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Polygon scanner system for ultra short pulsed laser micro-machining applications

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Abstract

Ultra short pulsed lasers have gained acceptance in micro-machining applications and many processes have been developed in the lab. Transferring the technology to the manufacturing floor started few years ago as soon as relatively high average power (> 5W) lasers became available. Now that high repetition rates and average powers of 50 Watt and more are reaching the market, the commercially available galvo based laser scanners systems limit the efficient use of this expensive laser power. We present a novel polygon based scanner system incorporating laser and scanner synchronization enabling writing speeds of 50 m/sec and higher.

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Keywords: polygon scanner, ultra short pulse laser, synchronization, speed, surface structuring, high volume ablation

1. Optimized volume ablation needs higher scanning speed

Laser material processing using ultra short pulsed lasers in the ps to fs pulse regime has been the topic of many research programs in the past and will gain in industrial acceptance in the near future. The possibility of processing many very different materials in the so called 'cold ablation' regime has opened a window to numerous new applications. Just to name a few: surface structuring, micro fluidics, thin film removal and other etch replacement processes by laser.

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Although many laser processes have been developed in research labs, not many of them have reached industrial applications as of today. The main factors hindering the industrial acceptance are the lack of available high average power pulsed lasers, and the lack of fast laser scanners. In the last two years average power ultra short pulsed lasers in the 30 to 50 Watt area have become available from companies like Lumera, Time Bandwidth, Amplitude, Eolite and others. Laser scanner technology used in the laser material processing applications is nowadays mostly galvo scanner based.

In order to efficiently exploit the higher available laser power a need for higher scanner speeds has arisen, and galvo scanner suppliers have responded by tweaking up the writing speed. Despite all the effort spot scanning speeds higher than 10m/sec can not be achieved using small spot sizes.

The need for scanning speed is recognized by theoretical modeling and experimental verification of material volume rates executed by the group of Neuenschwander at Bern University of Applied Science [1].This research concludes that the optimal operating point for maximal volume ablation rate given the available amount of average laser power, material to be processed and required focused spot size dictates the optimum pulse repetition rate to be used. Reason is that for a given material, spot size, and wavelength there is a corresponding optimum pulse energy for maximal volume ablation. Utilizing a higher pulse energy while keeping the rep rate constant will ablate more material, but the removal rate does not scale linearly with the pulse energy. When keeping the pulse energy at the optimum level and raising the rep rate, the material removal rate does scale up in a linear way. So when higher average laser power becomes available we should work at higher rep rates to obtain highest material removal rates. Typical operating conditions for copper at 1064 nm are 60 kHz for 1 Watt average power. This optimal operating point scales up to 3 Mhz for 50 Watt average power. In case of a 25 μm spot with a 60% overlap (10 μm pulse spacing) this would require a scan speed of 30 m/sec. Available galvo based scanner technology is limited to scan speeds in the order of 10 m/s.

2. Polygon based scanner technology delivers highest volume ablation rates

Next Scan Technology (NST), a Dutch/Belgian company specialised in laser scanning and modulation technology has developed a radically different scanner technology capable of moving the focused laser spot at 25 to 100 m/sec and higher. The NST system does not use a set of galvo scanners (figure 1 left column), but relies on rotating or polygon scanner technology (figure 1 right column).

The novel NST approach deflects the incoming laser beam by means of a multifaceted mirror or polygon. The polygon is rotating at a fixed speed around a mechanical axis, and every time a flat facet of the polygon is traversing the incoming beam an angular deflected scanning beam is produced. When the beam traverses the corner between two facet mirrors the laser is shut off, and the beam position flips to beginning of the line again.

By nature rotating scanners are one dimensional scanners, they produce a scanned line, to obtain a 2D scanning system a secondary linear motion is required. The direction of the secondary motion is perpendicular to the line scanned by the polygon scanner, and is synchronized in speed with the latter rotational speed, to obtain a line by line scan of the target surface. This type of scanning is usually referred to as 'raster scan'.

Since the polygon is rotating at a constant speed, in contrast to the back and forward motion of the galvo mirror scanners, a high number of scanned lines per second can be realized. Similar to existing scanners an f-theta scanning lens focuses the scanned beam to a spot in the flat writing plane, taking care of a highly linear relation between scanner angle and spot position.

Polygon scanner technology is well known in the graphic arts industry, and are used in desktop laser printers but have received little attention in laser micro-machining applications. Reason for this is the lack of availability of standard off-the-shelf systems. Building a polygon scanner set-up from scratch is a major project since it requires tedious synchronization of polygon speed (X-direction), material traversing (Y-direction) movement and laser pulse timing (spot location). In addition to designing a state of the art optical scan unit Next Scan Technology has developed a scanner system controller box that handles all synchronization issues. For the first time an of the shelf polygon scanner solution is available to the market.

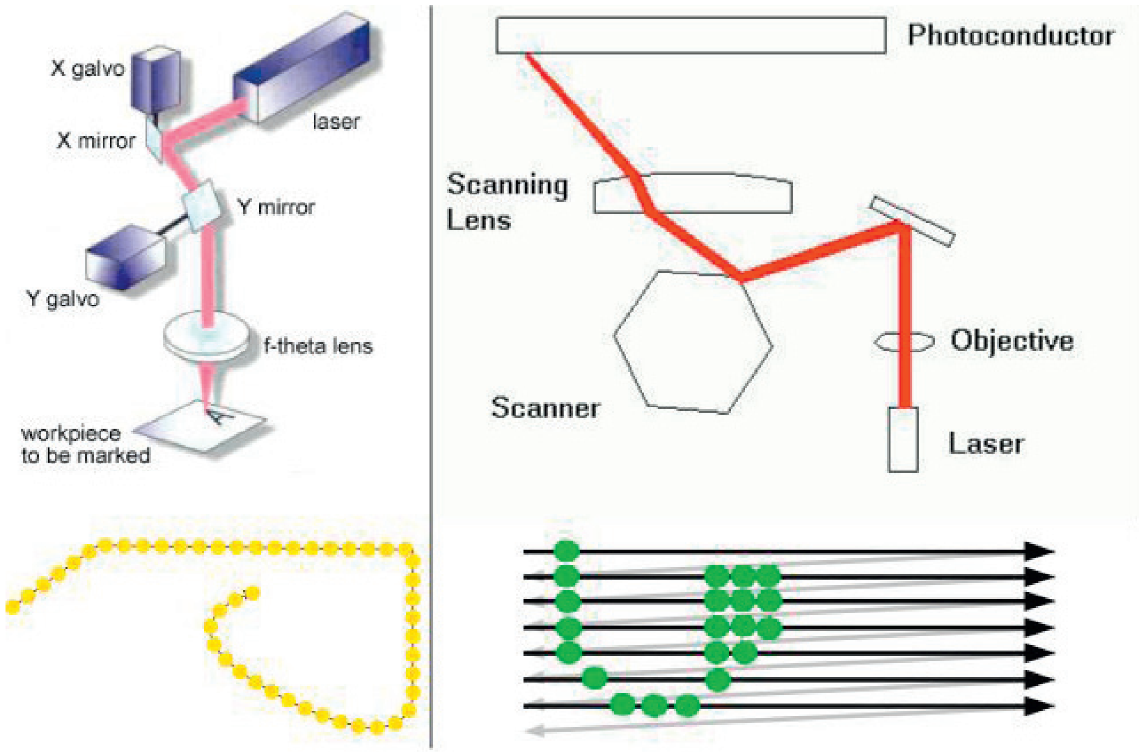

Fig. 1. Galvo versus polygon scanning

Although polygon or rotating scanner technology is new to the laser micro-machining market, raster scanning operating mode is available in most of the galvo scanner software packages. These packages support both the so called 'vector mode' and the 'raster scan' mode. The software front-end is switching silently from one mode to another. Single lines are written in vector mode, but thicker lines and filled character or logos are written in raster scan mode. Polygon scanner technology can be seen as a 'hardware' implementation of the raster scan mode, and because of the hardware implementation it delivers much higher scanning speeds.

Raising the scanning speed using polygon technology raises concern about laser pulse rate and scanner speed synchronization. We refer to an excellent publication on this topic by Jaeggi, Neuenschwander et all [2] discussing the pulsed laser spot positioning using no synchronization, sky-writing (writing when the scan speed is constant only) and laser/scanner synchronization. In this paper a galvo scanner system is operated in raster scan mode, and the importance of scanner/laser pulse synchronization is discussed. Without any synchronization, the start and ends of the scanned lines are written at lower scanning speeds, producing higher than intended spot overlap, so more material is removed at the start and end of the lines. Using skywriting mode, the laser is only pulsed during the constant speed period of the scanned path. This results in constant spot overlap and constant material removal, at the expense of lower 'mechanical' efficiency. The laser is not removing material during the speed-up and speed-down period. When pushing the scan speed up, the speed-up and speed-down time is increasing by the galvo's maximum acceleration rate. For high speed scanning this can add up to more than 50% of the total line writing time.

In sky writing mode the laser pulses have identical overlap, but the start position of the scanned line jitters by a distance equal to the pulse jitter multiplied by the scanning speed. The jitter can be nulled when the laser pulse timing is synchronized to the scanner raster writing resulting in an accurately defined starting position of the first spot in the line (figure 2). Jaeggi has implemented this requirement by slaving the galvo scan mirror speed profile to the rep rate signal of the laser used.

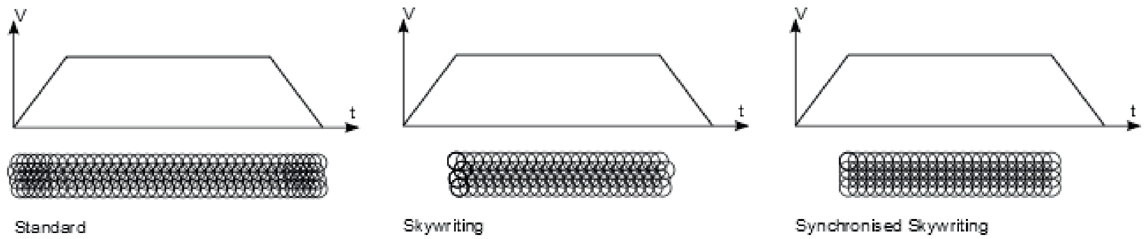

Fig. 2. Raster scanning writing modes

By nature of its design a polygon scanner operates always in the sky-writing mode. The polygon motor speed is set according to the demanded scan speed and from then on the polygon keeps spinning at a constant speed and never changes during the whole machining cycle. A highly linear f-theta optic converts the constant angular speed in a constant spot scanning speed. Because of the high scanning speeds obtained laser/scanner synchronization now becomes even more necessary. NST has developed a proprietary synchronization technology (SuperSync) for MOPA type lasers in order to obtain best in class performance repeatability laser dot writing positions.

3. The NST polygon Laser Scan Engine

The NST laser scan system offers a complete off-the-shelf ready to use polygon based scanner solution. The system consist of a state of the art polygon laser scanner, and a system controller box. Combined with a laser and linear stage a high speed laser writing set-up can be operational in few days (figure 3).

The scanner unit consist of the rotating polygon, input optics and f-theta optics. In the LSE 170A the f-theta optics are fully telecentric, offering a scanning beam that is always directed perpendicular to the scanned surface and a diffraction limited round focused spot across the 170 mm scanned width. The optical design is fully reflective (including the f-theta), the scanner takes both green and NIR beams. The focal length (190 mm) is equal for all wavelengths. By avoiding the use of glass, and applying high tech coatings to the mirror system pulse dispersion is no longer an issue. The maximum diameter of the incoming parallel beam is 6 mm.

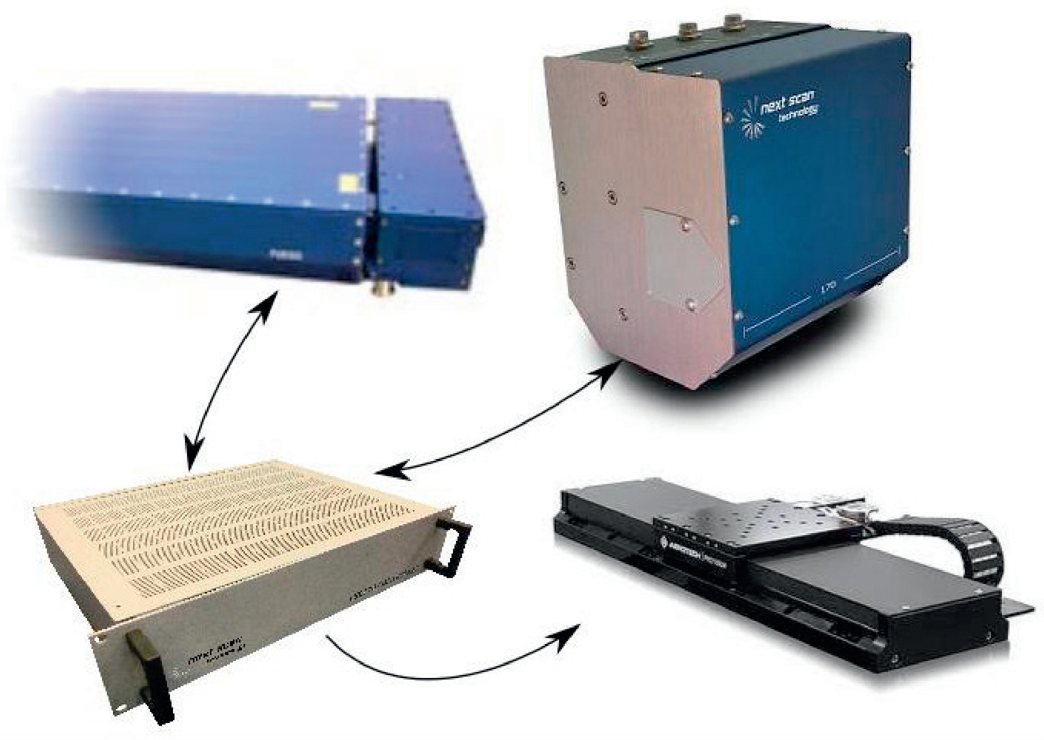

Fig. 3. Next Scan Technology laser system set-up

Combining a linear stage movement with a one dimensional f-theta lens enables the construction of a simple yet very performant system. The one dimensional f-theta system can be made telecentric and highly linear. Telecentricity provides for constant light matter interaction across the scan, the impeding beam is circular, constant in size, constant in peak intensity across the scan. Out of focus scribing does not result in loss of spot placement accuracy. The scan grid shows no pincushion distortion and no error compensation tables are required to achieve an accuracy better than 5 µm.

The LSE system controller takes care of synchronizing the polygon rotational speed to the laser master oscillator or rep rate clock, the control of the linear stage and the gating of the laser pulses. The standard controller synchronizes the start of a scanned line within a rep rate clock period, adding the Supersync option synchronizes the start of line time within a master clock period, reducing the synchronization jitter by a factor of 10 to 50.

To obtain a 2D scan the processed material needs to be moved perpendicular to the scanned line. This movement also needs to be synchronized to the polygon speed. Each time a new line starts the material must have moved by exactly one line spacing. The material motion is handled by a high quality linear stage or roll to roll feed system using commercially available drives. To control the speed of the material feeding system the LSE controller provides for a simulated quadrature encoder output that serves as the master axis for the linear stage motion controller.

The combined synchronization of polygon speed, stage speed and laser pulse timing defines a two dimensional grid of laser writing positions. The x and y grid spacing can be set independently. All patterning of the surface must now be handled by selectively gating the laser at the defined grid positions. So we can see the scanned surface as a very high resolution display having 17000 rows of 17000 pixels (for a 10 µm dot and line spacing). The information visible on this display can now be stored in a bitmap file. The LSE system controller has an ethernet connection to receive black and white bitmaps. The information in the bitmap is used to gate the laser pulses as the laser beam scans the 2D surface.

4. Experimental set-up

Experiments were executed on a lab set-up using the LSE 170A polygon scanner and Laser Scan Engine (LSE) controller (Next Scan Technology) , a Duetto/Fuego laser (Time Bandwidth) operating at 1064 nm, a linear motor stage (Anorad) and SB1381 motion controller (ACS). The Duetto/Fuego laser was equipped with the 'NST SuperSync' option. The NST LSE controller is the master of the system set-up and takes care of the synchronization between scanner speed, stage positioning and laser synchronisation and gating. The controller has an Ethernet connection and writes bitmap pattern at a preset speed and spot spacing on demand. For this experiment the 44 µm 1/e2 laser spot laser pulses have been separated deliberately by 50 µm to visualize single lasered dots. The laser was operated at a 1 Mhz rep rate, resulting in a 50 m/sec scan speed. Samples were written on a silk screen painted microscope glass, and have been evaluated under a microscope equipped with digital camera. We use a dark light (i.e. shearing side light) illumination configuration so the pits excavated by the laser pulse are dark in on the microscope display.

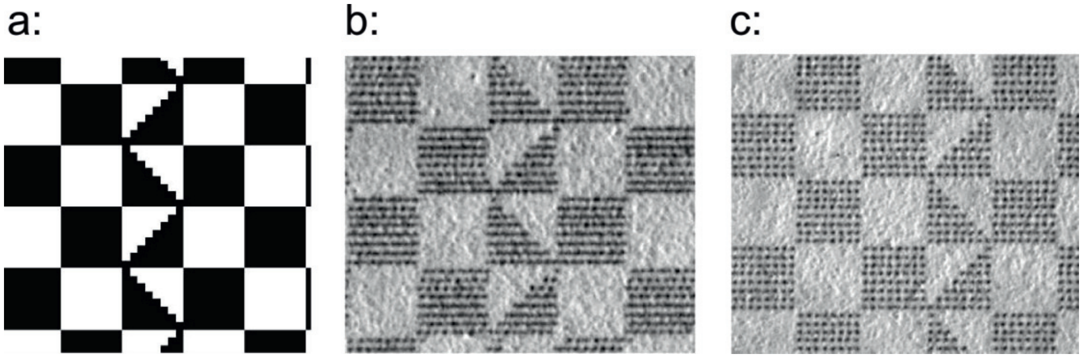

Fig. 4. (a) bitmap; (b) sky writing (no sync); (c) SuperSync synchronization

The test samples were written using a computer generated test bitmap (figure 4a), Writing parameters and bitmap files are transferred to the controller using the standard tftp protocol. Once the bitmap has been transferred to the LSE controller, the sample writing is done automatically by the controller. To evaluate the system repeatability we wrote five layers on each sample, in case of perfect repeatability the resulting samples should show nice distinct pits corresponding to the bitmap pixels.

5. Results and Discussion

At 1 Mhz rep rate their exists a writing timing uncertainty of 1 µs. The laser POD (pulse on demand) module is triggered when the scanner has reached the theoretical spot position in the fast direction (horizontal in the figures). When the scanner is used in sky writing mode, the 1 µs timing uncertainty results in a position jitter of one pulse separation or 50 µm. This is clearly observed in figure 4b, on most of the horizontal features we do see a horizontal short line in stead of eight separated dots. On some lines we just were lucky and can see separated dots, this is where the five layers exactly match up. Upon enabling the SuperSync synchronization option the position jitter is reduced to a few microns resulting in perfect matching of superposed layers as can be seen in figure 4c.

6. Application areas

The polygon scanner is a natural fit for high density patterning, stripping, laser direct writing, hexagonal dicing, high density hole drilling, complex 3D printing and many other applications.

Although the article has emphasized on the use of a linear transport for the slow axis movement, it should be realised that a polygon scanner combines very well with roll to roll transports. This makes the transfer of lab results (achieved using a linear stage) to manufacturing (using roll to roll) really simple. NST is offering customisation to obtain the best fit scanner width, spot size and writing speeds.

References

[1] B. Neuenschwander, B. Jaeggi, M. Schmid, V. Rouffiange and P-E Martin, *Optimization of the volume ablation rate for metals at different laser pulse durations from ps to fs.* Proc of SPIE Vol 8243 824307.

[2] B. Jaeggi, B. Neuenschwander, U. Hunziker, J. Zuercher, T. Meier, M. Zimmerman, et all*, Ultra high precision surface structuring by synchronizing a galvo scanner with an ultra short pulsed laser system in MOPA arrangement*. Proc of SPIE Vol 8243 82430K

Appendix A. LSE170A specification

LSE170A head		
Scan speed	100-400 lines per second	
Moving spot speed	25-100 m/sec	
Scanner mechanical efficiency	71%	
Optical efficiency	>85% (GR, NIR)	
Input beam diameter($1/e^2$)	6 mm, collimated beam	
Input clear aperture	10mm	
System focal length	190mm	
Scan Width	170 mm	
Position accuracy	+/- 5 µm	
Repeatability	<3µm	
Wavelength	515/512 nm (GR)	1030/1064 nm (NIR)
Minimum spot (FWHM)	13µm	26µm
Minimum spot ($1/e^2$)	22µm	44µm

Laser source		
Pulsed Laser[2]	User supplied, pulse triggered by LSE170A controller	
Average laser power	25 W GR	50 W NIR
Minimum pulse width	7 ps	
Maximum pulse energy	400 µJ	

Mechanics	
Head mechanical interface	Industry standard interface in one of 3 (L/C/R) positions
Scanner to substrate clearance	22 mm
Head controller	2U 19" rack.
Cable length	Max. 5 meter between head and control electronics
Linear cross scan transport	User supplied, slaved to LSE170 controller

Control system	
System control PC	User supplied, Windows 7 OS
PC Connection	Ethernet connection with TCP/IP protocol Usb 2.0 connection for serial line interface
Pattern data	B/W bitmap