5°	LC 2° 3.5mm	LC 2° 4mm	LC 2° 4.5mm	LC 3° 3.5mm	LC 3° 4mm	LC 3° 4.5 mm	MS
Mean Transmission	78.0	75.0	76.8	77.7	78.4	<b>78.8</b>	76.0	76.7	77.3	76.2	77.0	78.0	<b>81.7</b>
Mean T up Quadrant	0	41.7	42.9	42.9	42.2	39.7	42.0	44.3	<b>44.6</b>	42.3	44.4	44.4	<b>56.2</b>
Redirected $20^\circ < \theta_{in} < 70^\circ$	0	55.6	54.8	54.1	52.7	50.0	58.7	<b>59.9</b>	57.7	59.4	59.9	56.9	<b>74.7</b>
Redirected $50^\circ < \theta_{in} < 70^\circ$	0	68.5	69.2	69.5	68.7	67.5	57.8	70.8	73.5	62.6	73.7	<b>74.0</b>	<b>84.8</b>

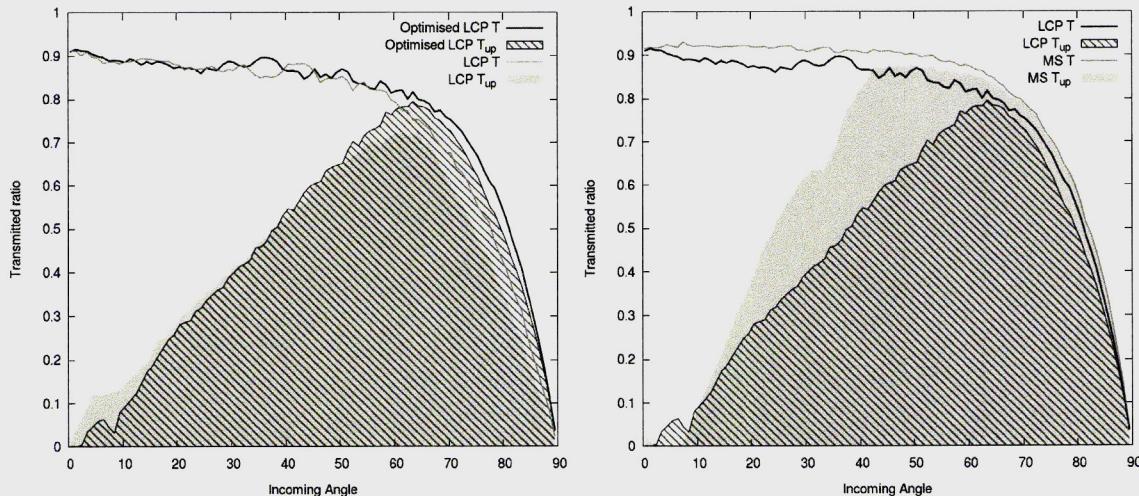
**Table 1:** Mean percentages for different glasses and different laser cut panels. SG is a standard single glazing with BK7 glass. LC stands for laser cut with different tilts angles and a 5mm periodicity. The periodicity is specified when different. MS stands for micro structure, a custom microstructure developed using the ray tracing tool.

Lines 1 and 2 in *table 1* show the mean values for the total transmission and upward transmitted quarter. At angles of incidence corresponding to direct solar radiation in Lausanne in summer (50 to 70°) the 2° laser cut panel is the most efficient at redirecting the light with 68.7% transmitted upward. The influence of periodicity of the cuts for 2° and 3° tilts was studied next. We find that the best design is a 3° cut with a 4.5mm periodicity. As stated in *table 1* with a 4.5 mm period, 74.0% of light incoming between 50° and 70° is redirected against 68.7% with a 5mm period. A custom micro structure (MS) reaching 84.8% was developed, the transmission distribution for this MS is compared with the 3° 4.5mm laser cut panel in *figure 4c and 5b*. This design is also superior for overall transmission, overall redirection and most important, the “useful” redirection between 20 and 70°: the span of solar elevation during a year in Lausanne. The redirected light is distributed around 30° for the MS when it is centred around 50° for the laser cut panel. *Figure 5a and 5b* illustrate the difference in transmission and redirected light between different designs. The MS design is much superior for angles around 40° and at very low angles, around the normal, it does not redirect light.

## CONCLUSION

There is no existing static system combining daylighting, solar protection and a seasonal behaviour for thermal control. To design an ideal CFS, a simulation tool was developed.

Preliminary results show that the daylighting goals can be reached and the parameters optimised. The resulting CFS outperforms existing structures in the simulations. The objectives differ depending on the type of building, the orientation of façades and the latitude on earth. A target function adapted to these conditions and evaluation simultaneously the visible light redirection for daylighting, the angular dependent energetic transmission, and a clear view factor needs to be developed.



*Figure 5: Comparing transmitted and redirected ratio in different CFS a) for Laser cut panel optimisation. b) For custom microstructured glass.*

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