Aberration improvement of gradient index rod lens

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The aberration of gradient index (GRIN) rod lenses induced by deviation from the ideal refractive index distribution is decreased by optimized thermal diffusion. The index distribution coefficients are estimated by a novel method. The lenses' heat treatment process and aberration testing system are described.

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As well known, gradient index (GRIN) rod lenses have a number of advantages[1], such as low insertion loss, small diameter, short focus, large numerical aperture (NA), small optical spot, good focusing and collimation properties, easy assembly, convenient use, and so on, which make them particularly suitable for use in optoelectronic devices in optical fiber communications[2] and optical signals processing systems, e.g., copy machines, facsimiles, and digital disk playing systems[3]. In such applications, the aberrations of GRIN-rod lens is of importance because it directly determines the performance of the systems. Most aberrations are related to the index distribution. In this paper, the index distribution of sample lens is measured, and a novel method to optimize the index distribution is investigated. GRIN-rod lenses with low aberrations are fabricated by optimized thermal diffusion.

Low aberrations, i.e., a small focused spot size and a large NA are necessary in the application of GRIN-rod lens. The refractive index distribution of GRIN-rod lens is expressed as[4]

$$n(r) = n(0)[1 - (gr)^2 + h_4(gr)^4 + h_6(gr)^6 + \cdots], \quad (1)$$

where r is the distance from the center axis, $n(0)$ is the refractive index on the axis, and g is the focusing constant. Most aberrations are related to the deviations of higher order coefficients in terms of Eq. (1) from the optimum values, i.e., $h_4 = 2/3$ and $h_6 = -17/45$. Yamamoto *et al.*[5] studied the relation of aberration and index distribution coefficients by imaging method, the results are listed in Table 1. It is important to know these values in order to evaluate the aberrations of a GRIN-rod lens. Many techniques have been reported for measuring the index coefficients[5]. However, a simple and precise method for evaluating the imaging properties and the index distributions is needed. We estimate the index coefficients by nonlinear curve fitting of the index distributions which can be measured precisely by longitude interference method.

Table 1. Expected Image Defects for a Quarter Pitch Lens[5]

h_4	h_6	Distortion	
		Near Axis	Far Axis
$> 2/3$	$> -17/45$	Pin-Cushion	Pin-Cushion
	$< -17/45$	Pin-Cushion	Barrel
$< 2/3$	$> -17/45$	Barrel	Pin-Cushion
	$< -17/45$	Barrel	Barrel

The NA of the lens is given by

$$\text{NA} = g \cdot a \cdot n(0)\sin(gl), \quad (2)$$

where a and l are radius and length of the lens, respectively. So the glass rod must be chosen so that the lens has a large focusing constant g and $n(0)$. NA is usually defined as $gan(0)$, it is convenient to evaluate the lens because it does not depend on the dimensions of the lens.

The GRIN-rod lens is fabricated by an ion-exchange technique, in which the glass rod containing the highly polarizable ion (i.e., Tl^+) is immersed in a melting salt (KNO_3) bath. The Tl^+ ions in the glass are exchanged with K^+ ions in the melting salt. The spatial distribution of refractive index which is determined by the distribution of Tl^+ ions in the glass rod is formed. However, it is clear that the fourth- and sixth-order coefficients, h_4 and h_6, in Eq. (1) cannot be simultaneously at their optimum values when one-step ion-exchange is used. It has been conformed empirically and experimentally that the aberrations in focusing fibers which were fabricated by diffusion exchange decreased with heat treatment[6]. Similarly, the aberrations in GRIN-rod lenses can be decreased with heat-treatment. In the paper, the ion-exchange and heat treatment process were done. The heat treatment process is an optimized diffusion process in which the Tl^+ ions and K^+ ions both in the glass rod are exchanged again, which leads the index distribution more close to the ideal distribution, and the aberration is deduced also. The procedure of heat treatment is as follows: The GRIN-rod lenses are placed in the heat treatment stove after ion-exchange. Then the temperature of stove is raised rapidly to heat treatment temperature T_b. Maintain the temperature for some hours, then let it cool down from T_b to lower limit temperature of heat treatment T_h, which is about 100 °C below T_b. The scope between T_b and T_h is called heat treatment region. At last, let the temperature decrease to room temperature T_k rapidly. The detailed heat treatment curve is shown in Fig. 1.

The principle of direct measurement of transverse aberration (spherical aberration) is shown in Fig. 2. The microscope can be shifted in the transverse direction and the shift distance can be measured precisely. From the microscope we can see the image resulted by the lens. In order to measure the size of aberrations a mesh with constant line intervals of 5 mm was employed as a pattern observed through a lens sample, the mesh was irradiated

Table 2. Optical Parameters of Index Distribution and Aberration for GRIN-Rod Lenses (Measured at Wavelength $\lambda = 632.8$ nm)

Sample	$n(0)$	g (mm^{-1})	h_4	h_6	Spherical Aberration	Distortion	NA
Ideal Lens	1.617	0.31	2/3	−17/45	0	0	0.430
Ion-Exchange	1.617	0.32	0.5262	−7.8271	0.30	13.1%	0.450
Heat Treatment	1.617	0.34	0.5880	−10.881	0.20	4.9%	0.435

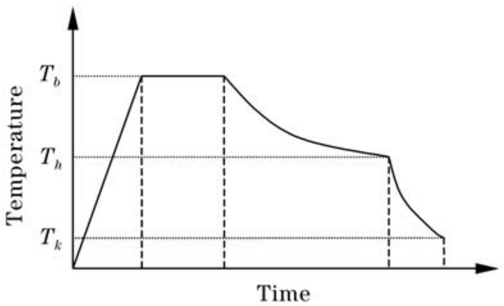

Fig. 1. The curve of heat treatment temperature.

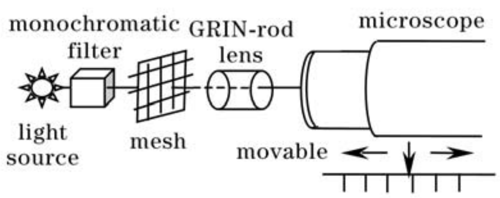

Fig. 2. Aberration testing system used for evaluating aberrations.

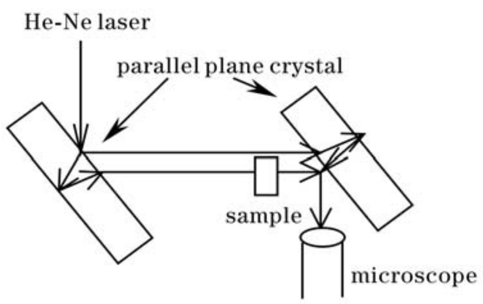

Fig. 3. Measuring setup for the longitudinal interference method.

by monochromatic light. Measuring the distance on the center axis, the spherical aberration was estimated. The amount of distortion was measured by observing each line image formed by lens sample through microscope.

The index distribution coefficients h_4 and h_6 were estimated in terms of Eq. (1) by nonlinear curve fitting of index distribution which can be measured precisely by longitude interference method[7]. The lens sample is cut in a thin round slice and its surfaces are polished to be optically flat. This thin sample is examined under an interference microscope, as shown in Fig. 3. The

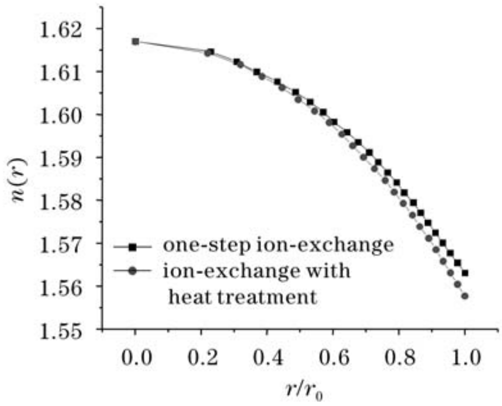

Fig. 4. The index distributions of ion-exchange and optimized heat treatment.

refractive index distribution is calculated from interference pattern. Thus the index distribution of the sample lens can be measured. From Fig. 4 we can estimate the index distribution coefficients by sech function curve fitting.

Optical parameters of index distribution and aberrations determined by the above procedure are listed in Table 2.

GRIN-rod lenses with small aberration were obtained using optimized thermal diffusion. The index distribution is more close to ideal distribution after heat treatment. The spherical aberration and distortion are decreased obviously. A novel method for measuring and estimating the index distribution coefficients is investigated. Because the heat treatment process is simple and easy to operate, it has great potential uses for the industrialization of GRIN-rod lenses in China.

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References

1. D. S. Liu, Physics (in Chinese) **23,** 321 (1994).
2. W. J. Tomlinson, Appl. Opt. **19,** 1127 (1980).
3. T. Miyazawa, K. Okada, T. Kubo, K. Nishizawa, I. Kitano, and K. Iga, Appl. Opt. **19,** 1113 (1980).
4. K. Iga, Appl. Opt. **19,** 1039 (1980).
5. N. Yamamoto and K. Iga, Appl.Opt. **19**, 1101 (1980).
6. K. Iga, K. Yamamoto, and Y. Matsuura, Trans. IECE Jpn. **E60,** 239 (1977).
7. W. E. Martin, Appl. Opt. **13,** 2112 (1974).