MGRIN Gradient Index Lens Model and Tools for ZEMAX

Radial GRIN and Ball GRIN Geometries

Version 1.0.0

April, 2016

Acknowledgements

This work was developed at the Naval Research Laboratory primarily by Guy Beadie and Richard Flynn. Many others contributed via their valuable feedback. In particular, we would like to acknowledge the input of Michael Brindza, Ozan Cakmakci, Howard Fein, Erin Fleet, Casey Kretzer, Predrag Milojkovic, Michael Ponting, John Rogers, Armand Rosenberg, and Yehudi Self-Medlin. The principal funding was provided by DARPA's Manufacturable Gradient Index Optics (M-GRIN) program, with additional support provided by the Office of Naval Research.

Disclaimer

Software summary

This suite of files was developed to implement various types of gradient index (GRIN) lenses in Zemax. There is significant overlap in execution and macros with the original release of the spherical GRIN model available at https://github.com/GrinLens/Zemax-Spherical-GRIN. The models in this new release are meant to address two common GRIN geometries: radial GRIN lenses and ball GRIN lenses.

Radial GRIN lenses are proven to be advantageous for optics, and there are several methods capable of manufacturing them. There has also been recent interest in the development of ball GRIN lenses, particularly in tandem with the development of curved sensor arrays

Since the previous release handled lenses with a spherical GRIN geometry, one might ask why we present a new DLL to support ball lenses, which also have a spherical GRIN geometry. Significant differences between the two DLLs are:

- The new Ball GRIN DLL accommodates a GRIN origin located within the lens volume.
- The new Ball GRIN DLL accommodates optimization of a spherical ball lens with an internal stop, which requires splitting the description of the ball into two separate Zemax surfaces. (In the new DLL, index parameters for the second half of the lens can simply be picked up from the first half during optimization. In the original DLL, the parameters cannot.)
- The new Ball GRIN DLL is ***not*** optimum for the geometries intended by the original DLL, where the GRIN origin is located well outside the lens volume.

As with the original release, the primary reasons for developing these tools is that native Zemax GRIN surfaces do not provide (to date):

(1) A realistic, easily manipulated material model for multi-color applications

(2) Visualization tools that allow one to easily examine the variation of index within the volume of a lens element

(3) Merit function operands which enable stable optimization of a GRIN lens, freely varying the index distribution in a lens without exceeding the refractive index limits of the material.

To address point (1) a key capability common to all these DLLs is the method of handling refractive index dispersion (wavelength-dependent index functions). A smooth variation in index is modeled by the smooth variation in composition of two, base, materials. This model can describe, or closely approximate, many realistic GRIN material systems. The base materials can be defined manually or selected from any Zemax glass catalog.

To address point (2) macros are provided which display the GRIN distribution in several ways. Annotated plots show not just the index variation within a lens, but also the variation of material composition. Additionally, to-scale contour plots of GRIN iso-index curves can be overlaid onto lens drawings. These contour plots show where in the lens the GRIN slopes are greatest, which provide insight into how the GRIN works to correct aberrations.

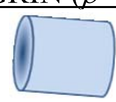
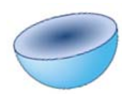
Lastly, to address point (3) a merit function operand ZPLM 18 is provided which will automatically scan one of these GRIN lenses in order to return not just the minimum and maximum refractive indices, but also penalty values for going out of bounds that work well with the numerical optimization routine used by Zemax. Without this operand, Zemax's optimization algorithms would quickly select unphysical refractive index distributions as preferred lens solutions.

In addition to more detailed reference information, below, two fully worked examples of GRIN optical design with these tools are provided at the end of this document: a *f*/3 radial GRIN achromatic singlet, and a *f*/1 polychromatic GRIN ball lens. These tutorials provide step-by-step examples of how to use the tools, as well as provide insight into how one can more efficiently design GRIN lens solutions to optical problems.

Quick Summary of Available Index Distributions:

The two new surface models are based on different geometries for the variation in index: radial and spherical. In addition to the different variations of index within the lens, each model can also implement an aspheric lens surface if desired, using an Even-Asphere-like model for the departure from a sphere.

Each model provides five different functions which can be used to describe the index variation within each geometry. The functional forms of each are provided as follows, remembering that the origin of Zemax's (x,y,z) coordinate system is located at the front vertex of the lens:

	Radial GRIN ($\rho^2 = x^2 + y^2$) 	Ball GRIN ($\boldsymbol{r} = \boldsymbol{r}_{lens} - \boldsymbol{r}_{GRIN\_origin}$) 
0	Safe: n=1.5 everywhere	Safe: n=1.5 everywhere
1	Polynomial: $\rho^0, \rho^1, \ldots, \rho^{10}$	Polynomial: $r^0, r^1, \ldots, r^{10}$
2	Even Polynomial: $\rho^0, \rho^2, \ldots, \rho^{20}$	Step Polynomial: n_o for $r<r_o$; $(r-r_o)^1, (r-r_o)^2, \ldots, (r-r_o)^9$ for $r>r_o$
3	Step Polynomial: n_o for $\rho < \rho_o$; $(\rho-\rho_o)^1, (\rho-\rho_o)^2, \ldots, (\rho-\rho_o)^9$ for $\rho > \rho_o$	Luneburg lens
4	Hyperbolic secant	Maxwell lens

The different function types are described in full detail in *Detailed GRIN Function Descriptions,* below.

The most important distinction between the Ball GRIN DLL here and the previously released Spherical GRIN DLL is that the Ball GRIN index is defined as a function of distance from the center of the GRIN distribution. The Spherical GRIN DLL index is defined as a function of distance from the *front vertex* of the lens surface. The latter case is important when the center of symmetry is located outside the lens volume, as was assumed for that model, but for true ball lenses it is far easier to use the center of the GRIN as an origin rather than the lens vertex.

Files and Installation Instructions

To install the software package, please refer to the Zemax OpticStudio manual for proper directories to place the MGRIN DLL and the macro files. (Windows 7 & 8 default: “C:\Program Files\Zemax OpticStudio\DLL\Surfaces\” and “~\My Documents\Zemax\Macros\” respectively).

If an error message such as “MSVCR100.dll is not found” appears when loading one of the DLLs, then you need to install the “Microsoft Visual C++ 2010 Redistributable Package”.

32-bit: https://www.microsoft.com/en-us/download/details.aspx?id=5555
64-bit: https://www.microsoft.com/en-us/download/details.aspx?id=14632

In addition to providing the final tutorial lens files, a series of other files is provided: at least one example file for each of the different index distributions in the DLLs.

DLLs
MGRINx64_Ball_v100.dll [64-bit version for 64-bit operating systems only]
MGRINx32_Ball_v100.dll [32-bit version for 32-bit operating systems only]

MGRINx64_Radial_v100.dll [64-bit version for 64-bit operating systems only]
MGRINx32_Radial_v100.dll [32-bit version for 32-bit operating systems only]

Macros
GRIN Base Material Index.zpl
GRIN Contour Plot.zpl
GRIN Material Report.zpl
GRIN Material Select.zpl
GRIN Mold Thickness Calculator.zpl
GRIN Profile Report.zpl
ZPL18.zpl **[User defined optimization macro – may need to be renamed with a different number if 18 is already in use.]**

Sample Files (*.zmx lens definition and *.zda layout files):

NOTE for 32-bit users: Use a text editor to replace all instances of “MGRINx64” with “MGRINx32” in any of the *.zmx files before opening them.

MGRIN_Ball_Tutorial_Final
MGRIN_Ball_Example_Poly
MGRIN_Ball_Example_PolyStep
MGRIN_Ball_Example_Luneburg
MGRIN_Ball_Example_Maxwell
MGRIN_Ball_Example_Maxwell_IntStop
MGRIN_Ball_Example_Maxwell_MultiAngle

MGRIN_Radial_Tutorial_Final
MGRIN_Radial_Example_Poly
MGRIN_Radial_Example_PolyEven
MGRIN_Radial_Example_PolyStep
MGRIN_Radial_Example_Sech
MGRIN_Radial_Example_Sech_MultiColor

Preface

For a quick overview of the GRIN model, the user should understand the basic concepts described in the "Overview" section of the MGRIN DLL description, starting on p. 6. Tutorials at the end provide step-by-step examples of how the tools work and some concepts behind GRIN optical design. The remaining documentation covers in greater detail the intent and use of each component of the GRIN design package.

The two tutorial examples demonstrate strategies for designing GRIN singlet lenses. The first tutorial demonstrates the Radial GRIN distribution. The second tutorial demonstrates the Ball GRIN distribution. While working through the tutorials, the user should refer back to the macro descriptions as needed. (Note also that the two tutorials are intended to be entirely independent of each other).

Table of Contents

Description of the MGRIN DLLs for Zemax

This software enables the design of gradient index (GRIN) lenses as part of the Zemax optical design suite. Developed as part of DARPA's Manufacturable Gradient Index (MGRIN) program, the primary vehicles consist of custom dynamic linked library (DLL) modules that define GRIN lenses for the Zemax analysis engine. The macros that come with the package will be discussed separately.

Once a GRIN surface is inserted in a Zemax design, the DLL variables are found both in the "Lens Data Editor" and in the "Extra Data Editor" (in Zemax-13 and earlier versions). Zemax OpticStudio (ZOS for short) no longer makes use of the Extra Data Editor and includes Extra Data Parameters in the Lens Data Editor. This difference, and other differences between Zemax-13 and ZOS, will be noted as appropriate throughout this document. The latest version of OpticStudio available at the time of this document is v15.5 SP3, with a release date of March 15, 2016. Performance of this version appears stable. See the Note on OpticStudio Versions for issues and possible workarounds observed in earlier versions.

Overview of the MGRIN DLL functionality:

GRIN DLLs for Zemax need to define the front surface shape and the refractive index distribution inside a GRIN lens. The surface shape is defined using variables similar to those in standard Zemax surfaces, which are generally easy to communicate. It is the definition of the index distribution which is less common in optical design.

The index distribution is described by two different sets of variables. One set describes how index varies with position inside the lens. With the Radial GRIN DLL, for example, one can switch between a quadratic or quartic variation of index, as a function of distance from the optical axis. Specifically, the parameter set describes an index curve through the lens at a single, reference wavelength. These variables are the ones generally optimized to achieve the best index distribution for an optical application.

The remaining set of variables describes two base materials, which are assumed to be blended together to form the GRIN lens. Generally *not* varied during optimization, these parameters are required to define how the lens performs at wavelengths other than the reference wavelength.

Binary Material Mixing Model:

These DLLs were originally motivated by a process which blends two separate polymers into thin films with controllable, intermediate index values that can be fabricated into GRIN lenses. Because one knows how two polymers combine to form an effective medium there's only one parameter needed to understand the material at a given point: the volume fraction of polymer A versus polymer B.

The strength of this approach is that it can be used to model other GRIN material systems, whether real or simulated. GRIN lenses rely upon a smooth variation of material composition from one point in a lens to the next. Whether the variation be due to polymer composition, diffused dopant concentration, density change, or some other underlying parameter, the optical behavior is likely to be quite well modeled by a blend of two materials. In the case of a mirage, for example, one has dense air and vacuum as the extremes. For materials with index values modulated via nanoparticle doping, the undoped and maximally doped hosts serve as the boundary materials.

The model for a GRIN lens in these DLLs, therefore, is one of a binary mixture of two materials. The user selects two materials to blend, either with the macros provided or by manually entering the information which defines their dispersion curves. Then, in analogy with Zemax's native GRIN surfaces, the user defines the variation of refractive index at a single, reference wavelength. Raytracing for the reference wavelength requires no further computation – the index variation is simply given by the user-defined curve. Raytracing at wavelengths other than the reference wavelength requires extra computation, all performed "under the hood" by the DLLs.

Though it is not necessary to know how this computation is done to use the DLLs, the math is shown here for reference. The process is based upon the following model for how materials A and B combine to form an intermediate material. To find the index n at wavelength λ in a medium with volume fraction η of material A, we define:

$$n(\lambda,\eta)^2 = \eta\, n_A(\lambda)^2 + (1-\eta)\, n_B(\lambda)^2 \tag{1}$$

where the dispersion curves for materials A and B are defined by $n_A(\lambda)$ and $n_B(\lambda)$, respectively. There are other models which describe the dependence of n on η, but this is the one chosen for these DLLs.

As mentioned above, to be consistent with Zemax's GRIN approach the user defines the variation of $n(\lambda_{ref})$ through the lens at some reference wavelength λ_{ref}. In other words, when a ray reaches some point in the lens at (x,y,z) the user has already defined the value of n_{ref} at that point. If Zemax is trying to trace rays at some other wavelength, then the DLL has to return the index at the non-reference wavelength. This is done by first computing the volume fraction via:

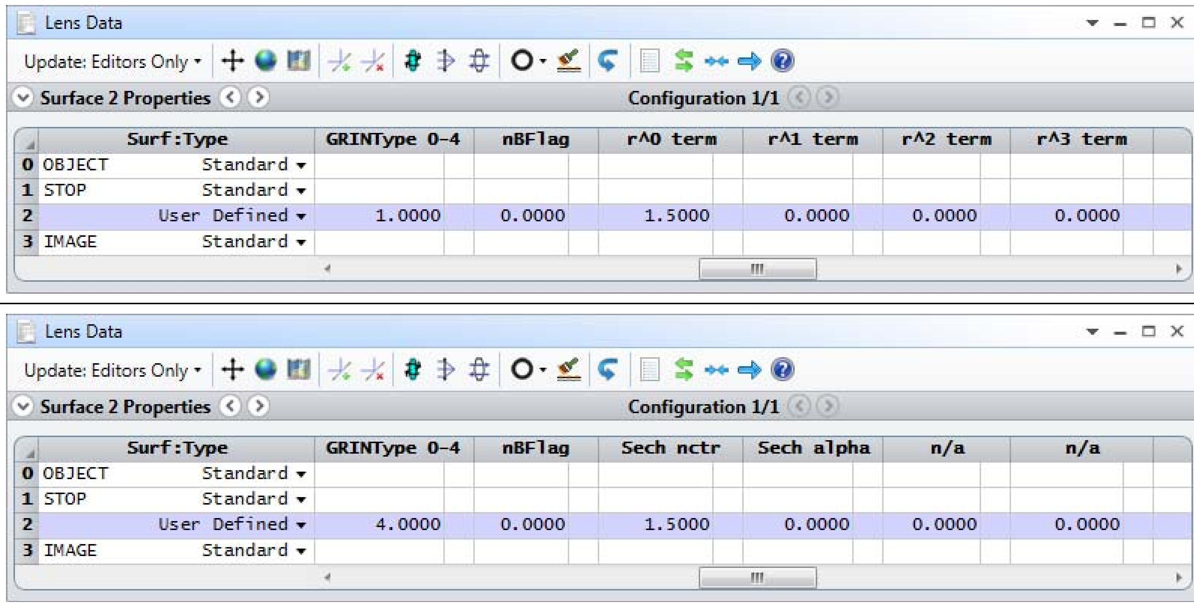
$$\eta = \frac{n_B(\lambda_{ref})^2 - n_{ref}^2}{n_B(\lambda_{ref})^2 - n_A(\lambda_{ref})^2} \tag{2}$$

and then computing the index at λ using Eqn. (1).

Spatial Variation of the Index:

For each of the Radial and Ball Lens DLLs, there is a variable `GRINType` which toggles the DLL between different functions, followed by a series of variables which describe the index variation. Importantly, there is another parameter `nBFlag` which determines the reaction of the DLL to index values which fall outside the boundaries allowed by the two materials to be mixed.

To reduce confusion among parameter definitions for different GRIN functions, the column labels change as `GRINType` is changed. Below are partial screenshots of how this works for the Radial GRIN surface.



Snippets of the Lens Data Editor in Zemax OpticStudio v15.5 when MGRINx64_Radial_v100 is selected as the User Defined surface. The top and bottom cases illustrate how the column headings change when switching the value of `GRINType`. *The* `GRINType` *column corresponds to the* `Par 17(unused)` *column of a Standard surface.*

In the top screenshot, `GRINType` 1 indicates a polynomial variation of the index. The column headings for the parameters indicate the variable definitions: coefficients of a polynomial equation from order r^0 to order r^{10}. By contrast, `GRINType` 4 is based on a hyperbolic secant function. The index value on the optical axis is given by `Sech_nctr`, and varies away from the axis as a hyperbolic secant of the radius times the `Sech_alpha` parameter. Similar behavior for the other options 0-4 is delineated for both DLLs, below.

Special Note on `nBFlag` :

The boundary flag parameter `nBFlag` determines how the DLL responds to index functions which evaluate to index values outside the boundaries set up by the two base materials. If the boundary flag `nBFlag` is set to 1 (TRUE), then the DLL will enforce the material constraints and clamp any out-of-bounds computation of the index to the closest available material. For example, at a particular location in the lens the index function might compute an index value of n=1.873, while the base materials A and B have index values 1.5 and 1.7, respectively. If `nBFlag` is left at 0 (FALSE) then the material constraints will not be enforced and the DLL will let Zemax use n=1.873. If `nBFlag` is 1 (TRUE) then the material constraint will be enforced and the index clamped to 1.7.

Typically,* `nBFlag` *should be set to zero (FALSE). The primary reason for this is to allow Zemax to keep track of how far an index is from the material boundary. Clamping the index function by setting this parameter to 1 (TRUE) never allows Zemax to know how far an out-of-bounds solution is, well, out of bounds. Thus, during optimization, there's simply no difference between a curve that evaluates everywhere to n=147 or everywhere to n=17. It is critical for Zemax to recognize that the n=17 solution is (generally expected to be) closer to realistic than n=147, which informs it to keep changing the index values in that direction during an optimization. A secondary reason is that by keeping `nBFlag` = 0 and restricting rays to the design wavelength, the user can explore academic GRIN designs from the literature without worrying about the materials involved. The Luneburg lens, for example, is a ball lens which varies from pure vacuum at the edge up to an index of 1.4 at the center. There isn't a realistic material system that can meet that performance (to date) but it serves both as an inspiration and an important analytic check on the accuracy of the GRIN raytrace computation engine. Bear in mind that index values computed for wavelengths other than λ_{ref} will generally result in anomalous behavior when $n(\lambda_{ref})$ exceeds the material bounds.

Detailed GRIN Function Descriptions

In the following function definitions, we differentiate between radial distance ρ for the Radial GRIN DLL and radial distance r for the Ball GRIN DLL.

In the Radial GRIN DLL case, ρ is the distance from the optical axis of symmetry to a point (x,y,z) in the lens, *i.e.* it is the cylindrical radial coordinate:

$$\rho^2 = x^2 + y^2 \qquad (3)$$

In the Ball GRIN DLL, r is the distance to (x,y,z) from the GRIN center of symmetry $\mathbf{P_o}$, defined in the parameter columns as (X_o,Y_o,Z_o), *i.e.* the spherical radial coordinate:

$$r^2 = (x - X_o)^2 + (y - Y_o)^2 + (z - Z_o)^2 \qquad (4)$$

RADIAL GRIN DLL FUNCTIONS:

(Radial DLL) `GRINType` 0 = Safe

For the Safe function $n(\lambda_{ref})$ = 1.5 everywhere in the lens.

$$n(\lambda_{ref},\ \rho) = 1.5 \qquad (5)$$

The material is nevertheless assumed to be a blend of materials A and B. The index at other wavelengths will differ from 1.5, in general, as outlined in Eqns. (1-2).

(Radial DLL) `GRINType` 1 = Polynomial

For the polynomial function

$$n(\lambda_{ref},\ \rho) = a_0 + a_1\rho + a_2\rho^2 + \cdots + a_{10}\rho^{10} \qquad (6)$$

The coefficients a_j are defined by the columns labeled "`r^j term`".

(Radial DLL) `GRINType` 2 = Even Polynomial

For the even polynomial function

$$n(\lambda_{ref},\ \rho) = a_0 + a_2\rho^2 + a_4\rho^4 + \cdots + a_{20}\rho^{20} \tag{7}$$

The coefficients a_j are defined by the columns labeled "`r^j term`".

(Radial DLL) `GRINType` 3 = Step Polynomial

The step polynomial function has a constant-index cylindrical core out to a radius ρ_{Step}. For radii greater than this core, the index varies as a polynomial. The index at the core boundary is continuous. The derivative of the index will also be continuous if the first-order term a_1 is set to zero.

$$n(\lambda_{ref},\ \rho) = \begin{cases} n_0 & \rho \le \rho_{Step} \\ n_0 + a_1(\rho - \rho_{Step}) + \cdots + a_9(\rho - \rho_{Step})^9 & \rho > \rho_{Step} \end{cases} \tag{8}$$

The coefficients n_0 and ρ_{Step} are defined by the columns labeled "`StepPoly no`" and "`StepPoly R`", respectively. The coefficients a_j are defined by the columns labeled "`r^j term`".

(Radial DLL) `GRINType` 4 = Hyperbolic Secant

For the hyperbolic secant function

$$n(\lambda_{ref},\ \rho) = n_{ctr}\, sech(\alpha\, \rho) \tag{9}$$

The coefficients n_{ctr} and α are defined by the columns labeled "`Sech nctr`" and "`Sech alpha`", respectively. This function is included because a GRIN rod with this index distribution is able to perfectly relay a point source of light focused at the center of its endface. Similarly, collimated light incident on the same rod can be focused down to a point.

BALL GRIN DLL FUNCTIONS:

(Ball DLL) `GRINType` 0 = Safe

For the safe function $n(\lambda_{ref}) = 1.5$ everywhere in the lens.

$$n(\lambda_{ref},\ r) = 1.5 \tag{10}$$

The material is nevertheless assumed to be a blend of materials A and B. The index at other wavelengths will differ from 1.5, in general, as outlined in Eqns. (1-2).

(Ball DLL) `GRINType` 1 = Polynomial

For the polynomial function

$$n(\lambda_{ref},\ r) = a_0 + a_1 r + a_2 r^2 + \cdots + a_{10} r^{10} \qquad (11)$$

The coefficients a_j are defined by the columns labeled "`r^j term`".

(Ball DLL) `GRINType` 2 = Step Polynomial

The step polynomial function has a constant-index spherical core out to a radius r_{Step}. For radii greater than this core, the index varies as a polynomial. The index at the core boundary is continuous. The derivative of the index will also be continuous if the first-order term a_1 is set to zero.

$$n(\lambda_{ref},\ r) = \begin{cases} n_0 & r \le r_{Step} \\ n_0 + a_1(r - r_{Step}) + \cdots + a_9(r - r_{Step})^9 & r > r_{Step} \end{cases} \qquad (12)$$

The coefficients n_0 and r_{Step} are defined by the columns labeled "`Step n`" and "`Step R`", respectively. The coefficients a_j are defined by the columns labeled "`r^j term`".

(Ball DLL) `GRINType` 3 = Luneburg Lens

The Luneburg lens distribution is defined by:

$$n(\lambda_{ref},\ r) = n_{Ext}\sqrt{2 - \left(\frac{r}{R}\right)^2} \qquad (13)$$

where R is the physical radius of the ball lens, defined by the column labeled "`Luneburg R`" and n_{Ext} is the index of the surrounding medium, defined by the "`Luneburg nExt`" column. Note that if this column has 0 entered, it is assumed $n_{Ext} = 1$. When properly matched to the environment, a Luneburg lens focuses incident collimated light into a perfect point on the opposite side of the sphere. Note that the index distribution needed for this to happen varies from being perfectly matched to n_{Ext} at the edge of the sphere to $n_{Ext} *\sqrt{2}$ at the center.

(Ball DLL) `GRINType` 4 = Maxwell Lens

The Maxwell lens distribution is defined by:

$$n(\lambda_{ref},\ r) = \frac{n_{ctr}}{1+\left(r/R\right)^2} \qquad (14)$$

The coefficients n_{ctr} and R are defined by the columns labeled "`Maxwell nCtr`" and "`Maxwell R`", respectively. This lens focuses a point source of light at one edge of the sphere perfectly onto a point at the opposite side of the sphere.

Asphere Surface Description:

The asphere surface parameters are ***almost***, but not quite the same as those for Zemax's Even Asphere surface. They differ by a scaling factor. The scaling factor results in larger coefficients, which are generally more stable for the Zemax optimization algorithms. For the N-th order even asphere term, the Zemax-equivalent parameter would be found by multiplying the MGRIN parameter by 10^{-N}, *e.g.* an entry of 4.0e-2 in the `6th Asph x10-6` column of these DLLs is equivalent to an entry of 4.0e-8 in the `6th Order Term` of Zemax's Even Asphere surface.

If one represents the DLL column corresponding to the N-th order term as v_N then the surface sag is expressed by:

$$sag(\rho) = \frac{\rho^2 R^{-1}}{1+\sqrt{1-(1+k)\rho^2 R^{-2}}} + v_2\left(\frac{\rho}{10}\right)^2 + v_4\left(\frac{\rho}{10}\right)^4 + \cdots \quad (15)$$

Without this scaling, Zemax generally chooses too large a step size when varying coefficients of 6th order and above during optimization, preventing surface shapes from optimizing properly.

NOTE: this rescaling works for lenses with semi-diameters of ~10 lens units. If working with lenses with semi-diameters much greater or smaller, the problems with optimization tend to recur. In these cases, it would be best to re-scale the lens design or change units to achieve a numerical value of ~10 for the semi-diameter of the GRIN lens(es). Another option is to start off the optimization with non-zero values entered into the columns to be varied, with magnitudes close to what might be expected of the solution.

This limitation arises because the Zemax optimization engine cannot infer the proper size scale for User Defined DLL variables such as these. Without *a priori* information on the proper range, it is difficult for numerical optimization algorithms to search through parameter space efficiently.

Note on Multiple GRIN Surfaces:

Although it is possible to include multiple MGRIN lenses in an optical design, note that Zemax does not allow two GRIN surfaces to be directly adjacent. Thus, the non-GRIN rear surface of an MGRIN lens (which, as mentioned, is the surface that follows the MGRIN surface and can be of type "standard," "even asphere," etc.) must be inserted before the front surface of another MGRIN lens, even if there is no gap between these MGRIN lenses.

MGRIN DLL Parameter Definitions:

Parameter descriptions come first, followed by a section on column numbers.

(Note that the Zemax Glass Type for the MGRIN layer is left blank, since the materials are defined in the Zemax extra data columns associated with the MGRIN DLL instead.)

Delta T	- Step size for Zemax ray tracing of an MGRIN surface. Lower values imply better ray path accuracy but slower calculation rate. See discussion of "maximum step size Δt" in Zemax manual under "Gradient 1" surface.
Design WaveL	- Design Wavelength, in units of um. The GRIN profile at this wavelength is used to calculate the fractional composition of each base material at any position in space.
Nth Asph x10-N	- Even asphere coefficients which describe the aspheric shape of the front lens surface. Covers 2nd to 20th order asphere. See definition of Zemax "Even Asphere" surface in Zemax manual. Each coefficient in the editor is scaled by 10^{-N} before computation, as explained in section "Overview of the MGRIN DLL functionality" above. (In other words, the numbers you see in the Editor are 10^{N} bigger than Zemax will use to compute an Even Asphere surface.)
GRINType 0-4	- Type of function used to describe the GRIN profile at the design wavelength. Accepted values for both Ball and Radial GRIN DLLs are 0-4. The different types are defined, above.
nBFlag	- Boundary flag for the GRIN profile function. This dictates the behavior when the refractive index exceeds the physical min/max index of the material blend. Out of boundary index values result in non-physical fractional compositions of materials (outside the 0-1 range) when calculating dispersion. When nBFlag = 0, the index is allowed to exceed the material limits. When nBFlag = 1, the index is clamped to the min/max index. During optimization, generally set nBFlag = 0 and instead constrain index range through the merit function.

<next 10 cols>	- Coefficients specific to the GRINType chosen. (see documentation, above)
Mat[X] Disp Fn	- Type of dispersion equation used to describe each of the 2 materials (X = 1 or 2).
Mat[X] A..J	- Coefficients of the dispersion equation, Mat[X] Disp Fn, for material X, where X = 1 or 2 (see "Dispersion Equations" section below).

MGRIN DLL Parameter Column Locations:

(See differences between Zemax-13 and Zemax OpticStudio noted below):

Tabulated below are the names and default values of the Zemax parameter and extra data columns for an MGRIN surface. Additional information about the GRIN profile functions and the dispersion equations can be found in the subsequent sections.

The GRIN lens parameters are all are located in the "Lens Data Editor" in Zemax OpticStudio. In Zemax-13 and earlier versions the parameters are split between the Zemax "Lens Data Editor" and "Extra Data Editor." The first table below applies to both Zemax versions. The second and third tables apply only to Zemax-13 and Zemax OpticStudio respectively, as labeled. Note also that in the Zemax OpticStudio Lens Data Editor, column 13 follows column 8, skipping numbers 9 to 12.

RADIAL GRIN DLL COLUMN HEADINGS

Lens Data Editor Columns:

Col#	Name	Default Value
1	Delta T	0.20
2	Design WaveL	0.587562
3..8	(2..12)th Asph x10-(2..12)	0.0

Extra Data Editor Columns (in Zemax-13 and earlier versions):

Col#	Name	Default Value
1..4	(14..20)th Asph x10-(14..20)	0.0
5	GRINType 0-4	0.0
6	nBFlag	0.0
7..17	<varies with Type>	0.0
18	Mat[1] Disp Fn	1.0
19..28	Mat[1] A..J	PMMA from MISC.AGF
29	Mat[2] Disp Fn	1.0

30..39	Mat[2] A..J	SAN from MISC.AGF

Lens Data Editor Columns (in Zemax OpticStudio):

Col#	Name	Default Value
13..16	(14..20)th Asph x10-(14..20)	0.0
17	GRINType 0-4	0.0
18	nBFlag	0.0
19..29	<varies with Type>	0.0
30	Mat[1] Disp Fn	1.0
31..40	Mat[1] A..J	PMMA from MISC.AGF
41	Mat[2] Disp Fn	1.0
42..51	Mat[2] A..J	SAN from MISC.AGF

BALL GRIN DLL COLUMN HEADINGS

Lens Data Editor Columns:

Col#	Name	Default Value
1	Delta T	0.20
2	Design WaveL	0.587562
3..8	(2..12)th Asph x10-(2..12)	0.0

Extra Data Editor Columns (in Zemax-13 and earlier versions):

Col#	Name	Default Value
1..4	(14..20)th Asph x10-(14..20)	0.0
5	GRINType 0-4	0.0
6	nBFlag	0.0
7..9	<Type> Xo, Yo, Zo	0.0
10..20	<varies with Type>	0.0
21	Mat[1] Disp Fn	1.0
22..31	Mat[1] A..J	PMMA from MISC.AGF
32	Mat[2] Disp Fn	1.0
33..42	Mat[2] A..J	SAN from MISC.AGF

Lens Data Editor Columns (in Zemax OpticStudio):

Col#	Name	Default Value
13..16	(14..20)th Asph x10-(14..20)	0.0
17	GRINType 0-4	0.0
18	nBFlag	0.0
19..21	<Type> Xo, Yo, Zo	0.0
22..32	<varies with Type>	0.0
33	Mat[1] Disp Fn	1.0
34..43	Mat[1] A..J	PMMA from MISC.AGF
44	Mat[2] Disp Fn	1.0
45..54	Mat[2] A..J	SAN from MISC.AGF

Dispersion Equations [Mat[X] Disp Fn, A..J]:

<u>EQUATION NOTES:</u>
Mat[X] Disp Fn determines the type of equation for material X, where X = 1 or 2
A..J are nine coefficients used by the dispersion equation. Some or all may be needed.
λ represents wavelength, in μm

Mat[X] Disp Fn [1 - 13] are defined according to the dispersion functions listed in the Feb. 2014 Zemax software manual, Chapter 23, "Using Glass Catalogs," in "The glass dispersion formulas" section. The order matches the then-current pull-down dispersion formula list in the Zemax glass catalog interface window.

Usually these values will be loaded using the GRIN Material Select macro, from existing Zemax glass catalogs. Advanced users may have cause to edit values directly, **with caution**: it is very easy to mistype a digit or choose the wrong column when entering as many numbers as is required to define a material. It can be very difficult to understand what is happening with a lens when the materials entered are not the same as what the designer intended.

Mat[X] Disp Fn = -1, Model glass from Ditteon, "Modern Geometrical Optics," Eqns. (1.37-1.39)

$n = A + \lambda_F^2 * \lambda_C^2 * (A - 1) / [B * (\lambda_C^2 - \lambda_F^2)] * (1/\lambda^2 - 1/\lambda_d^2);$

here A is n_d and B is the Abbe number of the model glass. $\lambda_F = 0.4861327$ μm, $\lambda_d = 0.5875618$ μm, and $\lambda_C = 0.6562725$ μm

Mat[X] Disp Fn = 0, Constant index

$n = A$

No variation with wavelength

Mat[X] Disp Fn = 1, Schott formula

$n = \mathrm{sqrt}(A + B*\lambda^2 + C/\lambda^2 + D/\lambda^4 + E/\lambda^6 + F/\lambda^8)$

Mat[X] Disp Fn = 2, Sellmeier 1

$n = \mathrm{sqrt}(1 + A*\lambda^2/(\lambda^2 - B) + C*\lambda^2/(\lambda^2 - D) + E*\lambda^2/(\lambda^2 - F))$

Mat[X] Disp Fn = 3, Herzberger

$\Delta = 1.0 / (\lambda^2 - 0.028)$

$n = A + \Delta*(B + \Delta*C) + \lambda^2*(D + \lambda^2*(E + \lambda^2*F));$

Mat[X] Disp Fn = 4, Sellmeier 2

$n = \mathrm{sqrt}(1 + A + B* \lambda^2/(\lambda^2- C^2) + D/(\lambda^2- F^2))$

Mat[X] Disp Fn = 5, Conrady

$n = A + B/\lambda + C/ \lambda^{3.5}$

Mat[X] Disp Fn = 6, Sellmeier 3

$n = sqrt(1 + A*\lambda^2/(\lambda^2 - B) + C*\lambda^2/(\lambda^2 - D) + E*\lambda^2/(\lambda^2 - F) + G*\lambda^2/(\lambda^2 - H))$

Mat[X] Disp Fn = 7, Handbook of Optics Formula 1
$n = sqrt(A + B/(\lambda^2 - C) - D*\lambda^2)$

Mat[X] Disp Fn = 8, Handbook of Optics Formula 2
$n = sqrt(A + B*\lambda^2/(\lambda^2 - C) - D*\lambda^2)$

Mat[X] Disp Fn = 9, Sellmeier 4
$n = sqrt(A + B*\lambda^2/(\lambda^2 - C) + D*\lambda^2/(\lambda^2 - E))$

Mat[X] Disp Fn = 10, Extended formula
$n = sqrt(A + B*\lambda^2 + C/\lambda^2 + D/\lambda^4 + E/\lambda^6 + F/\lambda^8 + G/\lambda^{10} + H/\lambda^{12})$

Mat[X] Disp Fn = 11, Sellmeier 5
$n = sqrt(1 + A*\lambda^2/(\lambda^2 - B) + C*\lambda^2/(\lambda^2 - D) + E*\lambda^2/(\lambda^2 - F) + G*\lambda^2/(\lambda^2 - H) + I*\lambda^2/(\lambda^2 - J))$

Mat[X] Disp Fn = 12, Extended formula
$n = sqrt(A + B*\lambda^2 + G*\lambda^4 + H*\lambda^6 + C/\lambda^2 + D/\lambda^4 + E/\lambda^6 + F/\lambda^8)$

Mat[X] Disp Fn = 13, Extended formula
$n = sqrt(A + B*\lambda^2 + C*\lambda^4 + D/\lambda^2 + E/\lambda^4 + F/\lambda^6 + G/\lambda^8 + H/\lambda^{10} + I/\lambda^{12})$

Mat[X] Disp Fn = default
Returns error value -1

Description of macros available for the Zemax MGRIN DLL

Several Zemax macros are provided to aid in the design of optical systems that include manufacturable gradient-index (MGRIN) lenses. The macros have been updated from their previous release with the spherical GRIN DLL to support both the Radial and Ball GRIN DLLs, while retaining backward compatibility. They have not been renamed.

`GRIN Material Select`

Selects base materials (1 and 2) to be used in the MGRIN lens design, from glass libraries previously loaded in the Zemax "General" dialog. Before using this macro, be sure that the libraries containing the desired materials have been included in the "General" dialog (or System > General > Glass Catalogs; for Zemax OpticStudio use System Explorer > Material Catalogs).

If there is only one MGRIN lens in the optical layout, the macro automatically detects it; if more than one MGRIN lens is present, the MGRIN surface number must be entered. For each MGRIN surface, enter the material number (`X = 1 or 2`), followed by the material name (exactly as it appears in the previously loaded glass libraries).

For each material (`X = 1 or 2`) in each MGRIN surface, the macro enters the appropriate dispersion formula (`Mat[X] Disp Fn`) and the corresponding coefficients (`Mat[X] A..J`) in the appropriate Zemax extra data columns.

`GRIN Material Report`

Reports the names of the 2 materials used in each MGRIN surface, as well as their refractive indices at the primary wavelength (as specified in Zemax). The material names are only reported if the refractive indices match exactly the values in the loaded glass libraries. This macro can be used to check that the base materials are entered properly.

The report includes information for all MGRIN surfaces in the lens design.

Informational output (text) only.

`GRIN Base Material Index`

Calculates the refractive indices of the 2 base materials used in each MGRIN surface at the specified wavelength. The wavelength must have been previously included in the Zemax "Wavelength Data" dialog. An integer must be entered, corresponding to the row in the "Wavelength Data" dialog where that wavelength appears.

The report includes information for all MGRIN surfaces in the lens design.

Informational output (text) only.

`GRIN Profile Report`

Calculates the GRIN profile, at a specified wavelength, of both the material blend and refractive index within the lens. The macro generates three or four windows. The first is a text window containing information about the lens geometry, materials, index bounds, and material volume fraction bounds identified within the lens. Two windows display plots of refractive index and material volume fraction, respectively. If a Radial GRIN, the plots run radially from the center line (optic axis) to the edge of the lens. If a Ball GRIN, the plots run over the full range of radii, measured from the GRIN origin, that encompass the lens volume.

Optionally, if the user chooses to "Display text output?" at the prompt, a fourth window displays the numerical data underlying both plots.

These plots are useful for visualizing the material distribution throughout the lens, and determining whether the design has exceeded the base material range. The GRIN profile at the design wavelength is defined by `GRINProfileType` and `n_Ps[0-9]`. Red "X"s are displayed on the plots if either the index or volume fraction exceed the boundaries of the materials, e.g. above the index of the highest index material or below the index of the lowest. The red "X"s are placed at the transition(s) between in-range and out-of-range values. If an out-of-range condition occurs, this will also be called out in the text report window.

The wavelength must be entered and is identified by an integer that matches the row of the chosen wavelength within the "Wavelengths" section of the OpticStudio System Explorer (as for the GRIN Base Material Index macro, see above). Hitting the Enter key chooses the primary wavelength by default.

If there is only one MGRIN lens in the optical layout the macro automatically detects it; if more than one MGRIN lens is present, the user is prompted to choose among the valid MGRIN surface numbers, or to choose all MGRIN surfaces at once.

GRIN Contour Plot

Displays a set of GRIN contour lines overlaid on a to-scale 2D line drawing of the GRIN lens. (*See important note on contour line color selection, below.*) This macro provides a clear visualization of the GRIN distribution within the lens, in terms of both contour shape and areas of the steepest GRIN gradient. The contour lines are evenly spaced in refractive index from minimum to maximum, using the selected number of contours. More closely spaced contours correspond to more quickly varying refractive index.

The wavelength at which the GRIN profile is calculated must be entered and is identified by an integer based on the Zemax "Wavelength Data" dialog, as for the GRIN Base Material Index macro (see above). The number of contours covering the index range can be selected (with the default value being 11).

If there is only one MGRIN lens in the optical layout, the macro automatically detects it; if more than one MGRIN lens is present, the MGRIN surface number must be entered. The macro skips any lenses with no GRIN variation (i.e. where `nmin = nmax`).

An index contour plot is displayed for each MGRIN lens requested, using the selected number of contours.

Contour Plot Line-Color Selections
Running GRIN Contour Plot with default settings generally produces plots that could use improvement. We have identified some issues regarding the way Zemax colors lines in its plots, and have some tricks for generating better-looking contour plots. However, this requires some manual tweaking of Zemax's color selections by the user.

Fundamentally, the PLOT command in Zemax's ZPL language can accept only integer values from 0-24 to denote different colors. Color 0 is black, while the colors corresponding to (1-24) can be adjusted at will by the user. Generally, colors 1-3 should be left alone as blue, green, and red, respectively, corresponding to the most common multi-color design philosophy of picking three colors to define the operational bandwidth. [Handy tip: we prefer picking a darker shade of green for color 2 … the default one is often hard to see on computer screens.] Since colors 1-3 are so often used by Spot Diagrams, Ray Fan plots, etc., adjusting these can make "normal" plots look different.

Barring any other preferences this leaves, at most, colors 4-24 available for contour plots. We tend to select 11 of the colors to use, specifically colors 13-23. That is because Zemax's default colors for these numbers also form a series of graded shades, if not very clearly discriminated ones. So, if we redefine the colors to form a set of our own shaded colors, any default behavior by Zemax which uses them will still show up as a graded set.

On top of this fundamental limitation of a small set of discrete colors, another issue is the order in which Zemax draws features in a plot. Testing has shown that this order isn't consistent. Zemax appears to start with black features, then grayscale features, then colors Thus, if you choose to draw the lens outline in black it has the unfortunate effect of showing up "behind" every other feature on the graph, including gray gridlines. The order in which the different colors are drawn isn't clear.

To ensure that the lens outline appears in front of the plot grid and contour lines, we recommend the following suggestions for setting up the default color settings:

- Open the Color Settings Dialog box
    - ZOS: Setup > Project Preferences > Colors
    - Z13: File > Preferences shows separate tabs for Colors 1-12 and Colors 13-24
- Set Color 24 to be *almost* black. This will be the color for your lens outline.
    - ZOS: You need to select the color and click "Advanced" to access the RGB values
    - Z13: RGB values of 0,0,1 in the three available text boxes work
- Identify the lowest color number CL you're comfortable reserving for contours (say, 13)
- Identify the highest color number CH you're comfortable reserving for contours (say, 23)
- Starting with CL and going to CH, we suggest picking colors in order from the table, below

Now adjust the variables in "GRIN Contour Plot.zpl" to match your choices:

- Open the GRIN Contour Plot.zpl file in a text editor
- Near the top of the file, under the line, **`! Settings`**:
    - Define **`lens_color`** to be 24
    - Define **`contour_color_Lbound`** to be your pick for CL

- Define **`contour_color_Ubound`** to be your pick for CH
- Save the file

Now when you run the macro, the contour lines should be ordered nicely from CL to CH.

If you choose to plot more contour steps than you have colors between CL and CH, then the colors will ***recycle*** from CL to CH again, as needed. A warning will show up to indicate that similarly colored contour lines won't always indicate equal values of index.

Here is the ordered list of colors that we suggest, from 13 to 24. The colors 13-23 run in order from maroon to purple to blue to green to orange. The suggested lens outline color 24 is chosen to be *almost* black – because black would show up behind any other feature of the plot:

ID	R	G	B
13	153	0	18
14	160	1	104
15	140	3	168
16	59	5	175
17	7	45	183
18	9	142	191
19	11	168	132
20	14	186	36
21	76	194	7
22	194	164	0
23	232	163	23
24	0	0	1

ZPL18

This macro is used in the Merit Function Editor for constraining the minimum and maximum refractive index during optimization of an MGRIN lens design. The macro checks the refractive index through the center of the MGRIN lens and along its front and back surfaces, and assumes rotational symmetry about the optical axis. User input to this macro consists of the MGRIN surface number, the minimum and maximum refractive index constraints, and the density of sample points. The minimum and maximum refractive index values found along the lens are updated at each iteration of the optimization process. The macro can output 4 possible values. The first two outputs are min & max index normalized from 0 to 1 (0 at middle of range, 1 at edge of range) and raised to the 8^{th} power. The last two outputs are the min & max index values. These outputs are further detailed below. Typical use would be to constrain the first two outputs to be less than or equal to one, to keep the materials within physical range. The last two outputs can then report the minimum and maximum indices found by the macro.

This "user-defined operand" is called by the ZPLM command in the Merit Function Editor. It does not directly read the Zemax data and extra data columns which define the MGRIN surface(s), and is compatible with all standard and user-defined Zemax GRIN surfaces.

Note that although the macro calculates 4 outputs, only one result (of the 4) appears in the "Value" column in each line of the Merit Function Editor (see "Optimizing with ZPL macros" in the Zemax manual). The choice of result in the "Value" column is determined by the integer (0-3) appearing in the "Data" column. A line calling Data = 0 must always appear first, followed by whichever other Data values are desired.

Inputs to the macro occur through the first ZPLM line where Data = 0. The inputs are entered into the `Hx`, `Hy`, `Px` and `Py` columns; the meaning of those inputs is described below. Subsequent ZPLM lines do not have these input columns, but instead report additional values calculated in the first macro call. Those values are also described below.

Description of the Merit Function Editor columns associated with a ZPL call:

```
Type            - "ZPLM" (chosen from dialog)
Mac#            - "18"
Data            - "0-3" Determines which of the 4 possible outputs
                   will appear in the "Value" column (see below).
Hx              - The MGRIN surface number.
Hy              - Sample density. Determines the number of samples
                   taken to find the maximum and minimum refractive
                   index. Hy is the number of samples along the
                   optical axis, between the front and back vertices
                   of the lens. Hy/2, rounded down, is the number of
                   samples taken along the front and back surfaces.
                   When Hy = 2 only the indices at the front and back
                   vertices of the lens are sampled (2 samples along
                   the optical axis, 1 sample at the front & back
                   surface). Each additional 1 point of Hy adds
                   another sample point along the optical axis; each
                   additional 2 points of Hy adds another sample point
                   along each surface of the lens (beginning with the
                   edges of the lens). Hy = 4 is the minimum value to
                   sample both vertices and both edges of the lens.
                   This is shown schematically in Fig. 1(left).
Px              - Minimum index to be used in the MGRIN lens design
                   (at the design wavelength).
Py              - Maximum index to be used in the MGRIN lens design
                   (at the design wavelength).
Target          - Target for the "Value" column.
Weight          - Weighting factor (in the 0-1 range) for the result
                   in the "Value" column, used to calculate merit
                   function value.
Value           - Output of macro, which depends on "Data" column. See
                   below for a detailed explanation of the
                   possibilities.
```

```
% Contrib        - Shows relative contribution of "Value" times
                    "Weight" appearing in the current ZPLM call to the
                    Merit Function (output by macro).
```

To determine initial values of `Px` and `Py`, it is recommended to use the GRIN Base Material Index macro and then enter the reported values of minimum and maximum index into the Merit Function Editor's `Px` and `Py` columns. Note that Zemax does not allow highlighted copy and paste from text output by a macro.

As mentioned, the output of the ZPL18 macro appears in the "Value" column, and depends on the "Data" column in the same ZPL call, as follows. In these equations, note that `nmin` is the minimum index actually found in the MGRIN design, `nmax` is the maximum index actually found in the MGRIN design, `navg = (Py + Px)/2` and `Δn = Py - Px`.

- if `Data = 0`, then `Value = ((nmin-navg)/(Δn/2))^8`
- if `Data = 1`, then `Value = ((nmax-navg)/(Δn/2))^8`
- if `Data = 2`, then `Value = nmin`
- if `Data = 3`, then `Value = nmax`

Note that calls of the ZPL18 macro in the Merit Function Editor generally appear in pairs, i.e., using `Data` = (`0` and `1`) or `Data` = (`2` and `3`). This is because of the Zemax limitation that a macro call can only return a single `Value` at a time (in each call). The ZPL18 macro was intended for optimization to proceed with the 1st Value pair of calls (using `Data = 0` and `1`). In this scenario, the 2nd pair of calls of the ZPL macro (using `Data = 2` and `3`) are for information purposes only. While it is also possible to optimize a design based on the 2nd `Value` pair, optimization is not intended to be performed based on both `Value` pairs, i.e. both (`0` and `1`) and (`2` and `3`), simultaneously.

For `Data` = (`0` and `1`), the purpose of raising the normalized difference between the minimum or maximum index found in the MGRIN design (`nmin` and `nmax`) and the average index to the 8th power is to keep `nmin` and `nmax` confined within the index range defined by the base materials. This function returns a very small value when `nmin` and `nmax` are within the materials' index range (between `Px` and `Py`), providing little optimization penalty in this case. The function returns unity when `nmin = Px` or `nmax = Py`, and then becomes extremely large as soon as `nmin` and `nmax` are outside the materials' index range, implying a very large optimization penalty in this case. An example of the penalty function is plotted in Fig. 1(right). Thus, for ZPL calls optimized using `Data` = (`0` and `1`), the "Target" columns could be set to 0. Also, the values in the corresponding "Weight" columns should not be too small, which would allow `nmin` and `nmax` to fall outside the base materials' index range (and would be unphysical for the chosen materials), nor too large, which would force `nmin` and `nmax` towards the average material index while also effectively ignoring other optimization operands.

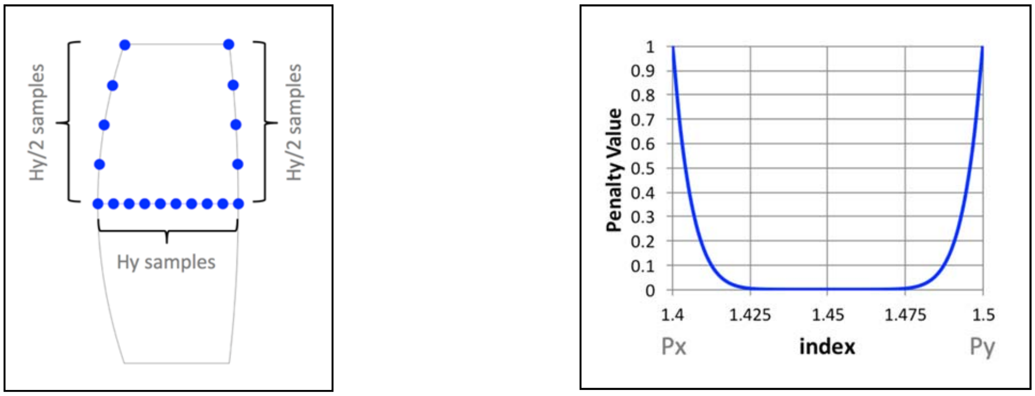


Figure 1: (Left) Illustration of the sampling strategy used for determining the maximum and minimum refractive index values in the MGRIN lens design. The blue dots indicate the positions of the samples. (Right) Example of the penalty function used during optimization of the MGRIN lens design. In this example, the minimum index to be used in the MGRIN lens design (Px) is 1.4 and the maximum (Py) is 1.5, and thus navg = 1.45.

Notes on OpticStudio Versions

The latest version of OpticStudio at the time of this document is Version 15.5 SP3, released March 15, 2016. While this version appears stable, some earlier versions of OpticStudio exhibited performance issues which affected workflow in the GRIN tutorials. In response to bug reports, Zemax addressed these issues in its latest release. For those who may not have upgraded, we list here two known issues that are not a product of our code, but do affect GRIN lens design. Again, we emphasize that Zemax was responsive in dealing with the issues, and they have been addressed in the latest release.

Versions Affected: OpticStudio v15 (5/14/15) through v15.5 (10/19/15)

Symptom: Calling any macro (such as GRIN Profile Report) after performing an optimization using ZPLM 18 causes OpticStudio to hang indefinitely.

Workaround: For the only smooth exit we can find, use CTRL-ALT-DEL to bring up Microsoft's Windows Task Manager window. Under the Applications tab, select Zemax OpticStudio, and click the "End Task" button. Note: under the Windows dialog box, a *Zemax* dialog box will also appear, asking whether you'd like to save your file before quitting OpticStudio. Select Yes in the Zemax box, and all will (hopefully) quit smoothly.

Notes: The problem here isn't related to GRIN or ZPLM 18. The problem is related to OpticStudio expecting values from a multi-output macro like ZPL18 under the macro interface. The same behavior can be found with all-Zemax-native surfaces and macros when performing an optimization with a multi-output macro in the Merit Function Editor and later executing even the simplest of macros.

Versions Affected: OpticStudio v15.5 SP2 Feb. 8, 2016

Symptom: When Ray Aiming is set to "Real" Zemax incorrectly computes the entrance pupil size.

Workaround: Ray Aiming must be set to Off or Paraxial, which will necessarily result in errors for Stops placed anywhere but at the front of an optical system.

Notes: What you see when opening a file in this version, which was saved under an old version with Ray Aiming set to Real, is that the Entrance Pupil collapses to zero. Changing the aperture size or stop size fails to change this behavior. A Cross-Section plot which might have shown a series of rays getting traced through the lens outlines of your system will, instead, show a single ray traced right down the optical axis. Similarly, Spot Size diagrams or Ray Fan plots will show anomalous results, consistent with a near-zero entrance pupil. Not much to do, here. For whatever reason, this release of OpticStudio fails to execute the algorithm associated with Real Ray Aiming.

GRIN LENS TUTORIALS

Overview of tutorials: the GRIN design approach

Gradient index optical design involves the optimization of variables unfamiliar to most optical engineers. This overview, in addition to the two tutorial examples provided below, attempts to make the transition to handling GRIN variables easier to understand. Be sure to note the GRIN visualization macros, GRIN Contour Plot and GRIN Profile Report, which help the designer visualize how index (*i.e.* material composition) is distributed throughout the lens.

The most important consideration in GRIN design is to keep variables bounded in a way that the index distribution inside the lens is consistent with the pair of base materials being used. The highest index in the lens should be less than or equal to the high-index material, while the lowest index should be greater than or equal to the low-index material. The tutorial examples that follow show how to properly use the merit function macro ZPLM 18 for this purpose.

When searching for a GRIN solution, it may help to view higher order GRIN variables as analogous to higher order aspheric surface terms. Thus, as with designs incorporating high-order aspheric terms, the path to a good solution generally involves a rational starting point and judicious incorporation of only a few variables at a time.

A basic GRIN design flow consists of the following steps:

(1) Optimize a homogeneous solution
(2) Optimize a simple GRIN solution
(3) Add more GRIN and aspheric surface terms together in sets, re-optimizing in-between
(4) Iterate step 3 as necessary

There are times when, with enough terms in the GRIN or surface asphere expansion, the iterative process of (3) and (4) might walk the solution into an undesirable local minimum. On occasion, one can find an alternate solution by reverting to the simple solution found in (2), setting all the higher order terms to zero, and trying to optimize all of them simultaneously. Sometimes this can work, and sometimes this simply freezes Zemax.

An important issue to monitor, particularly when tweaking GRIN terms by hand to “kick” a solution out of a local minimum, is unphysical GRIN distributions. If a manually adjusted GRIN parameter results in Merit Function operand values for ZPLM 18 (0 and 1) which exceed 1, then such a solution is generally so far out of bounds that Zemax will have a difficult time recovering through an optimization.

The two tutorials below each demonstrate design with one of the two GRIN distributions, Radial and Ball. Both examples are achromatic designs in the visible at the F, d, C wavelengths.

Radial GRIN DLL Tutorial: *f*/3 Achromatic Singlet

In this tutorial, we design an achromatic GRIN lens similar to one published in *Optics Express* [vol. 23, no. 17, pp. 22069-86, 2015]. The paper outlined the ideas which led to the choice of glass materials used in the lens, N-SK4 and N-KZFS4, both listed in the Schott glass catalog. The lens of this tutorial will have nearly identical performance to the one delineated in Table 6 (glass pair 2) of the paper. This will be a 24 mm clear diameter, *f*/3 lens designed for the visible spectrum.

The latest version of OpticStudio available at the time of this document is v15.5, SP3 with a release date of March 15, 2016. Notes on some bugs seen with previous versions of OpticStudio can be found in an earlier section of this document. This tutorial has also been tested successfully in Zemax 13 Release 2 SP4 (Aug. 20, 2014).

We have found that different versions of Zemax and even different computers running the same version will generate slightly different designs, generate different merit function values, and require different numbers of optimization iterations when performing optimizations, even if initialized with the same starting lens. The precise details on your screen may vary from the enclosed screenshots, but for the different computers and Zemax versions tested so far the solutions we found have been near-identical.

Start by opening Zemax and setting up a new lens design:

- File / New

Set a few basic parameters:

Zemax OpticStudio (ZOS) note: Replace "System / General" and "System /" below with "System Explorer"

- System / General: Aperture > Aperture Type > Float by Stop Size
- System / General: Ray Aiming > Real *[Not strictly necessary here, but a good habit to get into when using GRIN lenses in systems which have STOPs located on the other side of a GRIN surface. NOTE: cannot set Ray Aiming to Real for OpticStudio v15.5 SP2 Feb. 8, 2016. See Notes on OpticStudio Versions, above.]*
- System / Wavelengths: Settings > Preset: F,d,C (Visible)
- System / Fields: use one field, Field Normalization: Radial, 0 degrees for both X- and Y-Field, Weight = 1

Configure the two Zemax surfaces that make up the lens:

- Insert two new surfaces before "IMA" in the Lens Data Editor. *(Note: To insert a new surface, select the "IMA" surface and then hit the "Insert" key — the inserted surface appears above the selected surface.)* These surfaces are automatically labeled "2" and "3" by Zemax.
- Set Type of Surface 2 to "MGRIN Radial v1.0.0" by right-clicking on "Standard" and selecting in the dialog: Surface Type > User Defined, Surface DLL > MGRINx64_Radial_v100.DLL if you have a 64-bit Windows operating system, or … > MGRINx32_Radial_v100.DLL if you have a 32-bit system. *(In ZOS, select "User Defined" from the "Surface Type" drop-down menu, and then select the proper DLL from the new dialog box.)*

(Note: In the following, numerical values are entered by typing directly in the corresponding cells of the Lens Data Editor.)

- Set Semi-Diameter of the “STO” (stop) Surface (Surface 1) to 12 mm
- Set Semi-Diameters of both Surfaces 2 and 3 to 12.5 mm
- Set Thickness of Surface 2 (thickness of GRIN lens) to 9 mm
- Set Thickness of Surface 3 (back focal length) to 72 mm (for a roughly f/3 lens)
- Set Radius of Surface 2 (front radius of curvature of the GRIN lens) to 40 mm

Start with a homogeneous refractive index:
The GRIN distribution is found by blending two materials with different indices. Based on the *Optics Express* paper, for this example we select N-SK4 and N-KzFS4 from the Schott catalog. After selecting the two glasses, we'll want to set up a homogeneous index value roughly the average of our two glasses. We begin by picking the two glasses for our GRIN:

- Run “GRIN Material Select” macro (ZOS: macros are available from the Programming tab > Macro List, Z13: macros are found in the Macros menu)
- *Type ‘a’ or ‘A’ in the dialog box to set All materials*
- *Enter (upper or lower case) ‘N-SK4’ as the glass name of material 1, then click on OK*
- *Enter (upper or lower case) ‘N-KzFS4’ as the glass name of material 2, then click on OK*
- *Review the information in the text window which begins with “Executing <path>\GRIN Material Select.zpl.” to ensure there were no errors, then close this window. (If the window is left open, future Update All (Ctrl+Shift+u) operations will re-run the macro.)*

With our materials selected, we need to see what indices each glass has at the design wavelength:

- Run “GRIN Material Report”
- *The macro will automatically recognize the GRIN surface and report the material names (if known) and the material indices at the primary wavelength.*

This will show that at 0.5876 um, the indices of N-SK4 and N-KZFS4 are 1.6127 and 1.6134, respectively. Clearly, these two glasses have nearly identical index values at the design wavelength. A feature of this glass pair, however, is that they have different dispersion characteristics, which get exploited as described in the *Optics Express* paper.

The next step is to set up our lens as a homogeneous lens with an index value about half-way between the two glasses. We start by entering 1 into the `GRINType` column to select the polynomial function and entering 1.613 (an average index for this glass pair) into the `r^0 term` column;

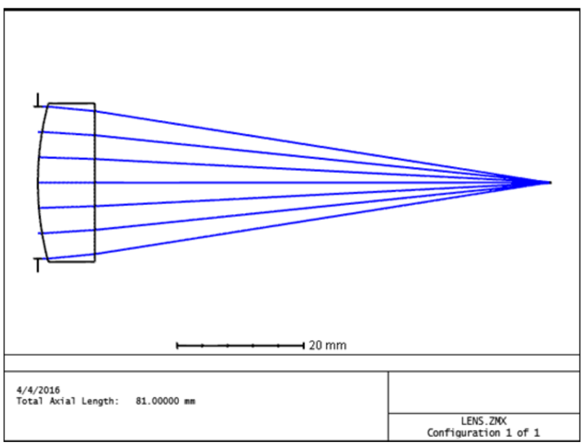
- Set GRINType (column 5 of the Extra Data Editor, or column 17 in ZOS) for Surface 2 to 1
- Set “r^0 term” to 1.613

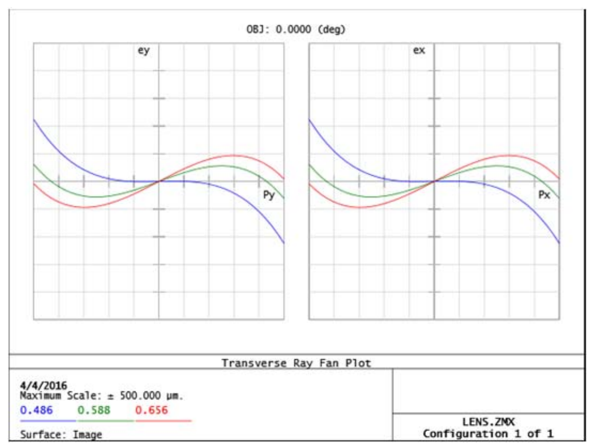
Optimize the (initial) front surface curvature of the homogeneous lens:
Perform an initial optimization of the front lens surface curvature:

- Set Radius of Surface 2 to “Variable” in the Lens Data Editor *(right-click on cell and select “Variable” from the list, or use shortcut: select cell, followed by Ctrl-z) (in ZOS use the shortcut Ctrl-z or click on the small cell to the right of the numerical value and select “Variable” from the list)*
- Open the Merit Function Editor (shortcut key F6, or Z13: Editors / Merit Function, ZOS: Optimize > Merit Function Editor)

- Prepare to enter automatic merit function:
  - Z13: Insert a Sequential Merit Function (Design / Sequential Merit Function)
  - ZOS: From Wizards and Operands dropdown menu, select Optimization Wizard
- Select RMS, Wavefront, Centroid, 7 Rings, 6 Arms
- Exit the dialog to complete merit function definition:
  - Z13: Close the Sequential Merit Function dialog
  - ZOS: Click on the OK button
- Perform a Local Optimization - Shift-Ctrl-O for either version, or
  - Z13: Tools / Design / Local Optimization and click the “Automatic” button
  - ZOS: “Optimize!” from Optimize tab), and click “Start”
- Click “Exit” when optimization finishes

After ~12 iterations the Merit Function value should be ~4.06. Note that the front surface (Surface 2) Radius has been changed to 48.23 mm in the Lens Data Editor. Open 2D Layout and Ray Fan windows (Z13: Analysis / Layout / 2D Layout and Analysis / Fans / Ray Aberration, ZOS: Analyze / Cross-Section and Analyze / Aberrations / Ray Aberration). The Ray Fan plot shows clear spherical aberration (S-shaped curves) and chromatic aberration (different colors cross the axis with different slopes).





We now optimize the focal length:

- Set Thickness of Surface 3 (back focal length) to “Variable” in the Lens Data Editor
- Add a line at the top of the Merit Function Editor: Edit / Insert Operand
- Type or choose operand “EFFL” from the list, with Target = 72 mm and Weight = 1
- Perform another Local Optimization (~13 cycles to a final value of ~3.9)
- Note that both the front surface Radius (Surface 2) and the back surface Thickness (Surface 3) have been updated in the Lens Data Editor
- Note also that updating the Ray Fan plot (Shift-Ctrl-U) shows little improvement

To minimize the geometric aberrations before we get to the chromatic aberration corrections provided by the GRIN, we now vary the conic constant of the front surface. This helps with the spherical aberration.

- Set Conic of Surface 2 (front surface of GRIN lens) to “Variable” in the Lens Data Editor

- Perform another Local Optimization (~12 cycles to a final value of ~3.6)

At this point, the optimized focal length of the homogeneous lens is 72.7 mm (as found in the "Value" column for the "EFFL" Operand in the Merit Function Editor). This exceeds the Target value of 72 mm, but optimizing the GRIN profile (as described in the following steps) will both improve the focus quality and allow the focal length target to be reached.

Add the base material index constraints to the Merit Function Editor:
The maximum and minimum refractive index values in the GRIN profile are bounded by the two base materials chosen above (namely, N-SK4 and N-KZFS4). We now constrain the material variation allowed during the GRIN profile optimization to remain within these limits. Add the following seven new lines to the Merit Function Editor (above the "DMFS" line):

- Line 2: Operand "BLNK" with comment "Set up GRIN material constraints:" (you can cut & paste the comment text from here)
- Line 3: Operand "ZPLM" (Mac# = 18, *but leave other fields at default values for now – we will return to this line)*
- Line 4: Operand "ZPLM" (Mac# = 18, Data = 1, Target = 0, Weight = 0)
- Line 5: Operand "ZPLM" (Mac# = 18, Data = 2, Target = 0, Weight = 0)
- Line 6: Operand "ZPLM" (Mac# = 18, Data = 3, Target = 0, Weight = 0)
- Line 7: Operand "OPLT" (OP# = 3, Target = 1, Weight = 1)
- Line 8: Operand "OPLT" (OP# = 4, Target = 1, Weight = 1)

For a detailed explanation of Lines 3-6 (above) see the description of the "ZPL18" macro. Briefly, Lines 3 and 4 return "penalty functions" that attempt to keep the refractive index range of the optimized GRIN profile within the range determined by the base materials chosen. Line 3 returns ((nmin-navg)/(Δn/2))^8 and Line 4 returns ((nmax-navg)/(Δn/2))^8, where nmin (nmax) is the minimum (maximum) index actually found in the MGRIN profile, and Δn and navg are the index range and average index, respectively, determined by the base materials. The purpose of Lines 7 and 8 is to optimize the GRIN profile by keeping the "penalty function" values calculated in Lines 3 and 4, respectively, below the Target value of 1. Additional details can be found in the description of the "ZPL18" macro.

We now return to Line 3 in the Merit Function Editor (see above). Since this line is the first call of the "ZPL18" macro, it must have Data = 0 and must include all inputs to the ZPL18 macro. This line reports the first output value of the ZPL18 macro. (Note that while Lines 4-6 are used for reporting the other 3 output values of the ZPL18 macro, the input values are only specified once, in Line 3.)

The remaining input values required on Line 3 are Hx, Hy, Px and Py. Hx is the MGRIN surface number *(i.e.*, 2 in this case). Hy determines the sample density used to find the maximum and minimum refractive index values in the GRIN profile; a good choice for Hy is 11.

Finally, we need to determine the input values for Px and Py in Line 3. These represent the material bounds, i.e., the minimum and maximum index (respectively) of the base materials at the design wavelength, which need to be entered manually. We determine these values by running the "GRIN Base Material Index" macro and selecting Wavelength 2 (the design wavelength) which should return values 1.61271761 and 1.61336019. Enter these values in Line 3 for Px and Py, respectively. Close the macro text window.

In summary, enter the following values for Line 3, above:

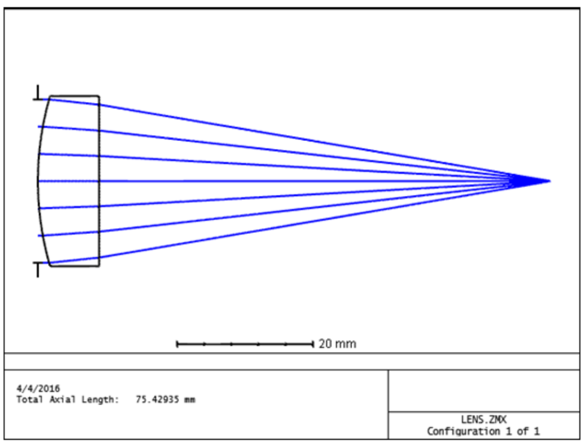
- Line 3: Hx = 2, Hy = 11, Px = 1. 61271761, Py = 1.61336019

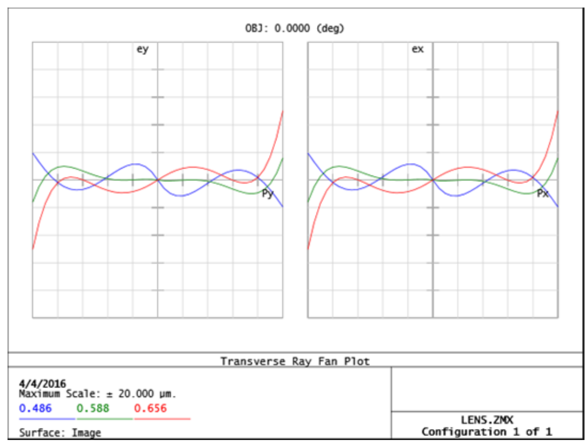
Optimize the GRIN profile (round 1):

To start the optimization, we allow the first 3 coefficients of the polynomial describing the GRIN profile to vary. When varying GRIN function terms for radial GRIN lenses, it is generally good practice to vary nearly the same number of terms in the surface asphere profile.

- Set terms r^0, r^2, and r^3 **(NOT the r^1 term** which would create an index cusp along the optical axis**)** to "Variable" (Ctrl-Z) for Surface 2
- Also set the 4^{th} and 6^{th} order asphere terms to "Variable"
- Perform a Local Optimization (Shift-Ctrl-O) and click the "Automatic" or "Start" button for Z13 or ZOS, respectively.

After ~20 iterations, the Merit Function value should drop to ~0.04. *(Note: We have found that the exact values of the Merit Function and the number of cycles required to reach them depend on several factors, including the version of Zemax and the type of computer being used. The corresponding numbers mentioned in this document should be taken as approximate guidelines only.)*





Upon updating the 2D Layout and Ray Fan windows (Shift-Ctrl-U) the ray fan plot is now bounded between ±20 um: 25x smaller than the previous ray fan plot. Also, note that the focal length (EFFL line in the Merit Function Editor) is now nearly equal to the target value of 72 mm.

While the green ray fan looks relatively smooth and near zero, the red and blue ray fans remain larger and oscillate out of phase. This suggests that the GRIN distribution likely needs some more terms to control the differential dispersion aberrations.

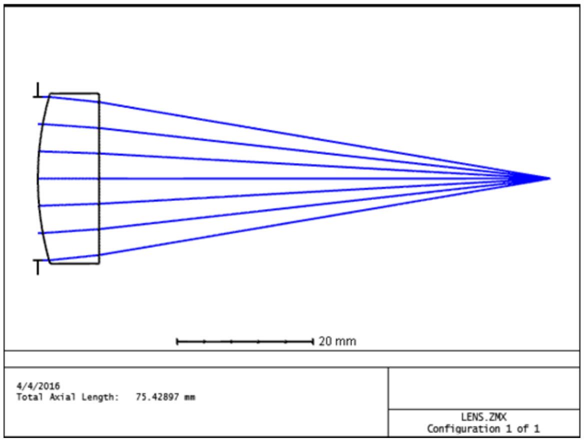
Optimize the GRIN profile (round 2):

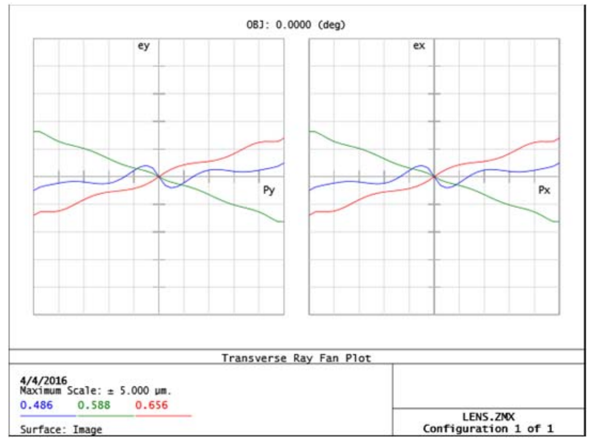
To start the next optimization, we allow the next two coefficients of the GRIN and surface functions to vary.

- Set terms r^4 thru r^6 to "Variable" (Ctrl-Z) for Surface 2
- Set 8^{th} and 10^{th} order surface asphere terms to vary

- Perform a Local Optimization (Shift-Ctrl-O) and click the “Automatic” button.

After ~45 iterations, the Merit Function value should drop to ~0.036. There are several lenses which can result from this optimization. Sometimes a solution much like the final solution is found. One of the least-optimized possibilities is shown here:

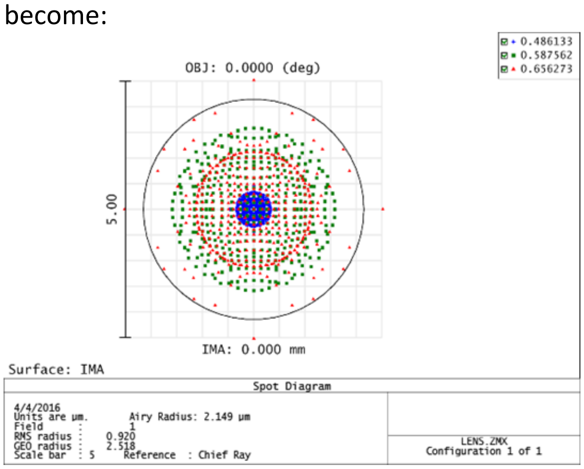


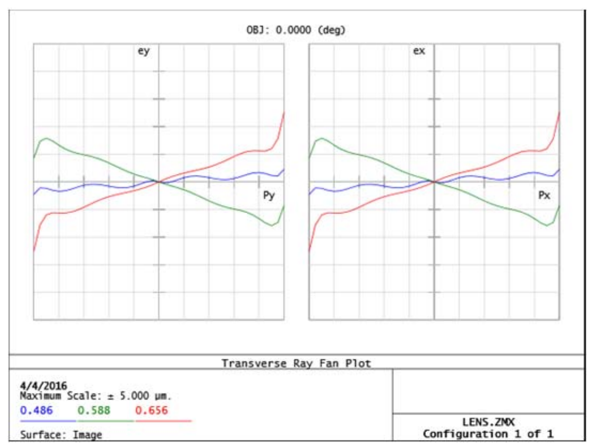


If this is the solution found at this point, a refinement can be found where the wiggle near the origin for the blue-wavelength ray fan is minimized by adding a LONA Merit Function operand right before the DMFS line.

- Add a new Merit Function line above DMFS
- Enter LONA into the type, Wave 1, Zone 0.1, Weight 20
- Run a Local Optimization (Shift-Ctrl-O)

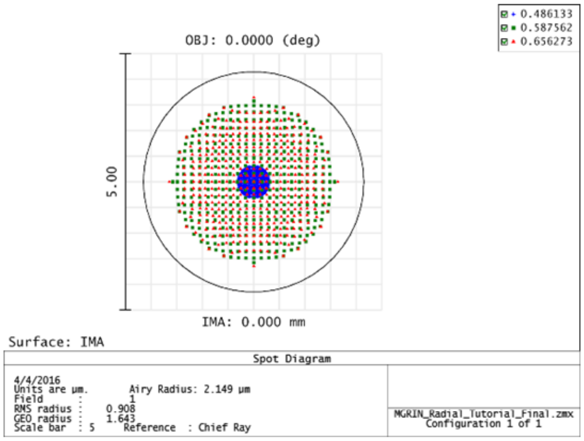
At this point the ray fan and spot size (ray density 11, square pattern, show Airy disk and symbols) become:

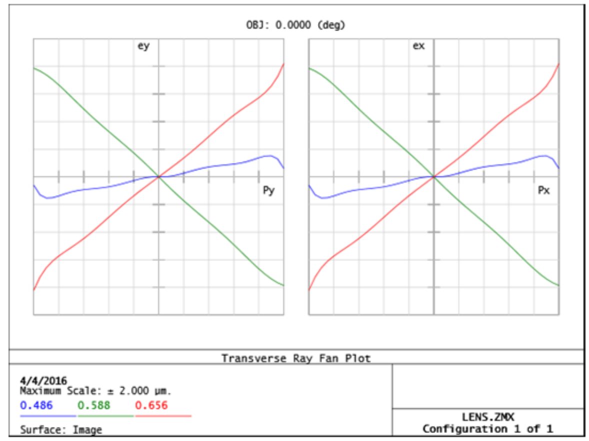




A further refinement can be found by tweaking the LONA command from this point.

- Change the LONA Zone to 0.05
- Run a Local Optimization (Shift-Ctrl-O)





This lens is as optimized as possible for this material pair. It may take a few tweaks of LONA and the Zone value to find it. It is saved as MGRIN_Radial_Tutorial_Final.zmx in the Example Files released with this package. There may be small discrepancies between the plots shown here and what is seen on another computer. Fine details of the optimization steps will vary across different CPUs and software versions.

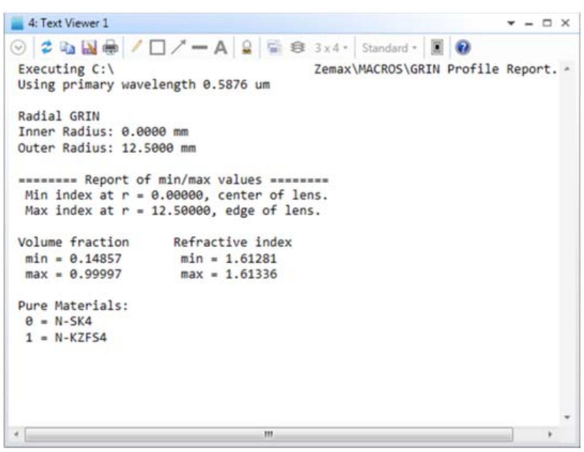
Plot the GRIN Profile:

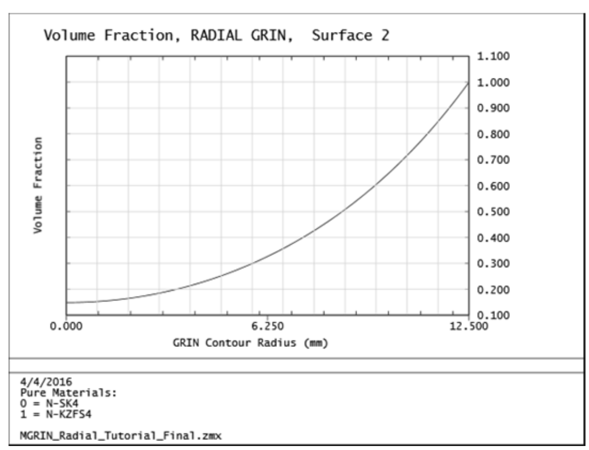
[NOTE: In ZOS versions 15 prior to 15.5 SP2, ZOS freezes upon running a ZPL macro after an optimization with ZPLM 18 in the merit function editor. (v14 is fine) You would need to ***save your work****, exit, re-start ZOS, and re-load the saved file before running the GRIN Profile Report macro outlined below.]*

We now examine the GRIN index distribution which makes this performance possible.

- Run the “GRIN Profile Report” macro
- Hit “Enter” at the first dialog box (plot index at the primary wavelength)
- Hit “Enter” at the second dialog box (no need to print out the numerical values of the plots)

The macro generates three windows, two plots and a status window. From the status window, we see the minimum and maximum indices and material volume fractions. The material distribution is viewed on the Volume Fraction plot. The horizontal axis of the plot starts at the lens center and travels out to the lens semi-diameter.

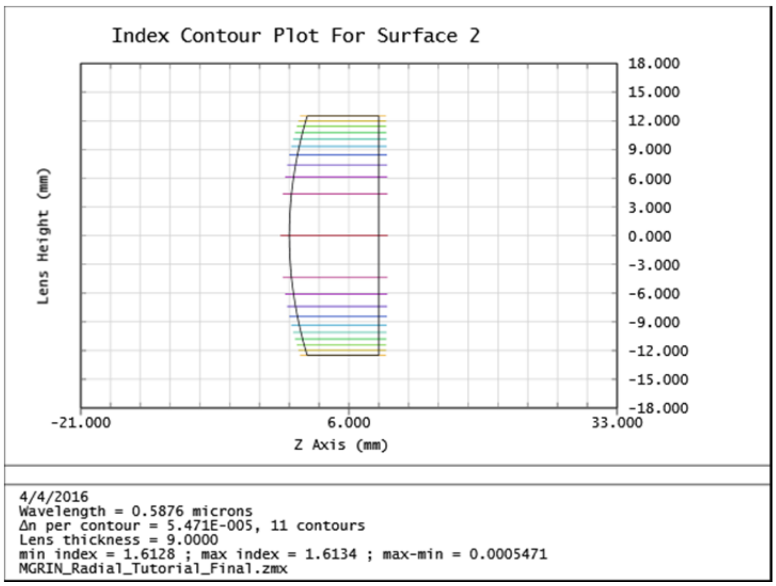




Note that the total index change is only ~0.0005, as shown in the text window, yet the Volume Fraction plot shows that the material composition varies from mostly N-SK4 (mixed only 14.8% by volume) at the center out to pure N-KzFS4 at the lens edge.

Display the GRIN Contour Plot on the Lens Outline:
A visualization tool which helps to convey spatial information on what the GRIN is doing is the GRIN Contour Plot macro. It is helpful when looking at these plots to remember that optical rays are bent away from lower index values towards higher index values. The amount of bending is proportional to the steepness of the gradient.

- Run the “GRIN Contour Plot” macro
- Hit “Enter” at the first dialog box (plot index at the primary wavelength)
- Hit “Enter” at the second dialog box (keep default number of contours to plot)

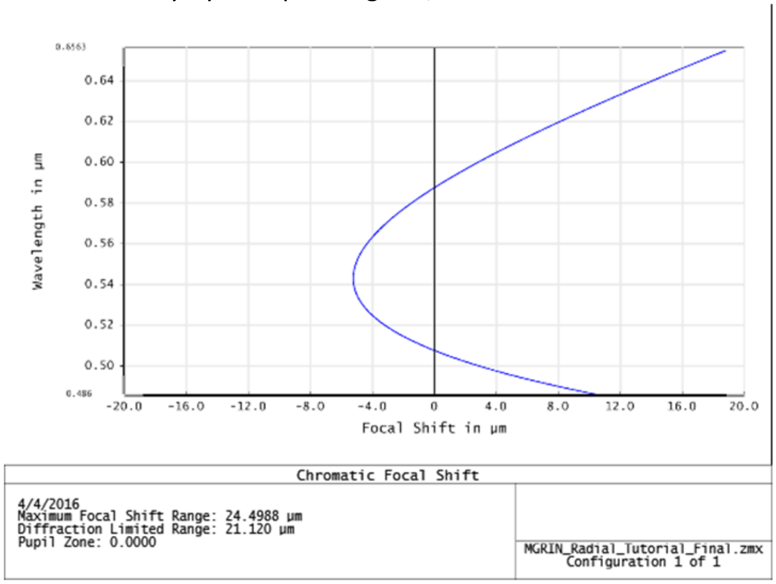


The contour lines show that the steepest index gradient (where the ray bending due to GRIN is the greatest) is out at the edge of the lens. A comparison between this contour plot and the Profile Plot, above, shows that the GRIN distribution is working to *defocus* rays, particularly near the edge. This is in agreement with the expected behavior of the GRIN in this achromatic singlet. The GRIN plays the part of a weak negative lens with high dispersion. Meanwhile, the curvature of the front surface acts as a strong positive lens with weak dispersion. Putting the two together results in an overall positive lens with the colors corrected to first order: from the ray fan we find that the normal blue-green-red order of focusing has changed to green-blue-red.

Just how corrected? We utilize Zemax’s Focal Shift plot:

- ZOS: Analyze > Aberrations > Chromatic Focal Shift
- Z13: Analysis > Miscellaneous > Chromatic Focal Shift

In a homogeneous lens, there is a monotonic relationship between focal length and color – blue will always focus faster than red, because the index is higher for blue wavelengths than red. From this plot, however, we see that the focal length (horizontal axis) as a function of the wavelength (vertical axis) isn’t monotonic. Though the plot isn’t a perfect vertical line (all colors focusing at the same spot) the text indicates that the maximum focal shift range is only 24.5 um, compared to a diffraction-limited range of 21.1 um. Thus, this lens has been color-corrected to the very threshold of diffraction-limited performance, as evidenced already by the spot diagram, above.



Ball GRIN Tutorial: *f*/1 Visible Ball Lens – 1 cm Diameter

In this tutorial, we design an *f/*1 ball lens for the visible. While its core will be a GRIN ball lens blended from the polymers PMMA and SAN, the core is nested inside a POLYCARB (polycarbonate) shell for color correction. The outer diameter will be fixed to 10 mm and we will require the focused light to converge outside the lens, onto a notional curved sensor.

The trick to getting this kind of lens to optimize properly is to link as many dependent variables as possible with pickups – not variables to be optimized independently. By insisting on a fixed outer diameter and a core nestled in contact with the outer shell, for example, it becomes clear that if the core grows the shell must get thinner, and vice versa. The one *free* parameter in this expansion is, say, the shell thickness. If one knows the shell thickness then one can calculate the inner radius of the shell, the outer radius of the core (equal to the inner radius of the shell), and the core thickness.

This tutorial will set up the lens first as a homogeneous system to get all the geometric pickups in order. After the lens is optimized as a homogeneous core-shell system, the core will be converted to a GRIN.

The latest version of OpticStudio available at the time of this document is v15.5, SP3 with a release date of March 15, 2016. Notes on some bugs seen with previous versions of OpticStudio can be found in an earlier section of this document. This tutorial has also been tested successfully in Zemax 13 Release 2 SP4 (Aug. 20, 2014).

We have found that different versions of Zemax and even different computers running the same version will generate slightly different designs, generate different merit function values, and require different numbers of optimization iterations when performing optimizations, even if initialized with the same starting lens. The precise details on your screen may vary from the enclosed screenshots, but for the different computers and Zemax versions tested so far the solutions we found have been near-identical.

Start by opening Zemax and setting up a new lens design:

- File / New

Set a few parameters in Zemax as follows:

Zemax OpticStudio (ZOS) note: Replace "System / General" and "System /" below with "System Explorer"

- System / General: Aperture > Aperture Type > Image Space F/#, with Aperture Value set to 1.0
- System / General: Ray Aiming > Real *[NOTE: cannot set Ray Aiming to Real for OpticStudio v15.5 SP2 Feb. 8, 2016. See Notes on OpticStudio Versions, above.]*
- System / General: Material Catalogs > select "MISC" glass catalog from list, then click "Use This Catalog" (In ZOS, drag MISC from "Catalogs Availale" to "Catalogs to Use")
- System / Wavelengths: Settings > Preset: F,d,C (Visible)
- System / Fields: use single field at 0 degrees in X&Y, with Weight = 1

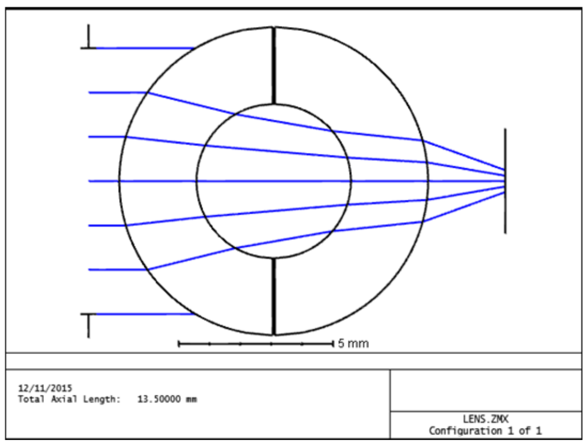
Configure the Zemax surfaces that make up the lens:

- Insert four new surfaces before "IMA" in the Lens Data Editor. *(Note: To insert a new surface, select the "IMA" surface and then hit the "Insert" key — the inserted surface appears above the selected surface.)* These surfaces are automatically labeled "2" through "5" by Zemax.

Before we get to defining the GRIN core, we set up a homogeneous core-shell lens that gets the geometry right, initially. We begin by typing the following values into the Lens Data Editor:

- For Surface 1 (STOP) set: Thickness=1
- For Surface 2 set: Radius=5, Thickness=2.5, Material=POLYCARB, Semi-Diameter=4.999
- For Surface 3 set: Radius=2.5, Thickness=5, Material=PMMA, Semi-Diameter=2.499
- For Surface 4 set: Radius=-2.5, Thickness=2.5, Material=POLYCARB, Semi-Diameter=2.499
- For Surface 5 set: Radius=-5, Thickness=2.5, Material=<none>, Semi-Diameter=4.999

At this point there should be a clear core-shell ball lens, though our (*f*/1 aperture) rays aren't going through cleanly yet, as seen in a Layout plot (Z13: Analysis / Layout / 2D Layout; ZOS: Analyze / Cross-Section):



As can be seen already, the diameter of the inner core will need to increase. Of course, as it does the thickness and inner radius of the outer shell will need to change to accommodate this. To facilitate these changes, we implement several pickups. To set a pickup for a given Lens Editor cell in Z13, right-click on the cell and select "Pickup" from the Solve Type drop down menu. In ZOS, left-click on the little box to the right of the desired Lens Editor cell and select "Pickup" from the Solve Type drop down menu.

Set up initial lens Pickups and Constraints:

For proper-looking drawings, where the surfaces are drawn almost all the way out to their maximum radii, we relate the Semi-Diameters of surfaces 2 and 3 to their radii of curvature:

- For Surface 2 set: Semi-Diameter Pickup: from Surface 2, Scale Factor 0.99995, Column Radius
- For Surface 3 set: Semi-Diameter Pickup: from Surface 3, Scale Factor 0.99995, Column Radius

The Semi-Diameters of surfaces 4 and 5 are linked to those of surfaces 2 and 3:

- For Surface 4 set: Semi-Diameter Pickup: from Surface 3, Scale Factor 1, Column Current
- For Surface 5 set: Semi-Diameter Pickup: from Surface 2, Scale Factor 1, Column Current

The thickness of the inner core (Surface 3) is given by twice the radius of curvature:

- For Surface 3 set: Thickness Pickup: from Surface 3, Scale Factor 2, Column Radius

The back half of the shell must match the front half. Thus:

- For Surface 4 set: Thickness Pickup: from Surface 2, Scale Factor 1, Column Current
- For Surface 4 set: Material Pickup: from Surface 2
- For Surface 4 set: Radius Pickup: from Surface 3, Scale Factor -1, Column Current
- For Surface 5 set: Radius Pickup: from Surface 2, Scale Factor -1, Column Current

The thickness of the outer shell and the diameter of the inner core are related. However, the way in which Zemax defines pickups doesn't allow for a direct pickup to constrain their relationship. Instead, the relationship must be imposed in the Merit Function. The relationship to uphold is:

$$Outer\ Shell\ Radius = \ Core\ Radius + Shell\ Thickness$$

In Merit Function parlance, radii of curvature *R* are addressed via the curvature (1/*R*) operand CVVA and center thicknesses by CTVA. After dividing both sides of the equation by the core radius, the relationship to enforce in the Merit Function is:

$$\frac{CVVA(3)}{CVVA(2)} = 1 + CTVA(2)\ CVVA(3)$$

Though not ideal, in this case we are forced to vary both the thickness of the outer shell and radius of the inner ball independently, while counting on the Merit Function constraint to maintain consistency of the geometry. To open the Merit Function Editor in ZOS or Z13, hit the F6 key.

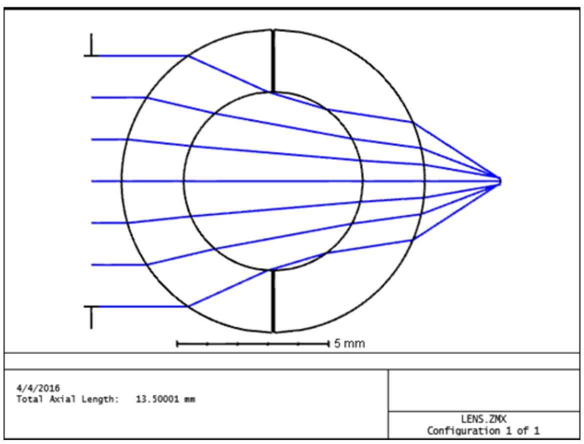
- Open the Merit Function Editor, and begin by adding a default merit function RMS Spot Radius (not RMS Wavefront) with 9 rings *(doing this first protects Merit Function entries – when a new default merit function is added, it will overwrite any operands unless the "Start At:" row is changed by hand.)*
- Ignore error message that pops up due to rays getting terminated by the too-small core.
- Add two new BLNK lines at the top (hit the *Insert* key twice)
- In Line 1 add a comment (you can cut & paste from here) "Constrain [Outer Shell R = Outer Shell T + Core R]"
- In Line 2 add a comment "Math for this: CVVA3/CVVA2 = 1 + (CTVA2)*(CVVA3)"
- Add three more new lines
- In Line 3 select CVVA for Surf 2 (1 / outer shell radius of curvature)
- In Line 4 select CVVA for Surf 3 (1 / core radius of curvature)
- In Line 5 select DIVI with 4 in Op#1 and 3 in Op#2, which computes (CVVA3/CVVA2)
- Add four new lines
- In Line 6 select CONS and enter 1.0 into the Target column
- In Line 7 select CTVA for Surf 2 (shell thickness)
- In Line 8 select PROD with 7 in Op#1 and 4 in Op#2, which computes (CTVA2*CVVA3)
- In Line 9 select SUMM with 6 in Op#1 and 8 in Op#2, which computes (1 + CTVA2*CVVA3)
- Add two new lines
- In Line 10 select DIFF with 5 in Op#1 and 9 in Op#2, for [CVVA3/CVVA2 – (1+CTVA2*CVVA3)]

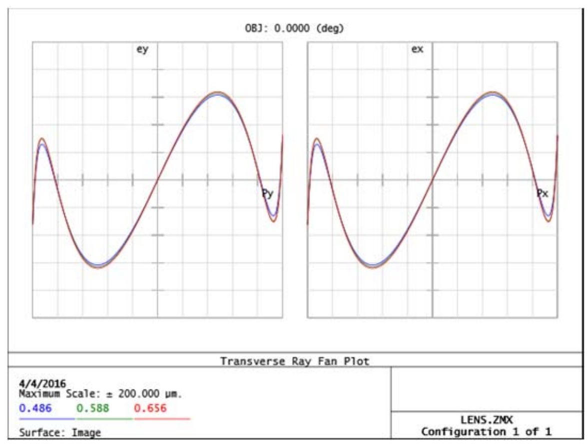
- In Line 11 select OPVA and enter 10 in the Op# column and -10 in the Weight column. (Trying to convince Zemax that Operator 10 ***must*** be held to zero during optimization.)

Come up with homogeneous lens, pre-GRIN starting point:
Before running an optimization, we adjust the shell thickness by hand to allow enough light through to compute the merit function:

- Set the Surface 2 Thickness and Surface 3 Radius entries to Variable (Ctrl-Z)
- Manually set the Surface 2 Thickness to 0.5
- Manually set the Surface 3 Radius to 4.5
- Run a local optimization (Shift-Ctrl-O)

This is our starting point. We have a homogeneous lens with rays that make it to the image plane, but the rays are highly aberrated. To see the ray fan in Z13 select Analysis / Fans / Ray Aberration. In ZOS, select Analyze / Aberrations / Ray Aberration. (I've added more rays, up to 50, in the ray fan to resolve the narrow wiggles at the edge of the field.) A look at the plot shows that the aberrations are dominated by geometric aberrations: the ray fans for all three colors are nearly identical. In this system the GRIN will primarily address these geometric aberrations, but in a way that does more to fix the problem while introducing less chromatic aberration than would be the case with additional homogeneous shells.





Initialize the GRIN Core:
We now convert the core to a GRIN.

- Set Type of Surface 3 to "MGRIN Ball v1.0.0" by right-clicking on "Standard" and selecting in the dialog: Surface Type > User Defined, Surface DLL > MGRINx64_Ball_v100.DLL if you have a 64-bit Windows operating system, or … > MGRINx32_Ball_v100.DLL if you have a 32-bit system. *(In ZOS, select "User Defined" from the "Surface Type" drop-down menu, and then select the proper DLL from the new dialog box.)*
- Note that "PMMA" is still listed in the Material column of Surface 3, so delete it. The Material column no longer has any effect on the lens, but we delete the text in this step to avoid confusion when looking at the Lens Data Editor.

- The default Design WaveL is the d-line and default GRIN materials are PMMA and SAN from Zemax's MISC catalog. These are what we want already.
- Enter 1 into the GRINType column (Z13: in the Extra Data Editor) to set the index function to Polynomial.
- Set up a Pickup on "Poly Zo" column of Surface 3 (Par 21 in ZOS, Extra Data column 9 in Z13) from Surface 3, Scale Factor 1, off the Radius Column. This ensures that the center of the GRIN distribution (Xo,Yo,Zo) coincides with the center of the core: at the center of the sphere defined by the front surface radius of curvature.
- Enter 1.5 into the r^0 term column.

Add the base material index constraints to the Merit Function Editor:
The core is now a GRIN, though currently modeled as a homogeneous material with an index a bit higher than PMMA. Before optimizing the GRIN, material constraints need to be set in the Merit Function to prevent Zemax from choosing non-physical material combinations. Add seven new lines to the Merit Function Editor, just above the "DMFS" line. When done, the DMFS operand should be on Line 19.

- Line 12: Operand "BLNK" with comment "Set up GRIN material constraints:"
- Line 13: Operand "ZPLM" (Mac# = 18, *but leave other fields at default values for now – we will return to this line)*
- Line 14: Operand "ZPLM" (Mac# = 18, Data = 1, Target = 0, Weight = 0)
- Line 15: Operand "ZPLM" (Mac# = 18, Data = 2, Target = 0, Weight = 0)
- Line 16: Operand "ZPLM" (Mac# = 18, Data = 3, Target = 0, Weight = 0)
- Line 17: Operand "OPLT" (OP# = 13, Target = 1, Weight = 1)
- Line 18: Operand "OPLT" (OP# = 14, Target = 1, Weight = 1)

For a detailed explanation of Lines 13-16 (above) see the description of the "ZPL18" macro. Briefly, Lines 13 and 14 return "penalty functions" that attempt to keep the refractive index range of the optimized GRIN profile within the range determined by the base materials chosen. Line 13 returns ((nmin-navg)/(Δn/2))^8 and Line 14 returns ((nmax-navg)/(Δn/2))^8, where nmin (nmax) is the minimum (maximum) index actually found in the MGRIN profile, and Δn and navg are the index range and average index, respectively, determined by the base materials. The purpose of Lines 17 and 18 is to optimize the GRIN profile by keeping the "penalty function" values calculated in Lines 13 and 14, respectively, below the Target value of 1. Additional details can be found in the description of the "ZPL18" macro.

We now return to Line 13 in the Merit Function Editor (see above). Since this line is the first call of the "ZPL18" macro, it must have Data = 0 and must include all inputs to the ZPL18 macro. This line reports the first output value of the ZPL18 macro. (Note that while Lines 14-16 are used for reporting the other 3 output values of the ZPL18 macro, the input values are only specified once, in Line 13.)

The remaining input values required on Line 13 are Hx, Hy, Px and Py. Hx is the MGRIN surface number (i.e., 3 in this case). Hy determines the sample density used to find the maximum and minimum refractive index values in the GRIN profile; a good choice for Hy is 11.

Finally, we need to determine the input values for Px and Py in Line 3. These represent the material bounds, i.e., the minimum and maximum index (respectively) of the base materials at the design wavelength, which need to be entered manually. We determine these values by running the "GRIN Base

Material Index" macro and selecting Wavelength 2 (or hit Enter since Wavelength 2 is the Primary wavelength), which should return values 1.49175571 and 1.56743976. Enter these values in Line 3 for Px and Py, respectively. Close the macro text window.

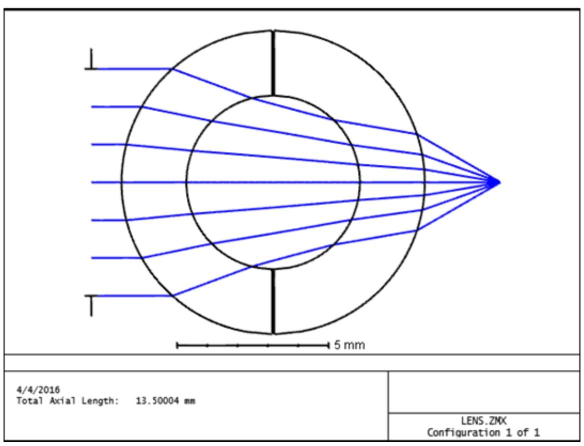
In summary:

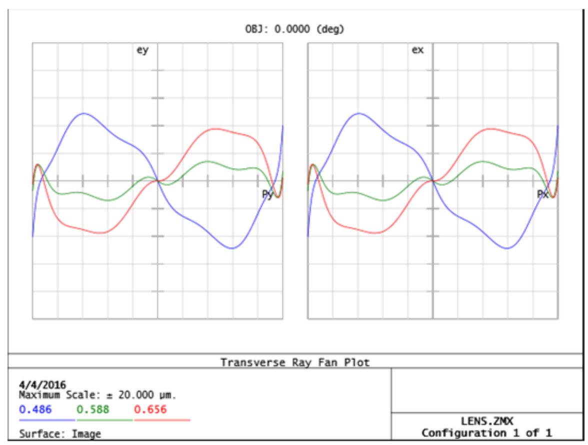
- Line 13: Set Hx = 3, Hy = 11, Px = 1.49175571, Py = 1.56743976, Target = 0, Weight = 0

Optimize the GRIN profile:
We are now prepared to introduce GRIN to improve the image quality of the lens.

- Set Surface 3 columns "r^0", "r^2", "r^3", "r^4", and "r^5" [**NOT r^1**, which would create a cusp at the origin] to variable (Ctrl-z)
- Run a local optimization (Shift-Ctrl-O)

After ~12 iterations, the Merit Function should end up close to 0.0023. The resulting lens is optimized, given the three materials of which it is made. The layout and ray fans should look like:





The ray fan plot scale is 10x smaller than for the homogeneous lens model, and the remaining aberrations are the result of sphero-chromatism – different parities of spherical aberration depending on wavelength.

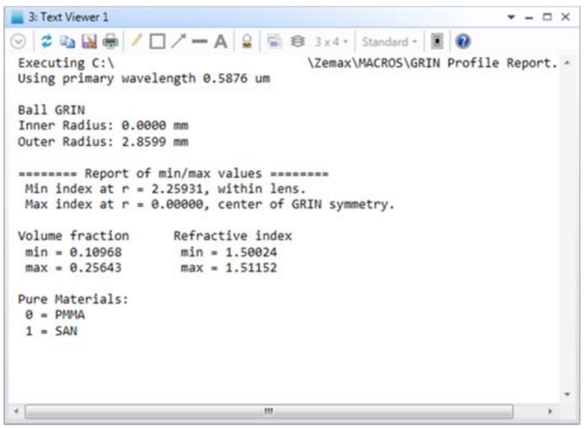
Plot the GRIN Profile:
*[NOTE: In ZOS versions 15 prior to 15.5 SP2, ZOS freezes upon running a ZPL macro after an optimization with ZPLM 18 in the merit function editor. (v14 is fine) You would need to **save your work**, exit, re-start ZOS, and re-load the saved file before running the GRIN Profile Report macro outlined below.]*
We now examine the GRIN index distribution which makes this performance possible.

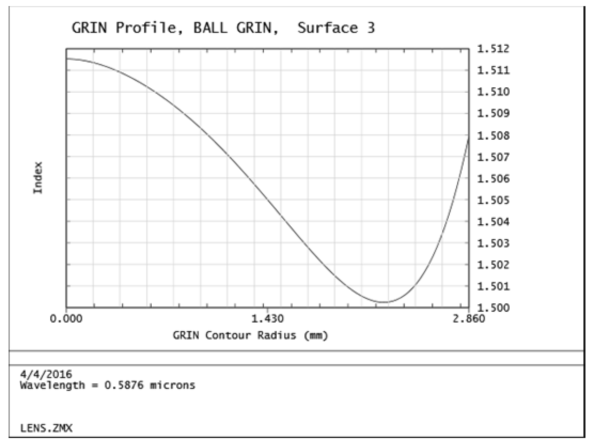
- Run the "GRIN Profile Report" macro
- Hit "Enter" at the first dialog box (plot index at the primary wavelength)
- Hit "Enter" at the second dialog box (no need to print out the numerical values of the plots)

The macro generates three windows: two plots and a status window. From the status window, we see the minimum and maximum indices and material volume fractions.

It is interesting to note that the lens performance, far improved over the homogeneous case where n=1.5, is achieved with only a modest index modulation. The index contrast of the design is only 0.011. This small contrast requires a similarly small variation in the material composition. Based on the volume fraction numbers displayed in the window, the lowest-index material composition in the design has a 11:89 mix of SAN:PMMA, while the highest-index composition is just 26:74.

The distribution of index can be viewed on the GRIN Profile plot. The X axis of the plot automaticlly starts with the minimum GRIN contour radius in the lens and ends with the largest GRIN contour in the lens. Since the core contains the GRIN origin, the minimum GRIN radius is zero. The maximum GRIN radius for this example is the radius of the core.

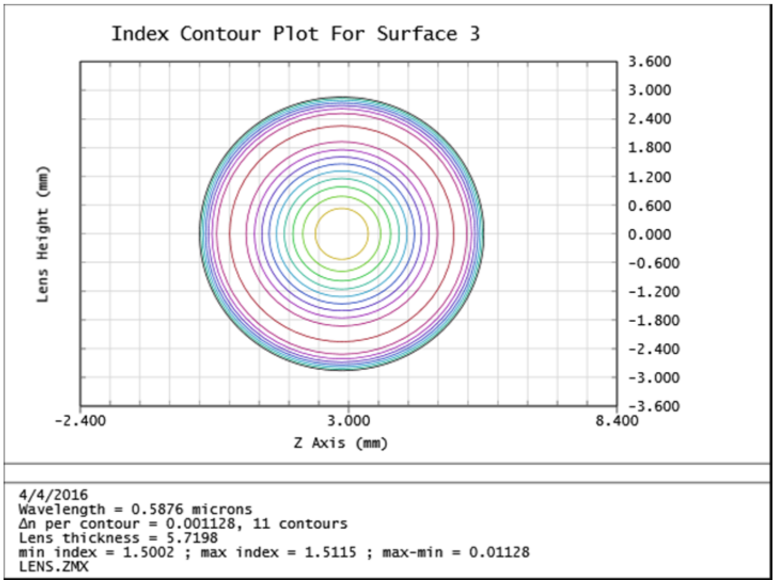




Display the GRIN Contour Plot on the Lens Outline:

A visualization tool which helps to convey spatial information on what the GRIN is doing is the GRIN Contour Plot macro. It is helpful when looking at these plots to remember that optical rays are bent away from lower index values towards higher index values. The amount of bending is proportional to the steepness of the gradient.

- Run the “GRIN Contour Plot” macro
- Hit “Enter” at the first dialog box (plot index at the primary wavelength)
- Hit “Enter” at the second dialog box (keep default number of contours to plot)

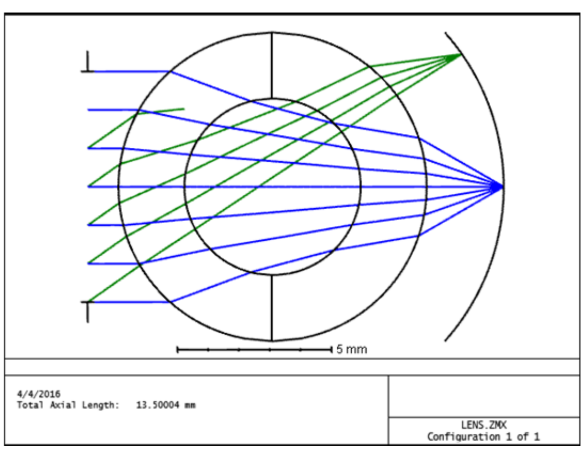


The contour lines show that the steepest index gradient (where the ray bending due to GRIN is the greatest) is out at the edge of the ball. A comparison between this contour plot and the Profile Plot, above, shows that the GRIN distribution is working to defocus rays near the edge of the GRIN ball. Meanwhile, rays near the center of the lens are focused, less strongly, towards the optical axis. The bending action of the GRIN, particularly at the edge of the ball, is distinctly noticeable in the Layout plot, above. The outer rays which pass nearest the edge of the inner ball are clearly curved away from the optic axis while inside the GRIN. This helps to mitigate the over-focusing of the edge rays in the all-homogenous design viewed before we put in the GRIN.

Investigate Off-Axis Optical Performance:

To see how this lens would integrate with a curved sensor we start with a simple first try:

- Set Surface 6 (IMAGE) Radius to -7.5, centering the image surface on the center of the ball lens
- Set the Surface 6 Semi-Diameter to 5
- Add a new Field: Field 2, X=0, Y=35 (degrees)
- Update the 2D Layout plot (possibly needing to go into the Layout settings to ensure that All fields are displayed)

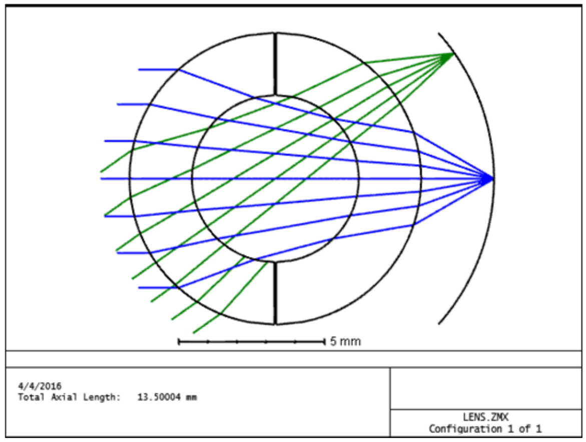


Note a problem here: because the stop is located outside the lens, the rays don't trace in a symmetric way through the ball lens. To get this to work properly, we should set up an internal STOP surface at the center of the lens.

Insert Internal STOP – Break the Core into Two GRIN Lenses:
Inserting an internal STOP requires breaking up the core into two different GRIN lenses, just as the shell is broken up into two different lenses. NOTE: Because Zemax will not allow adjacent GRIN surfaces, a non-GRIN surface must be placed between the two halves. The steps to do this are provided as follows:

- Insert a new surface after Surface 3 (select Surface 4 and hit *Insert*)
- Select the whole Surface 3 row and copy it (Ctrl-c)
- Click on Surface 5 and paste it (Ctrl-v). The IMAGE surface should now be Surface 8.
- Set Surface 4 Radius to Infinity
- Set Surface 5 Radius to Infinity, and remove the Variable tag so that the radius is fixed.
- Change the Thickness Pickup on Surface 3 so that the Scale Factor is 1 rather than 2.
- Set the Thickness Pickup on Surface 5 to be from the Current Column, Surface 3, Scale Factor 1
- Set the Semi-Diameter of Surface 5 to be Picked up from the Current Column, Surface 3, S.F. 1
- Set the "Poly Zo" column of Surface 5 to Fixed (remove the pickup) and set its value to 0.0 (centering the GRIN function at the center of the ball)
- In case changes are made to the GRIN later, set up all the "r^*j*" columns of Surface 5 to be picked up from their counterparts in Surface 3.
- Set Surface 4 to be the STOP (In ZOS, click on the surface in the Lens Editor and then click the down arrow next to Surface 4 Properties, at the top-left of the Editor, for the drop-down menu. Click on Type > Make Surface Stop. In Z13 right-click on the Surf Type column for Surface 4. Click on Type > Make Surface Stop.)
- As an aesthetic choice, I set the Radius of Surface 1 to be centered on the lens (Radius = 6)
- For similarly aesthetic reasons, under Surface 1 Properties I choose Not to Draw this surface (Open Surface 1 Properties and click on the Draw > Do Not Draw This Surface checkbox *and don't exit this dialog box yet …*)
- I also choose not to draw Surfaces 4 & 5 (… by cycling straight from the Surface 1 Properties to the Surface 4 & 5 Properties windows. In ZOS click on the right arrow (> sign) near the top and in Z13 click on the Next Surface button, until you cycle through to Surface 4, click the Do Not Draw box, and then move to Surface 5 to click Do Not Draw again. Close the Properties window.)
- The Layout Window may need to be told to draw rays out to the Last Surface of 8, rather than 7.

We now have a central STOP surface so that rays (almost) get through cleanly. A current snapshot of the Layout window, however, shows that another issue has arisen: rays at the bottom half of the off-axis field aren't making through to the image plane.



The reason for this is subtle: even though the STOP thickness is zero, it nonetheless has an index value of 1 associated with it. Thus, when a ray approaches that interface from within the higher-index material of the core, at a high enough angle to exceed the total internal reflection condition, Zemax registers an error and won't propagate the ray further.

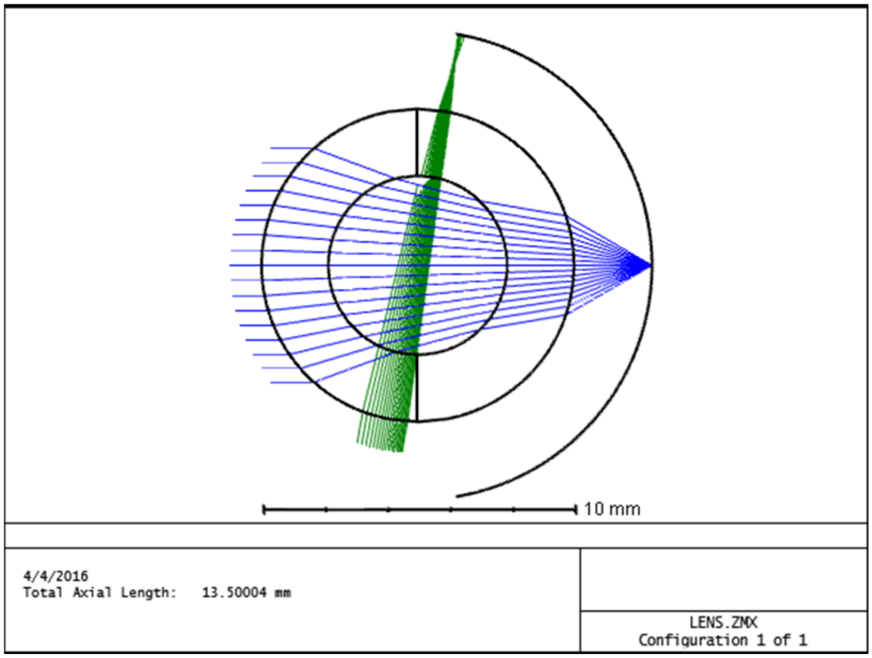
Ensure STOP Surface Avoids Total Internal Reflection:
To avoid this problem, set the Material of the STOP surface to something with an index higher than anything in the core. If I set the Material of Surface 4 to a Model glass with index 2, I recover the rest of the rays in the layout plot.

- Set the Material for Surface 4 to a Model glass with Index nd = 3. (ZOS – click on small box to the right of the cell, and Z13 right-click directly on the cell to select: Solve Type > Model, and enter 2 in the nd text field.)

Decrease "Delta T" for Extreme Rays If Needed:
Let's see how far out we can push the input angles in Zemax:

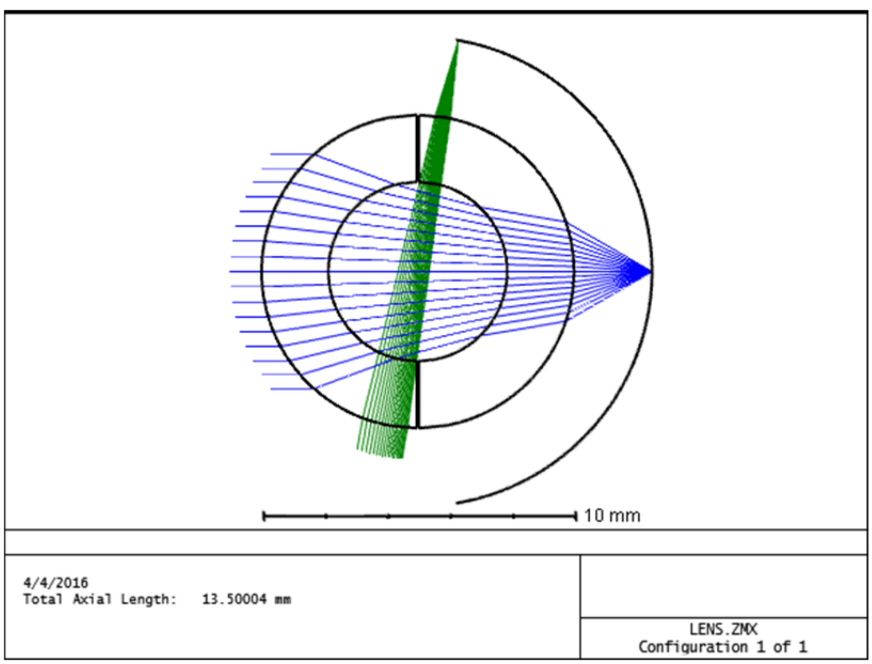
- Set the IMAGE Semi-Diameter to 7.4
- If in OpticStudio, change the Line Thickness of the Layout Window to Thin
- In the Layout Window settings, change the number of rays to 17
- Change the angle of Field 2 to 80 degrees

The layout Window now looks like:

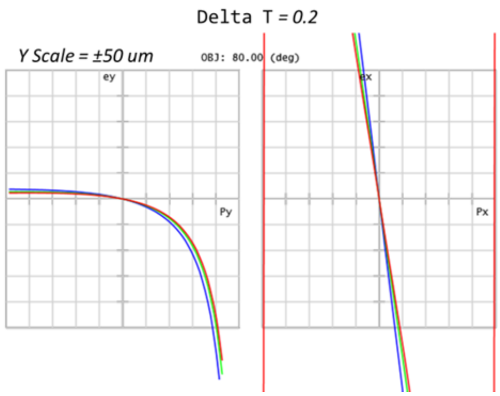


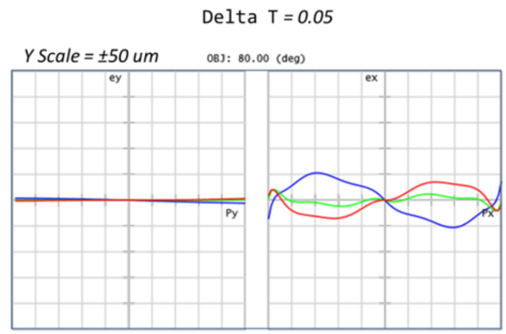
There appear to be some artifacts near the top edge of the STOP and, contrary to the focusing quality at zero degrees incidence (the blue rays) the off-axis rays visibly fail to focus properly onto the image surface.

In this case, we are seeing a rare instance of the impact of the value of Delta T. In order to trace the off-axis rays accurately enough, we need to decrease Zemax's numerical stepsize Delta T for tracing rays through a GRIN medium. Changing Delta T from the default 0.2 to a value of 0.05 for both Surface 3 and 5 does the trick. Though the Layout makes it appear to be fixed:



confirmation is assured by a before & after comparison of the off-axis ray fan plots:


Delta T = 0.2
Y Scale = ±50 um
OBJ: 80.00 (deg)
ey
Py
ex
Px


Delta T = 0.05
Y Scale = ±50 um
OBJ: 80.00 (deg)
ey
Py
ex
Px