Design, manufacturing and experimental validation of a bonded dual-component microstructured system for vertical light emission

Michael Jakubowsky1 · Jerome Werder2 · Christian Rytka2 · Per Magnus Kristiansen2,3 · Andreas Neyer4

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Abstract
This article presents a bonded dual-component microstructured planar device made of acrylic glass for vertical light emission. It features optical, cone-like undercut microstructures for efficient illumination from a light guiding plate. This microstructured light guide is designed with the help of numerical raytracing simulations for the use as an innovative luminaire for room lighting. It can also find application in display technology for efficient backlight units. To realize such undercut microstructures in acrylic glass, a variothermal injection molding process, complemented by an ultraviolet radiation assisted thermal bonding procedure is introduced. By modifying the glass transition temperature of a thin surface layer of the microstructures the undercut microstructures can be bonded thermally to a light guiding plate without any glue or solvent, while the shape of the microstructures is perfectly preserved. Measurements verify the high bonding quality and confirm the good correspondence between measured light emission and ideal optical simulations.

1 Introduction

Microstructured light guiding plates (LGPs) are typically used for the illumination of edge lit liquid crystal displays (Kondo 2009) or analog displays, for example in the automotive sector (Ledermann 2017). They attract interest for other applications as well, like luminaires for office room illumination (Müller and Sasso 2015). In LGPs, the light—typically from light emitting diodes (LEDs)—is coupled in at one or more edges and propagates inside the LGP by total internal reflection. When the light reaches the edge of a microstructure, it is coupled out in predefined directions as shown schematically in Fig. 1b.

A novel field of use for microstructured LGPs are (semi-) transparent luminaires using LEDs for office illumination. The LGP and LEDs can be integrated in a frame and used as surface emitters with a directed, single sided light emission for direct or indirect illumination. In the joint research project TaLed (Jakubowsky and de Boer 2019) we went one step further and integrated such luminaires (including LEDs and LGP) into a window for room illumination (Jakubowsky et al. 2018). There, it can be used as a source for indirect room illumination as depicted in Fig. 1a. The LED light is emitted only at the room side of the microstructured LGP and is directed towards the ceiling, where it is reflected diffusely, illuminating the room. Additionally, it can be combined with microstructured daylight redirecting systems (Jakubowsky et al. 2018). The adjustable color temperature of LED lighting can be set to correspond to this natural lighting, thereby reproducing benefits of natural lighting, if sunlight is not available due to clouds, daytime or louvers.

The microstructures used on these LGPs were designed to emit light in a small angle referring to the LGP surface. However, a larger propagation angle is preferable, in order to enable a deeper and more uniform illumination (Jakubowsky et al. 2019). In this paper, we present a dual-component microstructure device made of poly(methyl...
methacrylate) (PMMA), enabling a vertical light emission
directed perpendicular to its surface by only one single
sided structured LGP. To avoid glare the LGP should be
placed in the upper part of a façade element (see Fig. 1a).
This also reduces the need for transparency, because an
opaque top area of the façade does not disturb the clear
view to the outside. The presented LGP can not only be
used as luminaire inside a façade, moreover, the potential
scope of application reaches from illuminated large area
partitions in architecture to single sheet backlights in dis-
play technology (Lee et al. 2007).

First, we discuss the design and simulation procedure of
an LGP, aiming at a directed light intensity distribution,
perpendicular to its surface (referred to as vertical here-
inafter). The proposed structure is an undercut
microstructure. The production of such LGPs with under-
cut structures has been reported for flexible materials like
silicone by Lee et al. (2007). However, for the production
in stiff materials like PMMA only highly complex methods
exist (Xue et al. 2010). A simple method to produce
undercut structures in such plastics, which is feasible for
mass production, is not available. However, it is needed to
put recent theoretical research into practice (Lee et al.
2007; Huang and Guo 2016a; Jakubowsky et al. 2019). The
presented method closes this research gap. We put
emphasis on the realization of the replicative manufactur-
ing by means of injection molding and the subsequent
joining of the microstructures to a planar back plane by an
ultraviolet (UV) irradiation assisted bonding process
(Werder 2017). In this way, a novel, comparatively facile
technique for fabrication of microstructured LGPs com-
pletely out of PMMA is introduced.

2 Design and simulation

We designed a simple microstructure for vertical light
emission, which acts as a feasible test object to develop a
reliable bonding procedure. The microstructure was
designed with the help of optical ray tracing simulations,
using Zemax OpticStudio 16.5 Premium Edition.

The simulation environment consists of a spherical
detector surrounding the whole setting to obtain the light
intensity distribution (LID). The simulated system consists
of three main parts: (i) the planar LGP, (ii) the light source
and (iii) the microstructures on a support plate. The sim-
ulation setup is schematically depicted in Fig. 2. The LGP
is based on a PMMA plate with lateral dimensions of
60 × 50 mm². A thickness of 2 mm was chosen to deliver
a high light output ratio while fitting to the width of
common LEDs. Using a coupling structure like the one
presented by Xu et al. (2019) the thickness can be further
reduced and the light output ratio can be increased, but at
the expense of a greater complexity of the LGP. At one
short edge 10 LEDs (OSRAM Duris E3) are positioned
uniformly with a distance of 100 μm to the LGP. All other
edges are coated with perfectly absorbing material. The
LEDs are surrounded by a box with absorbing surfaces,
except for the near edge of the LGP, to avoid any emitted
light passing by the LGP. The microstructures are placed
next to each other on one side of the LGP. They are cov-
ered by a support plate and placed in an area slightly
smaller than the LGP (47 × 47 mm²). The thickness of the
support plate is again 2 mm. The entire LGP is embedded
in a perfectly absorbing measuring frame.

![Fig. 2 Simulation setup in front view (left) and cut through (right)](image-url)
In LGP backlights often micro grooves are used as microstructures for a vertical light emission (Chen and Kuo 2014), but those LGPs are commonly complemented by a nontransparent, reflective layer on its backside to achieve a high single sided light emission. The advantage of the design presented below is the existence of only one component and a partial transparency. A simplified, truncated micro-cone array was optimized and simulated for an LGP for single sided, vertical light emission made of PMMA. It is based on a practical design for vertical light emission realized in poly(dimethyl siloxane) (PDMS) by Lee et al. (2007) and a theoretical design combining micro-cones and freeform optics in PMMA by Huang and Guo (2016a). The flank angle of these micro-cones was found to be most suitable for vertical light emission, when set to 58°. The angle was determined by comparing simulation results of different flank angles, taking into account the initial LID of the LEDs used. The flank angle is almost identical to the one found by Huang and Guo (2016a) which is 57°. The simulated two-dimensional LID and the dimensions of the truncated micro-cones are described in Fig. 3. For a prototype sized LGP for use as a luminaire with a length of 600 mm and a width of 800 mm a high light output ratio of 88% was simulated. Thanks to the relatively large flank angles, the micro-cone design is intrinsically suitable for production by injection molding. The height and aperture of 600 μm (aspect ratio not higher than 1) was chosen to keep the manufacturing costs of the required molding tool reasonably low for this study and assure a molding process as simple as possible.

3 Manufacturing and functional sample

The main purpose of the presented work is to manufacture and experimentally validate the specifically designed surface topography. The latter cannot be readily achieved in a single production step due to the presence of pronounced undercuts. Therefore, the functional microstructure is at first prepared by injection molding replication of truncated micro-cones from a microstructured master. The subsequent bonding to a planar back plate enables the preparation of undercut structures on LGPs made of PMMA without the use of any primer, which would lower the optical quality of the LGP surface.

3.1 Injection molding of truncated micro-cones

To produce optical microstructures by injection molding, microstructured mold inserts were manufactured in brass by precision milling at LT Ultra-Precision Technology (Herdwangen-Schönach, Germany). These mold inserts were then fitted into a dedicated injection molding tool designed for versatile process validation in context with polymer replication on the micro- and nanoscale (Rytka et al. 2015). Detailed information on the molding tool can be found in the latter reference. The mold insert of primary interest in this work is presented in Fig. 4.

Variothermal injection molding was employed to assure accurate replication of the master structures, thereby avoiding incomplete filling of the micro-cavities by the PMMA (PMMA 7 N, Evonik) melt. All injection molding trials were carried out on an Arburg 320 A (Lossburg, Germany) employing a melt temperature of 240 °C, an injection velocity 20 cm³ s⁻¹, and a holding pressure of 750 bar for 12 s prior to demolding. Variothermal cycling of the mold temperature (90 °C at the moment of injection,
50 °C at part ejection) was accomplished with the help of a 2-chamber water system composed of two control units (HB-160Z2) with a pump capacity of 60 l min⁻¹ and a cooling power of 30 kW combined with a dedicated switching unit (HB-VS180-20) from HB-Therm (St. Gallen, Switzerland).

The injection molded micro-cone arrays displayed in Fig. 5 show very good replication fidelity. The corrugations on the side walls are replicated from chatter marks of the brass insert, which originate from the mold insert manufacturing process.

### 3.2 Bonding of undercut microstructures made of PMMA

As already mentioned in the previous section, the conical microstructures produced by replication actually represent the mirrored version of the designed structure. Thus, the bonding of micro-cone arrays to a flat plate is essential for the creation of a functional prototype with undercut micro-features and validation of their illumination performance characteristics (i.e. LID). Using classical thermal bonding the substrates are exposed to high stresses, which ultimately leads to deformations of the optical microstructures and concomitant deterioration of the resulting illumination characteristics. Exposure to a solvent (like isopropanol or ethanol) for the purpose of solvent bonding causes a significant reduction of optical surface quality. Besides the increase in surface roughness, a disturbing clouding effect appears, accompanied by non-satisfactory LID performance. The use of a UV glue layer causes menisci at the edges of undercut structures and thereby distorts their optical behavior.

By applying a UV-treatment, adapted from earlier work on microfluidics (Truckenmüller et al. 2004; Tran et al. 2013), these problems could be overcome and the microstructures were successfully bonded to the LGP back plate without any noticeable deterioration of the surface quality.

Exposure of PMMA to short wavelength UV irradiation causes chain scission within an approximately 400 nm thick surface layer (corresponding to the depth of UV light penetration). Thereby the molecular weight is substantially lowered, which causes a significant reduction of the glass transition temperature within the surface layer (Chidambaram et al. 2017). If this surface layer is heated above the glass transition temperature the mobility of PMMA chains rises and secondary valance bonds are broken. The polymer chains of the compressed surfaces diffuse into the other surface and hook into each other. During cooldown, they begin forming secondary valence bonds once again and are firmly bonded after cooling. Consequently, the surface can be thermally bonded at lower temperature without significant deterioration of the shape of the microstructures. A positive side effect of the UV-treatment is a concomitant selective surface smoothening (reduction in surface roughness) of the boundary layer, which occurs during UV-treatment and subsequent thermal treatment during the bonding process (Chidambaram et al. 2017).

The UV-assisted bonding process is schematically outlined in Fig. 6. To bond the PMMA microstructures to the planar PMMA sheet the joining surfaces were irradiated by UV-light with a wavelength of 172 nm (465 mJ cm⁻²) for 60 s (EX-mini, Hamamatsu Photonics). Following this initial step, the two parts were bonded at 103 °C (which is below the glass transition temperature of the used PMMA, i.e. 110 °C) employing a load of 11.2 kg (corresponding to a contact pressure of 336 kPa) for 20 min.

The above described process resulted in a dual-component microstructured device characterized by high bonding strength (not quantitatively measured) and good

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**Fig. 5** Scanning electron micrograph of injection molded PMMA micro-cone array, illustrating very good replication fidelity

**Fig. 6** Bonding process and parameters for joining undercut micro-cones to a PMMA-LGP
4 Experimental validation

We tested the bonding quality of the produced samples by optical inspection of the illuminated LGP. Its functionality is validated by measuring the two-dimensional LID and comparison to the simulated data. Figure 8 schematically shows the measurement setup based on a setup, which we successfully used in former research (Tengler et al. 2014). The light is coupled into the LGP from below. The angle-dependent intensity is monitored at varying angles in 5° steps by an automated goniometric measurement system controlled by a LabVIEW script. An optical power meter with an aperture of 9.5 mm is used to measure the radiant flux between the wavelengths 400 nm and 1000 nm at a distance of 15 cm from the center of the sample. The window in the measurement frame is adapted to the shape of the microstructured area, which in our case is a circle with 40 mm diameter, covering the outer part of the support plate.

The bonding quality of the produced dual-component sample is very good as can be seen from the photograph in Fig. 9b. Each micro-cone glows, when light is coupled into the LGP (the slightly visible two red dots at the edge are unimportant marks). The photograph is taken with an exposure time of 1/8000 s and a film speed of ISO-200. No color distortion caused by the microstructured LGP can be observed.

The experimental LID of the sample correlates quite well with the simulation results of the designed structure. As can be seen in Fig. 9a, the experimental sample displays a slightly wider light cone. Most likely the roughness of 87 nm on the outer surface of the support plate is responsible for the observed deviation. This roughness is caused by an imperfect surface of the bonding equipment. Additional simulations show that the small additional peak around 135° observed in the experimental LID is caused by slight deformations at the top of the truncated cones, as can be seen in Fig. 7b. Simulations show, that the chatter marks on the side walls (compare Fig. 5) have no effect on the LID.

![Fig. 7 Picture of a bonded sample with micro-cones on the LGP (a) and the cross section of a PDMS replica of the bonded PMMA device (b)](image)

![Fig. 8 Measurement setup for the determination of 2D polar LID function](image)

![Fig. 9 Measured and simulated LID of the microstructured LGP (a) and a front view of the illuminated sample proving good bonding quality (b)](image)
The sample is not perfectly transparent with respect to a clear view, which is not necessary for an application in the scenario mentioned in the introduction. If a higher transparency is needed, the density and size of the microstructures should be reduced. If on the other hand a uniform light emission from the LGP surface is needed (for example for the use as display backlight) the density of the microstructures could be modified in different ways (Kang et al. 2010; Kim 2013; Huang and Guo 2016b; Huang et al. 2017; Lin et al. 2017), but always at the expense of the device’s light output ratio, because the overall density will be lowered.

5 Conclusion

We designed, simulated and manufactured LGPs with undercut microstructures for vertical light emission made out of PMMA. To the knowledge of the authors, no feasible efficient production method has been reported for this kind of structures. We applied a UV-assisted bonding technique adapted from the field of microfluidic devices in combination with injection molding replication. By this means a novel 2-step procedure for the manufacturing of dual-component LGPs has been developed with optical undercut microstructures in PMMA, featuring rather perfect bonding quality, without using any solvent or glue. The experimentally determined LID and the predictions based on optical simulations revealed good agreement for the produced LGPs.

The introduced design and manufacturing processes are very promising for the applications of LGPs used in luminaires and display backlights. The achieved results indicate that the processes described may be readily applied for mass production. Furthermore, the results of the research presented can be applied to any field of microsystem technology in which polymer microstructures have to be reliably bonded without altering the original shape of the structures.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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References

Chen C, Kuo S (2014) A highly directional light guide plate based on V-groove microstructure cell. J Disp Technol 10:1030–1035. https://doi.org/10.1109/JDTE.2014.2335813
Chidambaram N, Kirchner R, Fallica R, Yu L, Altana M, Schift H (2017) Selective surface smoothening of polymer microrelief by depth-confined softening. Adv Mater Technol 2:1700018. https://doi.org/10.1002/admt.201700018
Huang B-L, Guo T-L (2016a) Integrated backlight module to provide a collimated and uniform planar light source. Appl Opt 55:7301–7313. https://doi.org/10.1063/1.4957307
Huang B-L, Guo T-L (2016b) Fast optimization method based on the diffuser dot density for uniformity of the backlight module. Appl Opt 55:1494–1499. https://doi.org/10.1063/1.4950149
Huang B-L, Lin J-t, Ye Y, Xu Y, Chen E-g, Guo T-L (2017) Pattern optimization of compound optical film for uniformity improvement in liquid-crystal displays. Opt Laser Technol 97:254–259. https://doi.org/10.1016/j.optlastec.2017.07.013
Jakubowski M, de Boer J (2019) TALED-Fassadenintegrierte Tageslicht- und LED-Beleuchtung mittels Mikroptiken. In: Proc. 2. Kongress Energiewendebrunn 2019, Berlin, pp 52–53. https://projektinfos.energiewendebrunn.de/publikationen/publikation2-kongressenergiewendebrunn-2019. Accessed 28 Oct 2019
Jakubowski M, Neyer A, Müller H (2018) Microstructured façade elements for energy efficient office room illumination by sunlight combined with LED light. In: Proc. SASEC 2018, Durban https://www.sasec.org.za/documents/SASEC2018_proceedings.pdf. Accessed 13 Aug 2018
Jakubowski M, Hubschneider C, Neyer A, Fang Y, de Boer J (2019) Microstructured light guiding plate for single-sided light emission as light source for room illumination. Appl Opt 58:76–86. https://doi.org/10.1364/10.00000076
Kang M-w, Guo K-X, Liu Z-L, Zhang Z-h, Wang B-C, Wang R-z (2010) Dot pattern designing on light guide plate of backlight module by the method of molecular potential energy. J Disp Technol 6:166–169. https://doi.org/10.1011/JDTE.2010.2039696
Kim YC (2013) Optimize pattern design for the thin LGP. Optik - Int. J. for Light and Electron Opt. 124:2171–2173. https://doi.org/10.1016/j.ijleo.2012.06.070
Kondo Y (2009) Technological trends of LED backlight units. In: Kobayashi S, Mikoshiba S, Lim S (eds) LCD backlights. Wiley, Chichester, pp 195–205. https://doi.org/10.1002/9780470744826.ch15
Liedermann A (2017) Einsatz von Kunststoffen zur Beleuchtung von Fahrer-Informationssystemen. Proc. VDI Wissensforum: 7. Fachkonferenz Kunststoffe in Optischen Systemen, Berlin
Lee J-H, Lee H-S, Lee B-K, Choi W-S, Choi H-Y, Yoon J-B (2007) Simple liquid crystal display backlight unit comprising only a
single-sheet micropatterned polydimethylsiloxane (PDMS) light-guide plate. Opt Lett 32:2665–2667. https://doi.org/10.1364/OL.32.002665

Lin S-F, Su C-Y, Feng Z-Y, Li X-D (2017) Microstructure density generation for backlight display using probability analysis method. J Phys D Appl Phys 50:435601. https://doi.org/10.1088/1361-6463/aa8687

Müller HFO, Sasso F (2015) Energy-efficient lighting by LED. In: Sayigh A (ed) Renewable energy in the service of mankind, vol I. Selected topics from the world renewable energy congress WREC 2014. Springer, Basel, pp 801–807. https://doi.org/10.1007/978-3-319-17777-9_72

Rytka C, Kristiansen PM, Neyer A (2015) Iso- and variothermal injection compression moulding of polymer micro- and nanostructures for optical and medical applications. J Micromech Microeng 25:65008–65023. https://doi.org/10.1088/0960-1317/25/6/65008

Tengler F-C, Jakubowsky M, Neyer A (2014) High transparent light guiding plate for single-sided light emission. Microelectron Eng 119:174–177. https://doi.org/10.1016/j.mee.2014.05.004

Tran HH, Wu W, Lee NY (2013) Ethanol and UV-assisted instantaneous bonding of PMMA assemblies and tuning in bonding reversibility. Sens Actuators B Chem 181:955–962. https://doi.org/10.1016/j.snb.2012.11.060

Truckenmüller R, Henzi P, Herrmann D, Saile V, Schomburg WK (2004) Bonding of polymer microstructures by UV irradiation and subsequent welding at low temperatures. Microsyst Technol 10:372–374. https://doi.org/10.1007/s00542-004-0422-3

Werder J (2017) Herstellung von lichtlenkenden Mikrostrukturen im Spritzgußverfahren. Bachelor’s thesis, FHNW Fachhochschule Nordwestschweiz

Xu S, Yang T, Miao H, Xu Y, Shen Q, Guo T, Cui Z, Chen E, Ye Y (2019) Tilted light coupling structure for the thickness reduction of a liquid crystal display backlight. Appl Opt 58:2567–2574. https://doi.org/10.1364/AO.58.002567

Xue L, Xing R, Han Y (2010) Facile one-step fabrication of an undercut structure by solution Dewetting on a water/ice mold. J Phys Chem C 114:9845–9849. https://doi.org/10.1021/jp1010567

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