Recent Progress In Gradient-Index Optics

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Recent Progress in Gradient-Index Optics

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ABSTRACT

A brief summary of gradient-index (GRIN) optical principles is given, followed by a state-of-the-art review. Much of the important recent work has been in the area of GRIN materials, specifically: new glasses for ion exchange, new ion exchange techniques, GRIN sol-gel glasses and plastic GRIN. New metrology techniques and fabricated GRIN imaging systems are also discussed.

1. PRINCIPLES OF GRIN IMAGING OPTICS

Optical materials which contain a distribution of refractive index and are used in lens design are called gradient-index (GRIN) materials. The parameters that define the index distribution provide valuable new degrees of freedom for designers of optical imaging systems[1,2].

The index distribution can be represented in its most general form by an index polynomial[3],

$$\begin{aligned} N(r,z) = \; & N_{00} + N_{01}z + N_{02}z^2 + \dots \\ & + r^2 \left\{ N_{10} + N_{11}z + N_{12}z^2 + \dots \right\} \\ & + r^4 \left\{ N_{20} + N_{21}z + N_{22}z^2 + \dots \right\} \\ & + r^{2p} N_{pq} z^q + \dots \end{aligned} \tag{1}$$

where z is the coordinate along the optical axis and r is the radial coordinate. Two special cases of the general expression for the index polynomial have proven to be particularly useful in lens design. The first of these, called an axial GRIN, is represented by equation (1) by eliminating all terms which include r. As can be seen from the left hand side of Figure 1, the iso-indicial surfaces are planes, and the index is a function of the coordinate along the optical axis only. An axial GRIN profile in combination with a spherical surface is virtually equivalent to an aspheric surface, with the refraction varied across the aperture by a local change in refractive index (as opposed to a local change in curvature). Figure 2 schematically illustrates the correction of spherical aberration using an axial GRIN profile. Axial GRIN profiles have been used to correct spherical aberration of collimators[4,5], binocular objectives[6] and distortion in eyepieces[7].

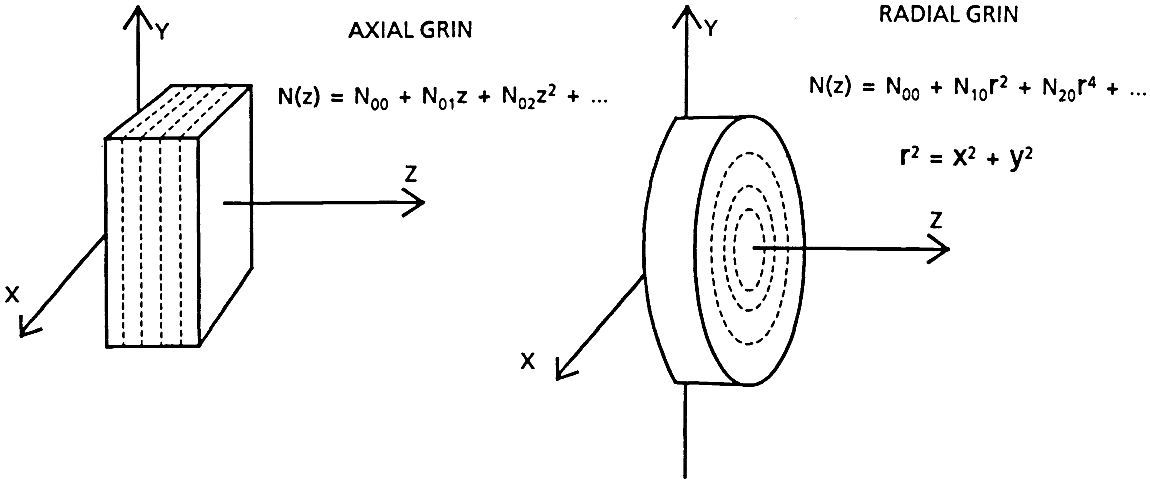

Figure 1. Axial GRIN profile geometry (left) and radial GRIN profile geometry (Right).

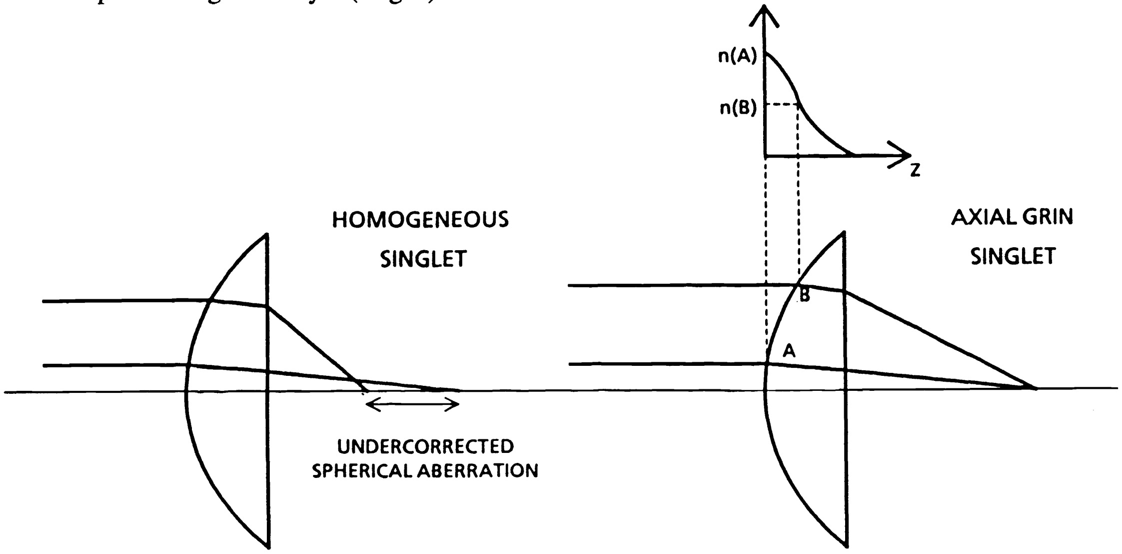

Figure 2. Spherical aberration in a homogeneous singlet with spherical surfaces (left). Correction of spherical aberration using an axial GRIN profile (right).

The second type is the radial GRIN profile, shown on the right hand side of Figure 1. This representation is obtained by eliminating all terms in equation (1) which include z. Its representation simplifies to the following expression:

$$N(r) = N_{00} + N_{10}r^2 + N_{20}r^4 + \ldots \tag{2}$$

The isoindicial surfaces of the radial GRIN are concentric cylinders about the optical axis. Radial GRIN lenses that have plano surfaces are known as Wood lenses, after R.W. Wood who invented them in 1905[8].

Several interesting features of radial GRIN design can be associated with individual coefficients in equation (2).:

1.) The index of the "base" glass is given by the constant term, N_{00}; it is the index that one specifies in a homogenous design.

2.) N_{10} is the coefficient of the quadratic term. This term has the most important consequences for GRIN optics. The power of a thin Wood lens is given by:

$$\phi_{grad} = -2N_{10}t \tag{3}$$

where Φ_{grad} is the power due to the GRIN profile and t is the thickness of the element. This power gives the designer two new degrees of freedom in controlling first-order properties: N_{10} and element thickness, t.

Because the GRIN profile has its own optical power, it is effective at correcting aberrations that depend on optical power. Petzval field curvature is a case in point. The contribution to Petzval field curvature due to the presence of the gradient is given by

$$\sigma_{4grad} = \frac{\phi_{grad}}{(N_{00})^2} = \frac{-2N_{10}t}{(N_{00})^2} \tag{4}$$

in analogy with the contribution due to the surface curvatures in homogeneous design. Note that this contribution is inversely proportional to the square of N_{00}. By using the GRIN profile to increase the power of an element, the designer incorporates less Petzval field curvature than by using the equivalent surface curvatures.

3.) N_{20} is the fourth power coefficient. It has no effect on power or Petzval field curvature. It can be used to correct other aberrations without changing previously corrected Petzval field curvature or first-order properties. In this way spherical aberration can be decoupled from Petzval field curvature, etc..

The conditions for zero paraxial axial color (PAC) in a GRIN system are derived in a paper by McLaughlin, et al[9]. The derivation is reproduced below.

The total paraxial axial color of a lens composed of thin lens elements in air is

$$PAC_{total} = \frac{1}{u'^2_{ak}} \sum_{i}^{\text{all elements}} y^2_{ai} (\Delta\phi_{surf} + \Delta\phi_{grad}) \tag{5}$$

where y_a is the height of the axial ray, and u'_{ak} is its final angle. $\Delta\Phi_{surf}$ is the difference in power of the surfaces due to the wavelength dependence of the base index. This can be shown to be

$$\Delta\phi_{surf} = \frac{\phi_{surf}}{V} \tag{6}$$

where V is the Abbe number of dispersion:

$$V = \frac{N_{00d} - 1}{N_{00F} - N_{00C}} \tag{7}$$

Here N_{00d}, N_{00F} and N_{00C} represent the base indices at yellow, blue and red light respectively. $\Delta\Phi_{grad}$ is the difference in power of the GRIN profile due to the wavelength dependence of the coefficients in equation (8). In the case of a radial GRIN profile, it is given by differentiating equation (3):

$$\Delta\phi_{grad} = -2\,(N_{10F} - N_{10C})\,t \tag{8}$$

By defining a measure of dispersion for each coefficient in equation (2) in analogy to equation (7),

$$V_{j0} = \frac{N_{j0d}}{(N_{j0F} - N_{j0C})} \tag{9}$$

and $\Delta\Phi_{grad}$ can be written

$$\Delta\phi_{grad} = \frac{\phi_{grad}}{V_{10}} \tag{10}$$

The total PAC for a radial GRIN thin lens singlet will be eliminated if

$$\frac{\phi_{surf}}{V} = \frac{-\phi_{grad}}{V_{10}} \tag{11}$$

The procedure is the same when more than one separate element is present, but the change in axial ray height must be included in the calculations.

Radial GRIN lenses have been used in design studies for color and Petzval field curvature correction in binocular[9] and camera objectives[10]. The

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