Redirection of Sunlight by Microstructured Components – Simulation, Fabrication and Experimental Results

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Abstract

This paper presents a non-tracking microstructured light redirecting device, which can be integrated into architectural glass. When fixed in the upper area of a window above eyelevel it redirects the light from solar altitudes between 15° and 65° and illuminates a room without causing glare. Ray-tracing calculations are employed as a tool for identifying suitable configurations and geometries. The results of the simulations show the advantage of combinations of lens-like with prism-like geometries in comparison to conventional micro prism arrays regarding the overall light redirection efficiency as well as the producibility. The redirecting device is more lightweight, gives better integration options and is producible in a more economic manufacturing process as systems with similar performance. Measurements of cast silicone prototypes (100mm x 100mm x 4mm) confirmed the simulation results. By now the performance has also been shown by large scale industrially produced acrylic panels with dimensions of 1500mm x 400 mm x 4 mm.

Keywords: Daylighting, Microstructure, Sunlight Guide Panel, Microreplication

1. Introduction

Not only recently energy efficiency is one of the most important objectives in most fields of research including the field of modern lighting. Daylighting, with sunlight as a natural and the most energy efficient light source, is one concept to reduce the electricity consumption while maintaining a high quality illumination. Because of sunlight’s high intensity, even relatively small window areas may be used not only to create a standard illumination but also to reach higher illuminances which are desirable for biological convenience (Van Bommel and van den Beld, 2004). Daylighting should not be affected by solar thermal control systems like shading devices or reflective glass. Conventional louvers, e.g., (see Fig. 1.a) reduce the daylight so strongly that additional artificial lighting is often needed to reach the required minimum illuminance (IEA, 2000). An advanced version of a louver system is one with the capability of light directing (Fig. 1.b) which allows to control the upper and lower part of the louvers separately. While the lower part is used for shading the direct sunlight, the upper elements are positioned in a way to reflect it into the room (Johnsen and Watkins, 2010). The sunlight is then scattered at the ceiling to illuminate the working area of the room indirectly. To maintain the level of illumination the louvers need to be tracked according to the solar altitude. In order to protect the redirecting elements against external influences like dust and rain, there exist louver systems which are integrated into double glazing (IEA, 2000).

Light directing glasses are non-tracking solutions for the redirection of sunlight (Fig. 1.c) and are
placed above eye level, as they cannot be looked through and would cause glare in lower positions.
The lower part of the window is shaded by louvers or other shading systems. In contrast to louver systems, the redirecting elements do not have movable parts which make them less vulnerable to malfunction.

Fig. 1: Solar control systems: a) conventional louvers b) partially light directing louvers c) light directing glasses with shading louvers

There exist various kinds of light directing glasses. One approach is to use special aluminum profiles which are similar to louvers with the exception that they are fixed inside the glazing (IEA, 2000). Other systems are using transparent materials (e.g. acrylics) which transmit the light and redirect it by total internal reflection. These transparent materials are naturally good thermal insulators and better suited for the integration into the glazing than metals since they do not build a thermal bridge. The systems can be distinguished by the geometry of the redirecting elements as well as by the process of how to shape them. In Laser-Cut panels PMMA (Polymethyl methacrylate = acrylic glass) panes are cut by laser (Edmonds, 2005). Their layout is therefore limited to straight slits which leads to a limitation of the light directing ability. Sometimes this is countered by tilting the system together with the glazing.

Prismatic structures which redirect the daylight “seasonally” or which are primarily used as sun-shading devices have been described by the Institute of Solar Energy (ISE) in Freiburg (Walze et al., 2005). However, the described solutions are unsuitable for redirecting efficiently a broad range of solar altitudes. (Hocheng et al., 2011) demonstrated a microstructural, prismatic sunlight guide panel based on UV-imprint technology. All the same, the employed hybrid polymers are too expensive for a wide use. Light directing glasses which are using holographic optical elements (HOE) also suffer from color effects and an overall low efficiency (IEA, 2000).

In LUMITOP® (Saint-Gobain Glass, 2006), stacked PMMA profiles are used as light conductors to redirect the light. The profiles are extruded and have a dimensions of 3,5mm by 12mm. Products with this macro structured system have already proved their good performance in daylighting (Mueller, 2006): The profiles redirect the direct sunlight of solar altitudes from 15 to 65°, which represent the conditions in Middle Europe, to the ceiling deep into the room. Most of the light will be redirected above eye level to establish a glare-free environment. The light is spread to reduce contrasts by very bright areas on the ceiling.

In this work the challenge was to create a light directing device which will be integrated into architectural glass and reaches an equal or better illumination performance than LUMITOP. By substituting the complex light conductors through a continuous micro structered PMMA pane, the thickness and total weight of the optically active elements can be reduced by two third and hot-embossing as a more economical manufacturing process may be utilized. Furthermore, by using a non-stacking but continuous pane the optically active element works as a third pane which should
improve the thermal qualities of the glazing (u-value). Also the assembly process of the glazing will be simplified significantly as integrating a single pane is far easier than integrating lots of elements above each other. Due to these benefits the final product should be less expensive than comparable alternatives.

2. Simulation

To identify high-efficient light redirecting configurations extensive ray-tracing simulations have been undertaken. ZEMAX, a tool for the general development of optical systems has been used. The analyzed systems were designed with a CAD program (Solid Works) and then imported by the raytracing software. The simulation environment was adapted to simulate solar altitudes between 0 and 75° taking into account the conditions in Middle Europe. Therefore, due to obstructions close to the horizon and to reduced radiation intensity, solar altitudes between 0° and 15° were of lower significance as well as sun altitudes of 65° or more, as they do not occur under these preconditions. The simulation process was not aimed at fully characterizing single systems, instead it should give a first estimation of the behavior of hundreds of different geometrical configurations. Therefore, the evaluation of the configurations was not as detailed as in Andersen et al., 2003 and it did not cover all directions of the incident light as proposed by Tregenza, 1987, but was limited to an azimuth φ=90°. By this way, a variety of systems could quickly be discarded and the results of promising configurations could be proved with a rather simple measurement set-up.

In order to avoid demoulding complications at hot embossing of the PMMA panels, first approaches led to prismatic structures such as saw-tooth. While such micro prism arrays may redirect the sunlight under certain conditions with high efficiency, they are restricted to a limited bandwidth of solar altitudes.

Simulations show that saw-tooth micro prism arrays which are placed on the inward surface of a pane are generally well suited to redirect the light of middle and high solar altitudes, while low incident light will be transmitted in a downward direction. To redirect sunlight also under low solar altitudes, the incident rays have to reach the prisms under a steep angle. By additionally structuring the sun-facing panel surface this can be achieved and a lens-like profile on the sun-facing panel side performs quite well.

Fig. 2 shows ray tracing figures for four incident angles for PMMA (group a)) and Polydimethylsiloxane (PDMS = silicone; group b)) as materials. At each optical transition ZEMAX splits a ray into a transmitted and reflected ray, calculates its intensity corresponding to the optical properties and then traces them separately. Note that in this picture only the parts of a ray are displayed which contain the larger fraction of light while the results discussed later also include the split rays with the smaller fractions. Due to the different refractive indices of PMMA and PDMS, with n_{PMMA} = 1.49 and n_{PDMS} = 1.41 for visible light, the light distributions vary. The comparison shows that with PMMA as a material a larger amount of light is redirected back to outside for solar altitudes of 45° and 60°. However, for both materials most of the light is redirected into an upward direction with about ca.15° as a turning point at which the majority of the light is successfully redirected. Due to the lens-like geometry the angle of the daylight is widened considerably and will reach the saw-tooth prisms under a steep angle which will be redirected. This spreading is a vital point since without the lens-like geometry critical sun altitudes may exist for which all the light is transmitted in a downward direction which may cause severe glare. By using lenses this amount is reduced to a negligible quantity.
Fig. 2: Raytracing results for a PMMA light directing element (group a)) with incident light of 15°, 30°, 45° and 60°. Microlenses at the sun-facing panel side spread the incident light widely and enable the light redirection also for low solar altitudes. b) Results for PDMS devices.

Fig. 2 also shows that the parallel incident rays are focused by the lens-like geometries and angularly distributed over the prismatic side. Care must be taken in the design of the panels that the focal length of the lenses is not longer than the panel thickness. If the foci are situated in the range of the prism side undesired effects may appear like a rapidly changing light direction at small changes of the incident light angle. These effects are avoided by limiting the minimum panel thickness to about the double of the focal length. The large scale PMMA panels described in this work use structures of 500µm (pitch and structure height) which limit the minimum thickness to about 3.5 mm. Thinner panels may be used together with smaller structures.

The simulations show that the lens-like microstructures lead to reasonably homogeneous angular redirection efficiencies. Furthermore, by the lens induced angular scattering color effects are avoided which are generally present in pure prismatic systems.

3. Fabrication

The numerically optimized designs have been transferred into high-precision micro tooled replication moulds and implemented in casting and in hot embossing processes. Casted prototypes were fabricated by using PDMS with structure dimensions (pitch and structure height) in the range of 250µm on an area of 100 x 100mm².

After experimentally proving the expected good light redirection efficiency of PDMS prototypes (see Fig. 5) the technology has been transferred to large scale industrial production by hot embossing (Jungbecker Technology, Olpe, Germany). In hot embossing, a thermoplastic material (here PMMA) is heated up above the glass transition temperature and then the moulds are pressed into the material. After cooling down, the products are separated from the moulds. In terms of precision engineering and costs, the creation of the replication moulds is expensive, but provided that a reasonable amount of light directing elements are created, hot embossing is an economical process. The total fabrication costs are expected to be significantly below the commercial LUMITOP.

Fig. 3 shows a fabricated panel. The size of 1500mm x 400mm x 4mm is a size well suited for implementation in standard windows or skylights. Due to reasons of fabrication, the structure dimensions were scaled to 500µm.
With a thickness of 4mm, the microstructured PMMA panel weights a third of the light conductor unit of the Lumitop system (thickness of 12mm) which leads to a saving of about 8kg per m².

**Fig. 3:** Large-scale prototype with dimensions of 1500 mm x 400 mm x 4 mm for implementation in windows / skylights

Fig. 4 depicts opportunities of how to integrate the micro structured daylighting system into the glazing. The integration into a separated skylight with a separating frame between upper and lower window area is the most obvious solution. In order to achieve a window image with continuous glazing (no separating frame between upper and lower part), two solutions are possible: Joining of PMMA and glass pane or continuous glass pane with micro structured plastic foils laminated at the desired positions. The appearance of a window which has been laminated with a prototype of a micro structured PDMS foil in the upper part is also depicted in Fig. 4.

**Fig. 4:** Integration into glazing. a) Separating frame between upper and lower window area. b, c) Lamination of micro structured foils (900 mm x 300 mm x 1.5 mm) in the upper part of a continuous glass panel

### 4. Experimental Tests

After fabrication, the accuracy of the produced sample geometry and surface roughness has been controlled by photographic and white-light interferometric measurements. With a surface roughness in the range of 10 – 20 nm for the casted and about 100 nm for the hot-embossed panels the daylighting systems meet optical quality. The overall appearance of the panes is rather homogenous.

The redirection performance was measured with a goniometrical setup as outlined in Fig. 5. As a light source a HE-Ne-laser with a wavelength of 633nm and a diameter of 3mm has been used. The “solar altitudes” $\theta_1$ between 0 and 75° have been measured in steps of 5°. For each resulting light distribution the light within a quadrant was detected by an optical power meter and summed up to
gain two clear values: one for the percentage of the light leaving the system in an upward direction (positive $\theta_2$, green quadrant and green graph in the diagram) and one for the downward direction (negative $\theta_2$, red quadrant / graph). Light which is reflected or redirected to the outside of the device is not included in the chart.

In order to measure the larger elements of LUMITOP, the outer glasses of two demonstrator systems were removed and the laser optics adapted to generate a line with a length of 18mm. To verify the reliability of the modified laser set-up some microstructured systems were measured with line and point laser. The results of these measurements showed a good conformity with a variance in the range of 1-2%.

In Fig. 5 the redirection performance is demonstrated with a torch.

**Fig. 5: a) Principal of goniometrical measurements. b) Diagram of redirection performance: Comparison between microstructured PDMS prototypes and a LUMITOP sample**

The obtained results (see Fig. 5) prove the expected high efficiency in redirecting the daylight without causing glare and confirmed the estimated results of the simulation. The microstructured PDMS samples achieve a redirecting overall efficiency of about 68% (mean value) for solar altitudes between 15° and 65° and prototypes out of PMMA reach values of 65%. Both variants surpass the value of the commercial system LUMITOP (mean value: 30% (first demonstrator) and 43% (second demonstrator)).

In **Fig. 6** the redirection performance is demonstrated with a torch.

**Fig. 6: Demonstration of light redirection performance: light distribution without (left) and with inserted PMMA redirecting device (right)**

5. **Comparison between calculations and experimental results**

As mentioned above, the transfer of a simulated layout to a physical redirecting device is a process of
many steps: micro scale diamonds have to be shaped with the specified layout and are used to create the metallic replication moulds. The two sides of the PDMS prototypes are cast separately and bonded together. Then the manually produced prototypes can be measured with the described goniometrical set-up. As each step has the potential of changing the desired light redirection performance a comparison between expectations and achieved results should be performed. 

*Fig. 7* shows a comparison between simulated (red lines) and measured light distributions at PDMS prototypes for incident angles of $\theta_1 = 15^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$. The blue lines are based on measurements at eight prototypes which vary in thickness between 2.5mm and 5mm. As predicted the thickness had no measurable influence on the redirection performance, as it did not come below the minimum thickness (Note: the PDMS devices have structure dimensions of 250µm and a minimum thickness of about 1.8mm).

Considering that the simulation values are based on ideal geometries and do not consider surface properties (e.g. roughness) and that the measured values contain all variables of a production process the compliance is rather good. Greater variances only exist for secondary peaks which are slightly shifted to the expected position as in diagram a), or for secondary peaks which were not expected at all (diagram c and d).

*Fig. 7: Transmission (%) vs. $\theta_2$ (°): Comparison between calculations and goniometrical measurements of PDMS prototypes for incident angles of $\theta_1 = 15^\circ$ (a), $\theta_1 = 30^\circ$ (b), $\theta_1 = 45^\circ$ (c) and $\theta_1 = 60^\circ$ (d).*

### 6. Options for modification

Concerning the total amount of the redirected light, the demonstrated daylighting device proved the expected high efficiency. However, under specific solar altitudes a stripe structure of the redirected light could be observed. In order to improve the homogeneity of the light distribution and to optimize the overall impression of the system, some modifications have been performed. By slightly adjusting the geometry of the prisms to a more curved layout, the stripe structure can be reduced and the light is directed deeper into the room.
Applying a defined roughness with an $R_a$ of about 900 to 1000nm on the outcoupling surface of the prisms is another tool for modifying the light distribution. The light will be spread horizontally which improves the soft transition between redirected light and the non-illuminated surrounding. Also the overall transmission will be increased, as the amount of light which is redirected back to the outside is reduced. *Fig. 8* shows the changes in the light distribution. The light distribution of the system with applied roughness has a perfectly clubbed form, but also causes a slightly higher amount of light which is directed downwards which might cause glare. Nevertheless, this modification should be considered as an option, as the light intensity will further be reduced by outer glasses which might lead to acceptable values.

![Fig. 8: Light distribution for light with a solar altitude of 30° (simulation results): a) The peaked graph is based on the basic system with straight bottom flats of the prisms. The shaded graph uses curved flats with a specifically applied roughness. Resolution of $\theta_2$ is 1°; the amplitude of both systems is normalized. b) Transmission (%) vs. $\theta_2$ (°): Comparison between basic system, a system with a modified geometry and a system with modified geometry and applied roughness for $\theta_1 = 30^\circ$.](image)

7. Conclusion

The development of a micro structured redirecting device which reaches an illumination comfort similar to established daylighting systems while reducing the complexity and thickness significantly was successful. Inconveniences of pure prismatic systems could be avoided by using lens-like geometries at the sun-facing side.

By applying large-scale hot-embossing technology, the presented daylighting system can be manufactured industrially and assembled in mass-production. This is a precondition for affordable high quality products and a wider market penetration of daylight illumination systems.

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