Advanced Laser micro-structuring of super large area optical films

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ABSTRACT

A novel laser micro-machining technique to produce high density micro-structures called Synchronized Image Scanning (SIS) was introduced a couple of years ago. Over this period of time, the technique was refined in a major effort to meet the needs of various industries.
There is an increasing demand for micro-structuring of large and super large area optical films, e.g. for Rear Projection TV, anti counterfeit packaging material and 3D displays. Especially in the display industry, where the screens are ever increasing in size, established micro-structuring methods like e-beam milling, diamond turning or the reflow technique struggle to keep up with the development.

This paper explains how it is possible to direct laser etch hundreds of millions of lenses into a 2 m x 1.5 m substrate. It looks at the advances made in SIS in recent years regarding seam reduction, overall accuracy and precision when structuring super large area optical films, and it presents the tools and subsystems needed to generate the features in those films. Furthermore, the potential of this exciting laser micro-machining technique for rapid prototyping for all sorts of optical and non-optical structures is mapped out.

Keywords: Laser micro machining, high precision processing, micro-lens arrays, super large area processing

1. INTRODUCTION

Although MEMS and OMEMS are established in consumer products and industries, it is not as big a market as some have expected. Small issues in the R & D stage of a product can become show stoppers for mass production. Nevertheless the demand for micro-components and micro-features is high and increasing. To meet these demands, lasers are widely used in developmental and production environments since they provide a unique combination of flexibility, efficiency and the ability to produce a wide variety of microstructures [1].

In a world where a huge amount of information is exchanged digitally with the speed of light and the Man-Machine-Interface is most of the time a monitor or screen, visualisation plays an ever bigger role. To transfer information rapidly from machine to man some sort of a display is required and that is one reason why there is a big boom in the display market. As the human eye is an incredibly good optical system, the field of view is large, and when looking at something, it is desirable for the image to fill that field. Therefore it is no surprise that TVs and other display screens get bigger and bigger. There is no question that there is a market for large area displays; it is only the question whether they can be manufactured with good quality at a reasonable price.

This paper presents a novel technique for micro-structuring super large area optical substrates with micro-features by laser mask projection. This technique is not only novel, but much more importantly opens up a whole range of new possibilities. It is believed that with Synchronised Image Scanning it is possible to create micro-structures that cannot be produced otherwise and this over an area of unprecedented size and with outstanding position accuracy.

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2. THE SYNCHRONISED IMAGE SCANNING TECHNIQUE

2.1. A short introduction

Synchronised Image Scanning is a laser direct writing micro-machining technique where the information for the ablation of a specific 3D feature is stored as a linear array on a chrome-on-quartz mask. SIS therefore requires a mask projection system. The feature is then written by synchronized motion and laser firing in such a way that the firing frequency of the laser corresponds to the spatial pitch of the features. The technique of SIS is explained in depth in three previous papers [2, 3, 4]. There are virtually no limits to the design of the features as long as there are no undercuts and no details smaller than the resolution of the imaging system. Freeform features and elliptical aspherical lenses can be as easily produced as simpler geometrical structures such as cones, pyramids, spheres and ramps. Figure 1 shows a collection of structures produced by SIS. It is believed that SIS enables the realization of product designs that could not be manufactured previously. SIS produces a whole range of features in size and complexity that are very demanding or not achievable with common techniques. SIS can close the gap between lithography-related techniques exposing a resist in one way or the other like LIGA or grayscale lithography and mechanical machining. The true power of SIS is revealed where the features are too big or too complex for lithography techniques, but are still too small for mechanical machining. The individual micro-feature is only one aspect; the sheer number of them when structuring super large substrates is another very important one. It is probably possible to create features such as those shown in Figure 1 with established techniques, but it would be prohibitively expensive to produce several hundreds of millions over a very large substrate. In this respect SIS breaks the boundaries of substrate size limitation experienced so far.

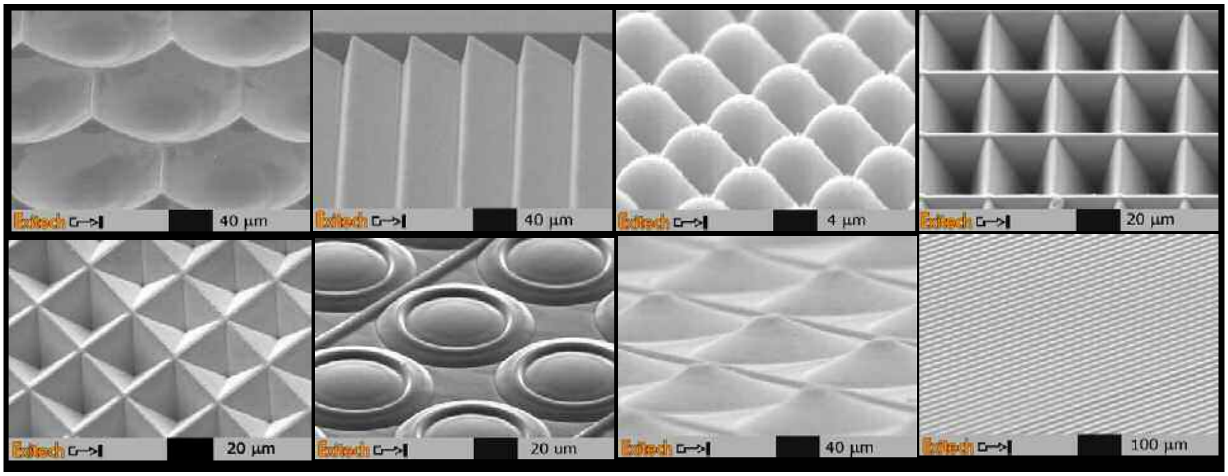

Figure 1 A collection of features machined with SIS

2.2. Automating the mask design for SIS

The mask plays a central role in the SIS process as it contains all the information about the shape of the features. Figure 2 below describes schematically how the mask design is derived from the 3D shape of the feature to be generated.

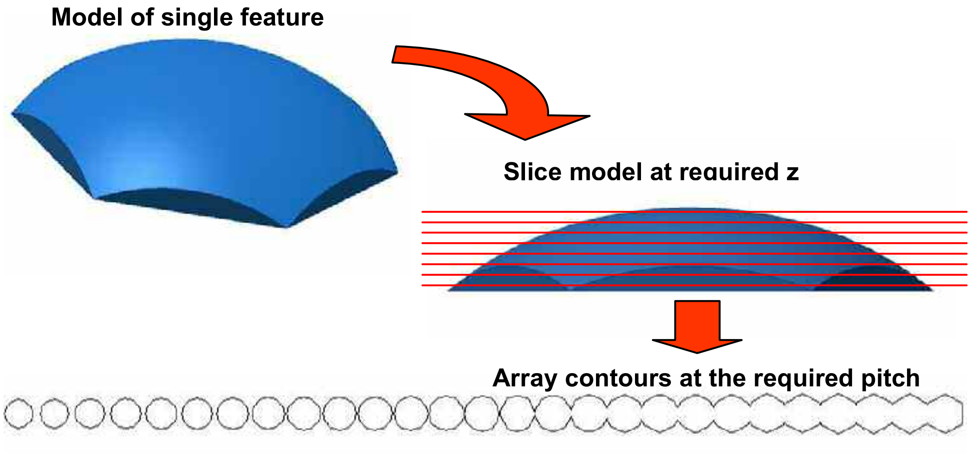

Figure 2 Steps from a model of a single lens to the mask design.

The arrays on the mask consist typically of 150 or more individual features as the ablation depth per shot should be ~ 200 nm to achieve a reasonable resolution in *z*. This makes it an extremely tedious and time-consuming task to design an SIS mask by hand. Additionally, in the case of micro-lenses the shape is usually defined by a complex sag equation in *x* and *y*, and determining the cross-section of the lens at a given height *z* is often not straight-forward, but involves considerable mathematical transformations. As an illustration, consider the following example of the sag equation for a biconic surface:

$$z = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 + k_x) c_x^2 x^2 - (1 + k_y) c_y^2 y^2}}$$

It is essential therefore for the efficient exploitation of the SIS process to be able to automate the mask design. This is accomplished using software to manipulate a CAD program in the following way:
The initial step is to generate a matrix, the indexes of which correspond to discrete values of *x* and *y*; the entries of the matrix are the solutions for *z* from the defining equation for these *x*- and *y*-values. A spline is drawn in the CAD for each row of the matrix connecting the (*x*, *y*, *z*)-points represented in this row. A surface is then swept over all these splines, using two splines along the first and last columns of the matrix as rails. Next, a solid vertical pillar is created, the cross-section of which is given by the packaging pattern, usually a rectangle or a hexagon. The previously generated surface is then used to cut material from this solid, thus producing a solid model of one of the features to be machined (cf. Figure 3).

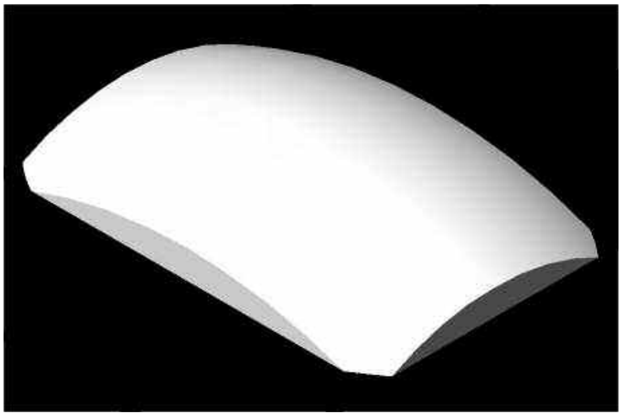

Figure 3 Solid model of a single biconic lens with rectangular packaging

This solid model is only an approximation, as it is based on interpolation of discrete values of x and y. However since the resolution of the imaging system is finite, this approximation does not introduce any inaccuracy provided the step from one x- or y-coordinate to the next is not too large. A grid of 0.5 μm spacing is a good value to start with.
The solid model of the feature is now sliced with the thickness of the slices corresponding to the ablation depth of each laser shot. From each slice, everything except the base section is deleted and this section is moved to the appropriate position in the array. The result of the whole procedure is shown in Figure 4.

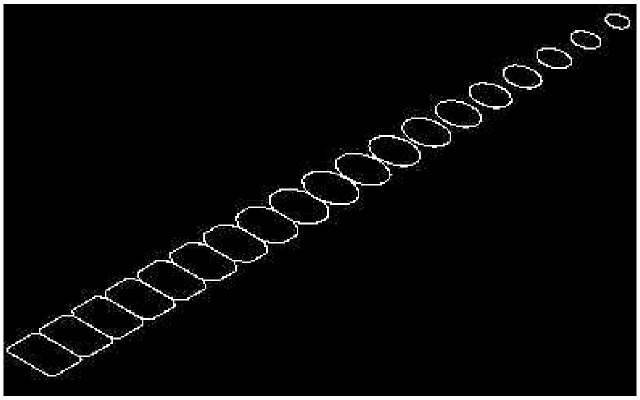

Figure 4 The outlines of the bases of the slices arranged in an array

2.3. Seam elimination

By producing convex structures a "wedge" is created between scans. The defect is caused by the imaging system. The fluence level used for SIS and the relatively low NA of the lens limit the wall angle that is achievable to a maximum of ~ 84 degrees relative to the sample surface. This is a critical issue for SIS as the scan direction is in the direction of the long axis of the image and one scan length will create a line of features in a trench. If the trench could be machined with vertical walls and the step was exactly the trench width, the features would seamlessly join each other (Figure 5A). Not having vertical walls and stepping the top width of the trench will leave a wedge between each line scan (Figure 5B).
The lateral dimensions of the wedge are directly correlated with the trench wall angle achieved and get therefore larger the deeper the structure is machined. Creating the "wedge" is not the biggest issue, more severe especially when machining micro-lenses, is the distortion of the feature itself. The effect of the "wedge" is to squeeze the lenses together, thus reducing the radius of curvature.
To delete the appearing wedge an oversized image can be designed. The principle is the same as for hole drilling applications: given the fact that it is only possible to drill tapered holes and if the exit hole is the critical one, then the entrance hole has to be bigger. This is also the case when machining convex micro features by SIS, the apertures at the mask defining the width of the trench or the lateral dimension of a single feature need to be stretched to compensate for the appearing wall angle (Figure 5C). A an illustration, to produce an array of 100 μm diameter lenses of 15 μm depth, the laser beam width defining the trench is required to be 103.6 μm to account for a wall angle of 6 degrees.

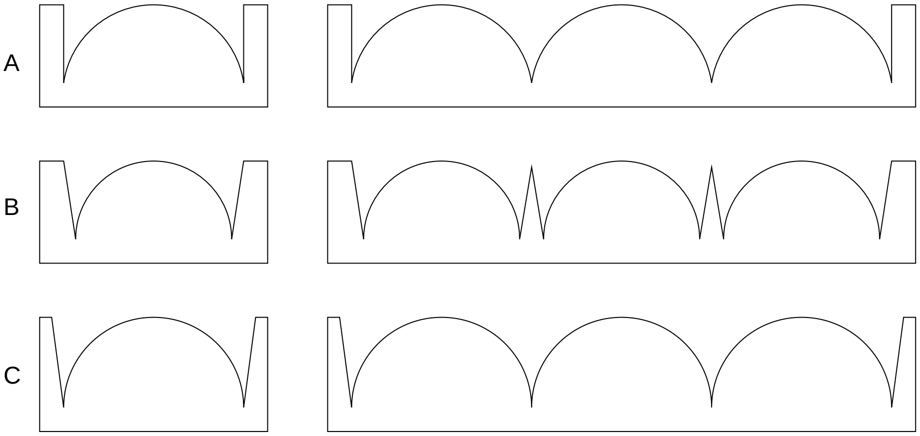

Figure 5 Illustration of how the wall angle influences the outcome of a series of SIS scans. A) shows a channel with vertical walls, which is not achievable with the low fluence used for SIS, B) shows the outcome if by the mask design the wall angle is not accounted for, C) shows the result with wall angle compensation.

Usually there is more than one row of apertures in one object as the micro-lenses are typically ≤200 µm and an industrial excimer laser has easily enough energy to expose an area of at least 15 mm^2 at the work piece. An image to produce a square packed lens array where the diameter of one lens is 100 µm and 140 shots are required to achieve the correct depth could therefore have 10 rows of apertures in it. By scanning this image along the work piece, ten rows of lenses are produced simultaneously. The offset for the next scan is 10 times the lens pitch, in this case 1 mm. Therefore the issue caused by the wall angle appears only every 1 mm. However since it also distorts the lens, it is still not acceptable and the wall angle correction must be applied. See Figure 6.

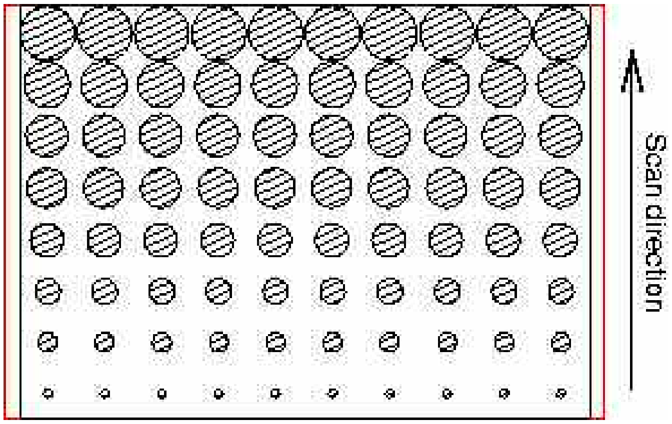

Figure 6 The the red line represents the correction for the wall angle compensation

In practice it is very difficult to compensate 100% for the wall angle and as the stage resolution accuracy has a finite value it is not possible to make the seam completely invisible.

3. STATE OF THE ART OF SUPER LARGE AREA MICRO-MACHINING

3.1. Fundamental requirements

After several years of process development it is now possible to introduce a micro-machining strategy which enables industry to pattern super large substrates (Generation 7 Displays 1.9 m x 1.5 m) with up to several billion lenses. As far as the authors are aware there is no other technique available today capable of that. To scale this exiting technique up to machine areas of a few square meters requires expertise in laser micro-machining tools. Top of the range and specially developed subsystems are required to realise large area machining.

To machine complex sub 100 µm features, the specifications of the stages have to be exceptionally tight in order to produce a high quality individual feature and requirement to position each feature very accurately over the area. The required accuracy for an individual feature is in the submicron range whilst the absolute position accuracy and repeatability is in the 1-2 µm range. To ensure no thermal drift the machine needs to be in a highly temperature controlled environment 20 +/- 0.5° C.

The heart of the tool architecture is a massive granite base including a 2 tonne chuck making up the y-axis and a granite gantry with lapped railings for an independent x-axis. Both axes run on air bearings and linear motors. Glass encoders coupled with multiplexers ensure a step size < 100 nm.

A permanently installed interferometer is used to cross check the absolute and relative accuracy. With this hardware in place it is possible to position the projection lens to any position on a 1.9 m x 1.4 m substrate to within +/- 3 µm.

The flatness of the chuck and the thickness variation of the sample is critical as the depth of field of the micro-machining lens is given by:

$$Dof = \frac{\lambda}{NA^2}$$

where Dof is depth of field, λ the laser wavelength and NA the numerical aperture of the micro-machining lens. As the wavelength used is 248 nm and the maximum NA of the optical system is 0.13, the Dof is ~ 15 µm. Although the chuck is flat within a few tens of microns over the whole process area, it is not possible to find a Polycarbonate sheet of that size with the required thickness tolerance of +/- 7.5 µm.

The relatively large sample thickness variation suggests that it is impossible to machine a large area substrate. The following section explains how this critical issue can be eliminated.

3.2. Subsystems

Traditionally excimer laser mask projection systems have the imaging lens and the object mask fixed in a vertical position. The lens is designed for a certain track length and magnification and therefore the distance between the mask and the lens has to be kept constant otherwise the magnification changes. Usually the work piece is located on an elevator stage so that different substrate thicknesses can be brought into focus. This type of system requires a very flat and carefully levelled chuck together with a substrate with tight thickness tolerances. In many cases when processing wafers or relatively small substrates this is not a problem. Additionally a height sensor can measure the thickness variation and the elevator stage will correct accordingly. However the display industry uses large substrates which do not require tight thickness tolerances for their display performance. This is a big challenge for laser micro-machining systems with fairly short depths of field, and it gets more and more difficult to find a suitable elevator stage the bigger the substrate gets.

Exitech has developed and patented a subsystem for its laser machining tools that ensures that the plate front surface is positioned to within ±5µm of the lens image plane at all times, even on plates with significant variations in thickness (±100 µm) and with significant sag (1mm). This means that the whole imaging system follows the surface topography. See Figure 7 for a comparison between traditional and Focafloat™ mask projection systems.

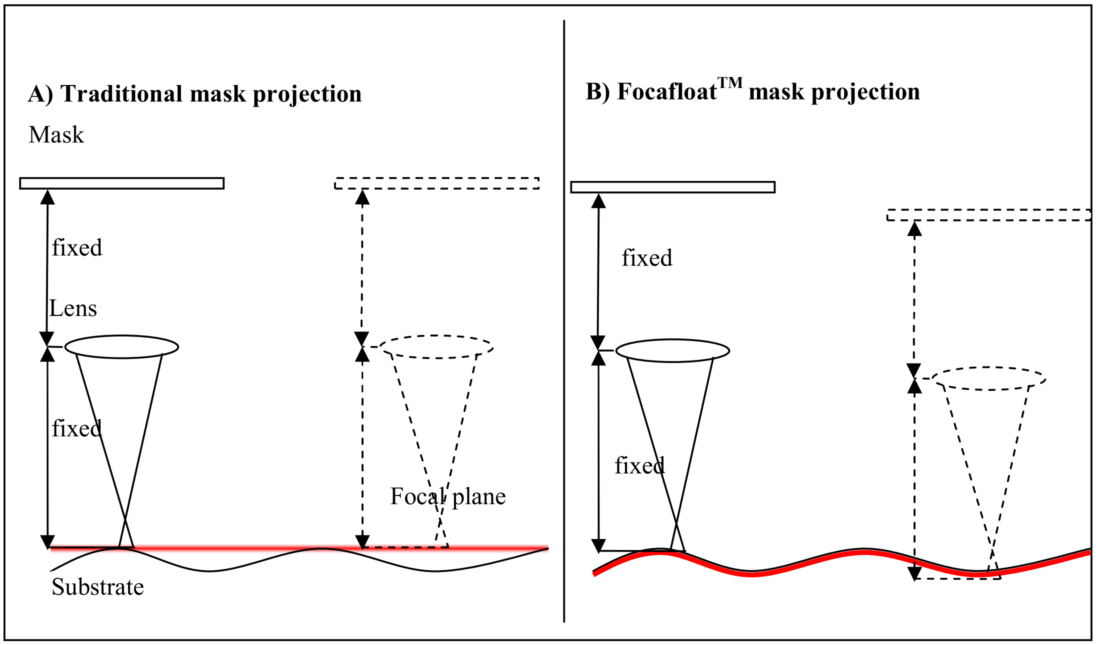

Figure 7 Comparison between a traditional A) and a Focafloat ™ mask projection system B).

Focafloat™ consists of a floating head or puck with the micro-machining lens and the mask all rigidly linked together. The floating head hovers at a fixed distance over the substrate surface and as the micro-machining lens and the mask are fixed to it, the critical distances of the imaging system remain constant. The floating head covers a certain area around the image and the very thin air cushion averages any small surface variations. This is a big advantage compared with a height sensor that looks only at a single point, So when scanning over a dust particle, for example, a sharp rise and fall is triggered which distorts the whole image area. The floating head on the other hand will blow the dust particle off the substrate and will generally react in a much more controlled manner to thickness variations in the substrate and ignore high frequency variation in the surface topography. The height sensor is scanning along a line and picks up any variation of the surface profile where it is scanning causing the whole imaging system to oscillate. This is especially critical if the height compensation happens between the ablation of the first and the last layer of a feature. The floating head as a contrast is covering an area and holds an averaged position compensating much more gently for height changes.

3.3. The PPM 2000 - a super large area micro-machining tool

All the requirements for super large area micro-patterning mentioned above are met in one machine able to structure super large optical films: the PPM 2000, designed and built at Exitech Ltd. (see Figure 8). The granite base with the massive chuck and the gantry with the optics box on top form the foundation for high precision micro-machining. The Focafloat™ is clearly visible in the center of the picture. The laser light is fed into the system on the left hand side to go through relay optics and to be homogenized inside the optics box, which is traveling along the gantry. This system has a high power industrial Excimer laser of 100 W integrated that guarantees at least 25 W at the work piece. Polycarbonate as a typical sample material has a removal rate of 1.5 mm^3/s at 25 W and a fluence of 300 mJ/cm^2 [5]. Theoretically this leads to a process speed of ~ 1.9 h per m^2 per 10 µm feature depth or for instance $2.5*10^9$ lenses of 20 µm diameter and 10 µm depth in ~1.9 h. In practice changes in scan direction and restrictions in the packaging of the features at the mask depending on the feature size and design add some additional time factor. This factor is unlikely to be >2. The machine shown below equipped with optics optimized for one particular micro-feature should therefore be able to produce a 10 µm deep structure on a generation 7 substrate in less than 10 h.

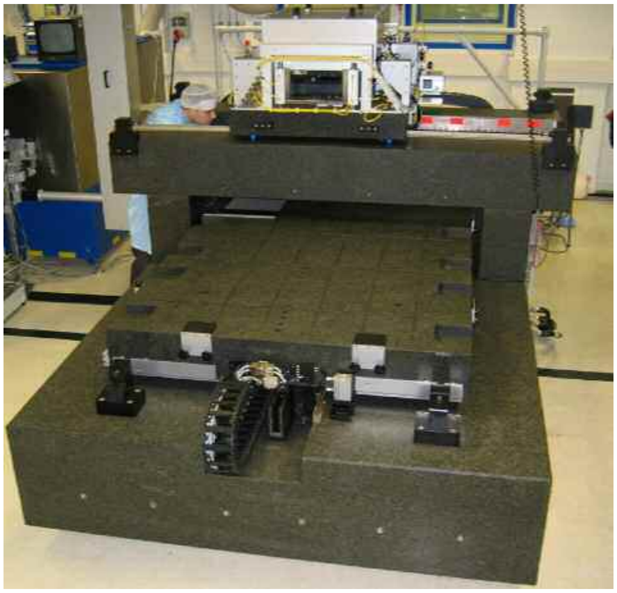

Figure 8 PPM 2000 an Exitech machine to pattern Generation 7 substrates (1.5m x 1.9 m)

4. CONCLUSIONS

After three years of intense process development Synchronized Image Scanning has matured to a micro-machining strategy which can not only challenge established technologies but can create structures very efficiently not seen in production before. Features from 10 µm to 200 µm with up to 120 µm in depth have been experimentally demonstrated and there is no reason why the technique could not be extended to smaller as well as bigger features. The focus in this paper is structuring super large substrates, but in addition SIS can be a very powerful strategy for rapid prototyping of micro-optics or micro-structures in general. The mask design software introduced above permit's efficient design of the required mask features even for complex geometries and reduces therefore the turnaround time for a chrome-on-quartz masks significantly. As the mask can incorporate many different feature patterns for the same price, a lot of different surface structure designs can be produced and tested without adding to the tooling cost. Hence, SIS is not restricted to process super large substrates used in mass production, but can as well enable R & D engineers to develop new products with novel surface profiles..

5. ACKNOWLEDGEMENTS

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REFERENCES

1. P.T. Rumsby "Advanced laser tools for display device production on super large substrates", IMID 2002, Digest
2. H.J. Booth "Recent Applications of pulsed lasers in advanced materials processing", Thin Solid Films 2004, to be published
3. C. Abbott et al. "New techniques for laser micromachining MEMS devices", Proc. of SPIE 2002, Vol. 4760, p.281, 2002
4. K.L. Boehlen, I.B. Stassen Boehlen "Laser micro-machining of high density optical structures on large substrates", Proc. of SPIE 2004, Vol
5. K.L. Boehlen, "R & D report about SIS machining of Polycarbonate", Exitech internal report, 2004