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DESIGN PRINCIPLES FOR PROJECTION AND FOCUSING OPTICAL SYSTEMS WITH DIFFRACTION ELEMENTS

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Abstract—Design strategy is discussed for optical systems relying on diffraction and refraction elements. Corrective capabilities of the simplest systems consisting of one diffraction and one or two refraction lenses are considered. Introduction of a diffraction lens into a system is shown to effect a complete elimination of the original monochromatic aberrations and a significant reduction of the level of higher-order residual ones.

Current improvements in the performance of optical systems owe much to the diversity of available design elements, including uniform refracting lenses, diffracting lenses, and lenses constructed from graded refractive index material. The utilization of diverse types of elements considerably enlarges the scope for correcting aberrations and, at the same time, allows one to effectively realize the potential of each element, by lessening the negative influences and limitations associated with outdated manufacturing technologies of these elements.

One of the main shortcomings of the most widely used uniform lens with spherical refracting surfaces is that it is practically impossible to eliminate spherical aberrations, and that the scope for correcting field aberrations within the Petzval condition and acceptable apertures is rather limited. Diffraction lenses suffer from strong chromatism, and imperfections in manufacture limit their diffractive effectiveness at large apertures. As for gradient lenses, present production techniques offer only limited scope for obtaining a specified refractive index profile and for effective correction of aberration via appropriate refractive index differentials.

In constructing an optical system which combines refracting and diffracting lenses one is led to two types of design for tackling the problems of field aberrations and chromatism [1]. In the first, the main component is purely refractive and the diffractive element functions as an aberration corrector. In this instance the optical power of the diffracting lens is low and its chromatism is of the same order as that of the refracting lens, while the diffractive effectiveness, even with presently available technology, may reach $\sim$90%. At the same time, the low optical power of the diffracting lens does not hinder control of its own aberration and thereby allows the aberration of the system as a whole to be corrected effectively.

The simplest example of this type of system is the doublet, constructed from a refracting and a diffracting aspheric lens, i.e. a zero-power diffracting lens. In such a doublet the diffracting aspheric eliminates spherical aberration, and a proper choice of the refracting lens shape, together with the intervening air between the elements, will correct field aberrations. The problem of correcting the aberrations of the doublet is thereby reduced to correcting the field aberrations of a uniform refracting lens with an exit pupil. As is known, there are precise ways of correcting the primary field aberrations of such lenses [2]. Thus, for a given magnification, one may simultaneously eliminate any two or three of the four primary aberrations (unless the combination possesses astigmatism, Petzval curvature or distortion). But the remanent field aberrations of higher order will limit the use of a doublet constructed from a refracting and an aspheric lens as a projection objective. Therefore, as a rule, one includes some uniform refracting lenses in a high resolution wide-field optical system which contains low optical power diffraction elements.

The other type of optical system consists of a single high-power diffracting lens, while uniform refracting lenses serve as aberration correctors. Such systems are designed to operate only with monochromatic radiation, but on the other hand even their relatively simple construction already corrects well for field aberrations. This is explained first of all by the fact that, for one and the same optical strength and roughly the same level of primary monochromatic aberrations, the level of higher-order aberrations of the diffraction lenses is significantly lower than the level of the corresponding aberrations of uniform refracting lenses, since the aberration series of a plane diffraction lens has better convergence.

Another essential point is that in a diffracting lens the numerical values of a number of field aberration coefficients are the same. For example, at the third order of smallness, the Petzval condition applies automatically, while in all the 17 coefficients of monochromatic aberration of the third- and fifth-order only 10 quantities must vanish to ensure the total elimination of aberrations in both these orders. The simplest example of this type of system is a doublet containing a high optical power positive diffracting lens, and a negative meniscus [3]. In this doublet, for a specified upper limit to the level of residual field curvature, one can completely eliminate spherical aberration, coma, and third-order astigmatism, whereby at this level of residual aberrations (including higher-order aberrations) such a combination doublet is equivalent to a projection objective comprising four to six uniform refracting lenses.

Consequently, using doublets which include a high-power diffracting lens, one can construct symmetric three-lens reproducing objectives with relatively high optical performance. In the layout of such an objective the diffracting lenses of the doublet are placed in one plane and are replaced by a single element, whereas the refracting lenses are menisci of various radii located near the object and image planes [4].

To conclude our general discussion of the construction of combination systems based on uniform refracting and diffracting lenses, we note that a common drawback, at least of the simple sort of system, is the difficulty of uniformly correcting astigmatism and field curvature in several aberrational orders. Combined optical systems in which refracting lenses are made from nonuniform material with specified refractive index profiles are largely free of this drawback. Such systems, even in comparatively simple configurations, manage to eliminate simultaneously all third- and fifth-order monochromatic aberrations, and to minimize residual aberrations in seventh and higher orders.

The simplest example of this type of system is a doublet containing a lens with a radial refractive index gradient, and a diffracting lens. If the gradient lens is chosen to be a bar with plane parallel faces, then in combination with a diffracting aspheric it forms an aplanatic component which, while eliminating third-order astigmatism, is free at least of coma and spherical aberrations in all orders. Such a component can obviously be used as a high-aperture focusing objective, or a projecting objective to construct a stigmatic image on a spherical surface. One can considerably enhance the scope for correcting the doublet if the gradient lens is bounded by spherically refracting surfaces. In that case, in addition to the aberrations enumerated above, one can also eliminate the Petzval curvature. Therefore, the doublet will become useful as a projecting objective, forming a stigmatic image on a plane surface. Finally, distortion may also be corrected if the diffraction element increases the optical power. We end up with an objective capable of forming a high resolution orthographic image over a wide field [5]. Both elements of the doublet are positive, so that its high aperture is attained by using comparatively low optical power individual elements. The first consequence of this is that the refractive index differential of the gradient lens is not large and is fully attained by current methods of manufacturing optical materials with graded refractive indices [6, p. 19]. Secondly, the dimensions of the requisite structural element of the diffracting lens are small, so that it can be manufactured on existing equipment with multilevel line profile, guaranteeing high diffractive effectiveness [1].

We have demonstrated in this work the corrective possibilities of combined optical systems constructed out of diverse types of optical elements.

REFERENCES

1. S. T. Bobrov, G. I. Greisukh and Yu. G. Turkevich. *Optics of Diffracting Elements and Systems*. Leningrad (1986).
2. M. M. Rusinov. *Technical Optics*. Leningrad (1979).
3. G. I. Greisukh. *Opt. i Spektr.* **44**, 168–172 (1978).
4. A.c. no. 1176281 (SSSR). *Byull. Izobr. i Otkr.* No. 32, 30 August (1985).
5. M. M. Butusov, G. M. Greisukh and S. A. Stepanov. *Opt. i Spektr.* **56**, 752 (1984).
6. I. M. Efimenko. *Gradient Optical Systems*. Moscow (1981).