11th CIRP Conference on
Photonic Technologies [LANE 2020]

Industrial Paper

High power, high speed, high accuracy: the world's smartest polygon mirror scanner

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Abstract

High throughput laser processing requires high deflection speed and high average laser power at the same time. To handle average laser power up to 5 kW at speeds up to 1000 m/s, a two-dimensional polygon mirror scanner with a large free aperture of 30 mm has been developed. High accuracy can be achieved with a distortion free double-polygon wheel and the fully digitalization of the device. Therefore, an FPGA-based on-board logic calculates the processing data for each line in real-time. Applying a parallel computing device enables a correction of geometrical and external influences and allows precise treatment of moving substrates. This system can be used for a wide range of 2D, 2.5D and 3D laser processes. The synergy of high speed and high precision is visible in the case of laser drilling, where each bore hole is treated with a single pulse per scan and in repetition with the subsequent ones.

Keywords: "Polygon mirror scanner"; "High laser power"; "High throughput"; "High accuracy"; "Laser scanning"

1. Introduction

The development of laser sources has brought out high average power lasers with several kilowatts in commercial systems. Proper working requires, that this laser power is distributed on the material resulting in moderate laser fluences (energy per unit of area). Otherwise, heat accumulation will occur and cause damage to the work piece. Achieving a moderate fluence from high power laser can typically be done in three ways: 1. high frequency lasers with low or moderate pulse energy, 2. large area laser spots, or 3. high speed laser beam deflections. Nevertheless, a heat accumulation due to multi pulse treatment of the same area can be avoided only with fast movement between material and laser beam in the first case. The drawback of the second solution can be seen in the low resolution, which would not allow micro structuring or high-resolution marking or engraving. The third case allows the usage of the full laser power on the full resolution of the used optical system, typically with spot diameters in the focal plane from 10 to 100 µm.

However, an ultra-fast beam deflection must be realized and the accuracy of the beam deflection unit must not reduce the optical resolution. Polygon mirror scanners offer high beam deflection speeds due to fast rotating mirrors (Streek and Lee (2017), De Loor et al. (2014), van der Straeten et al. (2018)). But at this time, only a few systems are available handling laser powers suitable for laser material processing. Furthermore, a couple of drawbacks are associated with polygon mirror scanners, which has to be considered in the system design. First of all, the polygon mirror itself deflects only in one axis. Thus, some devices on the market using an additional external axis, while other systems use a galvanometer scanner for the second direction. Furthermore, the reflection point on the polygon mirror facet fluctuates during a passage. This causes distortions of the scan field reducing the accuracy or requires expensive special optics for correction. A third issue is the position true processing with pulsed laser systems, since the laser pulse repetition rate and the position frequency have to be synchronized. The position frequency is determined by the rotation speed, because a certain position along the scanned line is coupled to a defined angular position of the polygon and this is rotating continuously. One solution is a second galvanometer mirror in front of the polygon correcting the position of the incoming laser beam on the polygon

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mirror. In this case, the first mirror is irradiated during the whole process on the same area, which increases the risk of thermal damage or thermal lenses.

2. Full-digital polygon mirror scanner

2.1. Optical set-up

The polygon mirror scanner consists of two separate areas, the optical area in the lower part and the electrical area in the upper part of the device. The device is shown in Fig. 1a, where the optical section is visible through the window at the side wall and the electronic section is behind the upper black side panel. The optical section includes all components that deflect the laser beam in two dimensions, while the electrical section contains the motor of the polygon wheel, and controlling unit based on an FPGA (field programmable gate array). Several connectors on the top side allow the integration of the scanner in a laser machine and the communication to peripheral devices such as the laser source or the incremental encoders of up to three axes of a workpiece handling system.

The optical components from the entrance window over the facets of the polygon wheel to the galvanometer

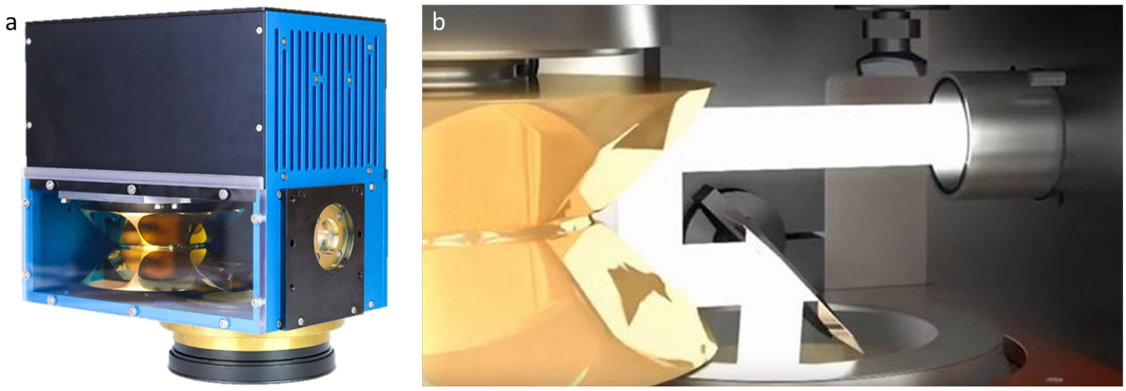

Fig. 1. (a) Compact polygon mirror scanner of the "*PM series"* from MOEWE and (b) detailed visualization of the laser beam propagation inside the scanner reflecting the laser light three times.

mirror, are designed with a free aperture of 30 mm, which is large for a compact device with a mass of 13 kg. The aperture of the focusing optic must also fit, but it is changeable. A couple of tested objectives are known to work properly with the polygon scanner. The size of the aperture, allows to working with large laser beam diameters enabling the high-power beam propagation. In experiments, laser beams of 20 mm ($1/e^2$ definition) and a power of a continuous wave (cw) laser of 5 kW or ns-pulsed laser of 2 kW average power have been tested successfully without damaging the optical surfaces. Additionally, all mirrors are permanently in a relative movement to the laser beam avoiding local heating with negative thermal influences on the reflective properties, such as thermal lenses.

An illustration of the laser beam propagating through the scanner is visible in Fig. 1b. After entering through the aperture, the beam is reflected twice at the double pyramidal mirror wheel. The lateral deflection angle is twice the mechanical angle of the mirror. Hence, the double reflection can be considered like a reflection at a flat mirror and the whole mirror wheel as a polygon with eight facets. Furthermore, the beam is leaving the polygon mirror at a lower level, that avoids a back reflection to the incoming direction. The fast-rotating mirror (up to 60,000 °/s) causes the beam deflection along the fast axis with scan speeds depending on the focal length of the variable objective. Additionally, the fluctuation of the reflection point on the mirror surface is compensated due to the second reflection, resulting in a distortion reduced scan field. With a 420 mm f-theta objective, scan speeds up to 1,000 m/s have been achieved with a focal spot size down to 35 µm. At the end of each facet, the beam is switched off, until the next facet is in position and the next line is processed. To achieve a two-dimensional scan field, the laser beam is reflected at a galvanometer mirror after the polygon wheel, which deflects the laser beam in the perpendicular direction. Consequently, the position of the scanned line is moved in the second dimension. The movement is typically performed during the facet change gap obtaining parallel scanned lines.

2.2. Fully-digital process control

The FPGA is the central element in the controlling unit. Compared to other processors, it allows parallel computing in a user configurated logic in short time. The fundamental clock time of the used FPGA is 5 ns (200 MHz). Around this FPGA several controlling devices, and input, output connectors are built. The whole controlling network schematically is shown in Fig. 2. The external devices are listed on the left side. The signals are coupled via interfaces to the FPGA. On the right side, the opto-mechanics are visualized, whereby they are also coupled to the FPGA with intermediate boards. Besides the FPGA, the central board contains two ARM-processors. One of them is used for communication with the host PC, which runs the controlling software. Once the parameters are configured and sent to the scanner, it works self-sufficient until changes arrive from the host PC. The second CPU is used for process monitoring.

A main task of the controlling unit is the steering of the opto-mechanical elements, including the motor control

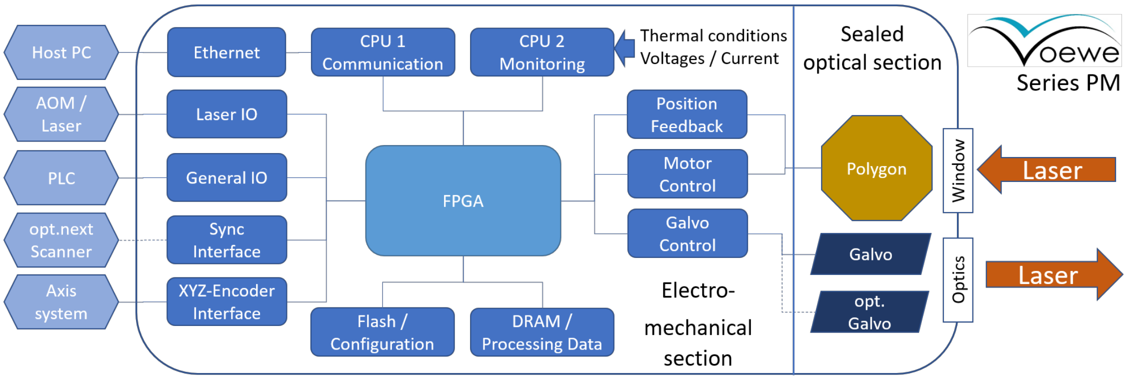

Fig. 2. Overview of the network within the fully digital controlling unit based on a FPGA

of the polygon mirror as well as the galvanometer mirror. Using an incremental encoder on the motor shaft, the current position of the mirror facets is taken into account for the calculations inside the FPGA in real-time.

The signals for the laser switching can be calculated position depending and are sent outside using high speed digital outputs TTL 5 V (high-resistance) or ≈ 4 V (50 Ω) with > 60 MHz or analog outputs 2/10 V (high-resistance) or 1/5 V (50 Ω), > 1 MHz. The facet resolution is 24 bits, which corresponds to a resolution of < 10 µm working with a 420 mm f-theta objective. Additionally to full area treatments, it is possible to load a bitmap file into the FPGA for marking or engraving laser processes. In this case, the laser is switched quickly on an off during a line scan, treating only the areas of the image. From the rotation speed and the spacing of the positions, the FPGA calculates a position frequency (scanned positions per second), which can be used at the high-speed output for pulse synchronized laser treatments.

An application using the full capability of the real-time calculation is the so-called shifter function. During standard processing it can be used to move the treatable area stepwise following a trigger signal. In combination with an external axes system with incremental encoders, the shifter allows the movement of the target area depending on the encoder signals of up to three axes (e.g. XYZ axis) for 2D, 2.5D and 3D processing. Furthermore, a real-time slicing of 3D solid models is possible. Thus, the system is able to follow a moving workpiece with the laser process. The position and laser switching are calculated for each line just in time, during the facet change gap. This feature allows not only the treatment of continuously moved substrates, but follows velocity changes or unwanted displacements.

Another smart feature is the synchronization option matching the polygon mirror rotation of multiple scanners. It allows the utilization of a single laser source at two or more work stations, e.g. in a manufacturing line. The laser beam is switched between the synchronized devices, that always one scanner is working during the other one is in the facet change. Hence, the utilization degree on the laser source is increased.

3. Laser drilling with a polygon mirror scanner

Most important for drilling is the pulse synchronization between consecutive scans, since multipass ablation is requiring high accuracy to hit the bore hole exactly in every scan. This synchronization was realized using a laser, which adjusts its pulse repetition rate to a given frequency signal provided by the scanner device. This signal is generated from the FPGA concerning the rotation speed of the polygon mirror wheel, respectively the scan speed, and the target positions on the material. The laser drilling experiments were performed on polycrystalline silicon wafers of 180 µm thickness and stainless steel with a thickness of 200 µm. A polygon mirror scanner has been used together with a 240 ns pulsed IPG fiber laser of 1 kW average power with a wavelength of 1064 nm. The pulse repetition rate was set to 1 MHz. In the used optical configuration, focal spot diameters of around 100 µm were obtained in a 320 x 320 mm² scan field. Thus, the resulting fluence was 13 J/cm². Depending on the bore hole spacing of 100 or 200 µm, the laser scan speed has to be set to 100 and 200 m/s, respectively.

In Fig. 3, resulting bore holes in silicon and stainless steel are visible from the beam entrance and the beam exit side. The holes in the silicon wafer are drilled with 30 pulses and a scan speed of 100 m/s. Consequently, the spacing results to 100 µm. The cumulative ablation generates hole entrance diameters of 61.8 ± 1.8 µm and 76.7 ± 3.0 µm perpendicular and parallel to the scanning direction, respectively. Due to the fast scanning speed, relevant distances of several micrometers are covered in the short times, such as the pulse duration, causing a prolonged ablation area in the direction of scanning. At the exit side the hole diameter was measured to 58.5 ± 3.7 µm. The process takes 10.25 s for an area of 20 x 5 mm² including 10,000 holes. If the full range of beam deflection along the fast axis would be used for the process, the number of drilled holes increase to 160,000 in the same time. Hence a drilling speed of > 15,500 holes/s can be obtained with an optimized set-up, since a line is always completely scanned just with the laser turned off outside the target areas. That would enable at least 5 times higher throughput compared to galvanometer scanning systems (Patwa et al. (2013)).

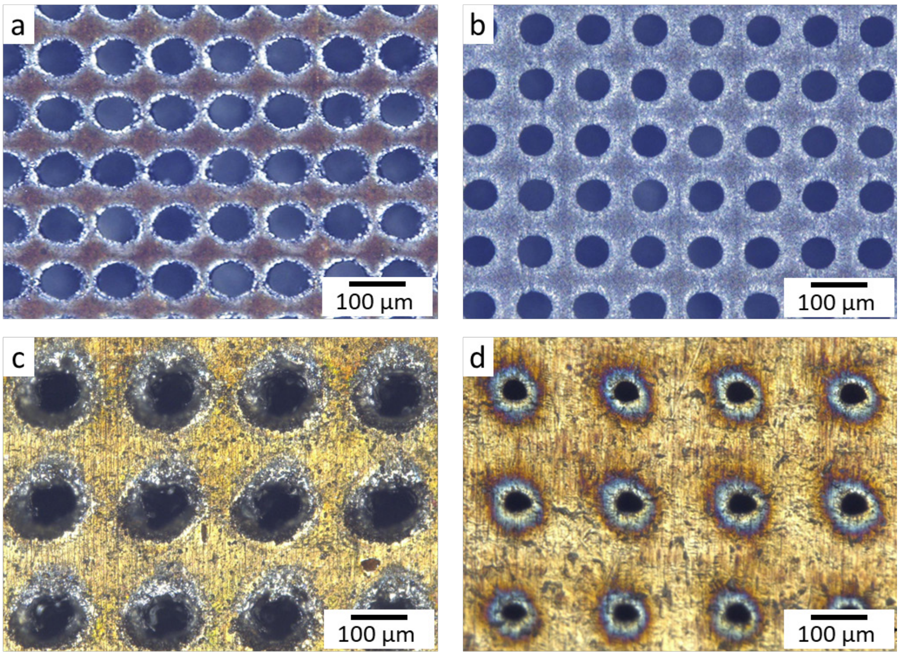

Fig. 3. High speed drilled holes in silicon wafers front side (a), back side (b) with a spacing of 100 µm x 100 µm using 30 pulses and drilled stainless steel front side (c), back side (d) with a hole spacing of 200 µm x 200 µm using 120 pulses

In the case of stainless steel, more pulses are required to drill through. The shown sample was treated with 120 pulses with a scan speed of 200 m/s resulting in a 200 µm spacing. At the entrance side, diameters of 107.4 ± 5.1 µm are measured perpendicular to the scanning direction. In the scanning direction, the scan speed depending elongation causes diameters of 128.9 ± 5.8 µm. The measured diameters at the beam exit side are 42.6 ± 5.5 µm. The image shows, that the positions are hit 120 times with a very low misalignment, which verifies the accuracy of the scanning system at these high scanning speeds. The process takes 12 seconds. Under optimal usage of the scanning field, 3,300 holes/s can be drilled.

4. Conclusions

Polygon mirror scanning offers ultra-fast laser beam deflection speed increasing the processing speed and throughput. The presented two-dimensional scanning device allows highest average power laser treatments of up to 5 kW (cw) or 2 kW (pulsed) at fastest speed from 10 m/s up to 1,000 m/s. This is combined with a real-time controlling concept in a compact design not much larger than a galvo scanner. A high accuracy during the process is obtained from both, the patented distortion free optical design and the patented fully digital, real-time FPGA process control. The incoming laser beam is reflected twice at the fast-rotating double pyramidal mirror wheel. Thus, a typical drawback of polygon mirrors has been overcome avoiding migration of the reflection point during a facet passage. Furthermore, a back reflection into the direction of the incoming beam is impossible. To enable a two-dimensional treatment, a galvanometer mirror is used after the polygon mirror moving the position of the scanned line. The powerful controlling allows precise laser switching during the scan correcting inaccuracies and external deviations in real-time. In combination with a position depending frequency generation, a position synchronization is possible, since the used laser follows this signal with its pulse repetitions rate. The

This functionality has been demonstrated in multipass laser drilling experiments, requiring highest accuracy to hit every bore hole position in up to 120 scans. The full available laser power of 1 kW was used to drill silicon wafers and stainless steel of 180 µm and 200 µm thickness, respectively. In the fastest configuration, silicon was drilled through within 30 scans, which corresponds to a processing speed of more than 15,500 holes per second under optimized conditions.

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