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Energy Efficient Room Illumination By The Redirection of Sunlight: New Micro Structured Components

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ABSTRACT

Non tracking daylight systems, which redirect the light from solar altitudes between 15° and 65° deep into rooms without causing glare effects, have been applied successfully in several office buildings recently. These systems are based on specially shaped polymer profiles which are inserted in double glass windows and which are commercialized under the label LUMITOP. Based on these macro structured systems, fixed in the upper area of windows above eyelevel, advanced solutions using micro structured components will be reported. Main objective of this new development is the reduction of material input (e.g. PMMA) and production costs. Additionally, the optical properties and redirection performance of the existing system should be improved. First, ray tracing calculations have been carried out to identify optimum solutions for micro structured components capable of redirecting daylight with high and almost homogeneous efficiency over the relevant angular range of solar altitudes and not showing colour effects. The simulation results show, that by using a combination of micro lenses and micro prisms an almost homogeneous sunlight redirection of about 70% is achieved in the angular range of solar altitudes between 25° and 65°. These results could be confirmed by prototypes fabricated in the highly transparent silicone polymer PDMS. Suitable industrial production processes for large area panels (1400 mm x 400mm x 4mm) are hot embossing in thermoplastic materials like PMMA and UV-embossing in special UV-curing resins. Both processes are under development and the status of the development will be reported.

REQUIREMENTS OF COMBINED SOLAR CONTROL AND DAYLIGHTING

Windows have to control solar heat gains effectively in order to avoid uncomfortable room temperatures respectively high energy consumption for cooling. The main design parameters of the façade influencing this performance are window area and orientation as well as shading coefficient of glazing and additional shading facilities.

Simultaneously the façade has to provide a high daylighting performance, especially in non-residential buildings like offices, in order to create a high quality illumination as to visual tasks and biological (circadian) effects of the user as well as to reduce the electricity consumption for artificial lighting. Latest research results demand illuminances much higher than the standard (DIN EN 12464-1) values for artificial lighting (300 lx to 750 lx). Desirable values should be up to 2000 to 4000 lx [1-1 to 1-2], at least under daylight conditions. The main design parameters in addition to those of solar control are position and shape of window, light transmittance of glass and shading facility. A differentiation of sky conditions, i.e. diffuse and direct sunlight, has to be taken into account.

PRINCIPAL SOLUTIONS

Conventional solar control systems like external louvers or roller blinds have the side effect to reduce the daylight transmission strongly so that the minimum illumimance often can only be provided by artificial light. In order to utilize the available daylight but control the solar heat gains simultaneously, combined shading and daylighting solutions have been developed [2-1]. They improve the illuminance, as compared to conventional louvers, partly light directing louvers and light directing glass in Fig. 1 shows.

Relatively small window areas are sufficient for redirecting sunlight to the depth of the room because of the intensity of direct solar light. In order to avoid glare only the upper part of the window above eye level should be used for sunlighting. If louver systems are used the lamellas have to be highly reflective, especially shaped and tracked according to the solar position. More robust are redirecting systems, which have not

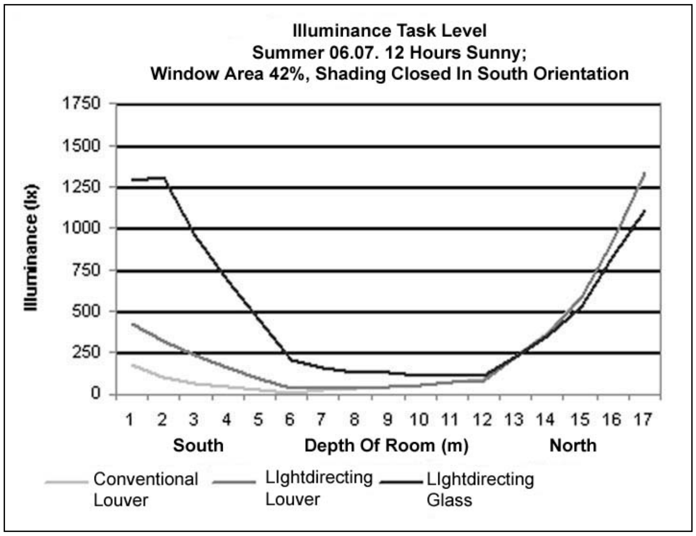


Figure 1a Illuminance (lx) and distance from window (m), south / north orientation, shading device closed in south, opened in north [2-2

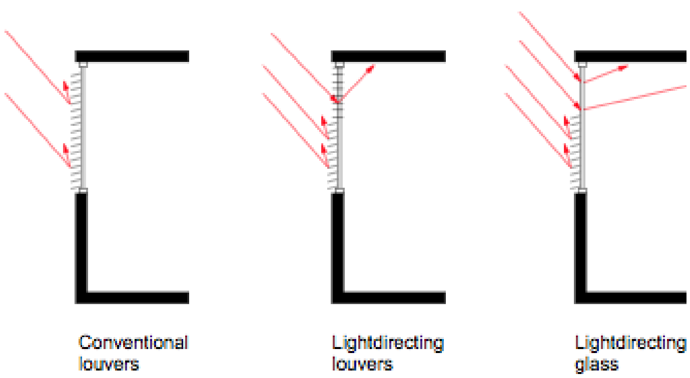


Figure 1b Three daylight and shading solutions: Conventional louvers, light directing louvers, light directing glass in upper and louvers in lower window area.

to be moved and which are protected against external impact like dust, wind and rain, e.g. in the gap of a double glass unit.

This study focuses on the fixed type of solar redirection with the following task: Redirection of direct sunlight in windows, facing east, south and west, from solar altitudes up to 65° in Middle Europe to the ceiling and depth of the room without causing glare. Because of reduced radiation intensity and obstructions close to the horizon a minimum solar altitude of 20° can be assumed. Most of the light has to be redirected above a horizontal level. The remainder of light an emergent angle smaller 0° must be less than 10% to avoid glare.

Principle solutions, all of which have a translucent image, are given in Table 1. The systems based on refraction have a higher efficiency than those based on reflection, as total internal reflection works without losses. The protection against external impact and deposition of dirt helps to avoid performance losses, thus the encapsulation in a multilayer glass unit is recommended. Although principle No. 3 with light conductors has proved a good performance in numerous applications [2-2],

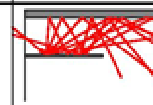
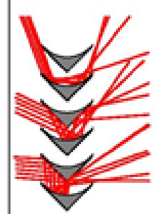
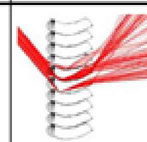
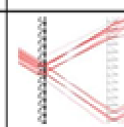
Physical effect	Principle solution	No.	Drawing	Aspects of selection
Reflection	Diffuse reflector (Lightshelf)	1		- limited reflection - limited trans-mission for covered sky conditions - glare for low solar altitudes
	Specular reflector (DLS-Fisch)	2		- limited reflection - limited trans-mission for covered sky conditions - dirt avoidance by enclosure in gap of double glazing - DLS-Fisch, Eckelt, [2-5]
Refraction (internal total reflection)	Light-conductor (Lumitop)	3		- reflection without loss - high transmission - dirt avoidance by enclosure in gap of double glazing - Lumitop, 11mm wide light con-ductors in gap, [2-5]
	Plane with two structured surfaces (Lumilight)	4		- reflection without loss - high transmission - dirt avoidance by enclosure in gap of double glazing - Lumilight, 4mm PMMA plane with micro structures, [2-3]

Table 1 Principle solutions for redirection of direct sunlight by fixed systems (no solar tracking)

it was taken as a challenge to reduce the complexity of the 11 mm PMMA profiles in the gap of a double glass unit.
Solution No. 4 was chosen for an advanced approach, a simple pane of transparent material with optical surfaces to be placed in a glass unit [2-3].
The development of suitable surface structures and their production in micro dimensions is shown in chapter 4 to 6.

BOUNDARY CONDITIONS OF APPLICATION

The boundary conditions of architecture and building construction have to be considered for the development: Different kinds of facades with single windows or larger glazed areas have to be taken into account as well as various types of solar control, which can be fixed or movable. There can be continuous glazing or a separating frame between upper and lower window part. A survey is given in Table 2. For the time being a maximum dimension of 1500 mm x 400 mm for light directing panels was derived from existing buildings with state of the art daylight systems.

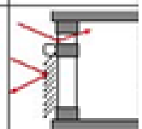
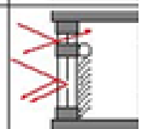
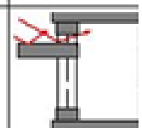
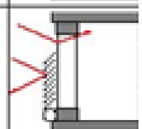
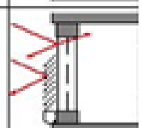
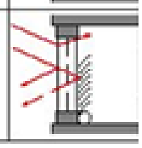
Integration of light redirection	Fixed solar control	Movable solar- and glare control	No.	Drawing
Upper window area separated by frame	None	Outside from above	1	
	Solar control glass, selective	Inside from above	2	
	External shading		3	
Without separating frame	None	Outside from down below	4	
	Solar control glass, selective	Outside from down below	5	
		Inside from down below	6	

Table 2 Boundary conditions for light directing systems in side windows

OPTICAL MICRO STRUCTURES AND RAY TRACING CALCULATIONS

The ray tracing calculations lead to a double sided microstructure as optimized configuration. The system combines lens-like structures at the light incident and prismatic structures at the light redirection side (see Fig. 2). The implementation of the lens-like microstructures at the light incident side leads to reasonably homogeneous angular redirection efficiencies and avoids colour effects which are generally present in pure prismatic systems.

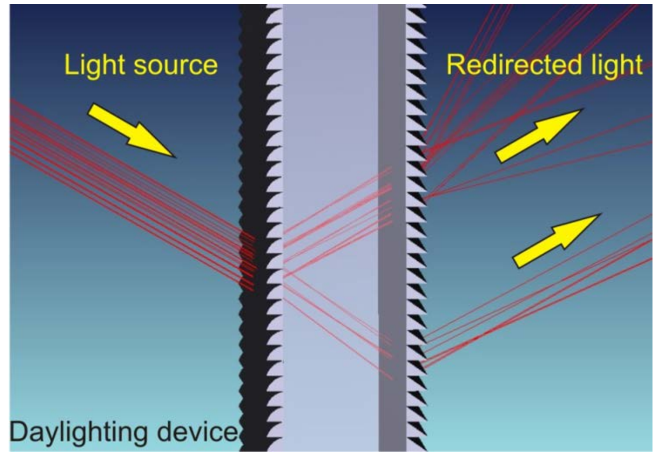


Figure 2 Schematic configuration of light redirection by double sided micro structured surface

PRODUCTION TECHNOLOGIES, PROTOTYPING, LARGE SCALE PRODUCTION

For the fabrication of micro optical elements a variety of high precision replication processes are available like precision injection moulding, hot or UV-embossing, or casting. All materials with high optical transparency are principally suited for the realization of such micro structured components, with preference of polymeric materials - due to their easier mass production capabilities.

In this work, the numerically optimized designs have been successfully implemented in casting and in hot embossing processes. Casted prototypes were fabricated by using PDMS (a highly transparent silicone polymer). The structure dimensions of the lenses and prisms were in the range of 250µm. After demonstrating experimentally the high light redirecting efficiency of PDMS prototypes (dimensions: 100mm x 100 mm) the technology has been transferred to large scale industrial production by hot embossing (Jungbecker Technology, Olpe, Germany). The size of the fabricated panels allows for 1500mm x 400 mm x 4 mm (Fig. 3), which is a size well suited for implementation in standard windows or skylights.

Research work by the Institute of Solar Energy (ISE) in Freiburg on prismatic structures showed that micro prism arrays are principally suited for light redirection [4-1], however with the drawback that the redirection efficiency varies considerably over the angular range of the daily solar altitudes. In consequence, at certain hours of the day the light redirection works with high efficiency, while at other hours the incoming sunlight causes severe glare. In this work ray tracing has been employed to develop a micro structured optical system which is capable of redirecting light homogeneously over the whole angular range of the daily solar altitudes.

Figure 3 First large-scale prototype with dimensions of 1500 mm x 300 mm x 4 mm for implementation in windows/ skylights

In order to achieve a window image with continuous glazing (no separating frame between upper and lower part), two solutions are possible: Joint of PMMA and glass pane in the gap or continuous glass pane with micro structured plastic foils laminated at the desired position on a glass sheet. Fig. 4 shows the appearance of a window which has been laminated with a micro structured PDMS foil in the upper part.

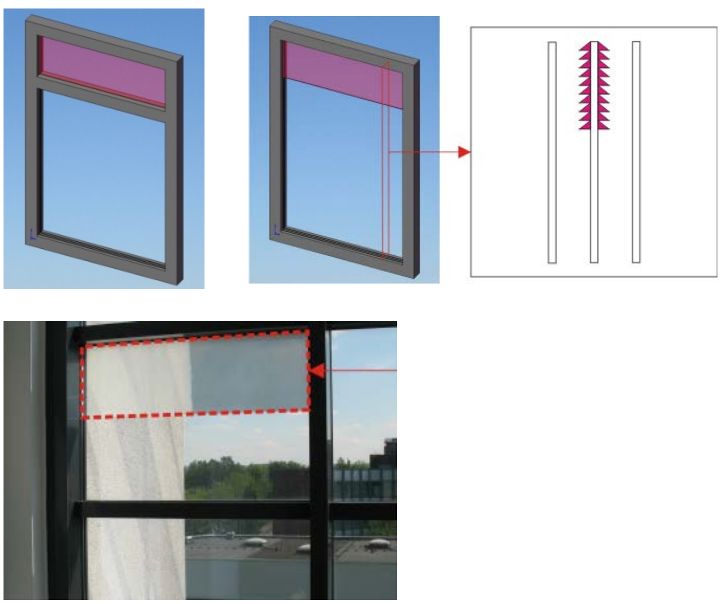


Figure 4 Separating frame between upper and lower window area, right: Lamination of micro structured foils (900 mm x 300 mm x 1.5 mm) in the upper part of a continuous glass panel

EXPERIMENTAL TESTS, OPTIMIZATION PROCESS

While a simple test with a torch already demonstrates the systems efficiency (see Fig. 5), the redirection performance was also measured with a goniometrical setup. The obtained results prove the expected high efficiency in redirecting daylight without causing glare and confirm the estimated results of the numerical simulation. First samples achieve a redirecting overall efficiency which surpasses the values of existing commercial systems.

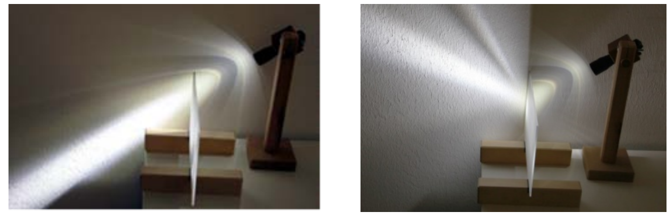


Figure 5 Demonstration of light redirection performance: light distribution without (left) and with inserted daylighting plate (right).

The diagram in Fig. 6 shows the percentage of transmitted light directed upwards (green line) and downwards (red line) over the solar altitude of the incident light. Overall, about 70% of the incident light (between solar altitudes of 15 to 60 degrees) is redirected and scattered to the ceiling. The remaining 10% of the transmitted light (red line) is diffusely scattered and may contribute to an additional illumination of the working area.

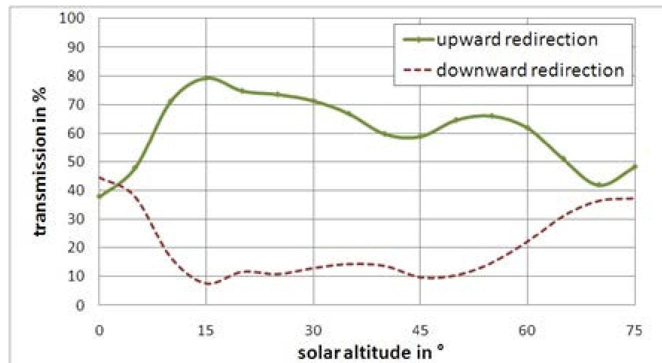


Figure 6 Diagram of redirection performance (based on measurements of a PDMS prototype).

CONCLUSIONS

The development of non tracked, micro structured solar lighting systems has been successful as to large scale embossing technology in dimensions of 1500 mm x 400 mm as well as to prototype testing. By mounting the PMMA pane between two glass panels the characteristics of a triple glass unit, as shown in Fig. 7, can be achieved. Depending on dimensions, coating and gas fill the following characteristics are expected:

- U-value = 0.7 – 0,8 W/m² K (2 low-e coatings & argon)
- Solar heat gain g = 0,25 – 0,30 (selective coating)
- Light transmission T = 0,50 - 0.60

In comparison to state of the art solutions efficiency of redirection and light transmission could be improved and material input of PMMA as well as complexity of construction be reduced. Depending on the boundary conditions like room geometry, window size, orientation, solar and glare control, high daylight quality (illuminances > 1000 lx), and low annual lighting energy demand (reduction 20% to 40% compared to conventional systems) can be achieved [2-3].

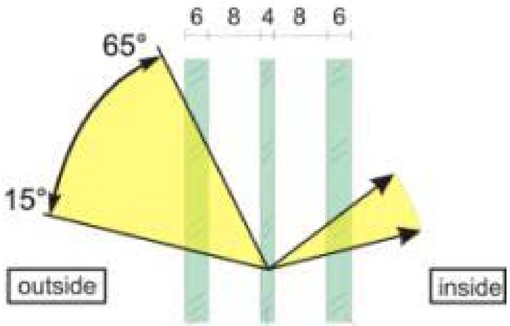


Figure 7 Example of micro structured light directing pane integrated in glass unit

The reported advanced micro structured daylighting system was designed to be manufactured by high-productivity processes. In addition, the slim design leads to a reduced material consumption and simplifies the assembly process of the final glass unit significantly. The resulting lower costs as well as the capability of integrating the system into windows with separate clerestory (frame) as well as without is considered a favourable pre-condition for a successful and deep market penetration.

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