Mirror Surface Nanostructuring via Laser Direct Writing—Characterization and Physical Origins

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The addition of an optically absorptive layer to otherwise standard dielectric mirrors enables a set of laser direct writing nanostructuring methods that can add functionality to such mirrors while retaining their high reflectivity. A thorough characterization of this method is given in this paper, and its physical origins are investigated. In particular, these measurements show that laser direct writing of such mirrors has a reversible and a permanent component. The reversible process originates from the thermal expansion of the surface and allows a simple yet precise way to temporarily modify the shape of the mirror. Scanning electron microscope cross-sectional images suggest that the permanent part of the nanostructuring process is due to thermally induced pore formation and enlargement in the tantalum oxide layers of the used dielectric mirror.

1. Introduction

The ability to manipulate the surface profile of dielectric mirrors while maintaining high reflectivity is key to effectively controlling the transverse flow of light in high-finesse optical microcavities.[1] Known methods for creating such profiles include focused ion beam milling,[2,3] laser ablation,[4] and controlled buckling.[5,6] The former two involve substrate milling, followed by dielectric stack coating, while in the latter a polymer is introduced into select regions within the stack, causing local delamination upon thermal annealing. A drawback of these methods is that they require time-consuming and expensive cleanroom procedures. This issue is overcome in a recently demonstrated optical nanostructuring method that uses laser direct writing on dielectric mirrors with an additional absorptive layer to routinely create surface structures with angstrom-level precision.[7] This method preserves the high reflectivity of the mirrors, as was previously demonstrated by cavity ring down measurements.[7] In this paper, we detail our implementation and advances to this method, perform time-resolved measurements of the process, and analyze its physical origins.

Thanks to this novel nanostructuring method, open-access optical microcavities have become a very flexible platform for experiments with two-dimensional photon gases, in particular, for the study of lasing phenomena and photon Bose–Einstein condensation (BEC).[8–13] A major future application of such systems may be spin glass simulation, allowing the system to be used as a computing platform.[14] Furthermore, the study of polaritonic quantum gases based on open cavities[15,16] may benefit from this method. Beyond studying optical condensation phenomena, nanostructuring of high-reflectivity mirrors via laser direct writing may also find novel applications in areas such as cavity ring-down spectroscopy,[17] wavefront shaping,[18] and precision interferometry[19,20] (and references therein).

In addition to the permanent modification of mirror surfaces, it is also desirable to perform time-dependent control over the transverse flow of light in microcavities. Mirrors with integrated piezo arrays,[21] heater arrays,[22] and electrostatic membranes[23] may be used for this purpose. As in the previously discussed case of permanent nanostructuring,[7] absorptive layers in the mirror also offer a solution to the problem of time-dependent control. This includes refractive-index tuning via laser writing of the thermo-responsive polymer poly(N-isopropylacrylamide) (pNIPAM)[24] added to the cavity medium, and thermal expansion of the mirror surface, which will be demonstrated in this paper. The former introduces an attractive potential, while the latter creates a repulsive potential. Since both techniques work on different timescales, they may be used in a complementary manner. Additionally, a certain degree of spatial complexity can be introduced by wavefront shaping the heating laser.

The dielectric mirrors used in this work are produced using ion beam sputtering (IBS), and have the following composition: a fused silica substrate, atop which lies an optically absorptive amorphous silicon layer of 30 nm thickness, followed by a quarter-wave dielectric stack with a reflectivity maximum at a wavelength of 600 nm. In most measurements presented in this work, this dielectric stack consists of 20 pairs of Ta₂O₅ and SiO₂. However, we also evaluate thinner dielectric stacks with 11 and 10 pairs. The essential point of this mirror design is the absorptive Si layer that provides a way to locally heat the dielectric stack and the optical medium using laser light—which is the basis of all the phenomena we show in this paper. In the first part of this work, we will demonstrate that such mirrors...
enable highly precise methods for permanently and temporarily changing the mirror surface. In the further course of this work, we will explain the physical origins of the method in more detail.

2. Point-Like Surface Structures

A schematic of the laser direct writing setup is shown in Figure 1a. It consists of two main parts: a white light Mirau interferometer used for obtaining the mirror surface height profiles, and the direct laser writing part. A 200 mW continuous wave (CW) laser operating at 405 nm is used as the writing laser, impinging on the sample mirror from the front side with an estimated beam waist (FWHM) of 1.39 µm. An initial investigation of the nano-structuring procedure is performed by writing a series of point-like structures while varying focus position and pulse duration. The writing order is somewhat randomized to prevent systematic errors. For each set of points, interferometric surface scans were performed both before and after the writing, with the analysis performed on the height difference in order to minimize the effect of the residual mirror surface roughness. Figure 1b shows the height map and reflected light intensity in two distinct cases: at the top, a point-like surface structure of ≈25 nm height, and at the bottom an example of a locally destroyed mirror, which may occur for sufficiently high irradiance. The height profiles of the point-like structures are generally observed to follow a Gaussian distribution with a certain lateral extent.

First, we examine the dependence of the structure height and lateral size on the laser beam focus position relative to the mirror surface, see Figure 1c,d, respectively. Six characteristic pulse durations are used. Both figures show a symmetry axis around a focus position of z = −3 µm, which is close to the location of the Si layer. Varying the focus position affects the writing process by altering the beam width at the position of the thin silicon layer (shown as a second x-axis in Figure 1c), and thus the irradiance. Writing in focus with sufficiently long pulses locally destroys the mirror, which results in missing or scattered data points. The smallest achievable lateral structure size is 3.5 µm (FWHM), which is roughly three times larger than the laser beam focus size. Overall, the lateral size of the written structures is somewhat independent of the diameter of the writing beam at the silicon layer. In particular, the minimum achievable feature size does not seem to be limited by the beam diameter. Four focus positions are chosen for further calibration: z = −2, −9, −25, and −40 µm, in the following text they are referred to as “calibration foci,” as marked by triangles on the focus position axis.

The dependence of the structure height on the pulse duration for the four calibration foci is shown in Figure 1e. For near-focus writing (z = −2 µm), the curve is incomplete because for the given laser power, pulse durations longer than 0.2 ms have a chance of causing local destruction to the mirror, as seen in Figure 1b bottom. Such events eject material from the mirror which lands in the surrounding area, contaminating other structures. The spread of observed point heights just before

Figure 1. Point-like surface structures. a) Schematic of the laser direct writing setup. b) Height map (left) and local reflectivity (right), of two written point-like structures. The upper structure is a typical example of a written point and its height profile follows approximately a Gaussian function. The bottom example shows a locally destroyed mirror as a result of excessive irradiance and pulse duration. c) Structure height and d) lateral size (FWHM) as a function of laser focus position relative to the mirror surface for six pulse durations. Four different focus positions are marked with triangles. e) Structure height as a function of pulse duration for the four foci, with an inset highlighting the low height (duration) region. f) Structure height as a function of pulse duration for three dielectric stack configurations, with laser focus set at the Si layer. g) Lateral size (FWHM) as a function of structure height for the four foci for the full stack (FS) case, and for the two half stack (HS) mirrors (in-focus writing only). In graphs (c)–(g) each data point corresponds to one written structure.
this phenomenon starts to occur indicate the onset of mirror destruction. The acquired data using the three other foci show that the structure height asymptotically tends toward a maximum value specific for that particular focus. The maximum achievable height is almost 200 nm, when writing with a focus position of about 20 μm. The observed trend that the structure height increases with the beam size of the writing laser at the silicon layer suggests that even higher structure heights might be achieved for higher laser power.

The role of the thickness of the quarter-wave stack on the structure height at given pulse durations is investigated in Figure 1f. In this case, all writing procedures are done in-focus to the silicon layer. The first striking difference is that the pulse durations required to achieve certain heights for thinner dielectric stacks are an order of magnitude lower than those for the thicker stack. Furthermore, a significant reduction is observed even with the removal of just one extra layer pair. In the case of 11 pairs, a pulse duration just above 30 μs starts to destroy the mirror. The lateral size (FWHM) of the written structures as a function of their height is shown in Figure 1g. In general, lower structures are also wider with the FWHM being about 4.5 μm for in-focus writing. As the structure height increases, the FWHM falls down to a value of about 3.3 μm, after which it rises again. Interestingly, the FWHM of written structures on a 10(11)-pairs quarter-wave stack is almost half compared to in-focus nanostructuring of the 20-pairs stack. Significantly smaller lateral structural sizes can thus be implemented in this way for applications that do not place excessively high demands on the reflectivity.

3. Plateau-Like Surface Structures

As complex structures involve writing a grid of overlapping points, writing plateaus of various heights is a reasonable starting point toward more arbitrary surface structures. The writing and interferometric surface scan procedure is the same as in the previous section, except for the fact that now the point spacing/density shows up as an additional parameter. Circular plateaus are written at the four calibration foci with various pulse durations, and a fixed point spacing of 1 μm is used unless noted otherwise. The writing is done from the bottom corner up.

The resulting plateau height as a function of pulse duration is shown in Figure 2a. Low pulse durations result in a behavior similar to that observed for point-like structures, however, only up to a maximum height of about 45 nm for all tested focus positions. Above that, in the case of near-focus writing we observe mirror destruction, while for other focus positions a sharp jump occurs suggesting the onset of delamination. The delaminated portion has a bubble-like shape, with the total height appearing to be limited by the plateau radius. We furthermore write plateaus using the 11-pairs stack, with the results shown in Figure 2b. The maximum achievable height is about 25 nm which is lower compared to the previous value of 45 nm. In contrast to point-like structures, the plateau height as a function of pulse duration is observed to be less dependent on the size of the dielectric stack. The radial height profiles are determined and plotted as a function of pulse duration in Figure 2c,d for the 20-pairs and 11-pairs dielectric stack, respectively. The profiles show a blurring of the boundaries of the plateau, which is more pronounced for the thicker dielectric stack. In the case of out-of-focus writing, similar but wider profiles are obtained.

Next, we evaluate the effect of the point spacing on the nanostructuring of extended structures. Circular plateaus were written for nine different point spacings, using a z = −9 μm focus position. The plateau height as a function of pulse duration is shown in Figure 2e. The previously determined maximum height of around 45 nm before the onset of delamination is observed to apply for all investigated point spacings. The height standard deviation within each plateau, as marked with the error bars, indicates how uniform the surfaces are. The height maps of 30 nm high plateaus written with different point spacings are shown in Figure 2f revealing that, for this particular focus position, point spacings equal or smaller than 2 μm already provide relatively smooth structures. The height deviation from the averaged plateau height is shown in Figure 2c, revealing that the plateaus start to become increasingly inhomogeneous with denser point spacing. This suggests that in the case of spatially overlapping writing processes, the relationship between structure height and pulse duration changes (the writing is done bottom to top). This effect is less noticeable with lower (≤20 nm) structures.

Finally, in order to check whether the direct writing method introduces additional surface roughness to the mirror, we carried out atomic force microscopy (AFM) measurements. In Figure 2h, we show a comparison between the height cross sections through a plateau-like nanostructure determined by AFM and by Mirau interferometry. The agreement between these methods on the structure height turns out to be very good. To investigate the surface roughness on a smaller lateral scale we performed AFM scans of nanostructured and non-nanostructured regions on the mirror of size 2 μm × 2 μm. An example for the case of a nanostructured region, that is, the top of a plateau, is shown in Figure 2i. Based on such measurements we determine the roughness of the mirror to be around 0.25 nm (RMS) for both the nanostructured and the non-nanostructured regions. It seems plausible that this value essentially represents the height resolution of the AFM under the given experimental conditions. In this respect, the obtained value should be regarded as an upper limit for the surface roughness. Nevertheless, the AFM measurements suggest that there is little to no excess roughness introduced by the laser direct writing, which is consistent with previous results using cavity ringdown measurements.[7]

4. Complex Structures

In order to write arbitrary structures, the data shown in Figure 2a,b is used to define a mapping between structure height and pulse duration (by fitting B-splines to the experimental data). This mapping can then be used to convert a target height map to a pulse duration map that can be written with the nanostructuring setup. For the purpose of testing the capabilities and repeatability of the so-defined
Figure 2. Plateau-like structures. a) Plateau height as a function of pulse duration for the four calibration foci in the case of a 20-pairs stack and b) for the 11-pairs stack (near-focus writing only). Each data point corresponds to one written plateau-like structure. The determined heights are an average of the height profile within half the plateau radius, with the error bars representing their standard deviation. c) The radial height profile for near-focus writing in case of the 20-pair stack and d) the 11-pair stack, with colors representing different pulse durations. The black lines show the intended plateau circle radius. e) Plateau height as a function of pulse duration for 9 point spacings using a –9 µm focus position. f) Height maps of plateaus of about 30 nm height for different point spacings. g) Replot of the data from (f) highlighting the height deviation from the plateau average. h) Height profile along a line through a 20 nm high plateau written using a –40 µm focus position. The profile is measured in two independent ways: Mirau interferometry and AFM. i) AFM height profile of a small area atop the same plateau as shown in (h).
nanostructuring procedure, we design a simple test structure featuring four height levels of 5, 10, 15, and 20 nm with sharp features of various lateral sizes. Writing the structure using the \(2\,\mu m\) focus calibration results in the height profile shown in Figure 3a. Here, unlike in the previous sections, no background subtraction was made and correspondingly the height map also contains the mirror roughness. The obtained height map is an average of ten interferometric scans. Some of the narrow features appear blurred or do not reach the intended height due to their small lateral size (compared to the point spread function of the writing process). The repeatability of the nanostructuring is tested by writing ten identical structures, and calculating the standard deviation in the obtained height. The result is shown in Figure 3b, indicating a standard deviation below 0.1 nm. These results show that the nanostructuring process is precise down to the level of single atomic layers. Test structures were written with the other three focus positions, and they show some additional feature broadening as expected. The repeatability, however, is the same. We furthermore repeat the writing process on the thinner 11-pairs dielectric stack, with the resulting height profile shown in Figure 3c. Here the features are noticeably sharper: the thin edge stripes reach the intended height and the valleys seem to reach the expected baseline as well. Five identical structures were written, and the standard deviation is shown in Figure 3d. In this case, a mirror with a rougher substrate was used, and the measured deviations again match the overall surface roughness.

5. Long-Term Stability

Surface measurements performed at intervals of a few months show that the nanostructuring is fairly stable with a slight shrinkage in the order of the measurement error, as can be seen in Figure 4a for plateau-like structures. This holds as long as the nanostructuring has been carried out in the non-delaminating regime. Point-like structures of various focus positions and durations also show good long-term stability both in height and lateral size (FWHM), see Figure 4b, with larger deviations present beyond the delamination threshold. In the delamination regime, on the other hand, our measurements show that the written structures exhibit a significant change over a period of a few days. Writing an uniform square using the \(-40\,\mu m\) focus position with long pulse durations resulted in the structure shown in Figure 4c, which features a bubble-like structure of 2.5 \(\mu m\) height near the bottom-right corner. The same structure was scanned again 11 days later, with the height map shown in Figure 4d. The observed growth of the bubble in both height and lateral size indicates the presence of a slow relaxation timescale in the delamination process of laterally extended structures.
6. Time-Resolved Measurements

To better understand the nanostructuring process, we perform time-resolved measurements of the surface profile during and after the heating pulses. A simplified schematic of the experimental setup is shown in Figure 5a. A 405 nm laser is used as the laser source with 65 mW of optical power focused (from the back side) down to an estimated beam waist of 7 µm on the mirror’s silicon layer. A portion of that light is captured by a photodiode, providing the temporal measurement of the pulse power, measured structure height, and lateral size (FWHM) as a function of time. The time-resolved measurement results showing the maximum achieved height during the nanostructuring process, as well as the permanent components are shown in Figure 5b. Figure 5c and 5d show the results for a pulse duration of 0.3 ms, where no permanent nanostructuring occurs, and 8 ms, where permanent nanostructuring is achieved. Figure 5e shows typical height profiles in cartesian (left) and radial (right) coordinates at various times during the writing process, as marked in (c,d).
power. A Mach–Zehnder interferometer (MZI) was constructed with the purpose of interfering the image of the surface with itself, offset vertically by a set amount. In this way, a flat region of the sample mirror is used as a reference plane for the interferometric height determination. A camera captures snapshots of a narrow horizontal strip with an effective temporal resolution of 40 µs, which is reached by combining multiple measurements in a stroboscopic fashion. Height maps are then calculated for each image, after a certain degree of noise removal.

Ten pulse durations were tested: 0.1, 0.15, 0.2, 0.25, 0.3, 1, 2, 4, 8, and 16 ms, with the pulse power over time closely following a square profile. The last five durations result in permanent structures. Height and lateral size (FWHM) of the structure for 0.3 ms pulse duration is shown in Figure 5c, which is the longest pulse duration that does not lead to a permanent structure. The data points (solid points) are connected using splines as a guide to the eye, except in the tail where an exponential fit is used. Despite the absence of a permanent structuring, it can be observed that heating the mirror with the focused laser beam creates a temporary surface elevation that can be as high as 17 nm. The creation and relaxation of this elevation occurs on the millisecond timescale, which is consistent with a thermal expansion process. The lateral feature size is observed to be more than twice than that of the permanent structures.

Further analysis, shown in Figure 5e, indicates that the experimentally obtained height profiles generally show a bimodal behavior. We basically observe a narrow feature on top of a broad background. The narrow distribution is found to approximately follow a Gaussian function. The broad background distribution follows approximately a Lorentz function. Below we analyze our data in order to distinguish between these two characteristics. To do this, we fit our data by superimposing a wide Lorentzian background (“L. Fit”) with a narrower Gaussian profile (“G. Fit”). These two contributions, that is, their amplitudes, are resolved in Figure 5c as a function of time (note that the sum of both components recovers the overall measured height). The usefulness of this data modeling is not obvious at first, but becomes apparent in the case of permanent nanostructuring with longer pulse durations. The measurement for 8 ms pulse duration, for example, is shown in Figure 5d. With this pulse duration, a permanent structure of about 35 nm height is created. Interestingly, it is observed that this permanent structure corresponds exclusively to the narrower Gaussian component of the height profile. The broader Lorentz-like component profile quickly disappears after the writing pulse power falls to zero. This circumstance corresponds to the aforementioned observation that the lateral structure size in the case of a reversible (thermal) expansion of the mirror surface is significantly larger than that of the permanent structuring.

The maximum height obtained within one pulse for the ten pulse durations that were tested is shown in Figure 5b, with the reversible and the permanent components indicated separately. The reversible component consistently saturates around 17 nm. The blue hatched bars show the structure heights as determined by the Mirau interferometer in the setup shown in Figure 1a. The observed mismatch is most likely due to an actual relaxation of the written structures shortly after the writing process.

7. Physical Origin of the Nanostructuring Process

In this section, we present experimental evidence that the permanent part of the nanostructuring method relies on thermally induced pore formation and enlargement in the tantalum oxide layers of the used dielectric layers. The amorphous oxide films used in the quarter-wave stack of our mirrors, Ta2O5 and SiO2, are produced via IBS using argon ions. These amorphous thin films are widely used and have been studied frequently[20,25–30] In particular, it is known that amorphous tantalum oxide layers produced by IBS show a high degree of mechanical energy, which can be released by annealing processes, whereby the layer thickness of the films increases by a few percent[31,32] Seen microscopically, this growth comes about through an enlargement of pore structures within the amorphous film. For SiO2, this effect also present but is significantly smaller.[19] While the mentioned results involve long annealing times, higher temperatures as they occur in the here investigated writing process may produce a similar effect on much shorter timescales.

In order to confirm this hypothesis, we prepare cross sections of several plateau-like structures using focused ion beam (FIB) milling, and image them with scanning electron microscopy (SEM). First, we investigate the non-delaminating regime of the writing process. More specifically, we evaluate a 40 nm high plateau written at z ≈ −2 µm focus position, which is shown in Figure 6a. The SEM image is focused onto the region around the silicon layer. From bottom to top we see the SiO2 substrate (dark gray), the thin Si layer (mid gray), and then interchanging of SiO2 (dark gray) and Ta2O5 (light gray) layers. Indeed, pores with sizes in the 10–100 nm range are visible in the bottom-most two Ta2O5 layers, but not in the SiO2. This is consistent with the previously reported results on annealing processes in the thin films concerned, despite the time scale and temperature of the annealing process being somewhat different. The fact that the nanostructuring takes place in the bottom layers of the dielectric stack explains why the reflectivity of the mirrors is not significantly reduced by the process.[7] Scattering in the bottom layer of the mirror leads to a lower absolute loss of optical power compared to scattering at the top layers, where the optical power is much higher. This also shows the importance of the embedded absorptive Si layer, which guarantees that the heating process takes place at the correct position within the mirror.

Additional SEM images (not shown) of 40 nm high structures written at a ~40 µm focus position reveal, however, no visible pores. The images of the cross sections are visually indistinguishable from a non-structured mirror. Due to the fact that the oxide layers are non-conductive, charges build up during SEM imaging which severely limits the resolution, such that feature sizes of ≤ 5 nm cannot be easily resolved. Furthermore the charge build-up distorts the imaging which makes it difficult to perform a layer thickness analysis.[11] As previously shown, using the ~40 µm focus setting requires an order of magnitude longer pulse durations to reach the same height as compared to the ~2 µm focus setting. This longer annealing at lower irradiance appears to result in smaller pore structures that cannot be resolved by SEM, but that lead to the same overall volume increase. Thus, these results do not necessarily contradict the pore hypothesis.
delaminated region). A cross section of a delaminated plateau structure written at the $-9 \mu m$ focus position and excessive irradiance is given in Figure 6c, showing regions that have melted, bubble formation, and cracks.

An interesting effect, which is not necessarily related to layer growth but still provides useful information about the physical processes during the writing process, is found in the behavior of the mirror transmission. We observe that the mirror transmittance is altered by the writing procedure for certain parameters. To further investigate this, we perform optical transmission measurements with 405 nm light. For a (blank) mirror with amorphous Si layer, the observed transmittance is $0.10 \pm 0.01$. A simple setup consisting of a camera and a microscopic objective is used to measure the transmission of various plateau-like surface structures, with the results shown in Figure 7. Structures with three target heights were written using the four calibration focus positions. The transmittance was averaged over the area of each structure, and the resulting values are shown next to the corresponding spatially resolved transmittance maps in Figure 7. For reference, transfer matrix calculations provide a transmittance value of 0.07 assuming an amorphous silicon layer in the mirror, and 0.45 for crystalline silicon. We can clearly see that, for structures written with sufficiently high irradiance, the transmittance is closer to that of what is expected for crystalline silicon, than for amorphous. This is consistent with other work, where it has been shown that laser direct writing can cause silicon to crystallize when using CW, nanosecond-scale, and even femto-second illumination.[34–37]

8. Conclusion

In this work, we performed extensive characterization of a novel mirror surface nanostructuring process based on the laser direct writing of dielectric mirrors containing an additional thin absorptive layer.[7] We show that the writing process has a reversible and a permanent component, where the reversible process originates from the thermal expansion of the surface. Scanning electron microscope cross-sectional images suggest that the permanent part of the nanostructuring process is due to thermally induced pore formation and enlargement in the tantalum oxide layers of the used dielectric mirror. We furthermore propose and discuss a calibration method based on the study of plateau-like structures that allows to accurately map target structures to writing procedures.

The investigated direct writing method is characterized by its simplicity, cost-effectiveness, and its exceptional precision. Angstrom-like precision in the growth direction can be routinely achieved without expensive clean-room technology. The nanostructuring process is fast, making it an excellent choice for prototyping. The use of this technique has contributed significantly to recent advances in the study of microcavity systems and we believe that other areas of optics can also benefit. This applies in particular to areas in which mirrors with highest reflectivity are used, for example, cavity ringdown spectroscopy or interferometric precision measurements. Last but not least, wavefront shaping,[38] specifically in the UV, can be a possible application.

Figure 6b features the cross section of a delaminated plateau structure written at $z = -9 \mu m$ focus position. Two types of delamination can be seen: a long jagged fracture consisting of connected bubbles, and a clean separation of the Ta$_2$O$_5$ and SiO$_2$ layer as marked with a red arrow. The latter extends toward the center of the plateau structure (i.e., the more strongly
9. Experimental Section

The dielectric mirrors used in this work were manufactured by Laseroptik GmbH using IBS with argon. The amorphous silicon layer added between the substrate and the dielectric stack was typically 30 nm thick. The dielectric stack consisted of 20 pairs of Ta$_2$O$_5$ and SiO$_2$. With the use of glue, layers were mechanically removed from the dielectric stack, allowing the evaluation of the nanostructuring in mirrors with fewer dielectric stack layer pairs, in this case 11 and 10.

The nanostructuring setup (see Figure 1a) consisted of two main parts: the white light interferometry and the direct laser writing. Both shared the imaging light source—an LED (Thorlabs M617D3) with an emission spectrum situated within the sample mirror’s high reflective region, and the camera (Basler ACA1300-200um). The sample mirror was mounted on an XY assembly consisting of two piezo stepping stages with a 26 and 52 mm travel range (Pi N-565.260 and Pi N-565.360). A 26 mm travel range piezo stepping stage (Pi N-565.260) provided the Z-axis motion and held two microscope objectives: a 20x Mirau interferometric objective (Nikon MUL40201) for surface profiling and a 40x objective (Olympus RMS40X) for the direct laser writing. The foci of the two objectives were intentionally mismatched in such a way that during operation, only one of them had its focus on any surface at any given time. A dichroic was used to insert the writing laser beam from a 200 mW CW laser operating at 405 nm (CNI MDL-NS-405), which was controlled via TTL switching.

The time-resolved measurement setup (see Figure 5a) used a 405 nm laser (NEJE B25425) as the heating laser, providing about 260 mW of optical power, reduced to 65 mW by a neutral density (ND) filter (OD = 0.6). The sample mirror was mounted on a manual XYZ stage with one of the micrometer screws (an axis perpendicular to the laser beam) motorized by a servo. A lens then focused the light onto the sample mirror’s silicon layer. On the imaging side, a standard microscope objective was used instead of the more convenient Mirau interferometric objective in order to avoid possibly damaging the internal reference mirror, as the sample mirror was partially transmissive at 405 nm. Instead, a Mach–Zehnder interferometer (MZI) was constructed with the purpose of interfering the image of the surface with itself, offset vertically by a set amount. In this way a flat portion of the sample mirror was used as a reference plane. The first beamsplitter of the MZI was actuated by a piezo in order to control the phase shift. A 650 nm fiber tester laser was used as the imaging light source, due to its intermediate coherence length. A narrow horizontal strip of the light exiting the MZI was captured by a camera (Basler acA4024-29um), which allowed the camera frame rate to be increased to 1000 frames per second (fps), providing a temporal resolution of 1 ms. Higher temporal resolution was needed, however, which was achieved using a strobe effect where the camera triggers were all offset by a set amount for each individual pulse, and multiple pulses were combined for the final result. With this, a frame rate of 25 000 fps, or 40 µs per frame was achievable. In measurements where pulse duration was short enough such that no permanent nanostructuring occurred, 1000 pulses were averaged to produce the final result. With longer pulse durations where permanent structures were created, only 25 pulses per measurement set were performed, and the servo was used to automatically move to a clear portion of the sample mirror after each write.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
All experimental data used in this study are available in the 4TU. ResearchData database under accession code https://doi.org/10.4121/22231669.v1.

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