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A DESIGN PROCEDURE FOR REPRODUCTION HYBRID MONOCHROMATS WITH GRADIENT-INDEX AND DIFFRACTION COMPONENTS

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Abstract—A procedure is described for designing, for reproduction purposes, hybrid monochromatic formulations composed of two gradient-index lenses and one diffraction lens. It yields the initial lens design parameters that ensure a rather rapid convergence of the aberration series and a good control of primary and secondary monochromatic aberrations. The method is illustrated by the design of a unit magnification lens.

Lenses intended for reproduction purposes have magnifications close to -1. Therefore, they are commonly symmetrical designs that consist of two identical halves symmetrically placed about a material aperture. The magnification $\beta = -1$ implies that the object and image are in the focal planes of the respective halves of the lens and the intermediate image between these halves is at infinity. This arrangement automatically cancels all odd aberrations (axial chromatic aberration, coma and distortion). The even transverse aberrations in the image plane are equal to the doubled aberrations of the second half of the lens. As a result, designing out the aberrations of a symmetric lens operating at unit magnification boils down to raytracing one of its halves with the object plane at infinity and the entrance pupil coinciding with the aperture stop of the lens.

This paper is devoted to automated design of a symmetrical air separated lens with a gradient index component in each half. It is assumed that the refractive index profile is given by

$$n|\xi| = \sum_{j=0}^{\infty} n_j \xi^j,$$

where n_j are coefficients of expansion of the refractive index function, and ξ is the squared distance from the optical axis.

Making use of the expressions for monochromatic third-order aberrations derived by Sands [1] it is an easy matter to demonstrate that for a single gradient-index lens, the spherical and all the even field aberrations can be simultaneously eliminated. However, this approach fails to control the residual even field aberrations of higher orders.

The situation will change appreciably if we omit the control of spherical aberration components in all orders of the expansion. In this case the spherical aberration of a symmetrical lens may be eliminated by inserting in the plane of the aperture stop a diffraction aspheric; i.e. a diffraction optical element with zero optical power and given spherical aberration.

Now, the task of eliminating the even field aberrations of a single gradient-index lens up to the fifth order reduces to cancelling two third-order aberration coefficients (astigmatism B_3 and Petzval curvature B_4) and five fifth-order coefficients (those of slant spherical aberration M_{2110}, $M_{2002} = N_{2101}$, astigmatism N_{2011}, and field curvature M_{2020}).

For a given optical power of the gradient-index lens, the number of constructional parameters that affect the aforementioned aberrations equals the number of independent aberration coefficients. Consequently, the objective may be formulated as simultaneous elimination of all field aberrations in the third and fifth orders. The solution of this problem is given below.

Having specified some values for n_0 and n_1 in the refractive index representation, and for the lens thickness d, we analytically solved the system of two equations to achieve the specified focal length f' and Petzval's condition ($B_4 = 0$). This system yielded the surface curvature $C_1 = C_2$. For the given and calculated values of parameters and a certain initial portion of the aperture stop, we determined n_2 and n_3 from the condition that the third- and fifth-order astigmatism should be canceled. Using the parameter values thus found we computed the coefficient M_{2002} and iterated it to zero by changing the position of the aperture stop.

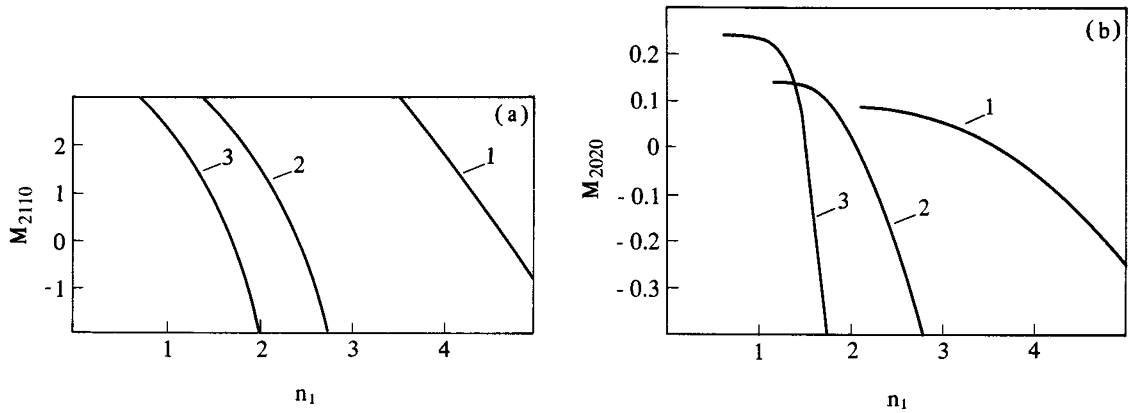

Fig. 1. Fifth-order coefficients of slant spherical aberration M_{2110} and (b) field curvature M_{2020} as functions of n, three values of lens thickness (1) $d = 0.2$, (2) $d = 0.4$ and (3) $d = 0.6$.

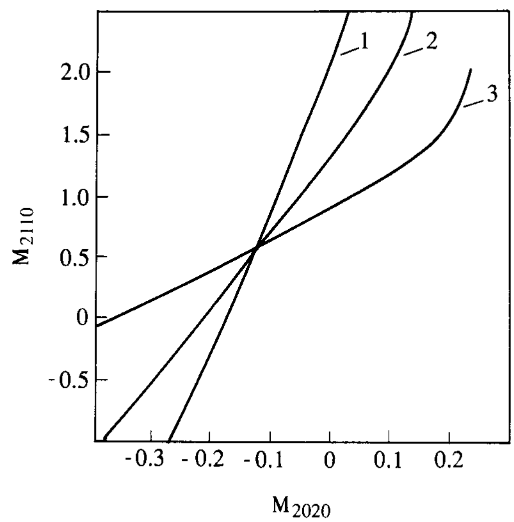

Fig. 2. M_{2110} vs M_{2020} for three values of lens thickness (1) $d = 0.2$, (2) $d = 0.4$, (3) $d = 0.6$

The aberration coefficients of the gradient-index lens were determined by the procedure of automatic raytracing of pseudorays computed in the approximation of aberrations of different order.

This computational cycle was repeated with given n_0 and f' for a number of values of n_1 and d to derive M_{2110} and M_{2020} as functions of these parameters. Figure 1 shows the plots of these coefficients as functions of n_1 for different values of d at $n_0 = 1.7$ and $f' = 1$. It can be seen that each of these coefficients M_{2110} and M_{2020} may be zeroed at least separately.

To see how they might go to zero simultaneously we constructed, with reference to Fig. 1, a family of curves $M_{2110} = f(M_{2020})$ for variable n_1 and fixed d (Fig. 2). Analysis of the curves indicates that for a gradient lens of any thickness d, a decrease in magnitude of one aberration coefficient is accompanied by an increase of the other. There is no way of breaking this dependence by using substantially thicker or thinner lenses. This is evident from the sharply increasing curvature of refractive surfaces and large differentials in the refractive index for thinner lenses. The maximum thickness of a gradient-index lens is limited by the possibility of cancelling B_4, $M_{2002} = M_{2101}$. This constraint depends on the refractive index n_0 of the lens along the axis (Fig. 3). Thus, a single gradient-index lens free of even, third-order, field aberrations may be freed of only three of four different even, fifth-order, field aberrations.

To sum up, a symmetric lens of two gradient-index lenses and a diffraction aspheric can be freed of all aberrations except field curvature. In the approximation of fifth-order aberrations this design will form a stigmatic image on a certain surface of rotation. When this image is projected on a

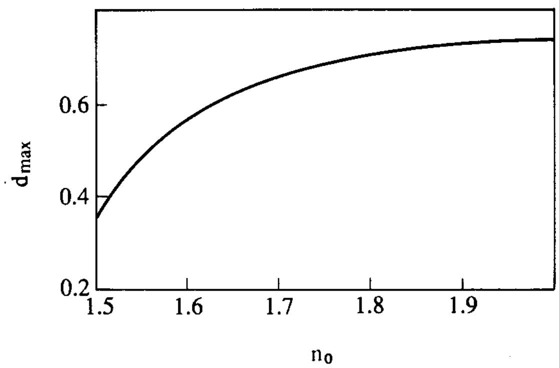

Fig. 3. Maximum thickness d_{max} (at which $B_4 = M_{2002} = N_{2101} = 0$ is still feasible) of a gradient-index lens vs the refractive index n_0 on the axis.

plane, the high-quality field will be limited. It can be expanded by violating the Petzval condition and by optimally balancing the field curvature of the third and fifth orders.

The resulting hybrid lens consists of one diffraction and two gradient-index elements. In terms of its compensation of monochromatic aberrations it is not inferior to the ten-element Foton-3 formulation [3], and it may be placed midway between two- and three-component diffraction lenses. In contrast with the latter, owing to the low spatial frequency of the single diffraction element, the hybrid lens has a transmittance comparable to that of a conventional lens, and its chromatic aberrations allow the use of gas-discharge sources like a mercury vapor lamp.

REFERENCES

1. P. J. Sands. Third-order aberrations of inhomogeneous lenses. *J. Opt. Soc. Am.* **60** (11), 1436–1443 (1970).
2. G. I. Greisukh and S. A. Stepanov. A method of aberration control in optical systems comprising gradient-index diffraction elements. *Abstracts of the All-Union Conference on Theoretical and Applied Optics*, pp. 266–267. Leningrad (1984) (in Russian).
3. M. M. Rusinov *et al. Vychislitelnaya optica* [*Computing Optics. A Handbook*]. Mashinostroyenie, Leningrad (1984).
4. S. T. Bobrov, G. I. Greisukh and Yu. G. Turkevich. *Optika diffraktsionnykh elementov i sistem* [*Optics of Diffraction Elements and Systems*]. Mashinostroyenie, Leningrad (1986).