Diffractive Optics in automotive Headlamps – thermal Effects and optical System Design

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Diffractive optical elements can be used for the design of light distributions and for the correction of thermal and dispersion effects. Therefore the ray tracing methods are modified by using a probability distribution to simulate diffraction by ray tracing methods. Because of the integration of thermal effects, this is based on the height profile in case of the eikonal equation and the diffraction efficiency.

1 Introduction

Semiconductor-based light sources in combination with the possibilities of polymers as optical materials enable new headlamp designs. That started with matrix systems and now is dealing with the development of high resolution systems. There is an increasing freedom of designing light distributions, but in contrast the number of optical elements is increasing too. Thus there is an increasing influence of the material properties like dispersion because of more superposition effects. Furthermore the thermal expansion is no longer negligible.

Diffractive optical elements can compensate thermal and dispersion effects. Hybrid lenses are still known for thermal or chromatic correction [1] and can be used for reducing colour fringes of cut-off lines. But the design is based on ideal light sources and the simulation of diffractive optical elements is not directly usable for headlamp design.

In this paper, the modifications of ray tracing algorithms to simulate optical phase elements by using the diffraction efficiency in ray tracing including the thermal behaviour of diffractive optics are introduced.

2 Simulation of diffractive elements

In contrast to ray tracing methods of geometrical optics, the simulation of diffractive elements is based on field tracing [2]. Dependent on the dimensions of the structure, either waves or rigorous approaches are used for. Whereas the ray tracing simplified a multi-dimensional problem to a one-dimensional one by tracing the rays through the system successively, field tracing has to propagate the whole field through the system at once. That impacts that the multi-dimensional problem cannot be simplified to a one-dimensional one, which depends on the formula of Kirchhoff [3]:

$$E_P \sim \frac{E_0}{j\lambda} \cdot \oiint_{Apertur} \frac{e^{jk(\vec{r}+\vec{R})}}{\vec{r}\vec{R}} \cdot \frac{cos(\vec{n},\vec{R}) - cos(\vec{n},\vec{r})}{\vec{R}} dS \quad (1)$$

Equation 1 is the basic formula of the scalar diffraction theory for calculating the electro-magnetic field consisting of amplitude and phase in the target area. Diffraction means the superposition of all elementary waves to get the diffraction pattern. The resulting light distribution can only be simulated by integrating the whole aperture area. For getting the numerical solution, the field plane is sampled. The sampling distance has to be small enough to resolve the structure of the optical surfaces, e.g. 1 µm if the structure size is about 3-5 µm. In this context, the numerical effort is increasing dramatically by decreasing the structure size of the optical element or by increasing the size of the field.

The schematically diagram of the refractive and diffractive design and simulation parameters is shown in figure 1. Normally, ideal light sources are

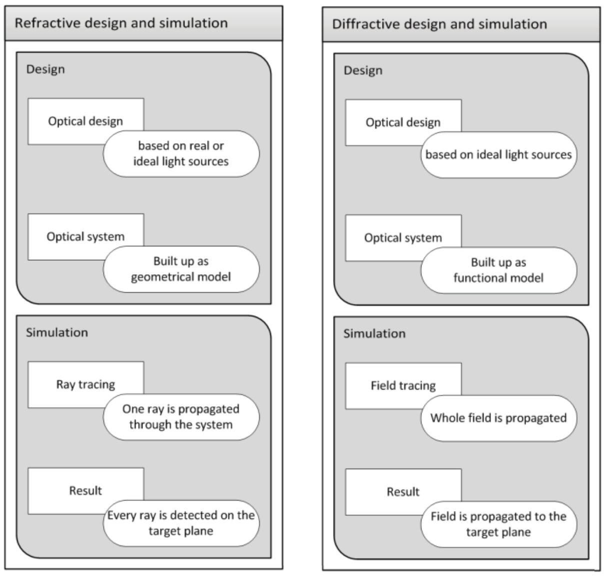

Figure 1: Schematic diagram of refractive and diffractive design and simulation

used for the diffractive simulation and impacts plane or spherical waves [4]. The field has to propagate to the first optical element by considering the physical behaviour. These propagation formulas take the resulting distribution in account, for example Fresnel (near field) or Fraunhofer (far field) diffraction.

3 Simulation of diffractive optics by ray tracing

The simulation of DOEs in headlamp systems has to be done by ray tracing because all other parts of the systems are modelled for refractive optics. Therefore it is not very useful to model all elements with wave optics attributes. In this context, the ray tracing has to be modified.
The DOEs that fulfil the function as mentioned in chapter 1 are phase elements whereby the amplitude is set as constant. That's why it is possible to divide the diffractive behaviour into two parts. On the one hand the wave propagation and on the other hand the diffraction effects.
Ray tracing theory is based on the assumption that the addition of all elementary waves can be approximated by one resulting wave. It is assumed that every incident ray is representing one spherical wave that starts at the light sources surface. That's why the light distribution can be approximated by one point light source per ray that is propagating in its direction. The direction of propagation can be calculated by the first derivation of the elements phase function, also called eikonal equation, which leads directly to the normal direction of the wave front. This principle is a physically correct calculation of the direction of propagation and therefore the first part for the simulation of diffractive optical elements.
For taking diffraction effects as second part into consideration, the diffraction orders will be used for. Primary, gratings and diffractive lenses are considered. The formulas of the linear grating approximation as well as the Fresnel lens include the design diffraction order and the actual diffraction order. That means that it can be easily calculated, which diffraction order in which direction deviates in the case of far field approximation. The energy density distribution of the diffraction orders is represented by the diffraction efficiency distribution. This means that for every ray a random diffraction order based on the probability function defined by the diffraction efficiencies is chosen. The more rays the more realistically results are simulated.
This case is utilized during the simulation process. First of all, the refractive and the diffractive refractions can be added to get the refraction by the optical surface. The refractive deviation vector is calculated by the vectorial refractive law that is dealing with the normal vector of the surfaces profile and the direction vector of the incident ray referring to the surfaces profile. If height profile and diffraction order are known, the deviation vector by the diffractive structure can be calculated. Therefore the diffraction efficiency distribution is calculated and normalized to 1 and thus represents a probably density distribution. Now, with a uniform random number between 0 and 1, the diffraction order depending on the diffraction efficiencies is chosen in which the ray is deviated. This process is done for every ray so that for a sufficient number of simulated rays the result still approximates the reality sufficiently.
It is important to mention that the validity of the simulation depends on the number of rays that are calculated and this again is depending on the number of diffraction orders and the number of wavelength that are simulated.

4 Integration of thermal effects

Thermal effects cannot be negligible because of the temperature range of -40°C…120°C. Furthermore the task of the simulation is the verification of legal requirements. That's why the normally used ideal formulas of thermal expansion have to be replaced by the results of a finite element approximation. This means the calculated displacement of sampling points of a sampled surface by considering boundary conditions like the behaviour of the substrate and surrounding elements of the headlamp system like mounts or brackets.
This enables the optical simulation of the headlamp system for the whole temperature range. The reason for that are the resulting parameters of the mechanical expansion by thermal dependencies. These resulting parameters can be transformed into a new height profile and therefore be integrated in the simulation process as introduced in chapter 3.

References

[1] Londono, C.: “Design and fabrication of surface relief diffractive optical elements, or kinoforms, with examples for optical athermalization”, dissertation,1992

[2] Wyrowski, F. and Schimmel, H.: „Elektromagnetisches Optikrechnen“, Sonderdruck Photonik, 6/2006

[3] Born, M. and Wolf, E.: “Principles of Optics”, 7th edition, Cambridge University Press, New York, 2002

[4] O'Shea, D. et al.: “Diffractive Optics - Design, Fabrication, and Test”, Bellingham: Spie Press, 2004