Application of Microstructured Surfaces in Architectural Glazings

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Abstract
Interference lithography is a promising technology to produce large areas of periodical microstructured surfaces on glass or plastic. Anti-reflective and anti-glare coatings, easy-to-clean surfaces and combinations of some of these features in one surface are possible. It also allows the miniaturization of light guiding and light reflecting optical elements. Two different types of optical elements with a strongly angular selective transmission were designed and fabricated: reflective prismatic structures and dielectric compound parabolic concentrators. Integrated in architectural glazings they can be a cost-effective solution for static seasonal sun protection.

Introduction
The control of light in architectural glazings is increasingly important in the planning of modern buildings. Maximum use of solar radiation for heating and daylighting on the one hand and minimum overheating and glare on the other hand are contrary requirements for a glazing. For this purpose it was proposed to integrate optical elements like retroreflecting prisms or dielectric compound parabolic concentrators (CPCs) in glazings [1][2]. Commercial solutions using macroscopic structures exist but they are usually heavy and material-intensive. In addition the visibility of the optical elements can be disturbing.

Objectives
In order to realize a leightweight and thus more cost-efficient solution, a miniaturization of the optical elements would be desirable. There exist several techniques to generate microstructured surfaces. Among these are mechanical micromanufacturing, grey tone lithography and interference lithography. Contrary to other techniques interference lithography offers the possibility to structure large areas with optical elements in one step. We therefore tested the application of this technology for the miniaturization of light redirecting elements on glass or plastic. Suitable surface relief structures had to be identified and fabricated in the laboratory. Their angular selective transmittance was measured. In addition the combination of new optically switchable coatings with microstructured surfaces to enable dynamic control of the shading function was investigated.

Methods
Interference or holographic lithography is a well known technology to produce periodic microstructures on surfaces in photoresist. By modification of different process parameters one and two dimensional periodic structures can be realized. Periods between 0.2 and 50µm are possible. The structure itself can be sinusoidal, parabolic, triangular or binary. In any case it can be combined with a stochastical structure.
The fabricated structure can be transfered into a nickel shim by an electroforming process. The shim is used as an embossing tool to replicate the structure on surfaces of plastics or glass (see figure 1).

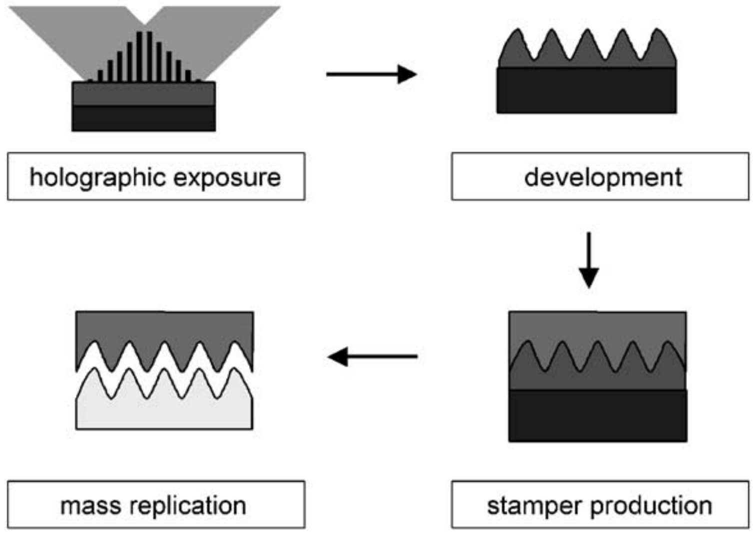

***Figure 1** Generation and replication process of holographic microstructures.*

Known replication techniques for microstructures on large areas are hot embossing or UV casting. Those technologies are already used for the commercial production of e.g. moth eye structures.
In the past we developed interference holography further to structure large areas with anti-reflective moth eye structures with a period of ~250nm [3]. At present samples of an area up to 60cm×80cm can be produced. The new approach in this work is the application of this technology to structures of sizes in the range 10-20µm.

Results
Two different applications were investigated in more detail. Both are static solar control or shading devices which prevent from overheating during summertime. A structured film can be laminated onto a glass sheet.
The first type is a special kind of reflecting prism which is designed to be integrated in vertically oriented glazings. The principle is shown in figure 2. The prismatic structure was produced with a period of 17µm (figure 3).

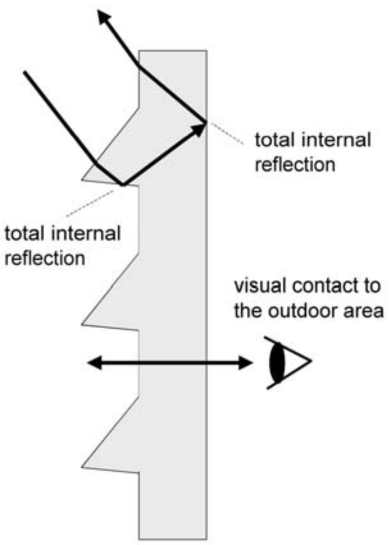

***Figure 2** Principle of reflecting prims.*

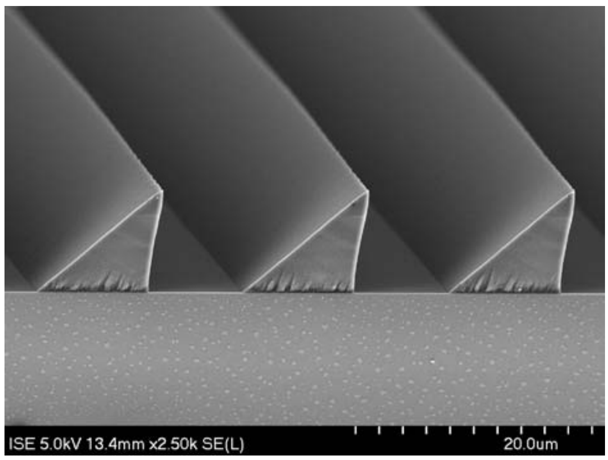

***Figure 3** Scanning electron micrograph of prismatic microstructures in photoresist generated by interference lithography. The distance between two prisms is 17µm.*

The spacings between the prisms ensure that visual contact to the outdoor area is achieved. At higher incident angles the spacings between the prisms are shaded. The prismatic structures lead to two successive total internal reflections and incident radiation is rejected. Figure 4 shows the calculated angular solar transmittance of such a prismatic structure for all possible sun positions and respective incidence angles over a year for a vertical facade oriented to the south at an altitude of 48° (Freiburg, Germany). The white region marks the times where the transmittance is minimal. The very good shading characteristics during summertime can be seen.

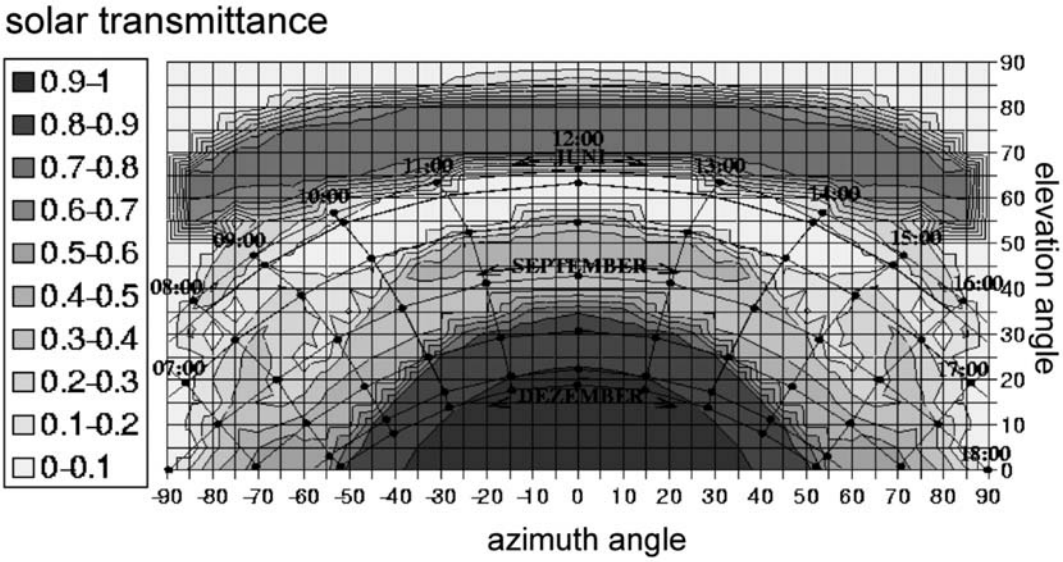

Figure 4 *Calculated angular solar transmittance of a prismatic structure for all possible sun positions and respective incidence angles over a year for a vertical facade oriented to the south at an altitude of 48° (Freiburg, Germany).*

Another type of structures are dielectric compound parabolic concentrators (CPCs) suited for application as a seasonal solar control for tilted glazings. CPCs reflect rays that are incident under angles centered at normal incidence. Thus the structured glazing has to be oriented towards the direction where the sun light shall be reflected. The principle is shown in figure 5. Rays incident from within the blocking region directly fall on a reflector or they are guided to the reflector by total internal reflection on the side walls. Rays incident from higher angles are diffusely transmitted. To realize CPCs as microstructures on surfaces the inner side of the window pane has to be structured. The tips of the structure have to be coated or put in optical contact with a reflector to ensure the reflection of rays within the blocking range of incident angles. The structure made by interference lithography is shown in figure 6. Its period is 9µm.

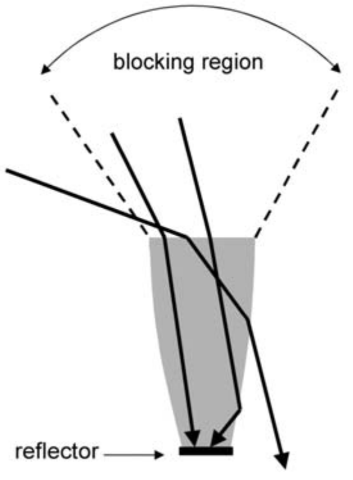

Figure 5 *Principle of a compound parabolic concentrator as angular selective transmission device.*

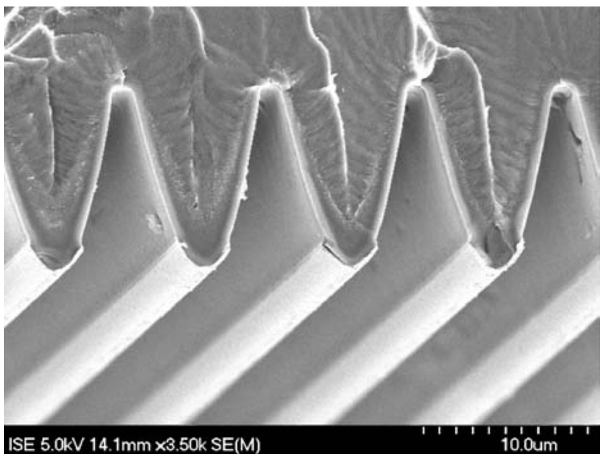

Figure 6 *Scanning electron micrograph of compound parabolic concentrator microstructures generated by interference lithography and replicated in PMMA. The period is 9µm. The tips are coated with metal.*

Small scale prototypes of both types of structures were characterised in the lab. Figure 7 and 8 show the angular direct-hemispherical transmittance of CPC and prismatic structures respectively, measured with Fourier Transform Spectroscopy. In order to measure the hemispherical transmittance directly, the samples were mounted on an integrating sphere.

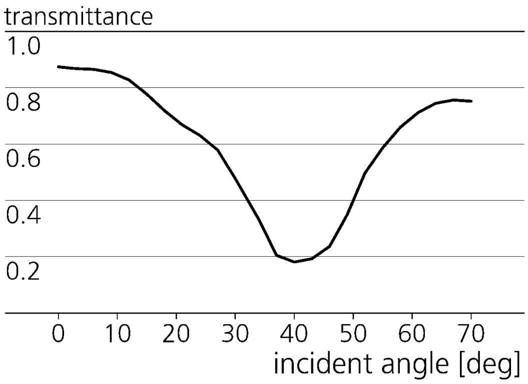

__Figure 7__ Angular direct-hemispherical transmittance of the prismatic structure shown in figure 3, measured with Fourier Transform Spectroscopy at a wavelength of 700nm and with mixed polarization.

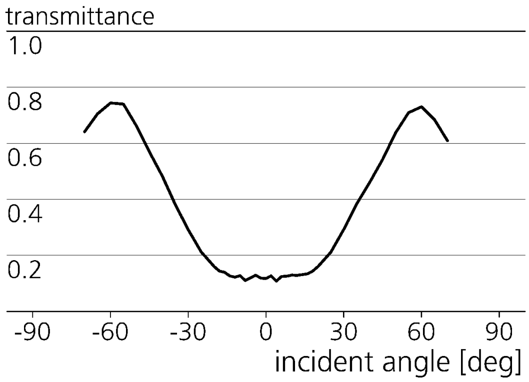

__Figure 8__ Angular direct-hemispherical transmittance of a CPC structure similar to that shown in figure 6, measured with Fourier Transform Spectroscopy at a wavelength of 700nm and with mixed polarization.

Both structures show a strongly angular selective behaviour. The reflectance within the blocking range is slightly better for the CPC structure than for the prism structure. Calculations using rigorous diffraction theory have shown that for CPCs with periods greater than 8µm a minimum transmittance of about 2-3% is possible if the real structure form is further optimized. However, for prismatic structures at periods of 17µm diffraction effects still play an important role and increase the transmittance. In order to suppress diffraction effects, periods greater than 30µm are needed.

It is clear that so far both solutions do not avert glare by direct sunlight. Therefore we have tested the combination of structured surfaces with switchable tungsten oxide coatings. The film transmittance is switched with low concentrations of hydrogen or oxygen („gasochromic switching“), as has already been demonstrated on non-structured glass panes in test facades at the institute [4]. In one case the coating was deposited on the upper facet of the prisms to retain the outside view even in the shaded state of the coating. Figure 9 shows the measured visual transmittance of a double glazing where the outer pane is 4mm float glass with hard low-e coating (k glass) and the inner pane is carrying a photoresist layer structured with the partly switchable prisms. This prismatic structure is not optimized and thus shows only moderate angular selectivity and blocking properties. However, we demonstrated the feasibility of strongly reducing the transmittance at higher angles of incidence due to the switching without strongly disturbing the outside view.

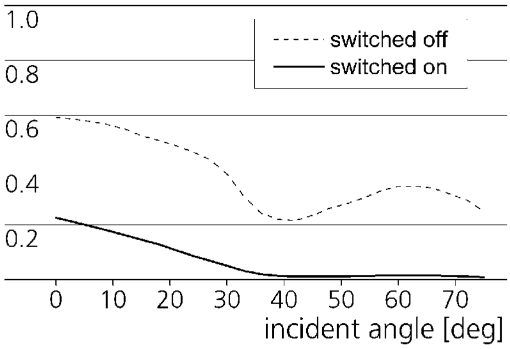

__Figure 9__ Angular visual transmittance of prismatic structures with a period of 17µm and a switchable tungsten oxide coating on the upper facet, measured with an integrating sphere.

Summary
We investigated interference lithography for the generation of light redirecting microstructures in glazings. Two types of structures were fabricated, characterised and compared. We showed how the structures can control the transmission and thus the g-value of the glazing. The main advantages of the prism system are the possible visible contact to the outside and the fact that compared to CPCs no reflective coating is needed. However the CPC prototype showed a better blocking effect at the periods which at present are technologically feasible. For prismatic structures, further development of the lithography process is necessary to achieve periods higher than 30µm where diffraction effects become negligible. A combination with switchable coatings was tested. It offers a dynamic control of the g-value and the potential of glare protection.

Acknowledgment
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