# Fundamentals of macro axial gradient index optical design and engineering

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**Abstract.** Homogeneous lens material is characterized by an index of refraction and a point on the glass map $n_d = f(\upsilon_d)$. Gradient refractive index (GRIN) lenses have a spatially varying index and dispersion and are represented by a line on the glass map. GRIN lenses open the door to a wide variety of optical design applications incorporating entire lenses of axial gradient refractive material (macro-AGRIN). Axial gradient material essentially gives biaspheric behavior to lenses with spherical surfaces and exhibits a controlled gradient in both index and dispersion. Thus, the applications for this material range from simple singlet lens used for imaging laser light, in which spherical aberration is eliminated, to complex multielement lens systems, where improved overall performance is desired. The fusion/diffusion process that produces this material is surprisingly simple, repeatable, and applicable to mass production. The advantages of AGRIN technology coupled with the recent advances in material development and its accessibility in commercially available lens design programs provides optical designers with the opportunity to push the performance of optical systems farther than with conventional optics. *© 1997 Society of Photo-Optical Instrumentation Engineers.* [S0091-3286(97)00406-6]

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## 1 Introduction

Traditional optical systems are based on the use of homogeneous refractive materials with spherical surfaces. A spherical surfaced lens will produce images with intrinsic optical aberrations. Basic optical principles lead to the use of multiple elements in a lens system to provide imagery across a required field with acceptably low aberration content. Fabrication of spherical surfaces can be carried out using several traditional methods to extremely high accuracy and smoothness.

Improved images with reduced aberrations can be obtained by using aspheric surfaces. The production and testing of nonspherical surfaces is more complex and considerably more expensive than for spherical surfaces. Generally, aspheric surfaces will cost about 10 times that of a spherical surface. Nevertheless, cost efficient mass production of optical elements with aspheric surfaces can be accomplished with plastics or glasses, usually to acceptable accuracy for some applications. While mass production of molded aspherics can be cost competitive, it is subject to extremely high startup costs, limited material selection and small diameters.

Axial gradient refractive index (AGRIN) offers an approach that would build specific aspheric effects into the refractive properties of the material while permitting the use of traditional spherical surface finishing methods. The refractive power at each point on a surface is determined by Snell's law, given in Eq. (1), where $\theta$ is the angle of incidence the ray makes

$$n \sin \theta = n' \sin \theta' \tag{1}$$

with the surface normal, $\theta'$ is the angle after refraction, $n$ is the index of refraction of the incident medium and $n'$ is the index of the refractive medium. The shape of the surface determines the progressive change in angle of incidence across the aperture that leads to image formation. This same relation determines the intrinsic aberration that will be produced by the surface. Additional control of the ray passage through a surface can be gained by using a material in which the index of refraction varies with the location on the surface and/or within the medium. If the refractive index varies along the optical axis, it is known as an axial gradient. If the index varies with radius, it is known as a radial gradient.

## 2 Axial Gradients

The term macro-AGRIN refers to a solid piece of axial gradient optical material with relatively large diameter, thickness and change in index ($\Delta n$), and is used interchangeably with the term AGRIN throughout this paper.


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Macro-AGRIN is made via a high temperature fusion/diffusion process described later in this text that turns a series of discrete glasses on the glass map into glass lines (see Fig. 1). An axial gradient is typically defined by a polynomial function in $z$, the distance along the optical axis. A common expression for this type of gradient is

$$n_0 = n_{00} + n_{01}z + n_{02}z^2 + n_{03}z^3 + \ldots \quad . \tag{2}$$

The most significant way an axial gradient affects aberrations is by the variation of index over the curved surface of the lens. Snell's law states that there are only two factors that determine how light is bent when it hits a glass surface. The first factor is the angle of incidence $\theta$ of the ray on the surface, and the second factor is the index of refraction $n'$ at the point of contact. An aspheric surface controls aberrations by changing the localized radius of curvature (surface normal) on the lens surface, thus changing the angle of incidence for a particular ray. An axial gradient lens affects aberrations by leaving the surface spherical and changing the index of refraction through the material. When a curved surface is put on a plane parallel piece of this material, the gradient is exposed because the curve of the surface exposes different depths $z$ in the material. This results in a changing index value tracking radially outward along the curved surface. A lens made from a solid block of axial gradient material has two surfaces exposing the gradient (front and back), thereby giving each lens the equivalent of two aspheric surfaces. The contribution to aberration at the surface of a lens, due to a gradient material is referred to as a *surface* term. In addition to the two surface terms, there is a *transfer* term as the wavefront propagates through the lens, between the two surfaces. In this region, the light travels in a curve as the wavefront encounters a continuous change in index and dispersion, identified by the Abbe number,

$$\nu_d = \frac{n_d - 1}{n_F - n_C}. \tag{3}$$

It is important to think in terms of wavefronts, as opposed to rays, when understanding how light travels through a gradient material. A wavefront always bends *toward* the high index, where light travels slower, similar to a marching band turning a corner.

Adding up the contributions from the two surface terms and the transfer term can give AGRIN an advantage over aspheric lenses. In addition, the spherical surfaces of lenses made of AGRIN are self generating, easy to test, plate fit to high accuracy and no more expensive to fabricate than conventional surfaces. The effect on aberrations from a macro-AGRIN lens can be adjusted by changing the lens shape factor or gradient profile[1] [Eq. (2)]. A multielement lens system can benefit from a gradient index lens by relaxing the requirements of the other lenses. The gradient material essentially acts like a ''work sponge,'' soaking up a portion of the work that would have previously been distributed among all the elements. Designing functionality into an optical material helps relax optical systems and paves the way to improved performance. Improved performance can be in the guise of smaller, cheaper, sharper, lighter or stronger products.

The importance of gradient index materials have been realized for over 40 years.[2–4] Extensive theoretical exploration and conceptual designs can be found in many scientific articles.[5–8] The poor reputation of GRIN material, however, comes from stagnation in the material development. Small size (up to 3 mm), poor repeatability, and high cost are associated with GRIN materials. Four major different processes, i.e., ion exchange, sol-gel, chemical vapor deposition (CVD), and high temperature fusion/diffusion are currently used to produce GRIN materials. Recognizable commercial products are Selfoc™ produced by Nippon Sheet Glass via an ion-exchange process, graded-index optical fibers via the CVD process and axial gradient laser singlets via fusion/diffusion. Theoretically, radial GRIN is more versatile than AGRIN because the radial refractive index gradient directly contributes to the optical power, Petzval and spherical aberration of the optical system. However, by the same token, this makes the performance of the radial GRIN lens more sensitive to manufacturing variations and repeatability in the gradient index profile than AGRIN lenses. A radial gradient lens will directly affect the first and higher order properties of an optical system because the gradient is perpendicular to the wavefront propagation. Repeatability is an important issue with radial GRIN.

The contribution to aberration correction from the transfer term of a thin axial gradient lens is secondary in that the gradient does not directly contribute to the optical power or aberrations of the lens, but rather, it is the exposure of the gradient along a curved surface that is responsible for most of the aberration correction. The gradient in this case is essentially parallel to the wavefront propagation, so the transfer term is not as dominant as it is with radial gradient. Therefore, the AGRIN lens performance is more tolerant to small manufacturing variations in the profile compared to the radial GRIN lens.

## 3 Fusion/Diffusion Process (Macro-AGRIN)

A process to produce solid blocks of AGRIN is based on controlled fusion/diffusion of different glasses at a high temperature. The process, developed by Hagerty and Pulsifer,[9] starts by identifying a specific family of glass compositions that span the desired range in optical index and dispersion. AGRIN glass is created by fusing together a stack of discrete molten glass layers, where each constituent layer has a distinctive composition and desired optical property. After a controlled diffusion process at high temperature (see Fig. 2), the glass layers fuse and diffuse into one piece of gradient index glass with a smooth variation of optical properties throughout. Prescribable index profiles (linear, quadratic and cubic), in lead and crown glass compositions have been achieved in large diameters, thickness and index variation.[10–13] The initial step function index profile of the layers is eliminated via the diffusion of constituent atoms within and across the layer boundaries. This process results in a smooth variation of index. By varying the index and thickness of each layer, and by controlling diffusion temperature and time, AGRIN can be produced for arbitrary monotonic index profiles. The profiles are typically monotonic because of the separation of the constituent molten glasses based on density. High temperature diffusion (1100 °C) yields high diffusion rates for all com-


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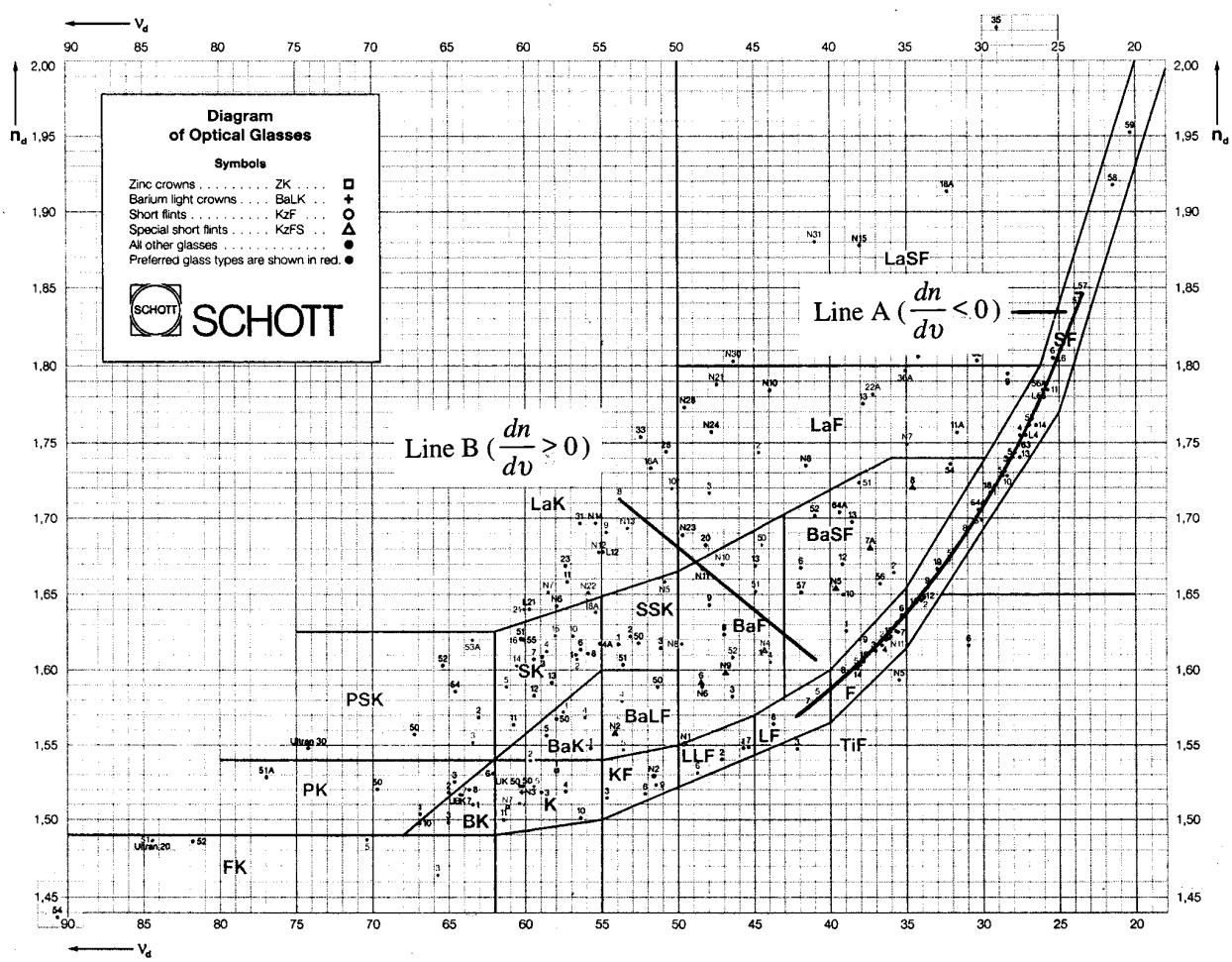


**Fig. 1** Glass map showing refractive index as a function of Abbe number.

ponents in the glass, therefore, a wide variety of glass families can be used to produce AGRIN with different index/dispersion relationships $[n_d = f(\upsilon_d)]$. Profiles with steep slopes $(\mathrm{d}n/\mathrm{d}z)$, experience more stress than profiles with small slopes. This stress is due to mismatches in the coefficient of thermal expansion of the constituent glasses after diffusion. The resultant stress manifests itself as residual asymmetric radial terms in the AGRIN material, limiting the useful aperture over which an optical quality wavefront can be obtained. Steeper sloped gradients have smaller useful diameter than shallower sloped gradients because of the residual stress associated with a more rapid change in material composition.

Two key factors of the fusion/diffusion process are (1) the selection of base glass compositions and (2) the diffusion process. The glass compositions must be compatible with each other, so that the compositional changes due to the diffusion between glass layers will not cause undesirable property changes, such as thermal expansion, phase separation and devitrification. The step function-like index profile between layers is eliminated via the diffusion of constituent atoms within and between the layers during the process; this eventually results in smooth variation in index as well as other physical and material properties. The process is illustrated in Fig. 2.

## 4 Diffusion Software

To prescribe the index profile, it is necessary to (1) establish the relation between glass properties, such as refractive index, dispersion, thermal expansion coefficients, glass transition temperature, and glass composition, and (2) understand and simulate the diffusion process. The design problem for prescribing the refractive index profile is to find the desirable glass family and an achievable initial index distribution $n(z,0)$ that will yield the desired index profile $n(z,t)$ to the accuracy required after diffusion at temperature $T$ for a time $t$. In the fabrication methods already described, the index of each layer can be fixed for a given sample batch; the design variables are then the thickness of each layer, the diffusion temperature $T$ and time $t$. Diffusion simulation software[14,15] determine these process variables quickly. The diffusion model is based on multicomponent interdiffusion theory. All constituents of



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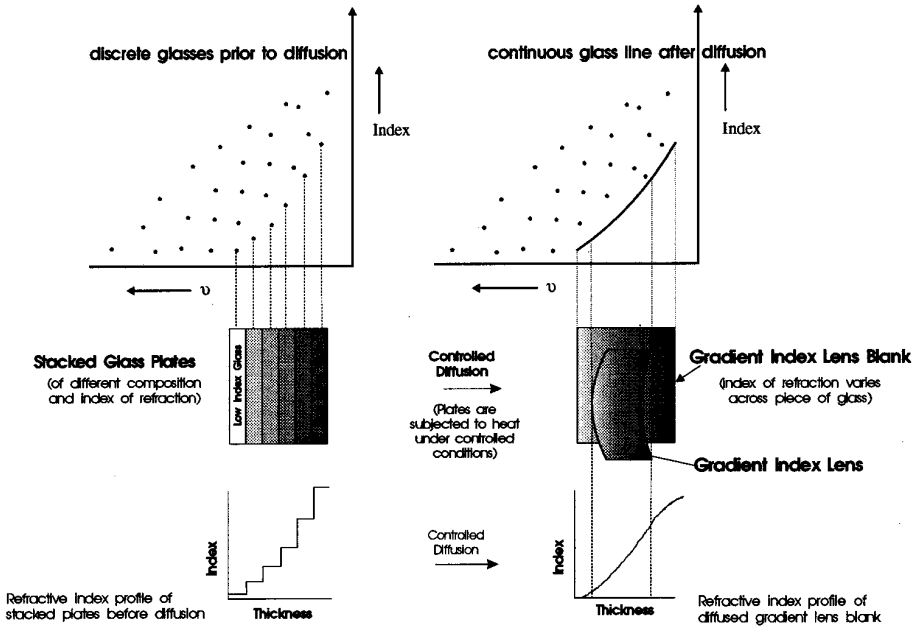


**Fig. 2** Fusion/diffusion process for axial gradient material fabrication.

the glass participate in diffusion at high temperature. The diffusion constants of these constituents are also functions of their elemental concentrations.

The change in the index distribution during the diffusion process was simulated using the diffusion software and is illustrated in Fig. 3 for a seven-layer sample. It shows that diffusion at the high index region is much faster than at the low index side. This is expected because of the higher lead densities in the higher index material. After being diffused at high temperature for the required time, the index profile becomes smooth and has a linear index gradient region between 1.580 and 1.750. Using the parameters established by the diffusion software, the calculated index profiles are in excellent agreement with the produced index profiles, demonstrating the effectiveness of the software in prescribing the index profile for specific optical designs.[10–12] Figure 4 plots the calculated index profile along with the measured data of the produced profile. The results from different diffusion experiments also show excellent repeatability in both the index profile and optical quality.

The unique aspect of this process for producing macro gradient index glass is that layers of glass possessing different physical properties can be fused together to produce a repeatable predetermined index gradient. The controlled diffusion of glass components such as Pb, Ba and La, provides a gradual transition in properties from layer to layer.

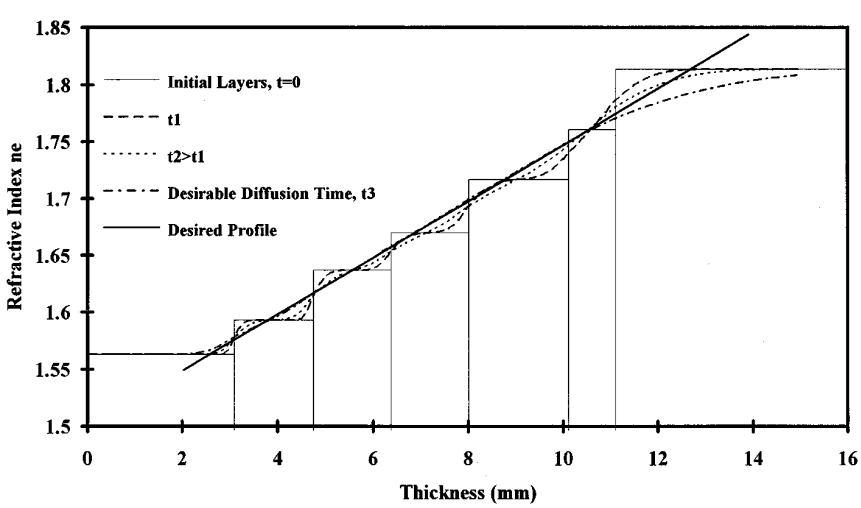


**Fig. 3** Diffusion simulation for seven-layer profile as a function of diffusion time *t* at 1000 °C.


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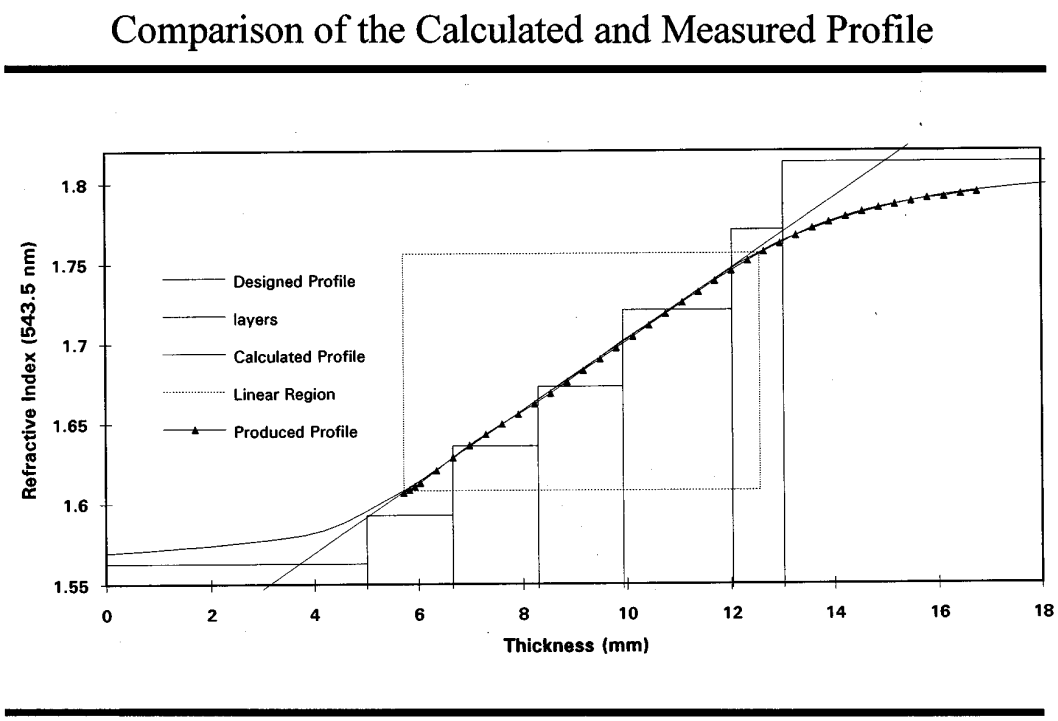


**Fig. 4** Comparison of the produced index profile with the profile calculated from diffusion software.

Carefully chosen glasses enable this high temperature diffusion process to produce gradient index glass having macro size, high $\Delta n$ and good wavefront quality.

## 5 Optical Design

Macro-AGRIN offers optical designers with a unique opportunity to incorporate lenses made from solid blocks of gradient material into their optical systems. Gradient materials are described by profiles. For axial gradients, the profile is a plot of the index of refraction at a reference wavelength (typically 0.58756 $\mu$m), as a function of axial position within the blank [Eq. (2)]. Profiles can be for either increasing or decreasing index as a function of position. The slope is negative for a decreasing index and positive for an increasing index. Some fundamental insights into the behavior of lenses made from this material follow, along with a process to define and model the dispersive properties of the gradient.

### 5.1 *Linear Versus Nonlinear Profile*

New issues have emerged while designing optical systems with macro-AGRIN materials. For instance, it has been found that nonlinear profiles are more advantageous than linear profiles because the relative slope of the gradient over each lens surface can be different.[1] Figure 5(a) shows calculated third order spherical aberration, (SA3) of an $F/3$ singlet lens, plotted as a function of lens shape factor $X$, for a linear gradient range of $-0.4 \leqslant \Delta n \leqslant 0.4$. The different curves represent different slopes, or $\Delta n$'s. For a lens with the object at infinity, minimum SA3 occurs near a shape factor, or bending, of $+1.0$, which corresponds to a convex first surface and a flat rear surface. To correct an $F/3$ singlet for SA3 using a linear gradient, $\Delta n$ must be between $-0.03$ and $+0.25$. Once that condition is met, there exists a solution for zero SA3. The most prominent aspect of this plot however, is that the curves tend to pivot about a point that has a shape factor of zero (equiconvex/convex). The phenomena that we call the pivot point has been observed for all cases analyzed, including root mean square (rms) spot size, coma, astigmatism and distortion. The pivot point also exists for spherical type gradient geometry's (but shifts as a function of the exact radius of the isoindicial surfaces). In essence, the existence of the pivot point implies that a monotonic linear profile throughout the material has no effect in controlling SA3 when the shape factor of the lens is near zero. Wang hints at this in his dissertation.[16] For an equiconvex lens with a linear axial gradient, the net effect of the gradient on spherical aberration is zero because the two spherical surface curvatures, of equal and opposite sign, have the same gradient slope over the saggita $z$ (sag), given by

$$z = \frac{cr^2}{1+(1-c^2r^2)^{1/2}}. \tag{4}$$

The contribution to spherical aberration from one gradient surface is canceled by the other gradient surface. For a lens bending $-1 \leqslant X \leqslant +1$, a linear axial gradient lens' optical performance is compromised by one of the surfaces. Meniscus lenses, however, have the property that the gradient contribution to spherical aberration is additive on both surfaces because their curvatures are of the same sign.

The existence of the transfer term, and the fact that the marginal ray heights are different on each surface for a



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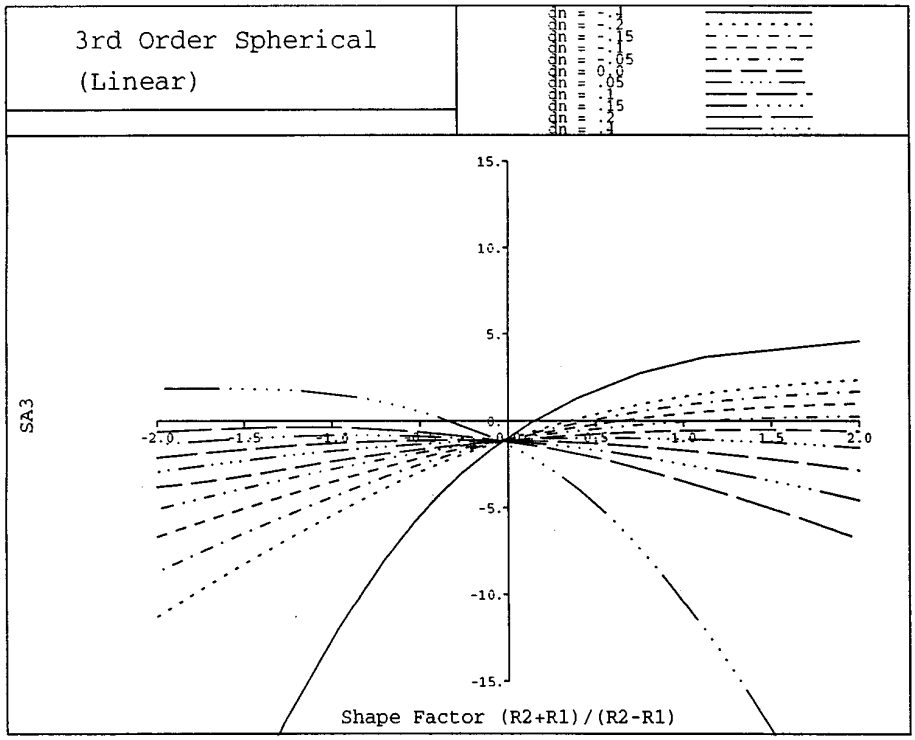
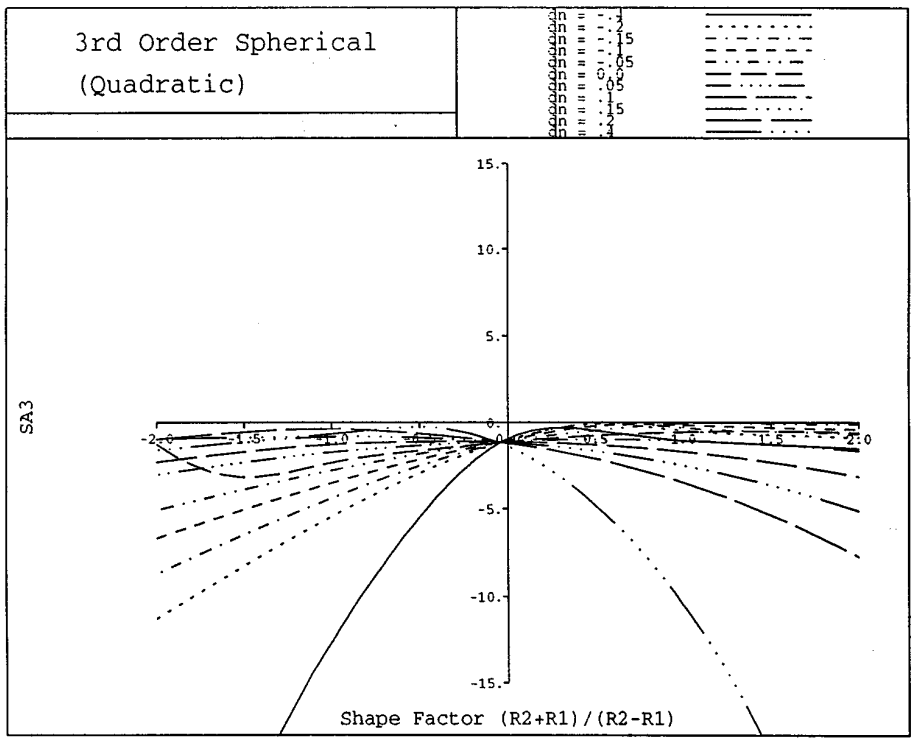



(a)




(b)

**Fig. 5** Third order spherical aberration versus lens shape factor for (a) a linear gradient profile and (b) for a quadratic gradient profile.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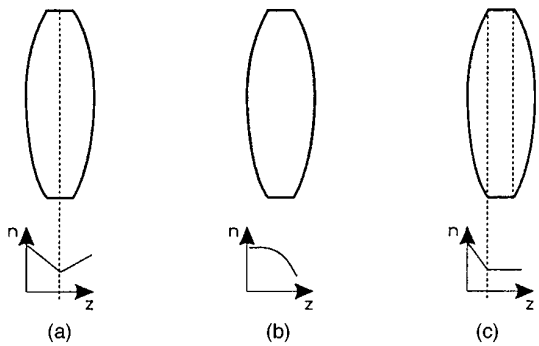


**Fig. 6** Three methods of altering gradient slope over each curved surface of a lens: (a) two cemented linear gradients, (b) nonlinear profile, and (c) grin cap.

given ray, shifts the pivot point slightly away from the zero shape factor. The proximity of the pivot point to the zero shape factor is direct evidence that the inhomogeneous transfer term is small compared to the surface term, and thus not a significant variable for monochromatic designs of thin AGRIN lenses. One consequence of the pivot point is that SA3 can be made to change sign with bending if $\Delta n$ is large enough. Another, is that less $\Delta n$ is required for positive bendings than for negative bendings to achieve this sign reversal. This is a direct consequence of the minimum SA3 occurring for a shape factor near $+1.0$ for a homogeneous lens. The pivot point provides useful insight when designing optical systems with this material. To maximize the potential of macro-AGRIN, lens shape factors near zero should be avoided, and lenses with shape factors between $\pm 1$ should be viewed with suspicion. There are situations however, in which it is desirable to have a lens with a shape factor near zero. Such situations might exist when trying to incorporate gradients into existing designs with minimal amount of redesign, when trying to balance other aberrations, or when working with finite conjugates. To effectively apply axial gradients to near equiconvex or concave lenses the gradient contribution over each surface must be changed by adjusting the relative slope of the gradient over each of the lenses curved surface.

Nonlinear sigmoid type gradient profiles can help address the problem of the pivot point cancellation. The slope of a nonlinear gradient may start out high and end low or visa versa. The nature of a nonlinear gradient therefore allows the GRIN aberration contribution on each surface to be changed by altering the relative slope of the gradient over each surface. Thus, nonlinear axial gradients are more effective than linear axial gradients because there is less compromise for lens bendings between $\pm 1$. Figure 5(b) shows the same plot as Fig. 5(a) for a nonlinear, monotonic (quadratic), gradient profile. There are many more solutions for zero SA3 using nonlinear gradients than for linear gradients. Note in Fig. 5(b) that SA3 does not change sign as it does for the linear gradients in Fig. 5(a). Once a particular $\Delta n$ hits zero SA3, it stays there for the remaining shape factors. Although the pivot point does not change with nonlinear gradients, there are many more useful solutions at other shape factors.

Figure 6 shows several ways to change the relative gradient slope over the two surfaces of a lens. The first, Fig. 6(a), shows two separate slopes, of opposite sign, over each surface. In this case, the gradient surface terms are additive for shape factors between $\pm 1$ and subtractive for meniscus shapes. Processes such as ion exchange will produce such profiles, of equal but opposite slope, but the small penetration depth of gradient into the material limits the useful diameter of the optics. Figure 6(c) shows a grin cap,[10] which essentially puts a gradient over one side of the lens and makes the other side homogeneous. In the case of a grin cap lens there is only one surface term. To make a grin cap lens, two lenses would be made (one gradient and one homogeneous) and cemented together. This adds complexity to the fabrication process. Figure 6(b) shows a natural quadratic profile that starts out shallow on the first surface and ends up steep on the second surface. The fusion/diffusion process that makes macro gradient naturally comes out in a sigmoid profile, flat on the top, steepest in the center, and flat at the end. Careful positioning of the lens within this type of profile allows for many more solutions to SA3 than with a linear gradient profile.

### 5.2 *Asphere Versus AGRIN*

To correct for a given amount of spherical aberration, the steepness of a gradient slope scales inversely as a function of lens aperture. The smaller the lens, the steeper the slope required to do the same amount of work as a larger lens. For example, the amount of $\Delta n$ required to correct the spherical aberration of a 10 mm diameter $f/2$ singlet is the same as that required for a 50 mm diameter $f/2$ singlet. Since $\Delta n$ is a constant, but $\Delta z$, the difference in sag between the two lenses is not, the slope $\Delta n/\Delta z$ scales inversely with aperture. Some of the issues relating the lens design process with the material fabrication process include practical limits to lens diameter and the quality of the transmitted wavefront. From a manufacturing perspective, steeper sloped materials are currently better suited to smaller aperture optics and shallow sloped materials may be used for larger diameter optics. The reason for this, is that residual thermal stress in the material is a function of $\Delta n$ and slope. Steeper sloped materials have higher stress which results in stronger residual radial terms distorting the transmitted wavefront in an asymmetric way. The higher stress results from the material changing rapidly over a short distance . To maintain comparable wavefront quality to that of shallower sloped material, the aperture must be reduced. Since this is a material and manufacturing issue, and not a fundamental limitation, these issues may be worked out in time.

To compare a lens with an aspheric surface to a macro-AGRIN lens requires some definitions. A direct comparison of AGRIN material to an asphere is difficult because of the transfer term associated with gradient material. To isolate the surface term of an AGRIN lens, it is necessary to examine a plano-convex lens, with the plano side facing a collimated wavefront. In this special case, the transfer term is zero and the plane wave propagates through the axial gradient undeviated. The wavefront is only affected by the gradient on refraction at the second surface, where the variation of index over the curved surface affects the bending of light differently than a constant index would. A



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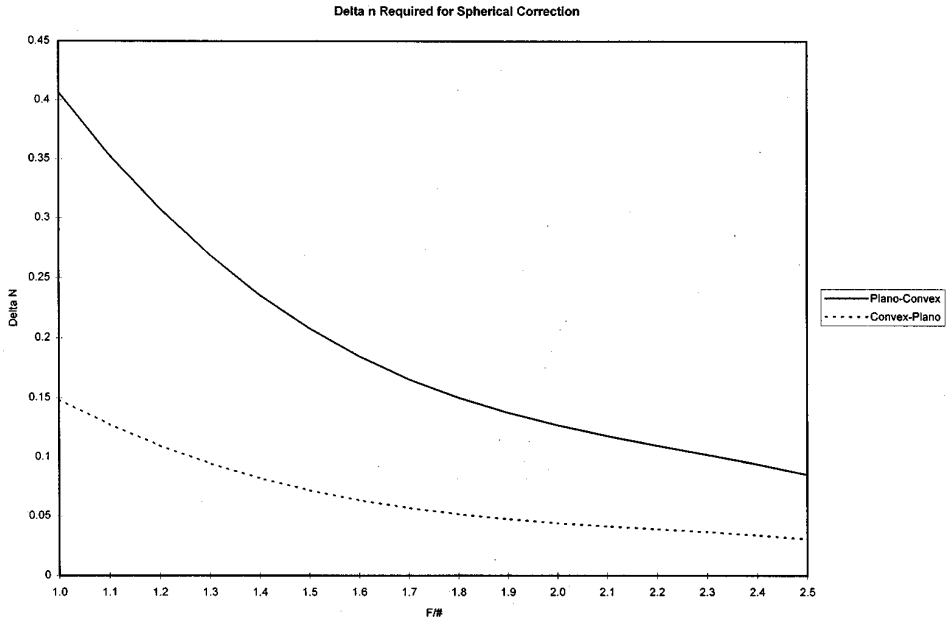


**Fig. 7** Delta index required to correct spherical aberration as a function of lens *f*-number.

plano-convex lens such as this, with a shape factor $X=-1$ has a fair amount of negative spherical aberration. The shape factor for minimum SA3 of a homogeneous lens is near a convex-plano lens ($X=+1$), where the convex side faces the infinite conjugate. The amount of gradient and/or asphericity required to correct a plano-convex lens for SA3 will be more than it would for a convex-plano, but the relative difference between $\Delta n$ and maximum asphericity reflect the work that the isolated surface terms are contributing to spherical aberration. Figure 7 shows a plot of $\Delta n$ required to correct spherical aberration as a function of lens $f$-number for surface contribution only. The $\Delta n$ values in these plots show what is required to correct all orders of spherical aberration for a one inch diameter, $f/2$ singlet of shape factor $X=\pm 1$.

Figure 8 shows the same plot as Fig. 7, for an aspheric lens of shape factor $X=\pm 1$. The $y$ axis represents the

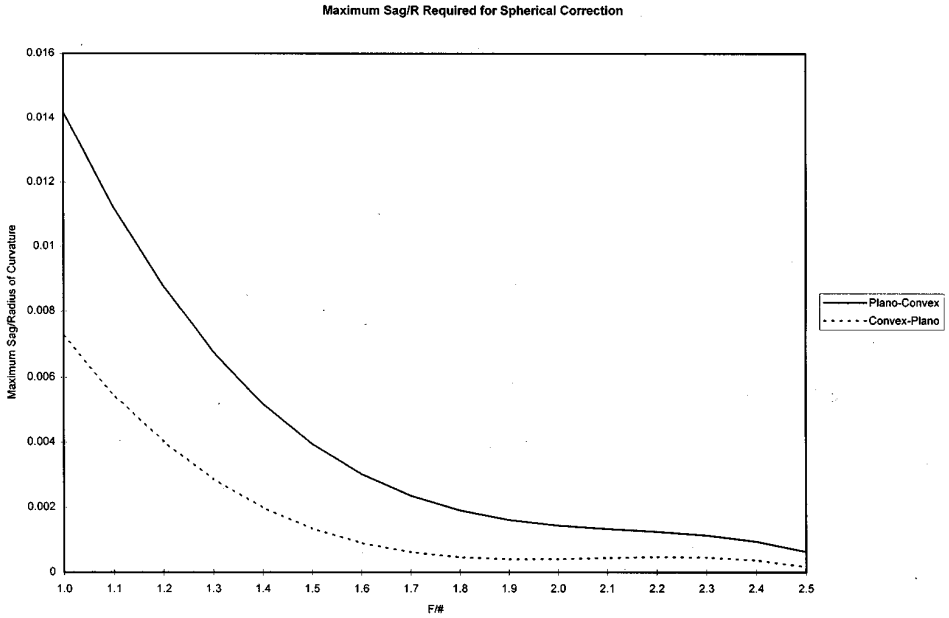


**Fig. 8** Normalized aspheric sag required to correct spherical aberration as a function of lens *f*-number.


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maximum amount of aspheric sag deviation required to correct spherical aberration. Since the maximum aspheric sag of a surface scales with radius of curvature, the aspheric sag values plotted in Fig. 8 are normalized to the radius of curvature of the aspheric surface.

## 6 Dispersion Modeling: A Walk Along the Glass Line

All points within homogeneous elements have the same value of index and are the same function of wavelength. GRIN elements have a spatially varying index function. The GRIN transfer term depends on the spatial derivative of the index. The index and its spatial derivative have different dispersion properties. This difference allows chromatic corrections to be dealt with in new ways in systems with GRIN elements.

Commercially available optical design software has been able to trace rays through an inhomogeneous material for many years. Some of the more popular profiles and geometries are programmed for user convenience. When a gradient geometry is selected (such as axial, radial, or spherical), the user may define the coefficients to describe a specific index variation (profile), throughout the material. These coefficients may also be variables during optimization.

It is generally known that index of refraction for optical materials is a function of wavelength.[17] This is also true for macro-AGRIN material where the index $n$ is a function of Abbe number $\upsilon$ [Eq. (3), Fig. 1]. The index profile is typically described by a polynomial [Eq. (2)]. Because of dispersion, the coefficients describing this profile vary according to wavelength. Designing white light optical systems with gradients requires the designer to control the relationship between $\Delta n$ and $\Delta\upsilon$ if the resultant gradient material is to be realistic. Since AGRIN is represented by glass lines, or monotonic curves, on the glass map, this relationship can be predefined for each specific family of glasses and thus transparent to the optical designer. Each constituent glass comprising the family has its own unique set of Buchdahl coefficients describing its dispersion. Fitting these Buchdahl coefficients to a function in index through the full range of the material links the dispersion coefficients to material position within the material.

Given the Buchdahl dispersion expression as follows,

$$\delta n = V_1\omega + V_2\omega^2 + V_3\omega^3 + V_4\omega^4,$$

where

$$\delta n = n_i - n_d, \quad \omega = \frac{\delta\lambda}{1+\beta(\delta\lambda)}, \quad \beta = \frac{1.0}{\lambda_d - 0.187},$$

$$\delta\lambda = \lambda_i - \lambda_d, \quad \lambda_d = 0.58756 \ \mu\text{m}.$$

Each glass in the family has its own set of coefficients, $V_1$, $V_2$, $V_3$, and $V_4$, to describe its dispersion. To model the gradual variation in chromatic properties within the gradient material after each glass has been fit to Buchdahl, the coefficients $V_i$ are fit to a cubic function in $n_d$, defined as the index at the reference wavelength (typically 587.56 nm). The result looks like

$$V_i = \alpha_i(n_d^3) + \beta_i(n_d^2) + \gamma_i(n_d) + \delta_i. \tag{5}$$

Since the Buchdahl fit in this case is carried out to the fourth term, there are four values of alpha, beta and gamma and delta each. Once $n_d(z)$ is known from the reference profile through the material [Eq. (2)], the Buchdahl coefficients can be calculated at that location. Once the Buchdahl coefficients are known, so is the index at any wavelength. This methodology has been implemented in several of the commercially available software codes where each AGRIN glass line has its own unique name that the designer can call out. Once the type of AGRIN glass is chosen (flint, crown etc.), the designer only needs to be concerned with the index profile at 587.56 nm wavelength. The software will fill in the indices at all the system wavelengths. This model contributes only $1\times10^{-5}$ uncertainty[17] in index and may be implemented from catalog data of constituent glasses prior to diffusion, or measured index data at several wavelengths after diffusion.[17]

For lens designers who want to use off-the-shelf AGRIN profiles, a gradient surface type has been developed allowing the use of predefined profiles that can be called by name. This capability can be found in CODE V (CODE V Optical Design Software is a product of Optical Research Associates, Pasadena, California), OSLO (OSLO, Sinclair Optics), and ZEMAX (ZEMAX Optical Design Program is a product of Focus Software, Inc., Tucson, Arizona). After the profile is selected, the lens is then positioned within the material. This profile library enables the designer to model an AGRIN lens with existing material as opposed to designing a new profile for the application. The designer designates either the distance of the lens vertex into the material, or the index value at the vertex of the lens. The distance $\Delta z$ can be a variable in optimization, with the index value reflecting the position of the front vertex. During optimization, the lens slides through the material searching for the best location of the lens within the index profile. For this type of surface, the measured index data has been fit to an 11th order polynomial in $z$, where $z$ is normalized to the maximum blank thickness. If done carefully, the rms error of the 11th order fit can be kept to within $\pm4\times10^{-4}$ nominally. Uncertainties in index measurements are typically of the same magnitude as the fit uncertainty in the preceding method. For high performance applications, a ''grin fit'' should be performed as described in Sec. 8 to eliminate the high order wrap of the 11th order polynomial, known as ''Gibs phenomena.''

For general gradient index lens systems, including singlets, the best design methodology found to date is to start by choosing a gradient surface type whose profile can vary during optimization, and whose dispersion may be defined using the preceding Buchdahl model (CODE V, OSLO, and ZEMAX). During the optimization process, keep the step size[18] through the gradient large enough to avoid local minima (0.5 mm or greater recommended) and bound the minimum and maximum index to appropriate values within the blank. It is also advisable to constrain the profile to be monotonic, either rising or falling.[1] After the design is well under way and controlled, the designer may switch to an off-the-shelf material, as discussed previously in the profile library, whose slope is nearest to the one obtained via the first round of optimization. Once the real material is cho-



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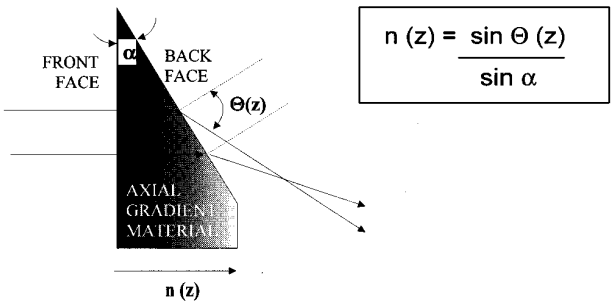


**Fig. 9** Basis of prism refractometer design.

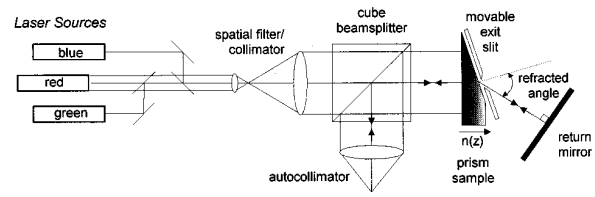


**Fig. 10** Schematic diagram of the prism refractometer as implemented.

sen, the rest of the variables of the lens, including its position within the gradient blank, are adjusted to optimize performance.

## 7 Metrology

Accurate measurement of the refractive index and dispersion as a function of position is essential to the successful application of AGRIN material to optical systems. Various approaches have been used to evaluate the refractive index variations within a gradient material. These approaches include, but are not limited to interferometry, the schlieren technique, prism refractometry, and the scanning total reflection method.[8,19,20]

### 7.1 *Axial Profiles*

To measure axial gradient profiles, we chose a method based on prism refractometry for its ability to measure thick axial gradient samples having large $\Delta n$'s and its amenability to automation.

The prism refractometer design is a straightforward application of Snell's law. Light incident perpendicular to the front face of a homogeneous right angle prism will refract at the prism's back face at angle $\theta$. To measure the refractive index variation as a function of material thickness in an axial gradient sample, the prism is fabricated such that the front face is uniform in refractive index, while the angled back face exposes the refractive index variation (Fig. 9). The refracted angle is measured as a function of position along the gradient prism back face and the axial index profile $n(z)$, is calculated via Eq. (6), where $\alpha$ is the prism apex angle:

$$n(z) = \sin\,\theta(z)/\sin\,\alpha. \tag{6}$$

The table top implementation of this measurement technique is diagrammed in Fig. 10. Three lasers (488.0, 543.5, and 632.8 nm) are coaligned, spatially filtered and collimated to provide a 2 in. diameter, three color collimated source. This collimated beam is split by a cube beamsplitter to provide a reference and a test arm. The reference beam is aligned on the reticle of an autocollimator. A video camera positioned at the autocollimator eyepiece displays the reticle on a monitor. The test beam passes through the cube beamsplitter and strikes the front face of the prism sample. The sample is adjusted in tip and tilt to align to the prism to the optical axis of the reference beam. After passing through the sample, the test beam is refracted and then retroreflected back through the sample, the cube beamsplitter, and into the autocollimator. Along the prism back face the exposed index gradient causes the refracted angle to vary as a function of physical location. A movable exit slit (approximately 0.25 mm in width), coincident with the angled back face of the prism, determines the location under test on the prism surface. The exit slit is scanned along the prism back face. At each slit location, the return mirror is rotated until the return beam is aligned with the reference beam. Both the exit slit and the rotary stage are mechanically driven, commanded by a single controller. The preceding procedure can also be performed with a stationary slit, aligned to the optical axis of the reference beam, while the prism hypotenuse is scanned across the slit. This configuration will eliminate angular errors as a function of aperture due to the spherical aberration of the collimator.

From this measured data, the refractive index is calculated and plotted as a function of sample thickness. To assess the absolute accuracy of the index measurement a homogeneous prism with known index is measured before each test. The accuracy and precision of this test device have been evaluated and quantified. Figure 11 shows the rms precision of the refractive index measurements to be $1.7\times10^{-4}$. Measurements of a homogeneous BK7 prism indicate that the absolute accuracy of refractive index is $\leqslant 4\times10^{-4}$. The Abbe number is known to within 0.28. To verify the dispersion model via the preceding Buchdahl technique, a minimum of five different wavelengths should be used, preferably in the shorter end of the spectrum. To date, this has not been done. The dispersion models being used in design codes are based on the constituent glasses in the particular family, or glass line, and not on measured data. Partial dispersion also needs to be characterized for these types of axial gradient materials.

## 8 Design Tips and Strategies

Three commercially available optical design software packages, CODE V, and ZEMAX, and OSLO (as already described), offer design capability with macro gradient index materials for which glass lines can be modeled via the method described. Designing lenses with gradients is easy. The placement of gradient lenses within an optical system is very similar to that of aspheres. The designer should select a lens or lenses to be gradient index based on the type of aberration to be corrected. To reduce spherical aberration, place the gradient in a lens near a stop or pupil. To control distortion or other field aberrations, try placing the gradient in a lens away from the stop or pupil. The gradient material currently available is composed of flint type glasses. For white light optical systems, flint glasses typi-


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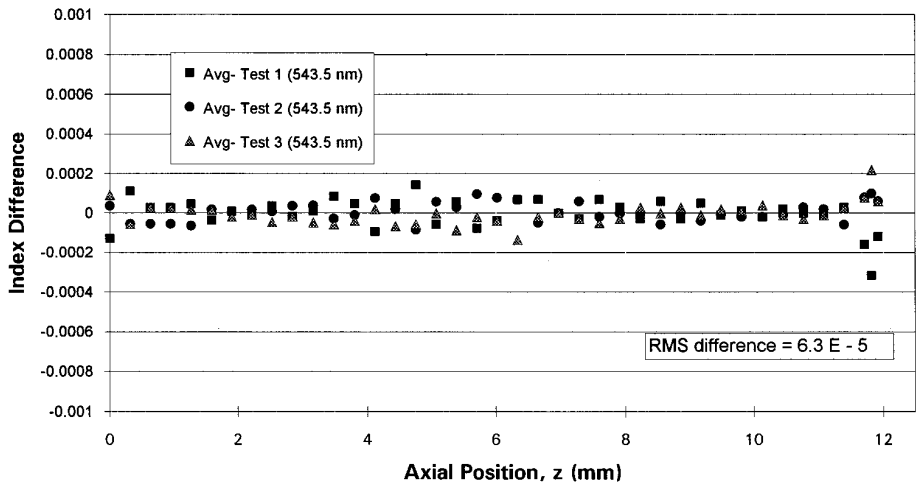


**Fig. 11** Refractive index measurement repeatability.

cally have negative power. After identifying where the gradient lens should be, rough out the design using the first three profile coefficients as variables (base index $n_0$, linear term $n_1$, and quadratic term $n_2$). Bound the maximum and minimum index within the lens to lie within a reasonable range for the family (typically $1.6 \leqslant n \leqslant 1.8$ for flint type glass). Also constrain the gradient profile to be monotonic.[1] Keep the step size greater than 0.5 mm to avoid local minima in the solution space. Some software has functions that specifically control these parameters and some software requires the user to write special macros. Global optimization works well with gradient designs. After a desired solution is reached with the profile varying, the designer has the option of having that specific profile fabricated, or finding a close match to existing profiles already in fabrication by lightpath technologies. In some software packages, these profiles are stored in a profile library that can be called by name. The sigmoid type profile is represented by an 11th order polynomial with a normalized $z$ coordinate. The coefficients for the library profiles are fixed. The only variable during optimization using pre-stored profiles is the position of the lens within the material, $\Delta z$. Try reoptimizing the lens first with the position fixed, then vary $\Delta z$ during the final stages of optimization. Since library profiles are ''catalog'' profiles, the index variation of the real material may differ from that described by the coefficients, very much like index data for any particular glass melt may differ from the index data found in the glass catalog. The rms error of the index data to the 11th order polynomial representation is around $\pm 4 \times 10^{-4}$ with the best fit occurring in the middle of the profile. For many applications, this variation will not be a problem. If the fit error reflected a simple uncertainty in base index of $\pm 4 \times 10^{-4}$, a small focus change could be used to compensate. The fit error, however, represents an rms error in the nonlinear profile, which is much less forgiving than a single index value. The diffusion process yields relatively low order sigmoid type profiles. The 11th order representation of the catalog profiles can sometimes result in the lens position slightly off from optimum. For high performance optics, a fit uncertainty less than $10^{-5}$, of the polynomial over the region of interest is recommended. This may be achieved via a ''gradient fit'' or ''profile scan,'' described later.

Optical design tolerancing of nonlinear gradient index profiles is not standard in most commercially available software packages. A methodology has been developed for evaluating the performance of a design using any AGRIN profile. This methodology states that once a design is complete, the AGRIN profile is measured and the design reoptimized around the existing profile via a process very similar to a melt fit. This is accomplished through some special software that essentially places the AGRIN lens at the beginning of the material profile, cuts and pastes the local part of the gradient that occupies the lens, fits it to a high order polynomial and reoptimizes the system variables and evaluates performance. As the lens is stepped through the material in software, each step is fit to a different subportion of the profile and the system is optimized and evaluated. A plot of performance versus vertex index, or thickness into the material, identifies the best part of the profile to be used. Since, at each step, the polynomial is fit to a subportion of the profile, the rms error of the fit is typically small, $\text{rms} \leqslant 2 \times 10^{-5}$. The system parameters for that location are obtained and frozen and the step process through the profile is repeated with focus as the only compensator. Figure 12 shows rms wavefront error versus vertex position for 12 separate runs of an $f/2.5$ half inch diameter lens series. There are several things to note in Fig. 12. First, the sweet spot of the profile is easily identified at the minimum of the plot (rms wavefront $= \sim 0.04$ waves). Second, the tolerance on the position within the material is obtained from the width of the minimum. Third, the performance of the lens is known based on using real material that has been fabricated and measured. The designer can tell right away if the profile will be sufficient. Finally, the variation in performance from melt to melt can be tracked, as it was in this case. Figure 12 shows that transmelt variations in the profile have little effect on the performance of the final product and all lenses may be fabricated the same. Figure 12 shows



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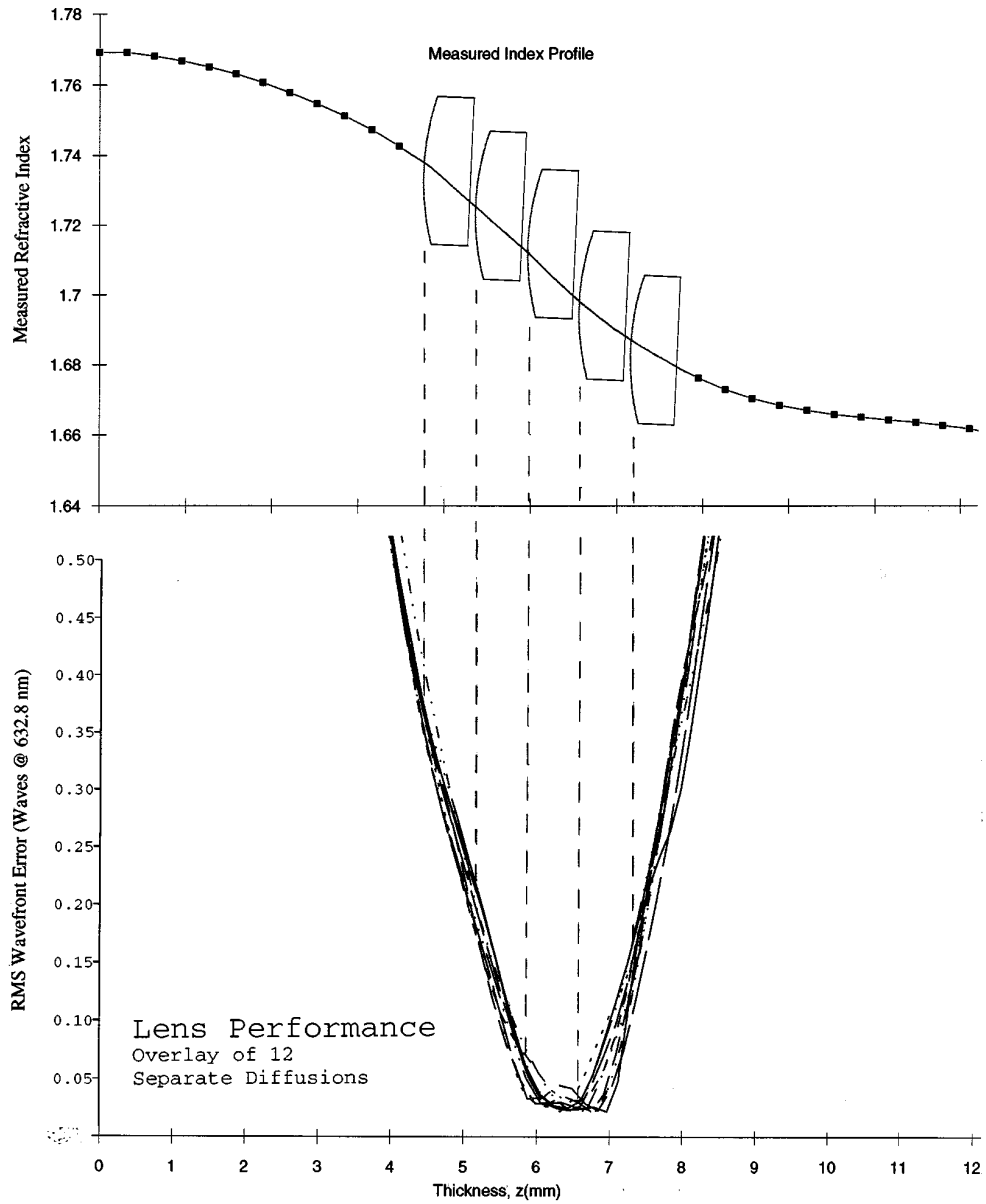


**Fig. 12** Profile scan technique. Software scans lens through measured profile data and plots performance as a function of position in the AGRIN material. This scan shows performance and repeatability of about 1000 *f*/2.5 singlets. Lens depth within AGRIN blank and positional tolerance are shown at minimum.

the design performance and material variation for over 1000 laser singlets.

## 9 Application Issues for AGRIN

AGRIN lenses are particularly well suited for use in high performance, high power laser systems.[20–23] It takes only one AGRIN lens to accomplish the same task that in conventional technology would require two to three elements. Figure 13 shows an interferometric comparison between a commercially available $f/3.3$ air spaced laser triplet and an $f/3.0$ AGRIN singlet, each 25 mm diameter. The benefits of this technology include lower surface scatter, small spot size at the focus, high energy densities, and high power handling capability, simpler, more compact and/or lower cost optical systems. In Fig. 13(b), the 1 in. diameter AGRIN lens out performs the triplet with an rms wavefront error at 632.8 nm of 0.02 waves.

Another place to apply AGRIN is in the replacement of aspheres.[20,21,23] Until now, gradient index manufacturing technology has been limited to ion-exchange, sol-gel and chemical vapor deposition. Limitations in element size, gradient depth and index range of these technologies have ensured aspheres a strong foothold in the optics infrastructure. Aspheres provide the optical designer a powerful tool


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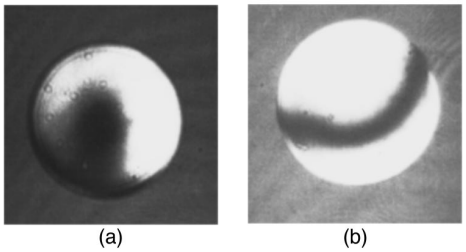

(a) (b)

**Fig. 13** (a) Interferogram of an *f*/3.3 air spaced laser aplanat; 0.25 waves PV and 0.029 waves rms and (b) interferogram of an *f*/3.0 AGRIN singlet; 0.141 waves PV and 0.02 waves rms.

in correcting aberrations and pushing the performance in state-of-the-art optical systems. But the nonspherical surfaces of aspheres are difficult to fabricate and test, especially in volume productions. Precision molded glass aspheres less than a half inch in diameter are high quality. Large diameter molded aspheres allow for high volume production but their poor quality limits their application to low tech consumer products that do not place a high demand on performance, such as condenser lenses. Molded aspheres appear in products that stress weight, size and cost as their metric for success. The properties of AGRIN can be designed and optimized for a specific optical application. The concept of *designer* glass is attractive for many reasons. To understand why, it helps to break the discussion down into three categories of consideration: performance, fabrication and materials.

For aspheric technology to be practical in a volume production, it is necessary to use molded aspherics because hand polishing is cost prohibitive. Molded glass lenses have a relatively poor polish on the surface, which contributes to scattered light, reducing contrast and degrading modulation transfer function (MTF). Molded plastic lenses are even worse than glass. By comparison, axial gradients require only spherical surfaces. Spherical surfaces are self generating, easily test plate fitted to high precision, and amenable to super polishing for low scatter surfaces. AGRIN lenses use conventional fabrication techniques and thus may be produced in high volume and could represent a significant cost savings over polished aspheres. In addition, AGRIN profiles with the fusion/diffusion process are very repeatable and the performance of fabricated lenses has been repeatable.[24] Figure 12 illustrates the performance of a half inch diameter, $f/2.5$ singlet AGRIN lens for 1000 lenses. The refractive index profile for each melt is measured and the lens design is stepped through the profile data in software. At each step, the used portion of the gradient profile is cut and pasted into the lens, and performance is evaluated in rms wavefront error. When plotted, the sweet spot in the gradient blank can be identified and the tolerance of the lens position within the blank can be noted. This profile scanning technique paves the way for high performance and repeatability in AGRIN lenses.

Molded lenses are limited in material choice. Typically, low index material such as Bk, LF and F glass is used for molding. High index lanthanum and short flint glasses are undesirable for molding because of their temperature/viscosity constraints and recrystallization problems. The use of low index materials means higher curvature/asphericity on the lens to accomplish the desired task, and hence, molded aspheres are more difficult to make and test accurately than hand polished, high index aspherics. In addition, limiting the molded aspherics to low index material makes them unattractive for negative elements. AGRIN exhibits a gradient in both index and dispersion. This is a key factor in optical design. A single lens made of this material essentially starts out with one glass and ends with another. It is a seamless, contiguous variation in index and dispersion. This variation of dispersion, not just index, can be advantageous for correcting chromatic aberrations in multielement white light optical systems.

Areas to apply AGRIN are in multielement laser lens systems or white light systems. AGRIN lenses have been used in lens systems to reduce the number of elements by 25 to 50%.[25] In addition to reducing element count, they can also be used to relax optical designs, lowering the sensitivity to alignment and fabrication errors.

When placed near a pupil, or aperture stop, an AGRIN element can do an excellent job of lowering spherical aberration. When placed away from the stop, it can be used more to correct field aberrations, including distortion. AGRIN elements have been successfully used in very wide angle applications to drop distortion from 10% to less than 3%.

Figure 14 shows a design example of an $f/2.2$ cemented doublet and how AGRIN can be used to control spherical aberration, and with the correct choices of glass lines, can be used to correct axial color and spherochromatism as well. Figure 14(b) shows the ray aberration curves for an $f/2.2$ conventional doublet with BK7 and F2 and a 12th order asphere [lens shown in Fig. 14(a)]. Figure 14(c) demonstrates the performance of a bi-AGRIN doublet with axial color and spherochromatism corrected. Both ray aberration plots are at a scale factor of $\pm 25\ \mu$m. The negative lens in the bigradient doublet uses a gradient glass line through the flints and short flints. The positive element uses a glass line through a crown family, with a negative slope on the glass map. Figure 1 shows these two glass families as lines A and B respectively. This crown family, line B, was selected by adjusting the slope $dn/d\nu$ of the glass line to minimize axial color when used in conjunction with the flint line A. Both gradient elements have positive slopes in index $dn/dz > 0$. The Abbe number of the crown element increases with thickness and the Abbe number for the flint element decreases with thickness. For a cemented doublet of negative power, the same families are used but the positive element is flint and the negative element is crown, and each gradient profile has a negative slope. In general, the same can be said for radial gradients correcting for axial color too. Table 1 summarizes the parameters for axial color correction with AGRIN lenses.

## 10 Summary

Macro-AGRIN is an axial gradient material represented by lines on the glass map. Because of its unique properties and biaspheric performance it can open the door to a wide variety of optical design applications. The applications for this material range from the simple singlet lens used for lasers, in which spherical aberration is eliminated, to complex multielement lens systems, where improved overall



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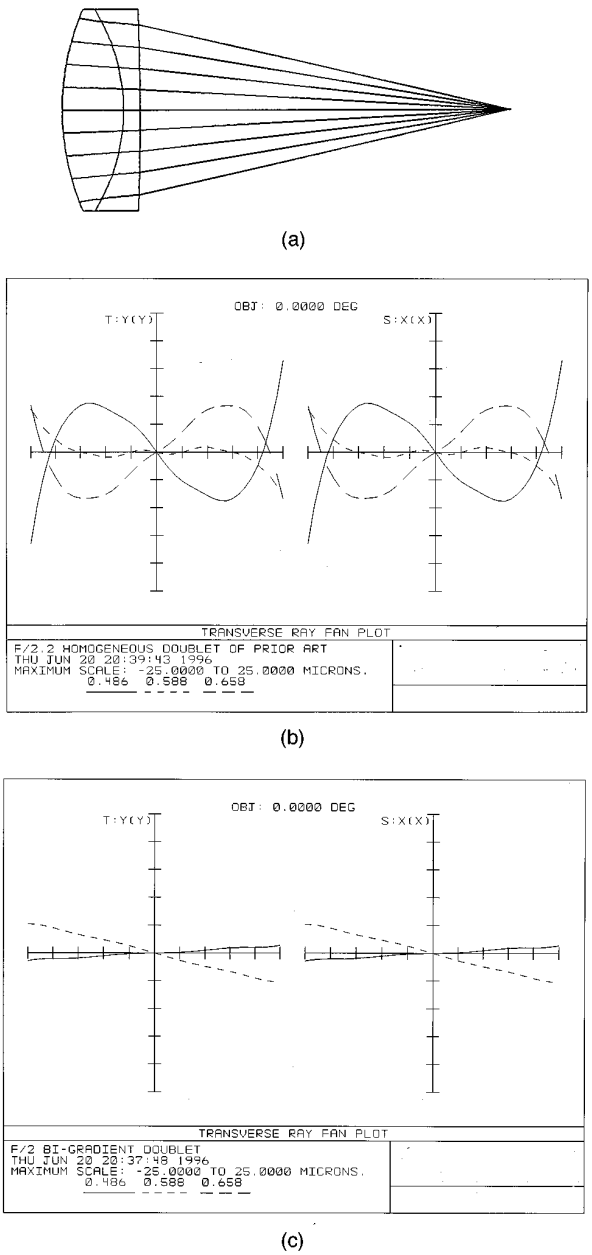


**Fig. 14** (a) *f*/2.2 cemented achromatic doublet, (b) ray aberration curves for homogeneous cemented doublet with 12 order asphere, and (c) ray aberration curves for bi-AGRIN cemented doublet whose AGRIN crown element is represented by glass line B and whose AGRIN flint element is represented by glass line A in Fig. 1.

performance is desired. The fusion/diffusion process that produces AGRIN and the diffusion/rotation process that produces radial GRIN (RGRIN)[26] are surprisingly simple, repeatable, and applicable to mass production. The advantage of GRIN and its accessibility in commercially available lens design programs, provides optical designers with the opportunity to push lens performance further than with conventional optics.

**Table 1** Guidelines for designing groups of bi-AGRIN lenses corrected for axial color and spherochromatism.

| Group Power | Glass Type | Element Power | $dn/dz$ | $d\nu/dz$ |
|---|---|---|---|---|
| + (positive doublet) | Crown | + | $>0$ | $>0$ |
| + (positive doublet) | Flint | − | $>0$ | $<0$ |
| − (negative doublet) | Crown | − | $<0$ | $>0$ |
| − (negative doublet) | Flint | + | $<0$ | $<0$ |


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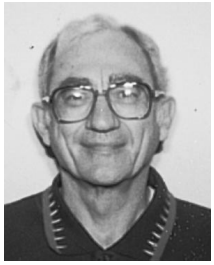

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