Design concepts for broadband high-efficiency EA-DOEs

Bernd H. Kleemann*, Markus Seeßelberg*, Johannes Ruoff**

*Corporate Research and Technology, Carl Zeiss AG, Oberkochen
**Lithography Optics, Carl Zeiss SMT AG, Oberkochen

mailto:b.kleemann@zeiss.de

Several design-concepts for broadband high-efficiency DOEs, so-called efficiency achromatized DOEs (EA-DOEs), are presented. Based on two surface relief approaches from the literature, we present the following new approaches: 1) gradient-index EA-DOEs and 2) sub-wavelength EA-DOEs.

1 Introduction

One of the main problems of Diffractive Optical Elements (DOEs) is their efficiency degradation for wavelengths λ deviating from the design wavelength λ_0, which often prevents them from a broader use in standard optical systems. This is a well known drawback for DOEs made of a single material, as they usually can be optimally designed only for a single wavelength. However, this deficiency has been overcome by approaches using two different materials with according dispersion relations as is nicely explained in detail in [1]. All these diffractive elements can be designed to exhibit high efficiencies larger than 95% over a broad spectral range.

We present several other design concepts of broadband high-efficiency DOEs, so-called efficiency achromatized DOEs (EA-DOEs), using gradient-index materials and sub-wavelength structures. Also these approaches are based on two different materials and according dispersion relations. The results are explained in more detail in [2].

2 Conventional DOEs

Fig. 1 shows the correspondence between surface relief profiles, gradient-index (GRIN) materials and sub-wavelength structures (from above), which all serve to implement a blazing phase. The darker the

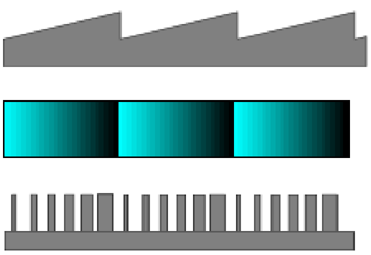

Fig. 1 *From above: Similarity between surface relief profiles, gradient-index materials, and binary blazed sub-wavelength structures all realizing a blazing phase.*

color of the GRIN-material in Fig. 1 the higher is the refractive index and the larger is the optical phase delay of the light ray passing through the material at that position. Similar phase modifications can be reached by artificial sub-wavelength structures (SWS) as e. g. binary blazed SWS (bottom drawing of Fig. 1). The structures may consist of ridges or pillars and all parts must have dimensions smaller than the smallest wavelength the DOE is designed for.

3 State of the art EA-DOEs

Substituting the air between the sawtooths of the surface relief DOE (top of Fig. 1) by a second material with another dispersion (results in a so-called **common depth EA-DOE**) allows for dispersion compensation in a specific wavelength interval. The necessary dispersion relation can only be fulfilled approximately for a restricted number of material pairs [2]. Rigorous 1^{st} order efficiency for three local zone widths and two incidence angles is given in Fig. 2 for a combination resulting in a total thickness of 7 µm. This actual thickness is

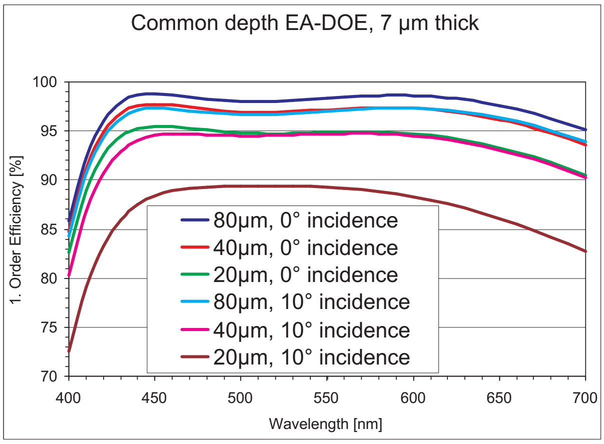

Fig. 2 *Common depth EA-DOE: rigorous 1^{st} order efficiency depending on local zone widths of 80, 40, and 20 µm and for the incidence angles 0° and 10°.*

the reason for the efficiency decrease of 1.5% to 6% for the small incidence angle of 10°. Hence, in addition to high efficiency, a small thickness of the resulting EA-DOE should be another important goal.

The so-called **multilayer approach** (cf. e. g. [2]) uses two separate surface relief DOEs of two different materials with appropriate dispersion relations resulting in high efficiency, which may be larger than 98 – 99% over a broad spectral range. This approach is known [1, 2] not to be limited by a special material combination. However, the two materials do determine the DOE-depths and the efficiency curve by their dispersion behavior. Depending on the dispersion functions of the two materials the profile depths and efficiency can be small or large. For an example from [3] with $n_\mathrm{d} = 1.513, \nu_\mathrm{d} = 51.0$ for material 1 and $n_\mathrm{d} = 1.857, \nu_\mathrm{d} = 5.7$ for material 2 using the Cauchy-formula with $\lambda_\mathrm{d} = 587.56$ nm one gets very small DOE depths $d_1 = 2.93$ µm, $d_2 = 1.05$ µm and the efficiency is larger than 99% from 400 nm to 700 nm. In Fig. 3 the refractive indices versus wavelength for the two example materials are given.

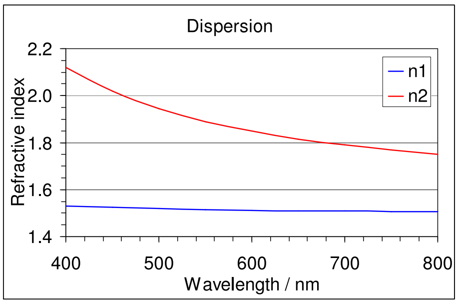

Fig. 3 *Dispersion curves for two example materials of the multilayer EA-DOE [3] resulting in very small DOE depths.*

4 Gradient-index EA-DOEs

EA-DOEs using GRIN-materials consist of two separate GRIN DOEs, each consisting of a layer of constant depth made from different materials, but with the same groove function polynomial (cf. Fig. 4). It is important to align the two DOEs in a way that the position of maximum refractive index in each zone of the first material is at position of minimum refractive index in the appropriate zone of the second material.

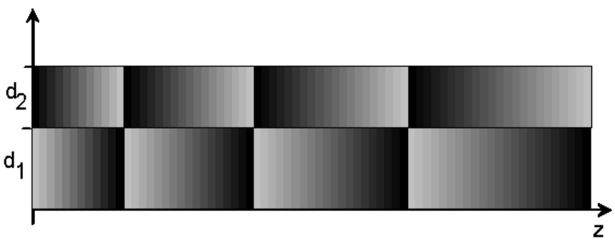

Fig. 4 *EA-DOE consisting of two GRIN-DOEs.*

The necessary conditions for high broadband efficiency are similar to those for multilayer DOEs. Hence, any pair of different GRIN-materials is suited to build a GRIN EA-DOE. As the refractive index difference for GRIN-materials is smaller than for surface relief structures, the resulting thicknesses are much larger [2] (in summary about 90 µm).

5 Sub-wavelength EA-DOEs

As it is possible to imitate gradient index behavior with SWS, EA-DOEs using two separate SWS can be made similarly to GRIN EA-DOEs as shown in Fig. 4. Another form of SWS EA-DOE considered here is depicted in Fig. 5. The two materials with

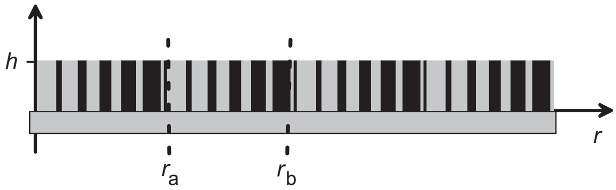

Fig. 5 *EA-DOE of binary sub-wavelength structures consisting of two different materials. The dimensions of all structures must be below the smallest wavelength the DOE is designed for.*

appropriately chosen different dispersion relations form a single layer. Since light of wavelength λ only resolves structures with dimensions larger than λ, it averages the permittivities ϵ ($\epsilon = n^2$) of the two materials. These resulting effective permittivity is polarization dependent and can be described by effective medium theory. Then, for both polarizations, one can derive an approximate linear relation for the effective refractive index which has been shown to hold with sufficient accuracy (cf. [2], Appendix B):

$$n_\mathrm{eff}(\lambda, r) = v_1(r)n_1(\lambda) + v_2(r)n_2(\lambda)$$

with the volume fractions $v_1(r) + v_2(r) = 1$ and r the distance from the optical axis. By proper choice of the volume fractions of the two materials such a layer of Fig. 5 forms clearly a DOE. To ensure that above layer is indeed an EA-DOE with scalar efficiency of 100% in the spectral working range, the refractive indices must be related by the same relation being also valid for the common depth EA-DOE of Sec. 3. In [2] dispersion curves, diffraction efficiencies, and thickness dependencies of the DOEs are given for some pairs of materials forming a SWS EA-DOE.

References

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