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Third-order aberrations in GRIN crystalline lens: A new method based on axial and field rays

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Abstract This paper presents a new procedure for calculating the third-order aberration of gradient-index (GRIN) lenses that combines an iterative numerical method with the Hamiltonian theory of aberrations in terms of two paraxial rays with boundary conditions on general curved end surfaces and, as a second algebraic step has been presented. Application of this new method to a GRIN human is analyzed in the framework of the bi-elliptical model. The different third-order aberrations are determined, except those that need for their calculation skew rays, because the study is made only for meridional rays.

PALABRAS CLAVE
Ojo humano;
Cristalino;
Aberraciones de tercer orden;
Rayos axiales y de campo

Aberraciones de tercer orden en los cristalinos con gradiente de índice: nuevo método basado en rayos axiales y de campo

Resumen Este documento presenta un nuevo procedimiento para el cálculo de las aberraciones de tercer orden en los cristalinos con gradiente de índice (GRIN), que combina un método numérico iterativo con la teoría de Hamilton sobre aberraciones, en términos de dos rayos paraxiales con condiciones de contorno sobre superficies generales con límite curvado, y que se ha presentado como segundo paso algebraico. Se analiza la aplicación de este nuevo método al GRIN humano en el marco de un modelo bi-elíptico. Se determinan las diferentes aberraciones de tercer orden, excepto aquellas cuyo cálculo precisa de rayos inclinados, ya que el estudio se realiza únicamente para rayos meridionales.

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Introduction

The most common models of the human crystalline lens are those found in the standard schematic eyes and they represent the optical structure by spherical and/or aspherical end surfaces and constant refractive index. Schematic eye models are used to estimate basic properties of the eye including paraxial properties, ocular aberrations, etc. The most successful eye model was proposed by Gullstrand[1] and updated by Le Grand.[2] This model reproduces the Gaussian properties of an average eye. All those models have the weakness that they do not use a variable refractive index and therefore do not accurately represent the optical structure of the lens. To understand the effect of inhomogeneity of the refractive index within the lens and then on the eye as a whole, we need understand the role of the gradient-index (GRIN) nature in optical quality of lens. One important problem is that the exact distribution of the refractive index of the human lens is not well known yet. Navarro et al. proposed a GRIN lens model with concentric iso-indicial contours mimicking the external conic surfaces of the lens. The GRIN spatial distribution includes the age dependence.[3] Goncharov and Dainty[4] used a different approach with a fourth-order polynomial for describing the GRIN lens of a wide-field schematic eye model. Diaz et al. used a combination of polynomials and trigonometric functions for describing the refractive index distribution.[5] These last two models also analyze the dependence on the age. Baharami and Goncharov[6] present a new class of GRIN lens based on experimental data. The model allows, in some cases, analytical paraxial ray tracing.

It is clear that the GRIN structure may play a primary role in paraxial domain and aberrations of different orders since it permits predict real behavior of the lens. Some schematic models have shown the crucial role of aspheric surfaces in keeping aberrations.[7] In the GRIN modeling of crystalline lens of the human eye, two different models are used. In one, refractive index profile is represented by a finite and discrete set of concentric shells, with a constant refractive index in each shell.[8–9] In the other model, the refractive index profile is described by continuous isoindicial surfaces of different shapes.[7,8,10–12] Some authors use numerical methods for ray tracing for evaluating radial, spherical or cylindrical refractive index gradient, and some consist of polynomial expansions of the ray trajectory inside the medium.[12] The most schematic GRIN lens models had aspherical-like refracting end surfaces as expected in real lenses.[13]

On the other hand, the aberrations provided by an optical system in rays traversing through it may be evaluated by either a ray tracing technique or by analytical method.[14] The first one involves step-by-step integration of the ray equation for rays starting from the object point and finding the intersection point in the image plane.[3,12,14,15] The second one determines algebraically the aberrations of the system by equations which describe the propagation of rays through it.[14,16,17] Regarding the commercial software, to our knowledge some ray tracing software (as Zemax or Code-V) does not correctly calculate the paraxial ray tracing when the optical system dealt with GRIN media. Hence, the slope and the height of rays are wrongly traced to the posterior surface of the lens. In our method we use an iterative calculation to exactly determine the position (height) and slope of the rays at the back surface of the lens. The analytical method for determining the third-order monochromatic aberration of a GRIN system has been developed by Luneburg and Buchdhal.[18–21] Both assumed that the system was symmetric and that the refractive index varies continuously throughout the system, that is, no interfaces between distinct media are allowed. Basing his analysis on the theory of quasi-invariants developed by Buchdahl, Sands[16] has made a study of the third-order aberration for any symmetric system with any number of interfaces between a pair of inhomogeneous media or homogeneous/inhomogeneous media, that is, for a system where no plane surfaces between media are allowed. Moore,[15,22] based on the third-order aberration coefficients developed by Sands, used glasses with continuously varying refractive index in the design and construction of GRIN singlets for imaging systems.[23] Thyagarajan and Ghatak[17] have extended Luneburg's results on Hamiltonian theory of aberrations to the third-order aberration of inhomogeneous lenses. Both gave explicit expressions for third-order aberration in terms of two paraxial rays obeying certain specific boundary conditions on the object plane and any other reference plane of the system. These results have been applied to a GRIN rod, GRIN medium with cylindrical symmetry, limited by plane parallel end surfaces.[14] Third-order aberrations in GRIN lenses with curved end surfaces may be studied in terms of two paraxial rays with boundary conditions on these non-planar surfaces.

Bahrami and Goncharov[6] use a description for aberration coefficients of a thin homogeneous layer for a general GRIN lens description. Díaz et al. use the ABCD matrix for obtaining the ray tracing that allows to calculate the third-order aberrations.[12,24] Recently, in 2012, Díaz et al.[25] reported additional insights considering the changes that the eye suffers with age. In this paper, they evaluated separately the role of the cornea as well as the lens. For the crystalline, third-order aberrations due to the refraction in the end surfaces and to its GRIN nature have been determined. Navarro et al.[7] developed an analyzed a method to obtain schematic models of individual eyes that were able to reproduce their monochromatic wave aberrations. In 2007,[26] these researchers proposed and analyzed an aging and accommodating human lens plausible in terms of shape, GRIN structure and optical performance. They apply this GRIN model to develop a schematic but realistic optical model of the human lens.

Chromatic aberrations have also been analyzed in the literature.[27–28] Goncharov and Dainty[4] presented a mathematical method to construct a GRIN lens with iso-indicial contour following the optical surfaces with a given asphericity. In this paper, the role of the GRIN structure in relation to the lens paradox is analyzed. Ocular wavefront aberrations as well as the effect of the aging on the anatomical structure of the age were studied. In 2012, Bahrami and Goncharov[29] analyzed the dispersion throughout the GRIN structure of the crystalline. They use the geometry-invariant GRIN lens monochromatic model and introduce wavelength dependence of the refractive index. They developed a paraxial ray tracing method.

The aim of this paper, as a first step, is to present a novel procedure for calculating the third-order aberration of GRIN lenses that combines an iterative numerical method with the