Volumetric modifications in fused silica using Gaussian and Bessel femtosecond laser beams

Domas Paipulas\textsuperscript{a}, Mindaugas Mikutis\textsuperscript{a, b}, Valdas Sirutkaitis\textsuperscript{a}, and Saulius Juodkazis\textsuperscript{c}

\textsuperscript{a} Vilniaus University, Laser Research Center, Saultekio av. 10, LT-10223 Vilnius
\textsuperscript{b} Altechna RD, Mokslininku st. 6a, LT-08412, Vilnius
\textsuperscript{c} Centre for Micro-Photonics, Faculty of Engineering and Industrial Sciences Swinburne University of Technology, Hawthorn, Vic 3122, Australia

ABSTRACT

In this work we present the results on volumetric fused silica modifications using femtosecond Gaussian and Gaussian-Bessel laser beams. We show that for specific photonic device, like volume Bragg grating, fabrication, Bessel beams are more superior to Gaussian, as the recording process is much faster and fabricated devices have better efficiencies. Also Gaussian beam tend to be more efficient in formation of nanogratings that causes the appearance of birefringence in modified zones. This reduces optical quality of fabricated device and limits overall recording velocity. We have successfully fabricated volume Bragg gratings in the bulk of fused silica that had absolute diffraction efficiencies reaching \( \sim 90\% \) using femtosecond Gaussian-Bessel beam, while gratings made with Gaussian beam reached only 60%.

Keywords: Volume gratings, Femtosecond processing, Integrated optics

1. INTRODUCTION

Transparent material modification with ultrafast laser pulses has attracted great scientific and industrial interest in the recent decade. If femtosecond laser pulse intensities are kept slightly above materials damage threshold, it is possible to induce well-defined regions with altered optical properties. Most common optical changes are variations in refractive index,\textsuperscript{3} induction of birefringence,\textsuperscript{2} or appearance of light scattering microcracks or voids.\textsuperscript{3, 4} This phenomenon opens doors for three-dimensional integration of various photonic devices in the bulk of transparent material using direct laser writing technique.

However, for some particular integration tasks, common direct laser writing method using Gaussian laser beam is not efficient. In order to achieve material modification in large band gap materials, such as fused silica, strong focusing resulting in small focal spot size is required. This complicates and prolongs recording of large-size photonic devices, such as thick volume Bragg gratings and etc. In order to overcame this problem some level of beam shaping is required. Femtosecond filamentation can be utilized for similar device inscription,\textsuperscript{5} however, this process is rather nondeterministic and limits optimization of essential recording parameters. Her we study the use of Gaussian-Bessel (GB) laser beam for photonic device inscription. We show that highly efficient (absolute diffraction efficiency \( \sim 90\% \)) volume Bragg gratings can be formed in pure fused silica without any post-processing or thermal treatment using femtosecond GB laser pulses.

2. EXPERIMENTAL SETUP

Direct laser writing in the bulk of fused silica was carried out with Yb:KGW laser ("Pharos", Light Conversion Ltd.) having central wavelength of 1030 nm, pulse duration of 170 fs (FWHM) and pulse repetition rate of 200 kHz. Laser beam was guided through automated attenuator and polarization controller and focused with 0.42 numerical aperture (NA), long working distance objective ("Mitutoyo Plan Apo NIR 50X") in the bulk of the sample. Fused silica glass sample ("Lithosil", Schott) with refraction index of 1.46, was mounted on high precision 3D positioning stage (Aerotech) and translated with respect to laser beam. Stage traveling speeds were

Further author information: (Send correspondence to D.P.)
: E-mail: domas.paipulas@ff.vu.lt
in range from 1 to 160 mm/s. However, the recording was aimed at the maximum speed which was optimized for stage acceleration, deceleration and recorded grating dimensions. Recording sequence was fully automated (software "SCA", Workshop of Photonics) and fabrication process was monitored in real time with imaging optics and CCD camera. Schematic representation of the experiment can be seen in Fig. 1.

In order to create Bessel type beam, fused silica axicon (apex angle – 179°) was inserted before the 0.42 NA objective. Additional plano-convex lens was used in order to image "non-diffracted zone" through objective, thus forming 4-f type afocal optical system with 75x demagnification (Fig. 2a). This resulted in GB type beam that is shown in Fig. 2b. Also, in GB experiments we used second harmonics of Yb:KGW laser, thus wavelength was 515 nm.

![Figure 1. A sketch of femtosecond direct laser writing system.](image)

![Figure 2. (a) Schematics of experimental setup for Gaussian beam transformation to GB. Axicon is used together with demagnifying telescope (4-f system) to reduce original GB beam size by 75 times. (b) Measured axial and lateral intensity distribution of GB after the telescope, inset shows GB beam profile, scale bar is 5 µm.](image)

For Gaussian beam the spot diameter and confocal length at the focus can be expressed by: $2w_0 = \frac{4\lambda f}{\pi D} M^2$ and $2z_R = \frac{\pi w_0^2}{2\lambda}$, where $w_0$ and $z_R$ are beam waist radius and Rayleigh length, $D$ is beam diameter before objective, $f$ is focal length of objective and $M^2 = 1.2$ is the quality factor of the used laser beam. For our
objective and laser focal spot was $2w_0 = 1.7 \, \mu m$ and $2z_R = 4.5 \, \mu m$.

Similar evaluation can be carried out with GB laser beam. For GB beam central core radii ($\rho_0$), and the axial extent of the "non-diffracting" zone ($z_{\text{max}}$) can be expressed by following formulas:

$$
\rho_0 = \frac{1.2024 \lambda}{\pi \sin(\alpha_0)}, \quad z_{\text{max}} = \frac{w_0 \cos(\alpha_0)}{\sin(\alpha_0)},
$$

where $\alpha_0 = \alpha(n_{\text{ax}} - n_0)/n_0$ with $n_0$ and $n_{\text{ax}}$ being refractive indexes of the ambient and axicon, respectively; and $\alpha$ is axicon's half-angle measured in respect of its base (in our case 0.5°). One would find that for ideal 1/75 demagnification $\rho_0 = 0.66 \, \mu m$ and $z_{\text{max}} = 116 \, \mu m$ (see, Fig. 2b). As can be seen, the axial extend of GB beam is by an order larger than Gaussian beam while waist diameter remains almost the same. It is noteworthy that the Eq. 1 are valid only for an ideal axicon.

3. MODIFICATIONS IN FUSED SILICA

Typical modifications created at various writing conditions with Gaussian laser beam (by inscribing single line 100 $\mu m$ bellow sample surface) are shown in Fig. 3. As can be seen from this picture, all modifications have elliptical cross sections with maximum axial length not exceeding 12 $\mu m$ at highest pulse energies, while lateral size is $\sim 2 \, \mu m$. Such shape is common for Gaussian beam recorded modifications at perpendicular-to-beam sample translation direction. If needed, this elliptical shape can be corrected using various beam shaping techniques, as successfully demonstrated in waveguide integration applications.

![Figure 3. Modifications induced in the volume of fused silica sample with Gaussian laser beam. Top and axial views are shown for separate lines, made at various pulse energies and sample translation speeds. Beam was focused with 0.42 numerical aperture lens 100 $\mu m$ below the surface. Laser repetition rate - 100 kHz.](image)

Other interesting feature of Gaussian-beam inscribed modifications is the fractalization of lines when sample translation speed is increased or pulse energy is decreased. It is natural to assume, that if sample translation speed is increased to the levels when pulses cease to overlap on the sample, resulted line would be rendered inhomogeneous. However, in our recording conditions (rep. rate 200 kHz) pulses stop to overlap at speeds exceeding 200 mm/s, but fractalization becomes apparent at speeds as low as 1 mm/s. Such behavior is caused by the non-regular formation of nanogratings.

Nanogratings self-form in the laser affected zones after multipulse exposition of the same sample area or when laser pulse duration is sufficiently long ($> 300 \, fs$). If multipulse accumulation is not sufficient, nanograting formation becomes non regular and causes apparent fractalization in laser-recorded lines. This fractalization also is a source of strong light scattering. Thus for homogeneous line recording sample translation speed should be kept sufficiently low ($\sim 100$ shots per area in focus, which result in $< 2 \, mm/s$, at our recording conditions). Lines

![Figure 3. Modifications induced in the volume of fused silica sample with Gaussian laser beam. Top and axial views are shown for separate lines, made at various pulse energies and sample translation speeds. Beam was focused with 0.42 numerical aperture lens 100 $\mu m$ below the surface. Laser repetition rate - 100 kHz.](image)
recorded in these conditions have much lower scattering, but all possess strong birefringence, observed through crossed polarizers.

In contrast, modifications recorded with GB beam have quite different look. In Fig. 4 it is shown cross sections and top views of similar lines recorded at various recording conditions. Lateral diameter of such modification was not larger than in Gaussian beam case; however, axial length increased tenfold and reached around 80-100 µm after single shot. No significant dependence of modification’s axial length on laser pulse energy was observed, implying that axial length is determined only by the choice of axicon (and/or additional focusing optics) according to Eq.1. However, as in Gaussian case, multipulse accumulation plays significant factor in modified line (or in this case – plane) quality. As can be seen from Fig. 4, if pulse density is higher than 2000 pulse/mm (meaning that each modified area is affected with at least 2 pulses), modification track consist of randomly spaced microcracks producing strong scattering. When there is no pulse accumulation, modification bear smooth and regular appearance.

In the picture it is also visible that typical modified track (for example 1.02 µJ at 625 pulses/mm) is also not homogeneous: there is a prominent dark central region surrounded by bright zones at the both sides of the modified track. Bright regions could be linked with the areas where material refractive index is increased (so called Type I modification), where dark regions are linked to the formation of scattering centers in fused silica (Type II modifications). Indeed, these two types of laser-induced modifications are well known to exist in fused silica, which development depend on the laser pulse intensity. By looking at the measured axial energy distribution of GB beam (Fig. 2b) it is clear that central part has twice as large intensity than the slopes, thus explaining the appearance of two different types of modification.

Also filamentation of GB beam should have to be avoided during the recording as it is known to produce scattering bead-like damage tracks along pulse propagation path. Typical example of such damage track is shown Fig. 5.

4. RECORDING OF VOLUME BRAGG GRATINGS

Volume Bragg gratings (VBG) are particular type of phase-gratings embedded into the volume of transparent material. In comparison with other diffraction gratings, VBG have additional dimension of depth (thickness), that can rise diffraction efficiencies even up to theoretical 100%. Having this property, VBG are widely used in many photonic applications. As grating depth/period ratio have to be considerably large, surface Bragg gratings are uncommon, thus traditional grating recording technique relay on photosensitivity of the transparent material where interference pattern from UW cw-laser emission or ultrashort laser pulses are recorded directly in the volume of the material. So far hardened gelatin polymer, photo-thermo-refractive and various types of UV-sensitive phosphate glasses were used as a medium for VBG recording. Femtosecond direct laser writing expanded the range of suitable materials where such devices can be recorded.
Figure 5. An example of bead-like damage appearance along the beam path when GB pulse power is kept above filamentation regime.

Diffraction properties of VBG’s are analyzed by coupled wave model. According to this model, VBG can reach the highest efficiency operating only at the Bragg diffraction conditions, that can be expressed as:

\[ m\lambda/n = 2dsin(\theta_B); \]

where \( \theta_B \) is a so called Bragg angle, \( d \) is a period of the grating, \( \lambda \) the wavelength of diffracted beam, and \( n \) is refractive index of the material where diffraction takes place (see Fig. 6). It is easy to see, that Bragg condition is validated when incident and diffracted angles are equal in absolute values, so angle \( |\alpha_{\text{inc}}| = |\alpha_{\text{dif}}| = \theta_B \).

Figure 6. The dependence of VBG diffraction efficiency on grating thickness for various refractive index modulation levels (left). A sketch of VBG depicting incident (\( I_{\text{inc}} \)), diffracted (\( I_{\text{dif}} \)) and nondiffracted beams (\( I_{\text{ntr}} \)) as well as main grating parameters: incident (\( \alpha_{\text{inc}} \)) and diffracted angles (\( \alpha_{\text{inc}} \)), grating period (\( d \)), and grating thickness (\( t \)) (right).

Diffraction efficiency is defined as ratio between diffracted and incident beam powers and can be expressed by the following formula:

\[ \eta = \sin^2 \left( \frac{\pi \Delta nt}{\lambda \cos(\theta_B)} \right), \]

here \( \Delta n \) is a magnitude of homogeneously modulated refractive index, \( t \) is the grating axial thickness. It easy to see that the product \( \Delta nt \) determines VBG efficiency for single wavelength at Bragg condition (Fig. 6). As laser-induced variations of \( \Delta n \) in non-photosensitive material is somehow limited, grating depth can be easily changed by using multiplexing procedure: stitching several layers of gratings on top of each other using direct laser writing technique. Typical laser induced refractive index variations are in range of 0.001 – 0.005, thus in order to fabricate efficient grating one needs to create grating with thickness of order 80 µm - 400 µm.

If we look at Fig. 7, the advantage of GB beams for VBG fabrication becomes immediately apparent. Using just Gaussian beam will need to fabricate many layers of gratings on top of each other in order to achieve sufficient grating thickness (Fig. 7a), while with GB beam single layer already results in 90 µm thick grating.
Figure 7. DLW approach for formation of thick volumetric Bragg gratings for a) Gaussian and b) Gaussian-Bessel laser beams.

Table 1. VBG recording comparison between Gaussian and GB beams

<table>
<thead>
<tr>
<th></th>
<th>Gaussian beam</th>
<th>Gaussian-Bessel beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period $d$ ($\mu$m)</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Thickness $t$ (/micro m)</td>
<td>90</td>
<td>350</td>
</tr>
<tr>
<td>Total layer number</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Sample translation speed (@100 kHz) (mm/s)</td>
<td>&lt;1 mm/s</td>
<td>20 mm/s (not limited)</td>
</tr>
<tr>
<td>Grating size (mm×mm)</td>
<td>1 × 1</td>
<td>6 × 6</td>
</tr>
<tr>
<td>Recording time (h)</td>
<td>&gt;3</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Diffraction efficiency at Bragg angle (@633 nm)</td>
<td>60%(p)/29%(s)</td>
<td>89%</td>
</tr>
</tbody>
</table>

Diffraction efficiencies of all VBG’s demonstrated in this work were measured using HeNe laser (633 nm wavelength) at Bragg condition. We estimated efficiency by measuring the total power of diffracted beam and compared it to the beam that freely passes through sample when grating is moved out of the beams path. In such configuration absolute efficiency was evaluated and glass absorption and Fresnel reflection loses were automatically eliminated.

The highest achieved diffraction efficiency recorded with GB beam was reached at 633 nm wavelength and was 89%. VBG thickness was 352 µm (formed by 4 layers of 88 µm each) and period – 1.5 µm, hence grating depth/period ratio was 234. Its lateral size was 6×6 mm², which took less than an hour to record with ultra-short GB laser pulses. The smallest period gratings recorded by axial multiplexing of $N = 5$ layers with GB beams was 1 µm.

Gratings made with Gaussian laser beam also show relatively high diffraction efficiencies (~ 60%), however, stronger focusing leads to the formation of Type II modifications with birefringence. Thus diffraction efficiency becomes polarization-dependent. VBGs made from Type II modification can have smaller depths as induced refractive index variation is three times larger if compared to GB case; however this does not help to reduce fabrication time as small modification’s axial length requires higher level of multiplexing ($N > 20$).

Comparison between main recording parameters is given in a Table 1. As can be seen, throughput of VBG recording with GB beams is increased by 40 times, and diffraction efficiency of such gratings are better.

In order to evaluate spectral bandwidth, White Light Continuum (WLC) was shone on the VBGs and spectrum of transmitted (undiffracted) beam was measured in order to evaluate which spectra components were
diffracted, thus absent, from WLC spectrum. These results are shown in Fig. 8. Spectral bandwidth is inversely proportion to grating thickness. As gratings made with Gaussian beam are thinner, its spectral bandwidth ($\Delta \lambda$) is large and could reach up to 150 nm. In comparison, thick gratings made with GB beam has spectral bandwidth $<10$ nm.

5. CONCLUSION

In conclusion we demonstrate that femtosecond Gaussian–Bessel laser pulses can be used for recording extended traces of optical modified material inside transparent dielectrics that could increase the range of possible applications for laser fabrication. Using this technique we fabricated $6 \times 6$ mm$^2$ footprint volume Bragg grating with 1.5 $\mu$m period having diffraction efficiencies of 89% in an hour.

ACKNOWLEDGMENTS

This work was supported by research grant No. VP1-3.1-SMM-10-V-02-007 (Development and utilization of a new generation industrial laser material processing using ultrashort pulse lasers for industrial applications) from the European Social Fund Agency.

REFERENCES


