International Journal of Optoelectronic Engineering 2015, 5(1): 11-15
DOI: 10.5923/j.ijoe.20150501.02

# Interferometric Estimation of Nonlinearity in GRIN Optical Fiber

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**Abstract** In many industrial applications, coupling high power laser beam into multi-mode graded-index fiber (GRIN) is an important issue especially when deeper penetration and speed cutting/welding processes are required. With increasing the laser power, nonlinear effects such as self-focusing takes place leading to a catastrophic damage for optical fibers. Construction of robust high power fiber-laser systems still need to analyze the different parameters that affect the nonlinear response of the fiber material and its waveguiding conditions. Due to its high spatial resolving power, interferometry is used to study the efect of waveguide and material dispersion profiles, and the central core-index dip on the Kerr nonlinear index profiles of GRIN fiber.

**Keywords** Interferometry, Nonlinear optics, Optical fibers

## 1. Introduction

The fabrication of fiber soliton laser was made possible by high damage threshold of single-mode silica fiber [1]. The second harmonic generation from mode-locked and Q-switched Nd: YAG laser pulses in silica fiber was also achievable [2]. There are limits to the optical power that can be supported by optical fibers used in automotive, aerospace, electronic, and heavy manufacturing. One of these ultimate limits arises from a phenomenon called self-focusing [3, 4]. Self-focusing occurs when a beam is focused in a transparent medium, caused by the beam itself through a nonlinear process. This causes the beam radius to be reduced, allowing optical intensities to become higher leading to immediate fiber destruction. A dynamic picture of the self-focusing process for cylindrical beams was suggested [5]. The first experimental observation of self-focusing in multi-mode fibers using high-peak power pico-second pulses was reported [6]. Damage has been observed when coupling Q-switched Nd:YAG laser light into larger fibers, arising from also self-focusing effect [7, 8]. Several examples of a fiber fuse resulting in catastrophic destruction of an optical waveguide were reported elsewhere [9-13]. In silica fibers, self-focusing due to nonlinear effect requires optical power of about 10 MW/cm$^2$ [14].

In comparison to step-index fiber, the gradient-index fiber intensity profile, for the same fiber diameter, has a smaller 86% radius. The peak intensity is often about five times that of a comparable size step-index fiber. Laser material processing requires very high irradiance, thus, the gradient-index fiber may be the most appropriate choice especially when deeper penetration and high speed cutting/welding are required [15]. In contrast to the step-index fiber, GRIN fiber is preferable because the fundamental mode of the GRIN fiber is relatively more confined. Also the mode-mixing caused by bending in a GRIN fiber couples modes together while preserving radial symmetry which yields a beam with a better focus [16].

The reported works [17-24] that studied Kerr nonlinearity in optical fibers practically used in high power fiber laser delivering systems are however insufficient because none of these reports were considering GRIN fibers. Therefore, in this work we report experimental determination of the second-order index of refraction, $n_2$, profiles in GRIN fiber. The Fizeau interferometric study revealed the importance of waveguide dispersion profile and effect of central index dip on the nonlinear index profiles of GRIN fibers.

## 2. Theoretical Considerations

Understanding of nonlinear optical processes in transparent medium involves two questions: 1) how does the electromagnetic field affect the medium, and 2) how is the field affected by the medium response. The nonlinear dependence of the refractive index on the light irradiance is expressed by:

$$n = n_0 + n_2 I \tag{1}$$

where $I$ is the beam irradiance in units of W/m$^2$, $n_0$ is the linear refractive index of the material, and the coefficient of proportionality $n_2$ is the nonlinear refractive index.

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Published online at http://journal.sapub.org/ijoe

Self-focusing of laser beams in isotropic transparent solids arises from three mechanisms: electrostrictive, thermal and Kerr nonlinearity. The response times for electrostrictive and thermal self-focusing, however, are much longer than the 125-ps pulse [24]. When the optical frequency is below the electronic band gap, the self-focusing for laser beam in isotropic media due to Kerr effect can be attributed to the third-order susceptibility, $\chi^{(3)}$, which has a minimum response time of order of $10^{-16}$ s. It is faster than the time resolution provided by the shortest optical pulses available today (<10 fs). Self-focusing occurs when a laser beam having a Gaussian transverse intensity distribution propagates through an optical medium whose refractive index is described by Eq. (1) considering $n_2$ is positive. Phenomenologically, in dielectric materials the nonlinear susceptibility is proportional to the linear susceptibility. Consequently, from Miller's rule $n$ is proportional to the third-order susceptibility, $\chi^{(3)}$ through the empirical formula [25]:

$$\chi^{(3)} = \left(\frac{n^2-1}{4\pi}\right)^4 \times 10^{-13} \quad \text{(esu)} \tag{2}$$

According to Vogel et al. [26], $\chi^{(3)}$ as a function of second-order refractive index, $n_2$, is given by the relation:

$$n_2 = \chi^{(3)}(\times 10^{-13}\ \text{esu})\frac{12\pi}{n} \tag{3}$$

or

$$n_2 = \frac{12\pi}{n}\left(\frac{n^2-1}{4\pi}\right)^4 (\times 10^{-13}\ \text{esu}) \tag{4}$$

Eq. (4) reflects the fact that a high $n_2$ is expected for glass with high linear index of refraction. For conversion esu unit to $m^2/W$ in the SI system of units, the following formula is used:

$$n_2(\text{m}^2/\text{W}) = 8.38\times 10^{-7}\frac{n_2(\text{esu})}{n_d} \tag{5}$$

The graded-index multi-mode optical fiber with a circular cross-section of radius $r_f$ introduced in a silvered liquid wedge interferometer has a cladding of constant refractive index $n_{cl}$, a graded-index core of variable refractive index $n_c(r)$ and radius $r_c$ and a graded-index dip of variable refractive index $n_d(r)$ and radius $r_d$. The fiber is immersed in a liquid of refractive index $n_L$ close to $n_{cl}$. The equation represents the shape of multiple-beam Fizeau fringes in the dip region, i.e., for a radial distance $x_1$, is given by [27]:

$$\left(\frac{\delta z}{\Delta z}\right)_{x_1}\cdot\frac{\lambda}{2} = 2\{(n_{cl}-n_L)\sqrt{r_f^2-x_1^2} + \Delta n_c\sqrt{r_c^2-x_1^2} - \frac{\Delta n_c}{(r_c-r_d)^{\alpha_c}}\int_{\sqrt{r_d^2-x_1^2}}^{\sqrt{r_c^2-x_1^2}}\left[\sqrt{x_1^2+y^2}-r_d\right]^{\alpha_c} dy - \Delta n_d\sqrt{r_d^2-x_1^2} + \frac{\Delta n_d}{r_d^{\alpha_d}}\int_0^{\sqrt{r_d^2-x_1^2}}\left(x_1^2+y^2\right)^{\alpha_{d/2}} dy\} \tag{6}$$

where $\Delta n_c = n_c(r_d) - n_{cl}$ and $\alpha_c$ is a shaping parameter controlling the shape of the core index profile. Also, $\Delta n_d = n_c(r_d) - n_d(0)$ and $\alpha_d$ is a parameter controlling the shape of the dip index profile. $\Delta z = \lambda / z n_L$ is the fringe spacing in the liquid region and $\delta z$ is the fringe shift in the fiber region, where $\lambda$ is the wavelength.

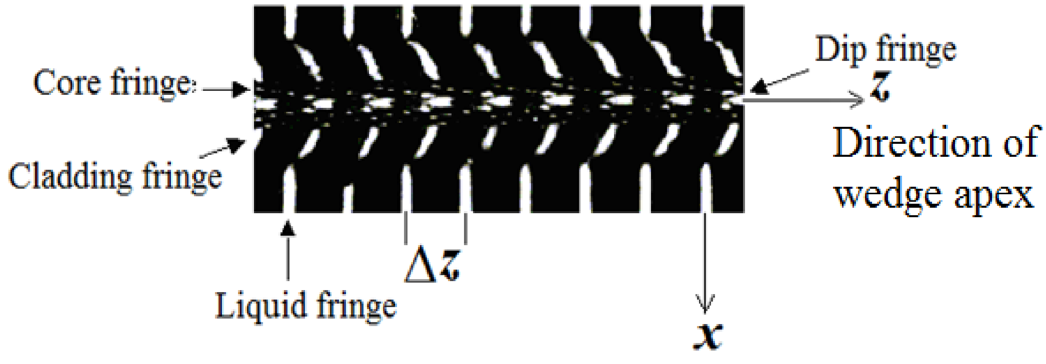


**Figure 1.** An interferogram of Fizeau fringes at transmission crossing transversally a strain-free straight GRIN fiber immersed in non-matching liquid, $n_L < n_{clad}$. The fiber is perpendicular to the wedge apex. The fringe shift across the dip region is in the direction of lower refractive index

# 3. Experimental

The experimental setup used to produce Fizeau fringes in transmission is described elsewhere [28]. A parallel beam of monochromatic light illuminates the liquid wedge interferometer. The wedge is adjusted so that the Fizeau fringes were crossing perpendicularly the fiber axis. The fringes in the liquid region were straight lines parallel to the wedge apex with an inter-spacing Δz. Immersion oil is usually used to prevent the fiber cladding from contributing a very large amount of fringe shift. The fact that light rays pass the fiber without deflection is assumed, considering only that their phases are retarded according to their optical thicknesses. Graded index multi-mode optical fibers (ITT Telecommunications Corporation, USA) with 6 dB/km average attenuation, 3.0 ns/km maximum dispersion, core diameter 50 μm and 125 μm outer diameter have been investigated.

Fig. 1 presents an interference pattern of Fizeau fringes at transmission crossing transversally a strain-free straight GRIN fiber immersed in non-matching liquid, $n_L < n_{cl}$. The straight line fringes in the liquid region as they cross the fiber cladding they follow an elliptic path. The fringe shift in the cladding represents a half ellipse of semi-principal axes $r$ and $(n_{cl}-n_L)r$. The direction of the half ellipse is towards the wedge apex for $n_L < n_{cl}$ which is the same direction of the core shift. The figure provides information about the core structure and the distinctive features of the index profile through the discontinuity in the core fringe.

The dotted line represents the envelope of the core index profile following the basic power law with core index difference $\Delta n_c = 0.016$ at $\lambda = 850$ nm. The extension of each layer is determined from the interferogram by the projection of the fringe segment on the $x$-axis. The steps (in $\Delta n = 0.0026$) [29] decrease toward the fiber center while the extension of each step remains constant. The measurements showed that the extension $\Delta r$ was the same for each contributing layer. The value of $\Delta r$ was found to be 2.78 μm. The obtained results from the micro-interferogram show that the central dip of the fiber core has a gradient index profile with a core is made from a binary compound material such as $GeO_2$-$SiO_2$ [27]. Fibers which made of binary compound materials are designed for high bandwidth propagation using a GaAs laser [30].

# 4. Results and Discussion

The cladding refractive indices of the fiber samples are found to be 1.4384 ± 0 .0001, 1.4395 and 1.4568 at $\lambda = 587.5$, 486.1 and 656.3 nm, respectively. Such values mean that the cladding could be made from doped fused silica. Fig. 2 shows that at $\lambda = 587.5$ nm the graded-index core-dip index profiles of the fiber examined is a succession of step-index layers with a step-pyramid-like index profile across the fiber core. As most common, the dopant concentration is increased in equal steps from one layer to the next keeping the layer extension constant. The central part of the core index starts at 2.5 μm from the optic axis to decrease reaching its minimum value with $\Delta n = 0.008$.

Using Eq. (4), Fig. 3 illustrates the waveguide dispersion of the calculated second-order nonlinear index radial profile of the GRIN optical fiber due to Miller [25] and Vogel et al. [26]. The nonlinear refractive index profile of the investigated graded-index multi-mode fiber is nearly parabolic following the linear refractive index behavior with an estimated error of $n_2$ is ± 0.1%. Taking into consideration the fundamental propagated mode, the presence of central index dip in graded-index fiber makes the comparison between GRIN fibers and multi-mode step-index fibers in the favor of GRIN fibers. GRIN fiber with central dip provides a considerable decrease in the self-focusing effect in an order of 6.5 %. This structure of waveguide dispersion profile would compensate the Gaussian laser intensity radial profile which has a maximum intensity at the center of the laser beam. This means that the index dip would provide fiber-laser delivering system endure more laser intensity. In addition, it was shown that the nonlinear refractive index, $n_2$, of germanium doped silica glass is a linear function the $GeO_2$ doping [31]. Thus, by decreasing the amount of $GeO_2$ dopant in the inner core layers there is a possibility to design a saddle-like shape for the radial profile of $n_2$ which is an optimum profile shape to minimize the effect of $n_2$.

On the other hand, ignoring the fiber material dispersion has a great deal of simplistic [32]. So measuring the material dispersion profiles for the fiber glass layers may provide a further test for right prediction of the calculated nonlinear index profile. Optical glasses are usually described by their refractive indices at the helium $d$ line (587.6 nm), $n_d$, and the Abbe number, $v_d$, which characterizes the material dispersion. The Abbe number is given by:

$$v_d = \frac{n_d - 1}{n_F - n_C} \quad (7)$$

The difference $(n_F - n_C)$ represents the material dispersion where $n_F$ and $n_C$ are the refractive indices for reference lines of hydrogen: $F$ (486.3 nm) and $C$ (656.3 nm), respectively. The nonlinear refractive index (in $m^2/W$) can be estimated from the values of $n_d$ and $v_d$ by using the following Milam and Weber expression [24]:

$$n_2 = 2.85 \times 10^{-18} \times \frac{(n_d - 1)(n_d^2 + 2)^2}{n_d v_d \sqrt{1.517 + (n_d^2 + 2)(n_d + 1) v_d / 6 n_d}} \quad (8)$$

Fig. 4 elucidates the radial change of waveguide dispersion of second-order nonlinear refractive index profile in the core and dip regions of the studied multi-mode graded-index fiber taking into consideration material dispersion. In spite of the index inversion seen in the dip region a decrease of 97.6% in the nonlinear index value in the dip region of is obtained. The waveguide dispersion of the nonlinear index profile does not follow the shape of $n_2$ profile which is constructed considering the linear index values (Fig. 3). To explain such behavior, the material dispersion of the fiber layers is plotted against the fiber radial distance as shown in Fig. 5. It is clear that the variation of the second-order index of refraction follows the material dispersion profile (Fig. 4) rather than the linear refractive index distribution profile (Fig. 3). This reveals that the material dispersion of the fiber layers plays the dominant role rather than linear index of refraction in the nonlinear properties of optical fibers. One of the recommendations here is to eliminate the central dip during fiber production. Also, the profile of material dispersion-base waveguide structure can be considered as a base to the proper design of ($n_2$) radial profile. The results are useful for production of optical fibers that can bear more laser power required for high-power ultrashort-pulse fiber laser delivering systems.

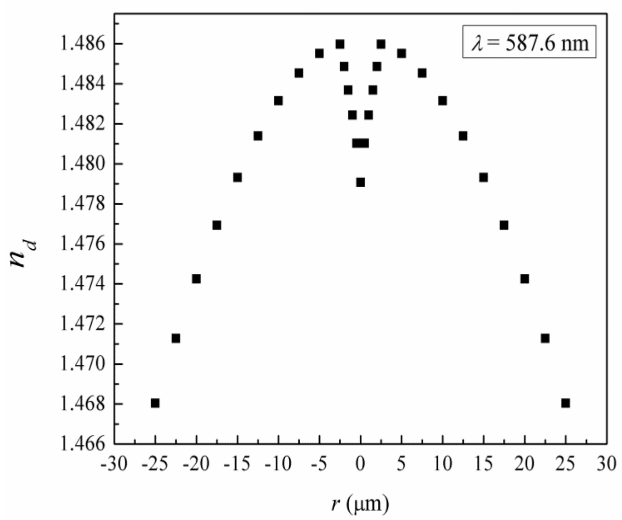


**Figure 2.** The radial refractive index profile (at $\lambda$ = 587.6 nm) of the fiber core which inclods a graded central dip

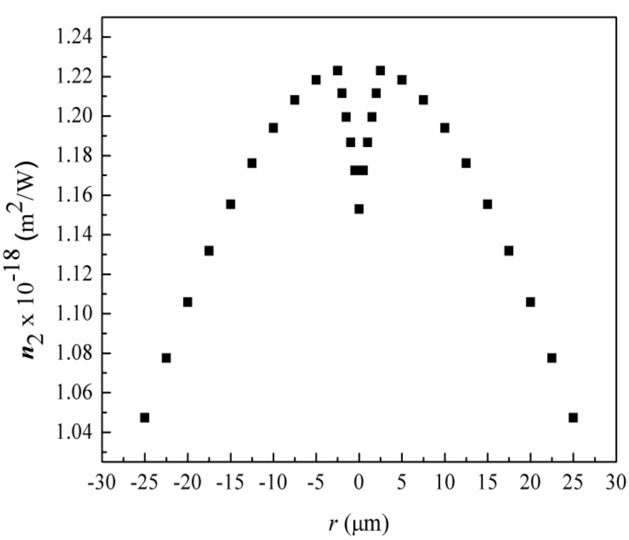


**Figure 3.** Secon-order nonlinear index profile of GRIN fiber based on linear index profile due to Miller [25] and Vogel et al. [26]

## 5. Conclusions

GRIN fiber has a large cross-section and superior confinement structure to the laser beam. This provides high-quality focusing properties. Determination of second-order index coefficient radial profile is highly recommended to acquire more understanding of self-focusing in optical fibers. Therefore, Fizeau interferometry is applied to estimate second-order index coefficient in GRIN optical fiber. The findings pointed out that in comparison with waveguide dispersion; the material dispersion profile is a critical parameter which shapes the $n_2$ profile. For high power laser propagation with elimination for self-focusing effect, GRIN fiber without central dip is suggested. The results would help to design fiber having waveguide dispersion profile that provides maximum transmission capacity of high power laser systems with a good focus quality.

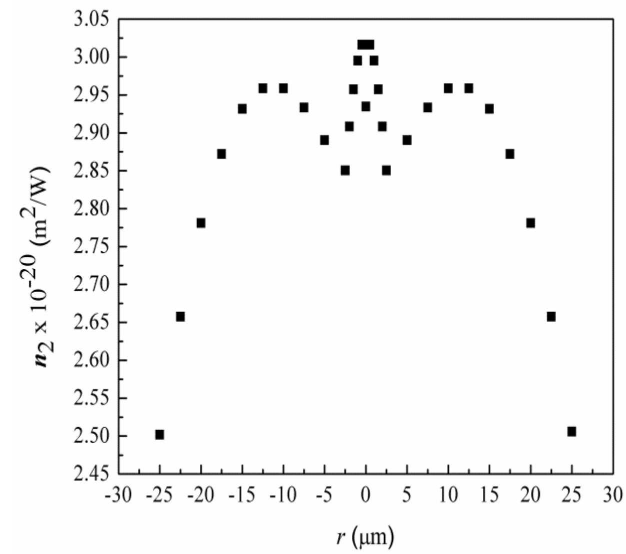


**Figure 4.** Secon-order nonlinear index profile of GRIN fiber based on the fiber material dispersion profile due to Milam and Weber [24]

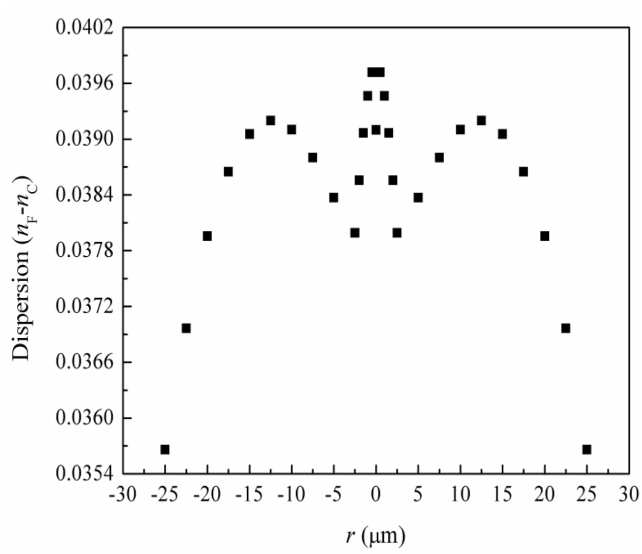


**Figure 5.** Material dispersion radial profile of core and dip of GRIN fiber

# REFERENCES


[1] K. J. Blow, D. Wood, "Stability and compression of pulses in soliton laser," IEEE J. Quantum Electron. QE-22 (1986) 1109-1116.

[2] U. Osterberg and W. Margulis: XIV int. quant. electr. conf. IQEC '86, Tech. Digest., San Francisco, 1986, p. 102.

[3] R. H. Stolen "Non-linear properties of fibres, in S. E. Miller and A. G. Chynoweth (Eds.) 'Optical fibre communications' (Academic Press, 1979).

[4] R. Y. Chiao, E. Garmire and C. H. Townes, "Self-trapping of optical beams", Phys. Rev. Lett. 13 (1964) 479-482, Erratum, ibid, 14 (1965) 1056.

[5] P. L. Kelly, "Self-focusing of optical beams", Phys. Rev. Lett 15 (1965) 1005-1008.

[6] P. L. Baldeck, F. Raccah and R. Alfanro, "Observation of self-focusing in optical fibres with picosecond pulses" Optics. Lett. 12 (1987) 588-589.

[7] S. W. Allison, G. T. Gillies, D. W. Magnuson, and T. S. Pagano, "Pulsed laser damage to optical fibers," Appl. Opt. 24 (1985) 3140-3145.

[8] R. Kashyap and K. J. Blow, "Observation of catastrophic self-propelled self-focusing in optical fibres," Electron. Lett. 24 (1988) 47-49.

[9] 1. D. P. Hand and P. St. J. Russell, "Solitary thermal shock waves and optical damage in optical fibers: the fiber fuse," Opt. Lett. 13 (1988) 767-769.

[10] T. J. Driscoll, J. M. Calo, and N. M. Lawandy, "Explaining the optical fuse," Opt. Lett. 16 (1991) 1046-1048.

[11] D. D. Davis, S. C. Mettler, and D. G. DiGiovanni, "A comparative evaluation of fiber fuse models," Proc. SPIE Laser-Induced Damage Opt. Mater. 2966 (1997) 592–606.

[12] R. M. Percival, E. S. R. Sikora, and R. Wyatt, "Catastrophic damage and accelerated ageing in bent fibres caused by high optical powers," Electron. Lett. 36 (2000) 414-416.

[13] 6. R. M. Atkins, P. G. Simpkins, and A. D. Yablon, "Track of a fiber fuse: a Rayleigh instability in optical waveguides," Opt. Lett. 28 (2003) 974-976.

[14] R. Kashyp and I. Blowk, "Spectacular demonstration of catastrophic failure in long lengths of optical fiber via selfpropelled self-focusing" $8^{th}$ National Quantum Electronics Conference, Session PD7, Univ. of St Andrews, 21-25 Sept. 1987.

[15] B. V. Hunter, K. H. Leong, C. B. Miller, J. F. Golden, R. D. Glesias, and P. J. Laverty, "Understanding high-power fiber-optic laser beam delivery," J. Laser Appl. 8 (1996) 307-316.

[16] X. Sun, J. Li, A. Hokansson, "Study of optical fiber damage under tight bend with high optical power at 2140 nm," Conference Proceedings of SPIE vol. 6433 (2007).

[17] L. Prigent, J. -P. Hamaide, "Measurement of fiber nonlinear Kerr coefficient by four-wave mixing," IEEE Photon. Technol. Lett. 5 (1993) 1092–1095.

[18] A. Boskovic, S. V. Chernikov, J. R. Taylor, L. Gruner-Nielsen, O. A. Levring, "Direct continuous-wave measurement of $n_2$ in various types of telecommunication fiber at 1.55 μm," Opt. Lett. 21 (1996) 1966–1968.

[19] K. Nakajima, T. Omae, M. Ohashi, "Conditions for measuring nonlinear refractive index $n_2$ of various singlemode fibres using CW SPM method," IEEE Proc. Optoelectron. 148 (2001) 209–214.

[20] J.-C. Antona, S. Bigo, S. Kosmalski, "Nonlinear index measurements of various fibre types over C + L bands using four-wave mixing," in: Proc. of 27th European Conference on Optical Communications, Amsterdam, The Netherlands, 2001, pp. 270–271.

[21] Y. Namihira, K. Miyagi, K. Kaneshima, M. Tadakuma, C. Vinegoni, G. Pietra, K. Kawanami, "A comparison of six techniques for nonlinear coefficient measurements of various single mode optical fibers," in: Technical Digest of the 12th Symposium on Optical Fiber Measurement, Boulder, CO, USA, 2002.

[22] A. Lamminpää, T. Niemi, E. Ikonen, P. Marttila, H. Ludvigsen, "Effects of dispersion on nonlinearity measurement of optical fibers," Opt. Fiber Technol. 11 (2005) 278–285.

[23] J. Fatome, S. Pitois, G. Millot, "Measurement of nonlinear and chromatic dispersion parameters of optical fibers using modulation instability," Opt. Fiber Technol. 12 (2006) 243–250.

[24] D. Milam, and M. J. Weber, "Measurement of nonlinear refractive index coefficients using time resolved interferometry: Application to optical materials for high power neodymium lasers," J. Appl. Phys. 47 (1976) 2499-2501.

[25] R. C. Miller, "Optical second harmonic generation in piezoelectric crystals," Appl. Phys. Lett. 5 (1964) 17–19.

[26] E. M. Vogel, M. J. Weber, and D. M. Krol, "Nonlinear optical phenomena in glass," Phys. Chem. Glasses 32 (1991) 231-254.

[27] H. A. El-Hennawi, F. El-Diasty, H. El-Ghandoor, and M. A. Soliman, "Multiple-beam interference fringes applied to investigate the index profile of the optical fiber dip," Opt. Quant. Electron. 43 (2012) 35–48.

[28] F. El-Diasty, "Characterization of optical fibers by two- and multiple-beam interferometry," Opt. Laser Eng. 46 (2008) 291-305.

[29] N. Barakat, H. A. El-Hennawi, and F. El-Diasty, "Multiple-beam interference fringes applied to GRIN optical waveguides to examine fiber formation." Appl. Opt. 27 (1988) 5090-5094.

[30] I. P. Kaminow, H. M. Presby, J. B. MacChesney, P. B. O'Connor, "Ternary fiber glass composition for minimum modal dispersion over a range of wavelength," Technical Digest Optical Fiber Transmission II, Opt. Soc. Am. PD5-1 (1977).

[31] T. Kato, Y. Suetsugu, M. Nishimura, "Estimation of nonlinear refractive index in various silica-based glasses for optical fibers," Opt. Lett. 20 (1995) 2279-2281.

[32] F. A. Abdel Wahab, F. El-Diasty, M. Abdel-Baki, "Dispersion dependence of second-order refractive index and complex third-order optical susceptibility in oxide glasses," Phys. Lett. A 373 (2009) 3355-3360.