Journal of the Optical Society of Korea
Vol. 13, No. 4, December 2009, pp. 468-471
DOI: 10.3807/JOSK.2009.13.4.468

Nondestructive Optical Measurement of Refractive-index Profile of Graded-index Lenses

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(Received May 25, 2009 : revised September 25, 2009 : accepted September 25, 2009)

We propose a simple nondestructive method to obtain refractive-index profiles of a graded-index (GRIN) light-focusing rod by means of a diffraction grating. In our proposed method, a laser beam is illuminated through a diffraction grating perpendicular to the axis of the GRIN lens and the separation between the zeroth and first-order diffraction peaks is measured and analyzed. The results demonstrate that the refractive-index profiles of commercially available GRIN lenses can be successfully reconstructed.

Keywords : Refractive-index profile, Graded-index lens, Diffraction, Grating
OCIS codes : (110.2760) Gradient-index lenses; (290.3030) Index measurements; (050.1950) Diffraction gratings; (060.2300) Fiber measurements

I. INTRODUCTION

In the last decades, gradient-index (GRIN) materials have been widely utilized in science and technology. In particular, many different types of GRIN rod lenses have been developed for on-axis and off-axis imaging, focusing, and collimation in optical systems [1, 2]. Linear arrays of GRIN lenses have been employed in laser printers, photocopiers, and fax machines [3-6]. Planar GRIN waveguides such as directional couplers and wavelength-division multiplexers have been realized for the integrated optical circuitry [7, 8]. GRIN plastic optical fibers (GI-POFs) have also attracted much attention for short distance networks due to their high bandwidth transmission capabilities [9-11].

The quality and efficiency of GRIN materials are heavily dependent upon the shape of the radial refractive-index profile. For instance, the bandwidth of a large-core GI-POF can be maximized when the distribution of the refractive-index in the radial direction of the fiber is parabolic [12]. A quadratic index profile of a GRIN lens can minimize the monochromatic aberrations. Therefore, various optical techniques to measure the refractive index profiles of GRIN structures have been extensively investigated, including beam deflection technique [13, 14], prism technique [15], longitudinal and transverse interferometry [16-19], and shearing interferometry [20, 21]. However, these conventional techniques require either complicated experimental arrangements or precise polishing processes.

In this paper, a simple nondestructive method to acquire refractive-index profiles of GRIN light-focusing rods (i.e., GRIN lens) is proposed. The method involves illuminating a laser beam through a diffraction grating perpendicular to the axis of a GRIN lens and recording the diffraction patterns at the focal plane of the GRIN lens. In particular, the separation between the zeroth and first-order diffraction patterns is measured and analyzed. The results demonstrate that the radial distribution of refractive-index of a commercially available GRIN lens can be successfully reconstructed by our proposed method.

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II. EXPERIMENTAL SETUP AND REFRACTIVE-INDEX DETERMINATION

The refractive-index of GRIN lenses varies continuously with radial distance from the axis. In general, the radial distribution of the refractive index of a GRIN lens can be written as [22]

$$n(r) = n_c\left(1 - \frac{A^2}{2}r^2\right) \quad (1)$$

where n_c is the refractive-index at the axis of GRIN lens, A is the gradient parameter determining index profile, and r is the radial distance from the lens axis.

Fig. 1 shows a schematic diagram of our experimental setup to obtain the refractive-index profile of GRIN lens. He-Ne laser and a chrome-coated Ronchi gratings are used for producing plane waves and diffraction patterns, respectively. If a laser beam is illuminated through a diffraction grating perpendicular to the axis of a GRIN lens, as displayed in Fig. 1, the Fraunhofer diffraction patterns can be observed at the focal plane. The distance between the zeroth-order principal maximum and the first order diffraction peak in the paraxial region is given by [23]

$$d = f\frac{\lambda}{p} \quad (2)$$

where f is an effective focal length of the GRIN lens, λ is the wavelength of the incident beam, and p is the pitch size of the grating, respectively. Note that the wavefront suffers bending of its path as a result of differential phase delays due to the varying refractive-index of the GRIN lens, containing information to reconstruct the index profile.

In order to get the index profile from the experimental data, at first, we assume that GRIN lens has a constant refractive-index n_o for $r \leq R$ and n_o is the refractive-index of the outermost part of the GRIN lens, as shown in Fig. 2(a). If the GRIN lens is located inside index-matching oil of n_{oil} , its focal length is given by [24]

$$\frac{n_o}{f - R} = \left(n_o - n_{oil}\right)\frac{2}{R} \quad (3)$$

where f is a focal length, R is the radius of the GRIN lens, and n_{oil} is the refractive-index of index-matching oil.

However, in our experiment, the GRIN lens is located partially in the index-matching oil as shown in Fig. 2(b). The incident ray impinged on the GRIN lens is deflected and produces the internal angle α and the intersection angle θ_f. If the minimum distance from the center of the GRIN lens to the ray is denoted by r^*, the focal length can be approximately written by [25]

$$f \cong \frac{y}{n_{oil}\left(2y/R + \alpha - \pi\right)} \quad \text{,where} \quad \alpha = 2\int_{r^*}^{R} \frac{n_{oil}y}{r\sqrt{\left[n(r)r\right]^2 - \left(n_{oil}y\right)^2}}dr \quad (4)$$

The r^* is the real root of the following equation,

$$n_c A^2 r^3 - 2n_c r + 2n_{oil}y = 0 \quad \left(0 < r^* \leq R\right) \quad (5)$$

which makes the denominator in the integral to be equal to zero.

As a second step, we assume that the index of refraction of the GRIN lens drops off parabolically from the central axis (shown in Fig. 2(b)), as described in Eq. (1), and the refractive-index of the outermost part of GRIN lens is given by n_0. The GRIN lens used in our experiment is of 1.0 mm in diameter and n_c can be expressed as

$$n_c = \frac{2n_o}{2 - A^2R^2} \quad (6)$$

by substituting $r=R$ into Eq. (1). Therefore, the refractive-index profile of the GRIN lens can be reconstructed by measuring the distance d to get f from Eq. (2) and finding α from Eq. (4) with given parameters like R, n_{oil} and y. Finally, the gradient parameter A is obtained by solving the integral equation in Eq. (4).

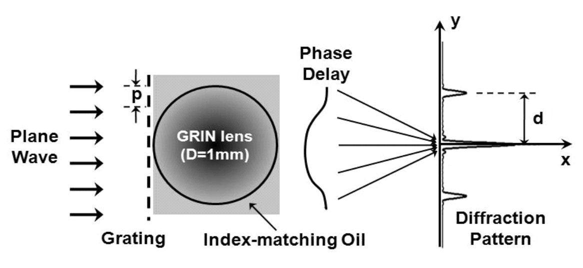

FIG. 1. Schematic diagram of experimental setup for measuring refractive-index profile of GRIN lenses.

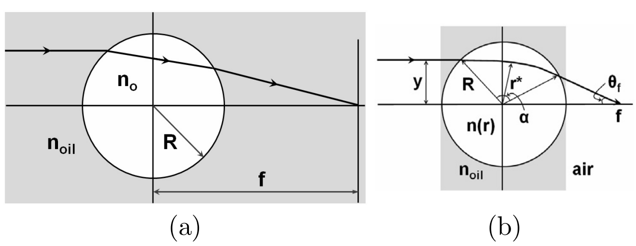

FIG. 2. The focal length of the GRIN lenses with (a) a constant refractive-index and (b) a graded refractive-index.

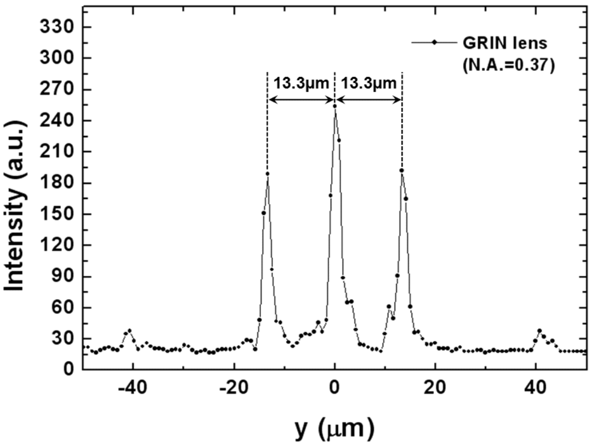

FIG. 3. Diffraction pattern of a GRIN lens with N.A. of 0.37.

Fig. 3 shows a typical diffraction pattern observed by a charge-coupled-device (CCD) camera for a commercial GRIN lens with numerical aperture (N.A.) of 0.37 at the focal plane. In order to measure the separation between the 0^{th}-order and 1^{st}-order diffraction peaks accurately, both diffraction grating and GRIN lens were simultaneously moved by a pico-motor actuator with less than 100nm resolution. By carefully monitoring the position of the 0th-order principal peak in the CCD camera as a function of moving distance by the pico-motor, we could confirm that the measurement accuracy of the distance between the 0th-order and 1st-order peaks is less than 0.5 μm. We would like to mention that the effective focal distance of the GRIN lens can be obtained from this measured separation between the 0^{th} and 1^{st} -order peaks by using the Eq. (2).

III. RESULTS AND DISCUSSIONS

The measured separation (d) between the 0^{th}-order and the 1^{st}-order diffraction peaks is found to be 13.3±0.1 μm for a SELFOC® GRIN lens of N.A.=0.37. From Eq. (2), therefore, the effective focal length (f) is obtained to be 1.7865 mm with the parameters of d=13.3 μm, λ=0.6328 μm, and p=85.0 μm. From Eq. (6), n_c can be expressed by A with a given index of refraction (n_0) of 1.5153 and R=0.5 mm. Then, by assuming paraxial approximation ($y \leq R/10$) and refractive index of matching oil, n_{oil}, of 1.4584, r^* is obtained as a function of A. Finally, by inserting this r^* in the Eq. (4), the gradient parameter determining index profile, A, is determined to be 0.5025, which is in good agreement with the parameter given by the manufacturer [26].

Fig. 4 shows the reconstructed refractive-index profiles obtained by our proposed method and the index profiles given by the company (SELFOC®) for GRIN lenses of N.A.=0.37 and N.A.=0.46. The result reveals that errors in refractive indices of n_c's are 0.0007 and 0.0046, indicating only 0.04% and 0.29% deviations from the n_c values provided by the company. All the acquired parameters are summarized in Table 1. The values of n_c and A in parentheses in the Table 1 are the specification data from the company. The error of a GRIN lens with N.A.=0.46 has larger than that of a GRIN lens with N.A.=0.37. Considering our paraxial approximation, it can be expected that the errors in refractive-index and index profile can be increased with increasing N.A. Measurements of refractive index profiles of various GRIN lenses with different N.A.'s are in progress to find the theoretical and experimental limits of our approximation and proposed method.

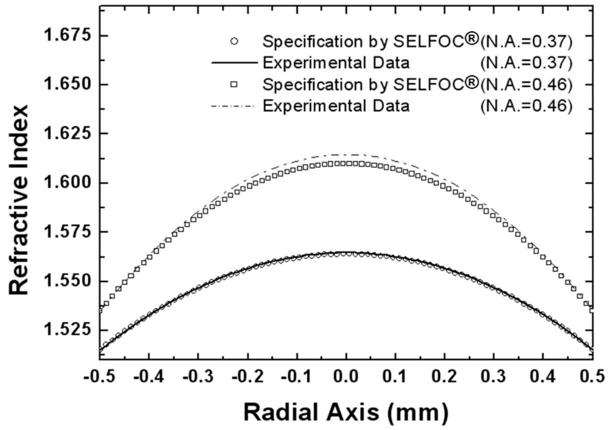

FIG. 4. The reconstructed refractive-index of a GRIN lens and its technical data given by the SELFOC®.

TABLE 1. A summary of various factors determining refractive-index profile of GRIN lenses

	GRIN Lens (N.A.=0.37)	GRIN Lens (N.A.=0.46)
Outermost Refractive index n_o	1.5153	1.5351
Position of 1^{st} order diffraction pattern d(μm)	13.3	9.1
Effective focal length f(mm)	1.7865	1.2223
Minimum distance r^*(μm)	46.6	45.2
Profile shape parameter A	0.5025 (0.499)	0.6278 (0.610)
Refractive index of center n_c	1.5647 (1.564)	1.6146 (1.610)
Error in refractive index of center	0.0007 or 0.04%	0.0046 or 0.29%

IV. CONCLUSIONS

A simple nondestructive method to measure the refractive-index profile of GRIN focusing rods has been demonstrated by means of a diffraction grating. In particular, the separation between the zeroth and the first-order diffraction peaks are utilized to obtain the index difference in the center and the outermost region of the GRIN lens as well as its index profile. The results show that the refractive-index profiles of commercially available GRIN lenses can be successfully reconstructed. In addition, we show that the refractive indices at the center of GRIN lenses have only 0.04% and 0.29% discrepancies, comparing with the index values provided by the manufacturer. We believe that our proposed method can be useful to get the refractive-index profiles of GRIN materials nondestructively and to control the quality of GRIN elements in the manufacturing process.

ACKNOWLEDGMENT

This research was supported by Korea Military Academy, the Next Generation Emerging Technology Program of the Ministry of Knowledge Economy, Brain Korea 21(BK21) Project and Pioneer Research Center program (Contract No. 2009-008-1527) through the National Research Foundation of Korea funded by the Ministry of Education, Science & Technology.

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