Research article

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# Accelerating laser processes with a smart two-dimensional polygon mirror scanner for ultra-fast beam deflection

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**Abstract:** In laser processing, the possible throughput is directly scaling with the available average laser power. To avoid unwanted thermal damage due to high pulse energy or heat accumulation during MHz-repetition rates, energy distribution over the workpiece is required. Polygon mirror scanners enable high deflection speeds and thus, a proper energy distribution within a short processing time. The requirements of laser micro processing with up to 10 kW average laser powers and high scan speeds up to 1000 m/s result in a 30 mm aperture two-dimensional polygon mirror scanner with a patented low-distortion mirror configuration. In combination with a field programmable gate array-based real-time logic, position-true high-accuracy laser switching is enabled for 2D, 2.5D, or 3D laser processing capable to drill holes in multi-pass ablation or engraving. A special developed real-time shifter module within the high-speed logic allows, in combination with external axis, the material processing on the fly and hence, processing of workpieces much larger than the scan field.

**Keywords:** high accuracy; high laser power; high throughput; polygon mirror scanner.

## 1 Introduction

High throughput laser processing requires high average laser power. Nowadays several kilowatt average power lasers are available on the market as continuous wave (cw) laser and as pulsed laser sources. Since the laser-matter interaction especially in ultra-short pulsed laser ablation is working on optimal fluences ($e^2$ of $F_{th}$) with pulse energy in the µJ range, repetition rates of the laser sources increase into several MHz instead of increasing pulse energy [1–3]. However, the laser power must be distributed over the workpiece to avoid thermal damage. Heat accumulation and shielding effects can occur during laser processing with high repetition rates [4–7].

A possibility to solve the distribution of high repetition rate laser pulses has been found in ultra-fast beam deflection with polygon mirror scanners [8–10]. The combination of multiple kilowatt high power laser handling and fast beam deflection, up to 1000 m/s enables the full utilization of high power lasers and can increase the throughput significantly [10].

Up to now, some drawbacks are known for working with polygon mirror scanners. The deflection of the polygon mirror itself is only one-dimensional, the pivot point migrates over the mirror surface during a trespass of a facet if flat mirror facets are used and the rotation frequency of the mirror and laser repetition rates are different, resulting in different pulse positions on the workpiece with each scanned line. The first problem can be solved either using an external axis for substrate movements or using a galvanometer mirror for the second axis movement. The pivot point migration causes scan field distortions that must be corrected with special optics and the pulse synchronization requires a second galvanometer mirror for corrections along the fast axis.

The presented optical design of this study solves pivot point migration with a double reflecting polygon mirror and allows both, axis movement of the substrate and two-dimensional scanning with a polygon and a galvanometer mirror combination. Finally, the polygon mirror scanner is fully digital and allows the prediction of the scanned position in a digital position synchronized signal, which can be adapted by some laser sources to follow with its pulse repetition rate. Furthermore, the real-time logic controls the laser switching and enables high accuracy of the laser positioning in this way.

Laser drilling has been performed in multi-pass ablation hitting each bore hole in up to hundred scan

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repetitions with single pulse ablation per scan. The scanner has also been utilized for engraving and layer removal and surface functionalization.

# 2 Results and discussion

## 2.1 Optical solutions for ultra-fast high power laser deflection

The polygon mirror scanner includes two sections; one includes the electronics and one the optics. As shown in Figure 1(a), the optical area is the lower one and contains an entrance window, the polygon mirror, a mirror on a galvanometer axis, and the focusing optics. The clear aperture of the entrance window is 29.5 mm and the mirrors are designed accordingly to handle such a beam size properly. At the exit, changeable optics can be used with an adapter ring, thereby the aperture must be large, to handle the large beam diameter also under deflected conditions. In practice, a couple of of-the-shelf optics with focal length 165, 255, and 420 mm have been shown proper results. Additionally, customized optics can be designed. Thus, the parameters scan field size, scan speed, focal spot diameter, and facet utilization can be tuned to a maximum, while they affect each other. Most important is the position of back reflections, to avoid damage of the mirrors. Up to now, the scanner was experimentally tested to work with high power lasers up to 10 kW (cw), 2 kW ns-pulsed, or several 100 W in the ultra-short pulsed range. The mirror of the polygon is designed for wavelength from near to far infrared (approx. 800 nm–10.6 μm), the other optical components are selected according to the process lasers. A version for ultra-violet (third harmonic, approx. 355 nm) wavelengths is currently under development. The beam propagation is shown in Figure 1(b).

After entering, the beam is reflected first at the polygon and afterward at the galvo mirror. It is also visible, that the polygon mirror is designed from two pyramids with eight facets. Thus, the beam is reflected twice per facet, once at the upper pyramid and once at the lower one. This patented design is similar to a retro reflector and has two main advantages. First of all, a back reflection into the incident direction is avoided. Secondly, the pivot point migration over the surface is compensated by the second reflection. The scanned lines are straight and have strongly reduced distortion due to the mirror setup [11]. A residual distortion caused by the attached f-theta optics cannot be prevented by this set up. However, the angular deflection between incoming and outgoing beam is twice the mechanical angle of the polygon mirror, which is the same as on flat mirrors. Afterward, the deflected beam is passing the galvo mirror, which moves the scanned lines perpendicular and consequently a two-dimensional scan field is created. The polygon mirror rotates with up to 10,000 rpm, which results in an angular deflection speed. Assuming an f-theta optic, the focal length predicts the resulting scan speed of the angular deflection following Eq. (1), with $f$ as the focal length and $R$ as the rotation speed.

$$v_f = 4 \cdot \pi \cdot f \cdot R \tag{1}$$

Figure 2(a) shows the scan speed as the result of the focal length and the scanning speed, while Figure 2(b) shows the spot size in the focus. The lines show calculated spot sizes following Eq. (2), while the dots represent experimental values. Estimated values for the diagram are a wavelength $\lambda$ = 1070 nm, an absolute beam diameter $D_L$ = 20 mm, and a beam quality of $M^2$ = 1.2. In practice, scan speeds up to 800 m/s are achieved within the motor

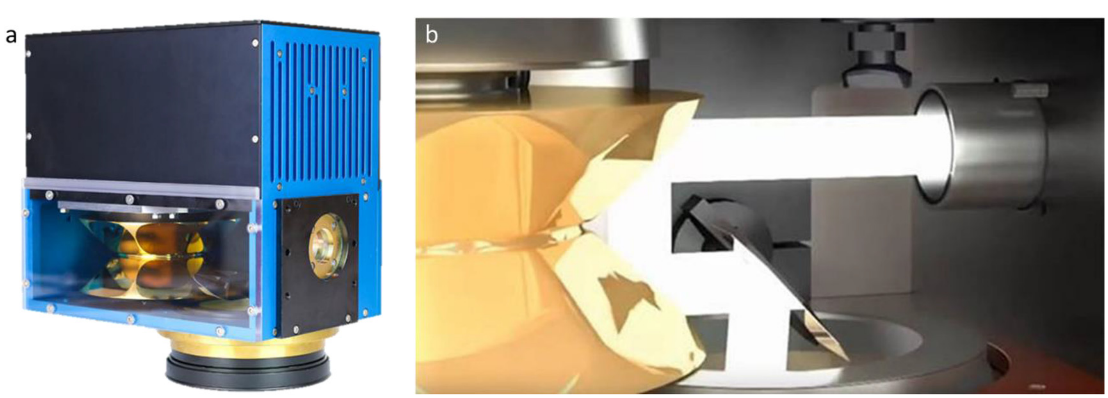


**Figure 1:** (a) A compact polygon mirror scanner of the "PM series" from MOEWE and (b) detailed visualization of the laser beam propagation inside the scanner reflecting the laser light three times.

specifications with 420 mm optics and the focal spot sized around 35–40 µm. With some overrun, 1,000 m/s has been achieved from 11,600 rpm under lab conditions.

$$d_f = \frac{4 \cdot f \cdot M^2 \cdot \lambda}{\pi \cdot D_L} \qquad (2)$$

Furthermore, the focal length has a strong influence on the scan field size, which scales chiefly with the focal length. The actual usable scan field size depends on several conditions, such as aperture of the optics and the scan field distortions, which can partly compensate by the scanner. In practice, scan length size of 310 mm (single line or diagonal of a square) or 141 mm can be obtained from 420 and 255 mm focal length, respectively.

Besides the scan speed, also the line frequency $f_L$ results from the polygon mirror design as shown in Eq. (3). This value states how many lines are scanned per second. The number of facets is constant $N_{fac}$ = 8. Hence, the line frequency depends only on the rotation speed.

$$f_L = N_{fac} \cdot R \qquad (3)$$

This is an important fact for the process design since the scan speed can be varied with the rotation speed and the focal length. Consequently, higher line frequencies can be achieved for same scan speeds utilizing shorter focal length, recognizing that the scan field shirks with the focal length. The overall processing time depends only on the line frequency and the number of lines in the workpiece.

## 2.2 Smart features for precise material processing

The upper part of the scanner contains the electronics and the polygon motor as well as the connectors on the top side. The PM-series is designed as a fully-digital device with an FPGA (field programmable gate array) as its central unit. The high clock cycle of 200 MHz allows real-time calculations within 5 ns in a parallel logic, which is specially designed for this scanner. Figure 3 shows schematically the connectors and sub-systems, which are steered and controlled by the FPGA.

The FPGA is supported by two processors; one of these is used for the communication to the host PC, where the user can set parameters for the operation in a graphical user interface. The data transfer is realized via Ethernet, allowing a network of scanners managed from a single PC. After setting the parameters, the scanner is working self-controlled until the intended process is finished or instructions were changed. The main task of the FPGA is the analysis and controlled mirror positioning and also the corresponding fast laser modulation out of digital stored datafiles. From the target scan speed and an optic specific factor, the rotation speed is obtained and commanded to the motor driver, which converts this signal into switching of the motor coils. At the same time, an encoder on the motor shaft reports the current position back to the FPGA. This feedback loop is further used to switch the fast Laser I/O, which consist of three transistor–transistor logic (TTL) digital outputs and two analog ones with 0–10 V. These outputs can be configured for different signal outputs, to enable the laser within the working area, to give a position-dependent signal or a fix frequency output. Thus, the scanner controls the laser. The repetition accuracy of opto-mechanics and laser control has been determined to ±10 µm (3$\sigma$) using 420 mm focal length optics, within a scan speed rage of 100–800 m/s. Outside of the working area or the scan field, the laser is turned off. During the facet change, the galvo mirror is moved to the next line position, and then the laser will be turned on again after the position is inside the scan field or the desired workpiece. Furthermore, a bitmap can be applied to the workpiece, modulating the laser accordingly to the bitmap values, in digital or analog modulation schemes. Thus, laser marking can be

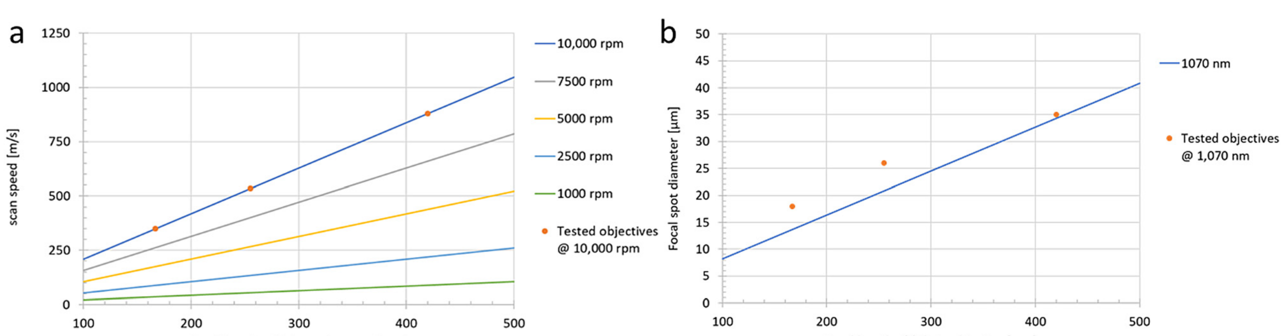


**Figure 2:** (a) Scan speed achievable with the PM series polygon mirror scanner depending on the rotation speed and the focal length of the optics, (b) the calculated and experimental spot size for different focal length (center of scan field) in the near infrared (NIR).

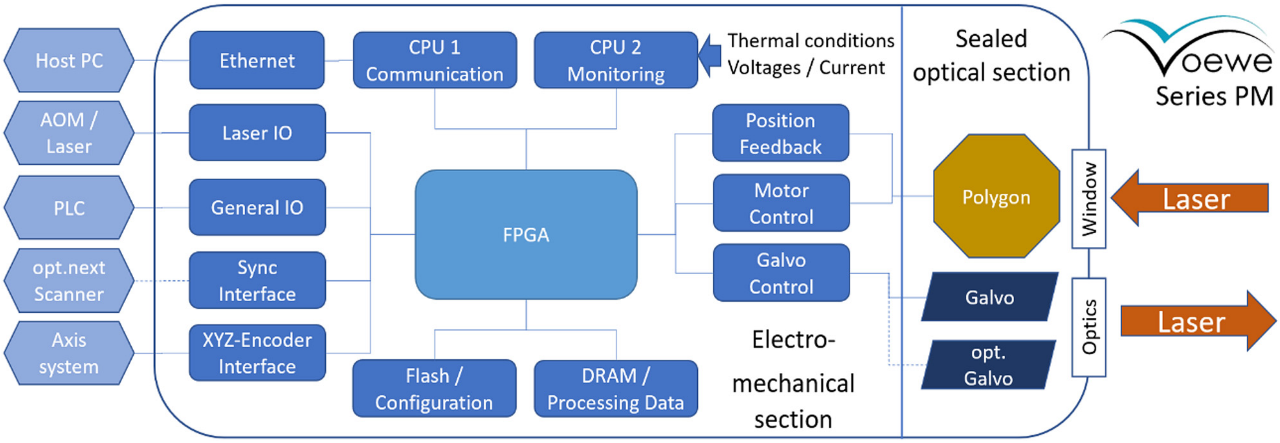


**Figure 3:** Overview of the network within the fully digital controlling unit based on a field programmable gate array (FPGA).

performed. With gray-value images, the modulation for different depth levels can be performed, enabling 2.5D engraving, by depth depending on the number of repetitions.

A smart feature of the FPGA-based process control is the capability to follow the movement of external axis systems. Using the axis encoder interface, up to three forwarded incremental encoders of the axis systems can be taken into account. Once connected, the user has to define the step width of these encoder steps and the workpiece movement is calculated into the position data in real-time. This allows on-the-fly treatments of moving materials or roll-to-roll processes, avoiding double irradiation of lines. Also, velocity changes and directions are considered and every new line is precisely positioned. If the workpiece is larger than the scan field, the velocity of the axis movement must be smaller than the line frequency times the line spacing.

## 2.3 Process design with the polygon scanner

Figure 4(a) illustrates a whole laser set-up, which has to be considered always in total. Before the laser system specifications are evaluated, some basic advantages and restrictions of the polygon mirror scanning should be recognized. With the polygon mirror scanner, high laser powers can be brought into process and the high deflection speeds of several 10 up to 1000 m/s distributes consecutive pulses. Thus, shielding effects have less influence and unwanted heat accumulation can be avoided. However, polygon mirror scanners are continuous deflection devices resulting in a line scan with constant speed and direction. The two-dimensional scanner allows the lateral displacement of the lines in the second direction, but in every line, the whole length is approached with the laser beam. In areas outside the workpiece, the laser is switched off. Thus, the process efficiency scales directly with the utilized scan length compared to the maximum possible scan length. In the case of line processing and large area treatments, high utilization degrees can be reached. In contrast, outline scanning will be inefficient with the polygon mirror scanner.

Furthermore, a single polygon mirror scanner will have a duty cycle (laser usage) below one since the beam is turned off during the facet change. The larger the beam diameter becomes, the lower is the duty cycle due to the fixed size of the facets. Presently, the duty cycle can be increased (up to almost 100%) by applying two synchronized working polygon scanners linked by the sync interface (Figure 3) and a single laser source.

Accelerating a laser process with the polygon scanner by using pulsed lasers is based on the single pulse laser fluence and the pulse-to-pulse distance (PD) as in other optical set-ups. If an existing laser process has to be accelerated, the already used fluence must be kept constant and pulse repetition rate, respectively, the laser power is scaled by the factor of throughput acceleration. In a first consideration, the pulse energy will be kept constant as well as the spot size. After the selection of the optics, this must be proofed and if necessary further iteration has to be done. The maximum available pulse repetition rate or power of the laser sources is limiting this scaling. Once a laser source has been selected and the scaling factor is known, the deflection speed has to be increased by the same factor. The pulse separation is following Eq. (4) as the distance scanned between two consecutive pulses. Since both parameters are scaled in the same way, the ratio keeps constant.

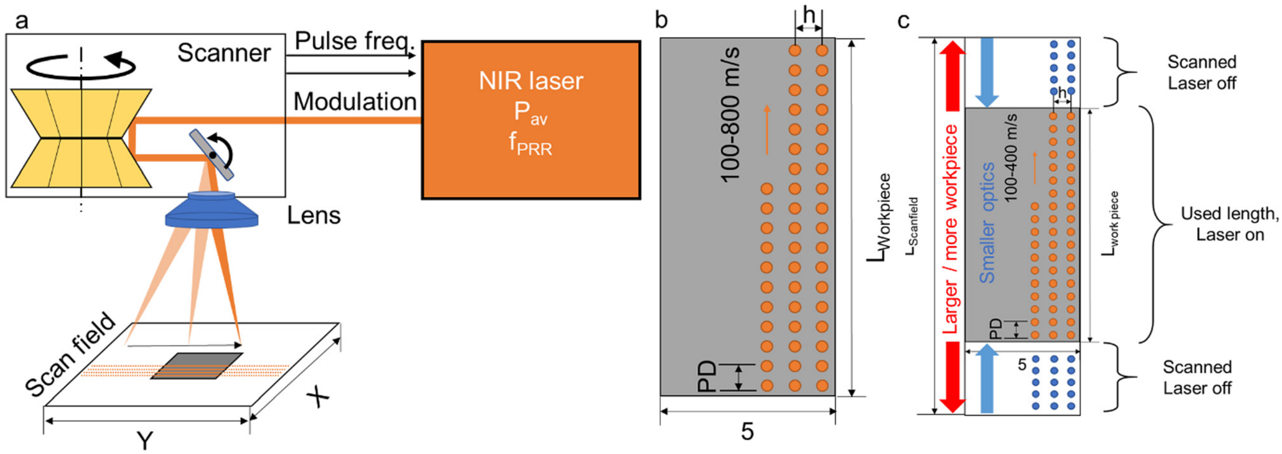


**Figure 4:** (a) Whole laser set-up with laser source, 2D polygon mirror scanner, and optics as well as the resulting scan field length, (b) pulse distribution on the workpiece with pulse synchronization between neighbored lines, (c) optimization scenario for the increased line efficiency using either larger or more workpieces in the scan field or reduce the scan field with smaller focal length optics.

$$PD = \frac{v}{f_{PRR}} \quad (4)$$

Figure 4(b) represents the pulse distribution over the surface. The pulses in a line are separated by PD and the lines are separated by the hatch distance h. Thus, the working area can be filled line-by-line. If residual heat is influencing the substrate, lines can be processed with a multiple of the hatch and the intermediate lines are filled later without loss of time. Due to a difference in the rotation frequency of the polygon and the repetition rate of the laser, the pulses in neighbored rows are not arranged to each other. Also, if a line is treated multiple times to increase the ablation depth, the pulses are arbitrarily arranged to the previous one. If pulses of several lines must be in an order, pulse synchronization is required. With the PM series, this can be achieved using lasers with adaptable repetition rate or pulse on demand lasers.

Finally, the focusing optics has to be selected, which goes along with a couple of limitations and optimization criteria. First of all, the fluence must be achieved, which can be done by keeping the spot size constant. In consequence, the maximum possible focal length is limited due to increasing focal spot sizes by increased focal lengths. On contrary, smaller focal lengths are possible, increasing the spot size to the target by defocusing. Thus, the focal length can be chosen smaller if necessary, but not longer. However, the focal length directly scales the scan field, which results in small scan fields working with small foci. Nevertheless, the scan field size is an important value. Figure 4(b–c) show the same work piece of a certain length and width. In Figure 4(c), blue pixels outside the workpiece are visible. Those are the positions scanned in the line before and after the area to be machined. There, the laser is turned off. This empty running reduces the efficiency of the laser process. Additional to the facet change gap, the line efficiency determines the utilizable laser power. That means in practice, either the workpiece must be fit to the scan field size as shown in Figure 4(c) with red arrows or the scan field size must decrease by using smaller focal length optics toward the workpiece size as shown in with the blue arrows to get the highest possible line efficiency. This consideration is necessary only along the fast deflection direction, the lateral size of the workpiece can be smaller or only a single line.

A large scan field can be filled for example with neighbored workpieces. Whereas, a smaller focal length would result in higher rotation speeds for similar scan speed, and thus in higher line frequency, respectively, shorter processing time. If the lateral size is also large, scan field distortions will occur in the edges. In limited ranges, they can be compensated. The galvo mirror will correct the position during a line scan in slow-direction. Due to the slower velocity of the galvo, compensations are possible but limit the scan speed. Strong corrections will also reduce the process speed since lines must be skipped for accurate positioning of the galvo system. Shrinking the scan field in slow-direction will allow corrections on higher scan speeds since the distortions become smaller in the center of the scan field. In fast direction, the compensation is done digitally, switching the laser on and off earlier or later, and correlate the position signal.

If the scan field is small, or an axis is installed, the cross movement can be performed with the axis, and the low-bended lines in the center can be used for the entire workpiece. The axis movement is also required if the workpiece is larger than the scan field and an increase of the focal length is avoided by the spot size.

## 2.4 Applications for polygon mirror scanners in laser material processing

The polygon mirror scanner is able to handle high laser powers at high deflection speeds. Due to its operating principle, the scanner is suitable to large area treatments filling the whole scan field length. A laser process showing the capabilities of the scanner is laser drilling, where the process is performed in multi-pass ablation. To hit the same position in every repetition pulse synchronization is required. In the performed experiments, a 1 kW ns pulsed (30–240 ns) IPG fiber laser was used and able to adapt the pulse repetition rate to an external signal in the range between 1 and 4 MHz. This signal was provided by the scanner as a frequency signal depending on the scan speed and the position spacing. The laser drilling experiments were performed on polycrystalline silicon wafers of 180 μm thickness and stainless steel with a thickness of 200 μm. Resulting bore holes are visible in Figure 5.

The silicon wafer was perforated after 30 pulses working with a scan speed of 100 m/s. The spacing is 100 μm. At the entrance side (Figure 5(a)), 61.8 ± 1.8 μm were achieved. In the scanning direction a prolongation of around 15 μm was observed. At the exit side (Figure 5(b)), hole diameters of 58.5 ± 3.7 μm were observed. The process was performed with roughly 1500 holes per second. With an optimized scan field size, more than 15,000 holes per second could be possible.

Similar experiments were performed with stainless steel. Thereby, 120 pulses were required to drill through at 200 m/s and 200 μm spacing. The diameters were 107.4 ± 5.1 and 42.6 ± 5.5 μm at the front (Figure 5(d)) and back side (Figure 5(e)), respectively. Here the drilling rate was 500 holes per second [12].

Figure 5(c) shows a polycrystalline silicon wafer of 152 × 152 $mm^2$ size with a blue SiN layer on top. This layer has been removed with a 500 W ns pulsed laser in the gray areas. This one-step process is able to cover the whole wafer but was modulated with a bitmap to write the image in the layer. The pulse repetition rate was 1 MHz, and the scan speed 200 m/s. Thus, the PD is 50 μm. Approximately, 3,000 lines were treated within 10 s to cover the whole surface. Similar results were obtained with a high power cw-laser [10].

Figure 5(f) shows a 2.5D engraving result in 316 L stainless steel. A 400 W cw-laser was used and modulated with an acousto-optical modulator for fast beam switching. A gray-value bitmap was used as a depth map to switch the laser on and off while the gray values include the depth information. Thus, up to 40 repetitions were performed depending on the depth level with an ablation depth in the

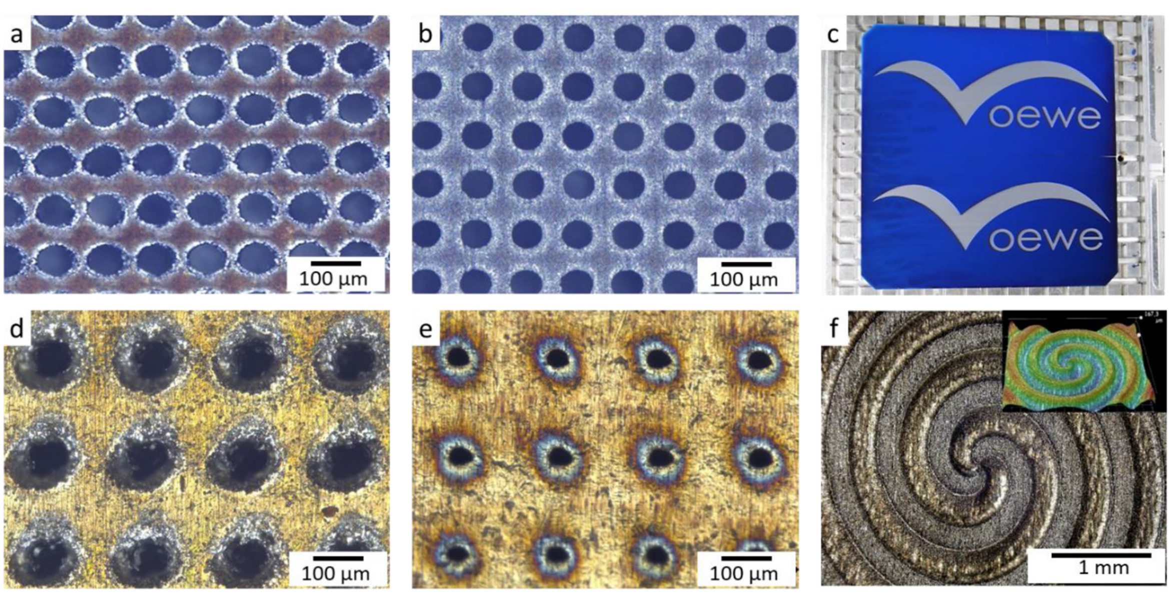


**Figure 5:** High speed drilled holes in silicon wafers front side (a), back side (b) with a spacing of 100 × 100 μm using 30 pulses and drilled stainless steel front side (d), back side (e) with a hole spacing of 200 × 200 μm using 90 pulses. (c) Shows an marking of the MOEWE logo using the bitmap modulation by an ablation of the silicon nitrite layer of a solar cell. An engraving of stainless steel in 2.5D is shown in (f).

range of 2–4 µm per repetition. The scan speed was 200 m/s achieving a laser interaction time per position of 100 ns, comparable to a performed engraving with an ns-pulsed laser. The hatch distance was set to 90 µm. The process takes 20 s and a maximum depth of 160 µm was observed [10].

Finally, the scanner is also able to handle ultra-short pulsed lasers for a lot of applications such as laser induced periodic surface structures (LIPSS) formation or surface texturing and functionalization. Several studies are published, where the polygon scanner was used to distribute ultra-short pulsed lasers in order to get a surface functionalization and an efficient fabrication at the same time [11, 13, 14].

## 3 Conclusions

Polygon mirror scanners allow the proper distribution of high power lasers without unwanted thermal heating to accelerate the processing speed and increase the throughput in several laser treatments. The presented device is able to handle multi-kW average laser powers tested with 10 kW of cw-lasers and 2 kW of pulsed lasers at deflection speeds from several 10–1000 m/s. The patented optical design allows less distortion scanning due to strongly reduced reflection point migration and avoids back reflection into the incoming beam direction. The combination of a high deflecting polygon mirror and a galvo mirror enables a two-dimensional material processing. The integrated real-time controller allows not only position true fast laser switching but also processing of large or infinity work pieces by utilizing external axis. The moving substrates can be processed on the fly by passing through the scan field and the integrated laser process control takes the current position into account. Thus, in roll-to-roll or similar processes, endless treatments are possible.

To obtain highest throughput and laser utilization, the whole laser set-up has to be tuned toward the target process. Since the utilization of a polygon mirror scanners has some processing characteristics differently from galvo scanners or axis systems, the process design has been discussed including limitations and optimization criteria. This includes the selection of the laser source under consideration of the deflection speed and the pulse energy and the choice of the right focusing optics taking the scan field to workpiece ratio and hence the line efficiency into account.

Finally, several applications of laser processes performed with a polygon scanner are presented. The most precision of the device is required for laser drilling, where each drilling hole has to be hit exactly again in several tens to hundreds of scans. This multi-pass ablation process has been used to perforate silicon wafers and stainless steel with thicknesses of 180–200 µm with 30 and 90 pulses per position, respectively.

Furthermore, layer removal on a silicon wafer ($152 \times 152$ mm$^2$) has been performed within 10 s. The single step laser process was additionally modulated following an image, processing only within black colored areas. A modulation with a grayscale image was performed to engrave stainless steel with a 400 W cw-laser. Thereby the depth information was coded into the gray-value. Hence, up to 40 repetitions with 2–4 µm ablation depth each were done resulting in a 160 µm maximum depth. The capability to handle also ultra-short pulsed lasers has been summarized from several publications, where the scanner device has been utilized for LIPSS formation or surface functionalization.

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