9th International Conference on
Photonic Technologies LANE 2016

Industrial Paper

Flexible beam shaping system for the next generation of process development in laser micromachining

Tobias Klerks[a], Stephan Eifel[a,*]

[a]*Pulsar Photonics GmbH, Kaiserstr. 100, 52134 Herzogenrath*

Abstract

Current developments in industrial laser micromachining with USP-lasers show that in new applications the process development using standard Gaussian intensity distributions is often no longer sufficient. For example complex laser processes like filament cutting or the need for a process parallelization demonstrate that there is a strong demand for shaping the laser beams focal intensity distribution in two or three dimensions. Phase modulation of the laser beam using a spatial light modulator is an effective method to electronically alter intensity distributions with high degree of freedom. In scientific literature multiple publications demonstrating the advantages of spatial light modulators (SLM) for micro processing can be found. However, until today this technology could not be transferred into an industrial product for laser micro processing. Within this paper a prototype of a fully integrated flexible beam shaping solution for machine integration is presented. Tested with average USP-laser powers of up to 60 W a powerful tool for the next generation of process development is demonstrated.

Keywords: Spatial light modulator; high power USP processing; process parallelization; beam shaping

---

1. Introduction

The use of beam shaping in ultra-short pulsed laser processing has become an approved tool to optimize the efficiency of micro ablation, cutting and drilling processes. Beginning with top hat beam shaping to reduce thermal heat accumulation effects and to increase the maximum ablation efficiency per pulse (Nolte et al. (2016), Neuenschwander et al. (2010)) over beam splitting as an effective way to overcome process limitations in maximum laser power per beam (Kuang et al. (2009), Pulsar (2015)), up to focal beam elongation to enable a fast laser cutting of wide bandgap materials (Lopez et al. (2015), Trumpf (2015)), focal beam shaping has already entered industrial processes. Further experiments with shaped laser beams documented in scientific literature, such as using non-diffractive Bessel beams for high aspect ratio laser drilling of wide band gap materials (Froehly et al. (2014)), using radially polarized beams for a more efficient laser cutting (Weber et al. (2014)) or using doughnut shaped beam shapes for a laser trepanning in percussion mode (Kuang et al. (2011), Hamazaki et al. (2010)), demonstrate that there is even more potential for creating new efficient laser processes.

Most of these focal beam shaping transformations from a Gaussian intensity distribution to a process adapted focal intensity distribution can be performed by diffractive optical elements (DOEs). With power efficiencies in the range from 70-95%, high damage thresholds and easy alignment, DOEs are both an efficient and reliable way for static focal beam shaping. For this reason first industrial processing heads have occurred in the market, which combine focusing or scanning and diffractive beam-shaping for glass cutting or parallel processing (Pulsar (2015)).

For example the combination of a diffractive beam splitter and a galvanometric scanning system allows to generate a static configuration of partial beams in the work plane of the focusing objective. By scanning the beam configuration over the workpiece it is possible to create multiple complex structures in parallel. Although

---

[*] Corresponding author. Tel.: +49-2407-5555-521 .
E-mail address: eifel@pulsar-photonics.de

this multi beam scanning approach is very efficient, one disadvantage of the DOE is that it provides only a static intensity distribution and that the DOE hence has to be changed if another spot configuration is required.

To bypass this drawback, spatial light modulators (SLM) can be used for dynamic beam shaping (Kuang (2010)). This electronically controlled module uses the orientation of liquid crystals and the resulting change in the optical path length to change the phase front of the incoming laser beam (Hamamatsu (2016)). Using a 2D chip, the phase of a laser beam can be shaped in two dimensions. The limit in accuracy of the beam shaping is given by the resolution of the SLM and hence through the number of pixels. The pixels are represented by pixel electrodes, each electrode can be addressed individually. For further modelling, the incoming laser beam can then be treated as a bundle of sub beams each modified in phase by a pixel of the SLM. The orientation of the liquid crystals of the SLM is controlled by the electric field between an ITO-electrode and the pixel-electrodes. The phase of an incoming collimated laser beam can so be changed depending on the alignment of the liquid crystals in each pixel. The phase can be controlled in a specific number of steps. After focusing of the modified laser beam, the sub beams with different phase delays interfere in the focal plane, so that a new beam shape is formed. This shape can be calculated and changed in a rate typically up to 180Hz, depending on the SLM type. Due to the flexible configuration of the SLM, a variety of intensity distributions can be created which makes it a powerful tool for focal beam shaping. The applications are the same possible with DOEs with the advantage to dynamically control the current beam shape and use it for other applications like holography or a shift of the focal plane (Lazarev et al. (2012)).

For creating different beam shapes or intensity distributions according to a given model a phase distribution has first to be determined. In order to calculate a phase distribution for receiving a new two dimensional intensity distribution in the focal plane, which is then displayed on the SLM, an algorithm can be used which is based on the Gerchberg-Saxton-Algorithm (Gerchberg, Saxton (1972)) and located in the group of the iterative Fourier transform algorithms (IFTA). In the first iteration (cf. Fig. 1) an amplitude distribution A is chosen (here the Gaussian shape) for the incoming beam while the phase φ is randomly given (1). This is then Fourier-transformed and the amplitude of the transformation is exchanged by the desired distribution (here the Pulsar Photonics logo) while the phase is kept (2). The next step is to inverse the Fourier transformation. At the end of the iteration loop the phase is kept and the amplitude is again changed to the shape of the incoming beam (1). The phase distribution will converge to a final distribution (Fienup et al. (2013) and Engström et al. (2009)). This distribution is then displayed on the SLM.

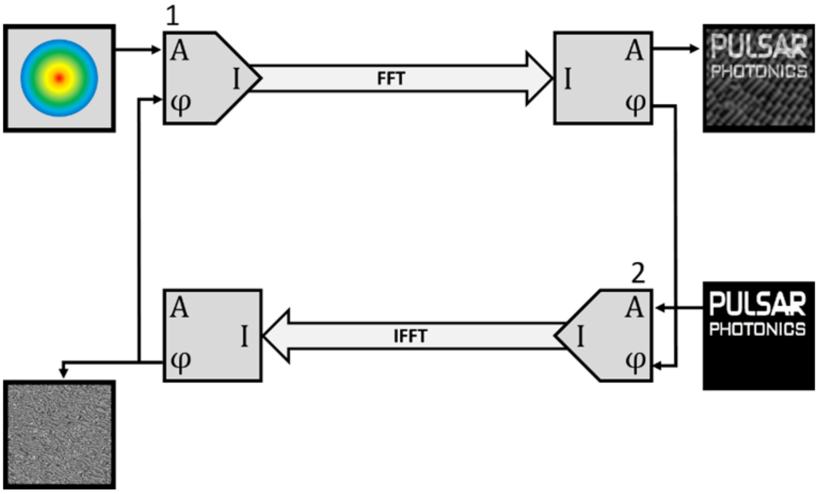

Fig. 1. Principle of the IFTA, the incoming beam is chosen as the amplitude profile to start the algorithm. After a fast Fourier transform the resulting amplitude profile is set to the desired profile while the calculated phase is kept. The inverse transformation leads to the phase hologram used for the SLM. To converge, the amplitude profile is again exchanged for the profile of the incoming beam. The phase is always kept and will converge to the final phase hologram.

The use of the SLM in micro processing has already been demonstrated in scientific literature for low laser powers (Kuang et al. (2010), Beck et al. (2010), Kuang et al. (2014)). However, to use the SLM to its full potential in laser micro processing, high power resistibility for ultra-short pulsed laser radiation is a must for the device. To our knowledge no tests with high power lasers (P>15W, Beck et al. (2010)) have been documented so far. The usage of high laser power can become a problem, because of the relatively high absorption of the SLM in the range of 2%. Hence, a laser induced temperature rise in the SLM-chip can change the phase distribution or in the worst case will irreparably damage the chip. As current commercially available spatial light modulators are not intrinsically designed for the use with high laser powers, the SLM-elements have first to be equipped with adapted cooling devices before their utilization for laser micro processing applications. Therefore the focus of this paper is to experimentally prove that it is possible to use SLM based beam shaping with average USP-laser power of 50W and more without the SLM-chip taking damage.

2. Experimental Setup

In order to investigate the performance of the SLM while it is exposed to high laser power an experimental setup with a high power USP Laser system as heating source is chosen. The main purpose is to show that an active cooling can conserve the optical properties of the SLM and therefore keep the resulting beam profile unchanged. To investigate effects on the phase distribution, the SLM is exposed to two different laser sources: a reference laser in form of a laser pointer and a heating laser. The beam of the reference laser will be used to measure a control parameter which will be defined in the following. The heating laser will work as the main source of laser power which will heat up the SLM chip. The two laser beams overlap on the SLM chip and cover about the same area so that also heating effects on the border of the Gaussian beam profile of the heating laser can be measured.

In the setup for the experiment a laser pointer is used for reference measurements (Fig. 2, green). First the beam passes a half wave plate (HWP) to rotate the polarization plane to the specific orientation required for the liquid crystals to shape the incoming beam. Behind the HWP the beam diameter is expanded via a beam expander. The light is then guided to the SLM (*Hamamatsu, model X13139-04*) which has a resolution of 1280x1024 Pixels. The beam then passes imaging optics with an image in between. In that image plane the 0th diffraction order can be optionally masked out. Behind the imaging optics the beam is introduced into a galvanometric scanner and finally passes an f-theta lens which focuses the beam to the image plane and into a camera system.

As heating laser, a *Trumpf TruMicro 5270* laser with a maximum output power of 60 W, a wavelength of 515 nm, repetition rate of 400 kHz and a pulse length of 6 ps, passes also a HWP and the diameter is expanded via a beam expander to match the size of the reference laser beam. The HWP is rotated so that the polarization plane is perpendicular to the specific orientation required for the liquid crystals. By doing so the absorption of the SLM becomes maximal in order to provoke maximum heating conditions. After the light is reflected by the SLM it goes into a beam dump. The SLM chip is actively cooled to a constant temperature.

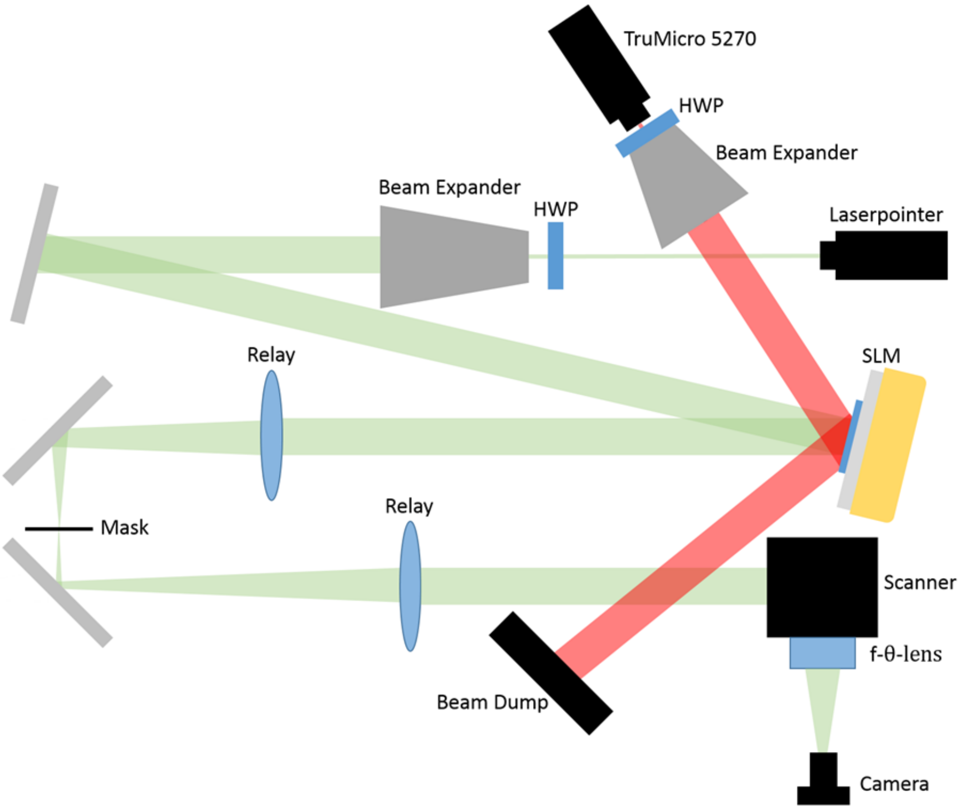

Fig. 2. Setup of the experiment using the general beam path (green) and a heating laser (red).

The whole experiment series are divided into three parts. In the first experiment the power of the heating laser is first increased in steps of 1W, starting with no laser power (0W) up to the maximal power of 60W. The temperature is measured at the liquid crystal display of the SLM via the integrated chip in the device. The temperature is held on a constant temperature of 14°C. After each step of the power increase the control parameter is measured. To explain this parameter, one has to know that the orientation of the liquid crystals are controlled by grey values between 0 and 255. In this way the phase shift caused by the orientation of the liquid crystal can be assigned to a grey value. For each pixel there is a specific grey value that is assigned to a phase shift of π. This grey value is the control parameter.

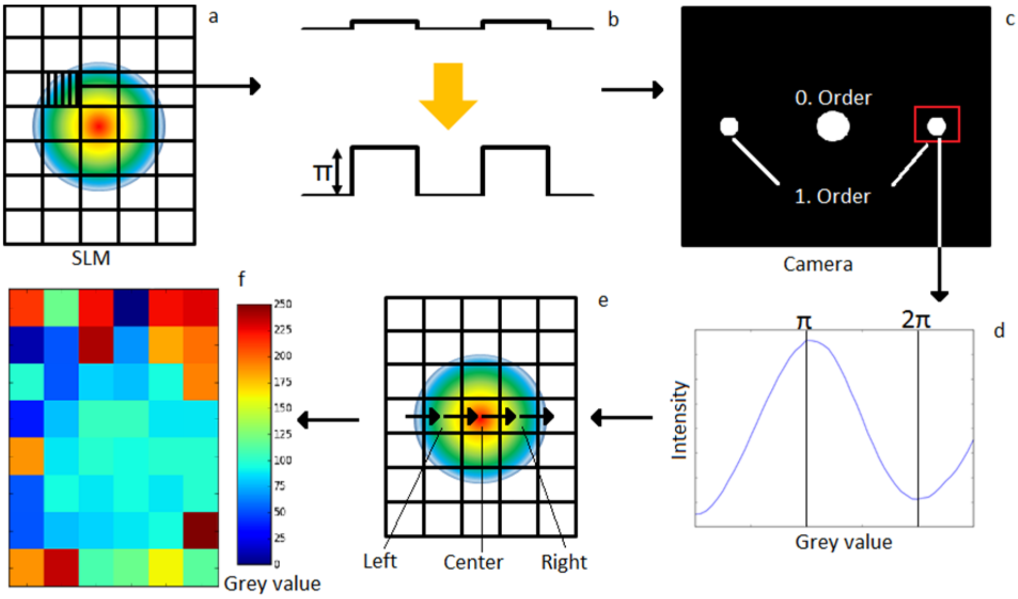

Fig. 3. Measurement of the control parameter in the different experiment parts. First, the SLM is divided into different areas with the size of 180x180 Pixel (a). Then a binary grating is displayed in each part and the difference between the ground plane and the top plane is varied from 0 to 255 in grey values (b). Simultaneously the intensity of the first order is measured on a camera (c). This intensity is assigned to the grey value and the resulting maximum corresponds to a phase shift of pi (d). This is the control parameter. The phase configuration in the different areas are changed during the measurement, in the first and third experiment only the three marked parts are investigated (e), in the second experiment the whole SLM is investigated. The resulting map displays the control parameters on the SLM (f).

The control parameter is measured the same way in both experiments. The SLM is divided into an array of squares with the size of 180x180 pixels. In each part of the array a binary grating is displayed as described in Fig. 3, (a). The grating has two main planes (b). The difference between those planes is varied during the measurement. Because the grating can be displayed on the SLM as a bitmap with different grey values between 0 and 255, the difference of the planes is also set in grey values. The intensity of the first order of diffraction is measured with each step of variation in the difference of the planes of the grating (c). When the resulting phase difference between these planes reaches π, the intensity of the first order of diffraction becomes maximal (d). In the first and third experiment, this measurement is used only with the three marked areas in (e). In the second experiment the whole array is investigated and control parameter fills the complete array (f).

In the second experiment the heating laser is turned to maximal power of 60W on the SLM chip for a time span of 2h. Before the laser is started the control parameter is measured in a grid on the whole SLM with a temperature of 14°C. After 2h this measurement is repeated while the temperature is held constant at 14°C and the laser still turned on. The measurement was only executed two times due to the long measurement time. To compare these results to non-active regulated cooling in a third experiment the power was increased in steps and the control parameter was measured without the active regulated cooling.

3. Discussion

The results of the first experiment are shown in Fig. 4. While the power is increased, the temperature is held at a constant temperature. The measured control parameters in different areas on the SLM where it is exposed to the heating laser only vary in the range of one measurement interval (5 grey value steps). Over the whole range of the power the control parameter does not change significantly in one direction. The active cooling prevents the chip to heat up and conserves the grey value to stay the same.

With an exposure time of 2 min to the high power laser beam per measured value in the first experiment, no statements about the long term behavior of the chip during permanent exposure to high power laser radiation can be made. For this reason the second experiment with a long term exposure was performed.

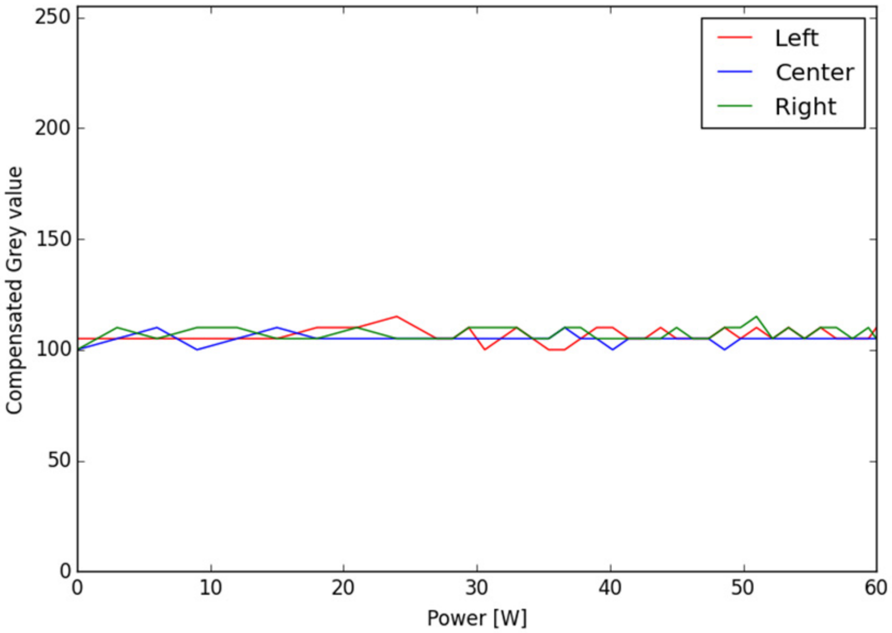

Fig. 4. Control parameter in different areas of the SLM (left, center, right) in dependance of heating laser power. The power of the heating laser is increased at a constant repetition rate of 400 kHz. The control parameter varies in the range of one measurement interval. The grey value has been compensated so that the starting points are in the same area of measurement. The power was increased in steps of 1 W.

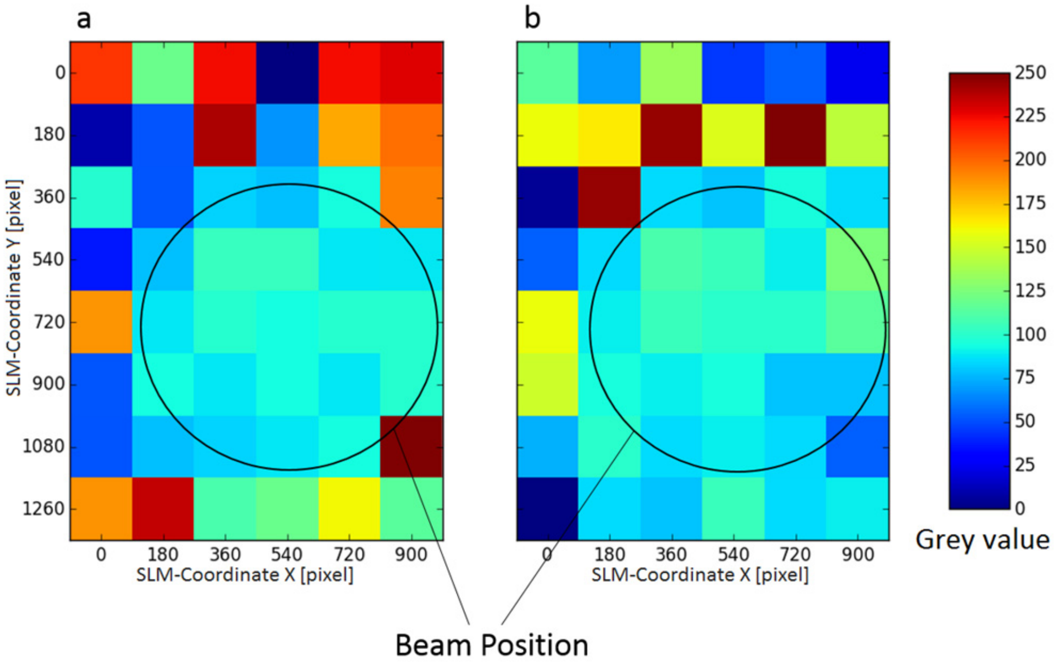

Fig. 5. Distribution of the measured grey values before (a) and after (b) 2 h of laser exposure on the SLM chip. The area in the marked circle is exposed to the laser beams. The results of the regions outside of the circle show strong variations. These results can however be assigned to incorrect measurement as these regions are not exposed to the reference laser beam, hence the measurements can be excluded from the analysis. The heating laser in (b) provides a power of 60 W with a repetition rate of 400 kHz. The control parameter on the different parts of the SLM do not change significantly while exposed to the heating laser for 2h.

The measured distribution of the control parameters before the laser start and after 2h of exposure can be seen in Fig. 5. The grey values stay nearly the same with a standard deviation of one measuring interval. This leads to the assumption that the temperature which was held at 14°C is essential for the phase distribution on the SLM. Because the temperature was held constant the distribution did not change. The third experiment was performed without an active regulated cooling. In this case the phase distribution changed significantly with increasing power. The test was stopped at a power of 32W because the control parameter went out of bounds. The resulting change of the phase shift with the power of the incoming beam affects the beam quality negatively. The system needs a recalibration if the power of the laser or the temperature of the module are changed. This especially shows the necessity of an active regulated cooling coupled with the SLM.

4. Industrial solution for SLM beam shaping – Flexible Beam Shaper

Based on the setup described in Fig. 2 and the results of the high power experiments a prototype of a process head for machine integration has been developed. The industrial prototype of the *FlexibleBeamShaper (FBS)* for laser micro machining as seen in Fig. 6 consists of the SLM-based beam shaping unit combined with a commercial galvanometric scanner to make the processing of larger areas possible and to allow a precise positioning of the modified intensity distribution on the work piece. An integrated cooling device allows to keep the temperature of the SLM-chip on a constant value and thus to work with higher laser powers. A core component of the system is the control software which allows the calibration of the whole system and the generation of the phase distributions for the SLM. In the software the beam can be shaped by loading a bitmap-file and using the implemented two dimensional IFTA for generation of a hologram. Also three dimensional beam operations are possible by integration of Zernike operators and algorithms for creating Fresnel lenses. Using these operations for example the focus plane can be shifted so that it is possible to work in three dimensions without using a z-axis. By using this feature it is also possible to create multiple foci distributions that are aligned along the z-axis. The software features allow to create a variety of different beam intensity distributions, which creates a flexible and powerful tool for process development.

40 Iterations
☑ Weighting
☑ ROI
0.7 eTarget
Phi π 130
Phi 2π (Max. 255) 255
☐ Wavefront Correction (Phase)

Fig. 6. Industrial prototype and Software of the FBS-System. The Software provides a live camera image and the control of the integrated HWP. A bitmap-file can be loaded and the phase hologram can be calculated. The different results can be saved and loaded.

In another experiment the prototype system has been tested with the *Trumpf TruMicro 5270* mentioned above as source of laser power. Different shapes were ablated on a steel sample by loading the bitmap data of the shapes into the software and calculating the phase distribution using the IFTA function. Fig. 7 shows the results of this experiment. The QR-Code (a) and the Pulsar-logo (b) were ablated speckle-free without using a galvanometric scanner. The laser parameters were 15W respectively with a repetition rate of 400 kHz. The squares (c) were produced in combination with the galvanometric scanner while the SLM worked here as a beam splitter producing 6 sub beams with a given distance. The distance between every part beam can be changed dynamically (in (c) changing from row to row) so that the limitations of a static DOE can be resolved. Further ablation experiments using 60W of laser power show some speckle effects, which can however be overcome by using an intelligent combination of scanner and SLM beam shaping or more complex phase distributions. For this, further experiments will be performed with the prototype system in the future.

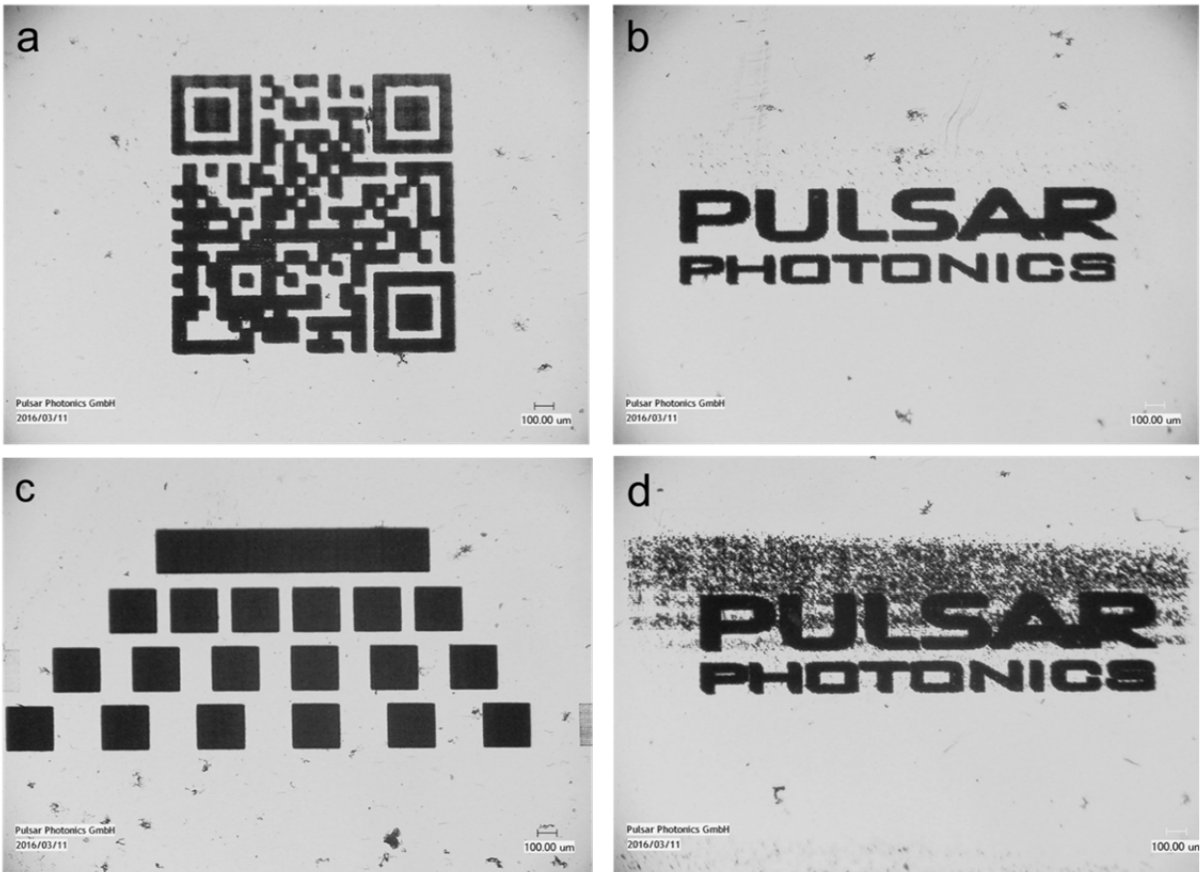

Fig. 7. (a) Ablation result of a QR-Code on steel using a power of 15 W and a repetition rate of 400 kHz. The ablation process was performed without a scanner movement using speckle free distributions. (b) Ablation result of a Pulsar-Photonics-Logo on steel with the same parameter set and the same method as the QR-code. (c) Ablation result of the variation of distances between part beams by row. The ablation was executed on steel using a power of 15 W and a repetition rate of 400 kHz. (d) Ablation result of the Pulsar-Photonics-Logo on steel using a power of 60 W and a repetition rate of 400 kHz.

5. Conclusions

Current developments in laser micro technology show that there is a demand for beam shaping technologies. Experiments in scientific literature further show that there is a great potential for new industrial laser micro processes based on intensity shaped laser beams, especially when using ultra-short pulsed lasers. SLM based beam shaping is an effective and dynamic way to create nearly arbitrary intensity patterns in the work plane of a focusing objective.

The basis for using the SLM technology for process development in laser micro processing is a tool that can be used with high pulse energies and average laser powers in the range of 50 W and more. Within this paper, it has been experimentally demonstrated that the SLM-chip can withstand USP-laser powers of up to 60 W with an active cooling even for longer exposure times. More important is that due to the cooling, the phase calibration of the SLM chip does not (or just minimally) change while exposed to high powers.

Based on the experimental results a prototype for the integration in laser machines was developed. The system has been used for laser ablation with a picosecond laser using a maximum average power of 60 W. The dynamically changeable beam distribution enables new methods in laser micromachining which has the potential to make especially short and ultra-shot pulsed laser processes more efficient. With the prototype system a fully integrated flexible beam shaping solution for machine integration was presented and demonstrated.

Acknowledgements

This work was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) through the Association of Industrial Research Organizations (AiF) within the research project “Multispot” (contract number KF3353301LT4). We would like to thank all funding organizations. We acknowledge Fraunhofer ILT for access to laser and experimental resources.

References

Beck, R. J., Parry, J. P., MacPherson, W. N., Waddie, A., Weston, N. J., Shephard, J. D., & Hand, D. P. (2010). Application of cooled spatial light modulator for high power nanosecond laser micromachining. Optics express, 18(16), 17059-17065.

Engström, D. et al., 2009, Grid-free 3D multiple spot generation with an efficient single-plane FFT-based algorithm. Optics Express 17; S. 9989.

Fienup, JR., 2013, Phase retrieval algorithms: a personal tour. In Appl. Optics 52; S. 45–56.

Froehly, L., Jacquot, M., Lacourt, P. A., Dudley, J. M., & Courvoisier, F. (2014). Spatiotemporal structure of femtosecond Bessel beams from spatial light modulators. JOSA A, 31(4), 790-793.

R. W. Gerchberg and W. O. Saxton, “A practical algorithm for the determination of the phase from image and diffraction plane pictures,” Optik 35, 237–246 (1972)

Hamamatsu: LCOS-SLM (Optical Phase Modulators). http://www.hamamatsu.com/jp/en/product/alpha/L/4015/index.html, 30.03.2016.

Hamazaki, J., Morita, R., Chujo, K., Kobayashi, Y., Tanda, S., & Omatsu, T. (2010). Optical-vortex laser ablation. Optics express, 18(3), 2144-2151.

Jenness, N., Wulff, K., Johannes, M., 2008, Three-dimensional parallel holographic micropatterning using a spatial light modulator. Optics Express, Vol. 16, No. 20, 15942-15948.

Kuang, Z., Perrie, W., Edwardson, S., 2014, Ultrafast laser parallel microdrilling using multiple annular beams generated by a spatial light modulator. Journal of Physics D: Applied Physics 47.

Kuang, Z., Liu, D., Perrie, W., Edwardson, S., Sharp, M., Fearon, E. & Watkins, K. (2009). Fast parallel diffractive multi-beam femtosecond laser surface micro-structuring. Applied Surface Science, 255(13), 6582-6588.

Kuang, Z.: Parallel diffractive multi-beam ultrafast laser micro-processing. Dissertation, Liverpool, 2010.

Lazarev, G., Hermerschmidt, A, Krüger, S., Osten, S., LCOS Spatial Light Modulators: Trends and Applications. Optical Imaging an Metrology: Advanced Technologies, First Edition.

Lopez, J. et al, Glass cutting using ultrashort pulsed bessel beams. Conference paper, International Congress on Applications of Lasers & Electro-Optics (ICALEO), Atlanta, 2015

Neuenschwander, B. et al. In (Niino, H. et al. Hrsg.): LASE. SPIE, 2010; S. 75840R.

Nolte, S,. Schrempel, F., Dausinger, F., Ultrashort Pulse Laser Technology – Laser Sources and Applications, Book, Springer 2016, ISBN 978-3-319-17659-8, S. 166.

Pulsar (2015), Mikroproduktion: http://www.mikroproduktion.com/fachartikel/artikel/damit-aus-ultrakurz-auch-effizient-wird.html, Pulsar Photonics GmbH, 03/2015.

Trumpf (2015), http://www.trumpf-laser.com/nc/en/about-trumpf/press/press-releases/press-release-detail/rec-uid/272395.html, 22.06.2015.

Weber, R., Michalowski, A., Abdou-Ahmed, M., Onuseit, V., Rominger, V., Kraus, M., & Graf, T. (2011). Effects of radial and tangential polarization in laser material processing. Physics Procedia, 12, 21-30.