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Glass Optics for LED Applications

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Historically seen, glass is a very old material and evolved with many different mixtures into a broad variety of applications, from objects of daily use to art objects and high end technical tools like optics. Dr. Thomas Hessling, Optical Engineer at Auer Lighting's R&D/Lighting Technology department explains why glass is also the first choice for secondary lenses in LED systems.

Glass has become such an integral component of a vast amount of everyday objects that it would be impossible to imagine today's world without it. Its use by humankind dates back several millennia and has evolved since then from a mere cutting tool to a wide range of applications, such as windows, vessels and the dominant optics material, to name just a few. The appearance of glass lenses in the middle ages led to great discoveries in the field of optics and astronomy that changed our view of the world and the universe forever.

In the field of illumination optics glass became invaluable with the invention of the electric light bulb. An evacuated glass housing was necessary to prevent the filament from oxidizing and glass was the material of choice. With the advance of artificial light sources to higher and higher powers glass remained the number one material due to its high temperature and mechanical stability. It easily withstands the operating temperatures of incandescent as well as even more powerful light sources and so it was also chosen as material for the primary optics such as reflectors, lenses or diffusers.

Light Emitting Diodes

In the middle of the 20th century a new light source appeared: the light emitting diode. At first it was only a side-product of the semiconductor revolution and found its niche applications in signaling or simple display systems in electronic devices. Their monochromatic light and low power was insufficient for any illumination purposes.

First LED optics

In these simple applications not much thought was spent on the secondary optics for these LEDs. The light distribution didn't matter much. So it was only natural to choose an already heavily utilized material in all electronic devices: plastics. The manufacturing tools for other parts were already present and the type of plastic easily exchanged to a transparent one like PMMA or polycarbonate. The mass production of these optical parts kept the prices low despite the usually high tooling costs of plastic manufacturing. This dominant role of plastic optics in LED applications survived to the present day. Although they nowadays are precision products with good surface accuracy the material still has its limitations.

Evolution towards illumination

As LEDs evolved from low-power signaling devices to high-power illumination light sources that they are today, the disadvantages of their plastic optics will become a limiting factor soon. The relatively low melting point of common plastics makes it susceptible to the strong heat produced by the increasingly powerful modules that can lead to deformations or worse. While this is somewhat manageable to a certain degree there are more, severe aspects to consider. Signaling lights and their optics are often placed in sealed environments and it's not really important if their optical properties degrade after some time as long as there's still some light. This is not true for illumination optics: long lifetimes and constant properties are required. Additionally harsher operating conditions are common, such as outdoor operation (street lighting, architectural lighting). In these environments the optics are exposed to UV light, chemicals and mechanical stress. All these pose challenges for plastics. Ultraviolet light makes plastics brittle and turn yellowish, simple cleaning often scratches the surface and it is easily affected by common chemicals. In summary plastic optics often have a low life expectancy in real-world applications.

Glass optics

Glass, on the other hand, is long known and valued for its resilience to tough environmental conditions. Operating temperatures of several hundred degrees Celsius, a high hardness and tolerance to most acids, bases and other chemicals ensure constant optical properties and brilliance over a long period of time. This makes it the perfect companion for long-lasting LEDs.

Despite high-grade optical glasses such as BK-7 other types of glass, like SUPRAX 8488, are available at a much lower price. The optical properties are similar to that of PC or PMMA in terms of index of refraction and bulk absorption. While the density of glass is almost twice as high compared to plastics it exhibits a low thermal expansion coefficient and high chemical resistance. Operation temperatures of up to 400°C allow its use even with the highest power LED modules. Its higher thermal conductivity than common plastics supports the cooling devices in transporting the heat away from the LEDs.

While imaging optics require highest precision that can only be achieved by repressing in illumination optics direct hot-forming is the standard manufacturing method. It delivers a high-quality surface and shape accuracy that commonly needs no additional processing steps, except milling or sawing. Generally lower tooling costs than in plastic manufacturing give an additional economic benefit.

Coatings, if necessary, can be applied by various methods that are suitable for mass production. The composition of the coating in combination with the low thermal expansion of the glass makes the coating efficient and durable.

Optical Design

The design process for LED optics is no different than for any other optical system. It starts with a detailed description of desired illumination properties, light source (ray-file) and geometrical and other constraints, e.g. color deviations. In a robust and fully non-sequential ray-tracing software the optical setup is implemented and the proper method for the particular problem selected. No ray-tracing software is an all-in-one solution for any optical element to be designed, especially not when it comes to free-form surfaces which are often found in LED optics. They only provide a solid foundation onto which the actual design software is tailored. For all the different kinds of optical elements, such as facetted reflectors or TIR (Total Internal Reflection) lenses, additional software must be developed and combined with the ray-tracer. If no analytical solution of a problem exists (e.g. for Fresnel lenses) the ray-tracer's optimization capabilities are of great value.

The final stage is the transformation of a constructed optical surface into a full 3D CAD model of the component. Verification of this model by importing it into the ray-tracing software is a crucial step and should always be done.

The range of LED optics made of glass spans from Fresnel lenses over TIR optics to reflectors, to name just a few. In the following a selection of such optics are presented.

Reflectors

A customer requested the development of LED reflectors for a down-light, designed as a direct replacement for common incandescent MR16 solutions. The requirements were very demanding: a set of four reflectors for different beam angles from 10° to 40° was to be designed with identical outer dimensions. It makes them easily exchangeable in the final system.

The resulting reflectors are shown in Figure 1. All of them have a free-form surface, specifically optimized for the intended optical properties. The facets ensure a good homogeneous light distribution and outstanding color mixing. A high-quality diachronic coating provides the necessary reflectivity (typically: 95 %) for a high system efficacy. The mounting is enabled by the directly pressed wings on both sides for a snap-in system. Tight tolerances ensure a proper alignment of the reflector with respect to the LED.

TIR Reflectors

TIR reflectors are a kind of hybrid optical element that are basically designed like the reflectors described before but don't use any coating. Instead the outer surface is beset with multiple prisms that light entering the interior surface of the reflectors fulfills the total internal reflection condition. They are very suitable for larger LED modules, such as the Zhaga book 3 (D = 25 mm) type modules. The multiple internal reflections have a positive effect on the color mixing and create a smooth light distribution. Although it is a bulk optical component absorption losses are only marginal and comparable to the coating losses of regular reflectors.

In addition to the benefits described above a particular advantage for lighting design is the small amount of upward light these optics exhibit. Most reflectors on the market are fully housed and direct all of the light downward leaving a completely dark ceiling. TIR reflectors, as they are aesthetically pleasing to look at, are regularly mounted without any housing and ensure a slight illumination of the ceiling.

Figure 1: **A set of four reflectors for different beam angles but identical outer dimensions and mounting clips**

Figure 2:
A TIR reflector specifically designed for Zhaga Book 3 LED modules

One such reflector that is designed specifically for Zhaga LEDs is depicted in Figure 2. It has a flexible design to adjust the beam angle by moving the module into the reflector.

Refractive Optics

Refractive optics are the most common type found today for LED applications. While their use is somewhat limited to smaller, low-lumen LED packages larger fixtures are often constructed of a multitude of smaller light points. The individual placement provides an additional degree of freedom to design the desired illumination profile but special care has to be taken to avoid glare by the small light points with a very high brightness.

Some typical examples of TIR optics are shown in Figure 3. These are single collimators for a specific LED, combined TIR lenses for a retro-fit application and Fresnel lenses. All of these are manufactured out of glass.

Summary

Today the majority of LED optics is made of plastics like PMMA or PC and date back to the origins of light emitting diodes with small power packages. Technological progress in LED manufacturing lead to a drastic increase not only in power rating but also in the efficacy of more than 3 orders of magnitude. Off-the-shelf products reach values of more than 100 lm/W and wattages of almost up to 100 W. This remarkable evolution is still in its early stages and the optical systems need to evolve alongside the LEDs themselves. Plastic has its limitations in dealing with the large amount of heat produced by today's modules. New application fields for illumination purposes, including harsh outdoor environments, pose additional hazards to the plastic optics, reducing its life-time considerably.

Optical components of glass have been the standard for almost all other illumination systems. Not only is it highly tolerant towards harsh environments but has a brilliant appearance and high perceived value. Contrary to plastics, which are manufactured from limited fossil resources, glass is made from natural non-toxic and abundant substances and is recyclable. All these advantages make it the optimal companion for today's (and future) high-power LED modules: long-lasting, efficient light sources with a highly efficient, aesthetic optic. ■

Figure 3:
A small selection of TIR collimators and Fresnel lenses commonly used for LED lighting