Lecture 22:
Gradient Index Glasses

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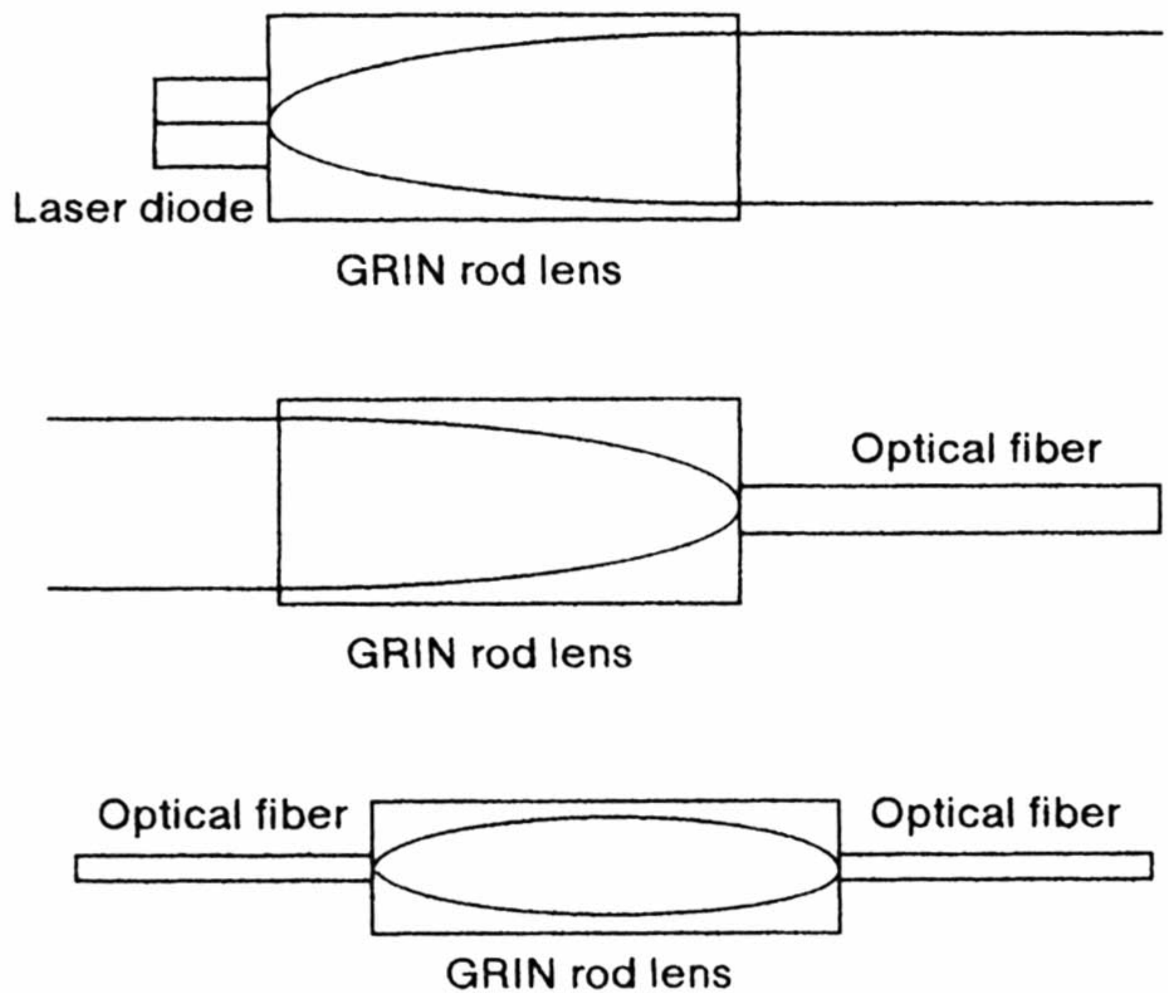
Gradient index glasses

Conventional optical glass components such as lenses have a homogeneous refractive index throughout the whole glass volume, e.g. to within ~ 0.00001. However, it is possible to fabricate lens elements whose index varies continuously as a function of a spatial coordinate. These are called GRaded INdex (**GRIN**) optical components.

In terms of refractive index gradient geometries, the main types are the axial and radial gradients, typically in cylindrical (rod) lenses. We will consider in more detail the fabrication and properties of radial gradient (r-GRIN) rod lenses.

There are two major applications of r-GRIN glasses. One is for focusing, where GRIN rod lenses with small diameters and flat surfaces are used, for example for optical disks or optical telecommunications, such that the light rays propagate sinusoidally along the rod axis; in this way, light from an optical fiber or a laser diode can be focused or collimated, or a light source (eventually a fiber) can be coupled to another optical fiber, as shown in the figure.

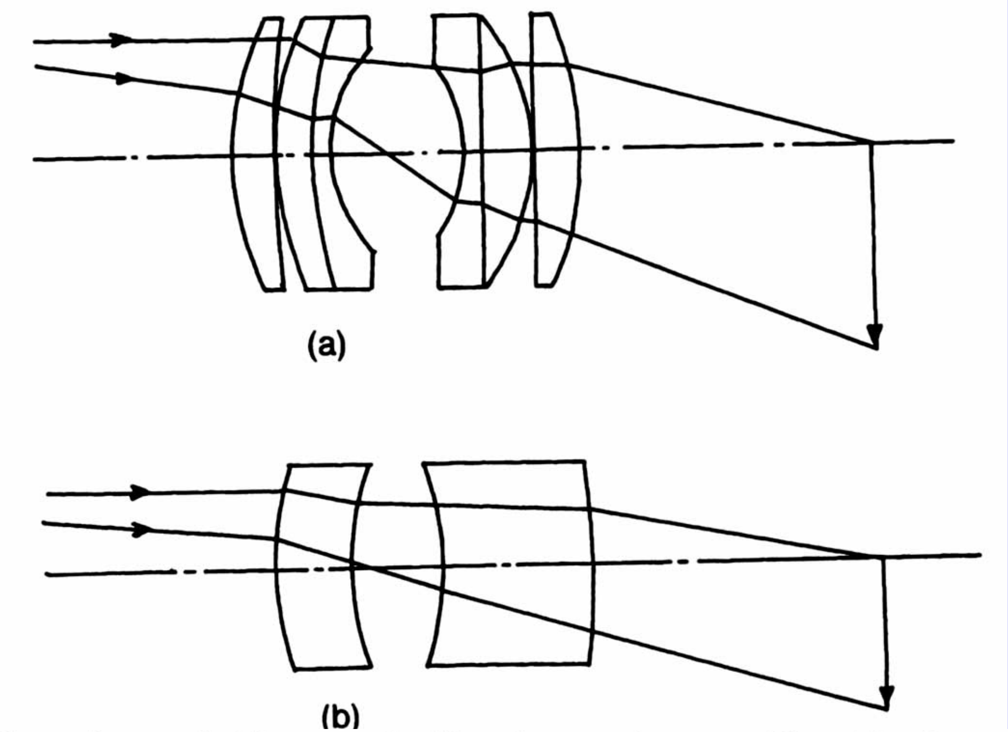


Schematic cross section of a coupler and collimator using GRIN rod lenses with small diameter and flat surface.

(Adapted from: *Glasses for Photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Another major application is for imaging purposes. For example, small diameter lenses are used in copy and fax machines in the form of GRIN lens arrays, where individual lenses may be 1 cm long and 1 mm in diameter.

Also another application is as part of the camera lens or the photographic objective lens. For example, a double Gauss photographic objective, consisting of six elements, may be replaced by only two radial GRIN lenses, while still correcting for spherical and chromatic aberrations. This is shown in the figure below.



Configurations of (a) new double Gauss photographic objective, and (b) GRIN photographic objective. [Reprinted from L. G. Atkinson, S. N. Houde-Walter, D. T. Moore, D. P. Ryan and J. M. Stagaman, *Appl. Opt*. **21** (1982) 993, copyright (1982) with permission from the Optical Society of America.]

(Adapted from: *Glasses for Photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

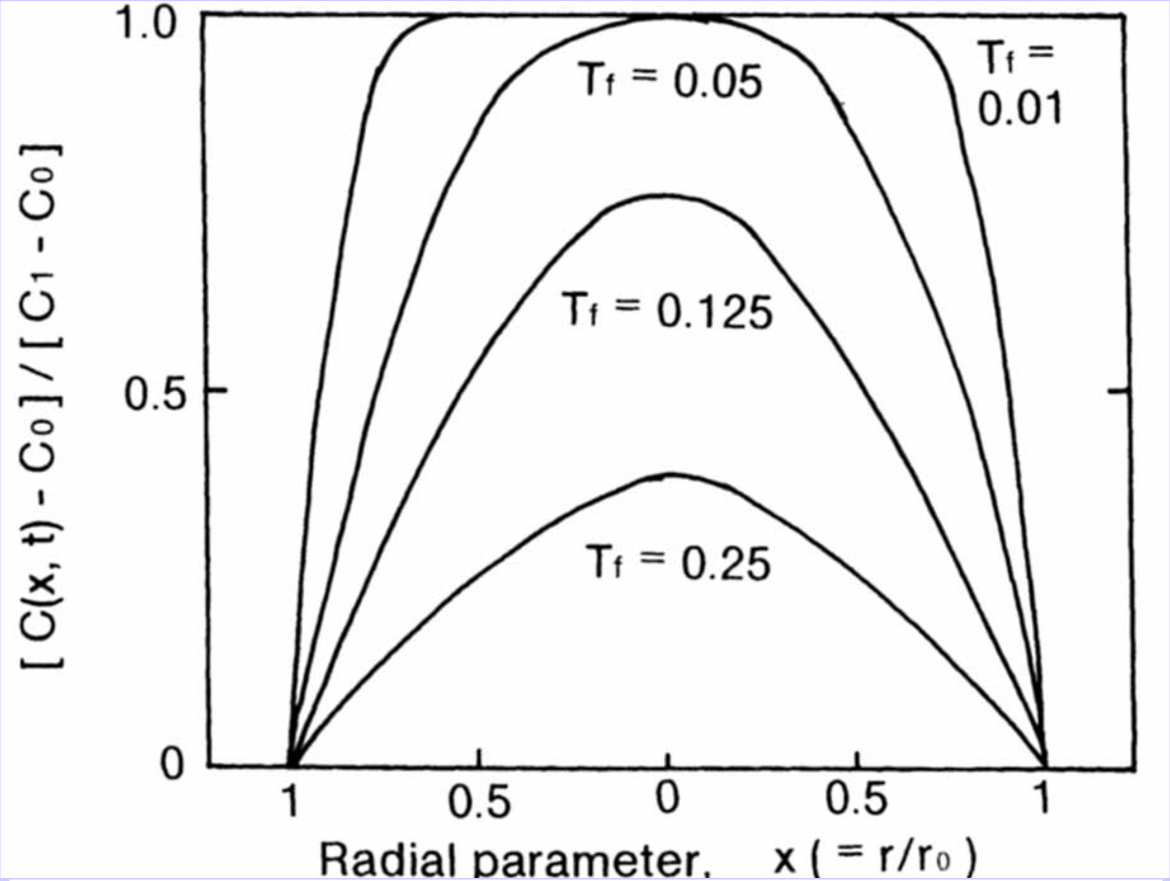
When light enters a GRIN material in which n decreases along the radial direction, from the central axis to the surface, it will be bent toward the axis, such that all light rays with different initial directions will travel with the same period. Parallel light rays, e.g., will focus at a point just as if they had passed through a conventional converging lens, alternately and periodically converging and diverging.

The most important parameter of the GRIN glasses is their refractive index profile, approximately parabolic in most cases, which can be controlled through the concentration profile of suitable index-modifying ions.

The main variable to control is the so-called *diffusion parameter*, $T_f = Dt/r_o^2$, where r_o is the rod radius, D is the diffusion coefficient and t is the treatment time.

Another important parameter is the maximum index difference, Δn, between the center and the surface of the GRIN rod. For example, if the index-modifying ion is highly polarizable and diffuses with ease in the glass above T_g, a large Δn will be obtained. Ions like Tl^+, Ag^+ and Cs^+, or sometimes Pb^{2+}, Ge^{4+} and Ti^{4+}, are often used.

This figure shows how variations in T_f will affect the obtained concentration profile for a r-GRIN rod along its radius. The concentration profile remains almost flat at T_f = 0.01, but it appears parabolic at $T_f \geq 0.05$. If the refractive index depends linearly on the diffusing ion concentration, then the refractive index profiles will have the same shape as the concentration profiles of the figure.



Variations of concentration profile with variations in T_f.

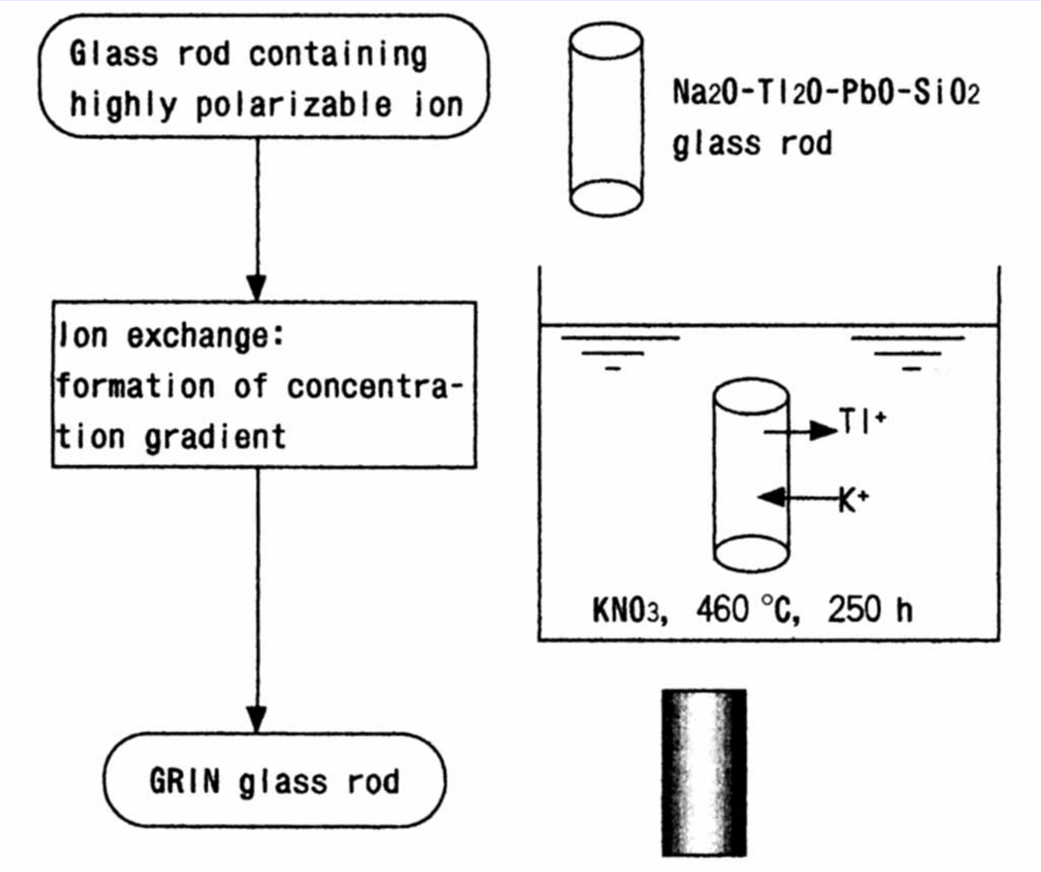
(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Ionic radii and electronic polarizabilities of index-modifying ions

Ion	Ionic radius [25] (A)	Electronic Polarizability [25] (A^3)	Refractive constant [26] a_d	Dispersion constant [26] a_{F-C}
Li^+	0.78	0.03	4.60	0.10
Na^+	0.95	0.41	6.02	0.16
K^+	1.33	1.33	9.54	0.20
Rb^+	1.49	1.98	12.44	0.24
Cs^+	1.65	3.34	17.48	0.31
Tl^+	1.49	5.20	31.43	2.55
Ag^+	1.26	2.4	15.97	0.63
Mg^{2+}	0.78	0.09	–	–
Ca^{2+}	0.99	1.1	12.66	0.26
Sr^{2+}	1.27	1.6	16.50	0.33
Ba^{2+}	1.43	2.5	19.80	0.34
Zn^{2+}	0.83	0.8	12.20	0.34
Cd^{2+}	1.03	1.8	–	–
Pb^{2+}	1.32	4.9	28.41	1.30
Si^{4+}	0.41	0.017	12.51	0.19
Ti^{4+}	0.68	0.19	25.00	1.34
Ge^{4+}	0.53	–	17.47	0.42

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

The most common fabrication technique for GRIN materials is by conventional ion-exchange. A glass containing a highly polarizable monovalent ion like Cs^+ or Tl^+ is immersed in a molten salt bath containing K^+ or Na^+, at a temperature above T_g, for sufficient stress relaxation due to the ion size mismatch. Thermal expansion mismatch will always occur, but is not a problem. This technique leads to a nearly parabolic index profile, for a rod diameter of a few milimeters, maximum.



Ion exchange process for fabricating r-GRIN rod.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

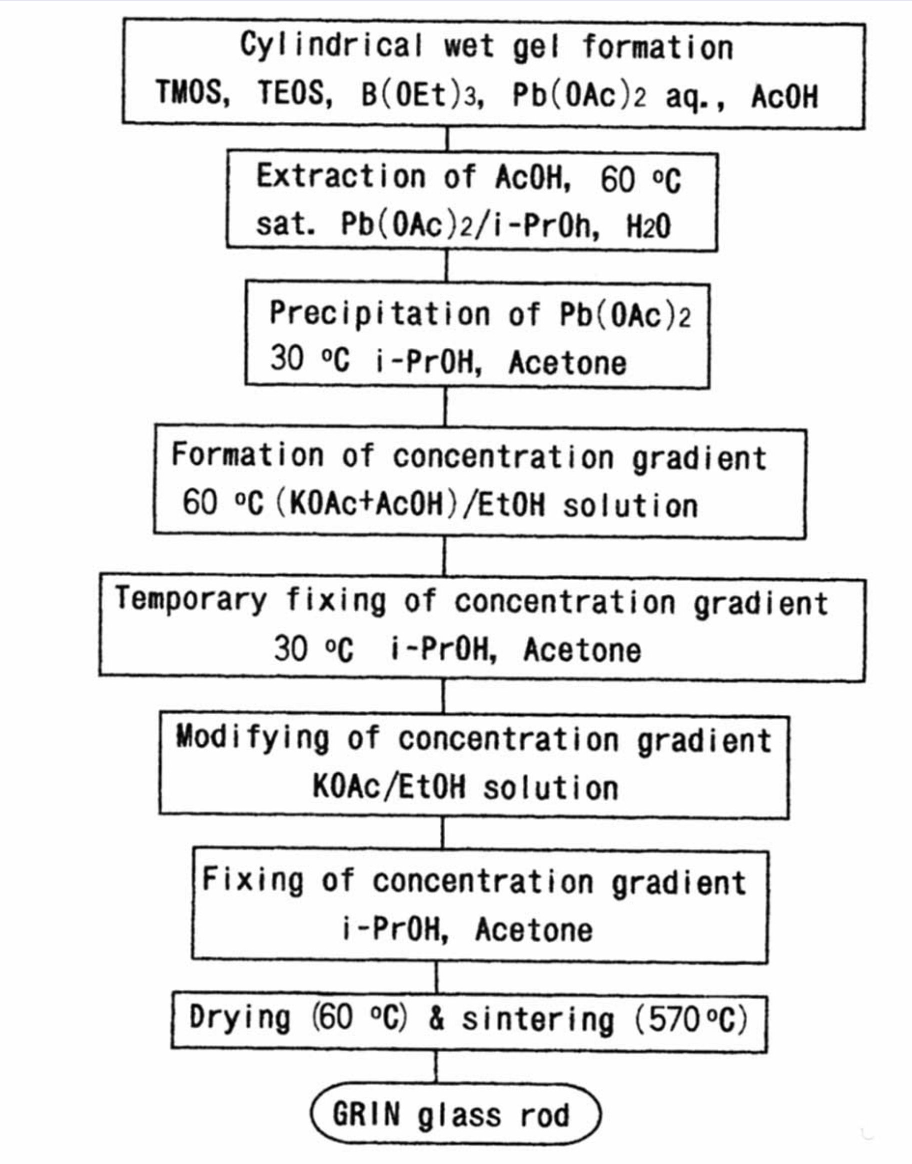
Some modified ion-exchange processes may allow the fabrication of larger r-GRIN rod lenses. An increase in the temperature is one of the possible alternatives.

Another possibility is a *molecular stuffing* process, which consists in depositing an index-modifying dopant from solution into a porous glass preform made by (spinodal) phase separation and leaching. An aqueous solution of $CsNO_3$ or $TlNO_3$ is normally used for index modification. After a multiple step processing, the doped preform is collapsed at ~ 850 ^oC and a consolidated solid glass rod is obtained.

Yet another alternative, somewhat similar to the previous one, is the use of the *sol-gel* technique. This can be applied either through partial leaching of index-modifying cations from an alkoxide-derived wet gel, or through interdiffusion of index-modifying cations in the liquid filled micropores of of a gel, using an aqueous metal salt solution as the external source of cations.

In the *partial leaching technique*, a cylindrical wet gel is first formed in a polymeric mold, containing elements such as Si, Ti, Al, Zr and Ge. This is followed by soaking the gel in a dilute acid, which promotes leaching of Ti and Ge and finally by drying and sintering the material to a glass rod. Processing time may be ~ two weeks to produce a r-GRIN rod a few mm in diameter. One example are rods 2 mm in diameter and 20 mm in length, with $\Delta n \sim 0.02$ and a smooth and nearly parabolic index gradient.

In the *interdiffusion technique*, e.g. a wet gel in the SiO_2-B_2O_3-PbO system is soaked in an ethanolic solution of potassium acetate to form a compositional gradient within the gel. The final gel is densified at 570 ^oC, as shown in the next figure. GRIN rods ~ 13 mm in diameter and 25 mm long can be fabricated by this process, with a smooth and large $\Delta n \sim 0.095$.



Fabricating process of GRIN rods by sol-gel process based on the interdiffusion of Pb^{2+} and K^{+} ions. [Reprinted from M. Yamane and S. Noda, *J. Ceram. Soc. Jpn.* **101** (1993) 11.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

Comparison of various techniques for fabricating r-GRIN glass materials

Method	Merit	Demerit	Matrix materials	Dopant ions	Maximum diameter, r_0 (mm)	Time for $n(r)$ formation, t_0 (h)	Optical properties	Applications
Ion exchange ($T < T_g$)[a]	Precise control of gradient index	Long manufacturing time	Alkali-borosilicate glasses	Tl^+, Cs^+	4.0	250	Δn:0.11 NA:0.62	Lens array for copy machines and facsimiles
		Small diameter		Tl^+:	($D = 10^{-9} \sim 10^{-10}$ cm^2/s)			Pick-up lenses for CD
[b] ($T > T_g$)[c]				Ag^+ Ag^+: Tl^+	4.0 ($D = 10^{-8}$ cm^2/s) 20	72 412		Connector and coupler for optical fiber communications
Ion stuffing[d]	Comparatively fast $n(r)$ formation	Little complicated procedure	Phosphate	Ag^+	16 ($D = 10^{-8}$ cm^2/s)	1200	Δn:0.06 NA:0.6	Objective lens for camera
Molecular stuffing[e]	Thermo and chemical resistive Fast $n(r)$ formation	Complicated procedure	Silica-rich	Tl^+, Cs^+	5.0 ($D = 10^{-6}$ cm^2/s)	< 1	Δn:0.025 NA:0.3	Slab lens devices for optical communications
Sol-gel process Leaching[f]	Fast $n(r)$ formation	Shrinkage during procedure	Silica and silica-rich glasses	Ge^{4+}, Ti^{4+}	7 ($D = 10^{-7}$ cm^2/s)	< 20	Δn:0.02 NA:0.2	Coupler for optical communications
Inter-diffusion[g]	Fast $n(r)$ formation Dispertion control (Ion selectable)	Shrinkage during procedure	Lead borosilicate glasses	Pb^{2+}	13 ($D = 10^{-6} \sim 10^{-7}$ cm^2/s)	$8 \sim 16$	Δn:0.095	Lens for zoom lens, compact camera and video cameras
CVD process[h]	Simple process	unsmooth $n(r)$	Silica	Ge^{4+}	2		Δn:2%	Coupler for optical communications

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)