Beam shaping and splitting with diffractive optics for high performance laser scanning systems

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Diffractive optical elements (DOEs) enable novel high performance and process-tailored scanning strategies for galvanometer-based scan heads. Here we present several such concepts integrating DOEs with laser scanners and the respective application use cases. Beam shaping DOEs providing a homogeneous fluence over a custom defined profile, such as a rectangular Top-Hat, enable increased process quality in Laser-Induced Forward Transfer (LIFT) compared to the Gaussian beam of the laser source. We show that aberrations which occur over the necessary large wafer-sized image field can be eliminated through the use of a synchronous XY-stage motion. Another application that benefits from the use of DOEs is laser drilling. Drilling in display and electronics manufacturing demands high throughput that can only be achieved through the use of beam splitting DOEs for parallel processing. To this end, the joint MULTISCAN project is developing a variable multi-beam tool capable of scanning and switching each individual beamlet for increased control.

1. Introduction

Technological developments in display and electronics manufacturing rely on the fabrication of components with ever decreasing feature size and increasing density. This introduces challenges to existing processing methods such as increased accuracy and throughput. The laser is a common tool for such material processing and is typically scanned using a galvanometer scan head and f-theta lens to provide fast (~2 m/s) and flexible beam positioning on a 2D flat image field. In such a configuration, the Gaussian laser beam is focussed to a small spot on the sample surface. A Gaussian intensity profile is, however, not necessarily what is required or optimal for the process and can reduce the processing quality. With regards to throughput, duplicating the laser-scanner setup is costly, space inefficient and limited in the scan field overlap of the separate systems on the workpiece (i.e. multiple systems can't work simultaneously on the same workpiece area). In both these cases, diffractive optical elements that shape and/or split the beam can be used to transform the existing setup into a higher performance system that overcomes these limitations.

1.1 Beam shaping in display manufacture

The current trend in the LED display industry is from traditional LED (chip size of >300 µm) towards smaller MiniLED (chip size ranging from 75 – 300 µm) and MicroLED (chip size of <75 µm) packages that offer improved resolution, brightness, refresh rates and luminous efficiency [1]. While the incremental evolution of technology capable of producing traditional LEDs is able to scale towards the smaller size dimensions of MiniLEDs, the costs and challenges associated with throughput are significantly increased. Fabrication of MicroLED packages, however, requires a major disruption to existing chip manufacturing, design and assembly technologies.

Lasers play a key role in the fabrication process. The RGB dies are grown on separate wafers, commonly sapphire at a density of ~8 million per 6" wafer totalling ~24 million dies. These are then transferred to a temporary carrier wafer using a laser lift-off (LLO) process. Finally, the RGB dies are transferred (each pixel colour separately) onto the substrate via LIFT. To mass transfer the MicroLEDs with an accuracy of a few microns, a mask is illuminated with a Top-Hat intensity profile [2]. Over 10k dies are typically transferred per shot and, with repetition rates of a few 100 Hz, this equates to a few million dies per second and a processing time of tens of seconds for a 6" wafer. Due to the large area illumination of the mask, a laser with excellent pulse-to-pulse stability and high pulse energy is required. Additionally, a wavelength in the UV below the 3.3 eV (376 nm) band gap of Gallium Nitride (GaN) but above the 9.9 eV (125 nm) band gap of sapphire, where the sapphire substrate is transparent and the LEDs are opaque, is required. UV ns-pulsed excimer lasers at 248 nm or 266 nm limit the interaction volume to a few nm and are the standard choice [2].

A current bottleneck in MicroLED manufacture is that, even with the highest yields, the mass transfer LIFT process will result in several thousand dead pixels per wafer that must be replaced. A mask-based mass repair approach is not possible as the positions of the dead pixels are random. The excimer laser focused onto the defective MicroLED site with a slightly oversized Top-Hat intensity profile can be used. However, for increasing throughput above several hundred Hz, solid state ultrashort pulse (USP) lasers with kHz repetition rates present a more capable and cost efficient solution. Such a high speed laser scanning system running at 2.6 kHz without

degradation in imaging performance of the Top-Hat over the entire wafer is presented in section 3.

1.2 Beam splitting for PCB drilling

Drilling vias is a time intensive stage in PCB manufacturing. The smallest mechanical drill bits have a 150 µm hole size lower limit in comparison to the laser that can achieve a 15 µm hole size and thus enables higher densities while also having the advantage of being a non-contact process that does not cause wear of the tool [3]. Furthermore, a laser-galvo scanner setup increases in drilling productivity with via density, as time spent positioning (moving & settling of the mirrors) is reduced [4].

The drive towards smaller feature sizes and higher densities for increasing performance along with the availability of ultrafast lasers with ever increasing average powers pose a challenge to conventional laser-scanner setups. Higher feature densities require increased throughput of the system to keep up with the current component processing rates. High average laser powers require beam splitting to divide the pulse energy across the beamlets and avoid excessive fluences on the target material that lead to undesired thermal effects like a heat affected zone (HAZ) or fracturing. The laser pulse energy is not a limiting factor as the tightly focussed beams lead to high fluences even at relatively low pulse energies.

Beam-splitting can be achieved by duplicating the scanner and imaging optics but is costly. Furthermore, two systems are limited in the scan field overlap and so cannot work on the same workpiece at once. The use of diffractive optics offers an economical alternative approach. A beam splitting DOE, engraved with a grating on one face, can be inserted before the scanner in the existing setup. The different orders of the diffracted input beam (beamlets), travel through the scanner with defined separation angles before being focussed by the f-theta lens, which results in a spot-to-spot spacing in the scan field corresponding to the $f \times \theta$ relationship.

While such a setup is suitable for applications like roll-to-roll surface texturing, the drill sites on PCBs vary in location and require additional control of the individual beamlets in the form of switching and positioning within the matrix. In section 4, the multi-beam engine, a highly integrated compact system with advanced scanning algorithms developed as part of the MULTISCAN project to overcome such challenges is presented [5].

1.3 Challenges of laser scanning

Laser scanning with a shaped or split beam is limited by the usable scan field. The arrangement of the galvo mirrors results in a pillow-shaped distortion and the f-theta lens gives a barrel-shaped distortion, which combine to give a barrel-pillow shaped image field [6]. The effect is significant at the image field extremities, corresponding to large galvo mirror deflection angles, as shown for a rectangular Top-Hat intensity profile in

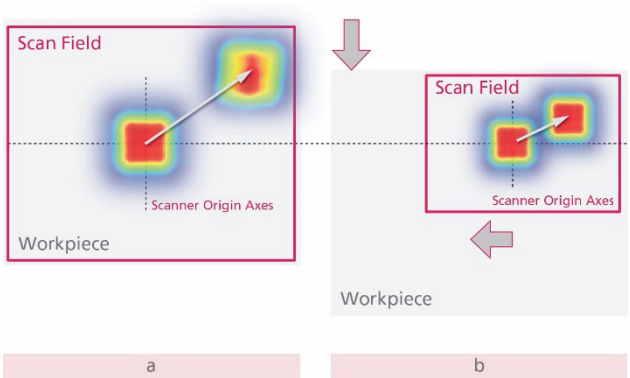

Fig. 1: Laser scanning with a Top-Hat shaped beam. (a) Warping occurs at image fields extremities due to increased aberrations and can be compensated by (b) a synchronous motion of an XY-stage during processing to limit the scan field size.

Fig. 1(a). Poor laser beam quality ($M^2 \neq 1$), wavefront errors introduced by optics in the beam path or clipping of the higher diffraction orders by the f-theta lens or galvo mirror apertures may also lead to significant distortion.

This is particularly problematic in micro-electronics applications requiring short focal lengths for a tight focus as the full scan field is required. To overcome this, an XY-stage with synchronised motion (e.g. SCANLAB's XL-SCAN) can be integrated to reduce the used scan field size while allowing workpiece sizes up to the travel of the stages to be processed, as shown in Fig. 1(b). Additional benefits include an increase in overall process speed due to the combined motion of the galvos and stage, elimination of stitching errors and smaller focal spots due to the reduction in required scan field enabling the use of shorter focal length f-theta lenses [5].

In this work, two novel laser scanning solutions employing a beam shaping or splitting DOE, a scan head with an f-theta lens and an XY-stage with synchronised motion are presented. Section 2 first presents the achievable accuracy and throughput rate with synchronised motion of the scanner and XY-stages. Section 3 shows how such a setup employing Top-Hat beam shaper can achieve the accuracy and throughput required for MicroLED repair, while Section 4 shows how multi-beam scanning for parallel processing significantly increases throughput in drilling for micro-electronics and display industries.

2. Scanning with synchronised XY-stages

XL *SCAN* from SCANLAB and ACS Motion Control achieves synchronised motion between the scan head and XY-mechanical stages with a band-pass filter that divides the mark trajectories into high and low frequency components to be carried out by the scanner and stage, respectively. The positioning accuracy of XL *SCAN* was compared with scanner only motion using a setup consisting of an excelli*SCAN* 14 scanner and f = 100 mm f-theta lens. The radial positioning accuracy was determined by firing single shots, pausing to allow the galvo mirrors to settle and then, once all the radial positions had been processed, measuring these with a coordinate

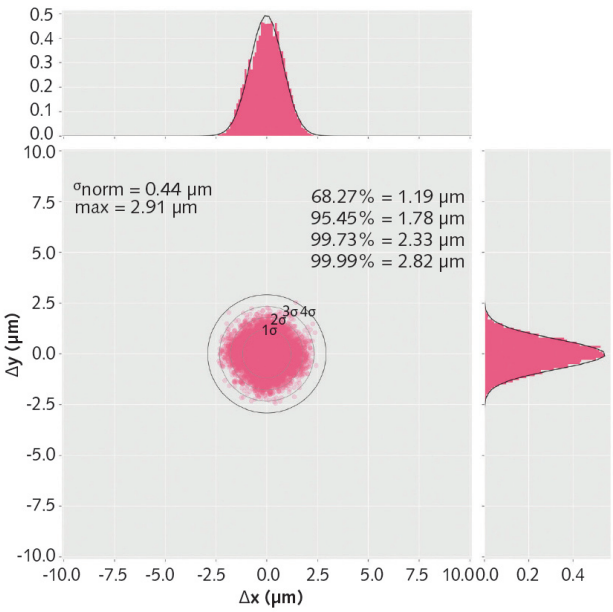

Fig. 2: 2D Scatter plot of the positioning error with a setup combing a scan head fitted with a f = 100 mm f-theta lens and a mechanical stage moving in synchronised motion (XL SCAN). Density plots along X and Y axis are shown separately and follow a Gaussian distribution.

machine. Note that the setup was calibrated prior to the experiments to correct for the barrel-pillow scan field distortion. The results showed an increase in the maximum error from approximately ±1.5 µm to ±4 µm at a radius of 4 mm and 25 mm, respectively [5].

Next, the XY-stages were moved synchronised with the scanner using XL *SCAN* to process 10,000 shots over the workpiece within a 6 x 6 mm^2 scan field at a rate of 2.6 kHz, as determined by the 100 µm pitch, jump delay of 40 µs and 150 µs processing time. The 4-sigma (99.99% of shots) absolute positioning error was just 2.82 µm, as shown in Fig. 2. Hence, the reduction of the scan field from the full 25 mm radius to just the central 4.2 mm radius resulted in a significant increase in the positioning accuracy that, through the travel of the XY-stages when using XL *SCAN*, does not depend on the workpiece size. Furthermore, a decrease in the pitch would continue to increase the drilling throughput without increasing the positioning error.

3. Top-Hat beam scanning

MicroLED repair has demanding requirements on the intensity profile at the sample surface. These include a small rectangular shape (e.g. 35 µm x 22 µm) with steep edges of 3 - 5 µm, a uniform flat region and minimal distortion at all sites on the wafer. To achieve these specifications, a high NA f-theta lens together with a custom Top-Hat DOE beam shaper, which has an improved edge sharpness of half a diffraction limit, must be used. The flat region size of such a sharp edge DOE beam shaper is only a few diffraction limits and requires highly accurate beam size, good centration of the beam and precise focusing to achieve the optimal performance.

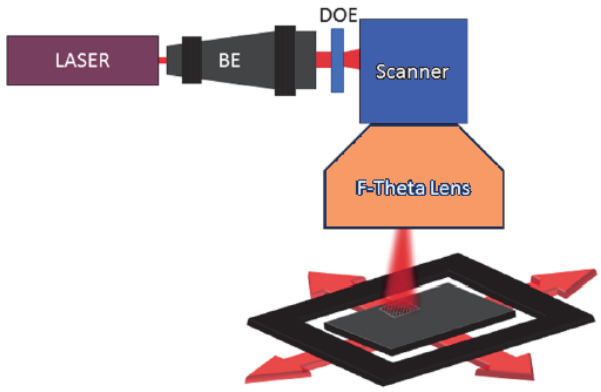

Fig. 3: Schematic of the experimental setup used to scan the Top-Hat laser beam over the image field.

The scanning setup is shown in Fig. 3. The raw Gaussian beam from a 355 nm laser (Coherent, Hyper Rapid 50 Classic) was expanded using a 1-3X variable beam expander before the Top-Hat beam shaper DOE (HOLO/OR, ST-350-U-Y-A), which was designed to have a Top-Hat size of 21.1 µm x 36.2 µm and transfer region of 5 µm with an input beam of 5 mm at 13.5 % intensity. The Top-Hat size is defined as the area between the 13.5 % normalised intensity level, while the transfer region is characterised as the area between the 13.5 % and 90 % normalised intensity levels. The laser beam was scanned using a 14 mm aperture galvo scanner (SCANLAB, excelli*SCAN* 14) and focussed using a f-theta lens with an effective focal length of f = 65.5 mm. Imaging of the focussed beam intensity profile was performed with a CCD camera mounted onto a z-translation stage and positioned in the focal plane. In order to automatically align the laser beam to the Top-Hat shaper and calibrate the system, a module from Pulsar Photonics with automated measurement routines and actuators was used. This automatic alignment ensures a stable calibration over longer processing times.

The Top-Hat profile quality was characterised in terms of its edge steepness and plateau uniformity according to ISO 13694:2000. The edge steepness is given by

$$S_{10\%,90\%} = \frac{A_{10\%} - A_{90\%}}{A_{10\%}},$$

where $A_{x\%}$ represents the effective irradiation area over which the energy density is greater than x% of the maximum energy density. The steepness approaches zero for an ideal flat Top-Hat with vertical transition region (i.e. a step function). The plateau uniformity was calculated according to

$$U_p = \frac{\Delta E_{FWHM}}{E_{max}},$$

where ΔE_{FWHM} is the full-width at half-maximum (FWHM) of the peak near E_{max} of the energy density histogram and tends to zero with increasingly flat topped profiles.

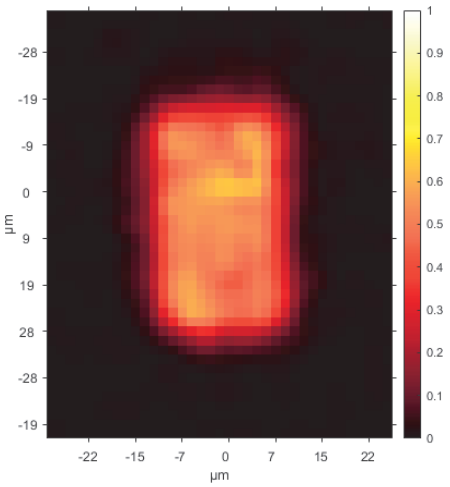

Fig. 4: Image of the experimentally measured Top-Hat intensity profile at (0,0) mm in the focal plane. The characterisation is presented in Table 1.

Parameter	Simulated		Experimental	
Axis	X	Y	X	Y
Input Beam Diameter (@1/e²) [mm]	5	5	6.78	6.29
Input Beam M^2	1.0		<1.3	
Input Beam Ellipticity	1.00		0.93	
Top-Hat Size (@1/e²) [µm]	21.1	36.2	23.8	36.3
Transfer region [µm]	5	5	5	5
Edge Steepness, $S_{10\%,90\%}$ [%]	47	27	42.1	26.6
Plateau Uniformity, U_p[%]	5	5	9.1	8.0

Table 1: A comparison between the simulated and experimental Top-Hat focal intensity profiles at the scan field position (0, 0) mm. The input beam diameter was optimised to give the highest edge steepness and plateau uniformity.

Using the variable beam expander, the setup was optimised to minimise $S_{10\%,90\%}$ and U_p at scan field position (0, 0) mm. An elliptical input beam size of (6.78, 6.29) mm resulted in a high quality Top-Hat close to the target design, as shown in Fig. 4 and presented in Table 1. A defocus tolerance test showed that a Δz > 20 µm had a measureable change in the Top-Hat size and increase in $S_{10\%,90\%}$ either side of the focus. The lateral alignment tolerance of the DOE evaluated by $S_{10\%,90\%}$ and U_p was < 60 µm.

Scanning over the entire 16 x 16 mm² scan field showed that acceptable imaging performance of the Top-Hat could only be achieved for a field of 2 x 2 mm² before U_p increased significantly. In order to process larger areas, the scan head must therefore be combined with XL SCAN, which allows an increase in the scan field of up to the travel range of the synchronized stage. As shown in Section 2, with this setup a 4-sigma positioning accuracy of less than 3 µm, which fulfils the requirements of

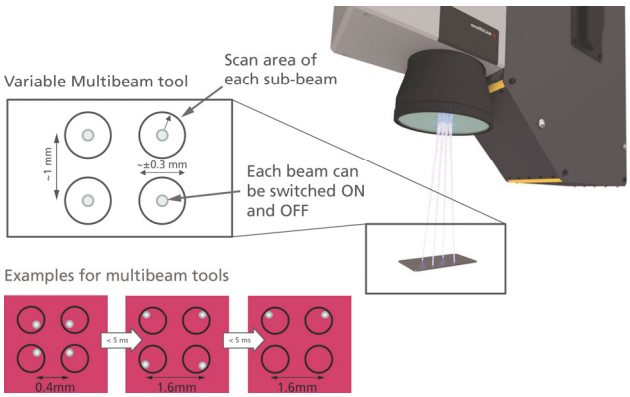

Fig. 5: Multi-beam engine for parallel processing. Each individual beamlet can be positioned on the workpiece with a within a small radius of 0.3 mm at nominal spacing of ~1 mm and switched on and off. The focal length 100 mm.

MicroLED LIFT pixel repair, can be achieved at a shot frequency of 2.6 kHz. Processing a 6" wafer can be achieved in a matter of seconds, satisfying industry throughput demands.

4. Multi-beam scanning

The multi-scan engine developed by Pulsar Photonics, as shown in Fig. 5, employs a beam splitting DOE before the SCANLAB excelli*SCAN* 14 scanner and f = 100 mm f-theta to divide the beam into a 2 by 2 matrix of beamlets with identical properties that have a default spot-to-spot spacing of 1 mm. Additional optics for individual beam control enable flexible variation of the vertical spot spacing of between 0.4 mm and 1.6 mm, individual beamlet positioning within a 0.3 mm radius and switching. The flexible definition of the beamlet matrix is controlled by advanced algorithms to analyse optimal configurations on the drill pattern on the workpiece and perform adjustments on the fly. In the results presented here, XL *SCAN* was used for processing to avoid the distortions discussed in section 1.3. However, should a larger scan field or no XY-stages be required, the individual positioning of beamlets can compensate for the distortions.

Using the 2x2 multi-beam engine, the single beam processing rate of 2.6 kHz, achieved in section 2, increases to 10.4 kHz, as shown in Fig. 6. With decreasing the pitch

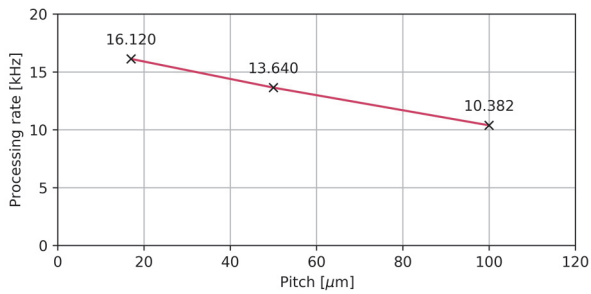

Fig. 6: Processing rate of the 2x2 multi-beam system at varying pitches. At 100 µm the process rate is almost a factor of 4 higher than for a single beam setup that achieved a processing rate of 2.6 kHz. The decrease in pitch also results in an increase in the throughput due to less time spent moving to the next position.

size the processing rate continues to increase due to the decreased time spent moving to the next position, so that at a 17 µm pitch a rate of 16.12 kHz can be achieved.

The accuracy of the multi-beam setup is comparable to the single beam setup, i.e. a sub 3 µm 4-sigma error can be expected.

This novel approach is ideally suited to high density processing, massively increasing throughput without sacrificing accuracy. The next stage of the project will increase the number of beamlets in the system for even higher upscaling of throughput.

4. Conclusion

In this work two novel laser scanning strategies employing beam shaping and beam splitting DOEs, a galvo scanner combined with a f-theta lens and an XY-stage, whose movement is synchronised to the scanner, have been presented. Using the XL SCAN solution (synchronised motion of the scan head and XY-stage), a 4-sigma positioning accuracy of < 3 µm was achieved when processing at a rate of 2.6 kHz with a pitch of 100 µm. This was an improvement in accuracy compared to the quasi-static scanner only approach that had a worst-case accuracy of approximately ± 4 µm and can be attributed to the reduced scan field.

Integrating a Top-Hat beam shaping DOE to the setup limited the scan field to the central 2 x 2 mm² scan field before aberrations reduced the intensity profile quality. The use of XL SCAN is therefore critical to achieve satisfactory processing of larger workpieces. The Top-Hat size of 23.8 µm x 36.3 µm with a transition region of just 5 µm and plateau uniformity of <9.1% satisfies the requirements for flexible LIFT repair of MicroLEDs. Furthermore, such a mask-free system enables rapid manufacturing and other LIFT-based processes like high resolution circuit printing in electronics and healthcare [7].

Alternatively, the multi-beam engine employs a beam splitting DOE to give a 2 x 2 matrix of beamlets spaced ~1 mm apart and that can be individually switched and positioned within a ~0.3 mm radius. Through parallelization, the processing rate can be increased up to fourfold compared to the single beam approach with highly symmetrical patterns, thus providing drill rates of over 10,000 per second while retaining accuracy on the order of microns. Future developments will increase the number of beamlets in the matrix.

The novel scanning strategies employing beam shaping and splitting diffractive optics presented here satisfy the current demands of increased throughput and accuracy in electronics and display industries and will continue to increase in importance as feature sizes continue to decrease in the next generation technologies.

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