Optical Design and Simulation

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Application of complex surfaces in modern optical design

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There is a rapidly growing interest in the employment of complex surfaces within optical systems. Examples of such surfaces are diffractive surfaces, facetted surfaces and freeform surfaces. Consequently modern optical design must sharpen its tools in order to properly handle these surfaces during modelling and optimization, and also to keep track with technological developments in the fabrication and testing of such surfaces:

For example recent lithographic technologies allow for the fabrication of high period diffractive structures on planar and curved optical surfaces with high precision. Such diffractive surfaces offer the optical designer extra degrees of freedom, which are of special importance for optical systems, where light collection efficiency is important [1]. In Fig. 1 we illustrate an eyepiece design, which could considerably be improved by a diffractive surface on the backside of a curved lens. For these hybrid design classes it is mandatory to include the realistic as-built performance of the employed diffractive elements into the design phase [2]. Correspondingly, we at the ITO, develop simulation techniques to include fabrication specific diffraction efficiencies and stray light into the optimization and evaluation process.

Stray-light and fabrication issues are also crucial for another class of complex surfaces, which are mainly used in illumination design: Fresnel surfaces. Figure 2 shows a design study of a solar concentrator optics for high efficient solar cells. A Fresnel lens is used as a primary element in order to concentrate the light into the secondary optics. The design of such Fresnel optics is mainly limited by the fabrication process, the achievable efficiency and maximum period of the element.

This illumination example also introduces the third class of complex surfaces, which is of rapidly growing interest: The secondary optics in Fig. 2 can be a freeform optical element. Freeform surfaces are today discussed and employed in various kinds of illumination and imaging optical systems. In conse-
quence methods for the design, the surface description and the fabrication and testing of such components need to be developed, as illustrated in Fig. 3.

At the ITO research is currently performed and planned in all three areas: During design the main problem is to be in control of the many degrees of freedom during optimization. A proper surface description is required in order to allow for an efficient optimization and an exact fabrication. Fabrication of freeform surfaces however is only possible if an adequate testing is available.

Fig. 3: Illustration of the interdependence of freeform optical surfaces to the design, surface description and fabrication.

References:
Phase space methods in geometrical optics

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In optical design especially in illumination design, the transport of radiance through the system is important. Typically used components in illumination design affect the spatial as well as the angular distribution. Therefore it is reasonable to use a description where angle and position can be illustrated simultaneously. The phase space concept provides an interesting access towards the radiometric quantities. Within an optical system a single ray is defined by its position and angle in space. Therefore every single ray propagating through the system can be associated with a point in phase space. Thus ray-tracing corresponds to a trajectory in phase space [1].

A light source occupies a certain angular and spatial extend which is a 4 dimensional volume in phase space called etendue. The flux per etendue is the radiance distribution \( L(x,u) \) as depicted in Fig. 1. The projection of the radiance to the angular or the spatial axis in phase space allows the calculation of the intensity \( I(u) \) and the irradiance \( E(x) \).

An analysis of the phase space transformation introduced by optical components provides an entire picture of the optical functionality. Paraxial free propagation corresponds to a shear of the phase space whereas propagation from the front to the back focal plane of a thin lens causes a rotation by 90 degree. Reflection on surfaces leads to a back-folded and mirrored distribution in phase space.

Integrator rods and double arrays are commonly used components in illumination design. Therefore it is of special interest to investigate these elements within the phase space picture [2].

Integrator rods mix the incoming light distribution resulting in a homogenization of the irradiance at the exit of the rod. The incoming light is reflected at the sidewalls of the rod leading to a segmentation of the phase space distribution Fig. 2c).

Optical arrays separate the incoming light in channels due to the apertures of the micro-lens. Different channels are superimposed at the target plane. Fig. 3 shows the phase space distribution at the target plane after a double array and an integrator lens. The effect is similar to the rod a homogenization in position and segmentation in angle.

The analysis of illumination components in phase space offers another access besides classical ray-tracing.

Fig. 1: Phase space illustration of the radiance \( L(x,u) \), intensity \( I(u) \) and irradiance \( E(x) \).

Fig. 2: a) Initial distribution at the entrance of a rectangular integrator rod. b) Distribution after free propagation of the length of the rod. c) Final distribution at the exit of the rod.

Fig. 3: Phase space distribution after propagation through a double array and an integrator lens, leading to a constant irradiance \( E(x) \) und a discrete intensity \( I(u) \).

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Hybrid endoscopic zoom system with integrated tomographic sensor

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As a part of the Baden-Württemberg Stiftung project “Hybride optische Technologien für die Sensorik”, this work aims at the development of a miniaturized zoom system which combines both, imaging and tomography. In this joint research project our project partner IMTEK (University of Freiburg) is improving and developing microoptical components, while the work at the ITO is focused onto the optical system design.

Extensive research effort has been put on the development of miniaturized active optical elements, such as tunable membrane lenses or micromirrors. The current technology allows the construction of small integrated active optical systems based on a modular approach (Fig. 1) [1]. As a more complex device, the conceived hybrid sensor system requires a sophisticated and well balanced optical design.

Figure 2 shows the latest concept with a system diameter of below 2 mm. It comprises two membrane lenses, which can be tuned independently in radius of curvature by applying an external fluid pressure. This enables zooming and focusing without mechanical parts at a high level of integration. Additionally to the imaging beam path which creates an image on the CMOS sensor chip, the system contains a second beam path for optical coherence tomography (OCT). A MEMS scanning mirror in side-looking configuration enables a laterally resolved OCT signal as well as an extension of field of view for the imaging part. Additional components such as diffractive optical elements (DOE’s) or aspheres can compensate for static aberrations.

In order to narrow down the parameter space, the concept has been modelled paraxially as well as within a raytracing software. Realistic lens profiles, obtained by finite element simulations and tactile measurements have been implemented (Fig. 3). The setup allows a systematic investigation with an automatic optimization in terms of the two lens pressures. Different parameters, such as wavefront errors or vignetting factors can be plotted as a function of working distance and magnification, allowing an evaluation of the expectable optical performance. Due to small numerical apertures given by the system, diffraction is limiting the achievable imaging resolution to ~2 µm. This is sufficient to resolve the most relevant features in common endoscopy inspections.

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