Structural Modification in Borosilicate Glass by Use of Femtosecond Fiber Laser at 1.56 μm

Takayuki TAMAKI*, Wataru WATANABE**, and Kazuyoshi ITOH*

*Department of Material and Life Science, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: tamaki@photonics.mls.eng.osaka-u.ac.jp
**Photonics Research Institute, National Institute of Advanced Industrial Science and Technology, 1-8-31 Midorigaoka, Ikeda, Osaka 563-8577, Japan

By focusing intense femtosecond laser pulses inside a transparent material, one can induce localized structural modifications including a refractive-index change. This technique can be applied to the fabrication of three-dimensional photonic devices. In this paper, we study on the structural modifications in borosilicate glass by using an amplified femtosecond Er-fiber laser system producing 947-fs optical pulses at a repetition rate of 155.1 kHz and a wavelength of 1.56 μm. In order to optimize the irradiation condition, we investigate the dependence of structural modification on the incident pulse energy, exposure time, and focusing condition. In a static exposure experiment, it is found that refractive-index change can be induced with a wider range of pulse energies compared to silica glass. The magnitude of refractive-index change is estimated to be 1.2×10^{-2} by measuring the diffraction efficiencies of a Raman-Nath grating fabricated in borosilicate glass.

DOI: 10.2961/jlmn.2007.01.0005

Keywords: femtosecond laser, fiber laser, borosilicate glass, grating, refractive-index change, scattering damage, laser processing, integrated optics devices

1. Introduction

The fabrication of three-dimensional micro- and nanostructures is crucial for the development of multi-functional devices consisting of three-dimensional optical circuits. Femtosecond laser-based micromachining technique has been regarded as a powerful tool for this purpose. When femtosecond laser pulses are focused inside a transparent material, the intensity in the focal volume can be high enough to cause absorption through nonlinear processes, leading to a localized structural modification in the focal volume. This process depends on various conditions, such as material, focusing lens, and laser parameters (i.e. wavelength, pulse duration, incident pulse energy, and repetition rate) [1], [2]. The resultant modification is classified broadly into three types: refractive-index change, scattering damage, and voids. Among them, the localized refractive-index change can be used to embed directly optical elements, such as waveguides [3] - [14], couplers [5], [15] - [19], lenses [20], and gratings [21] - [26] in a wide variety of glasses.

Up to now, various laser systems have been used for inducing the refractive-index change, while a Ti:sapphire system at 800-nm wavelength region is a popular one. The other examples are listed as follows: Saliminia *et al.* demonstrated the waveguide writing in fused silica by use of 1.5-μm femtosecond laser pulses from an optical parametric amplifier [10]. Osellame *et al.* used a cavity-dumped Yb:glass oscillator generating 1040-nm, 300-fs pulses for writing an optical waveguide in Er:Yb-doped phosphate glass [11]. Recently, fiber lasers have attracted much attention because of its superior reliability and robustness as compared with solid-state lasers. Shah *et al.* and Eaton *et al.* performed the waveguide writing in borosilicate glass and fused silica with femtosecond laser pulses at the fundamental wavelength (1040 nm) and the second-harmonic wavelength (522 nm) of amplified femtosecond Yb-fiber laser pulses [12] - [14]. We have recently reported on the structural modification in fused silica using an amplified femtosecond Er-fiber laser system at a wavelength of 1.56 μm [27]. Although this demonstration proved the applicability of Er-fiber laser to micromachining in fused silica, the parameter ranges of processing conditions were quite narrow therein.

In this paper, we study the micromachining in borosilicate glass by using a similar Er-fiber laser system. We demonstrate that the parameter ranges of processing conditions of borosilicate glass are broadened and the magnitude of refractive-index change is larger than that of fused silica.

2. Experimental method

The optical setup for inducing structural modification inside borosilicate glass is shown in Fig. 1. We used an amplified femtosecond Er-fiber laser system (IMRA America, FCPA μJewel B-250), which consists of three diode-pumped Er-fiber stages: an oscillator, a pre-amplifier, and a large mode area Er-fiber power amplifier. The center wavelength was 1.56 μm and the pulse duration was 947 fs. Although the repetition rate was variable, it was set at 155.1 kHz. These laser parameters were similar to those in our previous study (1558 nm, 870 fs, and 173 kHz) [27]. The sample was a bulk of borosilicate glass. It was mounted on a two-dimensional translation stage (Physik Instrumente V102.2L). The resolution of the stage was 100 nm. The pulse energy was adjusted by rotating a half-wave plate in front of a Glan-laser polarizer. In this experiment, the maximum power through the Glan-laser polarizer was 400 mW, which corresponds to a pulse energy of 2.58 µJ. We controlled exposure time with an electromagnetic shutter. The laser pulses were focused with an objective lens (OB1) at a depth of 200 µm beneath the surface. The objective lens was selected from those listed in Table 1. Transmittances of the objective lenses were experimentally measured at a wavelength of 1.56 µm and were shown in Table 1. We obtained transmission white-light microscopic images in the vicinity of the focal spot in the *xy*- and *xz*-plane.

Table 1 Properties of objective lenses

Model	Magnification	Numerical Aperture	Transmittance
Olympus LMPlan 10×IR	10×	0.25	72 %
Olympus LMPlan 20×IR	20×	0.40	66 %
Olympus LMPlan 50×IR	50×	0.55	50 %

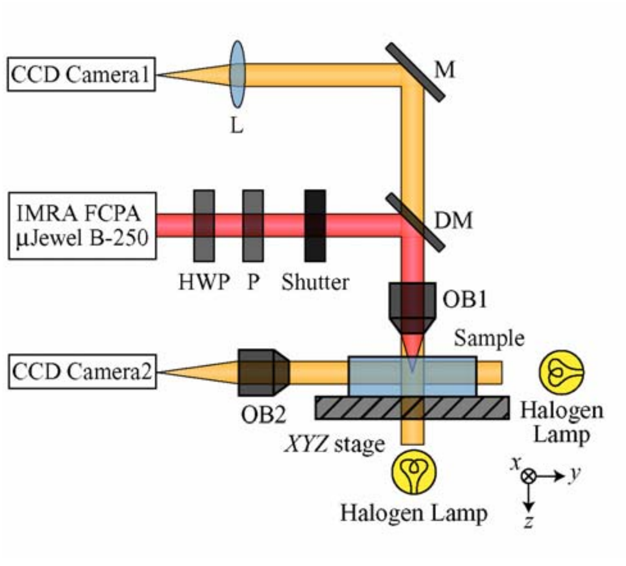

Fig. 1 Schematic diagram of the experimental setup for inducing structural modification in borosilicate glass. L, achromatic lens (focal length f = 200 mm); HWP, λ/2 wavelength plate; P, Glan-laser polarizer; Shutter, electromagnetic shutter; DM, dichroic mirror; OB1 and OB2, objective lenses; M, mirror.

3. Investigation on structural modification in borosilicate glass with 1.56-µm pulses

In this section, we optimize the irradiation condition for inducing refractive-index change through a static exposure experiment. We investigate the dependence of structural modifications on pulse energy, exposure time, and numerical aperture (NA) of focusing lens.

3.1 Dependence on incident pulse energy

We investigated structural modifications by varying the incident pulse energy (average power) from 2.26 µJ (350 mW) to 2.58 µJ (400 mW) with a step of 0.06 µJ (10 mW). The exposure time was fixed to 100 s. We used a 10× focusing lens with a NA of 0.25.

Figure 2 shows the optical images of plasma luminescence in the vicinity of the focal point during irradiation of the laser pulses. It is clearly seen that the luminescent regions were lengthened along the laser propagation axis (*z*-axis). This means that we could induce filamentations inside the borosilicate glass. As was reported previously, filamentation occurs as a result of a balance between the Kerr self-focusing of the laser pulse and the defocusing effect of the plasma generated in the self-focal region [2], [7]. It is noted that the region of filamentation is lengthened both in the +*z* and –*z* directions as the incident pulse energy increased.

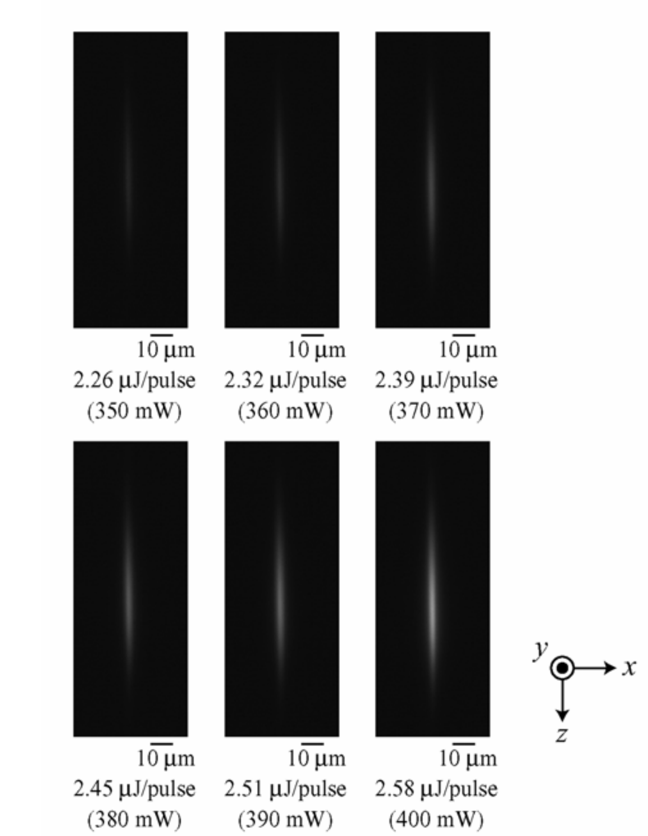

Fig. 2 Optical images of plasma luminescence from filamentation along the laser propagation axis (*z*-axis). The incident pulse energy (average power) was varied between 2.26 µJ (350 mW) and 2.58 µJ (400 mW).

Figures 3(a) and (b) show the optical images of the resultant structural modifications in the *xz*- and *xy*-plane, respectively. The lower threshold of pulse energy, at which the refractive-index change was induced, was found to be 2.32 µJ. In Fig. 3(a), it is clearly seen that the modified region was elongated both in the +*z* and -*z* directions as the incident pulse energy increased. This may be a result of the elongation of filamentation as mentioned above. In contrast, previous papers [7], [28] reported that the modified region elongates only in the –*z* direction as the pulse energy increased. The reason of such a different dependence has not been clarified yet.

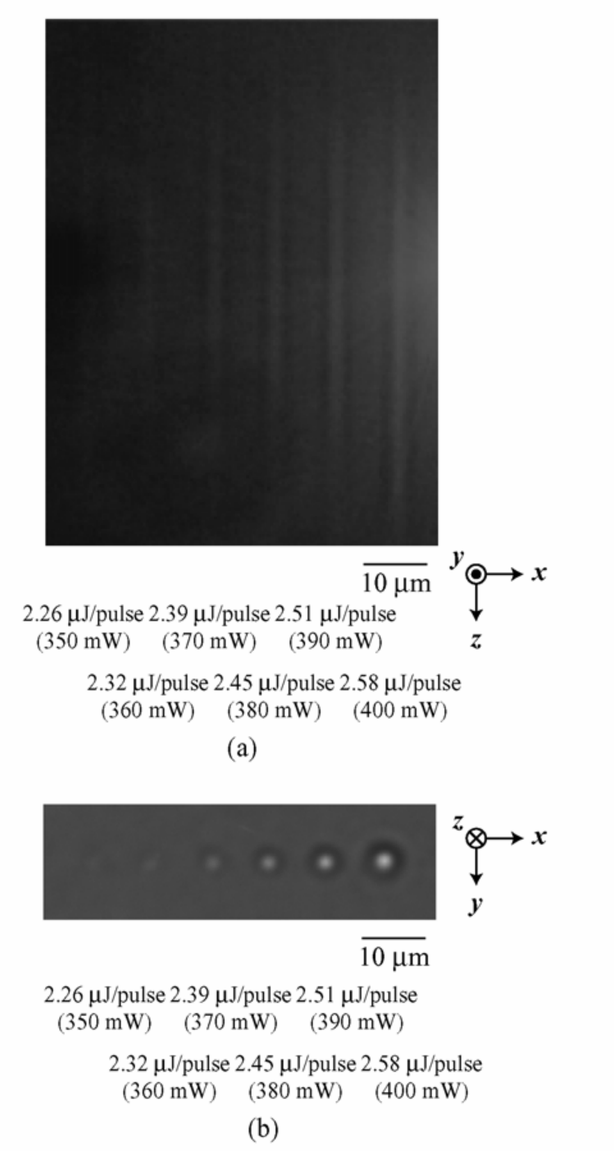

Fig. 3 Optical images of refractive-index change in borosilicate glass. The incident pulse energy (average power) was varied between 2.26 µJ (350 mW) and 2.58 µJ (400 mW). (a) *xz*-plane. (b) *xy*-plane.

From Fig. 3(b), it is found that the central diameter of the region of refractive-index change expands from approximately 2.3 µm to 3.5 µm as the pulse energy increases. The ratio of the diameter to input energy was not constant. This means that the structural modification was mainly due to the heat accumulation effect [8], [14], [29]. Moreover, the bright elliptical region in the *xz*-plane indicates that the sign of refractive-index change was positive. Therefore, this structural modification can be applied to waveguide writing.

In order to compare the length of and diameter of the regions of filament and refractive-index change, in Fig. 4, we summarized the dependence of the dimensions on the incident pulse energy. From Fig. 4, it is clearly seen that the length of and diameter of the regions of refractive-index change are narrower and shorter than those of the filamentation. We presume that the region of refractive-index change was generated at a portion of filamentation. This phenomenon may be explained by a distribution of heat and/or pressure in the filamentation, while we have not clarified this point yet. Additionally, from Fig. 4, it is found that the length of and diameter of the regions of filament and refractive-index change were expanded when the incident pulse energy increased. This result shows that we can control the dimensions of the region of refractive-index change with the incident pulse energy.

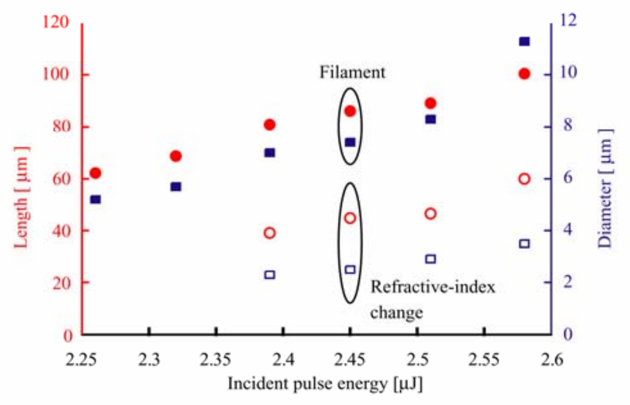

Fig. 4 Measured dimensions of the filament and the refractive-index change vs. incident pulse energy. Filled circle (●) and filled rectangle (■) indicate the length of and diameter of the filament, respectively. Open circle (○) and open rectangle (□) indicate the length of and diameter of the dimension of refractive-index change, respectively.

3.2 Dependence on exposure time

We investigated the dependence of the exposure time in the static exposure experiment. We used a 10× objective lens. The pulse energy was fixed to 2.58 µJ. The result is shown in Fig. 5. The lengths of the regions of refractive-index change along the *z*-axis were elongated with increasing the exposure time, and were almost saturated with an exposure time of >300 s.

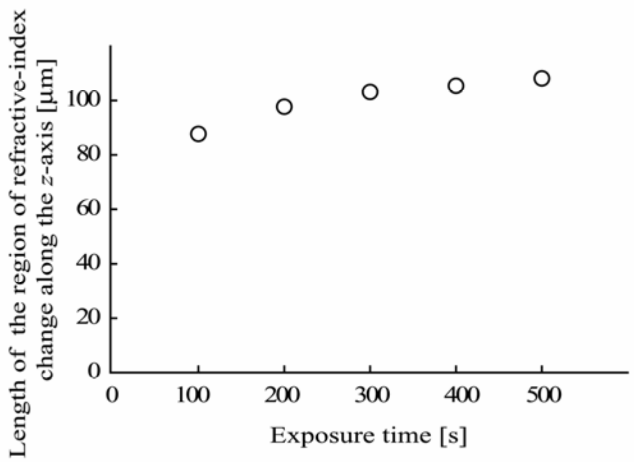

Fig. 5 Dependence of the length of the region of refractive-index change along the z-axis on the exposure time between 100 s and 500 s.

3.3 Dependence on NA of focusing lens

By varying the NAs of the object lenses, we investigated the dependence of the laser-induced structural modification on focusing conditions. The threshold of refractive-index change and that of the scattering damage in borosilicate glass were investigated. The results are summarized in Fig. 6. With each objective lens we tested, the refractive-index change or the scattering damage could be induced. When a 50× objective lens was used, the threshold of the refractive-index change was 0.52 µJ and the threshold of the scattering damage was 0.90 µJ.

For comparison, we also measured the laser-processing window of fused silica. The result is shown in Fig. 6. In fused silica, no laser-induced structural modifications were induced by using 10× and 20× objective lenses. With a 50× objective lens, the threshold pulse energies for the refractive-index change and for the scattering damage are 0.60 µJ and 0.61 µJ, respectively. Thus, the processing window of fused silica was quite narrow, as was already reported in [27]. In contrast, the processing window of borosilicate glass is much wider than fused silica, in terms of the pulse energy and NA of objective lens.

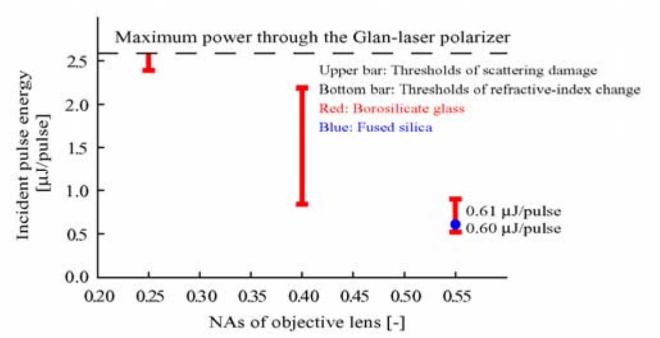

Fig. 6 Dependence of the threshold of the refractive-index change and the scattering damage in borosilicate glass and fused silica on focusing conditions.

4. Fabrication of Raman-Nath gratings

To estimate the magnitude of the refractive-index change in borosilicate glass, we fabricated a Raman-Nath grating. In the experiment, the sample was displaced along the *y*-axis, perpendicular to the optical axis (*z*-axis), over a distance of 200 µm at a scan speed of 2 µm/s. The writing procedure was repeated 20 times by moving the sample with a step of 20 µm in the *x*-axis. Femtosecond laser pulses were focused at the depth of 200 µm beneath the surface by a 50× objective lens. The incident pulse energy was adjusted to 0.84 µJ so that the refractive-index change was induced.

Figure 7 shows the optical images of the grating fabricated in borosilicate glass. The grating thickness was measured to be 12 µm. In order to check whether the grating is Raman-Nath type or Bragg type, we calculated the Klein-Cook (Q) parameter [30] given by

$$Q = \frac{2\pi\lambda T}{n_0 \Lambda^2}. \quad (1)$$

Here, λ is the wavelength of the light (0.632 µm) that incidents on the grating, T is the grating thickness, n_0 is refractive index of the material (1.47), and Λ is the grating period (20 µm). By substituting these values in Eq. (1), Q was calculated to be 0.08 << 1. Therefore, the fabricated grating was confirmed to be the Raman-Nath type.

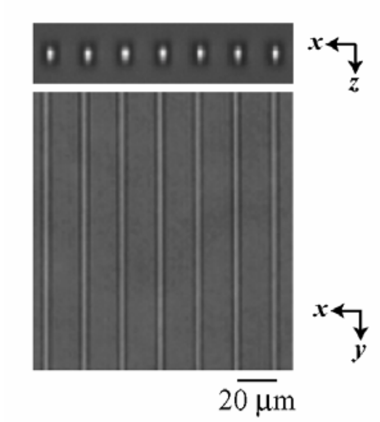

Fig. 7 Optical images of the fabricated Raman-Nath gratings in borosilicate glass.

The magnitude of refractive-index change in Raman-Nath grating can be estimated from the diffraction efficiencies of all orders [27], [31]. We led a He-Ne laser beam to the grating and measured the diffraction efficiencies. As a result, the magnitude of refractive-index change was estimated to be 1.2×10^{-2}. This value is the same order as the previous report where borosilicate glass was modified with 1040-nm laser pulses [13]. It is also noted that this value was approximately 10 times larger than the magnitude of refractive-index change induced in fused silica with 1.56-µm laser pulses [27].

5. Conclusion

In conclusion, we have demonstrated structural modification in borosilicate glass using an amplified femtosecond fiber laser at 1.56-µm wavelength. The dimensions of laser-induced structural modifications at various incident pulse energies and exposure times were measured. We found that the relation between the dimensions along the *x*- and *z*-axis and incident pulse energy was linear. The dimensions along the *z*-axis was almost saturated with an exposure time of >300 s. The thresholds of refractive-index change and scattering damage were investigated. With a 0.55-NA objective lens, the processing window in borosilicate glass was wider than that in fused silica by a factor of more than 30. The magnitude of refractive-index change in borosilicate glass was estimated to be 1.2×10^{-2} from fabricated Raman-Nath gratings. Our result suggests that the structural modification in borosilicate glass with Er-fiber laser pulses is an attractive candidate for femtosecond laser-based microprocessing.

Acknowledgments

The authors would like to acknowledge the support of H. Nagai and M. Yoshida for the use of a femtosecond fiber laser system (IMRA FCPA µJewel B-250) and of S. Onda, S. Sowa, and J. Nishii for helpful discussions.

References

[1] L. Sudrie, M. Franco, B. Prade, and A. Mysyrowicz: Opt. Commun. **191**, (2001) 333.
[2] S. Onda, W. Watanabe, K. Yamada, K. Itoh, and J. Nishii: J. Opt. Soc. Am. B **22**, (2005) 2437.
[3] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao: Opt. Lett. **21**, (1996) 1729.
[4] K. Miura, J. Qiu, H. Inouye, T. Mitsuyu, and K. Hirao: Appl. Phys. Lett. **71**, (1997) 3329.
[5] D. Homoelle, S. Wielandy, A. L. Gaeta, N. F. Borrelli, and C. Smith: Opt. Lett. **24**, (1999) 1311.
[6] S. H. Cho, H. Kumagai, K. Midorikawa, and M. Obara: Opt. Commun. **168**, (1999) 287.
[7] K. Yamada, W. Watanabe, T. Toma, K. Itoh, and J. Nishii: Opt. Lett. **26**, (2001) 19.
[8] C. B. Schaffer, A. Brodeur, J. F. Garca, and E. Mazur: Opt. Lett. **26**, (2001) 93.
[9] M. Will, S. Nolte, B. N. Chichkov, and A. Tünnermann: Appl. Opt. **41**, (2001) 93.
[10] A. Saliminia, R. Vallée, and S. L. Chin: Opt. Commun. **256**, (2005) 422.
[11] R. Osellame, N. Chiodo, G. D. Valle, S. Taccheo, R. Ramponi, G. Cerullo, A. Killi, U. Morgner, M. Lederer, and D. Kopf: Opt. Lett. **29**, (2004) 1900.
[12] S.M. Eaton, F. Yoshino, L. Shah, A. Arai, H. Zhang, S. Ho, and P. R. Herman: Proc. SPIE 5713, San Jose, (2005).
[13] L. Shah, A. Y. Arai, S. M. Eaton, and P. R. Herman: Opt. Express **13**, (2005) 1999.
[14] S. M. Eaton, H. Zhang, P. R. Herman, F. Yoshino, L. Shah, J. Bovatsek, and A. Y. Arai: Opt. Express **13**, (2005) 4708.
[15] A. M. Streltsov and N. F. Borrelli: Opt. Lett. **26**, (2001) 42.
[16] K. Minoshima, A. M. Kowalevicz, I. Hartl, E. P. Ippen, and J. G. Fujimoto: Opt. Lett. **26**, (2001) 1516.
[17] A. M. Kowalevicz, V. Sharma, E. P. Ippen, J. G. Fujimoto, and K. Minoshima: Opt. Lett. **30**, (2005) 1060.
[18] S. Nolte, M. Will, J. Burghoff, and A. Tuennermann: Appl. Phys. A **77**, (2003) 109.
[19] W. Watanabe, T. Asano, K. Yamada, K. Itoh, and J. Nishii: Opt. Lett. **28**, (2003) 2491.
[20] K. Yamada, W. Watanabe, Y. Li, K. Itoh, and J. Nishii: Opt. Lett. **29**, (2004) 1846.
[21] T. Toma, Y. Furuya, W. Watanabe, K. Itoh, J. Nishii, and K. Hayashi: Opt. Rev. **7**, (2000) 14.
[22] L. Sudrie, M. Franco, B. Prade, and A. Mysyrowicz: Opt. Commun. **171**, (1999) 279.
[23] K. Yamada, W. Watanabe, K. Kintaka, J. Nishii, and K. Itoh: Jpn. J. Appl. Phys. **42**, (2003) 6916.
[24] Y. Li, W. Watanabe, T. TamakiI, J. Nishii, and K. Itoh: Jpn. J. Appl. Phys. **44**, (2005) 5014.
[25] K. Kawamura, N. Sarukura, M. Hirano, and H. Hosono: Appl. Phys. Lett. **78**, (2001) 1038.
[26] Y. Li, W. Watanabe, K. Yamada, T. Shinagawa, K. Itoh, J. Nishii, and Y. Jiang: Appl. Phys. Lett. **80**, (2002) 1508.
[27] T. Tamaki, W. Watanabe, H. Nagai, M. Yoshida, J. Nishii, and K. Itoh: Opt. Express **14**, (2006) 6971.
[28] D. Ashkenasi, H. Varel, A. Rosenfeld, S. Henz, J. Herrmann, and E.E.B. Cambell: Appl. Phys. Lett. **72**, (1998) 1442.
[29] C.B. Schaffer, J.F. García, and E. Mazur: Appl. Phys. A **76**, (2003) 351.
[30] H. Kogelnik: Bell Syst. Tech. J. **48**, (1969) 2909.
[31] K. Yamada, W. Watanabe, J. Nishii, and K. Itoh: J. Appl. Phys. **93**, (2003) 1889.

(Received: May 30, 2006, Accepted: January 17, 2007)