Stability of glass versus plastics for transmissive high-power LED optics

C. Paßlick*, A. Hellwig, U. Geyer, T. Heßling and M.C. Hübner
Auer Lighting GmbH, Hildesheimer Str. 35, 37581 Bad Gandersheim, Germany

ABSTRACT

In the past, the major part of transmissive LED optics was made from injection molded polymers like PMMA or PC. Recent LED developments now show constantly increasing levels of luminous flux and energy densities, which restrict the usability of such polymer optics due to their limitations in thermal stability. Thermal simulations have shown that light guiding/mixing structures (rods) made from polymer materials can easily reach temperatures above their melting point due to the absorption characteristics. However, there is a great demand for such light rods from the automotive and entertainment industry and thus glass is becoming increasingly important as an optical material.

Glass has typical transformation temperatures of hundreds of degrees Celsius and therefore withstands the conditions seen with LED without any problems. Square-shaped glass light guides show temperature advantages over round light rods, which are known for being able to produce caustics inside the material causing absorption and temperature hot spots, respectively.

This paper presents some comparative thermal simulations by means of the Finite Element Method for a light conductor as an example and gives corresponding assistance for an appropriate material and light guide shape selection for high-power LED optics.

Keywords: high-power LED, glass, plastics, transmissive LED optics, heat resistance, light guide, FEM simulation

1. INTRODUCTION

Until now, most of the refractive optical components for low-power and low-flux LED applications were made of transparent polymer materials like Polymethylmethacrylate (PMMA) or Polycarbonate (PC) mainly caused by the already well-known plastic production processes and available injection molding machinery for electronic components. Recent LED developments, however, come with such high luminous fluxes that some polymers are not applicable anymore. Chip manufacturers are even trying to further increase the LED light output density, in particular for automotive and stage lighting systems which often use high-power LEDs in conjunction with light guides to gain the desired light distribution and color mixing. In order to exploit the maximum potential of the system, special attention has to be paid to the material choice of these secondary optical elements. Thermal simulations in this work will show that for a typical application example, light guides made of polymers easily reach temperatures above their deflection temperature due to their absorption characteristics.

Furthermore, outdoor applications like street lighting or architectural lighting require long-lasting optics with constant optical properties. In these scenarios, the material is exposed to short-wave light (UV, blue) as well as chemical and mechanical stress. Typical degradation effects of many polymer optics are yellowing by short-wave light, scratches on the surfaces, e.g. by cleaning, corrosion by environmental influences like corrosive gases (nitrogen oxides, etc.), acid precipitations, soot particles and cleaning agents, which reduce the overall optical performance. Without special stabilizers and recipes against aging, respectively, polymers would already not be found in this area anymore. Their new challenge now is to survive the higher temperatures and higher luminous fluxes when switching to high-power LEDs, which cause higher diffusion velocities of the aggressive, low-molecular substances into the polymer matrix and put higher thermal load into the material. Recently, some plastic manufacturers brought moldable optical silicones on the market, which have the advantage to withstand even higher temperatures up to 150°C, but at the same time show significantly higher thermal expansion coefficients leading to noticeable changes in the volume (length) of the optics as a function of temperature.

*christian.passlick@auer-lighting.com; phone +49 5382 701-472; fax +49 5382 701-132; auer-lighting.com

Glass, on the other hand, is known for its usability and strong resistivity even in extreme aggressive environmental conditions. The high mechanical stability and surface hardness as well as the high chemical resistance ensure constant optical properties and surface brilliance for a long lifetime. Because of the high glass transition temperature, e.g. for the borosilicate glass Suprax 8488, above 500°C, the glass is able to easily survive higher LED powers.

In order to study the materials' heat resistance in more detail, this paper focuses on the coupling of optical raytracing with thermal simulations to predict the temperature ranges occurring in secondary optical elements. As an actual example, a light guide is irradiated by a high-power RGBW LED. The optical volume absorption inside the light guide is investigated for different materials and geometries via optical simulations and the results are used as starting condition for thermal simulations by means of the Finite Element Method (FEM). The solutions of this analysis method are feasible to evaluate high-power LED systems in terms of an appropriate material and optics geometry choice.

2. MATERIALS

The market offers several material possibilities for light guides. However, when it comes to high-power LED applications, one should take a deeper look into the different material characteristics, which in the end can be decisive for the performance, the functioning or failure of the whole lighting system. This applies not only to light guides discussed here, but also to other secondary optics like collimators or lenses in high-power LED systems. In this work a closer look is taken on the most commonly used optical plastics, i.e., Polymethylmethacrylate (PMMA), here *Plexiglas* from Evonik, and Polycarbonate (PC), here *Makrolon* from Bayer, and a comparison is drawn to an optical silicone, here *MS-1002* from Dow Corning and a borosilicate glass *Suprax 8488* from Auer Lighting. The following sections give a brief overview about their different optical and thermal properties.

2.1 Optical properties

For determining the optical losses inside a material, the wavelength-dependent material absorption as well as the wavelength-dependent refractive index, $n(\lambda)$, is important. Absorption follows Beer's law, $T = \exp(-az)$, with the absorption coefficient, $a(\lambda)$, and the propagation distance, z. Figure 1 compares a for PMMA, PC, silicone and glass.[1-5] PC shows the lowest absorption above 600 nm, while almost similar values to *Suprax* are observed between 450 nm and 580 nm. In the short-wavelength region from 330 nm to 450 nm, *Suprax* shows the smallest absorption among the four materials. PMMA shows values which are almost one order of magnitude lower over the visible spectral region, but a strong absorption increase below 425 nm.

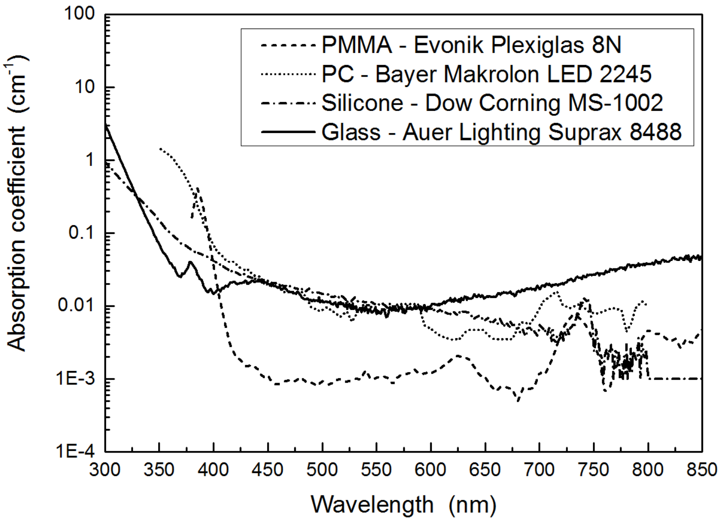

Figure 1. Absorption coefficient versus wavelength for the four different materials PMMA (dashed), PC (dotted), silicone (dash-dotted) and glass (solid).[1-5]

Taking a look onto the refractive index, optical silicone shows the lowest value with 1.424 at 587 nm and room temperature, PMMA and Suprax provide almost similar values with 1.491 and 1.482, respectively, while PC shows a significant higher value of 1.584. This leads to a drastically increased reflectance, R, and accordingly decreased light transmittance, when light is hitting and crossing the boundary between material and air as R follows $R=(n-1)^2/(n+1)^2$ in case of normal incidence. A higher refractive index also results in a smaller Abbe number and thus in a larger dispersion for polymers.[6]

For the optical simulations done here, all materials were assumed to be perfectly homogeneous, i.e., without anisotropic density fluctuations or impurities, which would cause additional light scattering inside the material.

2.2 Thermal properties

Transmissive LED optics require a high thermal stability in order to ensure stable mechanical and optical properties. Table 1 lists important thermal properties for the materials compared here. Optical polymers provide permanent operating temperatures below 80°C for PMMA and 120°C for PC, while glass (here: Suprax) is even able to withstand 400°C. Optical silicone is well suited for higher temperatures up to 150°C, but shows an almost 61 times larger linear thermal coefficient of expansion than glass and also a non-neglectable temperature dependence of the refractive index. In lighting situations involving large environmental changes, these properties can have a huge impact, e.g., on the focal distance of the optics or the length of a light guide. For instance, a 70 mm long light guide made from silicone would gain additional 1.05 mm in length when increasing the temperature from 20°C to 80°C, while it is 0.02 mm for glass. It is necessary for the optical designer to consider these facts when developing optical elements and choosing materials.

Table 1. Overview of some important thermal material properties.

	PMMA[1,7,8]	**PC**[2,7,9]	**Silicone**[3,10]	**Glass**[4]
Thermal conductivity [W/(m K)]	0.19	0.20	0.31	1.20
Density [kg/m³]	1190	1190	1020	2310
Heat capacity [J/(kg K)] @ 25°C	1470	1170	1370	785
Thermal expansion coefficient [10^{-6}/K]	80	70	250	4.1
Permanent operating temperature [°C]	80	120	150	400
Thermo-optic coefficient [10^{-4}/(dn/dT)]	-1.1	-1.07	-5.0 to -1.5	0

3. OPTICAL SIMULATIONS

3.1 Source preparation and analysis

The OSRAM Ostar RGBW LERTDUW S2W LED is used as a high-power LED light source, which is available on the market and can be driven up to 15 W electrical power. The source rayfiles and corresponding spectral data for optical simulations are freely accessible from OSRAM and contain rays which are already traced towards the outer exit surface of the cover glass and are then shifted by +90 µm in z direction.[11] Table 2 lists the characteristics of the respective LED chips which were implemented in an optical ray tracing software. The electrical and optical properties of the single chips were weighted towards their maximum allowed values with respect to the specified data for 1 A direct current and 85°C junction temperature provided by the LED manufacturer. For the simulations in connection with the light guide, the distance between LED cover glass and light guide entrance is 0.4 mm. Only rays hitting the entrance plane are included in the calculations.

Table 2. Characteristics of the LED sources for 1 A direct current per chip and 85°C junction temperature.

color	**# of rays**	**radiant power (mW)**	**electrical power (W)**	**radiant efficiency (%)**
deep blue	500,000	919.9	3.42	26.9
true green	500,000	304.9	3.52	8.7
red	500,000	308.2	2.65	11.6
ultra white - blue	500,000	270.0	3.42	20.9
ultra white - yellow	500,000	446.4		
total	2,500,000	2249.3	13.10	17.3

3.2 Light guides

Three different light guide geometries are investigated. All designs provide the same typical length of 70 mm with parallel side walls, but different entrance and exit surface geometries, which are shown in Figure 2. “Square” (left), “square with rounded corners” (middle) and “round” (right) shapes are used to evaluate their influence on the optical absorption inside the light guide material. The entrance and exit surface areas are kept constant at 9 mm^2 in order to ensure an almost similar entrance light flux, while the surface areas of the side walls vary according to the different input shapes.

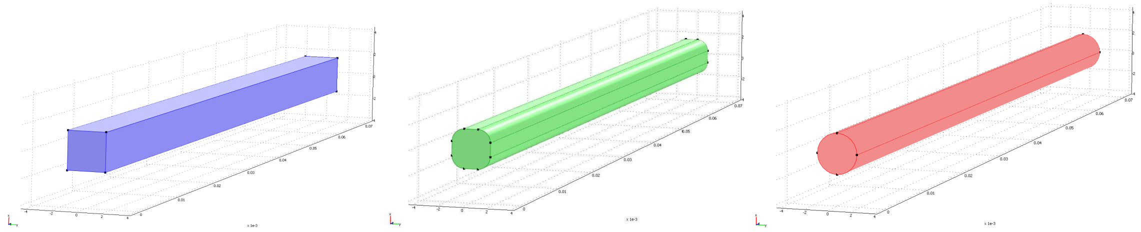

Figure 2. Overview of the different light guide end face shapes: square (left), square with rounded corners (middle) and round (right). The entrance and exit surface areas of all geometries are equal.

3.3 Calculation of the optical volume absorption

In order to determine the optical volume absorption inside the light guides, the flow of power as it propagates through the volume is recorded. Therefore the light guide and its surrounding space are subdivided into a number of 3D cells (voxels) and the spatial distribution of power transfer between adjacent cells is captured during the raytrace. In more detail, the absorbed power per voxel is the ray power sum for all rays incident on the cell surfaces less the sum for all rays leaving the cell surfaces. Figure 3 shows a 2D view of the absorbed flux on a light guide entrance plane with rounded corners. In this example, the volume was subdivided into 20 x 20 voxels for the calculations. The optical absorption behavior of the three different light guides is compared in Figure 4 by looking at selected 2D slices through the 3D voxel grid. It appears that the introduction of rounded corners and the round shape result in a different volume absorption with pronounced absorption regimes caused by arising caustics inside the light guide.

The power density is obtained by dividing the absorbed power by the volume of each cell, which is $(100\ \mu\text{m})^3$. This resulting 3D grid of heat sources is then transferred into the thermal FEM simulations.

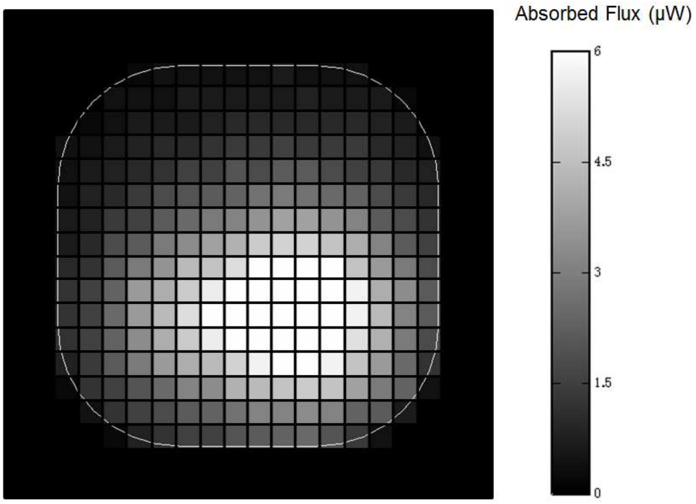

Figure 3. 2D view of the absorbed flux on a light guide entrance plane with rounded corners. The volume was subdivided into 20 x 20 voxels for the calculations.

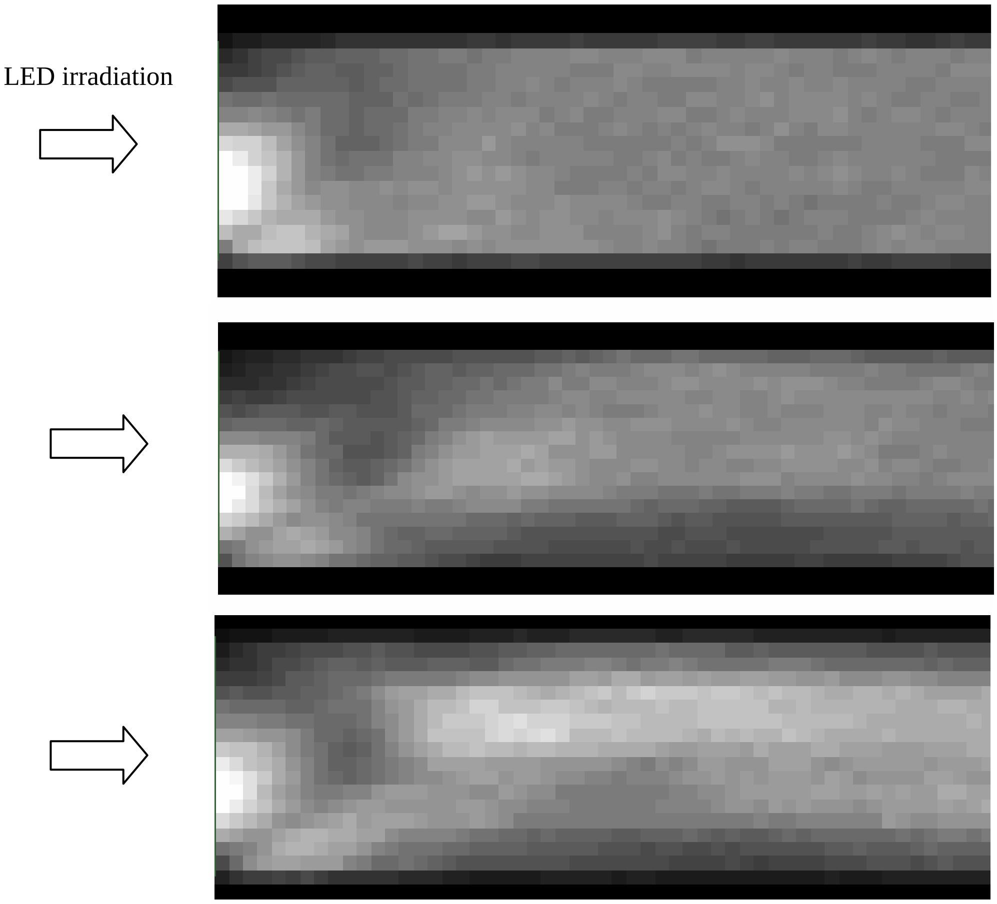

Figure 4. 2D slices through the 3D voxel grid showing absorbed fluxes for the three different light guides. Top: square shape; Middle: square shape with rounded corners; Bottom: round shape. The shades of grey refer to the legend of Figure 3.

4. THERMAL SIMULATIONS

The three different light guides shown in Figure 2 are modelled in the FEM simulation software COMSOL Multiphysics in conjunction with the Heat Transfer Module package. The thermal calculations are done for ambient temperatures from 20°C to 120°C in 10°C steps. Heat radiation to the surroundings and additionally natural external convection flow of air are assumed using the built-in heat transfer coefficients. Therefore, the long light guide side is aligned horizontally. The 3D grid of heat sources obtained from the optical raytracing is embedded into the FEM system. Data outside of the specified grid is calculated by an interpolation function. The heat transfer by conduction for all heat sources, Q, is calculated via the heat equation:

$$Q = -\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \left(-k \nabla T\right), \tag{1}$$

with the material density, ρ, the heat capacity, C_p, the thermal conductivity, k, and the temperature, T. In this work, an isotropic and homogeneous material and a steady-state model is assumed, i.e., the temperature does not change with time and thus the first term vanishes:

$$Q = \nabla \cdot \left(-k \nabla T\right). \tag{2}$$

The material specific thermal conductivity values are taken from Table 1. For the heat flux for surface-to-ambient radiation the general formulation of the Neumann boundary condition is used:

$$-\vec{n} \cdot \left(-k \nabla T\right) = q_0 + h\left(T_{\text{inf}} - T\right) + \varepsilon\sigma\left(T_{\text{amb}}^4 - T^4\right), \tag{3}$$

with the normal vector of the boundary, $\vec{n}$, the inward heat flux, normal to the boundary, q_0, the convective heat transfer coefficient, h, relative to a reference temperature, T_{inf}, a constant emissivity of $\varepsilon = 0.86$, the Stefan-Boltzmann constant, σ, the starting ambient temperature, T_{amb}, and the temperature, T. In order to simulate the heat flux from the LED on the entrance face of the light guide, the LED is assumed to behave as a black body with a constant temperature, T_{op}. This means that emissivity and absorptivity equals 1 and reflectivity equals 0. For T_{op} = 85°C the inflowing heat flux is then given by $q_0 = \sigma T_{\text{op}}^4$ = 932.9 W/m². No mechanical contacts or holders are taken into account.

5. RESULTS

Figure 5 shows an iso-surface view of the occurring temperature ranges for all three light guide geometries made from Suprax at a constant LED operating temperature T_{op} = 85°C, and a constant ambient temperature T_{amb} = 60°C, which is a typical temperature (at the lower end), e.g. in an LED stage lighting system. It is clearly visible that for the light guide having a square entrance and exit shape the lowest minimum and maximum temperatures occur among the three versions. This is mainly caused by the 13% larger surface area of the four lateral surfaces compared to the round side area (11% larger compared to the square shape with rounded corners), which increases the heat exchange to the surroundings. The twenty iso-temperature surfaces provide additional information about the temperature distribution inside the light guides and hence reveal the influence of the different shapes. A variation of the ambient temperature from 20°C to 120°C results in temperature bands shown in Figure 6. For a constant LED operating temperature and constant distance between LED and light guide, the round light guide always shows the highest temperatures, while the square shape shows the lowest. Therefore, the square shape was used as reference shape and evaluated for the different materials. It should be kept in mind, that for this reason, the following calculated temperatures tend to be an estimation downward. Figure 7 shows the comparison versus varied ambient temperature. At the same T_{amb}, usage of silicone yield the highest simulated temperatures inside the light guide, while PMMA yields the lowest.

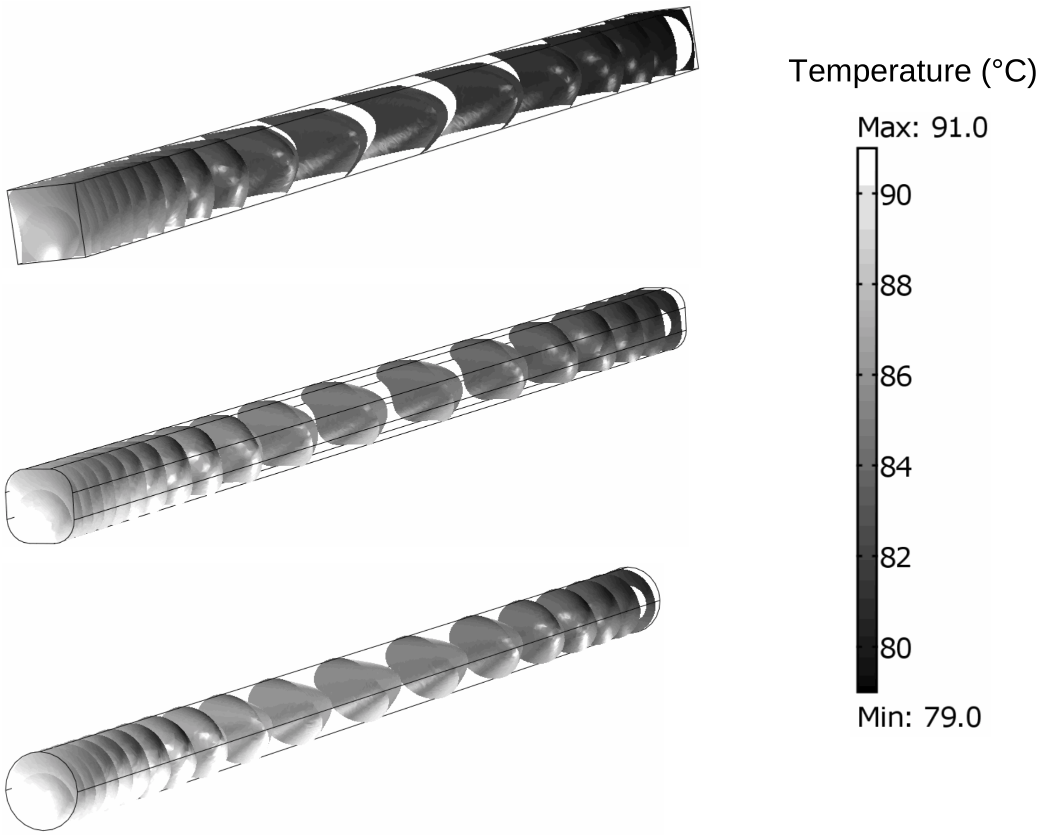

Figure 5. Iso-surface plots for the three different light guides made from Suprax at a constant LED operating temperature T_{op} = 85°C, and a constant ambient temperature T_{amb} = 60°C. Top: square shape; Middle: square shape with rounded corners; Bottom: round shape.

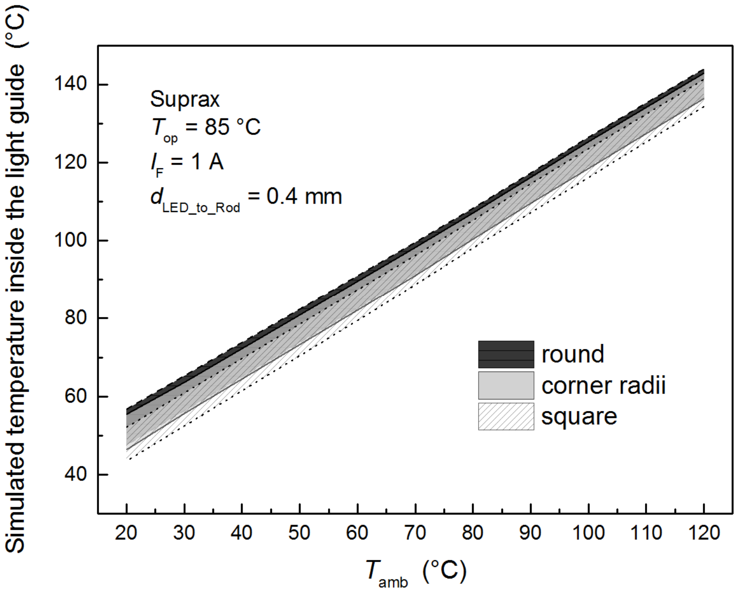

Figure 6. Simulated temperature ranges inside the light guides for different ambient temperatures and shapes for a Suprax light guide.

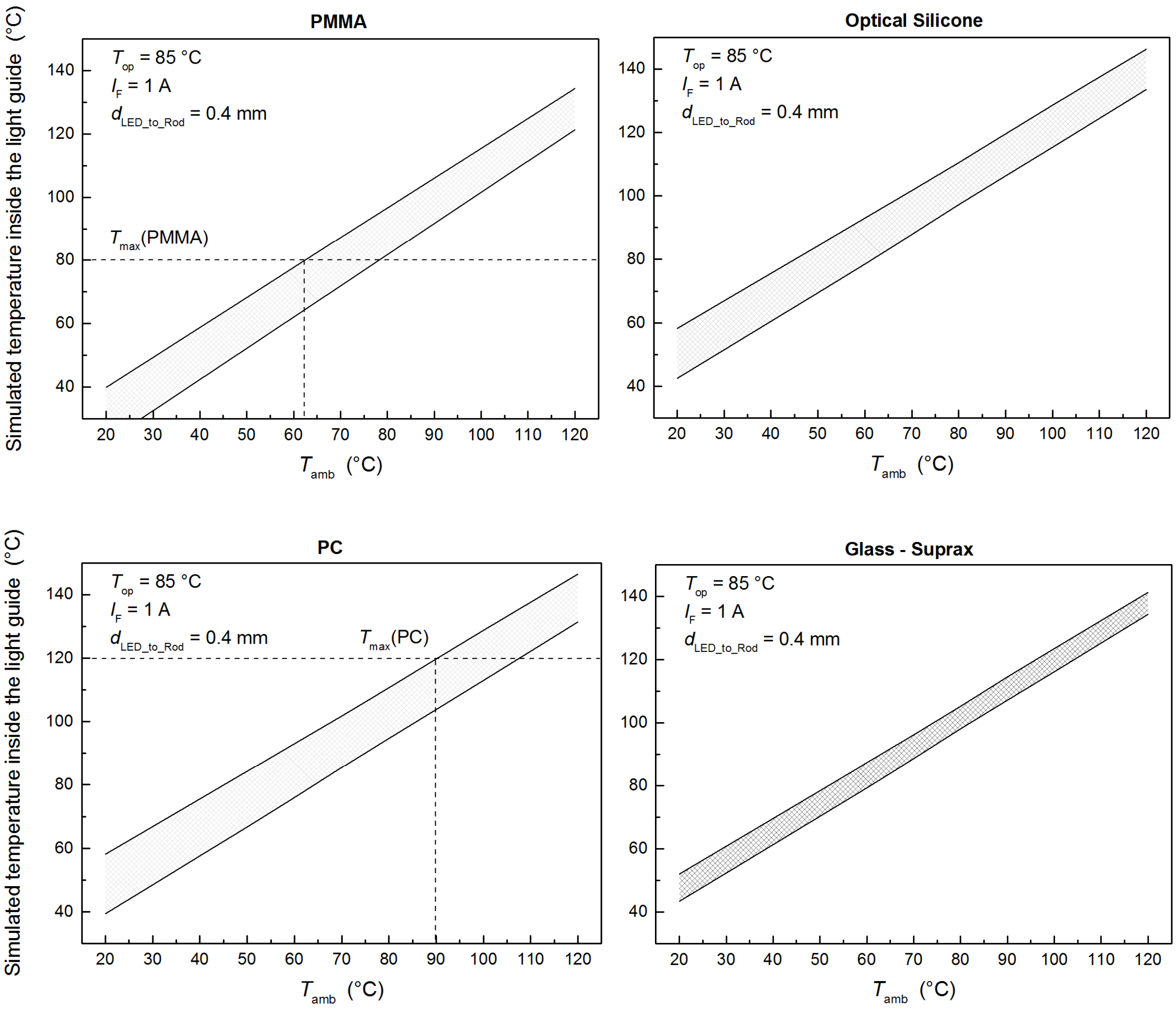

Figure 7. Simulated temperature ranges inside the light guides for different ambient temperatures and different materials for a square-shaped light guide.

In case of PMMA, the maximum allowed operating temperature of T_{max}(PMMA) = 80°C is reached for an ambient temperature slightly above 60°C within the above mentioned boundary conditions. T_{max}(PC) = 120°C is reached for 90°C ambient temperature, while Silicone withstands ambient temperatures up to 130°C in this setup. Suprax glass shows a narrower band of maximum and minimum temperatures lying in between all other materials. With maximum allowed permanent operating temperatures around 400°C, all light guide shapes and designs can be used. In Figure 8, the simulated temperature curves which occur in axial direction through the center of a square-shaped light guide are shown for the different materials (left) as well as for different temperature conditions when using a light guide made from Suprax (right). Here, the differences in thermal conductivity and optical absorption are clearly visible: The highest thermal conductivity of Suprax, 1.20 W/(m K), results in a flat temperature curve along the light guide with a maximum simulated temperature of 87°C at the light guide entrance and a minimum temperature of 80°C at the light guide exit. Also the lowest absorption in the blue spectral range around 400 nm has an impact on this behavior. The lowest thermal conductivity (0.19 W/(m K)) and lowest spectral absorption in the visible spectral range of PMMA leads to the lowest starting temperature of 78°C and a fast temperature decrease in the first 10 mm dropping down to 62°C at the light guide's end. Again, silicone shows the highest temperatures inside the light guide, but the lowest negative curve slopes at the light guide entrance among the polymers, because of its highest thermal conductivity of 0.31 W/(m K).

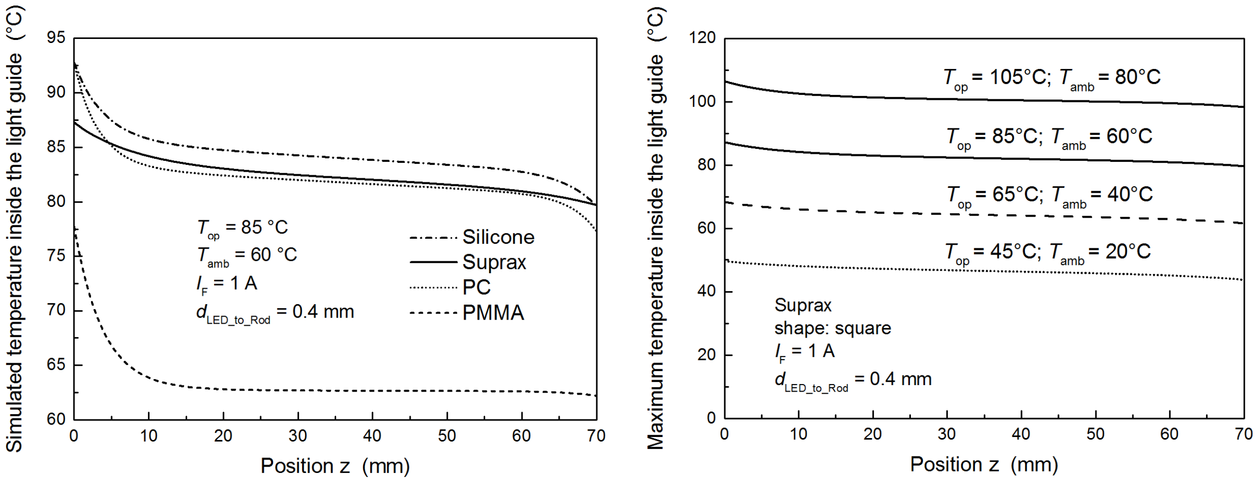

Figure 8. Comparison of the simulated temperatures occurring in axial direction through the center of the square-shaped light guide for the different materials (left) and different temperature conditions in case of square-shaped Suprax light guide (right).

The PC curve is located in the middle, but shows a similar behavior towards the light guide ends as for silicone. Figure 8 (right) shows the calculated maximum temperatures inside a square-shaped Suprax light guide for different temperature conditions. The ambient temperature was increased by 20°C starting from 20°C and going up to 80°C. The LED temperature was always assumed to be 25°C above the ambient temperature.

6. CONCLUSION

This paper uses a method which couples optical raytracing results, i.e. 3D spectral absorption data of a light guide, with thermal FEM calculations, where the absorption voxels are used as small heat sources. The method was applied to light guides of three different shapes and four different materials in order to evaluate their practical feasibility. It was shown, that a square-shaped light guide of similar entrance and exit areas provides the lowest occurring temperatures, because of the highest surface area and better mixing properties than, e.g. the round light guide, which showed caustics in the light distribution. It must be noted that the obtained results can be influenced by a number of boundary conditions including the electrical power of the LED, which can vary for real LEDs, the influence by mechanical contacts on the temperatures, e.g. the mounting of the LED chip or by forced convection, e.g. from active cooling by a fan. Furthermore, the calculated luminous fluxes for the LED chips were based on the mean values given by the manufacturer. Using their given maximum values would increase the used total flux by a factor of 1.4 and hence also the temperature loads on the light guides.

However, the results of this technique give some general insights into the stability of glass versus plastics for transmissive high-power LED optics. For LED systems, e.g. in the automotive and stage lighting areas, ambient temperatures of up to 80°C can already occur in the systems and might further increase in the near future. The coupled simulations have shown that in such cases PMMA would be not applicable anymore and also PC would come close to its thermal limits. Figure 9 shows a photograph of an irreversibly damaged PMMA light guide caused by radiation of the physical counterpart to the LED used for the simulations here. The difference in optical power densities of the four LED chips is noticeable and leads to different degrees of damage. Only optical silicone and glass, here the borosilicate glass Suprax, are able to withstand the highest thermal loads of the discussed optical setup. Silicone, however, comes with the disadvantage of its 61 times higher thermal expansion coefficient compared to Suprax, which makes it extremely difficult to use it in systems with changing environmental and thermal conditions, respectively.

In addition, glass shows the higher mechanical and chemical resistance: It does not gas out, resists corrosive gases in the atmosphere, shows no yellowing by short-wave radiation from the sun or even the LED itself, is easily cleanable due to its hardness and chemical stability against cleaning detergents and shows no water absorption.

Future work will focus on the implementation of the temperature dependent spectral refractive index.

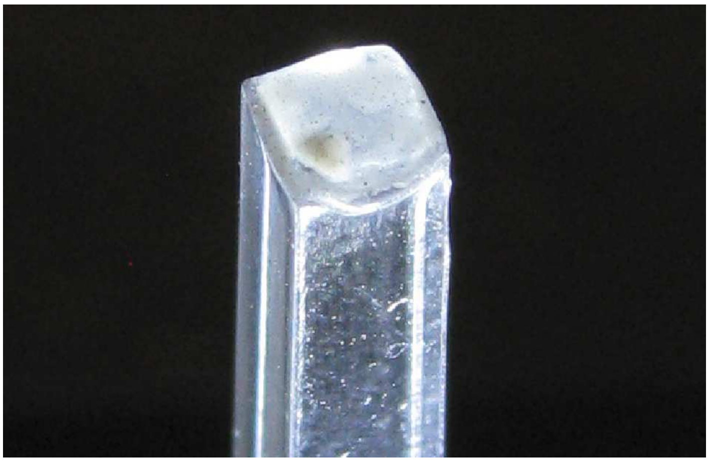

Figure 9. Photograph of an irreversibly damaged PMMA light guide caused by LED radiation.

REFERENCES

[1] Technical data of Plexiglas® provided by Evonik Industries AG

[2] Technical data of Makrolon® provided by Bayer MaterialScience AG

[3] Technical data of MS-1002® provided by Biesterfeld Spezialchemie GmbH

[4] Technical data of Suprax8488® provided by Schott AG / Auer Lighting GmbH

[5] Kasarova, S. N. et al. "Analysis of the dispersion of optical plastic materials", Optical Materials 29, 1481-1490 (2007).

[6] Minami, K., "Optical Plastics", Bäumer, S., Ed., [Handbook of Plastic Optics], 2nd ed., WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 123-160 (2010).

[7] Rodriquez, F., [Principles of Polymer Systems], 3rd ed., Hemisphere Publishing Corp.: New York, 589-594 (1989).

[8] Wunderlich, W., "Physical Constants for Poly(methyl methacrylate)", [Polymer Handbook], 3rd ed., Brandrup, J. and Immergut, E. H., Eds., Wiley: New York, V77-V80 (1989).

[9] Saleem, M.R. et al. "Towards athermal organic-inorganic guided mode resonance filters", Optics Express 24242, Vol. 19, No. 24 (2011).

[10] Technical data of MS-1002® furnished by Dow Corning

[11] Datasheet for OSRAM Ostar Stage LE RTDUW S2W, Version 1.3, 2013-08-01

[12] Bejan, A. [Heat Transfer], Wiley, New York (1993).