LASER ABLATION AND NANOIMPRINT LITHOGRAPHY FOR THE FABRICATION OF EMBEDDED LIGHT REDIRECTING MICROMIRRORS

A. Kostro[1], M. A. Gonzalez Lazo[2], Y. Leterrier[2], E. Siringil[3], P. Hoffmann[3], A. M. Schüler[1]

1: LESO-PB, EPFL, Station 18, Bâtiment LE, EPFL, 1015 Lausanne, Switzerland

2: LTC, Station 12, Bâtiment MX, EPFL, 1015 Lausanne, Switzerland;

3: EMPA, Advanced material processing, Feuerwerkerstrasse 39, 3602 Thun, Switzerland;

ABSTRACT

Light redirecting devices usually increase the daylight illuminance level far from the window but also affect the visual comfort to some extent. Some designs achieve high redirection rate but are not transparent, others offer a partial view through but with reduced performance. Miniaturizing the light redirecting mirrors and encapsulating them has the potential to increase both view and performance. The shape of such encapsulated micro mirrors was optimised in a Monte Carlo ray-tracing model. In simulations, the redirected proportion of light could be increased with minimal influence on the transparency of the device. Maximal transparency was conserved at near to normal incidence with a strong redirection of light beams providing both daylight and glare protection.

In this study, the fabrication process of micro mirrors embedded in a transparent medium is described. The later process consists of a succession of four steps: mould fabrication, replication in an ultraviolet (UV) curable resin, partial coating with a reflective material at an imposed deposition angle and embedding using the same UV curable resin. The mould was fabricated by laser ablation at EMPA and replicated into polydimethylsiloxane (PDMS) to enable correct unmoulding of the resin. This negative mould was used to replicate the original structure into a transparent low-shrinkage hyperbranched acrylate polymer (HBP). It was identified that the direction in which the UV curable resin is polymerised is of crucial importance. Embedded micro mirrors provide transparency at normal incidence and the redirected proportion of light impinging at 60° was measured to be greater than 80%.

Keywords: Microstructures, daylighting, Nanoimprint lithography, laser ablation

INTRODUCTION

The combination of light redirection and elevation angle dependent transmittance offers the possibility to combine daylighting, glare protection and seasonal thermal control. Indeed, light redirection extends the depth where daylight is available; glare from the direct sunlight is simultaneously reduced. And with a low transmittance only for elevation angles corresponding to summer sun, the thermal gains are reduced in summer while they remain important in winter. Through Monte Carlo ray tracing, an advanced microstructure with such properties was proposed [1]. In addition the view through at near to normal incidence with such a design fabricated on a micrometric scale should be preserved. The design comprises an embedded parabolic mirror and a second mirror on the back surface of the device, located at the focus point of the first parabola. The parabola is designed to focus light incoming with an elevation angle equal to that of the summer sun and the back mirror reflects light from this direction. The high aspect ratio of the embedded mirrors enables the redirection of a major part of light incident at elevations angles between 35° and 90°. Challenges and results on the fabrication of the embedded mirrors are presented in this paper. The various questions regarding the backside mirror will not be assessed.

To embed parabolic mirrors, a four step process is proposed. Firstly, the shape of the desired mirror needs to be fabricated in a hard material later referred to as the mother mould. The mould has to reproduce the desired geometry accurately and present smooth surfaces of optical quality. Secondly, the shape is replicated to a transparent polymer, for this purpose an intermediate PDMS mould later referred to as the mother mould is used. For replication an acrylated HBP is hardened by photo-polymerisation using a UV nanoimpront lithography process (UVNIL). Thirdly the resulting structure is placed in vacuum in a physical vapour deposition chamber and coated with aluminium. To coat only one side of the structure, the sample is tilted. Finally the resulting structure is encapsulated in the same transparent resin to obtain two parallel surfaces and provide transparency. This process is illustrated in Figure 1. The main challenges are in the fabrication of a proper mould and in the encapsulation step.

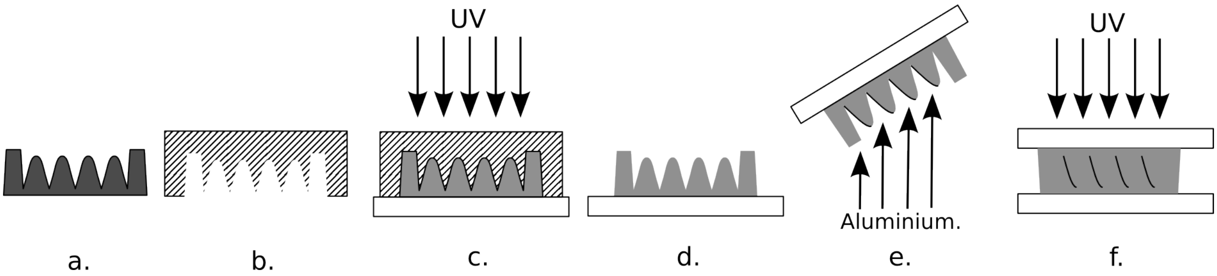


Figure 1: Fabrication process for embedded micromirrors: a-b. Father PDMS mould made from mother mould. c-d. Replication by UV nanoimprint lithography. e. Coating with aluminium at tilted angle of incidence, d. Embedding of micromirrors into the resin (UV polymerisation).

For the mould, the required dimensions (50-300 microns for period and respectively 112-700 microns depth) are well above the nano scale and at the lower limit of micro scale. Few techniques are suited to produce structures with high aspect ratios in this range. In addition, the produced surfaces need to be of optical quality. Several techniques were studied: mechanical tooling, electrical discharge machining (EDM), conventional lithography, grey scale lithography, interference lithography, 3D printing, stereo lithography and laser ablation. EDM was first used to fabricate a mould with a resolution below a micrometre but generated rough surfaces not suitable for optical devices. Laser ablation was retained as the alternative choice because the offered aspect ratio and surface quality comply with the requirements.

UVNIL is a well-established process for the replication of micron and sub-micron scale features into photopolymerizable resins. Different shapes, namely gratings or stellar like structures with dimensions between 30 *nm* and 100 *nm* have been successfully transferred on silicon wafers with good dimensional stability [2] and in HBP composites with high fidelity [6-9]. For window-like transparency it is important that the uncoated surface disappears completely when embedding the structured polymer. This implies that no interfaces remain and no void should be formed following the shrinkage of the resin.

METHOD

Laser ablated mould

Pulsed lasers are well established in industry where these are used as tools to machine materials. Lasers with femto- or picoseconds pulses or nanosecond pulses with deep UV radiation allow direct ablation of material with little heat-affected zones (HAZs). The use of excimer lasers (at 193 *nm* or 248 *nm* for example) allows very high resolution especially in aromatic polymers. The laser is used to structure polymers directly; typical individual feature sizes are in the range of 2 to 200 microns. The first significant advantage is that the machined structures directly present optical quality. The second main advantage of this technique for application to glazing is the possibility to produce optical devices on large areas [3,4]. Well-engineered micro geometries can be machined over large areas up to 3 m^2.

PDMS mould

By reproducing the microstructure into an intermediate moulding material, a negative mould is created. This intermediate step makes it possible to choose a material well suited for moulding of the final material: such as a UV curable HBP introduced hereafter. PDMS (Dow Corning DC 184 in this work) is a silicone based organic polymer that is known to work well as a mould for most resins and has been widely used to replicate microstructures. An interesting feature of PDMS is its low, temperature dependent shrinkage. At about 55°*C* it is slightly above 0.5% and rises almost linearly to 3% at 140°*C* [5]. To fabricate the mother mould, a container for the PDMS in liquid state is required.

Resin replication

Numerous different types of UV-curable resins exist, amongst them two types were studied in this project: an epoxy resin with a cationic polymerisation mechanism and an acrylate with a free radical polymerisation mechanism. The epoxy was rapidly abandoned because of its yellow colouration and because high aspect ratios were harder to unmould. Amongst acrylate resins, HBP were found to be well suited for nano and micro-replication due to their low polymerisation shrinkage and low internal stress [6,7]. Acrylated HBPs were previously used to fabricate polymer micro- and nano-structures with high accuracy [8,9]. The HBP used in this study was a polyester acrylate oligomer (CN2302, Sartomer) with functionality of 16, a volumetric shrinkage 9% and a glass transition temperature in cured state equal to 165°*C* (by dynamic mechanical analysis). The photoinitiator was trimethylbenzoyl phosphine oxide (Esacure TPO, Lamberti) at a concentration of 6 *wt*%.

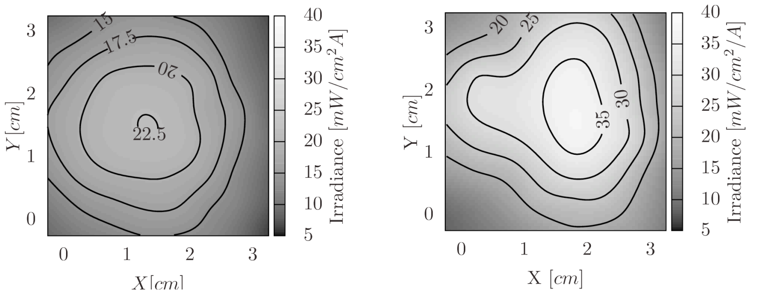


Figure 2: Distribution of UV radiation as generated by the LED UV source without (left hand side) and with diffuser.

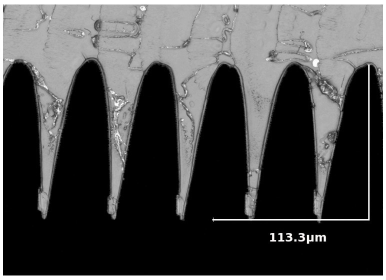


Figure 3: confocal microscopy image of mould profile.

A custom UV source was built using a timer, a controllable power source, three power UV light-emitting diodes (LEDs) with a peak centred at 375 *nm* and a cooling board from a computer graphical card. The LEDs are fabricated by Seoul Semiconductors (P8D2 275) and have an optical power output of approximately 250 *mW* each with a full width at half maximum (FWHM) of 11*nm*. The light from the LEDs was collimated using optical reflectors designed to provide a narrow, 6° wide cone of light. The resulting distribution of intensity was measured with a UV wattmeter in a plane at 12 *cm* distance, taking measurements every 0.5 *cm*. The intensity distribution for the area of interest is shown in Figure 2a. The distance was increased to 15 *cm* and an etched glass produced by Fällander was added to increase the uniformity of the distribution as shown in Figure 2b.

RESULTS AND DISCUSSION

Mould obtained by laser ablation

First trials using the 248 *nm* excimer laser setup resulted in a sample of parabolic like structures engraved directly in polycarbonate (PC) with a period of 50 μm. The short pulse duration of about 20 *ns* limits the HAZ in polymers to some tens of nanometres. After a cleaning process the depth of the grooves is about 93 μm. A confocal microscopy image illustrates the profile of this sample (Figure 3), the structure is asymmetric and provides two different facets, one tilted at appropriately 4° and the other one at 12°. The produced samples with not optimized laser ablation parameters did not yet have the exact desired shape; to reach the desired geometry some ablation parameters in the mould fabrication have to be modified. This first structure was however used to produce promising light redirecting samples with embedded mirrors. The laser ablation was performed on an area of approximately 2 cm^2, this can be extended to larger areas on the same equipment. Direct laser writing combined with chemical etching of glass is a new technique that is being looked into for prototype fabrication. The latter technique is however limited to 10x10 *cm* samples.

PDMS mould

The structured PC sheet was placed at the bottom of a formwork and an alignment gauge was added to ensure the structures are perpendicular to the sample edge during replication. An extra gauge was added to the formwork in order to provide a constant and controlled thickness in the replicated structure. This reference also prevents contact (and hence deformation of the soft mould) between the mould peaks and the substrate during the UVNIL step. The formwork was fabricated out of aluminium using a milling cutter. The accuracy of the used cutter is in the order of 10 μm to 50 μm, making it possible to create gauge with dimensions of several tenth of a millimetre. 150 μm grooves were milled in the PC to provide a separation between the structures and the substrate. The gauge required to provide and control the gap during the embedding step could not be fabricated. Because of its limited thickness (0.5 *mm*), the structured PC part could not be maintained mechanically and was fixed with double sided tape in the bottom of a flat container.

Resin choice and limitations of the replication process

To achieve a satisfying optical performance, the used resin needed to be transparent and colourless. As already mentioned, the epoxide resin, which has a yellow tint, was eliminated for this reason. As illustrated in Figure 4, the acrylate HBP showed promising optical properties wit a spectrally flat transmittance of 80% in the visible range. However the attenuation of the UV radiation after half a millimetre of resin was found to be larger than 300 fold using a UV luxmeter. In such a range of thickness, the resin blocks UV light and polymerisation can no longer continue. Above this thickness, a haze can appear at some viewing angles when looking through the sample. Varying refractive indexes between polymerised and unpolymerised resin might cause the haze. It was found that by putting the PDMS stamp first in the path of a light beam, the flux of the source was not reduced significantly. This can be verified in the transmittance measurement shown in Figure 4 (90% transmittance). The polymerisation process however then starts on the structured side, which enables easier unmoulding and better finish of the replicated structure tips. Furthermore the interface between resin and glass polymerises last; it is likely that this reduces internal stresses that are responsible for delaminations in case the substrate is placed first. This delamination of the structured resin from the substrate happens in particular if the UV dose is large and the polymerisation fast.

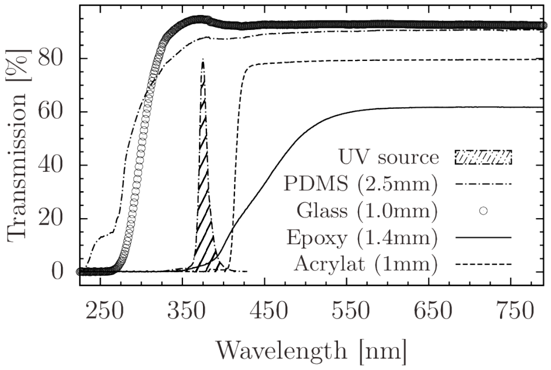
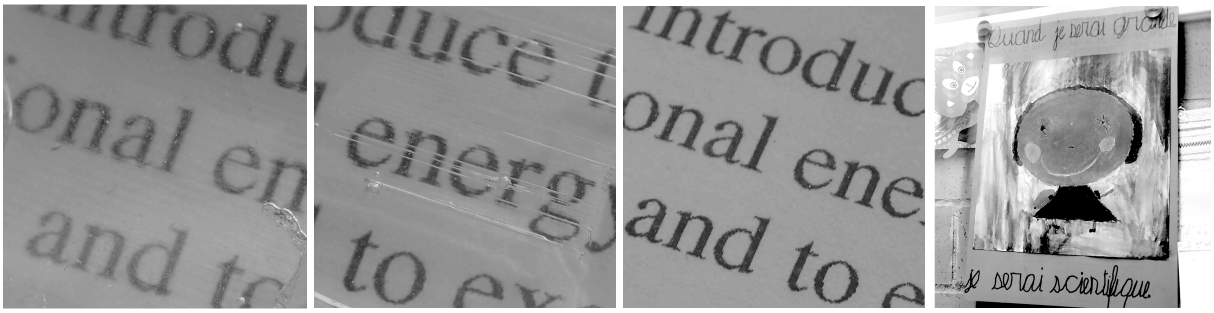


Figure 4: Spectral transmittance of PDMS, Glass, Epoxy resin and Acrylate Resin compared to the emission peak of the UV LED used for polymerisation.

Parameters of the embedding process

Regarding the embedding step, structures without coating were embedded first and two challenges were faced. Firstly, during embedding and probably due to resin shrinkage, voids appear at the very bottom of the structures. Secondly, even when no voids are present, the sample is not fully transparent but generates haze.



a) b) c) d)

Figure 5: . a-c) Assessment of transparency: un-coated microstructures should be invisible when embedded in a material with same refractive index. Results for various thicknesses and surface qualities: a) 880 µm, with rough surface, b) 540 µm, smooth surface. c) 180 µm, optical surface. d) View trough a sample with embedded mirrors.

The voids disappeared when slowing down the polymerisation. It is supposed that rapid polymerisation from one direction only favours curing on the side exposed to the UV source. Because the polymer shrinks during the curing process, lack of material and higher constraints are created on the opposite side towards the end of the curing process. It was also observed that bubbles could be formed overnight due to ageing processes in the resin during the first days. This also is possibly linked to the shrinkage of resin that was not fully polymerised.

The partial transparency can be explained if the interfaces do not disappear completely when a resin structure is filled with the same material. This creates certain diffusion and reduces overall transparency. A small index mismatch combined with the strong roughness of the interface enhances this effect. Reducing roughness should dramatically decrease this effect. Various other samples with no coating (3M prism, flat shape with rough surface) were also encapsulated in order to verify if the embedded surface becomes invisible. These experiments confirmed that the roughness of the embedded surface highly influences its invisible integration. In particular, the significant roughness of a flat mould fabricated by EDM is still visible once embedded and creates a slight haze in transmission.

When embedding the smaller structures with surfaces of optical quality, as those produced by laser ablation at EMPA, both problems disappeared as illustrated in Figure 5. In this case the total resin thickness is only 180 μm; in comparison, the first samples had a total thickness of 880 μm. The polymerisation was carried out through the mould in the replication step and through the structured sample in the embedding step. When polymerising from the side where resin is added to embed the structure, bubbles appear. These findings confirm that during embedding it is advantageous to expose the side in contact with structures first and that total thickness and surface roughness are key parameters for a clean encapsulation. A sample coated with aluminium was also embedded and is shown in Figure 5.

CONCLUSION

A fabrication process was proposed for the encapsulation of micro mirrors. It has been tested and light redirecting samples with see-trough properties have been produced. The encapsulation problems have been solved and the thickness limitation was identified. At an incident elevation angle of 60°, the produced samples redirect 80% of light, most of it in a near to horizontal direction. At normal incidence, the samples remain highly transparent and the view through is not altered. This promising result opens up for new perspectives in the field of light redirecting devices. The up scaling of the process can possibly be realized in a roll-to-roll approach.

ACKNOWLEGMENTS

The authors would like to thank the Swiss federal office of energy (OFEN) and the Swiss competence centre for energy research (SCCER) for founding. The authors are grateful to Pierre Loesch for the mechanical tooling and to Eve Gasser for her drawings.

REFERENCES

1. Kostro, A. et al : Embedded microstructures for daylighting and seasonal thermal control, Optics and Photonics - Proceedings of SPIE, vol. 8485, 2012.
2. Vratzov, B. et al: Large scale ultraviolet-based nanoimprint lithography, Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, 21, 2003.
3. Boehlen, K.L. et al : Advanced laser micro-structuring of super-large-area optical films. Progress in Biomedical Optics and Imaging - Proceedings of SPIE, volume 5720, 2005.
4. Pedder, J. E. A et al : Pulsed Laser Ablation for Volume Micro-Optical Arrays on Large Area Substrates. Photonics West - Proceedings of SPIE, volume 6462, 2007.
5. Krogh, M. : My Little Guide to Soft Lithography, 2003.
6. Schmidt, L. E. et al: Time-intensity transformation and internal stress in UV-curable hyperbranched acrylates, Rheologica Acta, 46(5), pp 693–701, 2007.
7. Schmidt, L. E et al: Acrylated hyperbranched polymer photoresist for ultra-thick and low-stress high aspect ratio micropatterns. Micromechanics and Microengineering, 2008.
8. Geiser,V. et al: Nanoimprint Lithography with UV-Curable Hyperbranched Polymer Nanocomposites. Macromolecular Symposia, 296(1), pp 144–153, 2010.
9. González Lazo et al. : UV-nanoimprint lithography and large area roll-to-roll texturization with hyperbranched polymer nanocomposites for light-trapping applications. Solar Energy Materials and Solar Cells, 103, pp 147–156 , 2012.