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Shaping the surface of optical glasses with picosecond laser and adaptive optics

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An application of a liquid-crystal-based spatial light modulator (LC-SLM) for shaping the surface of Borofloat®33 glass is presented. In this approach, high-repetition-rate picosecond laser pulses of wavelength 515 nm are patterned with an SLM, and delivered to the workpiece in order to generate specific surface deformations. Since optical glasses such as Borofloat®33 are transparent to visible light, the glass surface is coated with a thin layer of graphite prior laser treatment in order to increase absorption of the workpiece, so that localized melting of the glass surface is obtained. In this paper, we also investigate the interaction of the graphite-coated glass with nanosecond laser pulses, showing that it is possible to produce simple diffractive optical elements, e.g., sinusoidal gratings with a 25 µm spatial period, using 65 ns laser pulses at a 1064 nm wavelength.

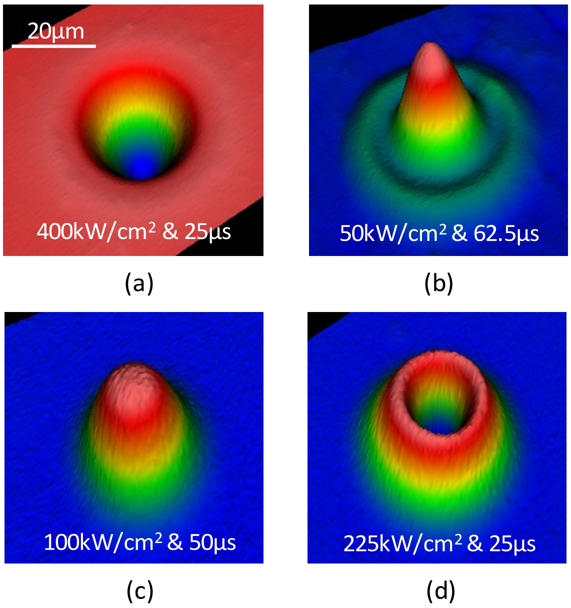
Keywords: glass, surface modification, nanosecond laser, picosecond laser, spatial light modulator

1. Introduction

Direct removal (ablation) of a solid material using lasers is far from ideal if optical quality surfaces are required, since such a material removal process creates a surface containing micron-scale roughness which significantly scatters incident light. In order to overcome this problem, it is better to use laser machining conditions which give melting but not ablation, and hence can create optically-smooth surfaces. One example of such an approach is the YAGboss process [1], which was developed by the High Power Laser Applications group (Heriot-Watt University, UK) and its industrial partner – Renishaw Plc (UK). In this process, UV nanosecond laser pulses are delivered to the metal workpiece in order to locally melt its surface, and via a localized melt flow process generate depressions with a well-controlled depth. The flow of the melt in this process is driven by the laser-induced gradient of surface tension. By synchronizing laser pulses with precise movement of the workpiece, the YAGboss process has been used to generate sinusoidal gratings with the spatial period of 8 µm, which further are used as scales in high precision optical position encoders.

Even though the YAGboss process is established for metals, e.g., Chromflex® stainless steel, currently it cannot be used for optical glasses because these materials are highly transparent in the UV range. However, the relatively high absorption and low reflectivity of optical glasses at the 10.6 µm wavelength suggests that a CO_2 laser is the ideal laser tool for shaping the surface of these brittle materials. Although many features, e.g., craters, rings, dome-shaped bumps, sombrero-shaped bumps, can be produced using such a laser, as shown in Fig. 1 [2], the relatively long wavelength means that the laser spot size is limited to tens of microns, and thus it is very difficult to generate surface features which are smaller than approximately 30 µm in diameter. Therefore, we have developed a novel technique which allows laser light with a shorter wavelength (1 µm or less) to be used for machining glass.

In this process, a thin layer of graphite is deposited onto the glass surface prior to processing with either nanosecond



(a) (b)
(c) (d)

Fig. 1 Various surface deformations produced by a single CO_2 laser pulse: (a) crater in fused silica (HPFS®7980, Corning), (b) sombrero-shaped bump in lead-silicate glass (SF57, Schott AG), (c) dome-shaped bump, and (d) ring in borosilicate glass (Borofloat®33, Schott AG). Peak irradiance and pulse duration embedded in figures.

or picosecond laser pulses. The aim of this work was to produce sinusoidal gratings with a spatial period of less than 30 µm, which cannot be readily achieved with a CO_2 laser beam. In addition, we demonstrate the use of a liquid-crystal-based spatial light modulator (LC-SLM) for parallel processing the glass surface.

2. Nanosecond laser treatment of Borofloat®33 glass

Fig. 2 shows the experimental setup used for processing Borofloat®33 glass. Here, we used a fiber-coupled, diode-pumped, Q-switched $Yb:YVO_4$ laser (from Spectra-Physics Lasers Inc.) that generates 65 ns laser pulses with a maximum rep-rate of 100 kHz and an average output power of up to 35 W. This laser operated efficiently at two different wavelengths: 532 nm and 1064 nm. The laser beam was delivered to the target via a galvo-scanner equipped with either a 125.1 mm or 108.5 mm focal length flat field (F-theta) lens, respectively for a wavelength of 1064 nm and 532 mm, giving a focal spot of approximately 20 µm in diameter. Borofloat®33 (Schott AG, Germany) was used as a workpiece. This is a commonly-used glass, and we found in our earlier research [2] that this material has a tendency to 'bump' when sufficient local heat is generated at its surface (e.g. using a CO_2 laser beam). Moreover, this glass has a relatively low coefficient of thermal expansion (CTE = 3.3 ppm/K), and thus there is low risk of material cracking when cooled rapidly following laser irradiation.

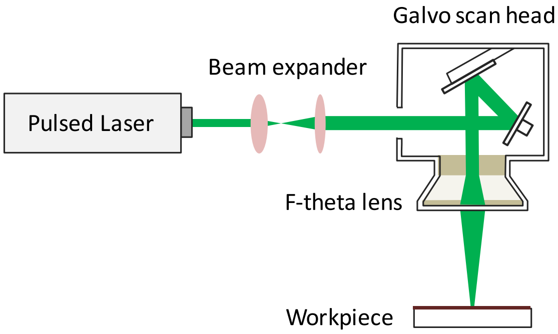


Fig 2 Experimental setup used for processing Borofloat®33.

The focused laser spot was scanned across the surface for a range of different speeds and powers. In the first attempt, we tested the ability of nanosecond laser pulses to generate deformations on the surface of 'as-manufactured' glass. The focused laser spot was scanned across the surface of the workpiece for various laser machining conditions. Different values of the laser power were tested ($P = 0.5 – 10$ W) for a range of different speeds ($v = 1, 2, 5, 10$, and 20 mm/s), pulse repetition rates ($f = 15$ and 100 kHz) and wavelengths ($\lambda = 532$ and 1064 nm). However, in all of these cases, there was insufficient absorption to melt or ablate the glass surface without material cracking, which started to appear at $P = 3$ W.

In order to enhance absorption of the glass we sprayed a thin layer of graphite (Graphit 33, Kontakt Chemie) onto the glass surface prior to laser irradiation. This approach allowed shallow grooves to be produced at the workpiece without material cracking, for an average laser power of less than 5 W. Following laser treatment, the glass surface was cleaned with isopropanol in order to remove the residual graphite, and then the 'transparent' sample was annealed for one hour at a temperature of 560°C in order to release glass from the laser-induced stress.

Fig. 3 shows 25 µm wide grooves which were produced by local ablation (evaporation) of the glass, using nanosecond laser pulses at $\lambda = 1064$ nm, $f = 15$ kHz, $P = 3$ W, and $v = 10$ mm/s. The average depth of the grooves was measured to be approximately 40 nm. This measurement was obtained with the Zygo non-contact 3D surface profilometer. Small lobes around the grooves suggest that either re-solidification or local melting of the glass has occurred at its surface.

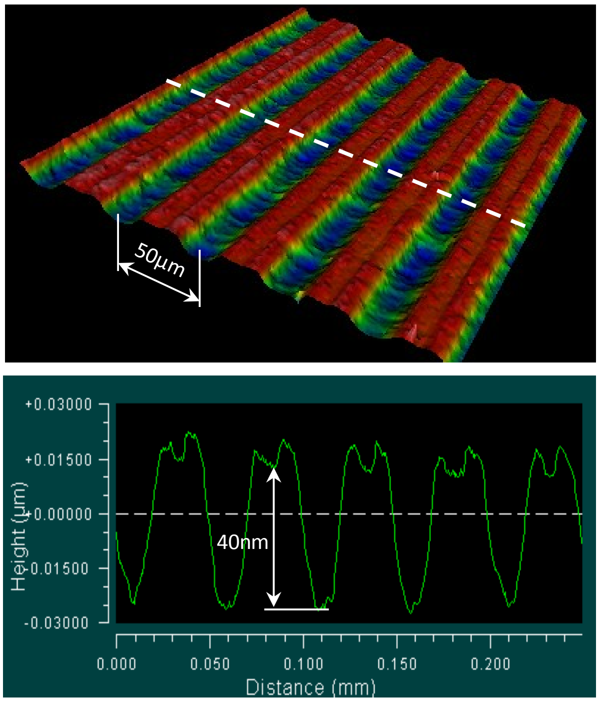


Fig. 3 Grooves produced at the graphite-coated surface of Borofloat®33 glass using nanosecond laser pulses. An average laser power and scan speed were: $P = 3$ W and $v = 10$ mm/s. Profile was taken when the residual graphite had been removed using isopropanol and then the sample had been annealed at 560°C for one hour.

By applying a 25 µm pitch (Δx) between the laser scans, it was possible to produce sinusoidal gratings, as shown in Fig 4. In this case, the grating was produced using the same wavelength and pulse repetition rate as before, but the laser power and speed was reduced to 0.5 W and 1 mm/s, respectively. Since the scan speed was much lower than that used for producing the grooves shown in Fig. 3, the depth of individual grooves was increased, giving the peak-to-valley (P-V) value of approximately 165 nm. The rms value along the laser-scanned tracks was measured to be less than 25 nm.

By increasing the laser power and scan speed to 2 W and 2 mm/s, respectively, it was possible to produce a sinusoidal grating with the P-V value of 280 nm. In this structure (not shown in this paper), the average rms value along the laser-scanned lines was less than 30 nm. When

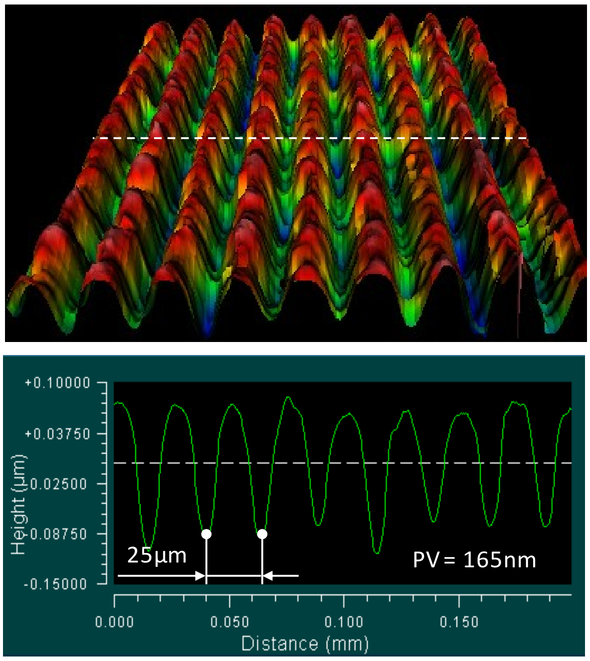


Fig. 4 Sinusoidal grating produced at the surface of Borofloat®33 glass using nanosecond laser pulses. Laser machining conditions were: P = 0.5 W, v = 1 mm/s, and Δx = 25 µm.

this grating was illuminated with the light from a laser pointer, it produced a diffraction pattern consistent with the theory. This means that sinusoidal gratings produced by nanosecond laser pulses may be used as optical components.

3. Picosecond laser treatment of Borofloat®33 glass

An identical experimental procedure to that described in Section 2 was applied to study the interaction of picosecond laser pulses with the same Borofloat®33 glass. The laser source used was a thin-disk laser (TruMicro 5x50, Trumpf) that generated 6 ps laser pulses at a maximum repetition rate of 400 kHz. This laser operated at three different wavelengths: λ = 343, 515, and 1030 nm. As before, we used a galvo scanner to generate a moving laser beam. The spot size at the target was in the range of 10 - 30 µm (measured at its $1/e^2$ intensity), depending on the laser wavelength used. In order to control accurately the value of the output laser power without affecting the laser operation, a half-wave plate and a polarizing beam splitter were introduced to the setup shown in Fig. 2. These optical components were placed between the laser output and the beam expander.

No melting effect was observed at the surface of ‘as-manufactured’ glass. However, craters and fractures were easily produced by picosecond laser pulses, independently of the laser wavelength used. In the case when the glass surface was covered with a thin layer of graphite, it was possible to produce ridges with a moving laser spot, as can be seen in Fig 5 (a). Unfortunately, the aspect ratio (height/width) of these surface features was relatively low, i.e., not greater than 1/250.

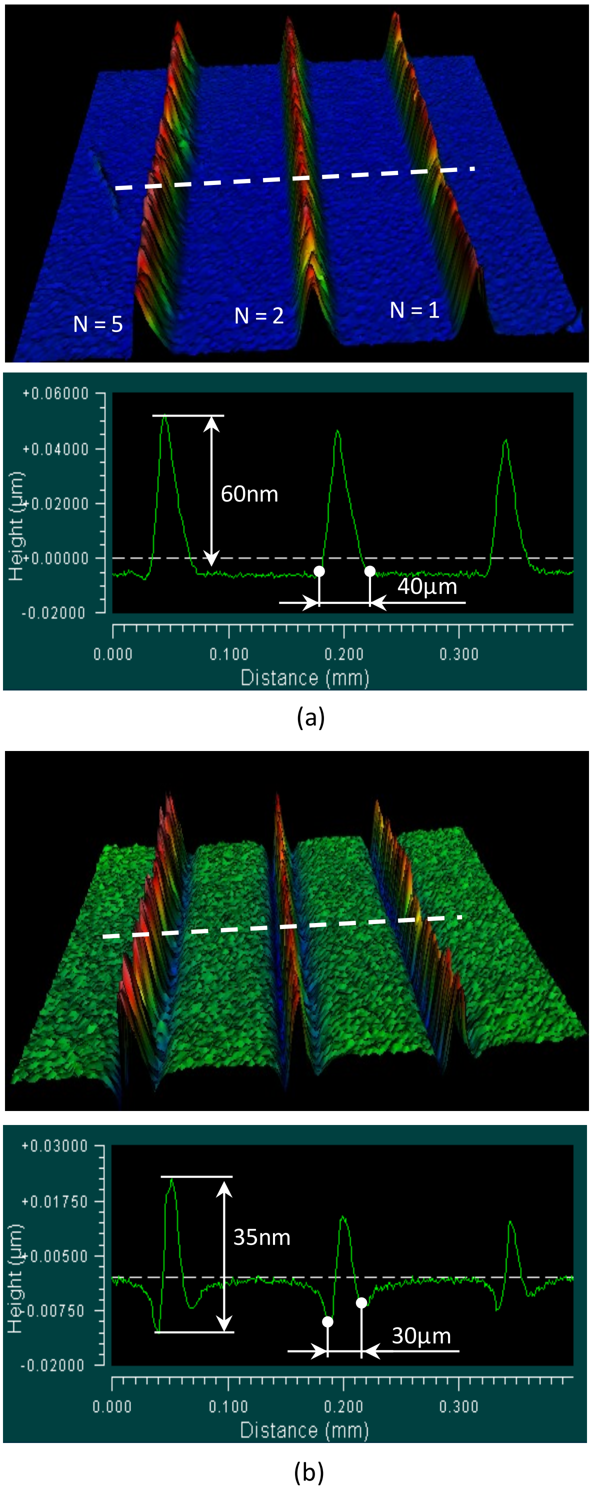


Fig. 5 Ridges produced by a 30 µm diameter laser beam moved along the line track with a 2 mm/s speed, using 6 ps laser pulses, 400 kHz pulse rep-rate, 150 mW average laser power, and 515nm wavelength. Profile of the ridges was taken: (a) before and (b) after annealing for one hour at 560°C. The residual graphite layer was removed before measurement. N value stands for a number of laser scans.

In general, the ridges were found to be produced by local melting of the glass surface. We recognized two mechanisms which were involved in the formation of these deformations. The first is called the Marangoni effect in which flow of the melt is driven by the gradient of surface tension that creates either depressions or protrusions, depending on whether the gradient is negative or positive [3]. In our case, the gradient of surface tension was positive because the melt was pulled towards the centre of the laser-irradiated area (the hottest site). As found in the literature [4, 5], the positive gradient of surface tension of SiO_2 and B_2O_3 melts (i.e. main components of Borofloat®33 glass) results from the oxides that dissociate with temperature.

The second mechanism that causes the formation of ridges is the so-called fictive temperature effect, which can result in localized changes in density and hence volume. The fictive temperature is a term proposed by A. Tool in 1946 [6], who suggested that glass which is cooled through the transformation range has an identical frozen-in structure as that of its melt at some equilibrium temperature. Depending on the cooling rate of glass in the transformation range, the glass network undergoes either faster or slower structural change, and thus the value of fictive temperature is modified. In general, glass cooled rapidly has a higher fictive temperature than the same glass cooled down more slowly. Commercial glasses have fictive temperatures between the strain point and the annealing point because they are cooled slowly in the manufacturing process. However, the value of fictive temperature can be increased (up to the softening point) if glass is re-heated above the annealing point, and then is cooled with a high cooling rate. Since glass in our experiment was cooled with a very high cooling rate during laser treatment, this material surely gained a high value of the fictive temperature within the laser-irradiated area, and thus some physical properties of the glass (e.g. refractive index, density) has been modified in this region. As reported by Bennett *et al.* [7], an increase of fictive temperature in many silicate glasses causes a decrease of the glass density. This means that the glass volume increases and deformations in the form of bumps or ridges are produced at the glass surface, as happened in our experiment.

Fig. 5 (a) shows the surface profile of three ridges produced by a 150 mW average power, 30 µm diameter laser beam focus (at λ = 515 nm) moving at a speed of 2 mm/s. The ridges are 60 nm tall and their shape results from both the Marangoni effect and a local increase of the fictive temperature within the laser-irradiated area. Once the glass sample was annealed at a temperature of 560ºC for one hour, using a low cooling rate of 2ºC per minute, the height of the ridges was reduced, as shown in Fig. 5 (b), resulting in no overall change in the glass volume compared with the original sample. This is because the annealing process restored the low value of the fictive temperature which had been originally gained during the manufacturing process of this glass. The remaining deformations are therefore those generated by the Marangoni effect.

4. Parallel shaping the glass surface with LC-SLM

The strong interaction of the picosecond laser pulses with the Borofloat®33 glass, as presented in the previous section, encouraged us to test a liquid-crystal-based spatial light modulator (LC-SLM) for parallel shaping of the glass surface at a wavelength of 515 nm.

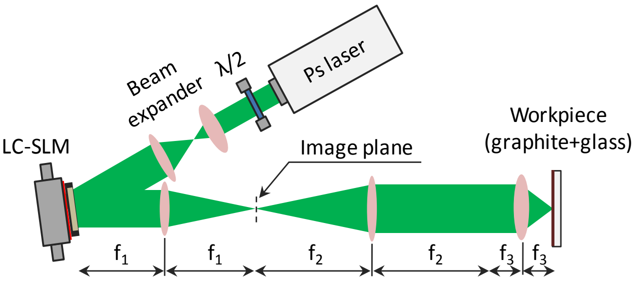
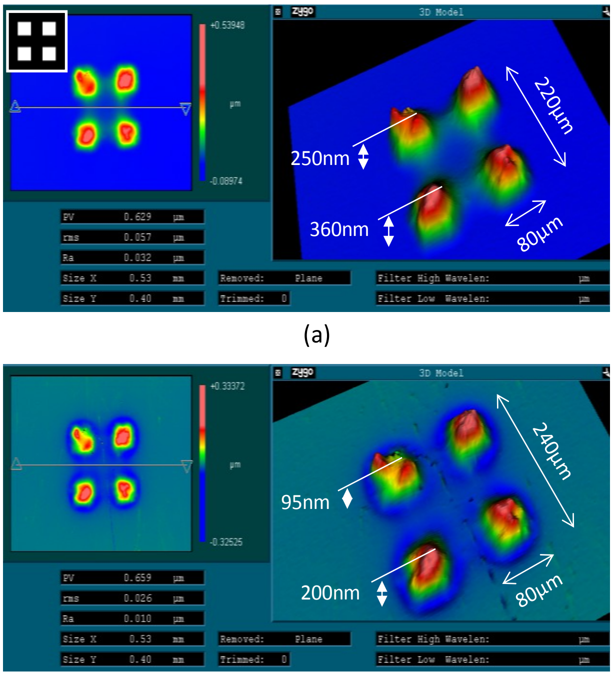


Fig. 6 Experimental setup used for parallel shaping the glass surface with the LC-SLM.

Fig. 6 shows an experimental setup used for shaping the glass surface with a LC-SLM. Here, picosecond laser pulses are delivered to the SLM display (model LC-R 2500 from Holoeye) via a rotatable half-wave plate in order to obtain the most efficient operation of the LC-SLM. The SLM display has a resolution of 1024 × 768 pixels with a pixel size of 19 × 19 µm. In this arrangement, the SLM works like a programmable diffractive optical element. The image produced by the SLM is delivered to the workpiece using a 6-f optical system. In addition to the diffracted light, approximately 50% of the incident laser power was undiffracted [8], causing unwanted damage to the glass surface. To prevent this damage, the undiffracted beam was blocked by creating a spatial filter at the first image plane (the FL of the first lens) using a thin silver wire with a rounded end.

Fig. 7 shows four bumps with square-shaped bases that were produced simultaneously by a 13.33 ms train of 6 ps laser pulses, using a 400 kHz pulse repetition rate and an average output laser power of 3.4 W. The profile of these



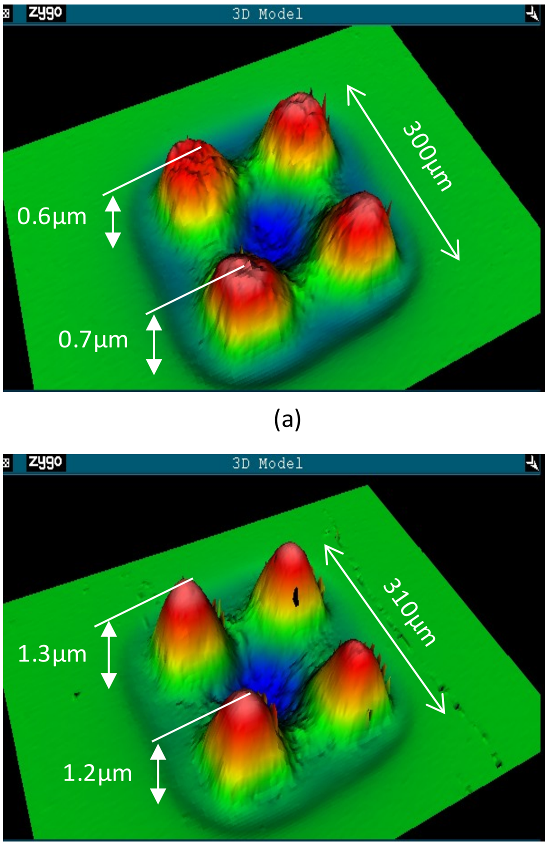
PV 0.629 µm
rms 0.057 µm
Ra 0.032 µm
Size X 0.53 mm
Size Y 0.40 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: µm
Filter Low Wavelen: µm

(a)

PV 0.659 µm
rms 0.026 µm
Ra 0.010 µm
Size X 0.53 mm
Size Y 0.40 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: µm
Filter Low Wavelen: µm

(b)

Fig. 7 Four bumps with the square-shaped bases that were produced simultaneously by a single 13.33 ms train of 6 ps laser pulses, using the LC-SLM that was illuminated with the average laser power of 3.4 W. The surface profiles were taken: (a) before and (b) after annealing the glass at 560ºC.



(a)

(b)

Fig. 8 Impact of the laser exposure time on the size of the SLM-generated bumps. An average laser power used was 6.5 W, whereas the laser exposure time was: (a) 13.33 ms and (b) 213.28 ms (16x13.33 ms).

bumps was taken: (a) before and (b) after annealing the glass at 560ºC. The height of the bumps was between 250 and 360 nm before annealing and between 95 and 200 nm after annealing. The difference in height between the bumps probably results from the non-uniform intensity distribution of the laser beam within the laser-irradiated area. In general, the shape of the bumps is consistent with the target image design which is shown in the top-left corner of Fig. 7 (a).

As presented in Fig. 8, the height of bumps can be increased by using either a higher average laser power or a larger number of laser pulses. In the case of multiple laser exposure, we applied a speckle reduction technique. This method relies on shifting a computer-generated hologram (CGH) between exposures in order to reduce the speckle interference generated by the LC-SLM. This technique was reported in details by Golan and Shoham in [9].

Finally, a sinusoidal grating generated by picosecond laser pulses and the LC-SLM is shown in Fig. 9. This grating was produced at an average laser power of 6.5 W, using four laser exposures (4×13.33 ms). Although the spatial period of this structure is quite large ($\Lambda = 60$ µm), this is another example of the application of a LC-SLM for shaping the glass surface using a thin layer of graphite sprayed onto the workpiece prior its laser treatment.

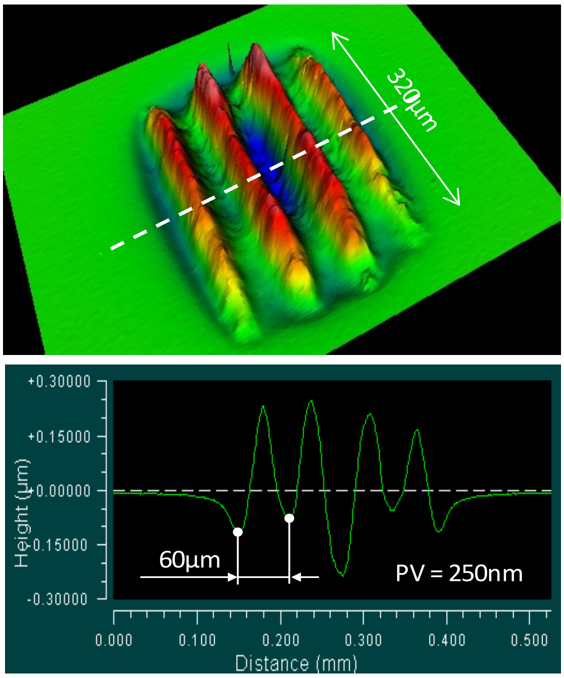


Fig. 9 Sinusoidal structure produced at the surface of the graphite-coated Borofloat®33 glass by the LC-SLM, using 4 x 13.33 ms laser exposure. An average laser power delivered to the SLM display was 6.5 W.

5. Conclusions

This paper has shown a pioneering approach for shaping the glass surface using a short-pulsed laser and a LC-SLM. By applying graphite onto the glass surface, we generated structures which normally cannot be obtained by a laser source operating in the spectral range between 343 and 1064 nm. Although CO_2 lasers are still the most efficient laser sources for shaping the glass surface, they cannot produce structures with feature sizes of less than 20-30 µm. In this paper, however, it has been shown that a sinusoidal grating with a 25 µm spatial period can be readily produced by nanosecond laser pulses at a wavelength of 1064 nm. Even though our laser-based shaping method still requires further investigation and improvement in terms of the surface quality and resolution of the laser-machined structures, it has potential industrial application for rapid manufacturing structures and optical components.

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