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Laser micromachining – parallel processing with multiple top hat beams

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Abstract

Many processes in laser micromachining like thin film ablation, require process optimized beam profiles. Top-Hat or donut shaped beams can improve process quality and efficiency. The so-called Focus Beam Shaping (FBS) concept allows the generation of square or round shaped Top-Hat profiles with diffraction limited spot sizes and high depth of focus comparable to a Gaussian beam. The relatively high output power and high pulse energy of today's lasers can often not be fully used in single beam processing. The use of diffractive beam splitters for the generation of multiple beams can help to increase processing speed and save costs. Within this contribution we show that a combination of beam shaping and beam splitting leads to higher process efficiency and improved ablation quality. We demonstrate scribing of ITO thin film layers on glass with nanosecond and femtosecond lasers. In particular we consider the impact of the bandwidth of femtosecond lasers on the performance of diffractive beam shaping elements for parallel processing with multiple Top-Hat beams.

Keywords: Beam Shaper; Beam Splitter; Top-Hat; Parallel Processing; Thin Film Ablation; ITO

1. Introduction

Former studies could show that the use of Top-Hat beam profiles can improve process quality and efficiency of thin film ablation, Raciukaitis et al. (2011), Baird et al. (2011), Bischoff et al. (2013), Rung et al. (2013). The use of diffractive beam splitters allow parallel processing with multiple beams, leading to a higher throughput and a more efficient use of the high pulse energy of DPSS-lasers, Gecys et al. (2011).

In this study we combined diffractive FBS Top-Hat beam shaping and diffractive beam splitting elements in one optical setup. In the first part we focused on the processing with nanosecond laser. We optimized processing of thin ITO layer on glass concerning burr volume and roughness for the generation of a single trench using FBS Top-Hat beam profile. Subsequent to this optimization we transferred these results to multiple Top-Hat beams generating 4 parallel trenches. In the second part of this study we applied diffractive beam shaping and splitting technique to femtosecond lasers. Here one has to consider that features like efficiency or diffraction angles of diffractive optical elements strongly depend on the used wavelength. Therefore we focused on the investigation of the influence of the larger bandwidth of such lasers on the performance of the used diffractive beam shaping and beam splitting elements.

2. FBS beam shaper and diffractive beam splitter

The transformation of the round single mode Gaussian beam profiles of the nanosecond and femtosecond lasers into a square profile with homogeneous Top-Hat intensity distribution is realized with the FBS beam shaper. This element generates a Top-Hat profile at the focal plane of any focusing optic. The outstanding

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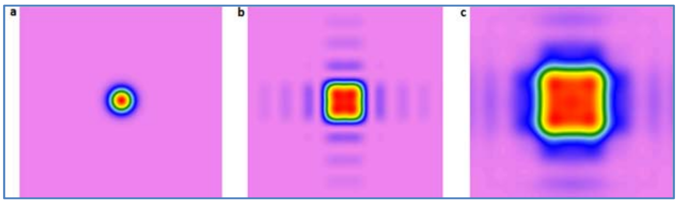
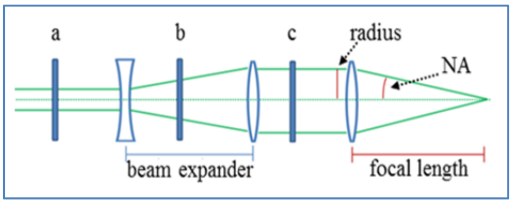
characteristics of FBS are the high efficiency (> 95%), homogeneity (+/- 2.5%) and depth of focus as well as the small size of the generated Top-Hat profiles. Furthermore it is possible to generate different Top-Hat profiles with one single element. The so-called 0^{th} Order Top-Hat is just 1.5 times larger than the diffraction limited spot size of an unshaped Gaussian beam.

By slight changes in the optical setup it is also possible to generate the so-called 1^{st} Order Top-Hat which is 2 times larger than 0^{th} Order Top-Hat, as shown in Fig. 1.

FBS beam shapers have no focusing power, so they can be easily installed in existing beam paths at different positions (Fig. 2). Requirements for using FBS are an input beam quality M^2 better than 1.5 and a clear aperture of minimum 2.2 times the beam diameter along the beam path.





Left: Fig. 1. Comparison of the intensity distribution for (a) Gaussian spot; (b) Zeroth Order Top-Hat; (c) First Order Top-Hat.

Right: Fig. 2. Possible Positions for integration of the FBS into the beam path: a) in front; b) within or c) behind beam expander.

For the generation of 1- or 2-dimensional spot arrays commonly diffractive beam splitters are used. These beam splitters are irregular structures with discrete height levels and structure sizes of several micrometers. The Iterative Fourier Transform Algorithm (IFTA) is one of the common methods for the calculation of such elements, Ripoll et al. (2004). The efficiency of the beam shapers depends on the number of phase levels. Binary structures can achieve an efficiency of already 81%. A higher number of phase levels leads to higher efficiency (for example up to 95% at 8 levels) but will be more expensive.

Two beam splitters are used in this study. For the ablation with the nanosecond laser a beam splitter for separation into 4 spots is used. The diffraction efficiency of the beam splitter is ~68% with homogeneity between the 4 spots of better ±1%. For the ablation study with the femtosecond laser a 1x5 beam splitter is used. The diffraction efficiency of this beam splitter is 72%, with homogeneity between the 5 spots of better ±2%.

3. Laser, optic and machine setup

For ITO scribing we used two laser systems, a nanosecond Q-switched laser (A) and a femtosecond laser system (B).

A: The nanosecond system consists of a 15 W (at 1064 nm) Nd:YVO4 laser (EKSPLA BALTIC, former Techno35C) with a maximum pulse energy of 750 µJ and $M^2 < 1.4$. Pulse duration is changeable from 6 up to 20 ns depending of the pump current and repetition rate (2.5 – 100 kHz). A Galilean telescope is installed into the beam path to increase beam diameter up to 6.0 mm (at $1/e^2$). The FBS Top-Hat beam shaper is installed within the telescope. For focusing the beam a single lens with a focal length of 153 mm is used. A diffractive fourfold beam splitter is inserted between telescope and focusing lens into the beam path.

B: For the femtosecond laser scribing we used a 10W (at 1028 nm) Yb:KGW laser (Light Conversion PHAROS). Due to its short pulse length the bandwidth of the fundamental wavelength is ± 5 nm. Pulse energy of maximal 200 µJ can be adapted either by amplifier current or by the integrated pockels cell. The pulse duration is adjustable from 216 fs – 15 ps and the repetition rate can be selected to any value between 1 kHz and 600 kHz. Raw beam diameter is increased by beam expander to 8.0 mm. The FBS Top-Hat beam shaper is installed behind beam expander. A diffractive 1x5 beam splitter is placed in front of scanner system. The beams are focused with an f-Theta lens with a focal length of 100 mm.

In the studies isolation lines in ITO thin film on glass with a thickness of 700µm are scribed. The ITO thin film is structured from the back (glass) side. The thickness of the ITO layer is 110nm and 170nm, respectively.

4. Scribing with nanosecond laser

The scribing experiments for the nanosecond laser were optimized with respect to burr volume and roughness of the individual scribe lines. In this way we determined the optimal pulse to pulse overlap for the investigated ITO setup. Our results showed that an optimum pulse to pulse overlap for Top-Hat beam is 28%, Rung et al. (2014). Compared to the typical pulse to pulse overlap of more than 50% using Gaussian beam, Homburg et al. (2007), Baird et al. (2011), Rung et al. (2013), the scribing with Top-Hat beam leads to an increase of the process speed by a factor of 2.

After the optimization of the single line ablation the fourfold beam splitter is added into the beam path. The beam splitter generates 4 individual lines. Each line had a width of ~75 µm, using 1st Order Top-Hat (see Fig. 1c). The used pulse energy of 125µJ for each line leaded to a pulse to pulse overlap of 28%. The scribing results are shown in figure 3. The line width of all four lines is nearly constant and was measured to 74.6 +/- 0.7 µm. We observed some deviation of the roughness along the scribing lines however such behavior can also be measured in single line ablation. The burr volume of all 4 lines is comparable and was measured to approximately 25µm³. We conclude that parallel processing with 4 scribing lines combined with Top-Hat beams shows same process quality in each scribe line. Therefore the parallel processing offers an efficient way to increase process speed (in case that laser source offers excess pulse energy) which is 4 times faster for given setup. Simultaneously the Top-Hat beam profiles improves quality of the scribe process and further increase process speed by a factor of 2 compared to Gaussian beam.

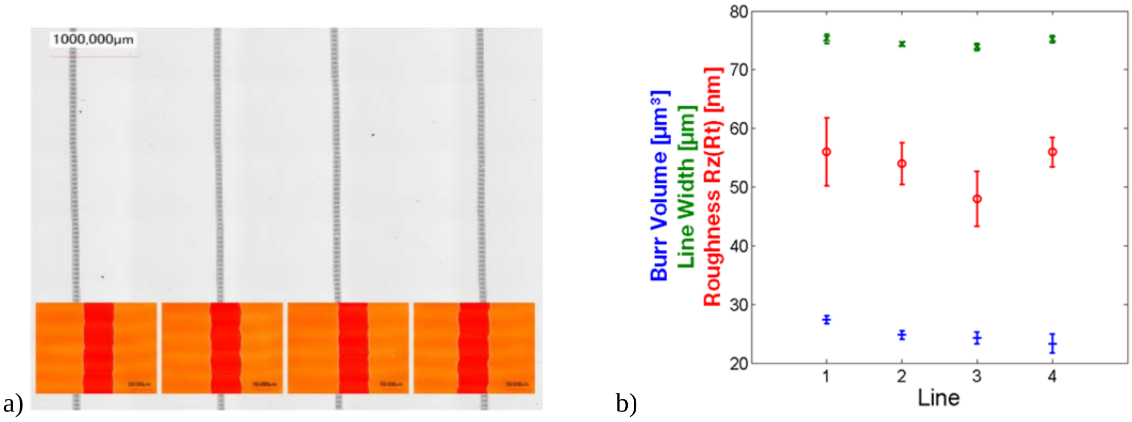


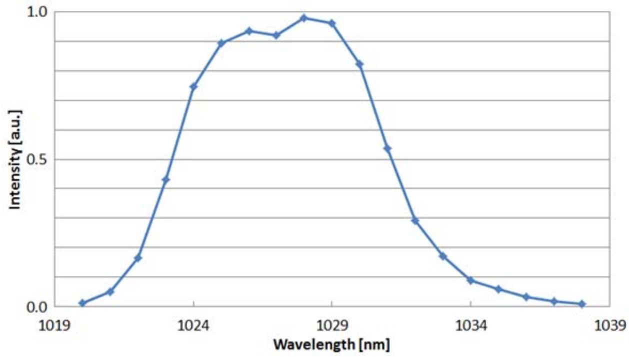
Fig. 3. Combination of Top-Hat beam shaper and beam splitter (4 times) for line scribing of 110nm ITO with nanosecond laser.
(a) Microscope picture of the 4 lines with zoom to each line; (b) Measurement values of the burr volume, line width and roughness Rz(Rt) for each line.

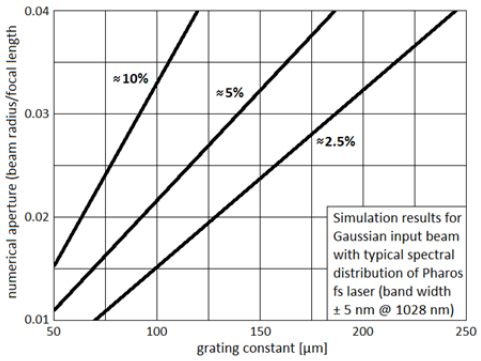
5. Scribing with femtosecond laser

In order to transfer the concept of parallel processing for fs-laser scribing we have to consider that diffractive beam splitters are highly dispersive optical elements. The bandwidth (Fig. 4) of the PHAROS laser (1028±5) nm affects the diffraction angle ϴ of the diffraction order m. The angle is defined by the wavelength λ and the grating period g of the beam splitter:

$$sin(\theta) = \frac{m \cdot \lambda}{g} \tag{1}$$

Therefore the beam splitting angle varies with the bandwidth and subsequently the focal spots get broader. Such increase of the spot size for all diffraction orders with |m| > 0 leads to decreases the power density of the focal spot. This could have a negative impact on the process quality. The widening of the ±1st diffraction order for PHAROS laser is shown in our simulation results presented in Fig. 5. For a given laser bandwidth the spot widening (here calculated for the unshaped PHAROS TEM_{00}-beam) is dependent on the grating period of the beam splitter and the numerical aperture of the focusing optics. The three lines within the graph represent the resulting increase of spot widening of 2.5%, 5% and 10% respectively. Subsequently the related power densities within the focus spots are decreased by same amount.





Left: Fig. 4. Spectral distribution of the femtosecond laser Pharos.

Right: Fig. 5. Widening of 1st diffraction order depending on the numerical aperture of the focused beam and the grating constant of the beam splitter for a femtosecond laser (Pharos) with 10nm bandwidth.

For our optical setup with numerical aperture NA = 0.04 and an effective grating period of about 200 µm (scribing line 2 + 4 in Fig. 6) and 100 µm (line 3 +5) the spot widening is approx. 5% and 10%, respectively - related to diffraction limited Gaussian spots. For our 1st Order Top-Hat beam (Fig. 1c), which is three times larger than the Gaussian spot, the relative spot widening is a third of that value (3.3%, 1.7%). The related decrease in power density is small enough and has no significant influence on the ablation process as can be seen in Fig. 5. The width of all 5 lines is approximately 28 µm, with a separation of about 500 µm. Due to the square shaped Top-Hat beam profile we could avoid lines with a saw-tooth pattern. The pulse to pulse overlap was also just 28%. In comparison to the typical pulse to pulse of more than 50% for Gaussian beam scribing, the Top-Hat processing is approx. two times faster. Furthermore we could show in a previous paper that the homogeneous energy distribution of Top-Hat beams is of significant advantage for selective scribing of sensitive layer stacks where one needs to avoid damages of underlying layers, e.g. for P3-scribing of CIGS-solar cells, Raciukaitis et al. (2011).

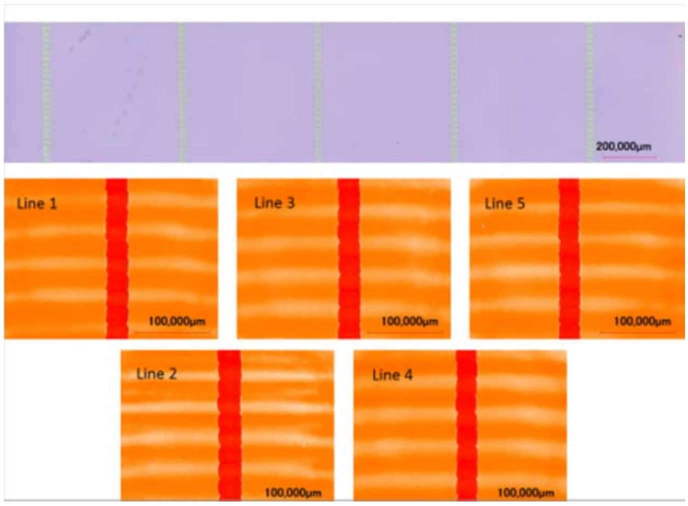


Fig. 6. Combination of beam shaper FBS and 1x5 beam splitter for line scribing of 170 nm ITO with femtosecond laser. Microscope picture with detailed view of ablated lines.

6. Conclusion

With the experiments of this paper we proved that the concept of parallel processing with multiple Top-Hat beams allows an improvement of process quality and a significant increase of throughput in thin film scribing with nanosecond lasers. We also showed that this concept can be transferred to ultrafast lasers with large bandwidth (~200 fs, ~10 nm) while using diffractive beam shaping elements. The overall scribing speed could be increased up to a factor of 10 while using diffractive FBS Top-Hat beam shaper and diffractive beam splitter.

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