Direct, Laser-based Production of Optics

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Micro lens arrays made of glass are optical components which, due to their complexity, can fulfill the function of many larger lenses at the same time. Optical arrangements can thus be miniaturized and made lighter. The production of such elements can be a challenge, especially for medium and small quantities. Therefore, at the ifw Jena, two direct production methods of such elements are being investigated: laser ablation with ultrashort pulsed (USP) lasers and ablation with a short-pulsed CO_2-laser respectively polished with a cw-CO_2 laser. The USP-laser produces the desired lens profiles precisely at moderate removal rates. The short-pulsed CO_2-laser on the other hand shows much higher removal rates, also without melting the substrate. The surfaces roughness after the laser ablation R_a ranges from 1 µm to 0.4 µm. This value was improved down to 40 nm by the laser polishing step. The experiments show a good homogeneity of the lenses as well as a high process speed.

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1. Introduction

The advancing understanding of optics and the demands of the market for space and weight savings in optical devices favor the trend towards free-form optics and micro lens arrays (MLA). The latter are arrangements of many identical lenses on a substrate, with the lenses each being smaller than a millimeter. These elements solve optical tasks that previously required a large number of spherical lenses made of different materials. By using these more complex optics, imaging errors can be avoided, mass and weight can be saved and completely new effects can be achieved, such as quasi-3D recording in light field cameras or the homogenization of laser beams.

From wearable applications in consumer products such as smartphones, mobile measuring devices and diagnostic devices to space applications, the integration of multiple functions in one optical element brings enormous benefits. In addition to saving weight and space, such optics are mechanically much less sensitive, since fewer functional parts can get out of place. In some cases, these optical functions can even be integrated directly into surfaces (e.g. windows), resulting in a monolithic design [1]. Possible areas of application for micro lens arrays are:

• Medical technology: sensors in endoscopes [2], imaging in laser scalpels, homogenization of laser light for hair removal/tattoo removal [3]

• Space: miniaturization, functional integration and weight reduction of optical elements for sky observation, distance sensors and earth observation

• Telecommunications: coupling/decoupling in fiber optic cables

• Production: Light homogenization in laser material processing, miniaturization and integration of optics in mechanical sensors

• Science and optics: imaging in light field photography (plenoptic camera) [4], measurement of optical wave fronts with Shack-Hartmann sensor [5]

• Consumer goods: miniaturization of imaging optics in smartphones, etc., light homogenization for lighting purposes and projectors [6]

However, the production of such non-classical optics is difficult, since they cannot be machined using rotationally symmetrical grinding and lapping tools. Plastic optics can already be produced in sufficient quality by molding processes, but require complex process development and expensive tools, which makes the use of these components in small quantities uneconomical. There is a variety of modern production techniques for MLA's made of polymers including laser catapulting [7], hot embossing [8], inkjet printing [9] and two-photon polymerization [10].

However, optical components made of glass are superior to those made of plastic in many fields of application in terms of thermal, chemical and UV resistance [11]. In addition, they have a broader range of optical parameters such as available refractive indices and dispersion, as well as lower residual absorption and scattering and are therefore more flexible in use.

There are some methods for manufacturing micro lens arrays from glass. [11] gives an overview of the possible techniques. Although individual elements can be produced by photolithography and ion beam etching, this requires masks for the lithography, which incur costs per design that are independent of the quantity. In photolithography, the resist masks required for etching are produced either by gray tone lithography or by the so-called reflow process. In grayscale lithography, an individual micro lens is exposed with an increasing dose towards the edge, resulting in a lenticular etch mask for subsequent transfer into the glass.

Alternatively, binary photolithography can be used to first produce small cylinders from the resist polymer, which are then melted at a higher temperature. Due to the influence of the surface tension, small lenses are formed from the resist polymer, which are proportionally transferred into the glass substrate again by reactive ion etching. The ion beam etching process takes a relatively long time if structures that are deeper than a few micrometers have to be removed. In practice, only relatively flat micro lens arrays (~20 µm lens height) can be produced economically that way [11].

Another modern method of producing micro optics directly in glass is laser assisted etching [12, 13]. Depending on the glass, the laser treated areas have to be heated to show a significant change in the etching rate, usually in a furnace. After the wet etching process, the roughness is dominated by the structure of the laser modified volumes, usually in the range between 1 µm and 100 nm. For optical use of the etched area, the surface has to be smoothened with another method, like the annealing discussed in [13].

Diamond micro-grinding is another manufacturing alternative for free forms. However, the system costs and process times here are so high that the process is only worthwhile if it is used to produce a mold from which the products are then molded. This is only possible for plastic optics. MLA in high-tech products are often specifically suited to their optical task, so they require certain optical parameters set by the customer. That means that it is in most cases not possible to buy catalog items. Also, in many high-tech applications, small quantities are required for prototyping, sometimes even individual pieces. Even in the case of series production of highly specialized equipment, only some tens of pieces might be required per year, which makes lithography masks for their production uneconomical.

Laser processes, on the other hand, offer the possibility of producing micro lens arrays directly on the glass by material removal and polishing. In addition, no masks are required, which saves time and money. For this reason, different laser processes are being investigated at ifw Jena in order to produce micro lens arrays directly, both with an ultra-short pulsed laser and with CO_2-lasers. The process is divided into contour removal and polishing. While polishing is always carried out using a continuous-wave (cw) CO_2-laser, both an ultra-short pulse laser and a short-pulse CO_2-laser are being tested for contour ablation. The first results of the CO_2-laser experiments have been published earlier [14].

2. Experimental Setup

The experiments were carried out on quartz glass and Boro-float® 33 (Schott). Typical MLA designs from project partners serve as the geometric target parameters: The lens radii are in the range of a few millimeters down to several hundreds of micrometers, the lens distances (pitch) are around 300-500 µm.

The experiments on ablation with the USP laser are carried out with a Lumera Hyper Rapid with a pulse duration of approximately 7 ps. A wavelength of 355 nm was used, the pulse repetition rate was 200 kHz and the average power was in the range of 1 W. For the processing, the laser beam was guided over the sample surface with a galvanometer scanner and focused through an F-Theta optic with approximately 100 mm focal length.

A FEHA microstorm was used as the ablation CO_2-laser. It emits pulses with a length of about 200 ns and a wavelength of 10.6 µm. The repetition rates used were in the range of 10-25 kHz with average powers of up to 80 W. The laser beam is guided over the work piece by a Scanlab Hurryscan and focused to a diameter of 140 µm by an F-Theta lens. The short pulse duration of 200 ns is used to reduce the heat-affected zone around the laser ablation point. The CO_2-laser ablation of quartz glass could therefore be carried out without preheating. A ceramic heating plate from Elstein (1 kW heat output, max. 1000 °C) was used for processing other glasses with the CO_2-laser and for the polishing process.

The polishing process used here has already been scientifically examined [15]. In this process, the defocused laser beam is directed very quickly in a line, while the line slowly moves perpendicular over the work piece. The glass is generally preheated so that the pyrometrically controlled laser beam has to use less energy for the glass surface to reach the softening temperature. The surface tension of the glass reduces the roughness when the viscosity is low enough.

A laser scanning microscope from Keyence (VK-X100) is used to assess the ablation results. Its software allows the recording of two-dimensional height profiles, sections, radius measurements and roughness measurements with frequency filtering to differentiate between the micro lenses and the roughness. All radii mentioned here were measured as the radius of curvature of the surface profile.

The background to the approach with two types of laser is the fact that USP lasers are relatively expensive and cause comparatively low ablation rates; often in the order of 1 mm^3 per minute and per watt of laser power. On the other hand, very precise thin layers (< 1 µm) can be removed with USP lasers and very fine geometric contours can be removed with focus sizes in the range of 20 µm. Due to the ultra-short pulses, the substrate is not heated up by the ablation. This means that glasses with high coefficients of expansion can also be processed without preheating.

CO_2-lasers for glass removal have completely different properties: They are significantly cheaper than USP lasers. Due to the linear absorption and higher power, the absolute ablation rate is higher and the precision in the ablation depth is limited. Due to the long wavelength compared to other lasers, the laser foci are often larger and geometric features smaller than 100 µm can hardly be generated. If the laser can be switched between cw- and short-pulse operation, contour removal and polishing can also be carried out on one laser, i.e. in one clamping, which simplifies the process. The question is, if the surface contour can be produced with sufficient precision by laser ablation and polishing.

3. Results

3.1 CO_2-Laser Ablation

Initially, parameter tests were carried out using the short-pulse CO_2-laser. The focus here was on the question of what minimum depth can still be reliably removed and what lateral structure sizes are created. The achievable removal depths are in the range that is relevant for the production of MLA. With the laser used here, layers from a thickness of around 5 µm can be removed in a reproducible manner. With higher pulse energies and several passes, removal depths of several 100 µm can also be produced easily.

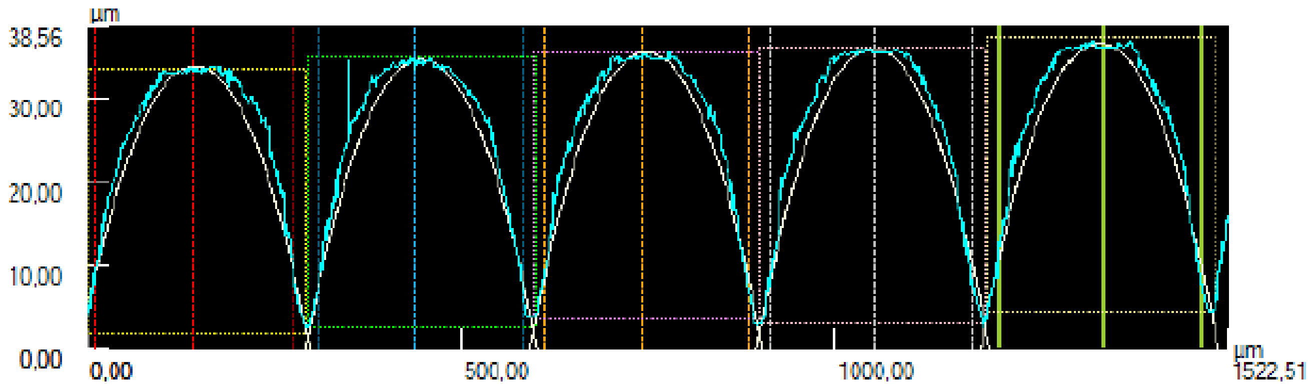

Fig. 1 Surface profile after CO_2-laser ablation before polishing; fused silica, target radius: 350 µm, measured average radius: 358 µm, standard deviation: 4,4 µm; the white curve is a manually fitted spherical contour to calculate the radius. The maximum deviation from the contour is about 8 µm.

The full width of the ablation tracks is between 100 and 200 µm and is therefore sufficient for the MLA designs aimed for here. The removal rate in these tests was up to 25 mm^3/min, so that even large MLAs with a lens height of more than 100 µm can be produced in a few minutes. This rate is very high compared to reactive ion beam etching (RIE). Depending on the material, etching depths of nanometers to micrometers per minute are possible with RIE [16]. A typical ablation trace has approximately a Gaussian profile and a roughness in the range of 1 - 2 µm.

We developed process strategies to ablate nearly spherical structures with said Gaussian ablation profiles by a suitable superposition. A typical lens profile can be seen in Fig. 1. Here, the resulting profile is not perfectly spherical and the radius is not exactly 350 µm as aimed for, but corrections in this order of magnitude will be caused by the polishing step. The surface has a roughness R_a of about 1 µm and shows no signs of melting.

3.2 USP-Laser Ablation

Parameter investigations were carried out in the same way on quartz glass and Boro-float® 33 with the USP laser in order to find ablation parameters which cause fine but rapid ablation with a simultaneously low resulting roughness. Then, MLA's were created with the appropriate parameters. Fig. 2 shows the section through a resulting lens profile. Twenty layers of material were removed to create it. It shows that the geometric target parameters such as diameter and radius could be realized precisely. The resulting roughness R_a without polishing is around 0.4 µm.

A total of slightly more than 1 mm^2 glass had to be removed from the substrate in order to expose the lens contour. This process took about 4 minutes including all machine times. This also includes mirror positioning times when the laser was turned off. The USP removal process is stable and reproducible. Only one problem occurred regarding an unstable ablation depth. It could be traced to an inhomogeneity in the float glass and can easily be avoided by a careful selection of the processing side.

3.3 Polishing by cw CO_2-Laser

For the polishing step the samples were preheated by the ceramic heating plate and the laser power was controlled by a pyrometer measuring the temperature in the middle of the fast scanning line. The laser parameters for the polishing step were tested on the different materials and optimized respectively.

The heating rate during the pre-heating has no influence on the polishing process, since the maximum temperature of this heating is well below the glass transition temperature (T_g). When the sample temperature is constant, the laser further heats the surface above the T_g. The heating/cooling rate for the preheating was chosen to be as fast as possible without damaging the sample or inducing additional tension.

Fig. 3 shows the laser ablated sample from Fig. 1 after the polishing step. The polishing reduced the surface roughness from about 1 µm down to 0.04 µm but the radii increased from 358 µm to 391 µm which is not surprising considering the steep lens flanks (Pitch: 300µm). This ef-

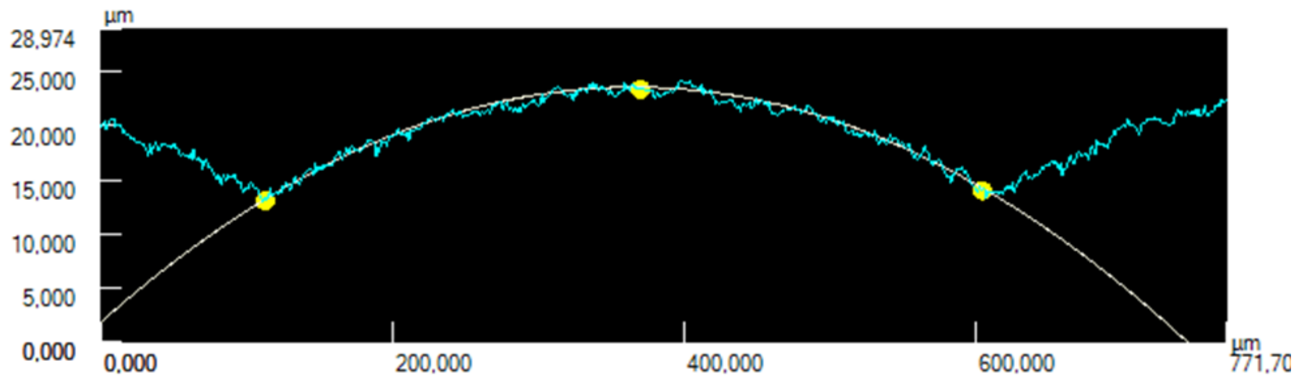

Fig. 2 Surface profile after USP-laser ablation; Boro-float® 33, target radius: 3000 µm, measured radius: 3075 µm

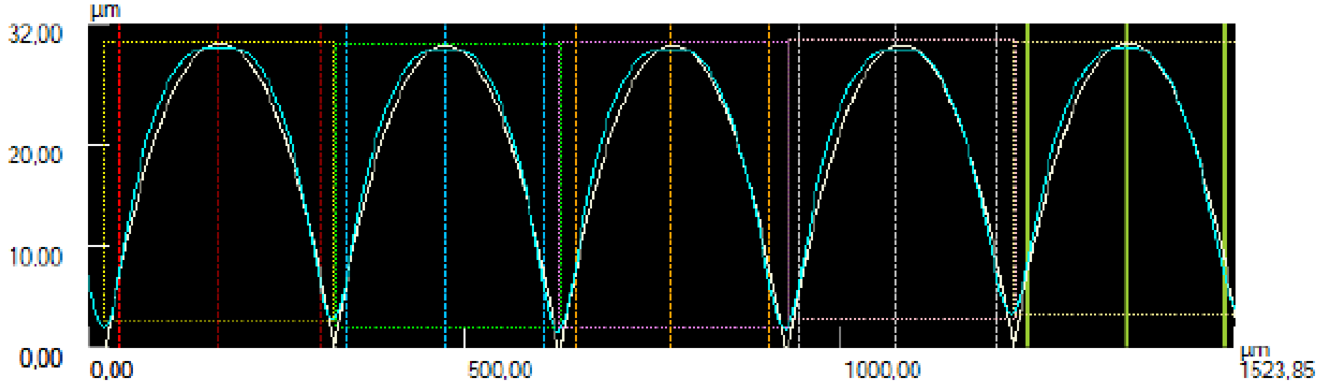

Fig. 3 Surface profile after polishing the surface from Fig. 1, measured average radius: 391 µm, standard deviation: 6,7 µm.

fect can be pre-compensated in the ablation step. The standard deviation of the lens radii in this array is about 6,7 µm (1,7% of the mean radius). The form deviation from the sphere is in the order of some micrometers with the main reason being the plateau-like shape of the lens center. This problem is inherent to the current CO_2-laser ablation strategy in is being worked on at the moment.

Fig. 4 shows a typical before-after-comparison of the polishing process of the USP-laser ablated samples: The surface roughness could be reduced down to $R_a = 0.04$ µm. This worked for the initial roughness of 1 µm in Fig. 1 as well as for lower values. The resulting 40 nm-roughness is close to the measurement limit of the laser scanning microscope, so it could be possible that the actual value is lower but we cannot measure it. The whole polishing process takes about one hour, depending mainly on the preheating temperature of the substrate. The polishing itself takes about a minute.

The shape of the micro lenses was changed slightly by the polishing step. In the example shown in Fig. 4, the lens radius changed from 3.145 mm to 3.241 mm, so about 3%. This value is dependent on the profile segment used for the calculation of the radius, since the change of the shape happens mainly in the contact area of neighboring lenses. The radius in the center of the lens is virtually constant. The polishing parameters still have to optimized to solve this problem.

3.4 Optical function

The micro lens arrays produced by USP-ablation and polishing were tested in a simple optical setup shown in Fig. 5. A cheap light source (LED) illuminated the optical path. The light was collimated by a spherical lens and hits the micro lens array. Since the radius of curvature of the

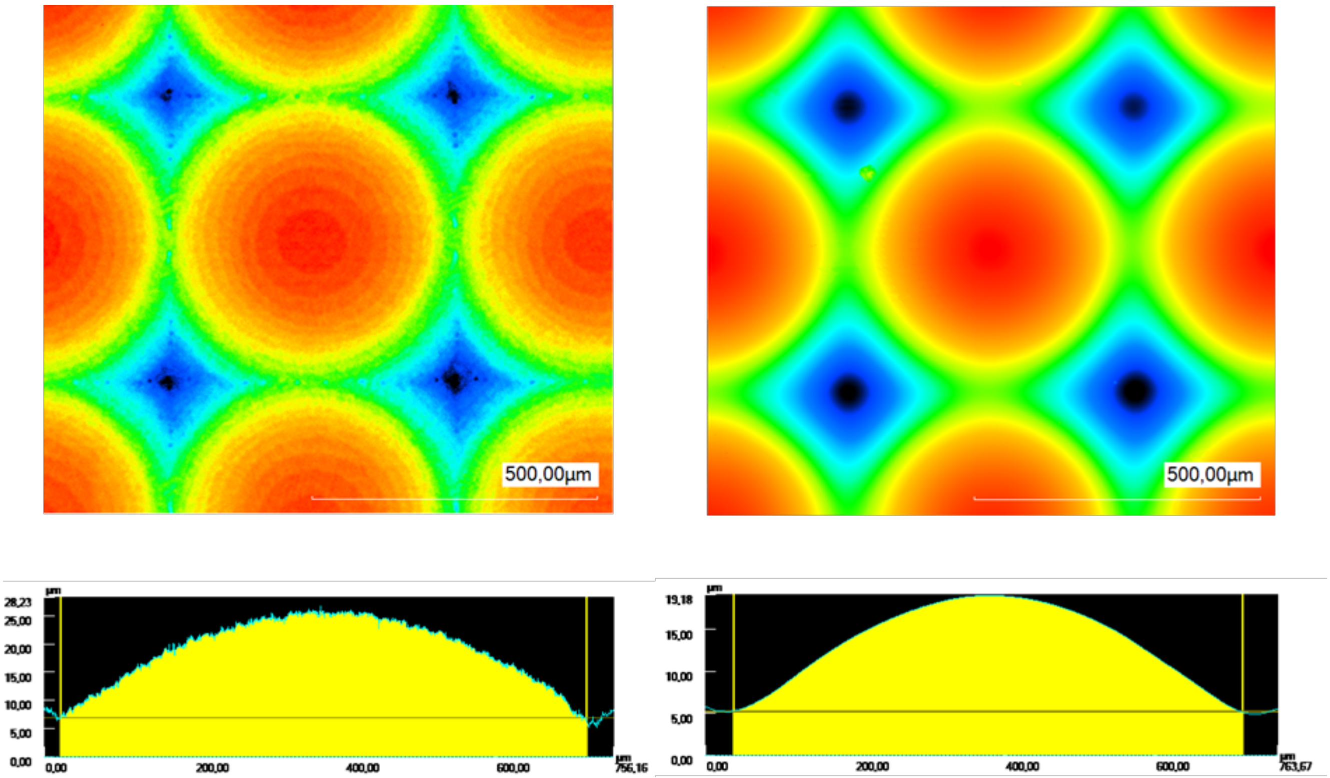

Fig. 4 Surface profile comparison with laser-polishing; Boro-float® 33, target radius: 3000 µm, target pitch: 500 µm; the lower part of the picture shows the diagonal cross sections

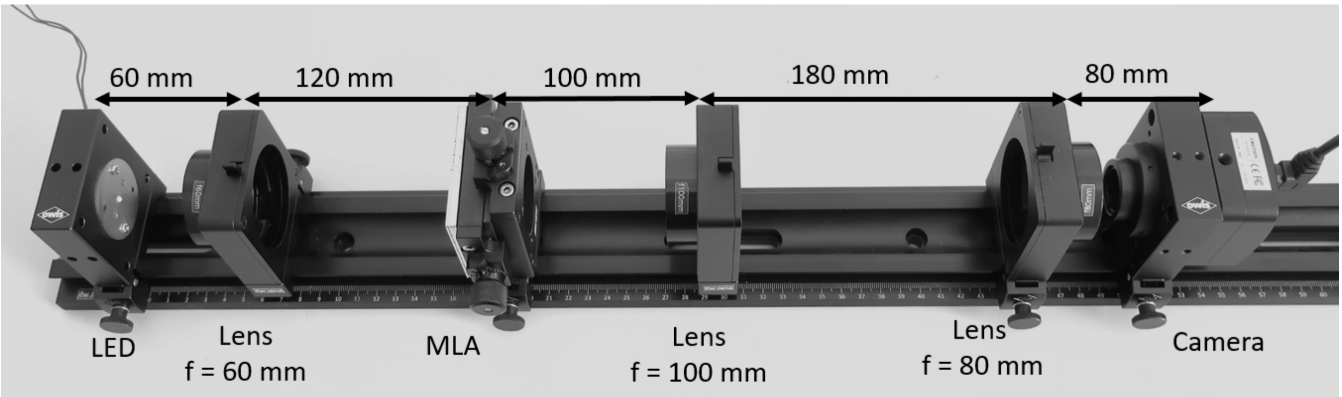

Fig. 5 Optical test bench for the micro lens arrays, from left to right: light source (LED), collimation lens, MLA, 4-f-setup, camera

(plane-convex) micro lenses was 3 mm, their focal length was about 6.5 mm. The lens foci could not be positioned on the CCD-chip directly because of the housing of the camera. For this reason, they were imaged onto the camera with a 4-f-seutp shown in Fig. 5. A resulting camera picture can be seen in Fig. 6. Since the light source is a simple LED, its chip is not emitting homogeneous and the inner structure of the LED is visible in the foci of the micro lenses, which are images of the light source. The test showed that the individual lenses share a common focal plane which means that the deviations of the individual focal lengths are small enough to not be seen here. Also, the foci are spaced equally which means that the lens pitch is constant over the MLA and the lenses are not tilted towards each other. While the optical setup is very simple and the spherical aberrations of the imaging lenses were noticeable, the optical function of the micro lenses was proven.

4. Conclusion and Outlook

Building on extensive experiments, strategies were found to generate the required spherical lens shapes with the USP-laser as well as with the much coarser CO_2-laser beam. The process time for the ablation of the lens profile is in the order of several minutes and requires no preheating. This is much faster than classical processes. The results show, that the target lens contours can be manufactured with sufficient precision by ablation using an ultrashort pulse laser. Significantly cheaper CO_2-lasers are able to generate lens profiles with pitch values of more than 300 µm. The resulting roughness is 1 µm for the CO_2-laser and 0.4 µm for the USP-laser, both are sufficient for laser polishing.

The polishing experiments show that the roughness can be reduced down to tens of nanometers. At the moment, a

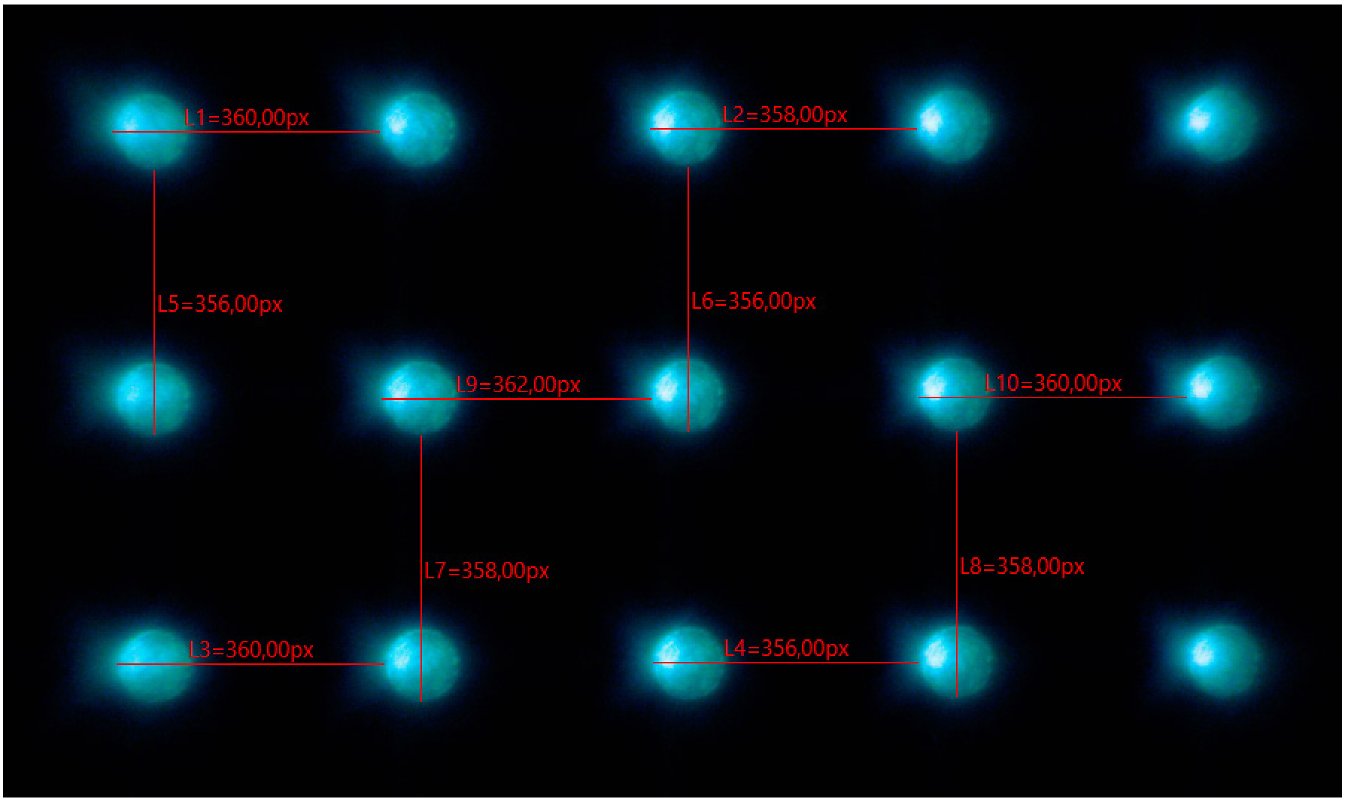

Fig. 6 Image of the MLA foci in the camera. The structure of the cheap LED light source is visible in the foci. The size and spacing of the foci is constant within the measurement uncertainty.

lower roughness probably cannot be measured with our equipment. The achievable surface roughness with this kind of polishing seems to be independent on the lens radius, pitch and laser ablation method. The process time for the polishing is dominated by the preheating and in the order of an hour.

Overall, both processes (USP-laser or CO_2-laser ablation with CO_2-laser polishing respectively) show form deviations from a sphere in the order of some micrometers. This is sufficient for lighting applications but not for optical imaging. The problem will be reduced in future experiments by respectively a different ablation strategy of the CO_2-laser and a more careful polishing of the edges of the USP-ablated lenses. These future experiments will focus on the contour change in the region between the lenses. Different techniques will be tested to prevent the change of the lens radius there. On one hand, the radius change in this region could be pre-compensated in the ablation step. On the other hand, an additional grove on the lens borders could be introduced to prevent the molten films of different lenses from interacting with each other. Also, the produced micro lens arrays are going to be measured more precisely regarding their shape and roughness in an interferometer-setup, so that these parameters can be further improved.

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References
[1] C. De Clerq, V. Moreau, J.-F. Jamoyem A. Z. Mrachi, and P. Gloesener: Proc. SPIE, Vol. 9626, (2015) 407.
[2] D. Musick: "Methods for high resolution Endoscopes", Master Thesis, University of Jena (2016).
[3] S. Keeney and Z. Huang. U.S. Patent US20120165800A1 (2012).
[4] O. Johannsen, C. Heinze, B. Goldlueche, and C. Perwaß: "Time-of-Flight and Depth Imaging. Sensors, Algorithms, and Applications" (Springer, Berlin, 2013). p. 302.
[5] V. Lin, H. C. Wei, H. T. Hsieh, J. L. Hsieh, and G. D. Su: Micro Nano Lett., 6, (2011) 523.
[6] C. H. Chen, C. C. Chen, and P. H. Yao: Key Eng. Mater., 364, (2008).
[7] S. Surdo, A. Diaspro, and M. Duocastella: Opt. Mater. Express, 9, (2019) 2892.
[8] S. S. Deshmukh and A. Goswami: Mater. Manuf. Process., (2022) 1.
[9] Q. Zhang, M. Schambach, S. Schlisske, Q. Jin, A. Mertens, C. Rainer, G. Hernandez-Sosa, M. Heizmann, and U. Lemmer: Adv. Opt. Mater., 10, (2022) 2200677.
[10] J. Li, S. Thiele, R. W. Kirk, B. C. Quirk, A. Hoogendoorn, Y. C. Chen, K. Peter, S. J. Nicholls, J. W. Verjans, P. J. Psaltis, C. Bursill, A. M. Herkommer, H. Giessen, and R. A. McLaughlin: Small, 18, (2022) 2107032.
[11] P. Nussbaum, R. Voelkel, H. P. Herzig, M. Eisner, and S. Haselbeck: Pure Appl. Opt., 6, (1997) 617.
[12] W. Zhou, R. Li, M. Li, P. Tao, X. Wang, S. Dai, B. Song, W. Zhang, C. Lin, X. Shen, T. Xu, and P. Zhang: Ceram. Int., 48, (2022) 18983.
[13] B. X. Wang, J. Y. Qi, Y. M. Lu, J. X. Zheng, Y. Xu, and X. Q. Liu: Mater., 15, (2022) 678.
[14] T. Schmidt and D. Conrad: Seventh European Semin. on Precis. Opt. Manuf., 11478, (2020) 35.
[15] J. Hildebrand, K. Hecht, J. Bliedtner, and H. Müller: Phys. Procedia, 12, (2011) 452.
[16] K. R. Williams, K. Gupta and M. Wasilik: J. of microelectromechanical syst., 12, (2003) 761.

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