SELFOC® MICRO LENS(SML), Technical Note

GRIN and SELFOC®

To understand the nature of SELFOC lenses, consider the way a conventional lens works. A conventional glass lens can bend light only at its surface. At the interface between air and glass, rays of light will change direction according to the abrupt change in the index of refraction. By carefully controlled the shape and smoothness of the lens surfaces, these rays can be brought to a focus and form an image.

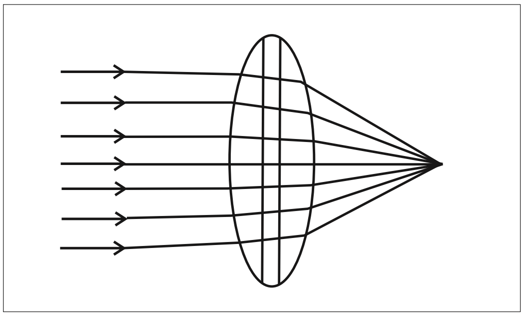

Figure 1: Profile of Conventional Lens

GRIN (**GR**adient **IN**dex) lenses offer an alternative to the often painstaking craft of polishing curvatures onto glass lenses. By gradually varying the index of refraction *within the lens material,* light rays can be smoothly and continually redirected towards a point of focus. The internal structure of the index "gradient" can dramatically reduce the need of tightly-controlled surface curvatures and results in a simple, compact lens geometry.

The key to gradient index technology lies in the controlled variation of the refractive index. This is achieved by a high-temperature ion exchange process within the glass host material. The SELFOC lens, manufacturing by GO!FOTON, is produced by a unique ion exchange process that yield stronger index gradients than any other method currently used in production.

With SELFOC technology, optical engineers and researchers have the ability to form a real image on the physical surface of a lens. This creates unique possibility for coupling light into an optical fiber or relaying an image through an endoscope. With a variety of options including AR (Anti Reflection) coating, metalization, and angled facet, SELFOC lenses may be customized to work for your application.

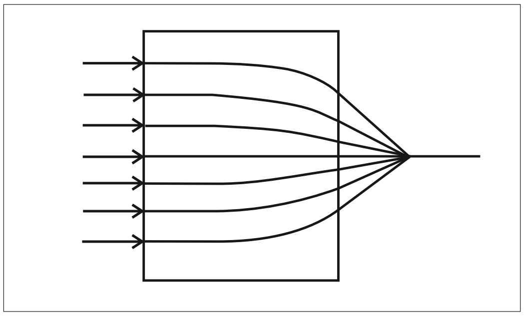

Figure 2: Profile of SELFOC GRIN Lens

The Gradient Constant

The SELFOC lens utilizes a radial gradient. The index of refraction is highest at the center of the lens and decreases with radial distance from the axis. The following equation describes the refractive index distribution of a SELFOC lens:

Equation 1

$$N(r) = N_0\left(1 - \frac{(\sqrt{A})^2}{2} r^2\right)$$

This equation shows that the index falls quadratically as a function of radial distance. The resulting parabolic index distribution has a steepness that is determined by the values of the gradient constant, √A.

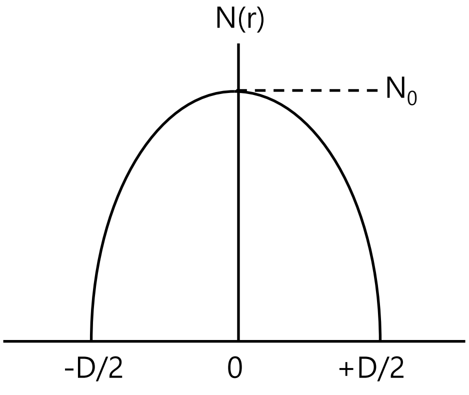

Figure 3 : GRIN Refractive Index Profile

Although the value of this parameter must be determined through indirect measurement techniques, it is a characterization of the lens' optical performance. How rapidly rays will converge to a point for any particular wavelength depends on the gradient constant.

The dependence of √A and N_0, on wavelength is described by the dispersion equations listed at later part of this technical note. Note that different *dispersion equations* apply to different lens diameters and numerical apertures.

Lens Length and Pitch

In a SELFOC lens, rays follow sinusoidal paths until reaching the back surface of the lens. A light ray that has traversed one *pitch* has traversed one cycle of the sinusoidal wave that characterizes that lens. Viewed in this way, the pitch is the spatial frequency of the ray trajectory.

Equation 2

$$2\pi P = \sqrt{\mathrm{A}}\,\mathrm{Z}$$

The above equation relates the pitch (P) to the mechanical length of the lens (Z) and the gradient constant. Figure 4 illustrates different ray trajectories for lenses of various pitch. Notice how an image may be formed on the back surface of the lens if the pitch is chosen appropriately.

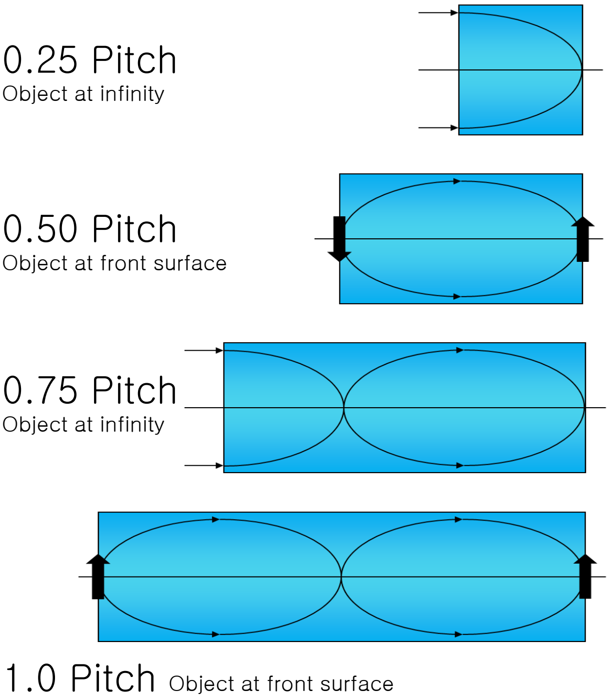

Figure 4 : Pitch Concept of SELFOC GRIN Lens

Paraxial Optics

In contrast to the optics of homogeneous materials, gradient-index optics involve smooth-varying ray trajectories within the GRIN media. The paraxial (first-order) behaviour of these materials is modelled by assuming sinusoidal ray paths within the lens and by allowing the quadratic term in Equation 1 to vanish in the ray-tracing calculations. All of the usual paraxial quantities may be calculated with the help of the ray-trace matrices given at the later part of this technical note. The formulae for common paraxial distances have also been tabulated for quick reference.

Numerical Aperture

Numerical aperture “NA” is a measure of the light gathering capability of a lens. For any particular object point, there is an associated cone of rays which can be transmitted into image space. The NA defines the maximum cone angle for a point object a distance L_1 from the lens surface. For a SELFOC lens, this angle is given by the following expression.

$$\mathrm{NA} = N_0\sqrt{A}\cdot\sqrt{r_0^2 - r^2}$$

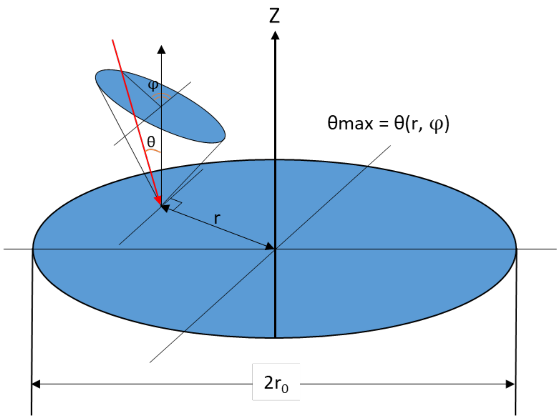

Figure 5 : Definition of NA

Where,

r_0 : Lens radius, (mm)

r : Radial distance from optical axis, (mm)

φ : Angle of input light

√A : Index gradient constant, (mm^{-1})

N_0 : On-axis refractive index

Dispersion Equations & Paraxial Optics Formulae

The following equations may be used to determine the on-aixs refractive index $N_0(\lambda)$ and the gradient constant $\sqrt{A}(\lambda)$ for all standard SERFOC Microlenses. These formulae are valid for wavelengths greater than 550nm.

On-Axis Refractive Index : λ (um)

SLW100, SLW180, SLC180, SLW200 :

$$N_0(\lambda) = 1.5868 + \frac{8.14 \times 10^{-3}}{\lambda^2}$$

SLW300, SLW400 :

$$N_0(\lambda) = 1.6107 + \frac{9.8 \times 10^{-3}}{\lambda^2}$$

SLH180 :

$$N_0(\lambda) = 1.6294 + \frac{1.12 \times 10^{-2}}{\lambda^2}$$

All of the common paraxial distances for SELFOC Microlenses may be derived from the following ray-trace matrices. Variables r_1 and θ_1 are the input ray height and slope respectively, in a medium of index n_1 (see Figure 6). At the rear surface of the lens, r_2 and θ_2 are the corresponding output variables in a medium of index n_2.

Paraxial Ray-tracing Matrices :

plano-plano lens :

$$\begin{bmatrix} r_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} \cos(Z\sqrt{A}) & \frac{n_1}{N_0\sqrt{A}}\sin(Z\sqrt{A}) \\ -\frac{N_0\sqrt{A}}{n_2}\sin(Z\sqrt{A}) & \frac{n_1}{n_2}\cos(Z\sqrt{A}) \end{bmatrix} \begin{bmatrix} r_1 \\ \theta_1 \end{bmatrix}$$

When $n_1 = n_2 = 1$(Air) and lens pitch is 0.25, equitation can be simplified as below

$$\begin{bmatrix} r_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{N_0\sqrt{A}} \\ -N_0\sqrt{A} & 0 \end{bmatrix} \begin{bmatrix} r_1 \\ \theta_1 \end{bmatrix}$$

Index Gradient Constant : $\sqrt{A}$ (mm^{-1}), λ (μm)

SLW100 :

$$\sqrt{A}(\lambda) = 0.5945 + \frac{3.936 \times 10^{-3}}{\lambda^2} + \frac{5.539 \times 10^{-4}}{\lambda^4}$$

SLW180 :

$$\sqrt{A}(\lambda) = 0.3238 + \frac{5.364 \times 10^{-3}}{\lambda^2} + \frac{2.626 \times 10^{-4}}{\lambda^4}$$

SLW200 :

$$\sqrt{A}(\lambda) = 0.2931 + \frac{2.369 \times 10^{-3}}{\lambda^2} + \frac{7.681 \times 10^{-4}}{\lambda^4}$$

SLW300 :

$$\sqrt{A}(\lambda) = 0.1973 + \frac{3.723 \times 10^{-3}}{\lambda^2} + \frac{2.050 \times 10^{-5}}{\lambda^4}$$

SLW400 :

$$\sqrt{A}(\lambda) = 0.1468 + \frac{2.654 \times 10^{-3}}{\lambda^2} + \frac{3.960 \times 10^{-6}}{\lambda^4}$$

SLH180 :

$$\sqrt{A}(\lambda) = 0.4151 + \frac{4.137 \times 10^{-3}}{\lambda^2} + \frac{7.652 \times 10^{-4}}{\lambda^4}$$

SLC180 :

$$\sqrt{A}(\lambda) = 0.3210 + \frac{4.474 \times 10^{-3}}{\lambda^2} + \frac{2.370 \times 10^{-4}}{\lambda^4}$$

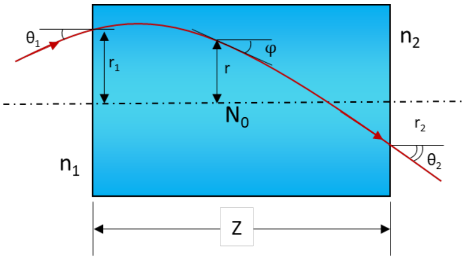

Figure 6 : Single Ray Through GRIN Lens

r_1 : Position of input light, (mm)
θ_1 : Angle of input light, (radian)
r_2 : Position of output light, (mm)
θ_2 : Angle of output light, (radian)
Z : Lens Length, (mm)
r : Radial distance from optical axis, (mm)
$\sqrt{A}$: Index gradient constant, (mm^{-1})
N_0 : On-axis refractive index
n_1 : Index of medium on input side
n_2 : Index of medium on output side

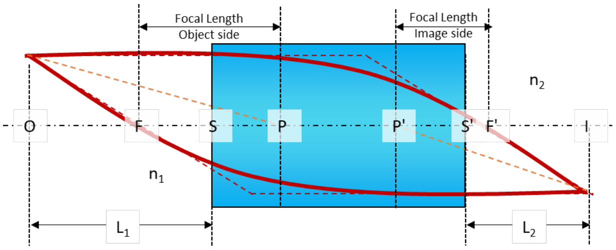

Figure 7 : Relative positions of cardinal points

This figure illustrates the relative positions of the cardinal points for a typical SELFOC Lens. Distances measured to the left of a reference are negative; to the right, positive.

Object Side	Image Side
F : Front focal Point	F' : Rear Focal Point
S : Front Surface Vertex	S' : Rear Surface Vertex
P : Front Principal Plane	P' : Rear Principal Plane
L_1 : Object Distance(OS)	L_2 : Image Distance(O'S')

Front Focal Length

$$\overline{FS} = \frac{n_1 \cos(Z\sqrt{A})}{N_0\sqrt{A} sin(Z\sqrt{A})}$$

Effective Front Focal Length

$$\overline{FP} = \frac{n_1}{N_0\sqrt{A} sin(Z\sqrt{A})}$$

Rear Focal Length

$$\overline{S'F'} = \frac{n_2 \cos(Z\sqrt{A})}{N_0\sqrt{A} sin(Z\sqrt{A})}$$

Effective Rear Focal Length

$$\overline{P'F'} = \frac{n_2}{N_0\sqrt{A} sin(Z\sqrt{A})}$$

Front Principal Distance

$$\overline{SP} = \frac{n_1[1 - \cos(Z\sqrt{A})]}{N_0\sqrt{A} sin(Z\sqrt{A})}$$

Rear Principal Distance

$$\overline{S'P'} = \frac{-n_2[1 - \cos(Z\sqrt{A})]}{N_0\sqrt{A} sin(Z\sqrt{A})}$$

Object Distance

$$L_2 = \overline{S'I} = \frac{-(n_1 n_2/\sqrt{A}) \sin(Z\sqrt{A}) - n_2 N_0 L_1 \cos(Z\sqrt{A})}{n_1 N_0 \cos(Z\sqrt{A}) - N_0^2 L_1 \sqrt{A} \sin(Z\sqrt{A})}$$

Transverse Magnification

$$M_T = \frac{n_1}{n_1 \cos(Z\sqrt{A}) - N_0 L_1 \sqrt{A} \sin(Z\sqrt{A})}$$

Longitudinal Magnification

$$M_L = \frac{n_1 n_2}{\left[n_1 \cos(Z\sqrt{A}) - N_0 L_1 \sqrt{A} \sin(Z\sqrt{A})\right]^2}$$

Angular Magnification

$$M_A = \frac{n_1 \cos(Z\sqrt{A}) - N_0 L_1 \sqrt{A} \sin(Z\sqrt{A})}{n_2}$$

Aberration

All optical systems exhibit aberration. There are many different varieties, however, and this publication will only briefly cover those pertaining to SELFOC lenses. Aberration contributes to coupling loss through incorrect magnification or image distortion.

Spherical aberration is the failure of the rays to converge on a perfect focal point. Negative spherical aberration is present when the outer rays (rays further from the optical axis) focus short of the inner rays (rays close to the optical axis). In this case, the lens is defined as undercorrected. In the opposite case, the outer rays focus further away from the inner rays, and this positive spherical aberration defines the lens as being overcorrected.

Chromatic aberration results in rays arriving at the focal point out of phase due to their differing wavelength. The underlying cause is two fold. The refractive index of the base glass material is wavelength dependent, increasing toward the blue end of the spectrum. Furthermore gradient index constant, $\sqrt{A}$, is also a function of wavelength. The dependence of $\sqrt{A}$ on wavelength means that the pitch of a SELFOC lens is always keyed to a particular wavelength. For example, SLW-18lens with a pitch of 0.25 at 630nm will be equivalent to a 0.24 pitch lens at a wavelength of 1560nm.

Astigmatism originates from many laser diodes, causing the beam to focus at two different locations from each plane of orientation. This aberration accompanies the elliptical beam shape of the diode, and can be undesirable, particularly in lase diode collimating applications. It should be understood that the SELFOC lens does not correct the astigmatism nor circularize the beam. Additional elements must be included in the optical system to reduce these effects.

Material Absorption and Transmission Properties

Like all oxide glasses, SELFOC lens material has a finite spectral transmission range. The operating wavelength range extends from 380nm through 2000nm, over which a minimum 89%transmission is guaranteed from non-coated lenses.

Anti-reflection, “AR” coating further improves the transmission up to 99.5% or more depending on the grade of coating. Figure 8 shows typical spectral transmission characteristics of the SELFOC lens.

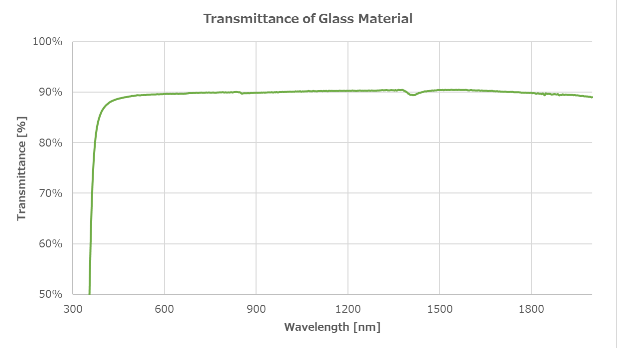

Figure 8 : Transmission vs. Wavelength
(for 5mm thickness)

Storage and Handling of Lenses

Storage

For extended periods of time, the lenses should be stored in a “dry box” environment. This entails the use of a desiccant (e.g., silica gel) or a heat source to prevent humidity from leaching the lens material. This is much more critical for non-coated lenses, since AR coatings help to protect the lens surfaces from humidity. For short term storage (less than a month), the plastic box and foam packing in which the lenses are shipped will provide adequate storage.

In addition to humidity requirements, the lenses need to have sufficient spacing to avoid potential damage such as chipping and scratching from other lenses. For this reason, GO!FOTON storage boxes have built-in slots in which the lenses are placed, with surrounding packaging to hold them securely in place.

Handling

After opening the lens boxes, it is important to exercise extra care in lifting the plastic shield. Particularly with smaller lenses, it is possible that they may cling to the shield and be lost during removal. Lenses should be handled with stainless steel tweezers, preferably those with a tapered end. Lenses should be picked up out of their individual compartments by firmly holding each by its side surface (not the ends).

Cleaning

At times it is necessary to clean the lens surfaces due to the presence of some dust or film which may impact the image. FGO!FOTON generally recommends the use of methyl alcohol as a cleaning solvent. Acetone may also be used, without harm to the lens, but it should be pure enough to not leave a residue on the lens’ surface.