

Optics Letters

Optical structuring and finishing toward mid-spatial-frequency error reduction using femtosecond lasers

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We demonstrate nano-structuring and the reduction of mid-spatial-frequency errors using femtosecond laser figuring and finishing. For the first time, to the best of our knowledge, we have corrected mid-spatial-frequency errors from 17 nm to one nanometer in magnitude. We established a method for creating and predicting periodic nanostructures. This demonstration opens the path of using femtosecond lasers to correct surface errors that inherently result from sub-aperture manufacturing techniques.

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Sub-aperture manufacturing techniques have been widely used for fabricating high-precision optical components, such as freeform and aspherical surfaces, for compact and high-performance imaging systems. Deterministic sub-aperture polishing locally removes a material using a small tool. The material is removed using dwell-based algorithms based on the initial surface figure and tool influence function. However, surfaces manufactured with these sub-aperture techniques, such as diamond turning, grinding, and magnetorheological finishing, can leave residual periodic ripples, or mid-spatial-frequency (MSF) surface errors, which can be a spiral, a spoke, or a raster pattern, depending on the sub-aperture tool path [1]. The periodicity of MSF errors is in the sub-millimeter to millimeter range [2]. Small-angle scatter from the MSF errors degrades the achievable resolution of imaging systems [3]. For laser applications, the MSF-error-induced diffraction patterns can turn into intensity modulation, causing downstream optic damage [4]. Thus, it is important to mitigate or remove MSF errors in manufacturing precision optics.

The magnitude of MSF errors can be reduced by either optimizing processing algorithms during fabrication or employing post-processing methods. However, most strategies are limited because of the slope variations on freeform or aspheric surfaces. Owing to their non-contact, no chemistry waste, and flexible nature, lasers are an attractive alternative to correct MSF errors. Previous works, such as surface micro-structuring by remelting [5–7], laser-induced plasma micro-machining [8], and pulsed

laser ablation [9], have been used for creating and controlling surface structures. However, these methods are typically used for micrometer-level structuring; therefore, they cannot precisely correct MSF errors that are often less than 1 μm . Moreover, some methods require complex physical modeling of laser ablation [9,10] or material ejection [11] to predict the resulting surface structures. Continuous-wave and longer pulse laser processing have been used for polishing and form correction, but the resulting surfaces come with subsurface damage and heat-affected zone [12]. Femtosecond (fs)-laser processing enables nanometer-precision material removal without inducing thermal melting and subsurface damage [13,14]. Deterministic material removal guided by deposited energy density can be tailored to correct different surface form errors. High processing quality with a sub-nanometer optical surface can be achieved by simultaneous surface figuring and finishing using a femtosecond laser [13]. It is, therefore, a promising technique for MSF error mitigation.

In this Letter, we demonstrate controllable surface topography creation and MSF error correction through simultaneous surface figuring and finishing of a Borofloat 33 (BF33) glass using a femtosecond laser. We have achieved controllable shape correction with nanometer precision and single-digit-nanometer surface roughness after the MSF error correction.

An ytterbium fiber laser with a central wavelength of 1030 nm and a pulse duration of 300 fs is used to process a BF33 substrate. The pulse energy is up to 40 μJ with a standard deviation of 0.12%.

The laser beam is focused perpendicularly onto the top surface of a substrate using a confocal imaging setup [13]. The focused laser beam raster scans the substrate positioned by high-precision three-axis translation stages (Jenny Science, Lxc 80F40) with a resolution of 100 nm. Pulse energies are precisely controlled by a motorized attenuator within a beam shaper (LASEA, LS-Shape). To ensure a constant pulse energy deposition during laser processing, a control program in LabVIEW was developed to integrate the motion of the stages and the laser on/off signals. The focal spot diameter was determined as 11.8 μm (at $1/e^2$ of the peak intensity) using single-pulse ablation experiments [15].

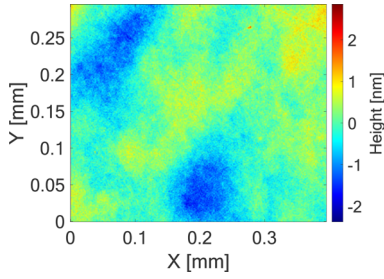


Fig. 1. White light interferometry of the initial BF 33 surface.

We investigate the nano-structuring of the BF33 using the femtosecond laser. The pristine BF33 glass substrate has a surface flatness of $4\text{--}6\lambda$ ($\lambda=633\text{ nm}$) and a surface roughness of 0.5 nm in root mean square (RMS). Figure 1 shows the surface map of an unprocessed surface, measured by a white light interferometer (Zygo NewView 600). The substrate has a dimension of $10\text{ mm} \times 10\text{ mm} \times 1.7\text{ mm}$. The bandgap energy of the BF33 is 4.0 eV , determined by a Tauc plot of optical transmission spectroscopy data [16,17].

To demonstrate the correction of MSF errors using fs laser technology, we performed controlled ablation experiments with a femtosecond laser. This laser was employed to both generate and eliminate periodic structures. The processing was conducted at the $10\text{--}50\text{ kHz}$ repetition rate and $1\text{--}20\text{ mm/s}$ scanning speed. The polarization direction is in parallel with the scan direction.

The resulting periodic patterns effectively simulate MSF errors, with a typical frequency range spanning from $100\text{ }\mu\text{m}$ to 1 mm . The choice of a periodic pattern over a random one was deliberate, as the precision required for positioning the former can be accommodated by our femtosecond laser processing system within a university laboratory environment.

Initially, we established a groove through laser ablation, which functions as a foundational element for the creation and removal of the periodic patterns. The groove was generated by raster scanning the focused laser beam, resulting in an ablated area. This area scan was formed by overlapping multiple line scans (70% overlap), each measuring a width matching the diameter of the laser's focal spot. The actual groove width is determined by the width, number of lines, and separation of the scan lines. The theoretical groove depth is determined by the removal depth per scan and number of scans. The actual groove profile is measured using a white light interferometer.

Figure 2(a) illustrates the surface map of a laser-ablated groove, measuring $0.2 \times 0.1\text{ mm}^2$. The surface roughness is approximately 0.5 nm in root mean square (RMS) in both the processed and unprocessed regions. Figure 2(b) shows the corresponding horizontally integrated vertical line profile plotted along the vertical direction using the mean value along the horizontal direction. The removal depth is 21.6 nm , and the width defined as the full width at half maximum valley is $103\text{ }\mu\text{m}$. The ratio of the ablated-groove width to the specified width is 1.03, which was used as a correction factor.

Periodic patterns can be created by overlapping a series of laser-ablated grooves with a designed groove spacing. The spacing is equal to the periodicity of the pattern to be generated. A periodic structure consisting of $2n + 1$ single grooves can be predicted by Eq. (1):

$$h_{2n+1} = h_s(x) + h_s(x + d) + h_s(x - d) + \dots + h_s(x + n \times d) + h_s(x - n \times d). \quad (1)$$

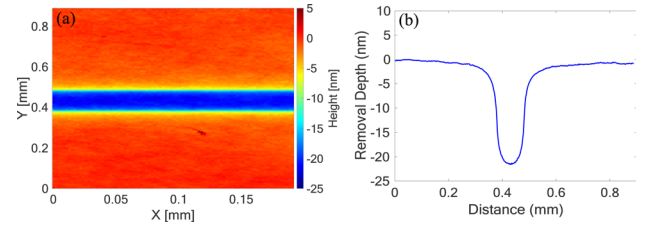


Fig. 2. (a) Surface profile of the laser-ablated groove and (b) horizontally integrated line profile.

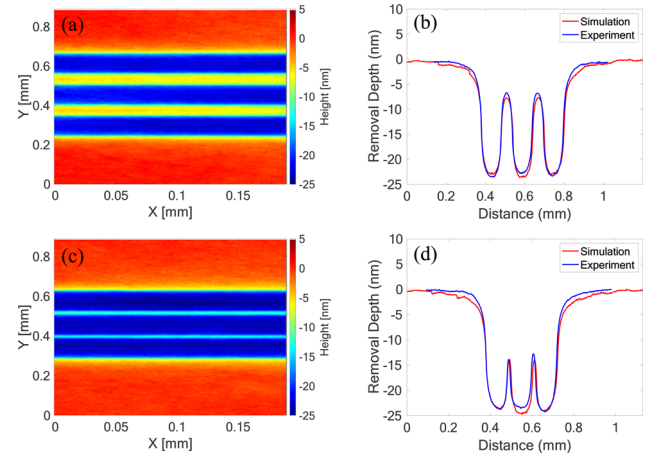


Fig. 3. (a) and (c) Surface map of two periodic grooves with spacings of 160 and $120\text{ }\mu\text{m}$, respectively; (b) and (d) overlays of experimentally achieved and theoretically predicted surface profiles with spacings of 160 and $120\text{ }\mu\text{m}$, respectively.

Here, $h_s(x)$ represents the single groove profile experimentally created and measured, d is the designed groove spacing, and $2n + 1$ is the number of grooves.

Periodical patterns with groove spacings of 160 and $120\text{ }\mu\text{m}$ were created by the fs laser. Figures 3(a) and 3(c) show the surface maps of two laser-created periodic structures with a 160 and $120\text{ }\mu\text{m}$ spacing, respectively. Figures 3(b) and 3(d) show the corresponding horizontally integrated line profiles, overlaid with the simulation predictions. The experimental and simulation predicted results [Figs. 3(b) and 3(d)] show excellent agreement, demonstrating the controllability of creating predictable periodic nanostructures using a femtosecond laser.

The influence of the groove spacing on the resulting periodic structure was further analyzed. The geometry and morphology of the resulting periodic structures depend on the single-groove shape and the spacing between adjacent grooves. The pillar height decreases from 16.5 to 10.5 nm (peak-to-valley), and the width decreases from 58 to $20\text{ }\mu\text{m}$ (FWHM) when the groove spacing reduces from 160 to $120\text{ }\mu\text{m}$.

To demonstrate the fs-laser-based MSF error correction, we first use the femtosecond laser to generate periodic grooves with a sub-millimeter periodicity. The groove width and center-to-center spacing between two adjacent grooves were set as 100 and $200\text{ }\mu\text{m}$. Figures 4(a) and 4(b) show the laser-created sinusoidal pattern with five cycles/mm and the corresponding line profile (horizontally integrated), respectively. The surface measures a peak-to-valley (PV) height of 17 nm and a pillar width of $97\text{ }\mu\text{m}$ (FWHM).

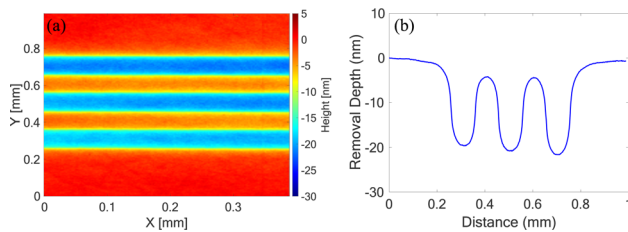


Fig. 4. (a) Surface profile of the generated sinusoidal pattern and (b) horizontally integrated line profile.

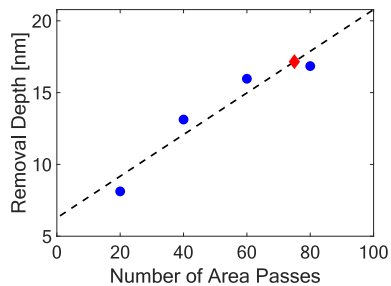


Fig. 5. Removal depth linearly increases with the number of area passes (blue dots), and the red diamond represents the number of passes required to remove the peaks of the sinusoidal pattern.

To remove each individual pillar, we constructed a laser-ablated groove by matching the pillar's size and location. The groove generated by area scan has the same width and location as the pillars in the periodical pattern. The required groove depth was further determined by performing a set of area scans ($0.8 \text{ mm} \times 0.1 \text{ mm}$) with an increasing number of passes. The material removal depth in relation to the number of area passes was characterized, and a linear relationship was derived [Fig. 5]. The deterministic material removal with nanometer-scale precision [13] was then performed to remove the sinusoidal pattern. Seventy-five passes of area scans were performed to remove the peak value of 17 nm.

Figures 6(a) and 6(b) respectively show the surface profile and the corresponding line profile after fs laser shape correction. The MSF pattern with a peak-to-valley of 17 nm is reduced to 1.4 nm. A complete PV reduction is achievable with further parameter optimization. Figures 6(c) and 6(d) show the intensity distribution maps of the unprocessed and processed areas, determined by an optical microscope. The uniform reflectance across the processed and the unprocessed regions indicates that the surface quality has been maintained after shape correction. We note that there was no detectable subsurface damage in the BF33 glass samples that we previously processed using the similar laser parameters [14]. Other effects of this technique on optical elements will be investigated in the next phase of our work.

In conclusion, we have demonstrated controllable nanostructure creation and MSF-like error correction on a glass material, BF33, using fs laser processing. This selective and deterministic material removal reduces mid-spatial-frequency-like errors to the single-digit-nanometer level in magnitude, resulting in an optical-quality surface. This demonstration opens the path

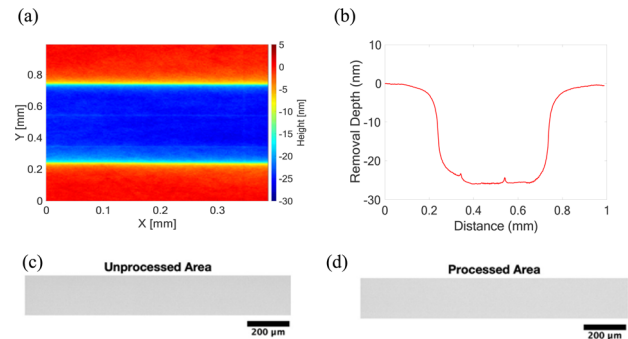


Fig. 6. (a) Surface profile across the processed and unprocessed areas after fs laser correction and (b) horizontally integrated line profile. The intensity maps of the (c) unprocessed and (d) processed areas.

of optical nano-structuring and MSF correction using fs laser processing. Additionally, the ability to create desirable surface topographies makes the method promising for fabricating integrated photonic and laser devices.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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