Optics of Diffractive and Gradient-Index Elements and Systems

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PREFACE

The development of new progressive technologies in various fields of science and engineering, and particularly the technologies using lasers, are expanding the applications of optics and complicating the problems it is called on to solve. This in turn requires the variety of optical element types to be broadened. It is common knowledge that an important breakthrough in any field of science and engineering almost always involves a change to new types of elements. The breakthrough in electronics caused by switching from tubes to transistors and then to modern chips is an example.

As far as the search for new passive optical elements is concerned, scientific energies have lately been directed to diffractive optics, and gradient-index (GRIN) elements. The term "diffractive optics" covers a wide range of optical elements that perform any kind of wave-front transformation using diffraction. From the viewpoint of the transformations they carry out, there are three basic types of such elements: deflecting (diffraction gratings), imaging (diffractive lenses), and correcting elements (diffractive aspherics, that is, diffractive lenses with zero optical power operating like the well-known Schmidt plate).

GRIN elements are made of transparent materials with a continuously varying refractive index. There are also three basic types of GRIN elements. First, there are components for transmitting optical signals (GRIN fibers); second, are thin-film transformers of optical signals (integrated optics elements); and last, imaging elements (GRIN lenses).

The classification of diffractive and GRIN elements given above is, of course, highly relative. For example, diffraction gratings with a varying spatial frequency can fall in either the first or second type of diffractive element. Matched holographic filters combine properties of diffractive elements of both first and third types, etc. The same is true with GRIN elements. In particular, a fragment of a multimode GRIN fiber can serve as a GRIN lens coupling single-mode fibers, and GRIN elements of integrated optics can function as fibers or lenses, etc. At any rate, the whole variety of diffractive and GRIN elements can be quite fully described under the above three types.

Diffraction gratings, fiber and film GRIN elements are the best-understood cases and well embedded in applied optics. Diffractive and GRIN singlets are beginning to find practical use. The most expressive examples of such use are diffractive crystalline lenses of the human eye; GRIN rod lenses are employed in optical fiber systems and copying machines. As far as the use of diffractive and GRIN lenses as components of imaging optical systems is concerned, the situation is quite different here. The reason is that the history of fabrication of imaging systems covers several centuries. Broad experience in designing such systems using conventional optics (mostly homogeneous lenses and mirrors) has been gained. A radically new kind of element is therefore more difficult to introduce in this field of optics than in fields with a relatively short history (optical communication, for instance).

Nevertheless, the possibilities of using diffractive and GRIN lenses as components of imaging optical systems have been investigated for as long as several decades. These elements have proved quite competitive. This is due to the uniqueness of their focusing and aberration properties, as well as the appearance of additional degrees of freedom for optical designing. In particular, there are possibilities of making both totally diffractive or graded optical systems and hybrid systems that consist of elements of different types (including conventional elements). Initial investigations showed that high optical characteristics can be achieved for simple systems consisting of a few such elements combined in one way or another. Still, to realize these possibilities, a more intensive study of properties of non-conventional elements, as well as the development of theory and methods of optical design of systems with such elements are needed.

This book deals with the problems listed above. The physical principles of diffractive and GRIN elements are expounded systematically in this book. Universal methods of paraxial and aberration calculations as well as those for evaluating image quality suitable for both individual elements and optical systems are given. The possibilities of correcting aberrations of diffractive, homogeneous, and GRIN elements are analyzed and compared by using these methods. Their advantages and disadvantages are exposed, and methods for the most effective use of such elements are considered. The principles of design of totally diffractive and hybrid optical systems, including elements of different types combined in one way or another, are described. Examples of such design for different applications are given.

At the same time this book does not present a systematic and complete course of optical systems theory. Although the text contains definitions of basic concepts and notions used in this area of optics, it is assumed that the reader is already acquainted with them to a certain extent. It must be also noted that the inclusion of material devoted to conventional optical elements has several objectives: first, to demonstrate that new methods developed for diffractive and GRIN lenses are quite applicable to conventional optical elements; second, to compare the optical performance and the correction possibilities of new and conventional lenses. The last objective is to show the benefits of hybrid optical system design with optical elements of different types. Below we give a short review of some phenomena, ideas, and concepts discussed in this book.

Every point of self-shining or illuminated object is considered in optics as a source of a spherical light wave, i.e. a wave having spherical wave-fronts with a center of curvature at this point. Applying the concept of light rays widely used in optics, it may be said that a homocentric pencil of rays comes from the object point (rays are perpendicular to the spherical wave-fronts).

The function of a lens is the transformation of every incident spherical wave into another spherical wave the center of curvature of which does not coincide with the prior one. That is called an optical image forming. The transformed wave may converge to some point (which is called a real image of the object point) or diverge from the point where no real light source is placed (a virtual image). As a result, the lens forms a real or a virtual image of the extended object.

The similarity of an initial object and its image is not ideal in practically all cases. Perhaps only a plain mirror forms an image of any object without distortions, but this image is always a virtual one and has the same scale as the object, so the possibilities of a plain mirror are quite limited. Generally spatial similarity is damaged first; for instance, an image of a plain object is arranged on a curvilinear surface. In addition the light wave forming a point of an image as a rule is not strictly spherical (in other words the corresponding pencil of rays does not converge into or diverge from the single point). This phenomenon is called an aberration and leads to the blurring of the image.

There are monochromatic and chromatic aberrations. Image distortions, which are called monochromatic aberrations, are found in rays with definite wavelengths. Chromatic aberrations occur because the monochromatic components making a polychromatic image do not coincide either in location or size, or on both parameters. As a rule, power series are used for mathematical description of aberrations, and that is why they are divided into aberrations of the first, third, and fifth orders, and so on. Different aberration types are identified within each order of aberration series. Each of these types is responsible for a definite characteristic of image distortion. In the first order there only chromatic aberrations; they are axial color and a lateral one. In the case of rotationally symmetric optical systems, the lowest order of monochromatic aberration is the third one. Spherical aberration, coma, astigmatism, field curvature (or Petzval curvature) and distortion exist here.

The design of optical element combinations that result in minimal distortions for a given size of image is one of the basic problems in optical systems. In the process of developing any system it is necessary to estimate the image distortion and to compare different variants of design with each other. These operations are carried out by means of a number of quality criteria the calculation of which depends on deviations of a real wave-front from the spherical one or a real pencil of rays from the homocentric one.

The aperture stop is the important detail of an optical system in addition to the elements transforming incident spherical waves. The thing is that the light waves forming each of the points of an extended image cannot have infinite wave-fronts; in other words the divergence angle of a corresponding pencil of rays is always less than 180 degrees. Usually wave-fronts in an optical system are limited by a special diaphragm, but even if it is absent, a rim of one of the lenses performs this duty. The operation of the aperture stop is especially obvious in the case of the simplest optical system, that is, a single lens: only the rays passing through the lens rim participate in image formation even if the light source shines in all the surrounding space.

On the one hand the aperture stop sets a limit on the resolution of the optical system, on the other hand this stop also limits distortions, because they increase with increasing aperture. But the main characteristic of the aperture stop consists in the fact that if the aperture stop and optical system elements are separated, only a definite zone of each element takes part in forming the image of the given object point. Generally these zones, which are individual for every object point, may be varied by replacing the aperture stop. If the thin lens is single, all the rays passing through the lens rim take part in the imaging of any object point. But if the aperture stop is shifted from the lens plane, the situation will be changed. The image of the axial object point will be formed as before by the pencil of rays passing through the central zone of the lens. But the images of the off-axis object points will now be formed by rays passing through different off-axis sections of the lens. The diaphragm setting of the ray's pencils (or wave-fronts) at the time of their propagation through the optical system is a powerful method of aberration correction which in many cases permits aberrations in the off-axis image points to be decreased both for the single lenses of any type and for complicated optical systems.

Here we discuss at greater length the main subject of this book, which is diffractive and GRIN lenses. A diffractive lens - the analog of a conventional lens with spherical refracting surfaces - is a diffraction grating with concentric annular rings. The width of the grating zones decreases with the increasing radius, and the spatial frequency of such a circular grating grows in a direction from the center to the periphery almost linearly. In the simplest case of an amplitude grating, the whole structure is alternate transparent and opaque zones of varying width that are drawn on a plane-parallel glass substrate. Unfortunately, a simple diffractive lens with a structure like that cannot focus more than 10% of the incident light energy. To focus all incident light (100% efficiency), the whole aperture of the diffractive lens must be transparent but the optical thickness within each circular zone must smoothly increase up to one and the same value which is a multiple of the wavelength. A concentric microrelief with a sawtooth profile of zones is formed on a substrate surface for this purpose.

By introducing corrections into the distribution of diffraction structure spatial frequency, the spherical aberration of the lens can be easily varied over broad limits without changing the optical power. Moreover, using corrections of different orders of smallness, it is possible to independently control the spherical aberration of the third, fifth, etc. orders. Recall that the spherical aberration of conventional lenses can be controlled only by making their surfaces aspherical, which requires considerable changes in the lens fabrication technology.

The simplicity in controlling spherical aberration and planeness determines the advantages of diffractive lenses over conventional analogs. First, aberration coefficients of diffractive lenses do not have additional terms responsible for surface sphericity, which results in more rapid convergence of aberration series. Second, some types of wave aberration have the same coefficients for plane diffractive lenses, which is not the case for spherical refracting surfaces. In particular, a diffractive lens has the same third-order coefficients of astigmatism and field curvature (i.e., Petzval curvature equals zero); in addition there are three pairs of the same fifth-order coefficients and still more same coefficients in the seventh order.

The possibility of controlling spherical aberration within wide limits, the rapid convergence of aberration series, and the equality of some aberration coefficients not only simplify aberration correction of optical systems consisting of diffractive lenses, but lead to qualitative and fundamental advantages. So, first of all there is no problem of spherical aberration correction of the system as a whole. The capabilities of correcting field aberrations are also extended owing to this fact. For example, the correction of an optical system for field aberrations may require some of its lenses to have considerable spherical aberration. In this case the spherical aberration of the optical system as a whole can be easily removed without affecting field aberrations by the choice of the corresponding spherical aberration of the diffractive lens located near the stop.

Owing to the absence of Petzval curvature, all third-order monochromatic aberration-free objectives can consist of diffractive lenses with only positive power. This allows the numerical aperture to be increased step by step from lens to lens, thus providing a low level of high-order aberrations. Recall that the correction of a conventional objective for Petzval curvature requires both positive and negative lenses, which gives rise to considerable high-order aberrations. This fact together with slow convergence of the aberration series of even a single spherical refracting surface makes it almost impossible to design a good large-aperture objective if the choice of its primary configuration is conditioned by the correction of only third-order aberrations, and if then the fifth, seventh, etc. orders of aberrations are corrected in succession using free design parameters.

Things are quite different if a designed objective consists of only diffractive lenses. Because of rapid convergence of the aberration series, even the primary two- or three-lens configuration, which is found on the basis of third-order aberration correction, provides quite good optical performance. The minimization of fifth-order aberrations allows to achieve almost maximum performance for the given number of lenses, as well as the minimization of both fifth and seventh orders. It is also necessary to stress that the above-mentioned possibility of separately controlling the components of spherical aberration of a diffractive lens allows the higher-order aberration of the objective to be minimized without upsetting the previous correction of lower-order aberrations.

The experienced reader may well ask, "What price should we pay for the above-mentioned virtues of diffractive lenses?" Yes, there is a price and it is rather high. This is axial color. The optical power of a diffractive lens is linearly dependent on the wavelength of light. This is a more serious problem for optical system designers than glass dispersion. The objectives consisting of diffractive lenses can be used only with monochromatic light (usually laser light) to form high-resolution images. True, there is a small counterbalance for this considerable limitation. With the same signs of optical power, diffractive and refractive lenses have opposite signs of axial color. Their axial colors are equal in magnitude if the optical power of a diffractive lens is 15-20 times less. Thus, the introduction of low-power diffractive lenses into systems consisting of refractive lenses is an effective means to correct chromatic aberration of such systems. Let us now finish this brief discussion of in diffractive lens properties and turn to GRIN lenses.

Three types of GRIN lenses are particularly interesting. They are the axial, radial, and spherical GRIN lenses. In the axial gradient type, the isoindical surfaces are planes and the refractive index is a function of the coordinate along the lens optical axis only. The index profile in a radial GRIN lens varies continuously outward from its optical axis so that the surfaces of constant index are cylinders whose axis corresponds to the optical axis of the lens. Finally, in a spherical GRIN lens the refractive index is a function only of the distance from a fixed point placed on the lens axis. In this type the isoindical surfaces are spherical.

The inhomogeneous material of an axial GRIN lens does not have optical power. The focusing properties of this lens are nearly completely defined by lens refracting surfaces, and the role of the inhomogeneity is only in controlling spherical aberration. Therefore, from the point of view of both aberration series convergence and the equality of some aberration coefficients to each other, the axial GRIN lens differs insignificantly from the homogeneous lens with aspherical surfaces.

There is a considerably different situation in the case of a spherical GRIN lens, because the material of this lens has optical power by itself. It is known that at the specific index profile the spherical GRIN medium, called in this case Maxwell's "fish eye", forms a stigmatic image of any point placed in this medium. In addition, the wave-fronts in the "fish eye" are spherical. That is why GRIN lenses made of this material can be the ideal focusing device, forming a stigmatic point image in homogeneous free space. However, this lens cannot form an aberration-free image of a plane extended object. Moreover, it is not possible to design an imaging system using several such lenses because through upsets of all the symmetry the significant aberrations increase instead of being mutually corrected.

The radial GRIN lens material has an optical power, too. However, wave-fronts propagating in such a medium from the point source are no longer spherical. Therefore, using this material it is impossible to fabricate a perfectly focusing lens forming a stigmatic image in free space. With this viewpoint, a single radial GRIN lens yields to a single spherical GRIN lens. But the first lens excels the other one in the next principal qualities. The introduction of a radial GRIN lens into a rotationally symmetric optical system does not upset its symmetry. The radial GRIN lens itself, as an element of the optical system, undoubtedly is superior to the conventional lens. Petzval's curvature correction and the rapid convergence of aberration series can be achieved with the successful distribution of optical power between the lens surfaces and its material, i.e., inhomogeneous medium. Moreover, it is possible to vary the spherical aberration over a wide range by the index profile correction without influencing the lens optical power and Petzval's curvature. It is important to note that not only spherical aberration as a whole but its different-order components can also be controlled. From the above it is clear that in principle the radial GRIN lens has all the positive qualities of a diffractive one, but differs from it by comparatively low axial color.

This book is organized in the following way. Chapter 1 deals with the theory of diffractive optical elements. A diffractive element is regarded as an infinitely thin transparency with a predetermined amplitude coefficient of transmittance. Since the transparency may be spherical (or even aspheric), such an approach allows a general description of focusing and aberration properties of thin optical elements of all types, including reflecting and refracting surfaces.

Chapter 2 concerns the fundamentals of graded-index singlet theory. An analytical description of ray propagation in inhomogeneous medium is given. The focusing properties of materials with spherical, radial, and axial index profiles are considered. Formulae for paraxial design of GRIN singlets are presented.

Ray tracing and image quality are treated in Chapter 3. Ray tracing methods for graded-index media and corresponding formulae for elements of different types are considered. The peculiarities of ray tracing in the diffractive corrector are analyzed. A review of numerical criteria for evaluating the quality of a point image is given and their correlation is investigated. Quite reliable criteria using the minimum of computer time are given.

Chapters 4 and 5 deal with aberration calculations of homogeneous and inhomogeneous hybrid optical systems. Homogeneous systems include both conventional and diffractive optical elements. Inhomogeneous systems side by side with those above also contain GRIN lenses. Paraxial color, third-order and higher order monochromatic aberrations can be computed using the methods presented. Optical invariants and quasi-invariants are used to calculate the paraxial color of both homogeneous and inhomogeneous systems, as well as third-order monochromatic aberrations of inhomogeneous systems. Monochromatic aberrations of homogeneous systems up to the seventh order are calculated by transferring aberrations from the surface of a preceding optical element to the surface of the next element. High-order aberrations of inhomogeneous systems are found by tracing pseudorays, that is, the rays the paths of which are traced in the approximation of aberrations of a given order.

The correction capabilities of diffractive, homogeneous, and GRIN singlets are considered and compared in Chapter 6. Diffractive and GRIN singlets are shown to have better correction capabilities than homogeneous ones. On the basis of these investigations, methods for using diffractive and GRIN optical elements to design simple high-resolution optical systems are considered.

Chapter 7 is devoted to diffractive monochromats. These are high-resolution systems that operate in laser radiation and consist of several diffractive lenses with certain optical powers (including zero power). The correction capabilities of air-spaced doublets and triplets are analyzed. It is shown that in aberration characteristics they can compete with multicomponent conventional monochromats. Methods and examples of designing two- and three-lens imaging objectives, as well as a two-lens Fourier-transform objective are given.

Chapter 8 concerns homogeneous hybrid optical systems. Two alternative ways of constructing such systems are considered. One way is to use a diffractive lens as a power element of a system, and refractive elements as aberration correctors. The other is to combine optically powerful refractive lenses with diffractive elements as correctors. Aberration properties and correction capabilities of some hybrid system designs are analyzed. Achromatic and apochromatic correction is shown to be possible and their conditions are defined. Methods and examples of designing imaging systems and objectives for focusing laser radiation are given. The optical performance of the designed focusing objectives meets the requirements set for the objectives of optical disk reading and writing systems.

Chapter 9 deals with hybrid inhomogeneous systems. Methods and examples of doublet design of three types are presented: a doublet consisting of a GRIN lens and a homogeneous refractive corrector (Smith lens), a doublet consisting of a GRIN lens and diffractive aspheric, and a doublet composed of a GRIN lens and a diffractive lens. These doublets' capabilities for producing an image with high resolution over a large field are analyzed. In terms of correcting monochromatic aberrations a doublet consisting of a GRIN lens and diffractive lens with roughly equal optical powers is shown to have the best performance. In terms of a high-quality image field size it falls between two- and three-lens diffractive objectives. The ways of designing front-to-back symmetric triplets with the use of GRIN-diffractive doublets are shown. Methods and examples of constructing such objectives are given.

The image quality criteria, the methods of balancing and correcting aberrations and the methods of optical system design presented in the above-mentioned chapters can be successfully used for conventional optics as well. Getting acquainted with them is certain to expand the possibilities for designers of optical systems, particularly those who are starting out in this field of optics. As to the complicated formulae overload in some chapters, that is a general feature of all books devoted to analysis of optical system aberrations. For the first reading it is quite unnecessary to study these formulae carefully; it is enough to make the acquaintance of their structure and purpose. On the other hand, these formulae are sufficient to prepare computer programs for computations of optical system aberrations up to fifth or seventh order of smallness.

The concluding Chapter 10 concerns the calculations of the parameters necessary for fabrication of diffractive elements with a required optical performance. The diffraction efficiency of surface-relief elements with sawtooth and stairstep zone profiles is investigated. The computation of design parameters providing a required efficiency is given. The effect of illumination conditions and deviation of actual parameters of a structure from design is analyzed. The parameters of elements with specific optical power and spherical aberration are calculated. How a departure of these parameters from optimal values influences the wave-front formed by the diffractive element is analyzed.

This book will be useful for a large number of readers (from students and postgraduates to engineers and scientists) specializing in the theory, design, and application of optical systems.

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Notation of Principal Variables

λ	is the wavelength;
n	is the refractive index;
G	is the eikonal of a wave;
m	is the number of the diffraction order;
Ψ	is the wave-front aberration;
b_i	are the coefficients of aspherical deformation of the diffractive lens recording eikonal;
μ	is the ratio of two wavelengths;
I_A	is Abbe's invariant;
g	is the paraxial invariant true for any rotationally symmetric system;
α	is the direction vector of the ray;
β	is the optical direction vector of the ray;
$\mathbf{N}$	is the direction vector of the surface normal;
σ_i	are the normalized aspherical coefficients of the surface;
s'_F	is the back focal distance;
M	is the linear magnification;
z'_p	is the distance from the exit pupil to the paraxial image plane;
R'_p	is the radius of the exit pupil;
D_{cl}	is the clear aperture of the element;
δ_R	is the Rayleigh resolution;
I_S	is the Strehl intensity (ratio);

λ_0, G_0	are the design wavelength and recording eikonal respectively used for analytical description of the diffractive optical element (DOE) structure;
l, u	are the geometrical and optical lengths of the ray path;
r, c	are the radius and curvature at the surface vertex;
s, s'	are the object and image distances;
t, t'	are the distances from the element's surface to entrance and exit pupil, respectively;
f, Φ	are the focal length and optical power, respectively;
NA, NA'	are the numerical apertures of the optical system in object and image space;
A, B, C, D	are the "black box" parameters or Gaussian coefficients used to describe paraxial properties of the optical system;
S_1, S_2	are the first and second chromatic Seidel's sums;
S_i, C_i, A_i F_i, D_i, P_i Z_i, M_i, B_i	are the monochromatic wave-front aberration coefficients;
$\Xi_1 - \Xi_5$	are the third-order monochromatic ray aberration coefficients;
$A_{l-p,p-q,q}$ $B_{l-p,p-q,q}$	are $(2l+1)$-order monochromatic ray aberration coefficients;
$E(\delta_R)$	is the relative energy concentrated within the Airy disk;
$Q_1 - Q_4$	are image quality criteria based on a spot diagram.