Introduction to Gradient Index Optics

The way a GRadient INdex (GRIN) lens works may be explained best by considering a conventional lens: An incoming light ray is first refracted when it enters the shaped lens surface because of the abrupt change of the refractive index from air to the homogeneous material. It passes the lens material in a direct way until it emerges through the exit surface of the lens where it is refracted again because of the abrupt index change from the lens material to air (see Fig. 1, right). A well-defined surface shape of the lens causes the rays to be focussed on a spot and to create the image. The high precision required for the fabrication of the surfaces of conventional lenses aggravates the miniaturization of the lenses and raises the costs of production.

GRIN lenses represent an interesting alternative since the lens performance depends on a continuous change of the refractive index within the lens material. Instead of complicated shaped surfaces plane optical surfaces are used. The light rays are continuously bent within the lens until finally they are focussed on a spot. Miniaturized lenses are fabricated down to 0.2 mm in thickness or diameter. The simple geometry allows us a very cost-effective production and simplifies the assembly of your product essentially. Varying the lens length implies an enormous flexibility at hand to fit the lens parameters as, e.g., the focal length and working distance to your special requirements without high research and development efforts and costs. For example, appropriately choosing the lens length causes the image plane to lie directly on the surface plane of the lens so that sources such as optical fibers can be glued directly onto the lens surface.

GRINTECH produces the GRIN lenses via silver and lithium ion exchange in special glasses. In contrast to the thallium technology, which is conventionally used for the fabrication of GRIN lenses, this unique GRINTECH key technology, where the special shape of the refractive index profiles is to be realized precisely, is non-toxic and bears no health and environmental risks for us as the producer and the user of our products. Refractive index changes up to 0.145, which are similar to those attained via the thallium ion exchange, GRINTECH achieves via the silver ion exchange. Embedding silver ions into the glass or, alternatively, removing them from it allows focussing and diverging lenses to be produced with numerical apertures up to 0.6 and acceptance angles up to 70° for the visible and infrared spectral range. Both processes are performed in rods and slabs resulting in rod lenses and cylindrical lenses with plane optical surfaces.

This large scope of focussing and diverging lenses in rod and cylindrical geometry enables GRINTECH to provide you with compact GRIN lens systems and subassemblies as, e.g.,
microoptical telescopes, complete endoscopic imaging systems, anamorphic beam shaping optics for diode lasers, and microoptical scanners, in addition to single high-performance lenses. With our competence in the optical design we fit the system to your requirements.

**Technical details of the optical design with GRIN lenses**

A radial refractive index profile of nearly parabolic shape realizes a continuous cosine ray trace within a GRIN focussing lens, the period or pitch length P of which does not depend on the entrance height and the entrance angle of the light ray (see Fig. 2).

Various imaging designs can be realized using the same index profile by choosing different lens lengths:
- a quarter-pitch lens images a point source on the entrance surface of the lens into infinity or collimates it, respectively. This configuration is usually applied to the collimation of single-mode and multi-mode optical fibers and laser diodes. For high-power laser diodes, GRIN cylindrical lenses are used for the Fast-AxisCollimation. Together with other GRIN components they are easily integrated to compact microoptical systems.
- a half-pitch lens images an object on the entrance surface inverted on the exit surface of the lens (magnification \(M = -1\)).
- a 1- (2, 3, or more, respectively)-pitch lens images an object on the entrance surface of the lens identically on the exit surface (magnification \(M = +1\)). Those lenses are used in endoscopes as relay lenses, which transmit the image from the front part of the endoscope to the eye-piece (see Fig. 3).

- Endoscope objective lenses are somewhat longer than a quarter-pitch lens and image the object field to be viewed at at a typical working distance between 3 and 25 mm and a large viewing angle (≥ ± 30°) on the exit surface of the lens on a reduced scale (see Fig. 3). GRINTECH produces these lenses via a non-toxic silver ion exchange in a special glass. A complete endoscopic imaging system is achieved by gluing the objective and the relay lens directly. Prisms, which change the **viewing direction** are easily mounted on the flat entrance surface of the objective lens.
- Various magnifications M and working distances s can be realized by choosing an appropriate lens length \( z_l \).

The refractive index profile has to fit an ideal shape most accurately to ensure an optimum imaging quality. For focusing lenses, the ideal shape is described by

\[
n(r) = n_0 \text{sech}(gr),
\]
a function which deviates slightly from a parabola, with its maximum index \( n_0 \) at the center of the profile. The pitch length \( P \) results from the gradient constant \( g \),

\[
P = \frac{2\pi}{g}
\]
The geometrical gradient constant \( g \) characterizes the steepness of the index gradient and with the lens length \( z_l \) it determines the focal length \( f \) and the working distance \( s \) of the lens,

\[
f = \frac{1}{n_0 g \sin(gz_l)}, \quad s = \frac{1}{n_0 g \tan(gz_l)}
\]

Typical focal lengths and working distances of GRINTECH standard lenses are listed in the GRINTECH product specifications. Figure 4 shows the procedure of optically designing an imaging GRIN system using these parameters.

![Fig. 4. Image formation by a GRIN focusing lens.](image_url)

The distance between the principal planes \( P_1 \) and \( P_2 \) indicates that GRIN lenses have to be treated as "thick" lenses. However, that fact does not influence the outstanding image quality and isoplanatic property of GRIN lenses.

The maximum acceptance angle of a GRIN collimation lens or the maximum viewing angle of a GRIN objective lens, respectively, \( \vartheta \) is determined by the numerical aperture NA. As in fiber optics, it is derived from the maximum index change of the GRIN profile,

\[
\sin(\vartheta) = NA = \sqrt{n_R^2 - n_0^2} = n_0 \sqrt{1 - \text{sech}^2(\frac{gd}{2})}.
\]

\( n_R \) is the refractive index at the margin of the profile, and \( d \) is the diameter or the thickness, respectively, of the lens.

In addition to focussing lenses, GRINTECH also offers GRIN diverging lenses of high numerical aperture (NA \( \approx \) 0.6) with plane optical surfaces. Diverging lenses are achieved by parabolic-shaped refractive index profiles, with the minimum of the index \( n_0 \) at the center of the profile,
A characteristic ray trace through a diverging lens is shown in Fig. 5. The very short focal lengths of the lenses \( f \) are also determined by the lens length \( z_l \),

\[
f = \frac{1}{n_0 g \sinh(gz_l)}, \quad s = \frac{1}{n_0 g \tanh(gz_l)}.
\]

Fig. 5. Ray traces in a GRIN diverging lens.

However, a periodic path of the rays is not obtained in this case. Those lenses are applied to the production of microoptical telescopes and scanners.

All information given here is valid for GRIN rod and cylindrical lenses, which GRINTECH offers you. GRIN lenses with a high numerical aperture (NA > 0.5) are produced by silver ion exchange in a special glass which avoids any coloration in the visible spectral range. The absorption edge of the silver containing glass occurs at a wavelength of \( \lambda_{0.5} = 370 \text{ nm} \). GRIN lenses with low numerical aperture (NA \( \leq 0.2 \)) are fabricated via lithium ion exchange. The absorption edge of the glass being used is at a wavelength of \( \lambda_{0.5} = 235 \text{ nm} \). You may find detailed specifications in the product information.

GRINTECH characterizes the refractive index profiles by a unique procedure, the Refracted-Near-Field method (RNF). The quality of collimation lenses is verified by Shearing interferometry and described by a RMS value of the wavefront error. Fast-Axis-Collimation cylindrical lenses are additionally tested by a high-power diode laser setup. The image quality of endoscope lenses is characterized by recording images of grid objects (periods down to 1 \( \mu \text{m} \)) using a CCD camera.