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Design and Simulation of LED-based Automotive Lighting Systems

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Abstract

Due to the development of High-Power-LEDs the application of monochromatic and white LEDs in the range of automotive lighting systems is state-of-the-art. The automotive industry is one of the most innovative markets and thus paves the way for this lighting technology. LEDs serve as light sources in tail lights and direction indicators, for example. They offer completely new possibilities for the optical designer. Consequently, the first automotive LED-headlamps are about to be launched this year.

This contribution describes the optical design of an LED-based automotive lamp by means of a practical example. The general approach, the consideration of the legal regulations, and the optical design will be elaborated. Special attention will be paid to the efficient light coupling from the LED into the optical device.

The development of LED-lamps is a complex interaction of different factors. First, European automotive lighting systems have to fulfill the specifications of the ECE regulations. Therefore, every type of lamp has to meet individual boundary values concerning, for example, the photometric quantities. Furthermore, new designs are increasingly governed by the customer's demand for the appearance of the final product. Additional design specifications emerge from the electrical and thermal layout of the LED-based lamp. Clearly, the task of the optical designer is to completely fulfill these demands.

1 Introduction

The technology of automotive lighting has undergone through substantial changes in recent years. Gas discharge lamps, for example, extended the features of front lighting systems. Currently, LEDs revolutionize the appearance of rear and front signal lights. The area of interior lighting experiences a trend towards new light sources as well [1]. The new illuminants are combined with new optical components such as light guides, pattern-free cover lenses or free-form reflectors. The challenge for the optical designer is to take advantage of these new design possibilities to improve the optical performance and to meet additional customer demands.

Many customers pay increasing attention to the daylight and nighttime appearance of the car. Especially the individual styling of signal lights guarantees a long term recognition factor. Consequently, the optical design of tail lamps is influenced by an increasing number of styling aspects, which contribute to the special character of the vehicle. Therefore car manufacturers are interested in a variety of night-time appearances.

LEDs are a good choice for automotive signalling lamps [3]. In the early 1990s they were first applied in Center High Mount Brake Lamps and they occur now in an increasing number of automotive signalling lamps. They operate with substantially lower power consumption than filament lamps, do not emit IR- or UV radiation, have a longer rating life, are vibration resistant, and permit considerably shallower packaging compared to most bulb-type assemblies.

This contribution is concerned with some aspects of the layout and the optical design of LED-based automotive lamps. The technique is demonstrated by a tail light example.

2 State of the Art

The ability to correctly estimate driving situations is essential to traffic participants. Information on vehicles and their movements are visualized by their signal and marking lamps. In order to ensure a reliable recognition of every single signal function they differ in colour, distribution, and in the permissible values of luminous intensity. In general, directional changes are indicated by brighter signals compared to signals for position and orientation. For reasons of standardization all exterior automotive lighting and signalling devices must comply with legal regulations, which stipulate minimum and maximum permissible intensity levels and horizontal and vertical angles of visibility. To recognize a signal, the emitting area should have a minimum size. The ECE regulations, for example, demand an emitting area of at least 40 cm^2 for daytime running lamps.

Conventional car signal lamps consist of at least three assembly groups. The bulb holder provides the position of the light source, the housing contains the reflectors and the cover glass usually creates the final light distribution. Other concepts are implemented by modern lamps, which use adequate optical components such as reflector optics, intermediate lenses, or light guides.

The application of LEDs in automotive lamps leads to innovative and highly efficient optical systems. Within classical designs, these comprise standard refractive or reflective optical components. Furthermore, light guide optics based on total internal reflection are used. They offer great opportunities to the optical designer. Their application to exterior lamps can significantly enhance the styling factor. For example, light guides can be used to build very long and thin lamps. They are a key component for ambient interior lighting as well.

Light guides are well-suited to generate a uniform light distribution. This is an important feature concerning the appearance of the lamp. Among other aspects this depends on the radiation pattern of the LED, the geometry of the optical surfaces, and the materials used.

Car manufacturers take three great advantages of using lamps with reduced depth compared to classical reflector designs. The first one is weight reduction, the second one is a higher usable volume inside the car, but the most significant one is cost reduction in the manufacturing of the car body. It is a simple fact that deep-drawing of the sheet metal is much more competitive and faster than cutting a hole in the body, and then rebuilding and connecting the deeper lying metal sheet surface onto the outer body afterwards [1].

Due to these facts the demand for thin lamps, whose mounting depth is measured in millimeters instead of centimeters, gave the initial impulse for the development. Thin LED lamps offer new design freedom to car manufacturers, but the development of flat optical systems is a challenge.

A signal lamp has to emit a specific colour. In conventional signal lamps these colours are generated by patterned lenses of the required colour which act as colour filters. The application of narrow banded, quasi monochromatic LEDs of the desired colour redundantises colour filters. So, it is also possible to use clear cover lenses without any colour filter elements.

3 Design Stages

In general, the design of an automotive lamp is determined by the light source, the technical requirements for the signal function as prescribed by regulations, the customer´s specific requirements regarding mechanical strength, air-tightness, resistance to surrounding pollution, the materials available, and the customer´s specifics on styling requirements [1].

The desired lamp shall combine the functions of a brake light and a tail light. By dimming the LEDs this is easy to realize within one optical component. An assembly of four red 1 Watt LEDs with nearly lambertian radiation patterns serves as light source. The emitted light flux of one LED is assumed to be 25 lm, so the whole emitted light flux results to 100 lm. The emitting area of the lamp is rectangular and its dimensions are 8 cm x 8 cm. Clear PMMA is chosen as light guide material. The thickness of the lamp shall be as small as possible.

With regard to the light distribution, the legal regulations demand two main aspects: first, the luminous intensity distribution itself with minimum and maximum permissible levels; and second, the visibility of the lamp at all relevant angles. In the case of a conventional tail light with filament bulbs, the visibility point is mostly satisfied just by the three-dimensional shape of the light exit surface. However, flat lamps possess quasi two-dimensional surfaces, so one has to take simultaneously both aspects into account.

The regulation ECE R 50 stipulates the minimum values of the luminous intensity for motorcycle brake and tail lights. Table 1 and 2 show the minimum values of the luminous intensity that are required by the regulation ECE R 50 for a motorcycle brake and tail light.

	-20°	**-15°**	**-10°**	**-5°**	**0°**	**5°**	**10°**	**15°**	**20°**
10°				8		8			
5°	4		8		28		8		4
0°			14	36	40	36	14		
-5°	4		8		28		8		4
-10°				8		8			

Table 1: Stipulated horizontal and vertical minimum values in candela for the brake light function

	-20°	**-15°**	**-10°**	**-5°**	**0°**	**5°**	**10°**	**15°**	**20°**
10°				0.8		0.8			
5°	0.4		0.8		2.8		0.8		0.4
0°			1.4	3.6	4	3.6	1.4		
-5°	0.4		0.8		2.8		0.8		0.4
-10°				0.8		0.8			

Table 2: Stipulated horizontal and vertical minimum values in candela for the tail light function

To avoid dazzling of the following driver the maximum values are 12 candela for the tail and 185 candela for the brake light function. It is not necessary to exactly obtain the above distributions. In the case of a brake light, a homogeneous light distribution with a value of, for example, 50 candela in the whole area would also satisfy this requirement. Unfortunately, today's LED's light flux is too low for such a simple approach. Consequently, the design goal is to reach the minimum values of the distribution by redirecting the emitted light in the most efficient way.

3.1 Efficient LED Coupling

The first step is to collect the emitted light from the LEDs. This step is essential for two reasons:

First, the overall efficiency of the whole system depends on the single efficiencies of all components, which influence it multiplicatively. So the coupling optic should collect light from a solid angle as big as possible.

Second, the quality of the beam emitted from the coupling optic (CO) into the optical system influences the possibilities and the complexity of the technical solution, which shapes the desired light distribution.

We propose a coupling optic with reflective and refractive components in one solid element with small dimensions. The design is best understood by considering a point source. In the first step we place the source into the focus of a parabolic mirror. Reflected rays are collimated, but rays at lower angles diverge. To collimate these rays as well an aspheric lens with focal plane is added in the position of the source. This lens forms the end of an air tube with the source inside. So the whole beam from the source is divided into two parts, which are collimated separately by different components. All components can be combined in a solid element, thus the total internal reflection works at the parabolic surface. Within the restrictions of a point source there is no geometrical loss of light. Figure 1 shows the light path through the coupling optic starting from a point source.

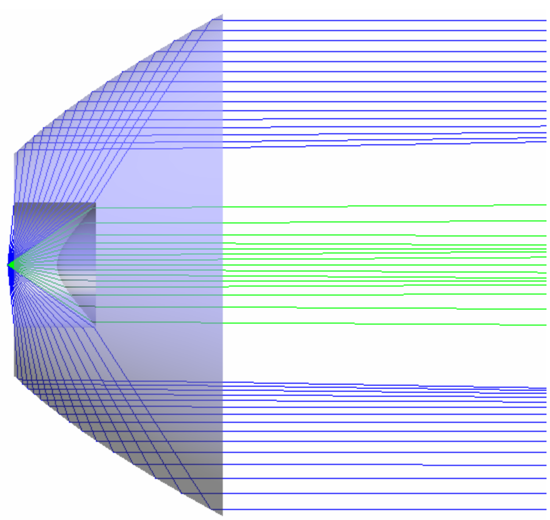

Figure 1: Coupling optic with point source

Approximately, this construction even meets the properties of an extended source. The emitted beam still has collimated chief rays; due to the finite source dimensions, however, the beam cannot be perfectly collimated.

3.2 Beam Forming Elements

For attaining a low mounting depth the LED-TIR-assembly is well-suited [4]. In our design example we use two groups of optical components to shape the beam.

First, a thin light guide similar to a plate made from PMMA is used to collect the light from the source. Three sides of this body are metallized. The side facing the LEDs and the output side, hereinafter called front side, are transparent.

The bottom side, hereinafter called back side, is no longer a plane surface but built from reflecting segments. They are the second group of the beam forming elements. Figure 2 shows the functional principle.

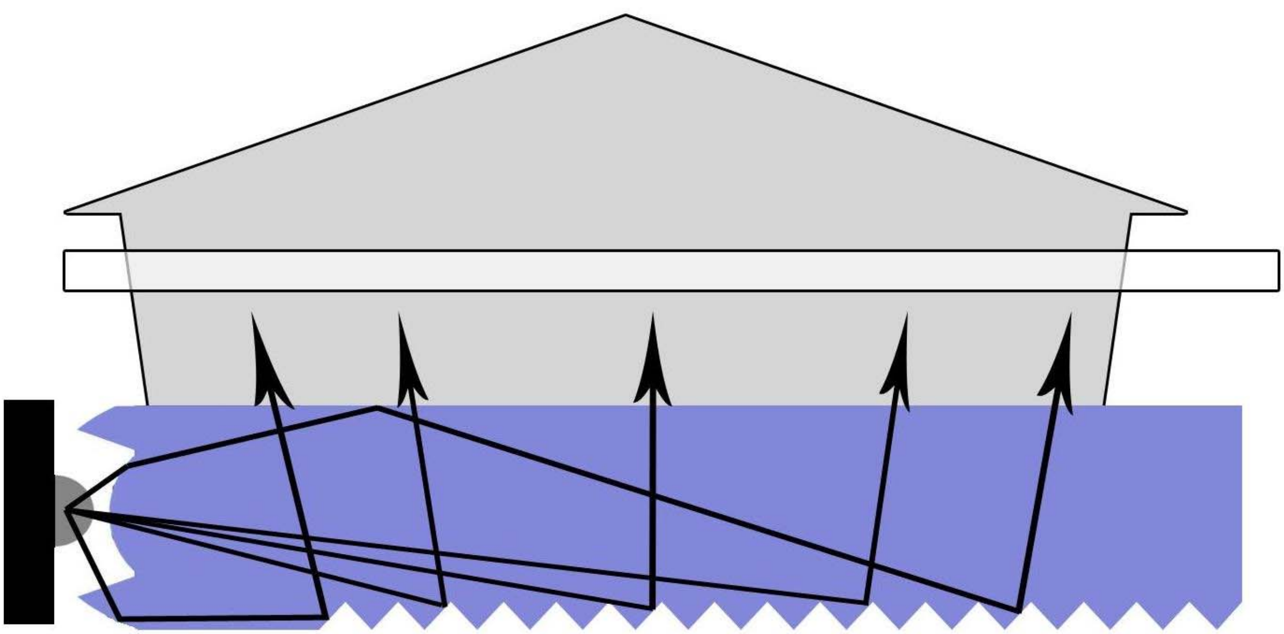

Figure 2: Functional principle and light path

All emitted light from the LEDs is coupled in from one side. The segmented mirror surfaces on the back side reflect the light to the front side where it is refracted. Thus, there are three stages to form the desired output light distribution body (LDB) from the LED´s one.

$$(LDB_{LED}) \rightarrow (LDB_{CO}) \rightarrow (LDB_{backside}) \rightarrow (LDB_{out\text{-}coupled})$$

The reshaping of one LDB into the next depends on the slope and curvature of the optical surfaces. The CO transforms the LDB_{LED} into the LDB_{CO}. The beam coming from the CO can be considered as an intermediate source with increased area and a LDB with decreased angles compared to the LED itself. Now the light hits the segments on the backside. The segments redirect the light to the front side of the device and create $LDB_{backside}$.

The number of segments is chosen to meet the customer´s demands for a homogeneous light distribution at the front side.

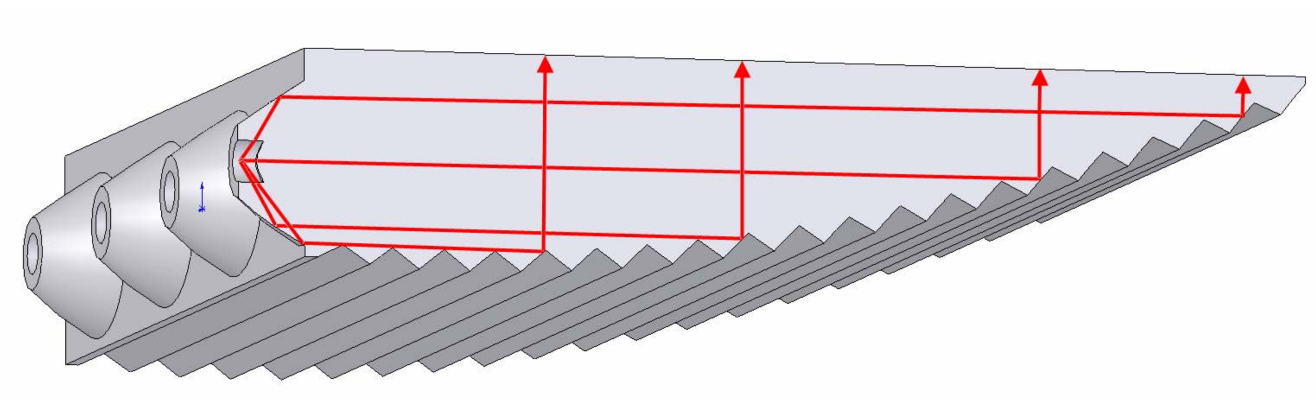

Figure 4: Sectional view of Design 1 with rotational symmetric TIR-CO and flat shaped segments

The position and the width of the segments both influence the quantity of light reflected by the segment. This results in a homogeneous distribution.

The shape of the segments mainly influences the intensity distribution of the outcoupled beam. Their shape (in an exaggerated view) is shown in figure 5.

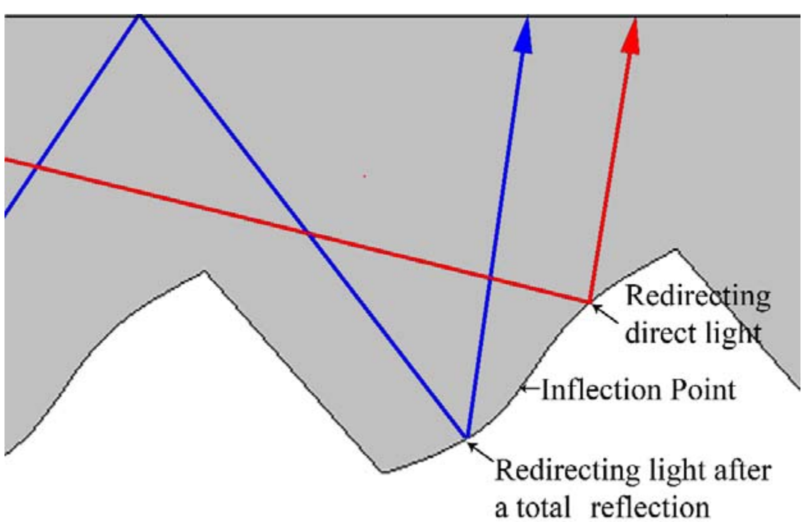

Figure 5: Principle of the backside shaping (see Design 2 and 3)

The part on the right side of the inflection point in figure 5 is used to redirect the light, coming straight from the CO. The part on the left has a different shape adapted to light that comes from the front side after one total internal reflection. Both shapes are designed separately for each of the 20 segments to create the desired divergence angle of the light.

The segment's shape perpendicular to the drawing plane is chosen to create the horizontal divergence angle. Each segment is divided into four parts to meet the geometrical demands of four LEDs. Automatic design is used to adjust the parameters of the segments for an optimized solution.

Figure 6 shows the overall view of the reflecting segments.

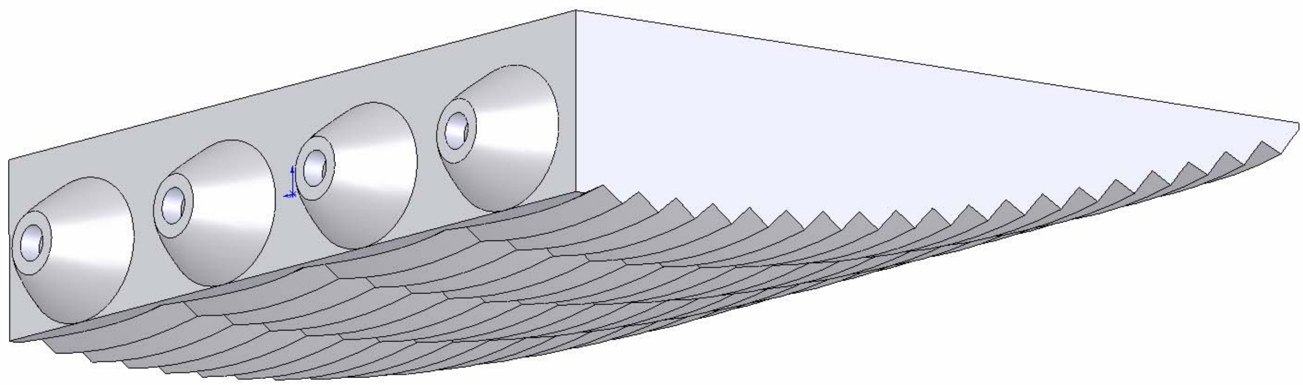

Figure 6: Design with four backside segments with parabolic shape (see Design 2)

The impact of the segments can also be understood in the following way, as well. They cut the incoming beam into parts, which are then combined to form an illuminated output area. The segments obviously enhance the size of the luminous area. If we consider this area as an intermediate source, its increased size results in a reduced luminance. This reduction is substantial because the etendue at the front side is much larger than the etendue at the LED-chip. Finally, the front side does not influence the proportions of the LDB because of its flat surface.

4 Results

In an earlier work we examined different concepts of light coupling into the specified tail lamp design [4]. The TIR-coupling technique, where the thickness of the PMMA-Plate can be reduced down to 9 mm by applying TIR-CO, is the most promising concept. That is the reason why it is elaborated in detail here. We show the options associated with this concept by giving three design examples.

Design 1: Rotational symmetric TIR-CO,
Segments with a plane shape perpendicular to the drawing plane (see Fig. 4),
Optimized with regard to the position, width and parabolic shape of each backside segment by considering light straight from the CO

Design 2: Asymmetric TIR-CO with an aspect ratio (horizontal diameter/vertical diameter) of 1.2/1.0,
Optimized with regard to the position, width and parabolic shape of each backside segment by considering light straight from the CO and light after one total internal reflection at the front side,
Divided backside into four segments with a parabolic shape in each division perpendicular to the drawing plane (see Fig. 5)

Design 3: Similar to Design 2, but with different shapes of the segments in both directions compared to Design 2 (see Fig. 5)

Design 2 and 3 operate with the same functional principle but with different shapes of the four segments perpendicular to the drawing plane. So, these two designs clarify the range with regard to the horizontal distribution and the values of the luminous intensity.

4.1 Homogeneous Luminance at the Front Side

Figure 7 shows spot diagrams of the three designs at the front side of the lamp. The spot density can be understood as proportional to the illuminance values or, alternatively, as luminance values integrated over the half sphere.

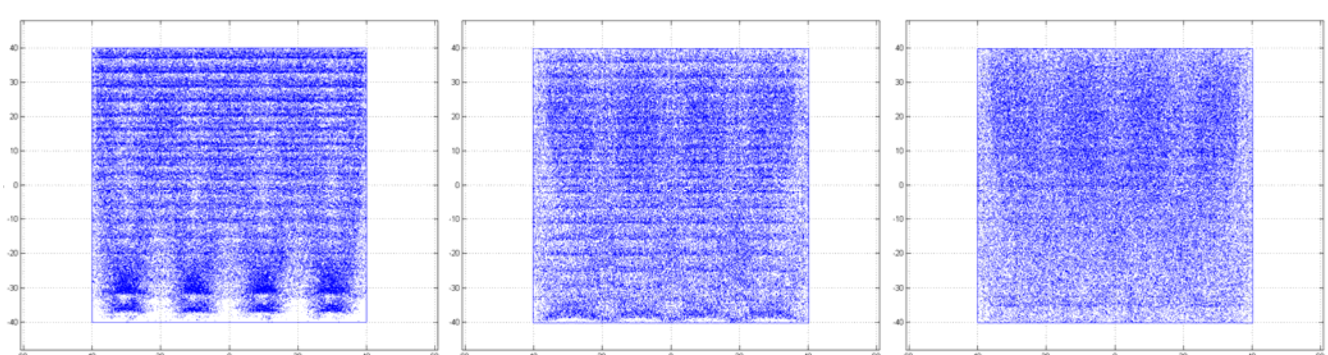

Figure 7: Spot diagrams of the front sides of the Designs 1, 2 and 3

The inhomogeneities near the sources (left picture) result from the rotational symmetric TIR-optic. They vanish with the asymmetric TIR-optic as shown in the two other pictures. On the other hand, Design 1 and 2 use similar segment shapes which cause some inhomogeneities (ripples) in the distributions. Design 3 (right picture) uses segments with increased curvature to overcome this.

4.2 Light Distribution Bodies and Luminous Intensity

It is quite interesting to have a look at the transformation of one LDB into the next one. Figure 8 shows the change of the LDB along the light path exemplified by Design 2, starting with the Lambertian light source, turning into the intermediate source produced by the CO, and finally the out-coupled LDB which leaves the lamp through the front side.

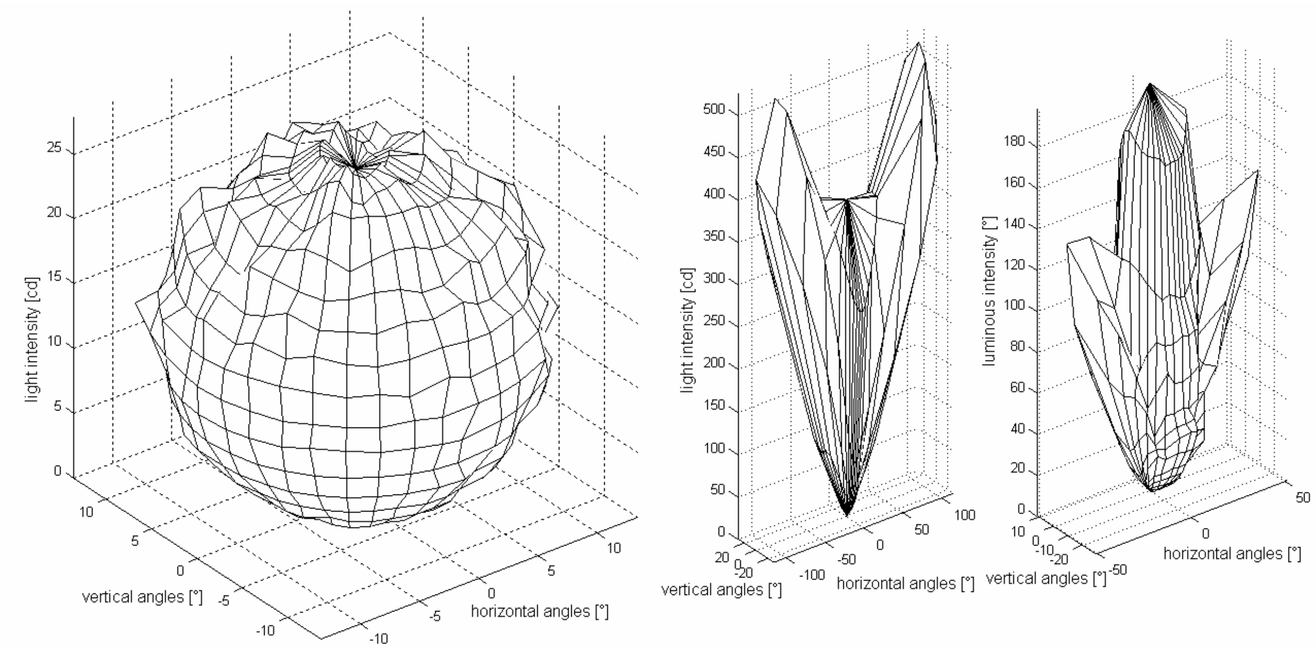

Figure 8: Transformation of the LDB (Design 2), LDB_{LED}, LDB_{CO}, $LDB_{out\text{-}coupled}$

As it can be seen in figure 9, the maximum luminous intensity values of the three designs differ very strongly. Compared with figure 7, they obviously correlate with the homogeneity of the luminance at the front side. The higher the luminous intensity values are, the more inhomogeneous the luminance results and vice versa.

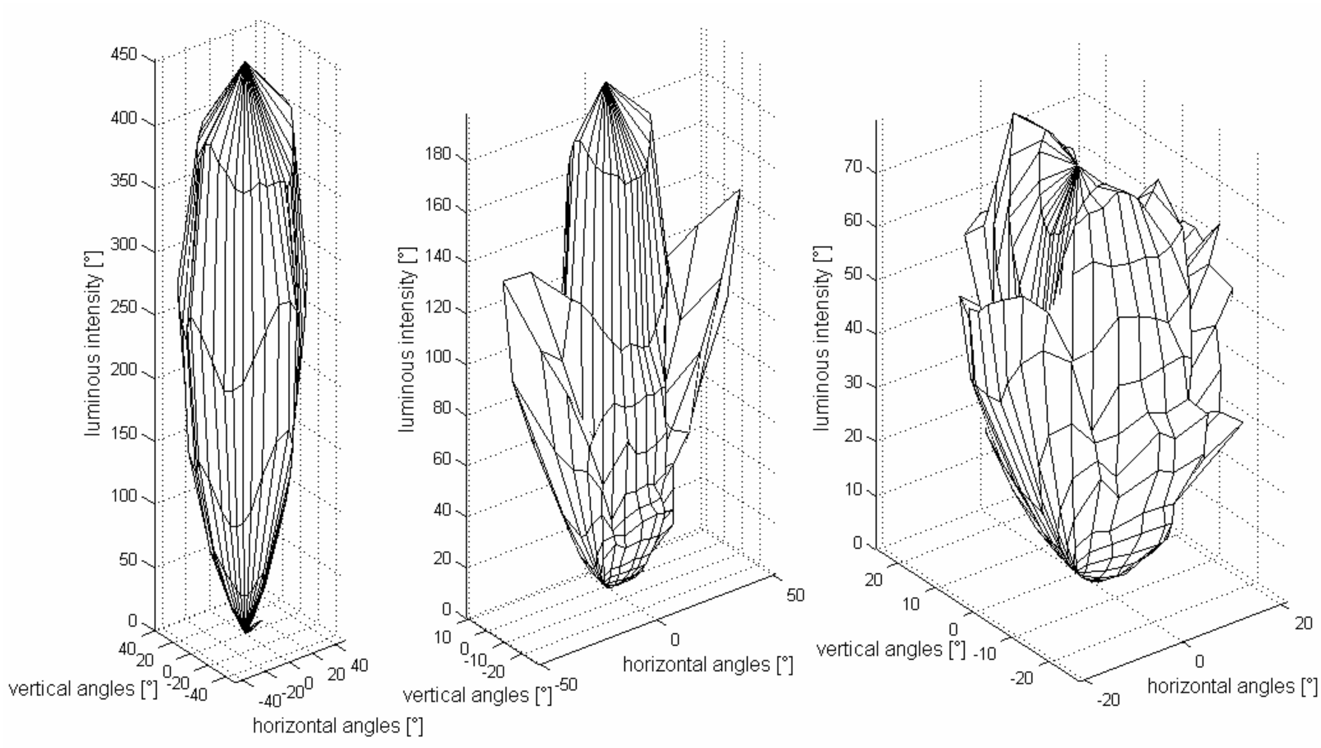

Figure 9: Comparison of $LDB_{out\ coupled}$ of the Designs 1, 2 and 3

4.3 Conformity with the ECE Regulation

The beam forming elements are designed to meet the minimum values of the ECE regulations. These values correspond to directions with angles between +/- 10° vertical and +/- 20° horizontal, measured perpendicular to the front side. Tables 3 to 5 show the simulated values in the demanded range of spatial angles. All three designs fulfill the requirements for a motorcycle brake light. Obviously, the LEDs in Design 1 have to be dimmed. Elsewise it would violate the dazzling demand not to exceed 185 candela in the optical principal axis.

	-20°	**-15°**	**-10°**	**-5°**	**0°**	**5°**	**10°**	**15°**	**20°**
10°	48	92	141	206	221	203	152	89	46
5°	58	117	206	325	393	327	212	124	58
0°	70	145	273	400	456	403	278	152	70
-5°	48	96	194	293	365	306	194	100	48
-10°	27	60	123	225	286	216	120	61	28

Table 3: Simulated horizontal and vertical values in candela of Design 1

	-20°	-15°	-10°	-5°	0°	5°	10°	15°	20°
10°	10	7	28	42	42	42	28	6	11
5°	61	38	51	110	118	109	50	38	61
0°	98	107	93	160	176	171	94	103	99
-5°	133	103	85	130	143	129	81	101	131
-10°	89	72	66	93	91	90	68	72	87

Table 4: Simulated horizontal and vertical values in candela of Design 2

	-20°	-15°	-10°	-5°	0°	5°	10°	15°	20°
10°	40	31	35	64	70	66	30	27	38
5°	46	39	37	63	68	65	34	35	45
0°	51	41	39	61	66	61	40	42	49
-5°	53	43	40	55	61	56	41	42	56
-10°	54	43	41	55	58	56	44	45	53

Table 5: Simulated horizontal and vertical values in candela of Design 3

Additionally, the ECE regulations demand minimum values to ensure the visibility of the vehicle. For the tail light function it is in detail 0.05 candela in the range +/- 80° horizontal and +15°/-10° vertical. For the brake light function a value of 0.3 candela is demanded in the range +/- 45° horizontal and +15°/-10° vertical.

The presented designs simultaneously fulfill both demands by light reflections from intermediate surfaces between the segments. The following figure shows the luminous intensity diagram of Design 3 in the horizontal plane at the vertical angle 0°. For better understanding all values larger than 0.3 candela are cut off.

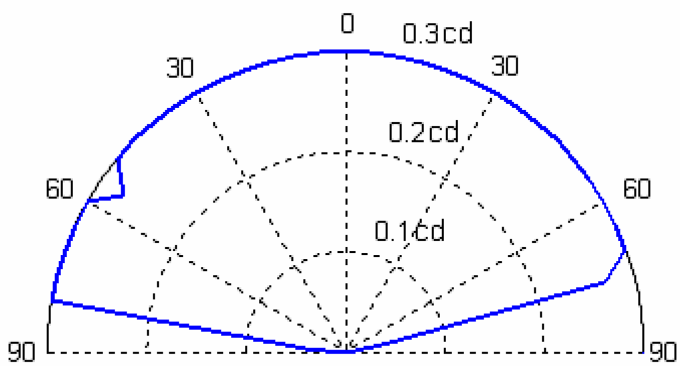

Figure 10: Luminous intensity of Design 3 in the horizontal plane

5 Conclusions and Outlook

LEDs offer new possibilities in automotive lighting. LED driven tail lamps with light guides can be designed as thin lamps with different aspect ratios, even “three dimensional”, thus complying with modern styling demands. They simultaneously fulfill the regulations for a tail light and a brake light. A TIR-based coupling optic offers a good quality of the emitted light and thus easily allows beam forming which meets the regulations and the customer’s demands. Automatic design helps to get a first design and to align it with the specifications.

A similar technical approach can be used to design tail lamps with non-rectangular front surfaces. Furthermore, the beam forming elements are powerful tools to shape the light distribution body to meet the demands of other automotive lamps.

6 References:

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