1. INTRODUCTION

Diffractive optical elements (DOEs) offer many very interesting design approaches that can be realised due to continuous improvements in various fabrication technologies. Computer aided design and modern fabrication methods give access to optical functions which are often not realisable by one single conventional bulk optical element. Their planarity allows low cost replication in plastic material using techniques such as hot embossing or injection moulding. This offers the possibility of their integration in opto-mechanical devices to reduce assembly costs. DOEs show a chromatic and thermal behaviour which can be used for chromatic or thermal aberration correction in hybrid elements. For broad band or white light applications, their strong chromatic dispersion is usually not wanted, but in many applications, using monochromatic laser light, it is of no importance.

Typical fabrication tolerances of DOEs mainly reduce the diffraction efficiency and lead to stray light. However, the wavefront quality in the image plane can be guaranteed with high accuracy for many applications. Nevertheless, the influence of stray light and efficiency reduction needs to be investigated carefully for each specific case.

In the following, we discuss some of the principal limitations and tolerances occurring in the process of the design and fabrication of planar optical elements and their influence on optical performance, especially on the diffraction efficiency. We concentrate on continuous relief structures, fabricated by direct laser writing into photoresist and subsequent replication in plastic material. Many of the following considerations can easily be transferred to other fabrication techniques.

2. DESIGN OF PLANAR OPTICAL ELEMENTS

A surface relief is computed which transforms an incoming wave into a desired transmitted or reflected output wave. This is done by calculating the phase function of the
DOE by analytical, ray tracing or iterative methods and subsequent conversion of that phase function into a surface profile.

If the phase function has an amplitude of many multiples of 2\pi, the phase function can be wrapped into intervals between 0 and M \times 2\pi, where the integer number M is the so-called phase-matching number. This procedure maintains the planarity of the element and leads to a discontinuous surface relief, consisting of individual segments. The choice of the phase-matching number is a degree of freedom which can be used to optimise the performance of the DOE under non-ideal, real conditions. In order to fulfil the phase-matching condition, only the height of the phase steps has to be an integer multiple of 2\pi; the position of the phase steps can be chosen arbitrarily, as is indicated in Fig. 1c. This is an additional degree of freedom in wrapping the phase function.

DOE performance is based on diffraction at the grating given by the position of the phase transitions. This lateral pattern can be fabricated by today's microfabrication methods with high accuracy. The continuous relief of the microstructure (blaze) distributes the light among the various diffraction orders. Usually it is the aim to concentrate all the light in one single order, the phase-matching order.

By using the phase-matching order M in the coding process as a design freedom, the number of segments of a DOE can be decreased by increasing the phase-matching order. For micro-optical elements, the phase variation over the aperture \(a\) is often an order of a few multiples of 2\pi, so the Fresnel number \(N = a^2 / (\lambda \cdot f)\) is therefore low. In this case the number of segments might be decreased to one by increasing M, leading to a lenslet without phase transitions, as shown in Fig. 2. The optical performance under the exact design conditions is nearly identical for the different surface profiles shown in Fig. 2. However real lenses are always operated at conditions which do not exactly match the design conditions. A lens with phase transitions ('diffractive lens') and a lens without phase transitions ('refractive lens') will show differences in their optical performance. In the case of development errors the refractive lens will shift its focal position, whereas the focal length of the diffractive lens will stay stable, but additional, unwanted foci appear. Often, in the first case, it is the wavefront quality in the far field which is affected by fabrication tolerances whereas in the case of diffractive lenses, the straylight increases. The use of direct laser writing into photoresist now allows the realisation all the cases of surface reliefs shown in Fig. 2. Depending on the application's demand, one or the other design will be chosen. It is interesting to note, that even in the case of two illuminated zones, a stabilisation of the focal length is seen in the presence of depth errors. 

Fig. 1 Various ways of coding a lens phase function into a surface relief: a binary phase zone plate (a) and a continuous relief element (b, c). In (c) an additional design freedom was used as described in the text.