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Complex Glass Optics for LED and Laser Headlamp Systems

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1 Abstract

Steadily growing power densities of light sources and a continuous trend to more compact designs increase the heat load within LED and laser headlamps. Particularly the optical elements are getting challenged in such an environment. As material engineering is getting more crucial, optics made from glass are the best choice.

Glass is resistant to high temperatures and temperature fluctuations. UV irradiation, dust, hydrocarbons and other environmental influences have no impact on this material. The optics will keep its mechanical and optical properties. Low dispersion guarantees constantly high color fidelity for refractive applications. Within this work important material characteristics are reviewed and allocated to the respective headlamps requirements.

Insights into new glass production possibilities are given, which offer considerable benefits in terms of more complex geometries, higher shape accuracies and smaller replicable features. Relevant application examples and new design options are presented.

2 Introduction

During the past years, glass has taken a back seat as optics material for automotive headlamps, mainly because of its higher density compared to polymer based optics. However, newer systems, in particular those with adaptive driving beam (ADB) functionalities, require small sized optics which are able to handle the high optical power densities of new LED and laser light sources. This is valid for both primary and secondary optics and hence glass is now returning as the optimal solution to withstand the harsher system conditions.

Coupled with new pressing technologies and surface micro structuring, nowadays complex glass optics can be produced that had been unimaginable just a few years ago. One example are components that combine multiple light functionalities in only one piece, reducing the number of total system components and increasing performance.

Depending on the normative requirements, potential challenges to smoothen a hard cut-off line can be addressed via additional micro structuring of the glass surfaces, i.e. the convex lens side can be equipped with appropriate features.

3 Requirements of Novel Headlamp Systems

Due to substantial safety and drive comfort benefits the number of cars with headlamps using Adaptive Driving Beam (ADB) or glare-free high beam technology is rapidly increasing. Paired with cameras and detectors for scanning the road and its surroundings, this technology is able to significantly reduce glare in traffic and to improve vision for the driver. Various methods to reach this goal are already in series production, like LED matrix and LED pixel light systems. Others are still subject of current research and development like μAFS, Digital Light Processing (DLP), Micro Electro Mechanical System (MEMS) and Liquid Crystal Display (LCD) systems.

All of these methods have the requirement of precise optical components and at least one lens to produce a high quality image of the light pixels on the road. Besides glare minimization, increase of driver’s seeing distance, smoothness and latency of light change, the image and pixel resolution is the key factor for a homogeneously illuminated area with separable bright and dark spots. The tunable light distribution can be produced via various optical concepts using reflectors, primary and secondary lenses. In many systems, e. g. with LED matrix or pixel lighting, the optical components need to sit close to the light sources (LED, laser) to deliver maximum luminous efficiency. In such cases, the optics material must withstand very high thermal loads as well as other external impacts like UV radiation and chemicals while maintaining its geometrical properties and optical performance over the complete car lifetime. In an LED matrix beam a fixed spacing between two adjacent light segments and also the optical focal level should not vary depending on the ambient temperature. Therefore, the thermal expansion coefficient of the optics material should be as low as possible.

LED pixel light systems come with a high number of small emitters, closely packed, each typically with the area of 0.5 to 1 mm^2. This setup results in a high luminance; a portion thereof is UV radiation. Due to the high electrical power it also generates significant heat within a small area. This can cause severe issues for plastic materials like polymethyl methacrylate (PMMA) and polycarbonate (PC) resulting in a fast degradation/yellowing up to melting of the optics. Sophisticated cooling concepts with complex heat sinks and even active cooling against the heat and additional coatings against the UV radiation can partially solve this problem. However, this results in an increase of total price, weight, complexity and overall size of the headlamp system.

New multi-pixel technologies like DLP and MEMS only need one imaging lens in principle. However, there are micro mirror chips on the mass market for video and cinema projection, whose resolution already succeeds the limit defined by the current projection lenses, i. e., chromatic lens aberration results in a smoothing and broadening of sharp pixel edges and produces multiple disturbing colors in close vicinity. Complex lens systems to correct this and other optical aberrations are therefore needed. This again affects total system size, weight and price.

The light performance improves when using lenses with high contour accuracies and low dispersion. The latter is particularly high for PC and optical silicone resulting in color artefacts. Temperature and humidity significantly influence the color artefacts in case of plastic materials [1]. Glass usually provides a high Abbe number, strongly reduces the dispersion effect and also keeps it stable during operation. Furthermore, glass can easily be coated for higher efficiencies. Such dichroic coatings improve reflectivity and allow for tailored transmission in narrow and broad bands. Besides optimized anti-reflective (AR) or infrared (IR) coatings, also the color impression in transmission and/or reflection can be customized. AR coatings are especially attractive on refractive optics for headlamp systems using lasers to minimize the scatter of light. Coated SUPRAX® borosilicate glass is perfectly suited for high laser power densities as it provides a high laser induced damage threshold (LIDT). Figure 1 shows the LIDT of coated SUPRAX® optics together with the region of power densities of typical continuous wave (CW) laser diodes for better classification.

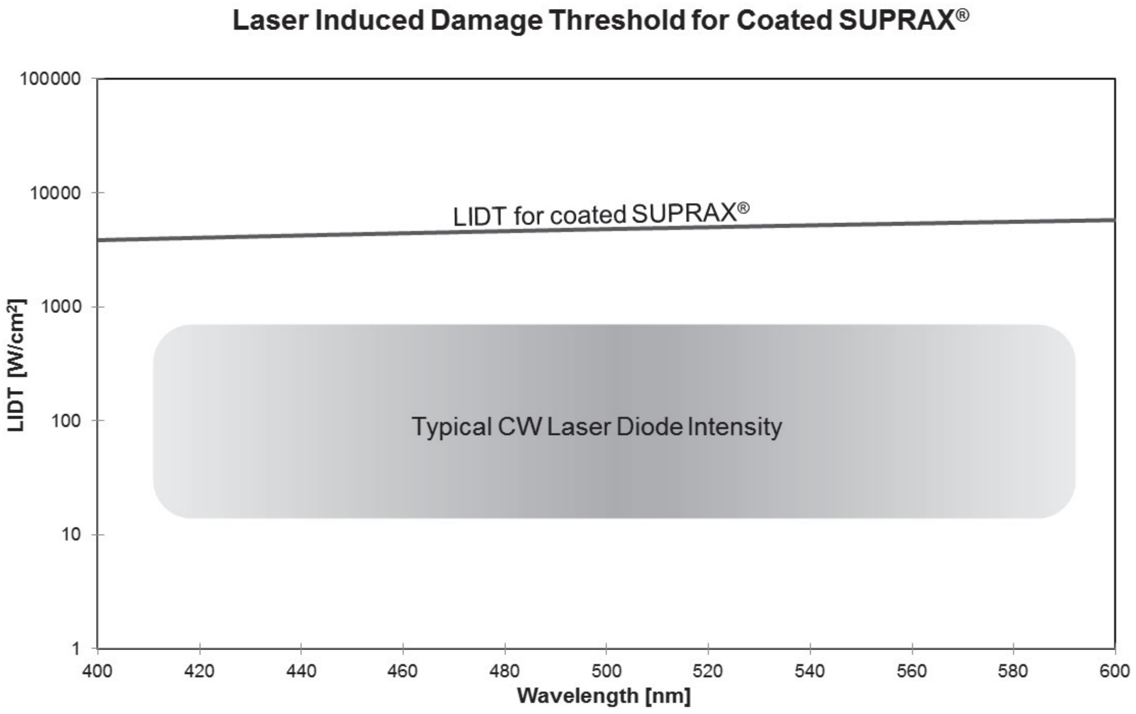
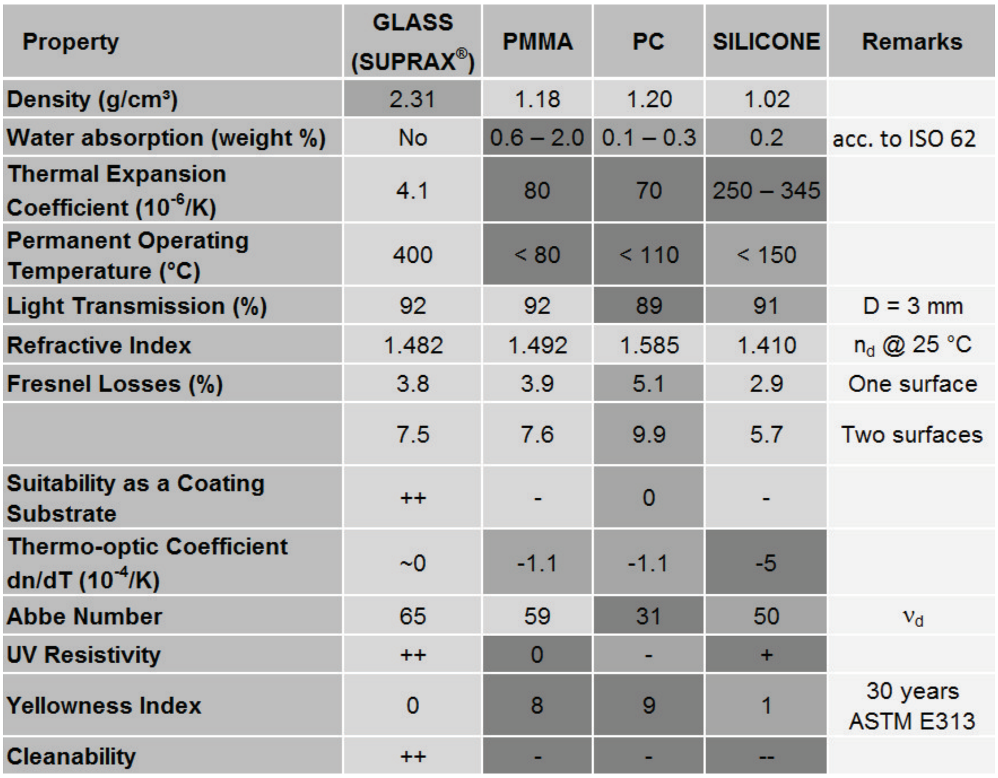


Figure 1: Laser induced damage threshold of coated SUPRAX® borosilicate glass.

Table 1: Material characteristics [1].



Property	GLASS (SUPRAX®)	PMMA	PC	SILICONE	Remarks
Density (g/cm³)	2.31	1.18	1.20	1.02	
Water absorption (weight %)	No	0.6 – 2.0	0.1 – 0.3	0.2	acc. to ISO 62
Thermal Expansion Coefficient (10^{-6}/K)	4.1	80	70	250 – 345	
Permanent Operating Temperature (°C)	400	< 80	< 110	< 150	
Light Transmission (%)	92	92	89	91	D = 3 mm
Refractive Index	1.482	1.492	1.585	1.410	n_d @ 25 °C
Fresnel Losses (%)	3.8	3.9	5.1	2.9	One surface
	7.5	7.6	9.9	5.7	Two surfaces
Suitability as a Coating Substrate	++	-	0	-	
Thermo-optic Coefficient dn/dT (10^{-4}/K)	~0	-1.1	-1.1	-5	
Abbe Number	65	59	31	50	ν_d
UV Resistivity	++	0	-	+	
Yellowness Index	0	8	9	1	30 years ASTM E313
Cleanability	++	-	-	--	

Table 1 lists all relevant material characteristics which have to be considered when deciding for an optics material. Regarding the requirements of current and novel LED and laser headlamp systems, glass clearly combines the best properties. Auer Lighting's SUPRAX® borosilicate glass shows no yellowing and aging and is usable between -80 up to 400 °C. Constant, highly efficient lighting and road vision over the complete lifetime is ensured providing a significant safety bonus for the driver. For deeper material information please check references [1 - 3].

4 Advanced Glass Technologies for Automotive Optics

Glass injection molding technology (GIMT)

Constant research and development in the field of glass pressing and processing offers many new possibilities for the design and production of cost-efficient, complex glass optics. A rather new technology is the proprietary glass injection molding (GIMT), which works comparable to the well-known polymer injection molding. The method allows for high length-to-width aspect ratios, which are especially useful for demanding primary optics like light guide arrays for ADB functionalities (see Figure 2). Furthermore, negative draft angles for design or mounting purposes can be directly introduced into the optics. Minimum weight limits of common direct glass pressing are easily undercut: products even below 3 grams can be realized. GIMT is able to produce very complex geometries with smooth 3D freeform surfaces and contour accuracies down to 10 µm.

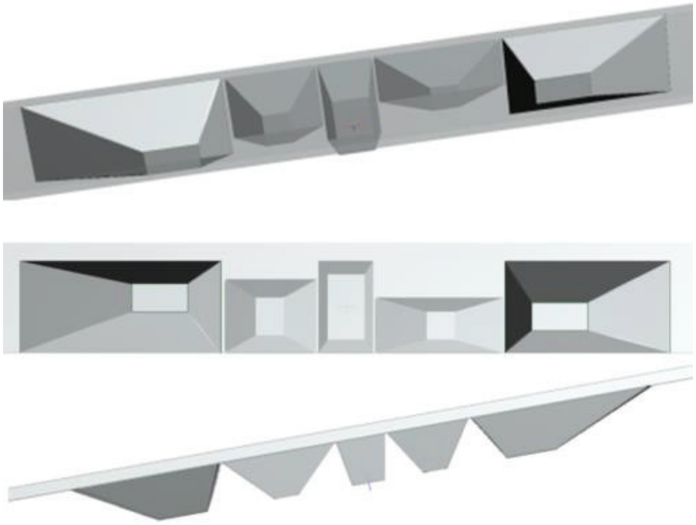


Figure 2: Example geometry of a light guide array from SUPRAX® borosilicate glass.

Glass micro structuring

Normative requirements define, amongst others, the transition between dark and bright areas at the cut-off. This can be achieved by adding scatter structures on the projection lenses. Abrasive processes like sand or glass bead blasting are state-of-the-art techniques. They often result in rough surfaces, which are causing undesirable high scattering angles. The roughness also lowers the light output efficiency since a non-negligible fraction of back-scattered light is produced.

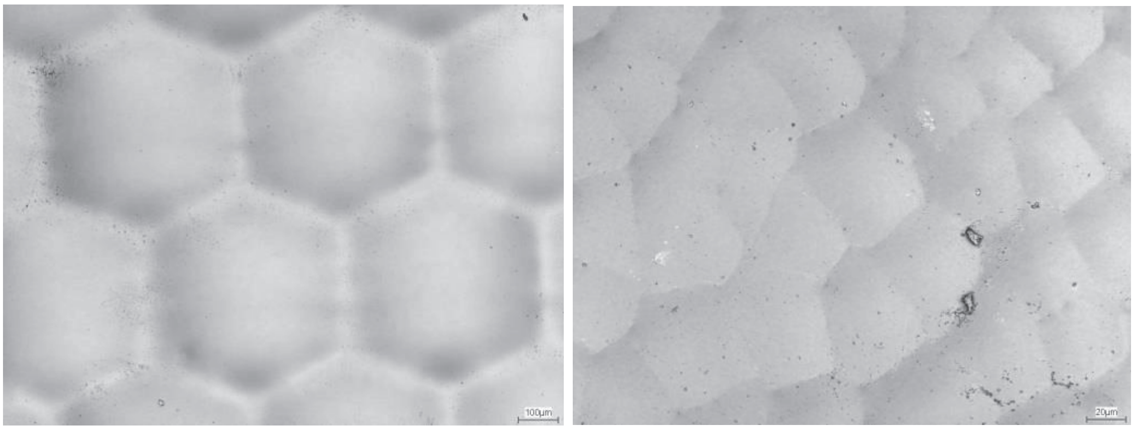


Figure 3: Replicated borosilicate glass structure with lattice constant of 500 µm (left) and with an averaged feature size of 50 µm (right) [5].

Defined micro structures solve both issues. Structure geometry, size and lattice distance can be optimized for defined forward and minimum backward scattering via optical ray tracing software. For production, instead of time-costly methods like precision glass molding, recently a faster glass structuring technology was qualified, which is able to replicate tailored gratings for example with lattice constants of 500 μm on a mass production scale (see Figure 3 and Ref. [5]). The possibility to even decrease the averaged feature sizes to 50 μm was also shown [5]. This is particularly important if the lattice separation should not be resolved anymore when imaged with a lens [6].

5 Application Examples

ADB systems are currently in the development focus. Those systems usually require complex optics and glass seems to get more popular as the perfect material choice. In Figure 2 a primary optics array is shown. Each frustum of a cone represents one addressable illumination area ("pixel") of the final light distribution. A large part of such optics is equipped with flat entrance surfaces, which then can be placed almost in touch to flat light emitters. This guarantees maximum light capture. The angled lateral surfaces are narrowing the angular light distribution of the LED. Angle and length are responsible for light spread and spatial separability between light of neighboring pixels in the final distribution. The frustum's footprint is imaged onto the street and hence determines the illuminated area. Therefore, the distance between two neighboring pixels should be as small as possible in order to not produce any dark gaps in the light field. The minimum distance is defined by the radii at the intercepts formed by two tapered surfaces. They are needed to ensure a sufficient long tool life during glass hot forming and, consequently, to keep product cost low. Possible arising shadows can be dissolved by lens defocusing, implementation of diffusing surface structures or geometry adjustments.

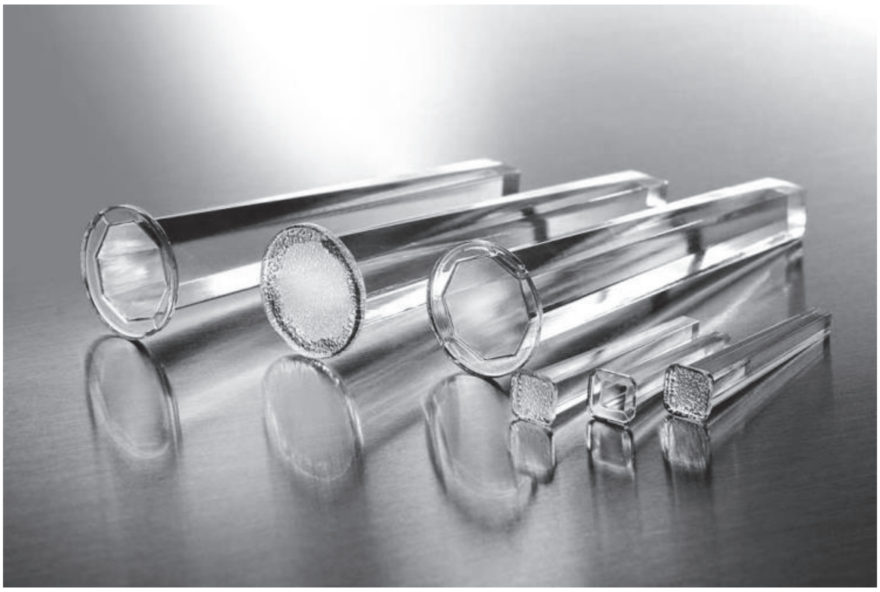


Figure 4: Example geometries of light guides from SUPRAX® borosilicate glass.

Figure 4 shows standard glass light guides for projection systems. Flanges and micro structures are directly integrated into the glass parts. Several optics are used within one system to enable tunable colors and homogeneous lighting. While systems like moving head fixtures offer zoom functionality via movable projection lenses, their positions are fixed in automotive headlamps. Light entrance and exit surfaces are often designed flat. However, the flat exit could also be designed as a convex free-form shape instead. This can be useful for ADB projection systems using primary and secondary optics that are mounted at a fixed distance. The optical imaging function of the projection lens could be transferred into the primary light collimating and mixing optics (see Figure 5). Not only the imaging, but also a certain amount of light scattering via a defined micro structured convex surface can be realized. This hybrid functionality increases optical efficiency, reduces the total number of system components and also simplifies their positioning.

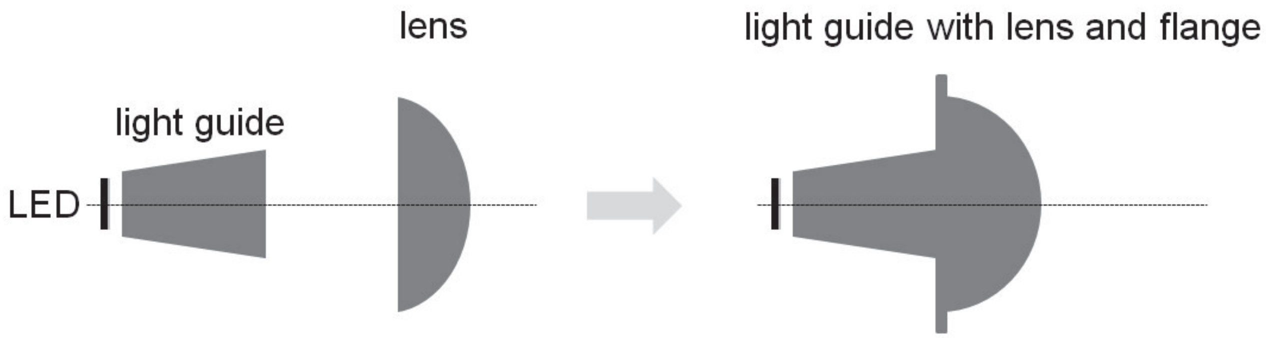


Figure 5: Schematic side view of a current two optical component projection system and the integration into a single component system.

Figure 6: Glass lens array for high power laser systems.

The high mechanical and chemical stability of SUPRAX® borosilicate glass and dichroic coatings makes it the perfect combination for any laser application. Figure 6 shows the example of a glass lens array, which is used to concentrate a number of laser light sources in an optical system. For consistent high optical performance the accurate positioning and the contour accuracy of all lenses is important. The complex hot forming is therefore always reinforced by 3D contour evaluation methods to ensure best quality for the customer.

6 Summary and Outlook

Pressing of optical glass components and subsequent surface treatment methods have evolved to a point where complex geometries with small surface features can be realized in glass. Not only the industry’s demand for optically stable material, but also new optical design ideas for high power applications can be covered. A concept was shown that combines multiple light functionalities in only one piece instead of using primary and secondary optics. Borosilicate glass injection molding is the ideal manufacturing process for such optics.

New glass micro structuring techniques allow optimum light diffusion on a mass production scale. The possibility to replicate feature sizes of 50 μm in glass was shown and there is also potential for further miniaturization. Complex tool making methods like laser structuring will support such a process.

Specialized coatings on glass can significantly enhance the optical system performance. Both refractive and reflective optics will benefit in efficiency and improvement of certain spectral areas.

Glass once again has established itself as the preferred choice for advanced optical designs in the automotive industry. There is no doubt that the further development of glass production technologies keeps the pace with the newest requirements of automotive illumination ideas.

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