Lithuanian Journal of Physics, Vol. **50**, No. 1, pp. 129–134 (2010) doi:10.3952/lithjphys.50109

MANUFACTURING OF DIFFRACTIVE ELEMENTS IN FUSED SILICA USING HIGH REPETITION RATE FEMTOSECOND Yb:KGW LASER PULSES

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Received 27 November 2009; revised 8 February 2010; accepted 19 March 2010

In this work we discuss volume phase gratings made in fused silica using high-repetition-rate femtosecond Yb:KGW laser pulses. By exposing fused silica to focused femtosecond laser radiation, regions of modified refractive index were induced. Exploiting this phenomenon gratings were fabricated in the bulk of fused silica by the direct laser writing technique. Gratings with index change of 0.008 and diffraction efficiency of 57% were successfully manufactured using 300-fs laser pulses focused in the fused silica with a 0.42 numerical aperture objective.

Keywords: volume phase grating, refractive index change, femtosecond microfabrication, fused silica

PACS: 42.40.Eq, 42.62.Cf, 42.70.Ce

1. Introduction

By tightly focusing femtosecond laser radiation inside the bulk of transparent material it is possible to induce highly localized structural changes with modified optical properties. Depending on laser pulse intensities these changes can manifest as uniform zones of modified refractive index [1], lead to birefringent zone formation [2, 3] or void-like structure creation if intensities are above the material damage threshold [4]. The key processes of this interaction are nonlinear multiphoton absorption followed by avalanche ionization that takes place in the focused region. Other physical phenomena, like colour centre formation [5], participate complicating the full understanding of the material changes. Nevertheless, the result is the deposition of a significant fraction of the laser pulse energy within the small focal volume inside the dielectric material. Ultrafast heating and rapid cooling under the high stress initiates resolidification and densification of affected zones thus forming regions with modified refractive index [6]. By moving the focus position inside the transparent material it is possible to fabricate various 3D photonic structures such as waveguides [1], diffractive components [7], data storage elements [4], and even, with the aid of chemical treatment, complicated microchannels [8].

Working in the regime of induced smooth refractive index change, Volume Phase Gratings (VPGs) can be manufactured inside the transparent material. These gratings have some advantages compared with common amplitude or profile gratings. As described in the following section, the VPG efficiency strongly depends on grating thickness and on the magnitude of refractive index modification. However, the last parameter remains problematic, because the causes of the increase of refractive index change are still not clearly identified. Thus, its value is hardly predictable and this has prevented successful manufacturing of high efficiency diffractive gratings.

Traditionally, high efficiency VPGs are fabricated using holographic technology. During the two laser beam interference process, a generated grating pattern is recorder in photosensitive material. The most popular material used for such devices is DiChromated Gelatin (DCG), which has a very high refractive index modulation property (Δn up to 0.1), while retaining good transparency in a broad spectral range. With this technology it is possible to form large area gratings with spatial frequencies up to 6000 mm^{-1}. After the exposure, the gelatin is chemically treated and sandwiched between glass plates for better robustness and handling [9]. A new and very promising material for VPG fabrication is Photo-Thermo-Refractive (PTR)

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ISSN 1648-8504

glass, which was developed and patented by a CREOL team in the recent decade [10]. It is a silicate based glass with silver, cerium, and fluorine doping. After UV illumination and thermal treatment, it can exhibit a refractive index change of up to 10^{-3}. That change is considerably smaller than for DCG, but it is more stable and frequencies up to 10000 mm^{-1} can be reached.

Fused silica is one of the most popular material used in optical systems; it is a widely available and reasonably inexpensive glass. The ability to change its refractive index after femtosecond laser irradiation allows creation of structures that were only possible with the abovementioned photosensitive materials. The holographic technique is not suitable for VPG fabrication in pure fused silica as high laser intensities are required to reach the smooth refractive index modification regime; however, the point by point Direct Laser Writing (DLW) technique can be applied for successful fabrication of such devices. This technique has advantages over the holographic method as any desired patterns can be fabricated. However, it still looses in the manufacturing speed category that is very important for industrial applications.

Several attempts to manufacture VPGs in pure fused silica by means of femtosecond laser radiation were made during the last decade [11, 12]. However, the efficiencies of these devices hardly reached 30% due to the problems described earlier. To our knowledge, the VPGs made in pure fused silica and having highest efficiencies (74.8%) were manufactured by Yamada et al. [13]. These gratings were fabricated using a filamentation process and modifying thick regions of the sample. Yet such a technique prevents the precise control of the critical parameters of the grating (in particular the grating thickness) thus preventing its optimization. Another drawback of this technique is slow fabrication speed, as it requires many hours to form a complete structure. In this work we demonstrate the possibility to manufacture VPGs with relatively high efficiencies in less than an hour by employing high repetition rate Yb:KGW laser pulses.

2. Volume phase gratings

Volume phase gratings with high diffraction efficiencies have become an important tool in optical systems, especially in those where spectral and angular selectivity is essential. In contrast with amplitude or profile gratings, diffraction in phase gratings is produced from periodic modulation of the refractive index, created in the bulk of transparent material. The VPGs theory is

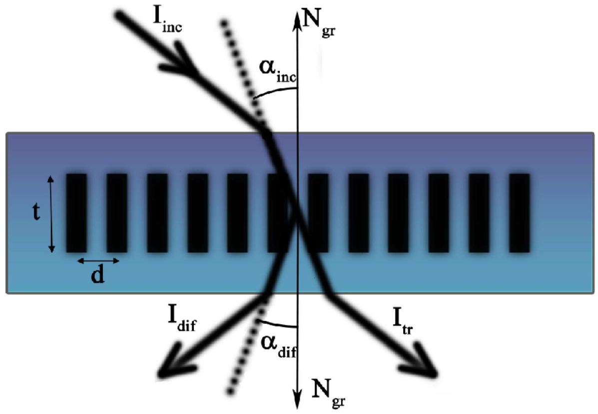


Fig. 1. Schematics of transparent volume phase grating. The equally spaced black stripes represent the region of sinusoidally modulated refractive index.

usually described using a coupled wave model derived by Kogelnik in 1969 [14]. Here we give a short summary of fundamentals of phase gratings based on Kogelnik's work.

Depending on grating orientation and diffraction angle, three main types of VPG exist: the reflecting grating is a grating in which incident and diffractive beams cross the same surface, the transmitting grating is a grating for which the diffracted beam crosses the back surface, and the grating is called prismatic if the diffracted beam exits the grating from a side surface. As theory of all the gratings is the similar, we analyse only the most common transmitting grating.

Such a transmitting grating formed in the bulk of the sample is shown in Fig. 1. Black stripes here represent region of sinusoidally modulated refractive index. The modulation magnitude is Δn, the period of the grating is d, and the thickness is t. An incident beam I_{inc} enters the grating at angle α_{inc}. This angle is measured between the normal of the grating N_{g} and incident beam. In this example, the normal of the grating and normal of the sample front surface plate are identical; however, in general they may differ (the detailed analysis of such gratings can be found in reference papers [14, 15]). Note, that external incident angle between beam and the sample surface differs from α_{inc}, as the grating is created below the surface; the external and interal angles are related by Snell's law. The diffraction condition for this grating is the same as in ordinary surface grating:

$$\frac{m\,\lambda}{n_{\mathrm{av}}d} = \sin\alpha_{\mathrm{inc}} - \sin\alpha_{\mathrm{dif}}\,, \qquad (1)$$

here m is an integer corresponding to the order of diffraction, λ is wavelength, n_{av} is the refractive index of the material, and α_{dif} is the diffracted beam angle.

Using this equation the angles of all diffracted beams (I_{dif}) can be calculated. However, VPGs have additional dimension of thickness that is capable of controlling the efficiency of diffracted beam of the particular order. That efficiency is determined by Bragg diffraction effects. The Bragg condition for a transparent grating is given by

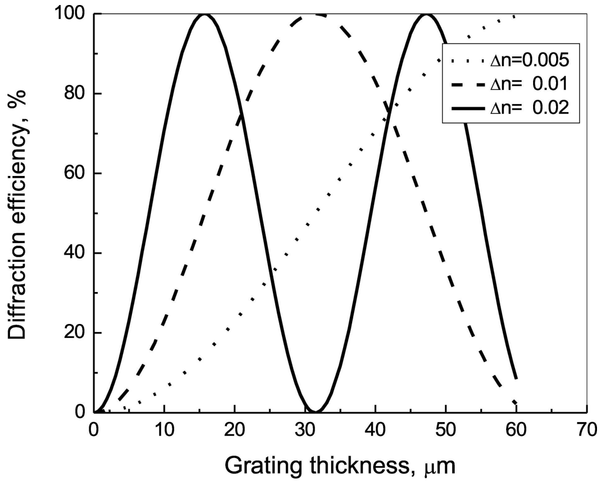
$$\frac{m_{\mathrm{B}}\,\lambda}{n_{\mathrm{av}}} = 2d\,\sin\alpha_{\mathrm{inc}}\,, \tag{2}$$

here m_{B} is an integer representing Bragg order. When the Bragg law is satisfied, incident and diffracted angles are equal, $\alpha_{\mathrm{inc}} = \alpha_{\mathrm{dif}}$. This angle is commonly referred to as the Bragg angle. The grating period d and the wavelength λ alone determine the angle at which Bragg condition is satisfied. The diffraction efficiency of VPG in the Bragg condition is given by

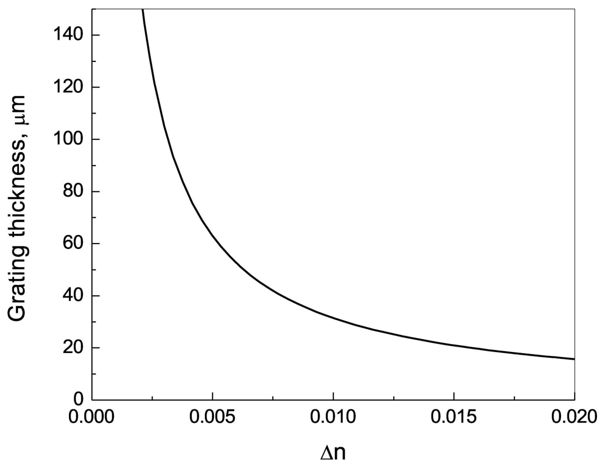
$$\eta = \sin^2\left[\frac{\pi\,\Delta n\,t}{\lambda\sqrt{1-\left(\dfrac{m_{\mathrm{B}}\,\lambda}{2n_{\mathrm{av}}d}\right)^2}}\right]. \tag{3}$$

In Kogelnik's theory of VPG, the diffraction orders of $m_{\mathrm{B}} > 1$ are neglected as small and are ignored. It means that only two beams take part in the diffraction process: incident beam and diffracted beam.

It is obvious that by choosing optimal design parameters it is theoretically possible to achieve diffraction efficiency equal to 100%. When the Bragg angle is out of tune, the overall efficiency decreases and has strong polarization dependence [16]. The most important parameters that play key roles in grating efficiency are grating thickness t and modulation of refractive index Δn. Calculated diffraction efficiencies for various grating thicknesses, with different refractive index modulation level, are shown in Fig. 2(a). As efficiency is a pure sinusoidal function periodic in the product $\Delta n \cdot t$, for a given Δn value, only gratings with specific thickness operate with 100% efficiency. The dependence of the minimum thickness t_0 of volume grating that produces 100% efficiency on refractive index modulation level is plotted in Fig. 2(b). As seen from the figure the minimum thicknesses range from several microns for high refractive index modulation level up to several hundred microns for low level. If the minimum thickness is known then all other thicknesses that give 100% diffraction efficiency will be at $(2k + 1)t_0$ thickness. Here k is any integer number. By varying this number it is possible to adjust spectral width at which the grating operates with high diffraction efficiency.



(a)



(b)

Fig. 2. (a) Diffraction efficiency dependence on grating thickness at various refractive index modulation levels; (b) dependence of minimal thickness of volume grating that produces 100% efficiency on refractive index modulation level.

3. Experiment set-up

We used a Yb:KGW based "Pharos" laser system ("Light Conversion Ltd.") as femtosecond laser source. This laser produces high intensity pulses with 1030-nm wavelength, at 300-fs duration and variable frequency up to 300 kHz. Such an amplified system with high repetition rate helps to speed up the manufacturing by several orders if compared to conventional Ti:sapphire based systems working at 1 kHz rate. The optical set-up of the experiment is shown in Fig. 3. Laser pulses are first attenuated and then focused into the bulk of fused silica with a 0.42-NA lens. The sample was mounted on a 3-axis "Aerotech" based nanopositioning system ("AltSCA", assembled by "Altechna Ltd."). The schematic structure of the grating is shown in Fig. 4. While translating the sample perpendicular

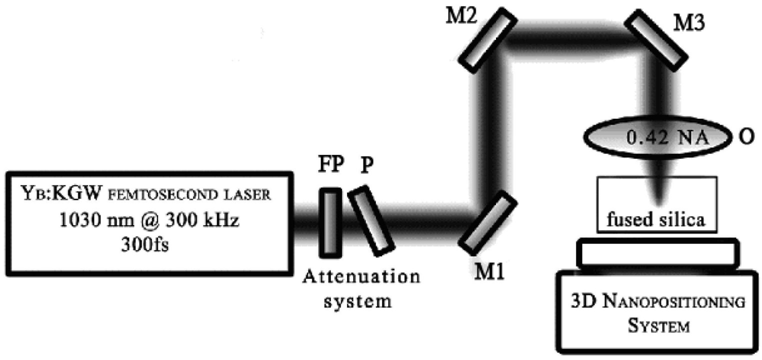


Fig. 3. Schematic of optical set-up for VPG writing. *FP* and *P* correspond to face plate and polarizer, *M1–M3* are guiding mirrors, *O* is the objective. Laser beam diameter at objective is 3.6 mm.

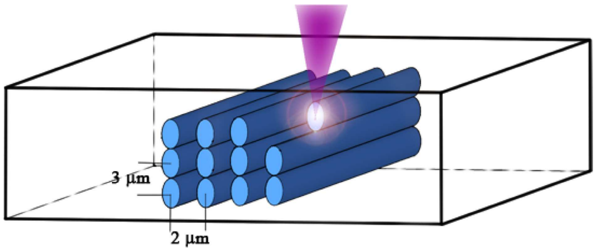


Fig. 4. Schematic layout of fabricated volume phase gratings.

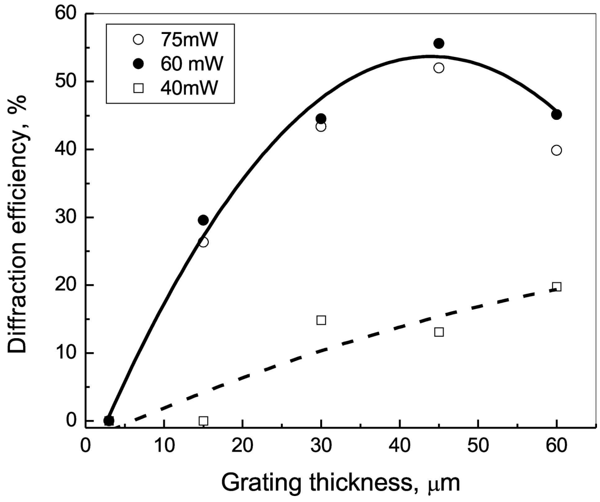
to laser beam, a single line of modified refractive index is created. By arranging such lines periodically, the desired grating structure is formed. Sufficient thickness of the VPG is created by fabricating several layers of gratings on top of each other with some spacing (in our case the spacing was chosen to be 3 μm which guarantees that each layer slightly overlaps). Gratings were formed in the bulk of fused silica 400 μm below the sample's surface.

Writing energy and scanning speed play major roles in creating uniform regions of modified refractive index. There exists a relatively tiny energy window in which a laser pulse is capable of modifying the material without damaging it. That window depends on the laser wavelength, pulse duration, focal geometry, and the purity of the sample, and in most cases it has to be found experimentally. In our case that window of single pulse power densities was between $6{\cdot}10^{12}$ and $3{\cdot}10^{13}$ W/cm^2. Below the lower intensity no residual modification was observed and above the higher intensity the material was permanently damaged. Our gratings were fabricated using 40–75-mW average laser power (that corresponds to $(1.5–2){\cdot}10^{13}$ W/cm^2 power density for single pulse) at 300 kHz repetition rate. It is also known that refractive index change undergoes an accumulation effect even if pulse repetition rates are not in the MHz range [17]. As a result, scanning speed influences the magnitude of the refractive index change and determines fabrication time for gratings produced by the DLW technique. In our experiment, the sample scanning speed was set to 3 mm/s, which means that each zone meant to be modified is affected by at least 100 pulses. Higher speeds lead to non-uniform distribution of modified regions.

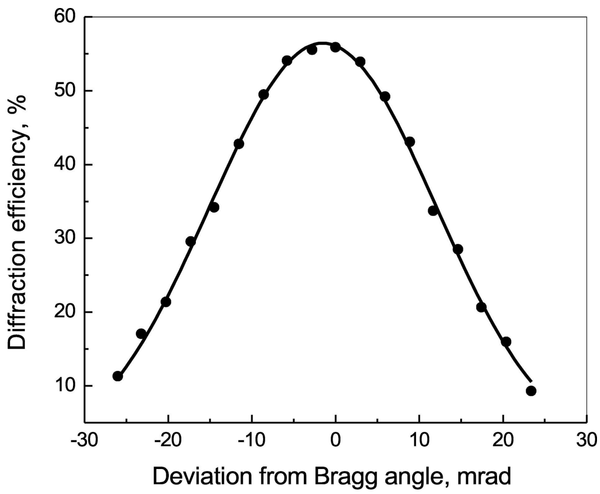
4. Results and discussion

Several 1×1 mm^2 gratings with different thicknesses were fabricated using various writing powers. Their diffraction efficiencies are shown in Fig. 5(a). The efficiency was measured with 633 nm wavelength at angles satisfying Bragg condition thus giving the highest efficiency value. It was found that the Bragg condition is satisfied at 9° external angle (6.2° after correction by Snell's law) for our 2-μm-period grating. This value coincides with the theoretical value (efficiency dependence on deviation from Bragg angle is shown in Fig. 5(b)). The maximum diffraction efficiency of 57% was observed with 633 nm wavelength in a grating with 45 μm thickness produced with 60 mW laser writing power. The measured overall efficiency dependence of this grating on incident wavelength is shown in Fig. 6.

By increasing (or decreasing) grating thickness the efficiency clearly drops. Thus it is safe to conclude that 45 μm thickness is an optimal thickness which produces highest diffraction. By referring to Fig. 2(b), it is also possible to evaluate the refractive index modulation level, which is 0.008. By increasing writing power up to 75 mW the overall efficiency slightly drops; however, maximum efficiency is observed at the same thickness. This suggests that by rising writing power it is not possible to get higher levels of uniform refractive index modification as material damage starts



(a)



(b)

Fig. 5. Diffraction efficiency dependence (a) on the grating thickness with different writing powers and (b) on the detuning from the Bragg angle. Bragg angle was 6.2°. Efficiency was measured with 633 nm He-Ne laser, comparing the intensities of diffracted and incident beams.

to appear, increasing scattering level and lowering the overall grating efficiency. When writing power is low, the modulation level is also lower, so for 40 mW the level is lower than 0.005 (the precise value was not found as the minimum thickness of highest efficiency was not determined in this experiment). The manufacturing time of the VPG depends on the number of grating layers; a single 1×1 mm^2 layer is fabricated in less than 3 minutes, though 45-μm-thickness gratings are fabricated in less than 45 minutes.

There are two main reasons that prevent higher diffraction efficiencies of fabricated VPGs. The first is scattering of incident beam from fabricated structure that is caused by scattering centres such as microdamages, which inevitably appear due to laser power fluctu-

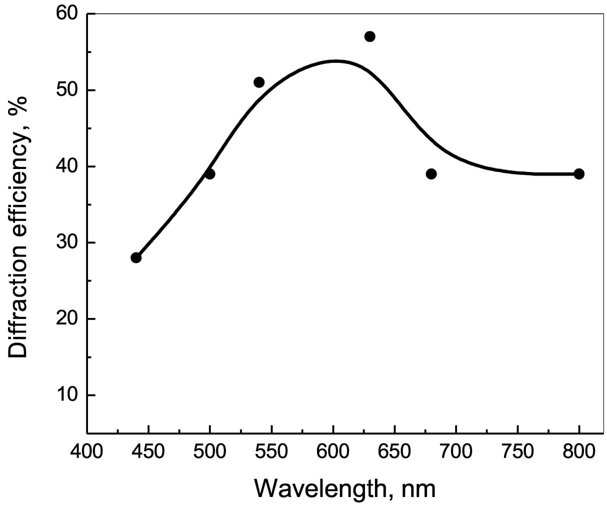


Fig. 6. Diffraction efficiency dependence on incident wavelength for a grating that is 45 μm thick.

ations during fabrication or sample impurity. It is possible to cope with this problem by reducing laser writing power, however it will lead to smaller refractive index modulation amplitude, thicker gratings, and longer fabrication times. The second cause is non-sinusoidal modulation of the refractive index change induced in the material. Theoretical models of VPG describe the sinusoidally modulated refractive index, however it is hard to achieve such distribution using direct laser writing technique as the modification profile after a single shot is rather complicated [18], which means that optimal writing conditions should be found experimentally. This suggests that even higher performance of the grating could be achieved by parameter optimization.

5. Conclusions

We have demonstrated that with a Yb:KGW based femtosecond laser system it is possible to create local structures with smoothly modified refractive index in the fused silica. The maximum magnitude of the refractive index change was evaluated to be 0.008. Using the direct laser writing technique, volume phase gratings with diffraction efficiencies up to 57% were fabricated in the fused silica showing the potential of this technology for microfabrication of dielectric material.

Acknowledgements

This work is supported by the Lithuanian State Science and Studies Foundation Grant B09/08 (Laser Micro-Processing with High Repetition Femtosecond Pulses). Authors thank Dr. R.C. Eckardt for manuscript editing.

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DIFRAKCINIŲ ELEMENTŲ GAMYBA LYDYTAME KVARCE, NAUDOJANT DIDELIO PASIKARTOJIMO DAŽNIO Yb:KGV LAZERIO FEMTOSEKUNDINIUS IMPULSUS

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Santrauka

Aptariami tūrinių fazinių gardelių veikimo principai ir jų įrašymo galimybės lydytame kvarce, naudojant didelio pasikartojimo dažnio femtosekundinius lazerinius impulsus, gautus Yb:KGV lazerine sistema. Veikiant ultratrumpąja spinduliuote, lydytame kvarce galima sukurti modifikuoto lūžio rodiklio sritis. Naudojantis šiuo reiškiniu, tiesioginio lazerinio įrašymo būdu buvo sukurtos tūrinės fazinės gardelės ir išmatuoti jų difrakciniai efektyvumai. Nustatyti optimalūs lazerinės spinduliuotės parametrai, kuriems esant pasiekiamas didžiausias (iki 57%) efektyvumas. Eksperimentiškai nustatytos difrakcinio efektyvumo priklausomybės nuo gardelės storio ir apskaičiuotos optimalios storio vertės. Įvertintas maksimalus lūžio rodiklio modifikacijos gylis, gautas fokusuojant 300 fs trukmės impulsus 0,42 skaitmeninės apertūros lęšiu, kuris siekia 0,008.