Multibeam laser processing for high throughput manufacturing-project report

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Summary

In this project aim was to develop industrial laser processing applications with a high throughput using adaptive optics. This was carried out by developing and building up spatial light modulator (SLM) base systems in both Joensuu and Lappeenranta. With this kind of system it is possible to utilize full potential of high pulse energy lasers like femtosecond systems. Added to this picosecond and nanosecond lasers were applied with SLMs. During the project, the manufacturers announced limit for power handling capacity of the SLMs were exceeded multiple times by adding the liquid cooling unit to the SLM.

Goals of the project set in beginning were achieved well. Controlling systems and designing algorithms for SLM were developed a lot during the project. Added to this industrial applications of the companies were developed much. In project multibeam hole drilling, marking and fabrication of the functional surfaces were studied. During the project, productivity of these surface processes was increased tens to even hundreds of times compared to standard processes with simple galvanometer scanner.

As a conclusion of this projects report it can be said that goals were met well although there is naturally still a lot to study and develop in this field.

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Preface

Project "Multibeam laser processing for high throughput manufacturing" (Multibeam) was carried out during the years 2011-2013. Project was performed with co-operation together with University of Eastern Finland (UEF) and VTT's research group in Lappeenranta. VTTs other groups in Espoo and Oulu also assisted to perform the project.

Project was funded by TEKES, participating companies and VTT.

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Project manager of this project was Dr. Kimmo Päiväsaari, UEF. In addition following researchers from VTT and UEF participated into project, which writers would like to acknowledge: Vesa Airas, Raimo Penttilä, Hanna Toppila, Ilkka Vanttaja sekä Martti Silvennoinen. Writers of this report would like to acknowledge the steering group and all companies in the project for active steering and good cooperation throughout the project.

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1. Introduction

During the last decade, femtosecond and picosecond lasers have been employed to obtain high precision surface micro-structuring of various materials, like metals and semi-conductors. These lasers have pulse lengths less than t < 10 ps and therefore they are also called as ultrashort lasers. By using these lasers, minor thermal damage on matter is caused due to their short timescale. In this timescale energy has no time to couple into lattice of the matter. In metals heat diffusion during the temporal ultrashort pulse width can be reduced into nanometers scale compared to the optical skin depth, when the fluence F is kept in low region (typically around $F \sim 1$ J/cm^2). Accordingly the pulse energy used in ultrafast laser processing is often kept in µJ level to achieve fine micro-/nano-surface structuring, due to the low and well-defined ablation threshold. Consequently, high gain regenerative amplifier systems running at repetition rate in level of 1 kHz and providing pulses with energy in range of mJ, have to be attenuated heavily. This naturally limits the usability of the total capacity of the laser power.

Previously it has been discovered that novel optics is needed means to be enable to utilize higher throughput of the high pulse energy and relatively low repetition rate femtosecond laser. In previous projects we have used conventional optical, like stationary diffractive gratings and elements, to realize this. We have used barrel or cylindrical lens to create a line focus which has worked well in manufacturing of grid like patterns. In this case Powell lens would be even more sophisticated option, due to Gaussian intensity profile of the femtosecond laser. This is because cylindrical lens is not optimal for the Gaussian shape to be able to generate even intensity line, whereas with Powell lens it is possible to realize flat intensity on whole focused line. In previous project other novel way of utilizing conventional optics was diffractive optics. This was applied to create hole matrixes in case of the laser drilling. Problem with traditional glass, usually quartz or fused silica, based diffractive optics is that they are not flexible. If the different intensity distribution is wanted new element is required. This is not very economical, because manufacturing of the traditional diffractive optics is relatively complicated and expensive.

The use of multiple parallel beams is a novel method to increase throughput and efficiency of femtosecond laser processing. By applying dynamic or adaptive diffractive optical elements like spatial light modulator or digital micro mirrors, arbitrary beam patterns can be realized. These kinds of methods are capable of flexible and variable beam pattern generation. A Liquid Crystal on silicon - Spatial Light Modulator (Lcos-SLM) is a programmable computer generated holographic (CGH) or diffractive optical element (DOE) which consists of pixelated liquid crystals with back mirror. Each pixel is individually cable to cause certain phase shift into incoming wavefront at that point on the panel. Parallel processing using multiple beams generated by a SLM has already been demonstrated to increase throughput and efficiency of ultrafast laser processing [15-18]. By synchronizing the SLM with a scanning galvanometer mirrors, diffractive multiple beams processing shows further flexibility and potential of the given laser system. Mechanical and optical components needed to build laser systems with SLM are nowadays already available. However, suitable laser processing solutions with optimized processes have to be still developed. Furthermore, the use and guiding of SLM has to be still improved. Added to this, there exists only limited amount of commercial programs to design proper CGHs. In some specific cases there is still no suitable programs available. In addition, to be able to divide laser beam into multiple beam with SLM, the laser has to have high enough average or peak-power to be able to process the materials, like metals and dielectrics.

During this project we have demonstrated the ability of SLM technology to increase productivity of high pulse power lasers like femtosecond laser system. Different kinds of lasers were tested to study their usability with spatial light modulator. A lot of work was also done in programming and controlling of the SLM because there was and there is still no proper commercially available software which would provide needed functions. Added to this a lot of study and improvements was done in development of the CGH’s designing and optimization.

2. Goal

The goal of this project was to develop high throughput systems for the industrial laser micro processing applications. This was carried out by developing and building the spatial light modulator based laser systems in Joensuu and Lappeenranta. With these systems it is possible to utilize the full potential of high pulse energies like in femtosecond laser systems. Always when high accuracy in processing is needed the pulse energy has to be close to ablation threshold and then in generally average powers are not too high. By increasing the productivity the laser beam needs to be divided into multiple spots or use higher repetition rate lasers. With high repetition rate the scanning speed might be a problem since nowadays the highest repetition rates are in the range of tens on megahertz and typically speed of the high accuracy moving systems, like galvanometer scanning mirrors, is in range of meters per second.

During the project a lot of work was done to improve the programming of spatial light modulators and designing of the computer generated holograms. By improving these, the efficiency and accuracy of these elements can be higher. This kind of programming and design is needed because commercial software, which can utilize all the features of SLMs, does not exist. UEF have extensive background on designing and optimization of the diffractive phase elements needed for the advanced controlling the beam pattern with SLM. Of course it is worth mentioning that these systems are only tools for making research in this field. In addition to more general improvement of the SLM technology, another goal of the project was to improve industrial applications. In this project we had several industrial based objectives which will serve as a platform to show the industrial potential of this technology. Main objectives on these applications were: functionalization of surfaces, drilling, marking and engraving.

This technology can also be applied with more traditional laser sources used in the industry. For example the nanosecond laser sources are the backbone of marking industry and usually in those applications speed is the crucial factor. In this project speed and flexibility of these processed were increased by using them with parallel beam processing methods. Power handling capacity of the SLM’s for different lasers was also one of the issues to be studied in order to see their real potential in industrial applications. Therefore SLM were applied with CW, µs-, nano-, pico- or femtosecond laser system in this project.

High power CW systems can also be used with SLMs but then normal diffractive optics is needed at really high average powers. Still the SLM can be used as good testing system to optimize the design of desired computer generated holograms.

One goal of this project was to gain knowledge from other research institutes on the field. This is why a 6 months researcher exchange was set as one goal to have deeper understanding what happens globally in this particular research field. This research exchange was realized in Heriot-Watt University at prof. Duncan P. Hand group by Dr. Jarno Kaakkunen. They are one of the leading groups in academic research in spatial light technology.

3. Fundamentals of SLM technology

3.1 Spatial light modulators

Spatial light modulator is an electrically programmable device that can be used to modulate the phase of the laser beam in a controlled manner. Usually this is done with fixed spatial pattern of pixelated liquid crystal cells where each pixel can produce the desired phase shifts between 0-2π to the incoming laser beam. Now this two-dimensional pixelated pattern can be used as a programmable diffractive optical element.

The phase shift to the laser beam in SLM is introduced by electronically driven nematic liquid crystals. The phase of the light travelling through the liquid crystal layer depends on the orientation of the liquid crystal cells. Orientation of the cells can be controlled using pixelated electrodes connected to the liquid crystal layer. In Fig. 3.1.1 is shown the principle of the liquid crystal SLM.

For laser micromachining purposes the most important parameter for SLM performance is the laser power handling capacity. When using femtosecond laser the liquid crystal cell must be able to handle high values of the peak power without damage. Other relevant parameters for the micromachining are the pixel size, light utilization efficiency and frame refresh rate of the SLM. The SLM chosen for this project was Hamamatsu X10468 series LCOS-SLM (Liquid Crystal on Silicon Spatial Light Modulator). Hamamatsu was chosen for its laser power handling capacity that was much higher than in models from the other manufacturers. This is mainly due to the use of dielectric mirror instead of metal mirrors in SLM module. As a drawback, dielectric mirrors work only for the limited wavelength range and in practice you need a different SLM module for different lasers. In Fig. 3.1.2 is shown the Hamamatsu SLM head and the control unit.

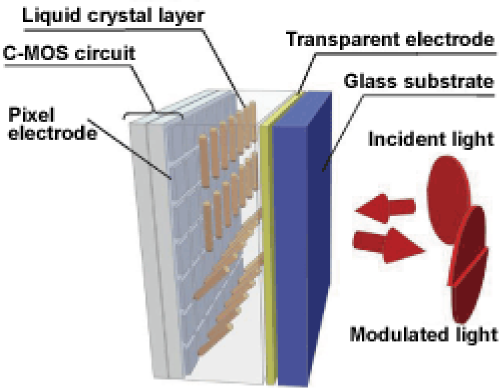


Fig. 3.1.1 Operation principle of the liquid crystal SLM.

Fig. 3.1.2 Hamamatsu SLM head and controller used in the project.

3.2 Software

Softwares used in the project for the controlling the SLM and calculation of the holograms were Hamamatsu Labview control software, VirtualLab and Matlab. Hamamatsu Labview control software is the operation software for the SLM. It can be only used for the feeding the

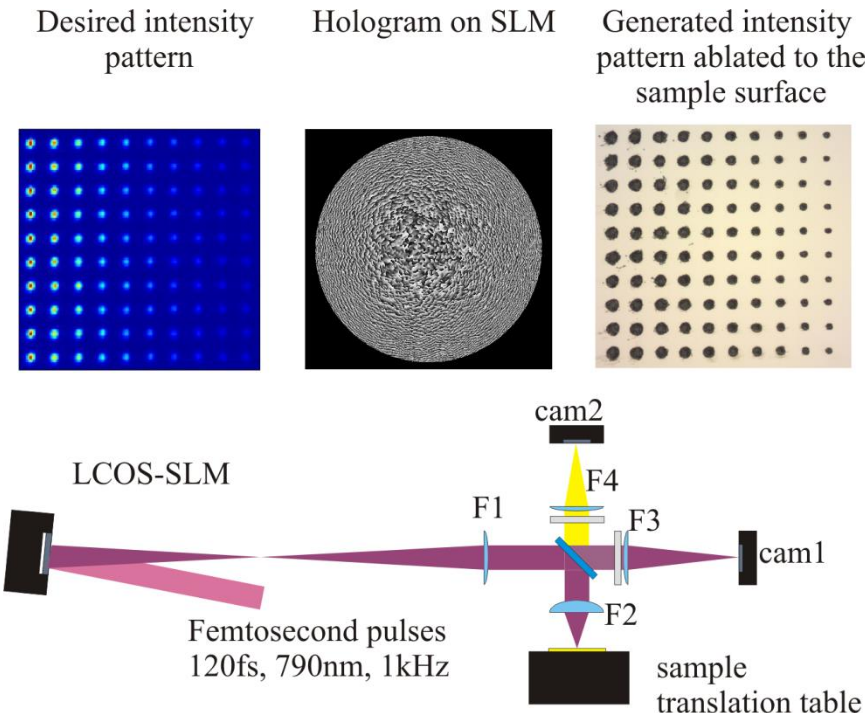


Fig. 3.1.3 SLM as a part of the laser micromachining setup.

holograms to the SLM and even this function can be bypassed to, for example, Matlab.

VirtualLab is a commercial program from LightTrans for the unified optical modelling. As the company web page say “The VirtualLab™ package integrates several toolboxes allowing the analysis of systems, design of diffractive optical elements, design of beam shapers, analysis of gratings, analysis laser resonators as well as the shaping and homogenization of LED light”. The program was used in the beginning of the project for the calculation of the holograms and it was good for the calculation of holograms with high diffraction efficiency, but the calculation times were usually long. In addition, the calculation of the some specific holograms, for example holograms generating intensity patterns with uneven intensities or in 3D, were complicated.

Matlab software made by Mathworks was used for the calculation of the majority of holograms used in the project. As the company web page say “MATLAB® is a high-level language and interactive environment for numerical computation, visualization, and programming”. The hologram designing using Matlab was based on the iterative Fourier transform algorithms (IFTA) and the procedure is explained in more details in chapter 5. In addition to the hologram calculation, Matlab was used for controlling the shutter and energy attenuator in optical setup used by the UEF.

4. SLM Workstations

4.1 SLM workstations used in VTT

Liquid crystal on silicon Spatial light modulators (Lcos-SLM) were studied using three different lasers: IPG YLP-20, IPG YLP-HP-100 and Quantronix Integra-C 2.0. Two first ones provides pulses in nanosecond and last one in femtosecond range. Both nanosecond lasers were operating in about 1064 nm wavelength and femtosecond laser in 790 nm wavelength. Because of different wavelength, two different SLMs were required.

4.1.1 Hamamatsu Lcos SLM

In studies two different SLMs were used due to two different wavelengths of the lasers. Both of the SLMs were provided by the Hamamatsu Photonics. First SLM was commercial available Hamamatsu Lcos-SLM X10468-02 and second one OEM Lcos-SLM X11840-03. First one operates in wavelength range from 750 nm to 850 nm and latter one from 1000 nm to 1100 nm. In Fig. 3.1.2 there is image of the Hamamatsu Lcos-SLM X10468 series SLM and in Fig. 4.1.1 image of the OEM Lcos-SLM X11840-03. In both of these SLMs there were 792 x 600 pixels with size of the 20 µm x 20 µm meaning that total size of the liquid crystal panel is 15.84 mm x 12.00 mm. Both of the SLMs have about 95 % reflectance and they can cause more than 2π-phase shift to designed wavelengths. Liquid crystals can only modulate linear polarization. Repetition rate of these SLM were 60 Hz.

With Lcos-SLM X11840-03 liquid cooling system was used. Cooling was realized with standard computer processor unit (CPU) liquid cooling system Corsair H100. In practice this cooling unit was simply mechanically pressed into backside of the Lcos-panel (see Fig. 4.1.2). Cooling system circulates liquid around the closed circle containing cooling unit itself and cooling fan unit (see Fig. 4.1.2). Cooling fan unit cools down the liquid that has warmed during the cycle in cooling unit. Cooling fan unit has two fans that blow air through the metallic grill. Silver thermal compound between cooling unit and SLM was used to

Fig. 4.1.1 Hamamatsu OEM Lcos-SLM X11840-03 display and controlling unit with the self-build cover.

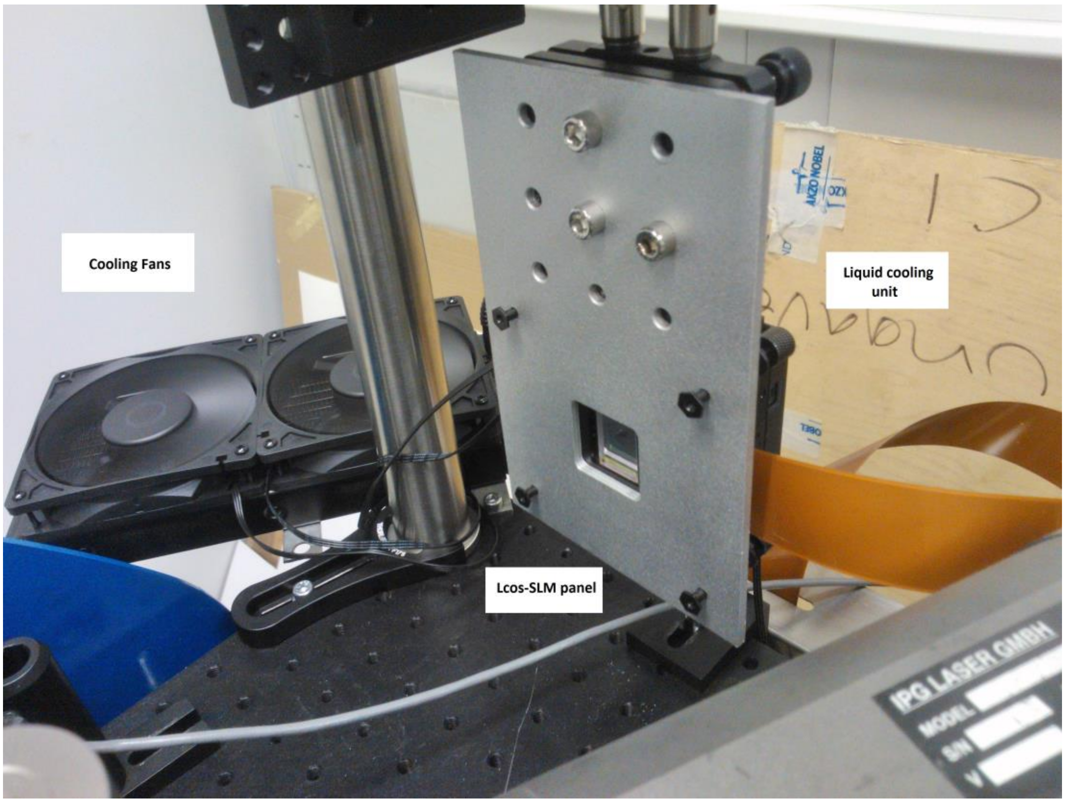


Fig. 4.1.2 Liquid cooling system with OEM Lcos-SLM X11840-03.

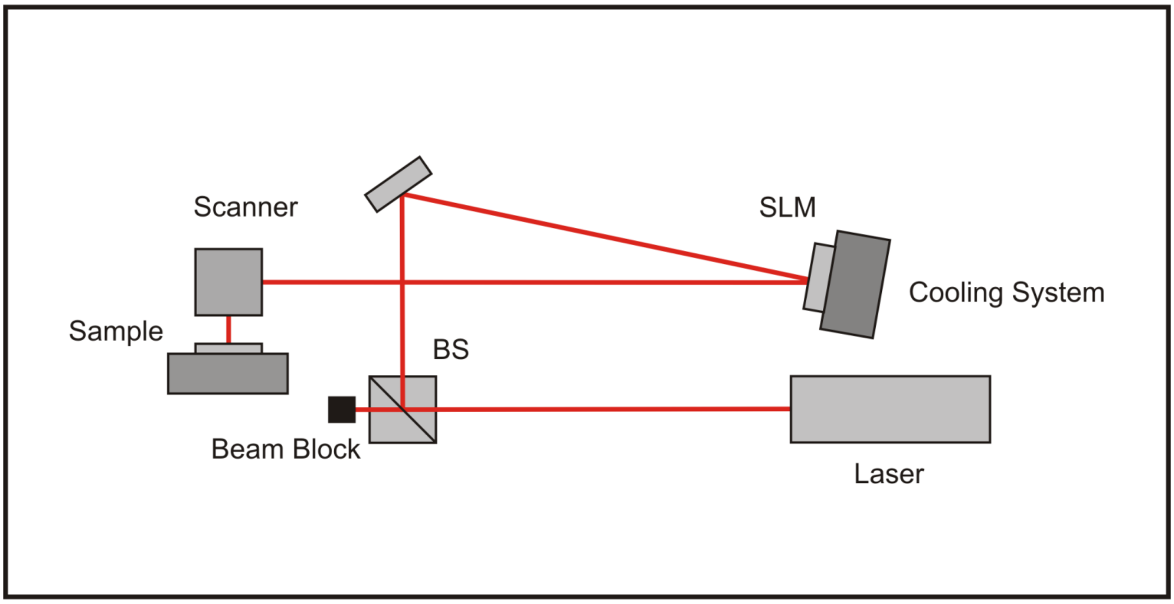
enhance thermal conductivity between them.

4.1.2 SLM with nanosecond fiber lasers

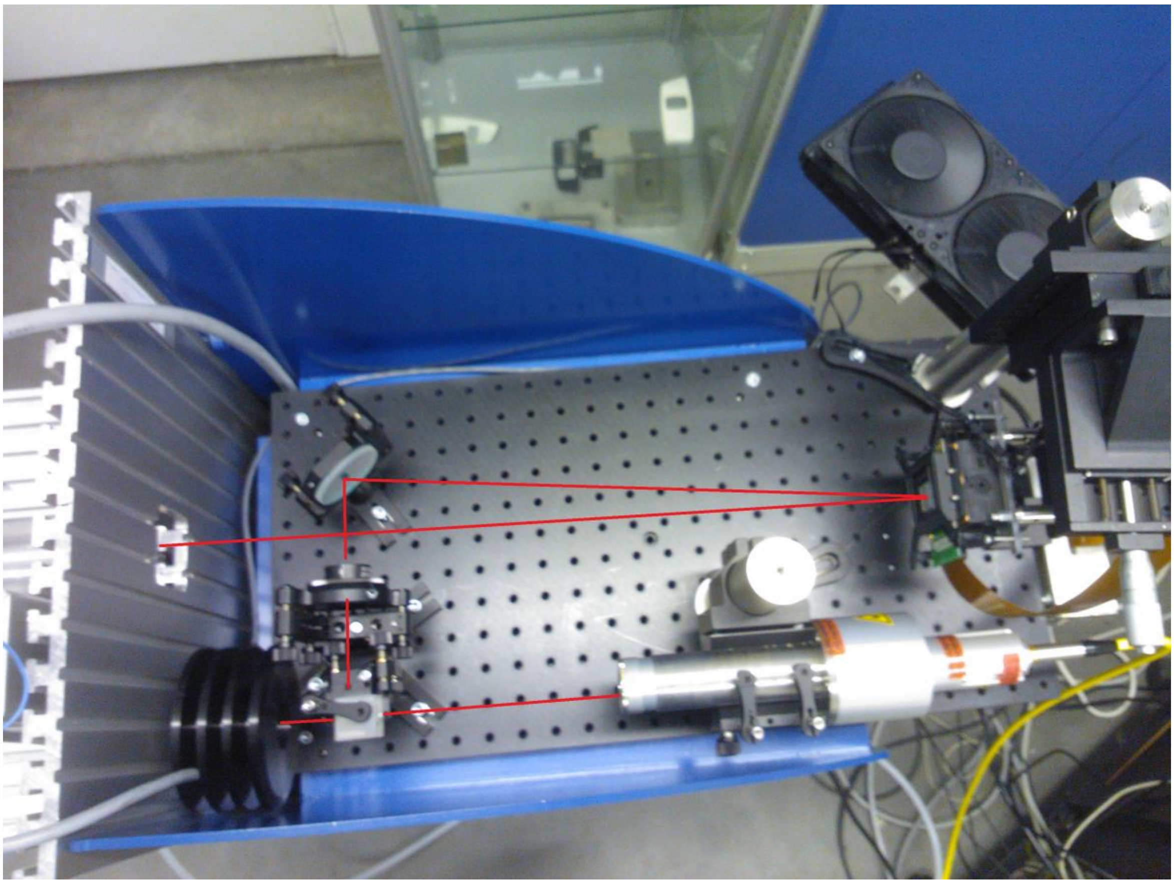
OEM Lcos-SLM was used with two different nanosecond lasers: IPG YLP-20 and IPG YLP-HP-100. In Table 4.1.1 specs of the lasers are shown.

Table 4.1.1: Specs of the nanosecond fiber lasers used in studies.

	IPG YLP-20	**IPG YLP-HP-100**
Pulse length	110 ns	1500 ns
Max. Pulse Energy	1 mJ	2 mJ
Repetition Rate	20 – 80 kHz	5 – 100 kHz
Power	20 W	100 W
Beam size	7.5 mm	7.5 mm



(a)



(b)

Fig. 4.1.3 Schematics (a) and camera image (b) of the setup used in nanosecond fiber laser experiments.

Beam quality M2 of the lasers was under 2. Both of the lasers were randomly polarized so before using those with SLM the polarization had to be filtered to linear polarization. In practice this means that half of the laser power lost. In Fig. 4.1.3 there is schematics (a) and

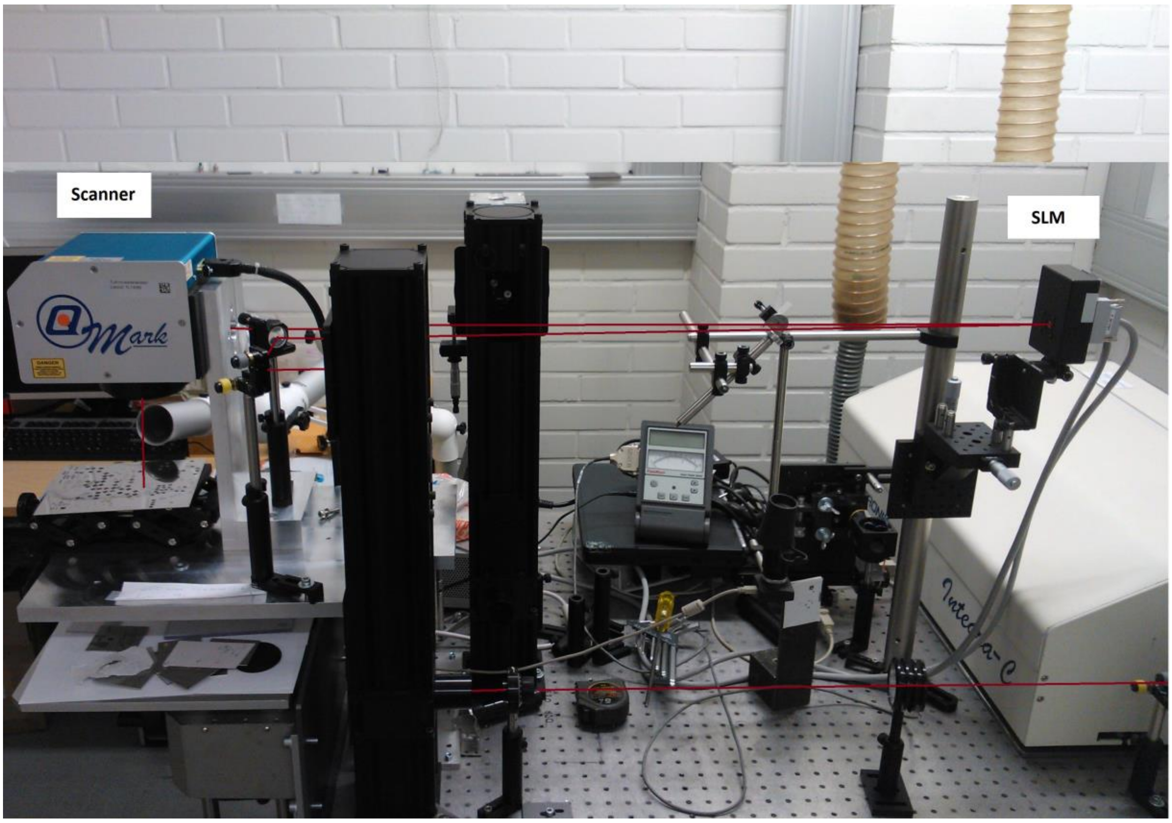
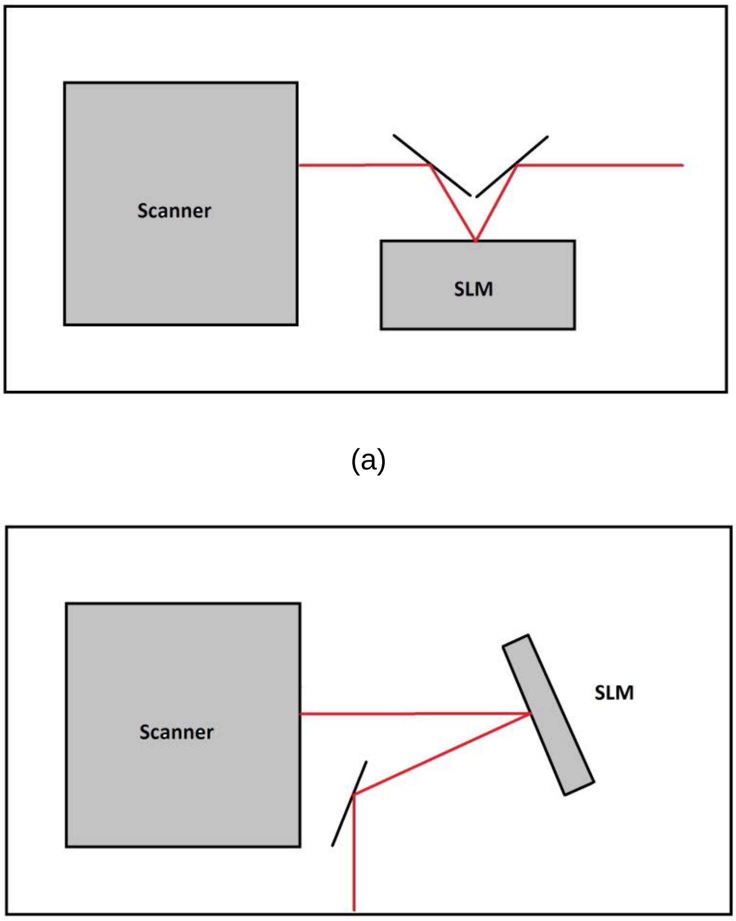


Fig. 4.1.4 Setup used in femtosecond laser pulse ablation with SLM.

camera image (b) of the setup used in studies. In this setup fiber laser head that can be easily changed to another is attached into angle tunable holder. After this laser beam is directed into polarizing beam slitter (BS). In this point polarization of the beam is polarization purified and half of the power is lost. This means that maximum power in SLM with IPG YLP-20 and IPG YLP-HP-100 was 10 W and 50 W, respectively. Unwanted polarization is directed into beam block and wanted one directed through λ/2-waveplate. With this λ/2-waveplate polarization of the pulses can be fine-tuned to be correct in SLM. In practice this was not always used because the polarization coming from polarizing beam splitter was already well aligned. After λ/2-waveplate pulses were guided into spatial light modulator using mirror. Beam was coming into the SLM with an angle of 3 degree. After SLM the nanosecond pulses were directed into galvanometer scanner containing F-theta lens. In studies F-theta lens with focal length of f = 100 mm was used. Used scanner was ScanLab hurryScan II. Distance between the scanner and SLM was about 830 mm.

4.1.3 SLM with femtosecond laser

As femtosecond laser Quantronix Integra C-2.0 was used. This laser provides maximum 2 mJ pulses with 1 kHz repetition rate meaning maximum 2 W power. Length of the pulses is 130 fs and their central wavelength is 790 nm. Setup used in experiments is shown in Fig. 4.1.4. After laser energy of the pulses is adjusted with attenuator based on polarization. There was also λ/2-waveplate, which can be used to adjust polarization of the linearly polarized pulses to be correct in SLM. Like in setup used with nanosecond lasers, this element was not necessary because the system could be aligned so that polarization after attenuator is already correct for the SLM. With femtosecond laser Lcos-SLM X11840-03 was used. After λ/2-waveplate pulses are guided into SLM with an angle of under 1 degree using mirrors. After this pulses are directed into galvanometer scanner (Q-mark from Quantronix) with f-theta lens (f = 100 mm). Distance between SLM and scanner was about 1100 mm.



(a)

(b)

Fig. 4.1.5 Schematics of the two compact optical configurations of the combination of the SLM and galvanometer scanner.

4.1.4 Industrial solutions for workstations

For some industrial application workstations shown in Sections 4.1.2 and 4.1.3 might require too much space. Setups shown in these sections require more than 1 meter optical beam bath. This is quite long if the real industrial applications are considered. However, there are also possibilities to compress these setups into more compact space. In Fig. 4.1.5 there are schematics of two possible setups that do not require much space and could be still used for micromachining proposes. This kind of optical configurations require even less than 100 mm x 100 mm space before the galvanometers scanner. Naturally, controlling unit and power supply are not included into this space.

However, it is worth remembering that if the Fresnel lenses are applied and small features are wanted with these setups relatively short focal lengths of the Fresnel lenses are required. In some cases this might be problematic because resolution of the SLMs is limited. If smaller Fresnel lenses are wanted, smaller pixels in SLMs are required. For example with used Hamamatsu SLM with 20 µm x 20 µm pixel size, smallest usable focal length of the Fresnel lens is about f = 300 mm.

4.2 SLM workstation used in UEF

Experiments in UEF were done using Quantronics Integra-C femtosecond laser providing up to 3 mJ pulse energy and 120 fs long pulses at 790 nm central wavelength with 1 kHz

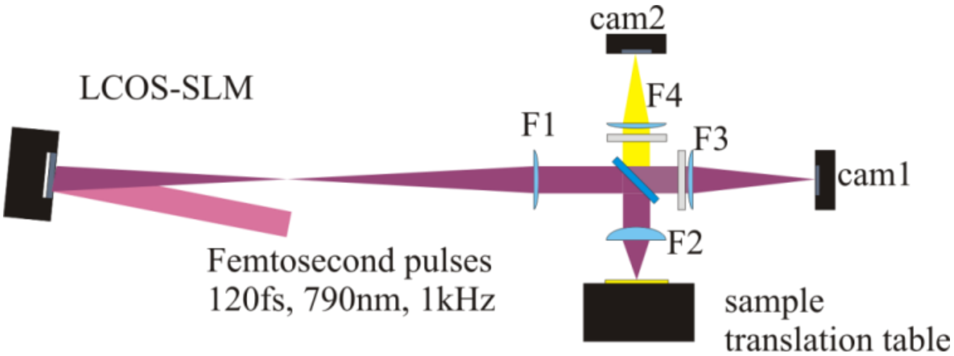


Fig. 4.2.1 Optical setup used by the UEF.

repetition rate. Hamamatsu X10468 series LCOS-SLM (Liquid Crystal on Silicon Spatial Light Modulator) was used in the experiments. The pulse energy was limited to 1.5 mJ due to the limited peak power handling of the SLM. The set-up also had a computer controlled energy attenuator. In the Fig. 4.2.1 is shown the schematic of the optical setup used by the UEF. Lens F1 collimates beams from SLM and F2 focus beams on the sample surface. Lens F3 focuses beams to camera 1 which is used to measure the amplitudes for calculation of the holograms. Camera 2 with lens F4 is used to monitor ablation process.

5. Generation of holograms

Usually in literature the phase distribution that is inserted to the SLM in order to get desired intensity distribution is called computer generated hologram (CGH). In this chapter the calculation procedure for the generation of the holograms is presented. Usually this procedure is based on the iterative Fourier transform algorithms (IFTA).

5.1 Iterative Fourier transform algorithm for hologram designing

The holograms for generating desired intensity patterns are usually calculated using iterative Fourier transform algorithm. IFTA is based on the fact that the field representing our desired intensity pattern in the image plane (in our case the sample surface) is a Fourier transform pair with transmittance function of the element in the component plane (in our case SLM). This enables the calculation of the phase distribution (hologram) on the SLM by iteratively travelling the field between the image and SLM plain using Fourier transforms while presenting design constraints in image and SLM plane. This procedure is presented in Fig. 5.1.1 as a block diagram.

The procedure showed in the block diagram can be explained step by step as follows:

- First the target signal amplitude obtained from the target signal intensity is combined with starting phase in order to form a field $E(x,y,z_i)$. The form of this starting phase can affect to the end result and should be chosen wisely.
- Field is transferred from the image plane to the SLM plane using Fourier transforms F. In Matlab this is done by using FFT2 function that can be found from Matlab's signal toolbox.
- In SLM plane field $E(x,y,z_0)$ is separated to the phase and amplitude components and amplitude component is replaced with the laser beam profile. New $E(x,y,z_0)$ is formed by combining the phase and laser beam profile.
- Field is transferred back to the image plain using Fourier transforms F^{-1}. At this point the amplitude is evaluated and if the result is acceptable, in the sense that the difference to the target signal amplitude is small enough, iteration is stopped. In this case the phase in the field $E(x,y,z_i)$ is the hologram that produce the target signal intensity when used in the SLM.
- If the result is not acceptable, amplitude is replaced with the target signal amplitude

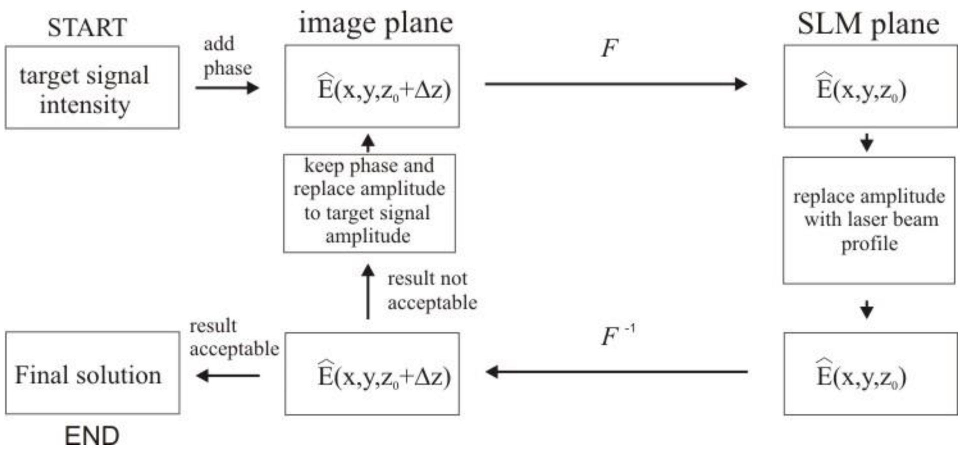


Fig. 5.1.1 Block diagram for IFTA.

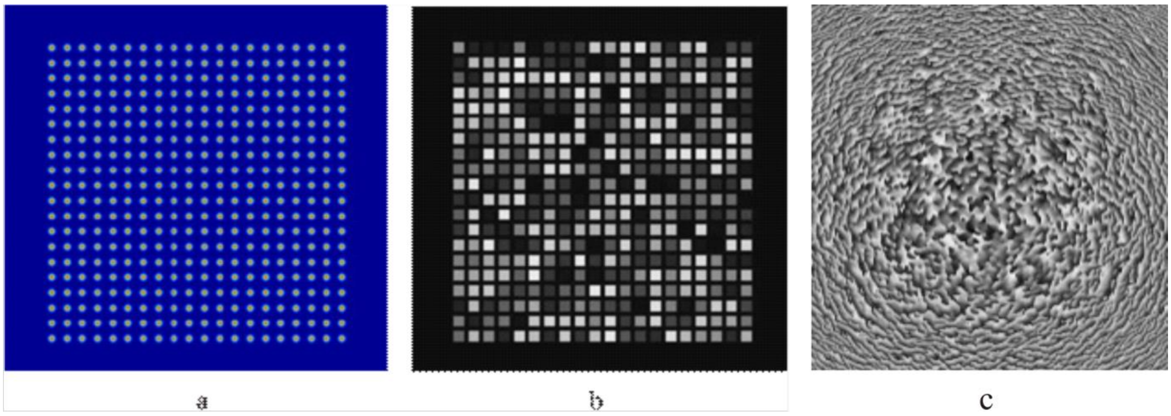


Fig. 5.1.2 (a) target intensity pattern.(b) starting phase for hologram calculation. (c) calculated hologram that produces target intensity pattern when applied to the SLM.

and next iteration cycle is started by transferring the field to the SLM plane by Fourier transform.

- If the iteration stagnates and refuses to deliver the acceptable result, new starting phase must be selected.

In order to illustrate the above described hologram calculation process. Fig. 5.1.2 shows a target intensity pattern (a), a starting phase (b) and the solved hologram (c) that generate the target intensity pattern when applied to the SLM.

5.2 IFTA using camera correction for hologram designing

Camera correction loop was implemented to the setup used by UEF. The camera feedback loop helps to align the setup and to correct amplitude errors coming from the environmental changes in the setup. In Fig. 5.2.1 is shown the block diagram for the hologram designing procedure using IFTA and camera correction. The procedure showed in the block diagram can be explained step by step as follows:

- First the target signal amplitude obtained from the target signal intensity is combined with starting phase in order to form a field $E(x,y,z_i)$. The form of this starting phase can affect to the end result and should be chosen wisely.

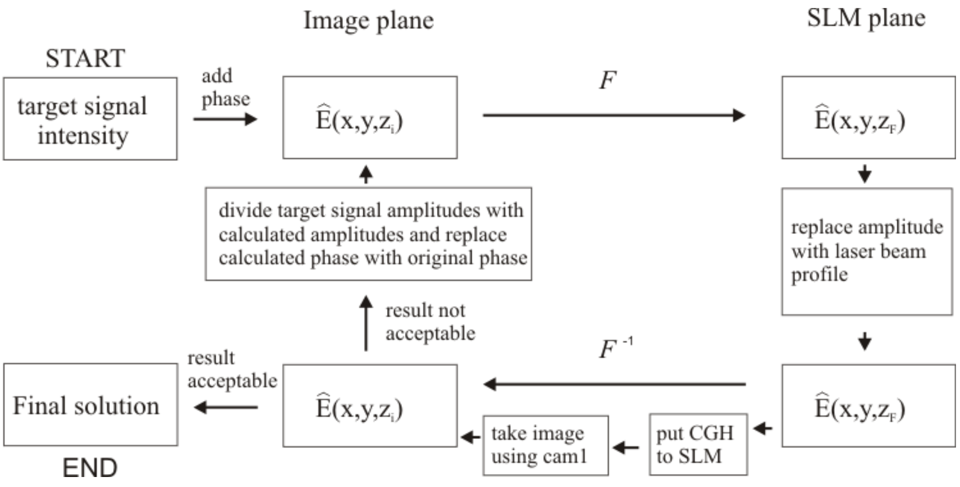


Fig. 5.2.1 Block diagram for IFTA.

- Field is transferred from the image plane to the SLM plane using Fourier transforms *F*. In Matlab this is done by using FFT2 function that can be found from Matlab’s signal toolbox.
- In SLM plane field $E(x,y,z_0)$ is separated to the phase and amplitude components and amplitude component is replaced with the laser beam profile.
- The phase is fed to the SLM and the signal intensity is photographed using CCD camera. Measured intensity data from the camera must be scaled to corresponding target intensity values. The signal intensity is compared to the target intensity and if the result is acceptable the iteration is stopped.
- If the result is not acceptable, target amplitude is divided by measured signal amplitude and next iteration cycle is started by transferring the field to the SLM plane by Fourier transforms F.
- If the iteration stagnates and refuses to deliver the acceptable result, new starting phase must be selected.

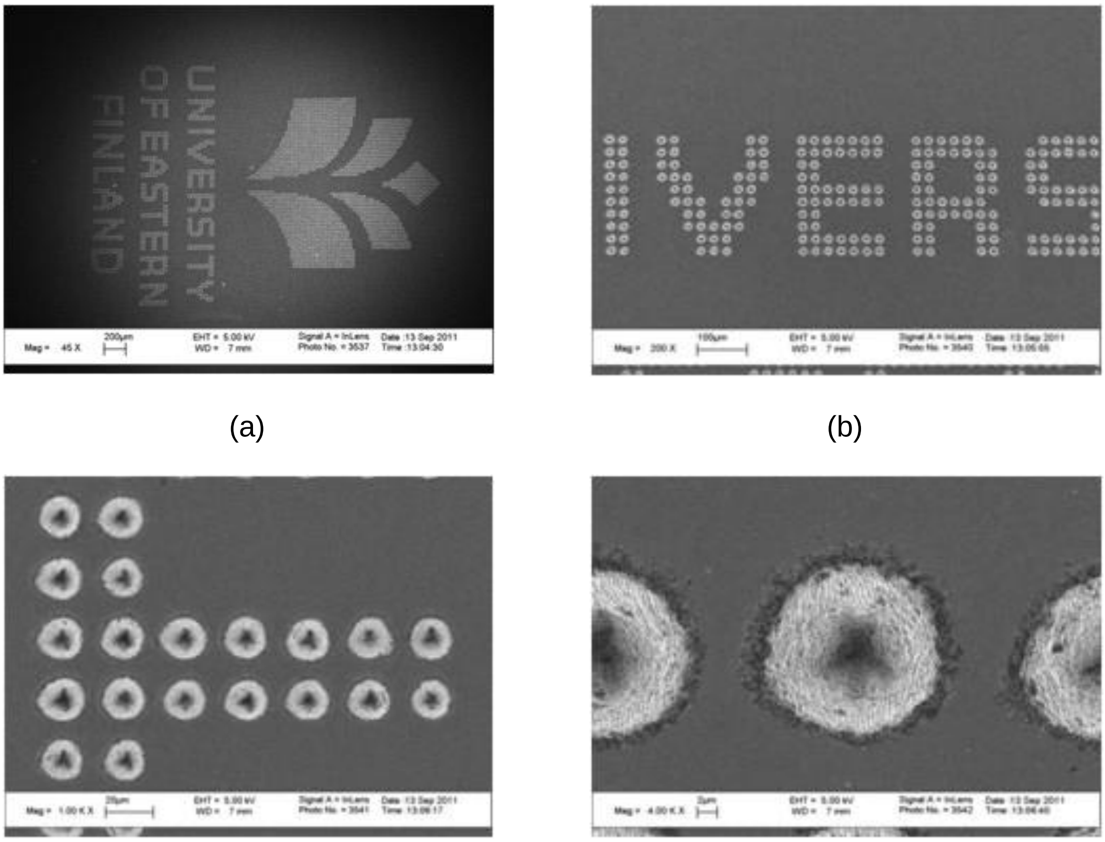
6. Results

6.1 Parallel ablation using SLM

In this project the SLM is used for generation of beam matrixes for parallel micromachining purposes. The original laser beam can be divided up to several hundreds of beams which position can be controlled accurately. In Fig. 6.1.1 is shown one of the projects first parallel ablation experiments using the SLM. The UEF logo is ablated using 16 different holograms so that the 256 spots are ablated simultaneously. This ablation confirmed that the SLM technology can be used for laser micromachining. High parallelism can be obtained and ablation using different holograms can be joined seamlessly. Small features can be generated and positioned accurately.

The degree of parallelism that can be obtained for the combination of femtosecond laser and SLM is shown in the Fig. 6.1.2. Original laser beam can be divided up to 2500 beams that are still above ablation threshold of the silicon. However, in this case the illuminated area is becoming so large that distortions start to appear on the edges of the intensity pattern. The original beam can be divided up to 900 beams without any obvious distortions as shown in the Fig. 6.1.2 (b).

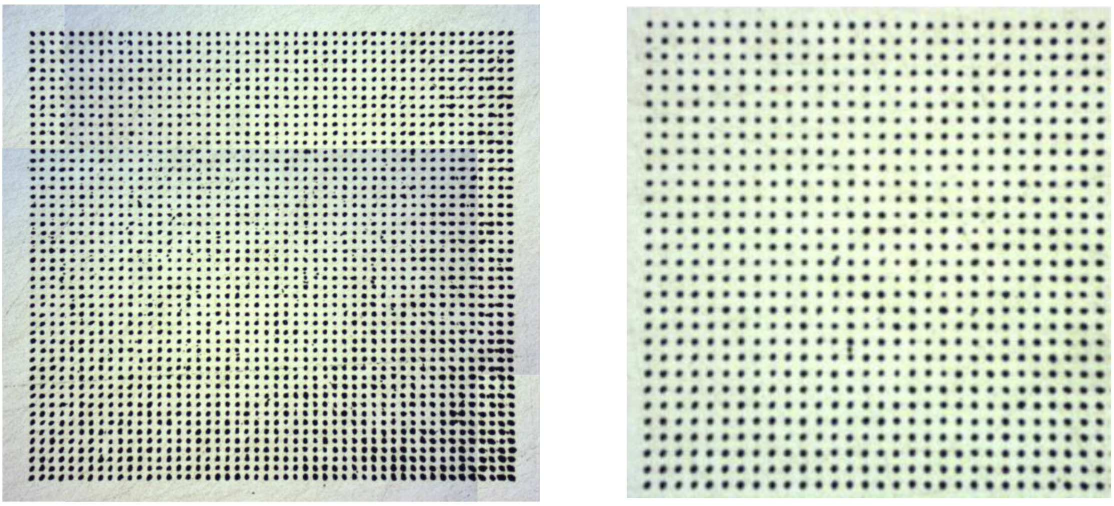
The feature sizes that can be generated using the optical setup shown in the Fig. 4.2.1 can be varied from hundredths of micrometers down to the one micrometer. In the Fig. 6.1.3 is shown the hole matrix having the hole diameter of 1μm ablated in silicon. This was obtained by using ordinary lenses for imaging the intensity pattern in ablation plane. Here the microscope objectives must be used for the generation of the smaller feature sizes



(a) (b)

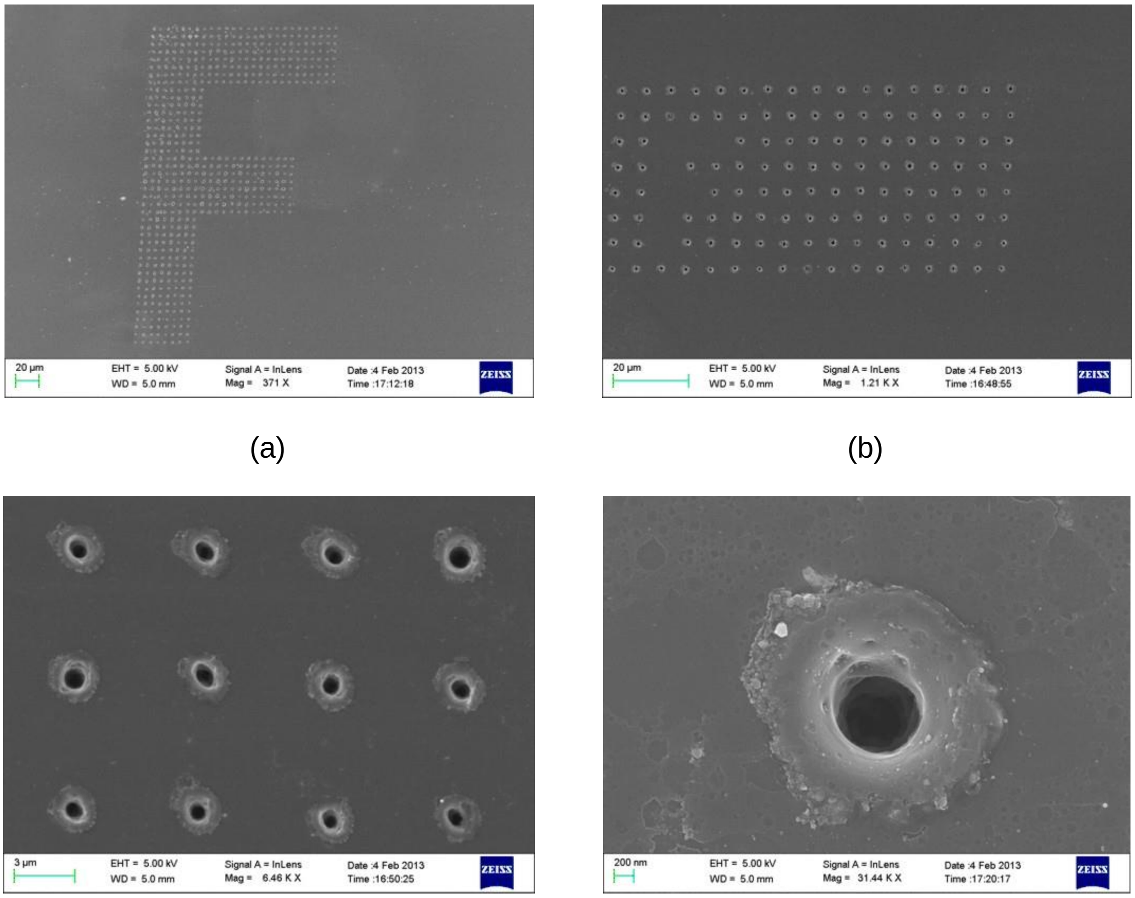
(c) (d)

Fig. 6.1.1 SEM pictures from UEF logo ablated to the steel. Scale bars are 200, 100, 20 and 2 µm.



(a) (b)

Fig. 6.1.2 Beam matrixes of 50 x 50 and 30 x 30 ablated to the silicon.



(a) (b)

(c) (d)

Fig. 6.1.3 SEM pictures of ablated UEF logo in silicon. Diameter of the individual hole is 1 µm. Scale bars on the pictures are 20 µm, 20 µm, 3 µm and 200 nm.

a b c d

Fig. 6.2.1 Picture of the Dr. Kaakkunen (a) copied using laser ablation to the silicon (b)-(d).

6.2 Parallel ablation using individually controlled beam intensities

In previous chapters are shown ablations using beam matrixes with equal beam intensities. However, when generating beam matrixes using SLM, the intensities can be controlled individually for each beam in the matrix. In Fig. 6.2.1 this is demonstrated by ablating a copy from the portrait of Dr. Kaakkunen into the silicon. The portrait is ablated using 42 different holograms. The original picture is sampled to the desired amount of pixels and divided to the sub-images of 20 x 20 pixels. The hologram is calculated for every sub-image and intensity patterns are ablated successively in order to form the whole portrait. The size of the ablated picture is 0.95 x 1.4 mm. Each hologram was illuminated with 40 pulses. The ablation process took 30 seconds where 7 seconds was used for laser illumination. The average calculation time for the each hologram was 25 seconds.

When ablating larger image areas than shown above the sample must be moved between the consecutive ablations. In Fig. 6.2.2 this ablation process with larger scale is demonstrated by copying a portrait of the former Finnish President Kekkonen. Now the image is divided to 150 sub-images and the sample is moved between the successive ablations using translation stage. In Fig. 6.2.3 are shown close-up microscope images of the ablated patterns. Images show that the holograms can be designed so that the ablations can be joined to each other almost seamlessly. The diameter of the ablated spot area varies from

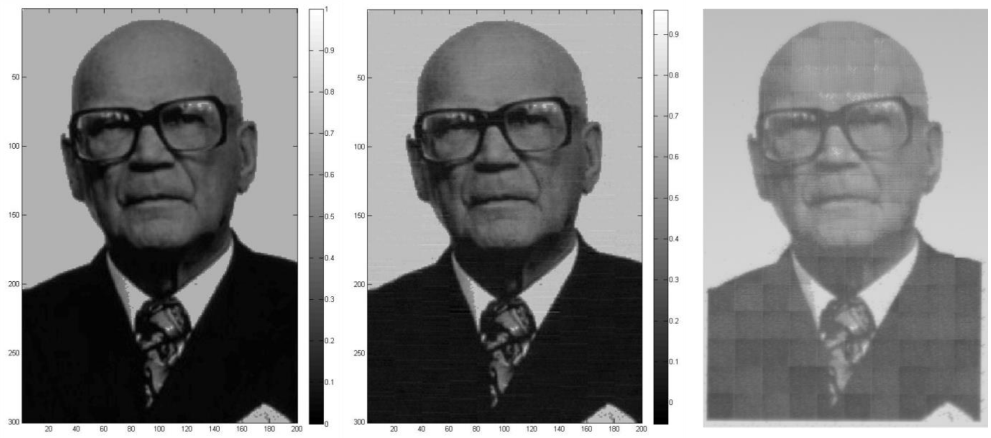


Fig. 6.2.2 Picture of the former Finnish President Kekkonen copied using laser ablation to the silicon.

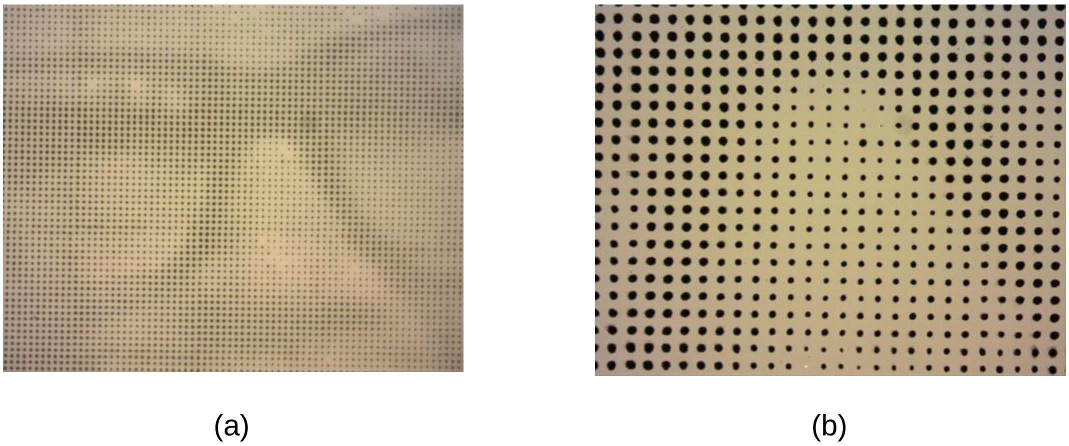

(a) (b)

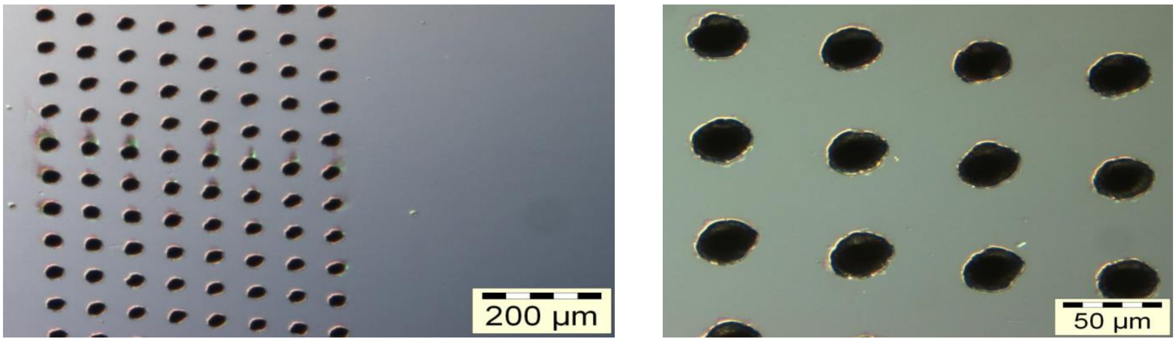
Fig. 6.2.3 Close-up microscope images of the ablated structures.

1 μm to 15 μm. The size of the portrait is 9.6 x 6.4 mm. The portrait is ablated using 200 pulses with each hologram. The ablation process took 10 minutes where 30 second was used for laser illumination and rest of the time was consumed by laser energy adjustment and translation table. Average calculation time for each hologram was 3 seconds.

6.3 Parallel hole drilling on silicon

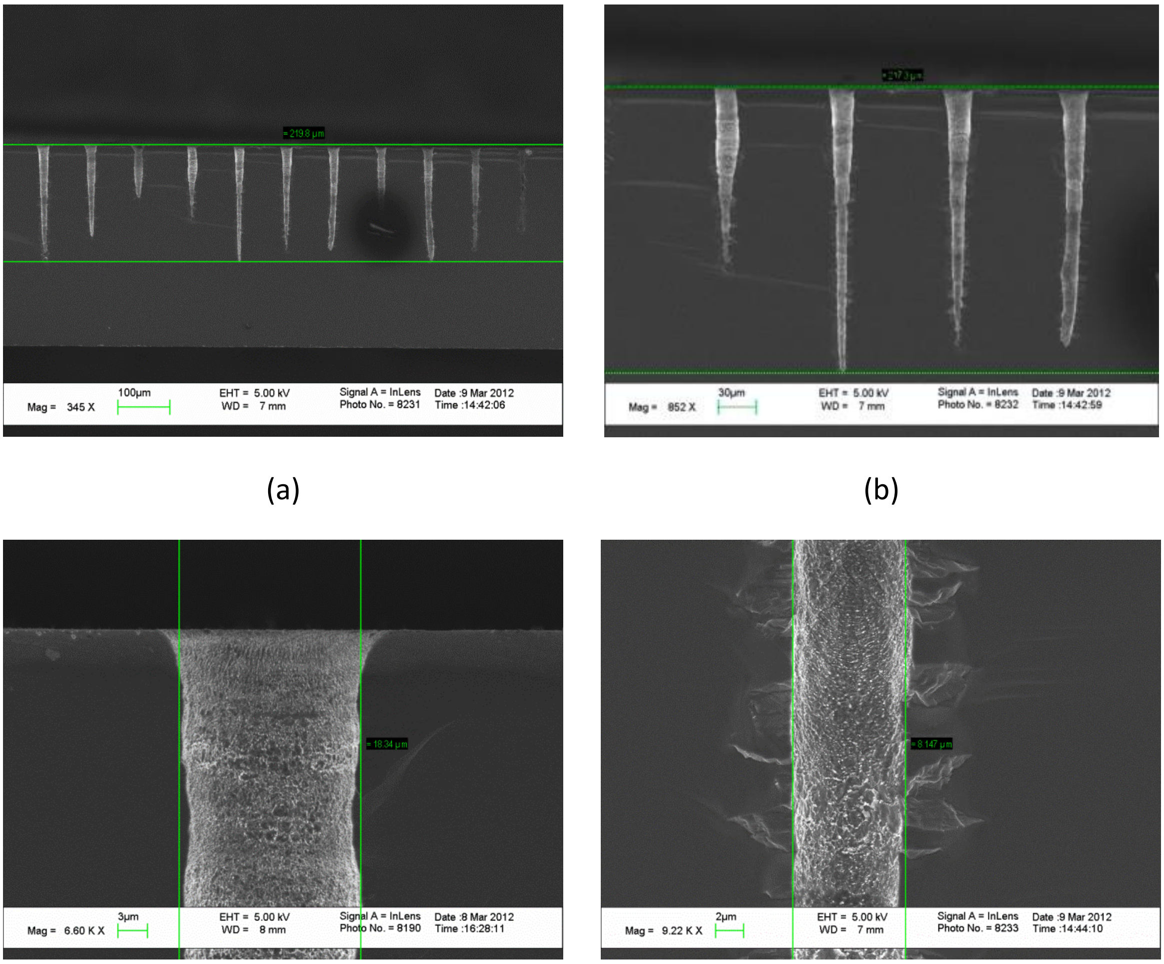
The drilling of the high aspect ratio blind holes or vias in silicon is a challenging and usually time consuming task. Here we have used parallel drilling in order to speed up processing time. The original laser beam was divided up to a 128 simultaneously drilling beams. A specific test pattern of 8x16 hole matrix, where adjacent holes formed a parallelogram, was used in the experiments. In Fig 6.3.1 is shown the entrance apertures of the drilled test pattern in silicon. The desired test pattern is produced accurately with minimal amount of noise in the ablated pattern. Diameter of 30 µm was achieved to the entrance aperture. Debris was removed using a water spray in the processing area during the ablation.

The depth of the ablated holes was measured by making large number of holes on the test wafer and then cracking the wafer along the crystallographic axis of the silicon. In this way one gets a very smooth surface at the cross-section. As a downside one have no control over the position of the holes in relation to the cross-section. This results different



(a) (b)

Fig. 6.3.1 Microscope images from the entrance of the ablated holes in silicon. 8x8 matrix of holes are ablated simultaneously.



(a) (b)

(c) (d)

Fig. 6.3.2 SEM images from the cross-sections from the ablated holes in silicon

hole depths depending on the position of the hole in relation to the cross-section. However, if you have large enough number of holes you will find a few holes that are cut exactly from the center. From these holes one can estimate the depth of the hole pattern. In Fig. 6.3.2 is shown the SEM figures from the cross-section of the ablated holes. The results from the depth measurements are plotted in the Fig. 6.3.3.

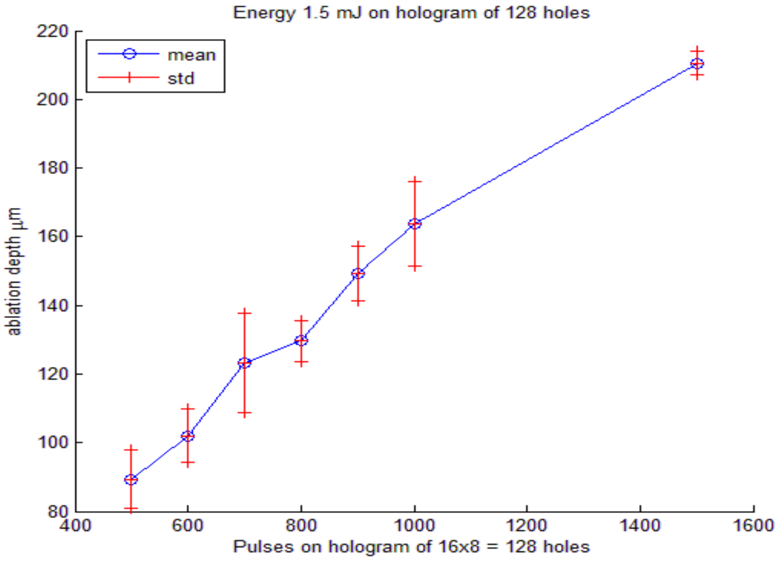
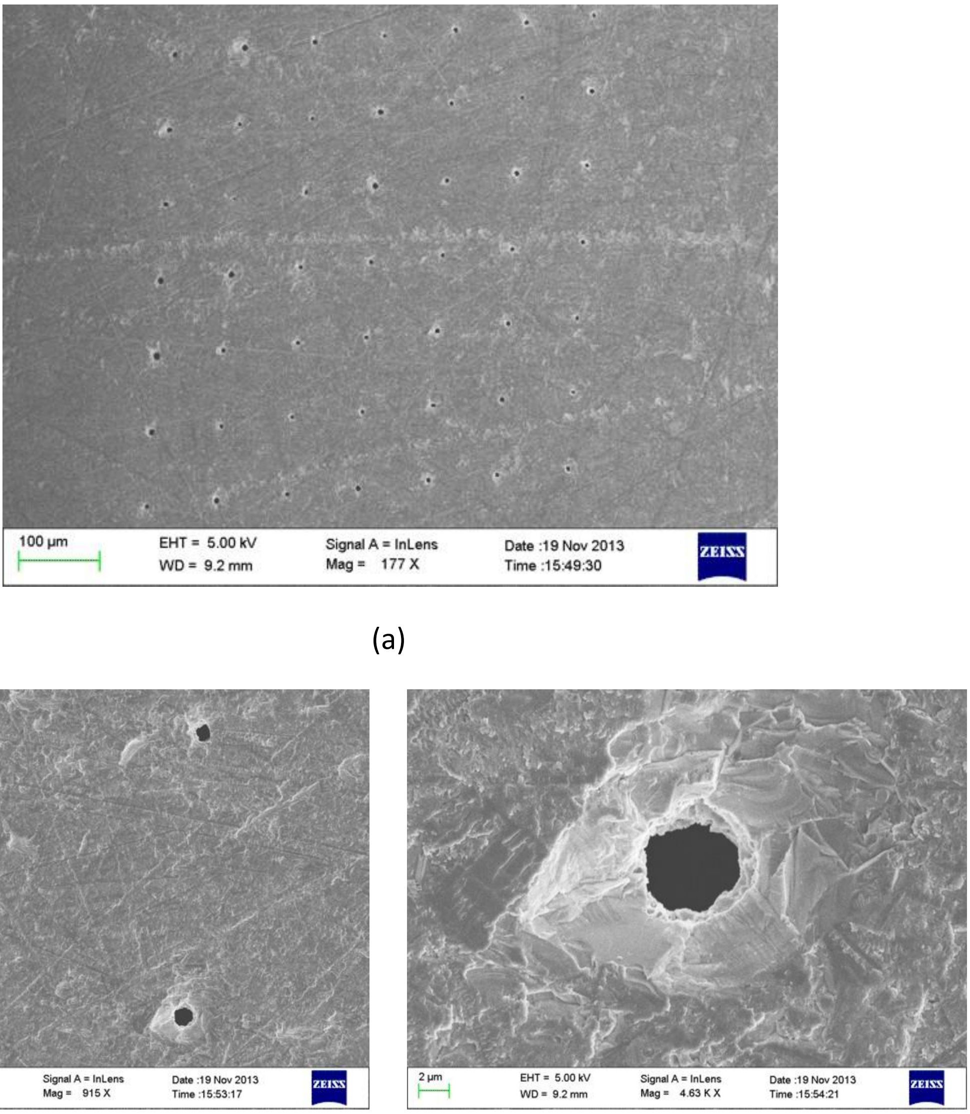


Fig. 6.3.3 Ablation depth as function of the pulse number for hole matrix in silicon.

The cross-section made in the above described fashion do not give any information of the uniformity of the ablated pattern. In order to test the uniformity of the ablated holes we drilled vias through 160 µm thick silicon wafer. If all beams in the matrix push through the wafer at the same time and the exit apertures are identical, this indicates that the pattern is ablated uniformly. In the Fig. 6.3.4 is shown SEM pictures from the exit apertures of test pattern. All the beams in the test pattern are drilled through the wafer using 800 pulses. Note, that the surface of the silicon is cracked around the exit and this makes it harder to evaluate the uniformity of the exit apertures. This cracking is related to the use of the water spray during the ablation. When ablating blind holes this cracking is avoided.



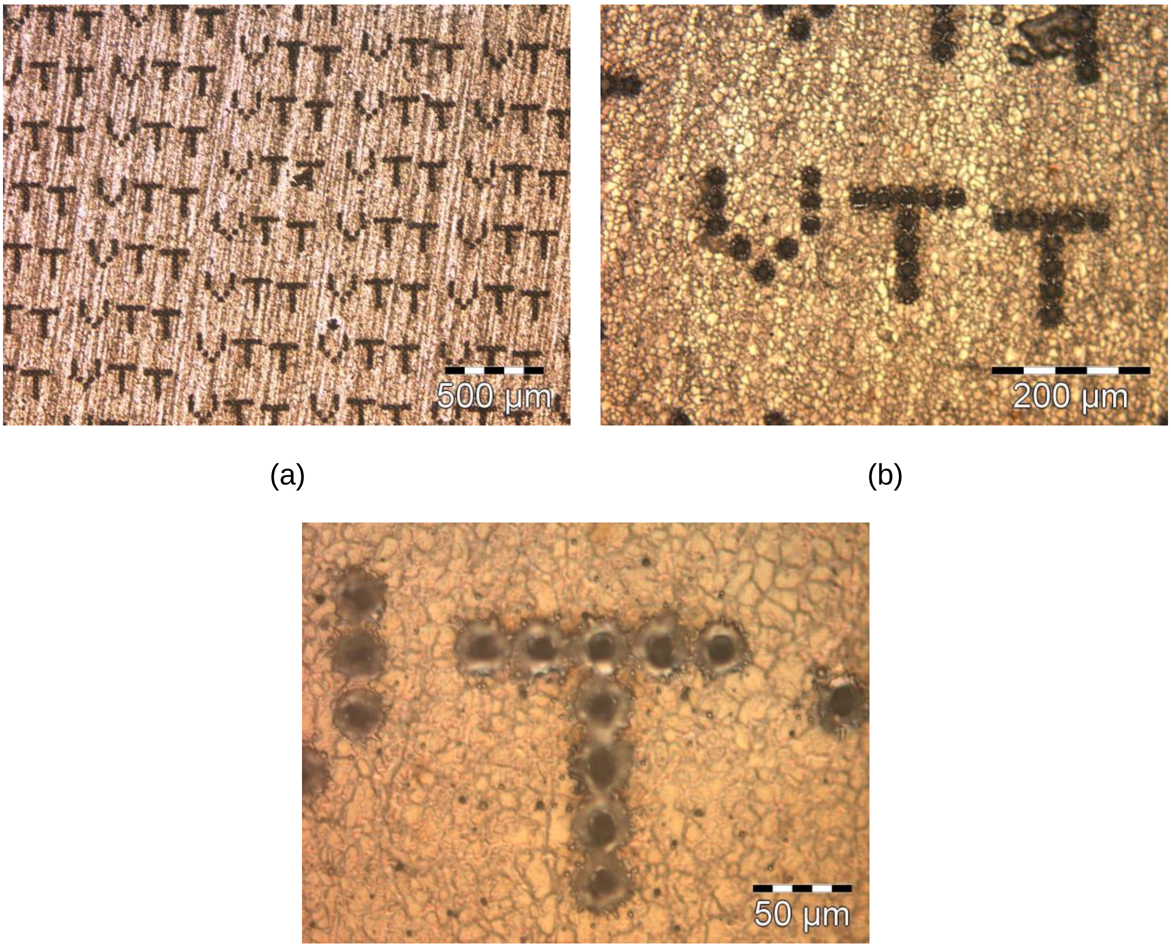
(a)

(b) (c)

Fig. 6.3.4 SEM pictures from the exit of vias ablated in the 160 µm thick silicon wafer.

6.4 Speed and capacity of SLM laser processing

Speed of the different laser processes with spatial light modulator was studied in this project. Speed of the SLM technology combined with galvanometer scanner was compared to speed of the simple scanner. This comparison was done in case of the groove engraving, hole drilling and marking. Application of the laser marking is quite obvious, but in case of the hole drilling and groove engraving purpose was to demonstrate fabrication of functional surfaces. Both of these cases are directly or via mass production applicable for example in different wettability applications like super-hydrophobic surfaces.



(a) (b)

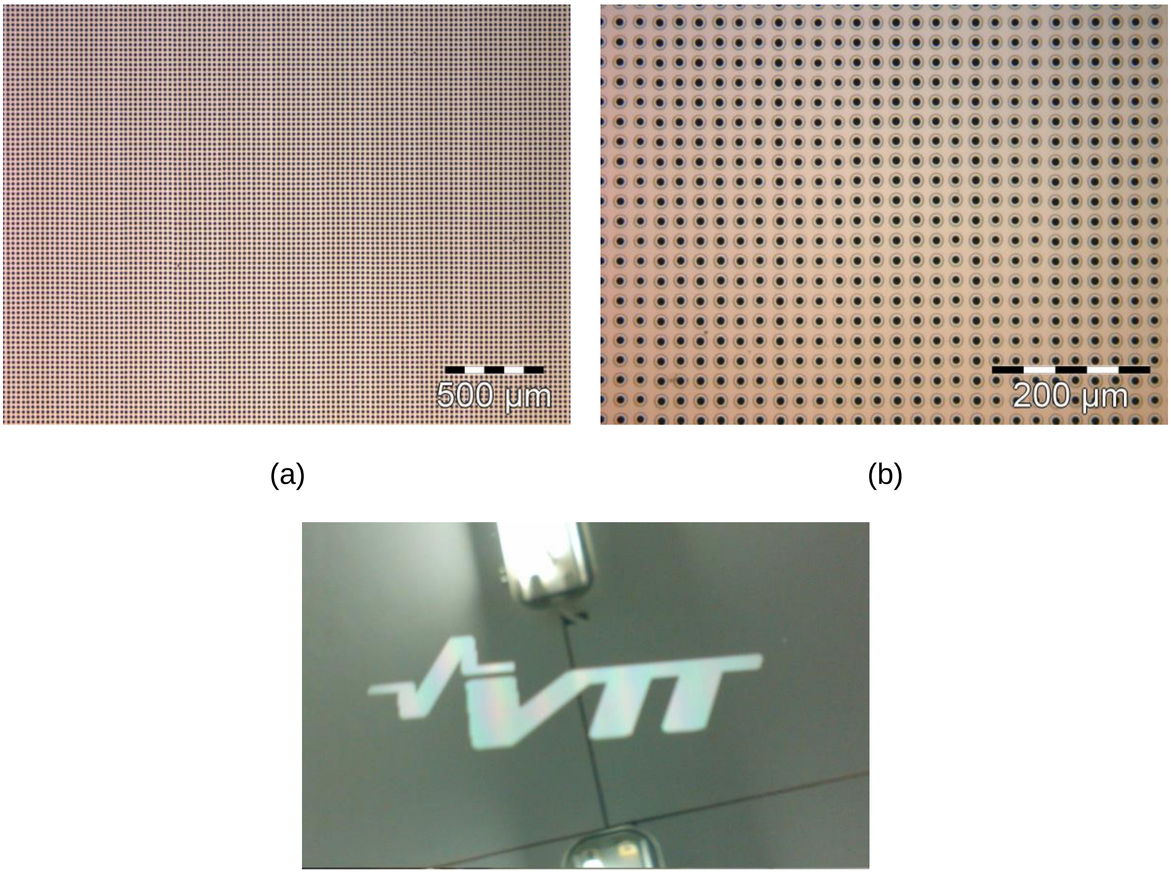
(c)

Fig. 6.4.1 Holes ablated using combination of the SLM and galvanometer scanner with IPG YLP-20 in steel. Here (b) is magnified image of (a) and (c) is magnification of (b).

6.4.1 Laser marking using SLM and galvanometer scanner

Setup shown in Chapter 4.1.3 was used to study speed of the laser marking with spatial light modulator. In these studies both IPG YLP-20 and IPG YLP-HP100 were used. With both of these lasers simple dot-matrix arrays and VTT-letter combinations were laser marked into silicon and stainless steel. In these studies, Fresnel lens with f = - 500 mm focal length was applied in computer generated holograms (CGH) to avoid problems with 0th-order and to achieve smaller feature sizes.

With IPG YLP-20 single pulse laser marking were applied to ablate 15 holes simultaneously into silicon. This was the maximum amount of this size holes that could be marked with this pulse energy simultaneously when applying single pulse. Maximum power P = 10 W (in SLM) and repetition rate of 20 kHz was applied. With this kind of configuration, diameter of the ablated holes was about 6 μm and period of them was 12 μm. If it is assumed that about 30 % of laser power is lost in optics and SLM, the used fluence was about 70 mJ/cm^2. With these parameters, it is possible to ablate 0.3 million holes per second and about 6.5 mm x 6.5 mm area in one second. If similar holes are ablated with same laser without SLM merely using galvanometer scanner, only 0.08 million holes can be ablated in one second. This means that combination of SLM and galvanometer scanner is about 4 times faster than only scanner. If merely scanner is used, the limiting factor is repetition speed of the laser. To achieve same speed than with SLM and scanner combination, 300



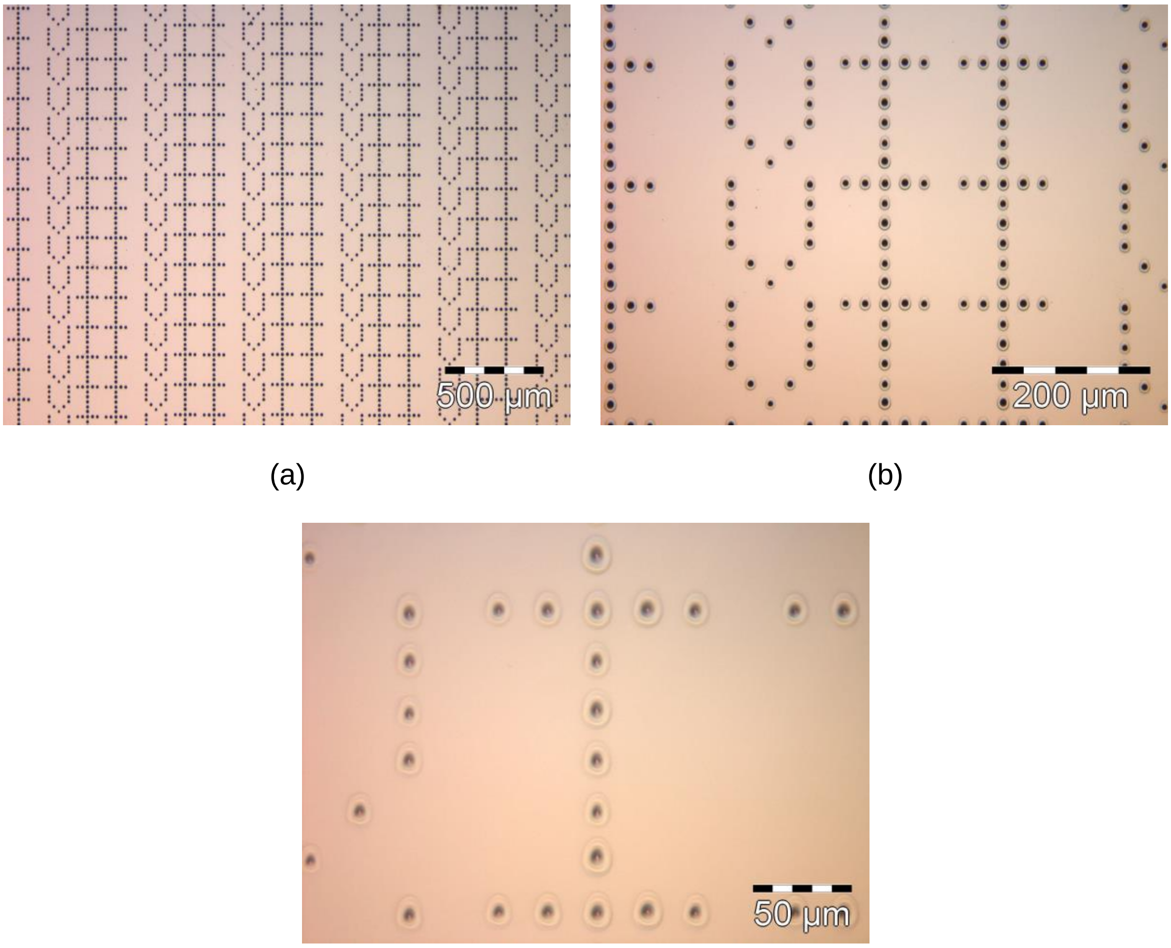
(a) (b)

(c)

Fig. 6.4.2 Optical microscope images of dot-matrix array ablated into silicon. Here (b) is magnification of (a) and (a) from (c). Dot matrix array was ablated into shape of the VTT-logo (c). In this logo, visual diffraction effect can be observed because of the small enough periodic structure.

kHz laser would be required. In this case moving speed of 3.5 m/s would be required from the scanner, which would not possible with used scanner.

IPG YLP-20 was also applied to ablate VTT-letter combination into stainless steel. Letters were realized with 9 spots, diameter of each spot was 25 µm and distance between neighboring spots was 30 µm. Also in this case used power in SLM was 10 W and 20 kHz repetition rate was applied. This means that the used fluence was 27 mJ/cm^2. In this case, each letter was marked with single irradiation. Due to relatively rough steel surface, single letter was ablated 4 times to achieve visually optimal visibility. In Fig. 6.4.1 there is images of these ablation made in stainless steel. Here (b) is magnified image of the (a) and (c) from (b). With this kind of configuration it is possible to ablate 5000 letter or 45000 holes in one second. If similar spacing between spots and letters is used about 25 mm x 12 mm area can be ablated in one second. Naturally this could be also realized using the scanner but in this case only about 2200 letters or 20000 holes per second could be ablated if the same laser would be used. In this case galvanometer scanner is more than 2 times slower than combination of the SLM and galvanometer scanner. Again with single spot marking speed of the system could be compensated with higher repetition rate of the laser. However, in this case the speed that would be required from the scanner is not anymore possible to handle with used one.



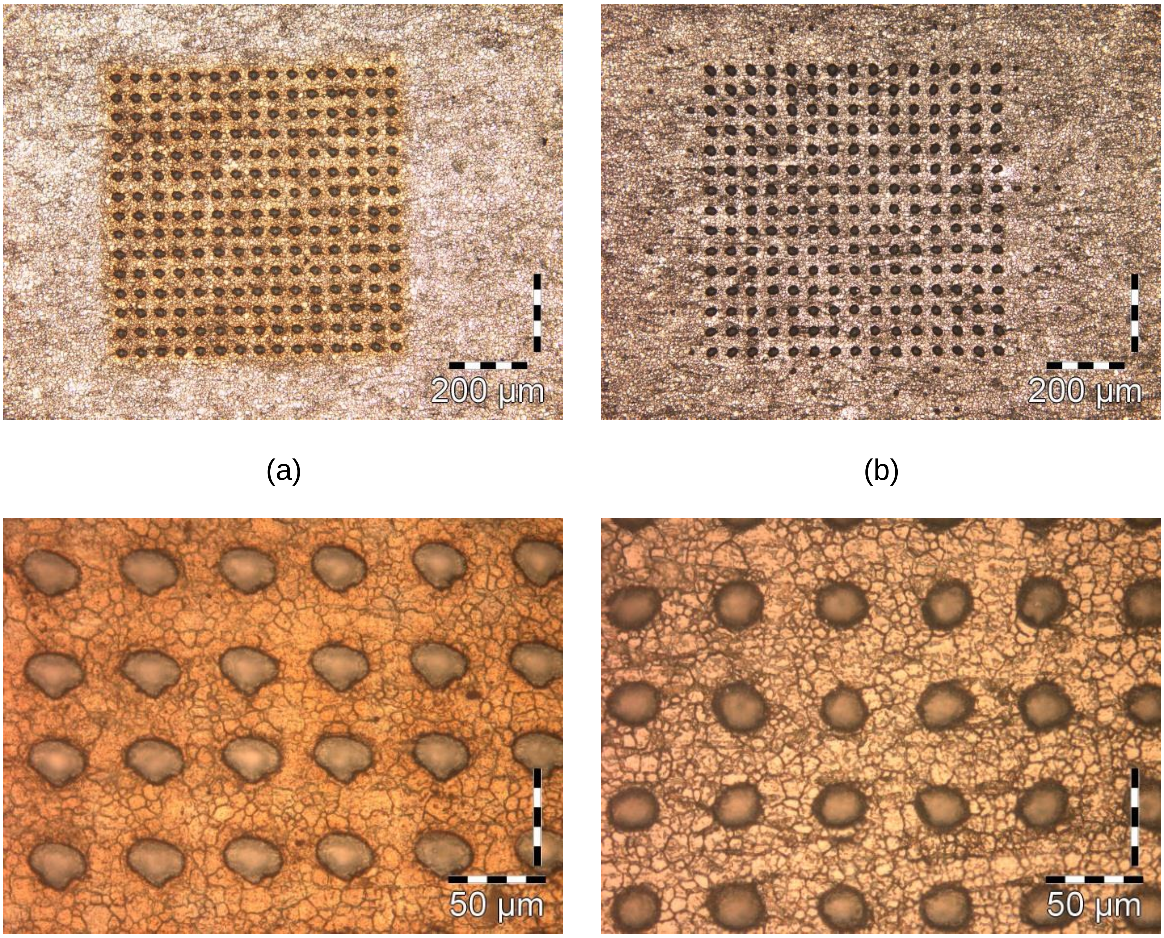
(a) (b)

(c)

Fig. 6.4.3 Optical microscope images of VTT-letter combination ablated into silicon. (b) is magnification of (a) and (c) from (b).

Same tests were also made using IPG YLP-HP-100. First periodic hole-arrays were ablated into silicon. In these studies 50 kHz repetition rate and maximum power P = 50 W was applied. Hole-arrays containing 12 spots were ablated into silicon using single spot. Diameter of the single spot was about 10 µm and their period was 25 µm. With these parameters, it can be assumed that used fluence was about 107 mJ/cm^2. In Fig. 6.4.2 (a) and (b) there is optical microscope image of these holes. Here (b) is magnified image of the (a) and (a) from (c). In these studies the spot array was applied into shape of the VTT-logo (see Fig. 6.4.2 (c)). With this kind of ablation parameters it is possible to ablate about 0.6 million holes per second. With similar spacing between the spots, this means that about 19 mm x 19 mm area per second is possible to be marked. If merely galvanometer scanner and same laser would be used only 0.1 million holes per second is possible. In this case SLM is 6 times faster than merely scanner. Same speed that SLM and galvanometer scanner can provide would mean laser with 600 kHz if merely scanner would be used. This would require 15 m/s scanning speed from the scanner. This is not possible for used scanner.

IPG YLP-HP-100 was also applied to ablate VTT-letter combination into silicon. Each letter is ablated separately using single pulse. Like in previous case, full power P = 50 W and repetition rate of 50 kHz was applied. Diameter of the single spot was about 7 µm and distance between neighboring spots was 25 µm. In these studies V-letter was realized using 11 spots and T-letter using 10 spots. This means that in V-letters the fluence was F = 155 mJ/cm^2 and in case of the T-letter F = 170 mJ/cm^2. In Fig. 6.4.3 there is microscope images of these samples. With these laser parameters it is possible to ablate 50000 letters or 0.5



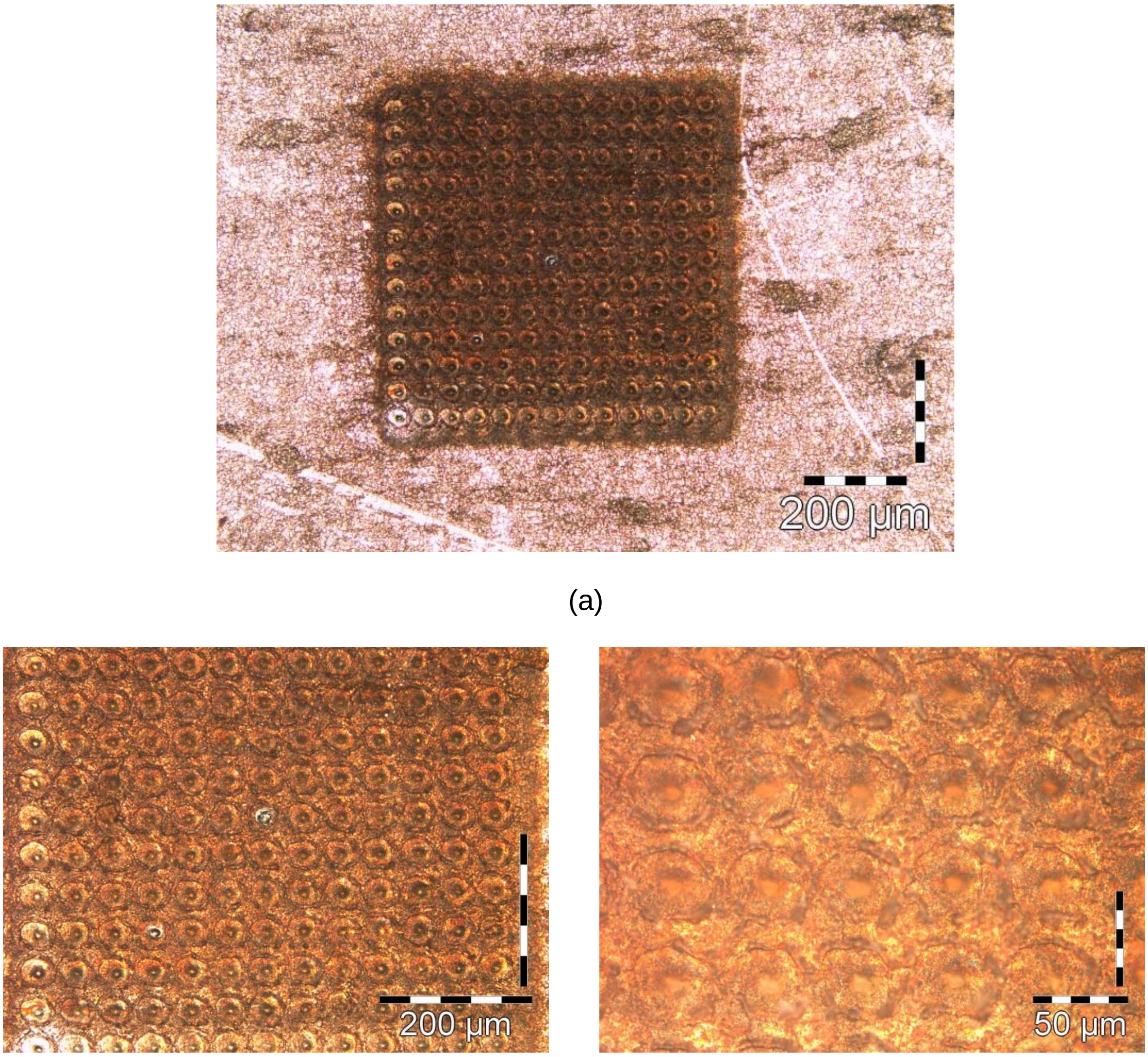
(a) (b)

(c) (d)

Fig. 6.4.4 Optical microscope images of the holes drilled with single (a,c) and with (b,d) multispot arrays. Here (c) is magnified image of the (a) and (d) from (b).

million holes per second. With similar spacing between the letters this means that 61 mm x 19 mm is possible to be marked in one second. Again if the same is realized using merely scanner and same laser only 0.1 million holes per second is possible. This means that in this case SLM is about 5 times faster than only scanner.

It is assumed that even higher marking speeds could be achieved with an optimal laser. Maximum powers of the lasers used in experiments were 20 W and 100 W (10 W and 50 W in SLM, respectively). In studies it was seen that SLM can handle 200 W continuous laser power and therefore it is assumed that it can handle at least same amount of power in pulsed mode. If such a laser would have been available, it is assumed that about 20 times faster marking rates than shown in these studies could have been achieved.



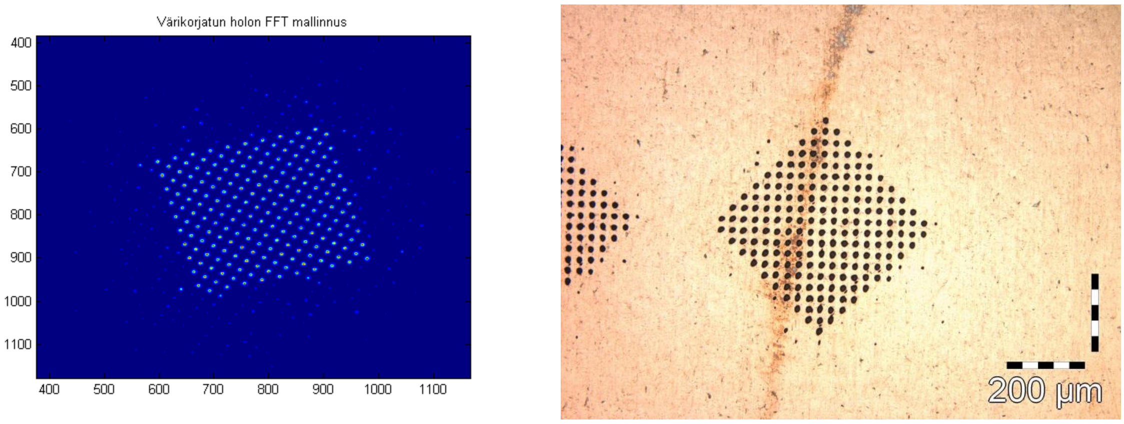
(a)

(b) (c)

Fig. 6.4.5 Optical microscope images of the holes drilled with single spot using higher pulse energy. (b) is magnified image of the (a) and (c) from (b).

6.4.2 Laser drilling using SLM and galvanometer scanner

Comparison of the laser drilling speed between the combination of the galvanometer scanner and spatial light modulator with simple galvanometer scanner, was realized using setup shown in Fig. 4.1.4. Using SLM, 15 x 15 dot matrix array with Fresnel lens (F_{Fres} = 1000 mm) was applied in these studies. With single spot studies same setup was used, but in this case only Fresnel lens with focal length of F_{Fres} = 1000 mm was applied in SLM. To be able to compare these two methods in case of the single spot drilling power in SLM was selected to be 1.67 times higher than power of the single spot in multispot ablations. This was done because there are some losses in SLM and in traditional single spot drilling no such losses exists. To be able to drill same size holes was the reason for usage of same setup in both cases. Total used power in multispot drillings was P = 900 mW meaning 2.8 µJ pulse energy per spot. Respectively, with single spot drillings power of P = 5 mW (3 µJ pulse energy per spot) was used. In these studies 100 pulses per hole were applied. Optical microscope images of these ablations are shown in Fig. 6.4.4. In Fig. 6.4.4 (a,c) there is hole drillings made with single and in (b,d) multispot arrays. Here (c) is magnified image of the (a) and (d)



(a)

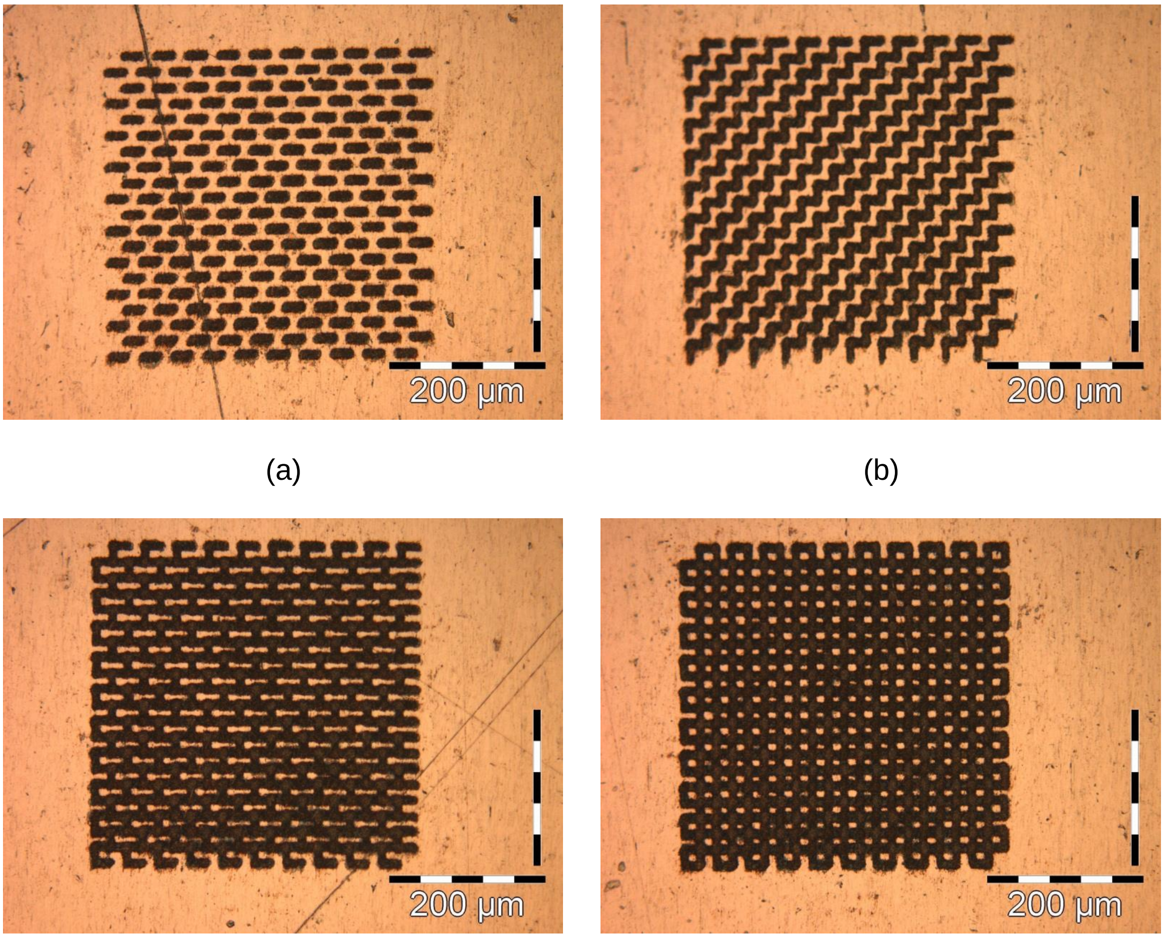
(b)

Fig. 6.4.6 Theoretically modeled diffraction pattern (a) and single ablation (b) made using it. This pattern was used in engraving experiments shown in section 6.1.3.

from (b). With multispot array drilling of this pattern takes 0.1 seconds whereas with merely scanner it took 26 seconds. This means that in this kind of the drilling configuration combination of the SLM and galvanometer scanner is 260 times faster than scanner alone. Fastness of the SLM and galvanometer scanner versus galvanometer scanner depends a lot on that how many holes with single irradiation can be drilled. In studies it was seen that SLM can handle about 1.5 W from used femtosecond laser. This means that the results shown here are not even in a limit of the maximum capacity of the SLM. If the total power would have been used, combination of the SLM and scanner would have been more than 500 times faster than scanner itself. Naturally if larger holes would be drilled the speed difference between these methods would not be so high.

With single spot the used power can be increased into same level than with multispot arrays to compensate the speed difference. In this case, the amount of the pulses applied in single spot can be decreased to achieve still the same amount of total energy in single spot. When applying the same power P = 900 mW in single spot, the energy of it is E = 630 µJ. This is more than 220 times the energy of the single spot in case of the drilling made with SLM. Same 15 x 15 spot array was drilled by using merely scanner with this pulse energy. In this case 4 pulses per spot were applied. Optical microscope images of these studies can be seen in Fig. 6.4.5. As this figures show, quality and depth of the holes are not so sharp and deep as they were with lower pulse energy and more pulses. To drill this 15 x 15 hole array took 4-5 seconds. This means that it takes 40 to 50 more times than drilling the same pattern with SLM and scanner combination. Most of the time is wasted into scanner movements. In order to these times to be totally comparable with multibeam drillings, only single shot should have been applied, but unfortunately 4 pulses per spot was the minimum amount of pulses per spot for this laser and scanner system. However, it is quite obvious that although one would overcame the speed problem of the laser (like faster repetition rate and lower pulse energy of the femtosecond laser), scanner movements will take relatively much time compared to single irradiation with multibeam array generated by SLM.

In studies the travelling table were not used or tested. This would be second option to move beam in sample instead of the galvanometer scanner. However it was not seen relevant to test this because it is quite obvious that travelling tables are slower to move samples than galvanometer scanners. With similar configuration than shown here the combination of travelling table and SLM would be still faster than merely scanner. Speed difference naturally depends mostly on that how many holes per irradiation can be drilled.



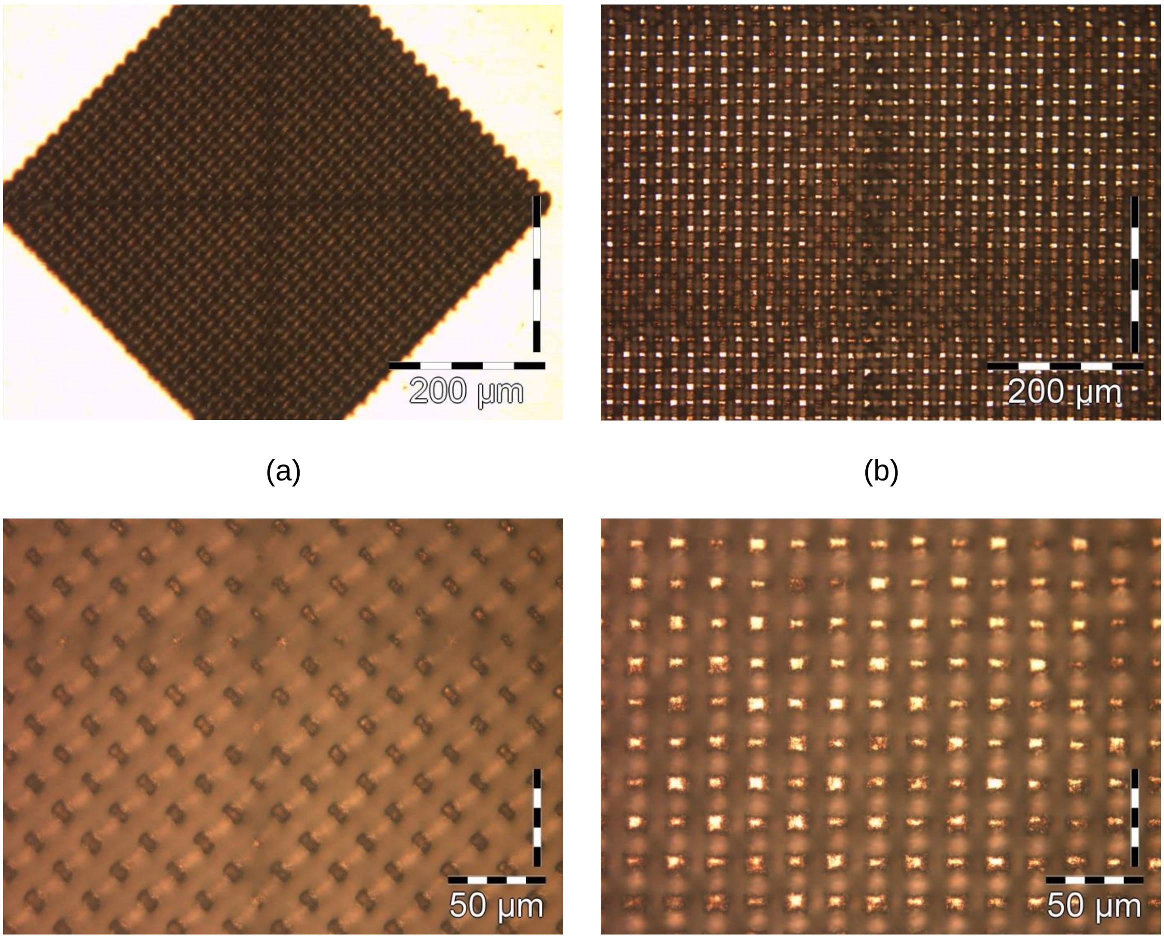
(a) (b)

(c) (d)

Fig. 6.4.7 Step by step fabrication method of the square pin structure using 10 x 20 spot array. First spot array is moved half-period into right (a), down (b), left (c) and up (d).

6.4.3 Laser engraving using SLM and galvanometer scanner

As a last comparison method, engraving the square pin structures into stainless steel was studied using single and multibeam configuration. These studies were realized using setup shown in Section 4.1.3. In these studies Fresnel lenses with focal length of f_{Fres} = 400 mm was used. Distance between SLM and galvanometer scanner was about 1100 mm. In these studies hole-arrays containing 20 x 10 spots were applied to engrave square pins (see Fig. 6.4.6). Every second line of holes was shifted with half period compared to previous one (see Fig. 6.4.7 (a)). With this way minimum period was achieved without having interference between the spots. Hole-array was moved with the galvanometer scanner into the shape of the squares (see Fig. 6.4.7). To generate square structure, spot array is first moved half-period into right (a), down (b), left (c) and up (d). This was then repeated several times to achieve deeper structures. Similar studies were also realized with single beam. As in drilling studies, Fresnel lens with same focal length than in CGH, was used to achieve same spot size than with multibeam pattern. In this case power losses in SLM were taken into account by using higher pulse energy than in single spot in case of the multibeam array. To save some time with single spot engraving, square pin arrays were realized by making scans across to each other. This leads to same result (same amount of energy per area) as making squares using 10 x 20 spot array.



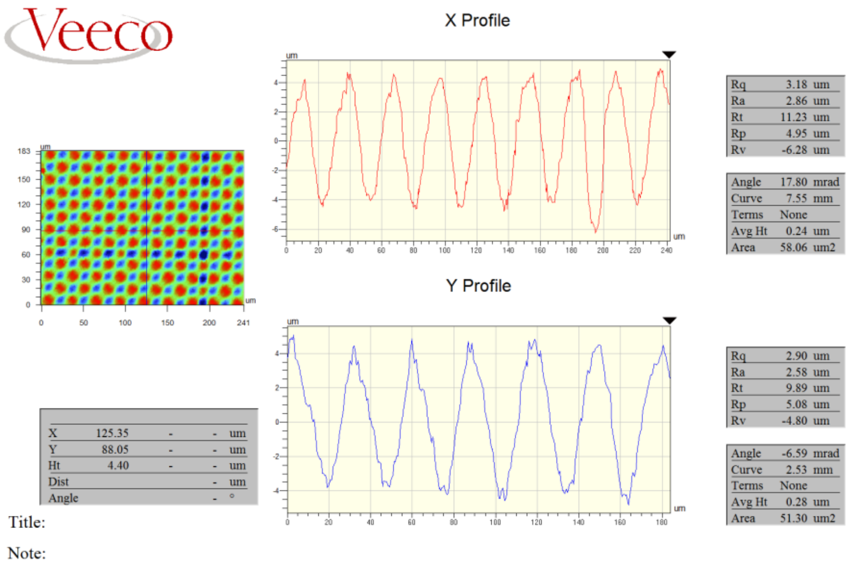
(a) (b)

(c) (d)

Fig. 6.4.8 Optical microscope images of the engravings made using 20 repeats with single beam (a,c) and multibeam (b,d) array.

In multispot engravings used power was P = 500 mW, meaning that single hole had pulse energy of E = 1.75 µJ. Respectively, in single spot engraving the used power was P = 5 mW meaning about 3.5 µJ pulse energy. Used moving velocity was chosen to be 1 mm/s in both cases. With multispot engraving area of 4 mm x 3.9 mm was ablated. Area is uneven because in another dimension the used diffraction pattern was slightly distorted, because of the asymmetric divergence of the laser beam. In case of the single beam ablation only 0.5 mm x 0.5 mm area was engraved because of too slow process speed. In both cases same raster patter was engraved by repeating the pattern 10 and 20 times to achieve different depths. In case of the multibeam engraving took 100 seconds and 200 second with 10 and 20 times repeat, respectively. Corresponding times in case of the single spot engraving was 4 minutes 20 seconds and 8 minutes 40 seconds. This means that engraving a single 1 mm^2 takes about under 7 seconds after 10 repeat and 13 seconds after 20 repeat with multispot array. With single spot engraving requires about 15 minutes to repeat pattern 10 times and almost 35 minutes with 20 repeats. In Fig. 6.4.8 there are optical microscope images of the sample areas made using 20 repeats. Images (a,c) are made using single beam and (b,d) using multibeam array. Here (c,d) are magnifications from (a,b), respectively. It can be seen that surface quality of the samples are quite comparable.

From Fig. 6.4.8 it can be seen that direction that is first engraved is slightly shallower than channel engraved later. This has also caused elongation of the squares. It is also worth mentioning that due to scanning technique corners of the squares are deeper than



X	125.35	-	-	um
Y	88.05	-	-	um
Ht	4.40	-	-	um
Dist			-	um
Angle			-	°

Title:

Note:

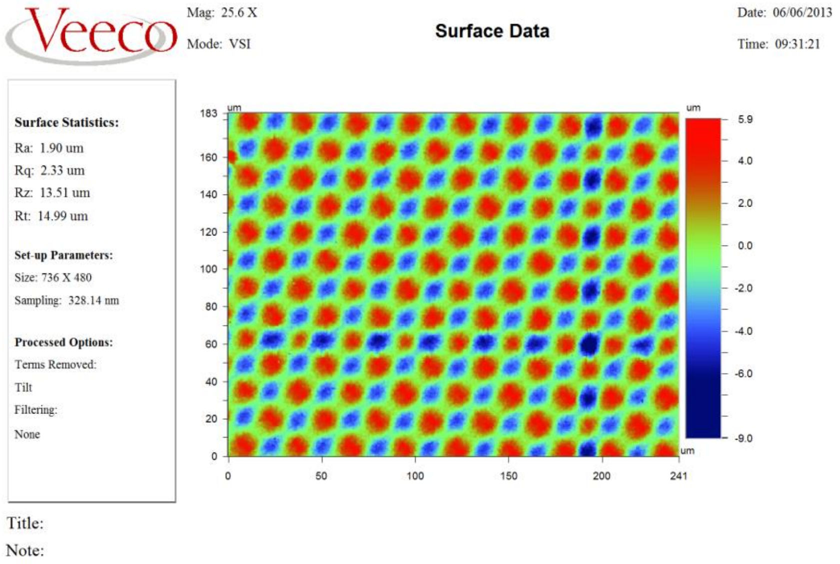
Rq	3.18	um
Ra	2.86	um
Rt	11.23	um
Rp	4.95	um
Rv	-6.28	um

Angle	17.80	mrad
Curve	7.55	mm
Terms	None	
Avg Ht	0.24	um
Area	58.06	um2

Rq	2.90	um
Ra	2.58	um
Rt	9.89	um
Rp	5.08	um
Rv	-4.80	um

Angle	-6.59	mrad
Curve	2.53	mm
Terms	None	
Avg Ht	0.28	um
Area	51.30	um2

(a)



Mag: 25.6 X
Mode: VSI

Date: 06/06/2013
Time: 09:31:21

Surface Statistics:
Ra: 1.90 um
Rq: 2.33 um
Rz: 13.51 um
Rt: 14.99 um

Set-up Parameters:
Size: 736 X 480
Sampling: 328.14 nm

Processed Options:
Terms Removed:
Tilt
Filtering:
None

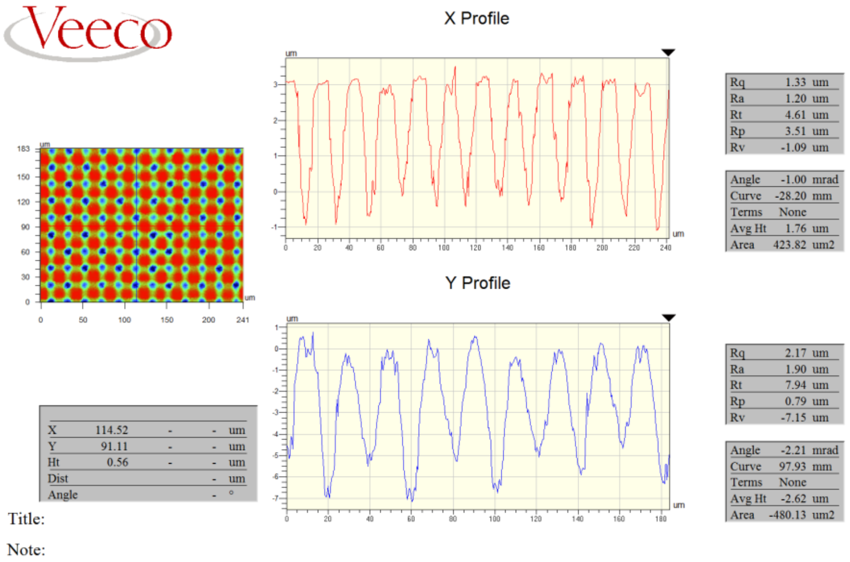
Title:
Note:

(b)

Fig. 6.4.9 Veeco white light interferometer images of the engraving made using 10 repeats with single beam.

channels between them. This means that beams are engraving corners two times than channels between squares.

Depths of the samples made using single and multibeam array were measured using Veeco white light interferometer. Results of these measurements showed that in both cases maximum depth of the structures is about 10 µm and 18 µm after 10 and 20 repeats, respectively. Example images of the Veeco white light interferometer are shown in Fig. 6.4.9 in case of the single beam and in Fig. 6.4.10 in case of the multibeam engraving. Both of these figures are taken from the sample made using 10 repeats. As these images confirm



X Profile

Rq	1.33	um
Ra	1.20	um
Rt	4.61	um
Rp	3.51	um
Rv	-1.09	um

Angle	-1.00	mrad
Curve	-28.20	mm
Terms	None	
Avg Ht	1.76	um
Area	423.82	um2

Y Profile

Rq	2.17	um
Ra	1.90	um
Rt	7.94	um
Rp	0.79	um
Rv	-7.15	um

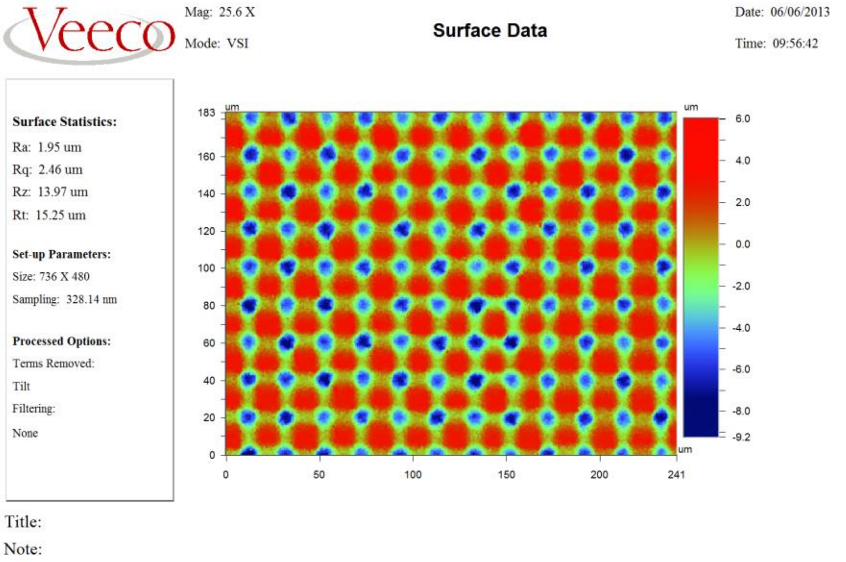
Angle	-2.21	mrad
Curve	97.93	mm
Terms	None	
Avg Ht	-2.62	um
Area	-480.13	um2

X	114.52	-	-	um
Y	91.11	-	-	um
Ht	0.56	-	-	um
Dist			-	um
Angle			-	°

Title:

Note:

(a)



Mag: 25.6 X
Mode: VSI

Surface Data

Date: 06/06/2013
Time: 09:56:42

Surface Statistics:
Ra: 1.95 um
Rq: 2.46 um
Rz: 13.97 um
Rt: 15.25 um

Set-up Parameters:
Size: 736 X 480
Sampling: 328.14 nm

Processed Options:
Terms Removed:
Tilt
Filtering:
None

Title:
Note:

(b)

Fig. 6.4.10 Veeco white light interferometer images of the engraving made using 10 repeats with multibeam array.

the quality of the both cases are quite comparable and uniform. There is no big difference between the hole depths.

6.5 Potential application areas

Spatial light modulators have lot of different kind of application in various laser based processing fields. They can be applied for example in laser marking, engraving, drilling, cutting, and even in welding. Nowadays the SLMs technical properties, like pixel number and size are suitable for most of the beam manipulation applications, but there are still some properties that would need to be improved so that they would be applicative in some fields. For example, although nowadays SLM can handle powers up to hundreds of watts some applications like welding and cutting of thick metals may require more.

Generally, in various laser applications it is useful to use multiple low pulse energies instead of few pulses with high energy to achieve optimal process quality or speed. Therefore high repetition rate lasers are generally used with galvanometer scanner in laser workstations to be able to process fast. Development of the galvanometer scanner has been fast and nowadays with the standard scanners accurate movements with a speed of several meters per second can be achieved. However, even though this is already enough in many application, already nowadays in some cases it is not enough (like in high speed role to role processes). This means that it is not reasonable to increase lasers repetition rate because processing system is typically limited by the speed of the scanner. To avoid this problem it is reasonable to use multibeam arrays instead of single beam. This way there is no problems with speed of the galvanometer scanners and total capacity of the laser can be utilized.

6.5.1 Laser marking

Already in this project it was shown that it is beneficial to use SLM together with galvanometer scanner in laser marking. Instead of marking single spot at the time, SLM can be utilized for multispot marking, simultaneously. SLM can be used to divide single beam into multispot array that can be used to mark several holes with single irradiation. This can be then after applied for example to mark visually diffracting marks or multi line marking. Of course the pattern that is wanted to be marked has to be in some sense periodic. Visually diffracting structures favor periodic structures and therefore SLM is useful in that. Second possible application is laser marking of periodic line etc. were multiple lines can be made simultaneously. In arbitrary structures ablation slowness of the refreshing rate of the SLM is an issue. In this project it was shown that even with relatively simple equipment it is possible to achieve such a marking speeds that could not be handled with standard galvanometers scanner using single spot. Naturally, SLM can also be utilized to mark certain structures or shapes directly with a single shot into material. In this case the size of this mark is limited by the usable pulse energy.

Like shown in Chapter 6.2, SLM can also be utilized to laser mark visually impressive amplitude modulated structures. This technique possibilities single shot laser marking of different size structures directly into wanted material. With this way grey level images can be laser marked into various materials.

6.5.2 Laser engraving

Like in laser marking, SLM can be utilized similarly in engraving. In this project it was shown that multispot arrays can be used to engrave periodic square structures simultaneously. SLMs are more beneficial to speed up processes were periodic or quasi periodic structures are engraved. With SLM these structures can be engraved much faster and in some sense with better surface quality than with single beam engraving. SLM can be used to generate multiple spots and therefore lower energy per spot can be utilized. This is beneficial in many processes were lower pulse energies are required. In this kind of cases the total capacity of the laser can be still utilized. One good example is glass and silicon engraving where lower pulse energies and multiple pulses are preferred instead of high pulse energies and few pulses. By using lower energies cracks on material can be avoided and better quality of the engravings can be achieved.

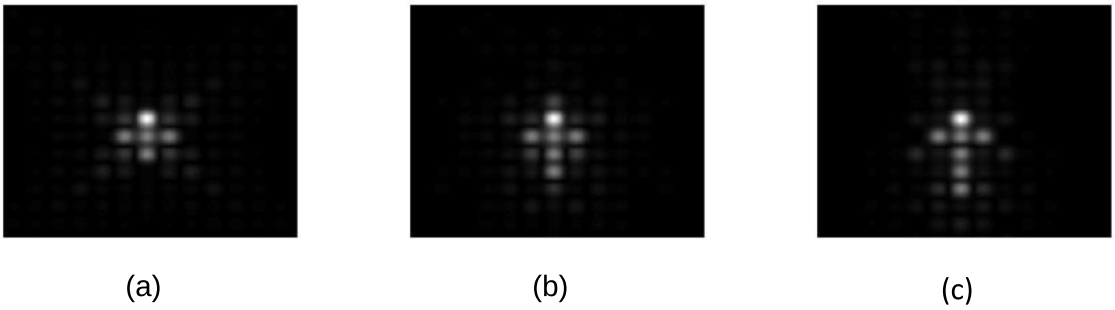

(a) (b) (c)

Fig. 6.5.1 Three different beam patterns that enhanced laser cutting parameters.

SLMs can also be utilized to speed up engraving of arbitrary structures. In this case SLM can be used to generate spot lines behind the main spot. This way multiple spots can speed up engraving of deep structures. In this case speed of the engraving has to be slow enough so that SLM can refresh itself fast enough. Naturally this is not problematic when engraving straight lines but in high speeds and fast change in curvatures might be challenging to realize.

6.5.3 Laser drilling

One of the most promising application of the SLM is laser drilling. Like in case of the engraving, in many drilling cases lower pulse energies are preferred instead of high pulse energies to avoid cracks and to achieve better surface quality. Therefore dividing the beam into multiple beams is beneficial to be able to utilize total capacity of the laser power. In this project it was seen that even the relatively high energy pulse can be divided into thousands of spots using currently available spatial light modulators. This way total energy of the pulses can be utilized in drilling process and still good edge quality could be achieved.

6.5.4 Laser cutting

During this project there was another project in VTT where laser cutting with modulated intensity profile was studied [19]. In these experiments 200 W continuous laser was applied with liquid cooled SLM to study laser cutting. It is worth mentioning that this amount of power is already tenfold higher than what manufacturer of the SLM promises. In this project it was shown that by even dividing the single beam into few beams it is possible to enhance laser cutting. Best results were achieved with so called Plus-shapes where there is adjusting spots in both sides and some spots after the main spot or 0^{th}-order (see Fig. 6.5.1). In these studies, main spot had about 70 % of total laser power, due to randomly polarized laser beam. Rest of the power was equally distributed among the other spots. By dividing the single beam into multiple spots it was possible to cut relatively thin metal sheets (under 1 mm) with lower assist gas pressures and still achieve similar cutting quality than with single beam.

6.5.5 Laser welding

One possible application of the SLM technology is laser welding with low powers. With SLM it is possible to either modify the intensity distribution of the single beam or divide it into multiple spots. With modified single spot it is possible to have more uniform welding quality than with standard Gaussian beam profile. There has been studies were so called M-shape beam profile (round beam that has more intensity in edges than in middle) has been applied into polymer welding. With this profile more uniform welding quality has been achieved. Other option is to divide beam pattern directly into wanted welding shape.

This method is quite flexible in sense of welding shapes and it is fast but it requires much power even in case of the polymer welding.

6.6 International co-operation

During the project there was a lot international co-operation. Ph.D. Kaakkunen visited half a year in Heriot-Watt University to adopt state-of-the-art information about SLM technology. There has been also co-operation with Hamamatsu which is manufacturer of the SLM. Added to these, results of the project were presented in international conferences.

6.6.1 Visit to Heriot-Watt University

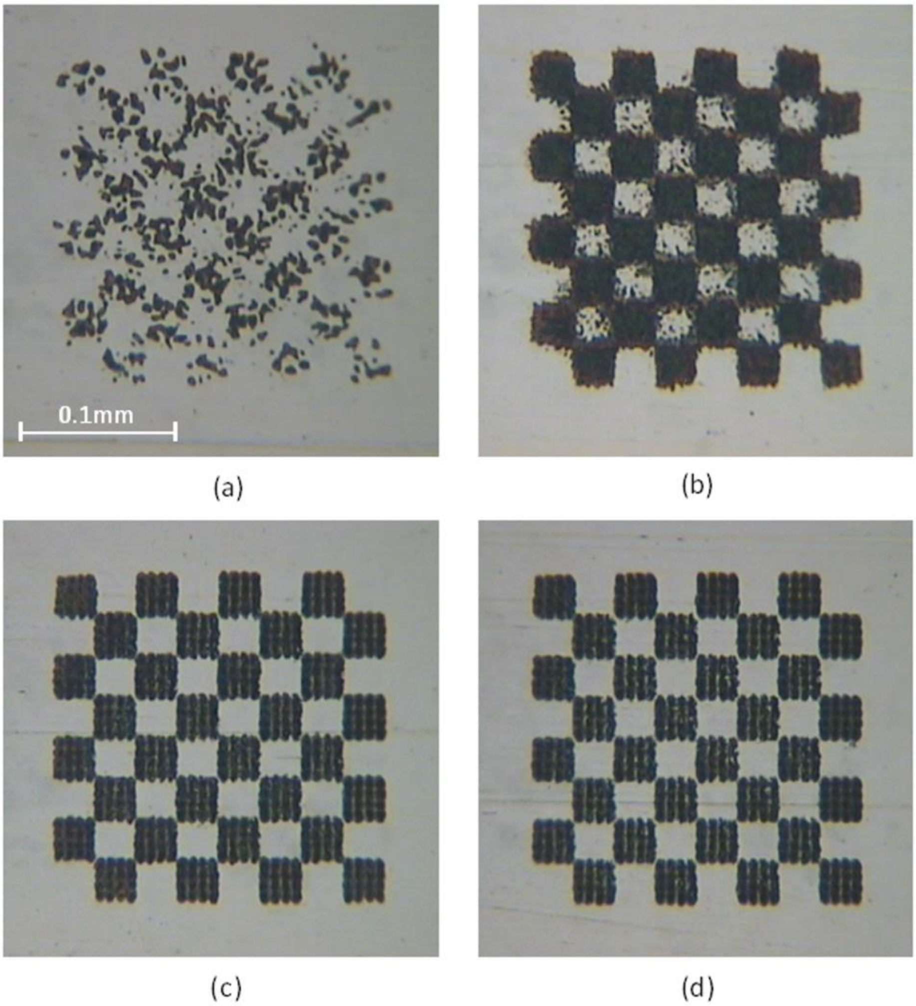
Ph.D. Kaakkunen was in Heriot-Watt University (HWU) in Edinburgh United Kingdom half a year in beginning of 2012. In HWU he was working in group of the prof. Duncan P. Hand. His group is one of the leading groups in a world in research of the laser processing using SLM technology. During the visit there were two main areas that were studied.

First research topic was related to SLM technology and frequency doubling. In these studies the purpose was to study frequency doubling after phase and/or amplitude modulating of wavefront with SLM or mask. This was done because there are no SLMs for UV wavelength and by frequency doubling green wavelength this wavelength range is able to be reached. In these experiments SLM from Holoeye was used, which was not a good thing. This is because Holoeye SLM rotates the polarization of the beam differently with different phase shifts. This is why the spatial polarization of the beam is more or less mixed after the SLM and no proper frequency doubling is possible. More detailed info on these studies can be found on separate report from the exchange period made by Ph.D. Kaakkunen.

Second topic that was studied during the visit in HWU was accurate security marking of small structures with SLM. One of problem with small features marking is the interference between diffracted spots [13]. To avoid or overcome this problem few different methods were compared with each other using picosecond laser from Trumpf. Two first methods were already studied and published by the HWU scientists [14]. In these methods interference problem is overcome by averaging interference between spots by periodically shifting the CGH several times. With this method relatively smooth marks can be achieved. These were compared with two different methods that were developed by Ph.D. Kaakkunen and Ph.D. Wlodarczyk. In both methods spots are divided so far from each other that they are not interfering with each other. This pattern is then copied so that wanted pattern is marked with high resolution and surface quality. In Fig. 6.6.1 there is optical microscope images of four different laser marks made using these four different methods. In (a) same CGH is just ablated 16 times, which does not lead to nice result due to interference between adjacent spots. In (b) so called speckle reduction method is used to average speckle. This is already quite nice but there is still some speckle in unwanted areas. In (c) single hologram that consists 4x8 spots is replicated 16 times to mark wanted pattern. Shifting of the spots is realized simply by moving the CGH in SLM display. (d) is just made for reference to the case shown in (c). Principle in (d) is the same as in (c) but here each hologram out of 16 is separately designed. This naturally requires much more time in design than the case shown in (c). Results, in both methods shown in (c) and (d), are really smooth and edges of the features are relatively sharp compared to laser markings shown in (a) and (b). For more information about this results can be found in [7]. Extended version of this paper is also sent to referee journal and it is accepted to be published in Applied Physics A: Materials Science & Processing [11].

6.6.2 Other international co-operation

Added to research exchange to Heriot-Watt University there has been a lot co-operation with Hamamatsu Photonics K.K. Hamamatsu is the manufacturer of the spatial light modulator that was mainly used in studies. In a first half of the project in May 2012



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

Fig. 6.6.1 Optical microscope images of the laser marking made using four different methods. In (a) 16 irradiations with same CGH is used. In (b) periodically shifting of CGH is used. In (c) single CGH is moved in SLM display to avoid speckle and in (d) same than in (c) is realized by generating 16 different CGHs.

people from Hamamatsu visited VTT Lappeenranta. Hamamatsu people were so convinced about the facilities and people working in both Lappeenranta and Joensuu that they agreed to send OEM SLM to be evaluated with different lasers. This OEM SLM was delivered into Lappeenranta in October 2012. After free testing period VTT Lappeenranta bought the OEM SLM. In Laser World of Photonics 2013 Hamamatsu people also invited researchers to visit them in Hamamatsu, Japan to deepen the co-operation. Ph.D. Kaakkunen visited them in Hamamatsu after LAMP2013 conference.

During the project, researcher has been visiting and presenting projects results regularly in many conferences. In these conferences new and old contacts has been created and strengthen. Here is the list of conferences where researcher has been visiting:

(a) 8th EOS Topical Meeting on Diffractive Optics, 2012, Delft, Netherlands.
(b) 31st International Congress on Applications of Lasers and Electro-Optics, 2012, Anaheim, USA.
(c) Photonics West, 2013, San Francisco, USA.
(d) Laser World of Photonics, 2013, Munich, Germany.
(e) 6st International Congress on Laser Advanced Materials Processing, 2013, Niigata, Japan.

(f) 32nd International Congress on Applications of Lasers and Electro-Optics, 2013, Miami, USA.

7. Conclusions

Aim of the project was to develop parallel processes for the different fields of the laser micro-processing. Purpose was to study how the adaptive optical elements like liquid crystal on silicon spatial light modulator can be applied with different lasers and in various industrial applications. Distribution of the work between UEF and VTT was divided so that UEF was focused on more scientific side and VTT in more industrial side of the project.

In beginning of the project, both parties bought the SLMs to them. Both bought the same SLM from Hamamatsu due to prevailing general development state of the art of them. Second reason for this was that with this way it was possible to avoid possible problems with designs and controlling when transferring info between UEF and VTT. In a beginning of the project and also still today real industrial and also scientific point of view the Hamamatsu SLM was and is the best choice due to its development state compared to other manufacturers.

Goals of the project set in a beginning and during the project were well achieved. Novel ways of applying the current SLM technology in real industrial and scientific manners were develop. Generally it can be said that state of the art in SLM based technology was achieved during the project. Good evidences of these are the referee papers in valued journals and general discussions in international conferences. Added to this Dr. Päiväsaari was invited to give a talk about “Femtosecond laser processing and spatial light modulator” in LASE2013 which is one of the conferences in Photonics West 2014. Photonics West is one of the biggest events in laser and photonics community.

A lot of work and study was done with a programming of the SLM and designing of CGH. Hamamatsu provides both program to control SLM and simple CGH design program. However, both of these programs are quite simple and relatively complicated to use. Basically, controlling software is only able to display designed CGH on SLM display and CGH design program is able to design very simple diffraction patterns. There exists few programs that are able to do a little bit more advanced designing, but they are not able to realize all possible features in CGHs. This is why a lot work was done to improve these issues. During project own codes to control SLM and design CGH were developed under Matlab. A lot of work was done in optimization of CGH’s designing. In this field novel methods were developed in a project.

When comparing the speed of the SLM added to galvanometer scanner to simple scanner it was shown that multibeam configuration is faster. In project it was shown that depending on the application speed of the laser processing can be hasten from few to even hundreds of times with multibeam configuration compared to single beam processing. In these studies the improvement of the processing speed would have been even higher if the proper lasers would have been available. However, even with used lasers the speed difference between single and multibeam configurations was enormous.

One issue with high speed processing is the limited moving capacity of the current beam delivering units. Currently fastest method to move beam in processing plane are galvanometer and polygon mirrors but already today they are too slow if high repetition rates of the laser are used. During the project such processing speeds were realized with SLM that are not possible with commercial available scanning systems.

During the project several publications in both refereed conferences and journals were made. Some of the publications are already conditionally accepted to be published in journals. Added to this Ph.D. Kaakkunen finalized his thesis during the project and Mr. Martti Silvennoinen has done most of the results to his thesis. He will shortly defend his thesis after this project. Here is the list of publication made in this project:

Dissertation

[1] Jarno J.J. Kaakkunen, “*Fabrication of functional surfaces using ultrashort laser pulse ablation*”, Dissertation in University of Eastern Finland, 2011.

Publications in international scientific referee journals

[2] M. Silvennoinen, J.J.J. Kaakkunen, K. Päiväsaari and P. Vahimaa, “*Water spray assisted ultrashort laser pulse ablation*”, Applied Surface Science **265**, p.865-869, (2013).

[3] M. Silvennoinen, J.J.J. Kaakkunen, K. Päiväsaari and P. Vahimaa, “*Parallel Microstructuring using Femtosecond Laser and Spatial Light Modulator*”, Physics Procedia **41**, p.686-690, (2013).

Refereed scientific conference publications

[4] J.J.J. Kaakkunen, M. Silvennoinen, K. Päiväsaari and P. Vahimaa, “*Femtosecond laser pulse ablation with two-dimensional two-grating interferometer*”, in proceedings of 8th EOS Topical Meeting on Diffractive Optics, 2012, Delft, Netherlands.

[5] M. Silvennoinen, J.J.J. Kaakkunen, K. Päiväsaari and P. Vahimaa, “*Fabrication of Linear Grating like Laser Induced Periodic Surface Structures*”, in proceedings of 8th EOS Topical Meeting on Diffractive Optics, 2012, Delft, Netherlands.

[6] P. Laakso, M. Silvennoinen, R. Penttilä, J.J.J. Kaakkunen, K. Päiväsaari and I. Vanttaja, “*Increasing the productivity of femtosecond laser using spatial light modulator*”, in proceedings of 31st International Congress on Applications of Lasers and Electro-Optics, 2012, Anaheim, USA.

[7] K. L. Wlodarczyk, J.J.J. Kaakkunen, P. Vahimaa and D. P. Hand, “*Speckle-free laser marking of metals with liquid-crystal-based spatial light modulator*”, in proceedings of 6st International Congress on Laser Advanced Materials Processing, 2013, Niigata, Japan.

[8] J.J.J. Kaakkunen, I. Vanttaja and P. Laakso, “*Fast parallel micromachining using the spatial light modulator and the galvanometer scanner with infrared nanosecond fiber laser*”, in proceedings of 6st International Congress on Laser Advanced Materials Processing, 2013, Niigata, Japan.

[9] J.J.J. Kaakkunen, M. Silvennoinen, K. Päiväsaari, P. Laakso and P. Vahimaa, “*Parallel Femtosecond Laser Processing using Intensity Modulated Diffraction Pattern Produced with Spatial Light Modulator*”, in proceedings of 32st International Congress on Applications of Lasers and Electro-Optics, 2013, Miami, USA.

Publications accepted to be published in international scientific referee journals

[10] M. Silvennoinen, J.J.J. Kaakkunen, K. Päiväsaari, and P. Vahimaa, “*Parallel femtosecond laser ablation with individually controlled intensity*”, Optics Express.

[11] K. L. Wlodarczyk, J.J.J. Kaakkunen, P. Vahimaa and D. P. Hand, “*Efficient speckle-free laser marking using a spatial light modulator*”, Applied Physics A: Materials Science & Processing.

Publications conditionally accepted to be published in international scientific referee journals

[12] J.J.J. Kaakkunen, I. Vanttaja and P. Laakso, “*Fast parallel micromachining using spatial light modulator and the galvanometer scanner with infrared nanosecond fiber laser*”, Journal of Laser Micro/Nanoengineering.

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