

# **Laser micromachining - new techniques and developments for display applications**

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## **ABSTRACT**

The area of display devices has experienced extremely rapid growth in recent years and these advances show no sign of declining. One of the major developments in this field has been the use of lasers for various microfabrication tasks. This paper describes some techniques which have been developed using excimer lasers for the production of novel microstructures in polymer materials. Examples of the types of microstructures which are produced are presented and their applicability for display device applications is outlined. Forthcoming developments in the laser manufacture of displays are discussed.

### Keywords:

excimer lasers, microstructures, ablation, mask projection, micromachining, displays, diffusers, microprisms.

## **1. INTRODUCTION**

The recent rise in digital communications and multi-media systems has led to increasingly complex technical demands being placed on personal electronic products, interactive entertainment aids and commercial and domestic display devices. Some of these developments have partly been driven by the requirements of volume manufacturing but other significant elements have had to be addressed purely due to the novel nature of modern microelectronic systems. To meet these demands, lasers are now being 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.

In many display applications, the use of non-birefringent photopolymer materials allows display properties such as the angle-of-view (AOV), feature definition and image brightness to be greatly improved [1]. These operational enhancements are often achieved by the combination of such photopolymers with additional micromachined structures to provide improved off-axis performance. In particular, liquid crystal display (LCD) devices, whether backlit or operating under ambient lighting conditions, have benefited from these developments. This paper describes some new methods for the manufacture of different microstructures produced using laser micromachining techniques which are designed for optical display devices.

## **2. MICROSTRUCTURES FOR HAND-HELD DISPLAY DEVICES**

There are many benefits in display devices (especially portable ones) using ambient light in normal operation, the most important one obviously being the reduction in power consumption. The use of ambient light, however, does have some constraints and the designs of the illumination systems need to keep such limitations in mind. In hand-held units such as mobile cellular telephones, for example, the user's head and body often obscure much of the available light and so special prismatic structures have to be used to redirect the incident light selectively. Figure 1 shows a schematic representation of a typical LCD display operation where the light from above the viewer's head is preferentially reflected towards the viewer, who can hold the display at a comfortable angle. It is the intention of these devices that the specular reflection is minimised to reduce "glare" and optimise the brightness of the viewed image.

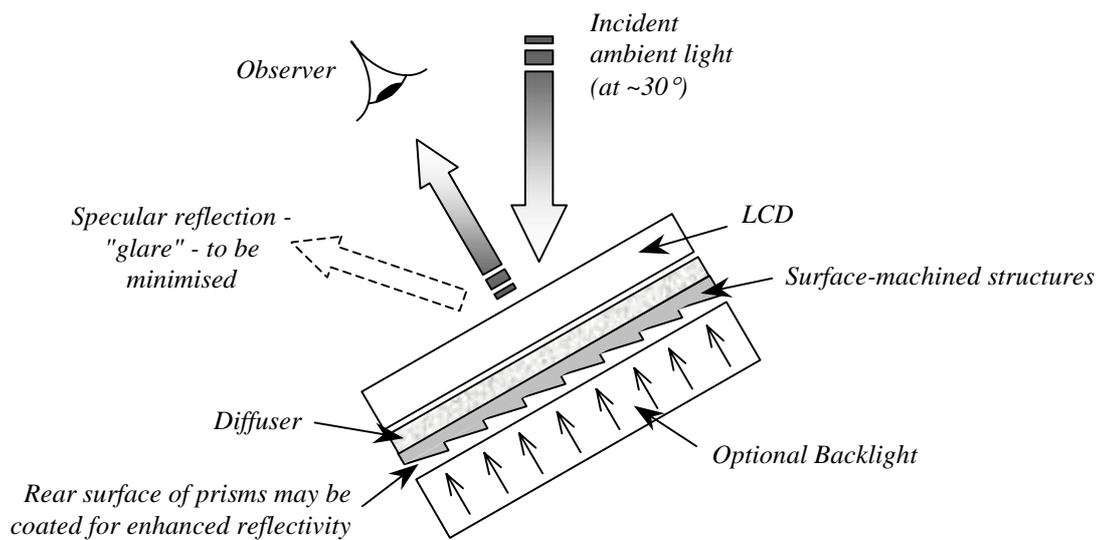


Figure 1. Schematic of the arrangement of a LCD display where prismatic structures are used to redirect light.

In figure 1, a backlighting source for the LCD is shown as an option because the prismatic structures can either be used in reflective, reflective plus transmissive, or purely transmissive modes, depending on the products. Since the prismatic features are in polymeric substrates, they are currently produced by the conventional replication from metal masters. Although the current methods produce high quality parts, they have a number of drawbacks, including

- Necessity for frequent and expensive re-tooling
- Inability to machine complex or multi-dimensional structures
- Speed of processing
- Multi-stage processing, i.e. a master has to be machined from which the required parts are made
- The existing metal masters are very fragile and susceptible to mechanical damage

Due to the above constraints, laser processing methods offer a very attractive option for the production of these prismatic features since they can be used to machine the desired structures directly into the polymer samples with great versatility and without contacting the material.

## 2.1 Laser Micromachining

An excimer laser micromachining system was used in all the work reported here due to the excellent performance of these UV lasers in the micromachining of polymers [2]. The technique of mask projection was employed to ablate various polymer samples directly and produce the prismatic structures under consideration.

A number of refinements to the basic principle of mask projection have been reported previously [3]. In particular, the use of *workpiece dragging* [3] is ideally suited to the production of prismatic features and offers many benefits, including the ability to:

- control the depth, length and cross-section of the microprisms.
- maintain high precision and resolution for the micromachining of structures.
- extend the technique to large sizes for mass production options.

To demonstrate the feasibility of laser micromachining methods for the applications discussed above, representative structures were micromachined to enable a direct comparison to be made between the existing metal-master route and laser techniques.

In the mask projection system, a standard excimer laser operating at a wavelength of 248nm and capable of pulse repetition rates of up to 150Hz was used together with a x5 0.125NA imaging lens. The lens had an image field size of 14mm which allowed up to 280 microprisms of 50µm width to be machined simultaneously by projection from a chrome-on-quartz mask. The laser beam was shaped and homogenised to form a rectangular-shaped “flat-top” profile at the mask plane with dimensions of 75mm x 10mm. The samples were held flat on XYZ tables which offered a lateral positioning resolution of 100nm and an elevation (focal) resolution of 50nm. It should be noted that a 0.125NA lens allows a depth of focus of approximately ±16µm so sample handling is an important issue in maintaining consistent image quality. Additionally, a directional nozzle was placed in close proximity to the ablation site to enable gas assist to be used during the laser micromachining.

The parameters for micromachining were optimised to determine the best set of conditions in terms of laser energy density, number of shots per area (for the depth required), laser repetition rate, sample motion speed (feedrate) and gas assist. The one other parameter which has an important effect on the quality of the final sample is the way in which the prismatic triangular patterns are scanned over the sample, and this is explained below.

The two main requirements for the microprisms were that they should have an angle of 10° and have a width of 50µm, which means that the depth of the deepest part of the microprisms has to be 8.8µm. At a particular laser energy density or fluence, it is a simple matter to determine the number of shots which give this depth but, in order to produce an optically-acceptable prismatic sample, other factors also have to be borne in mind. Figure 2 shows a representation of the way in which the micromachining is accomplished.

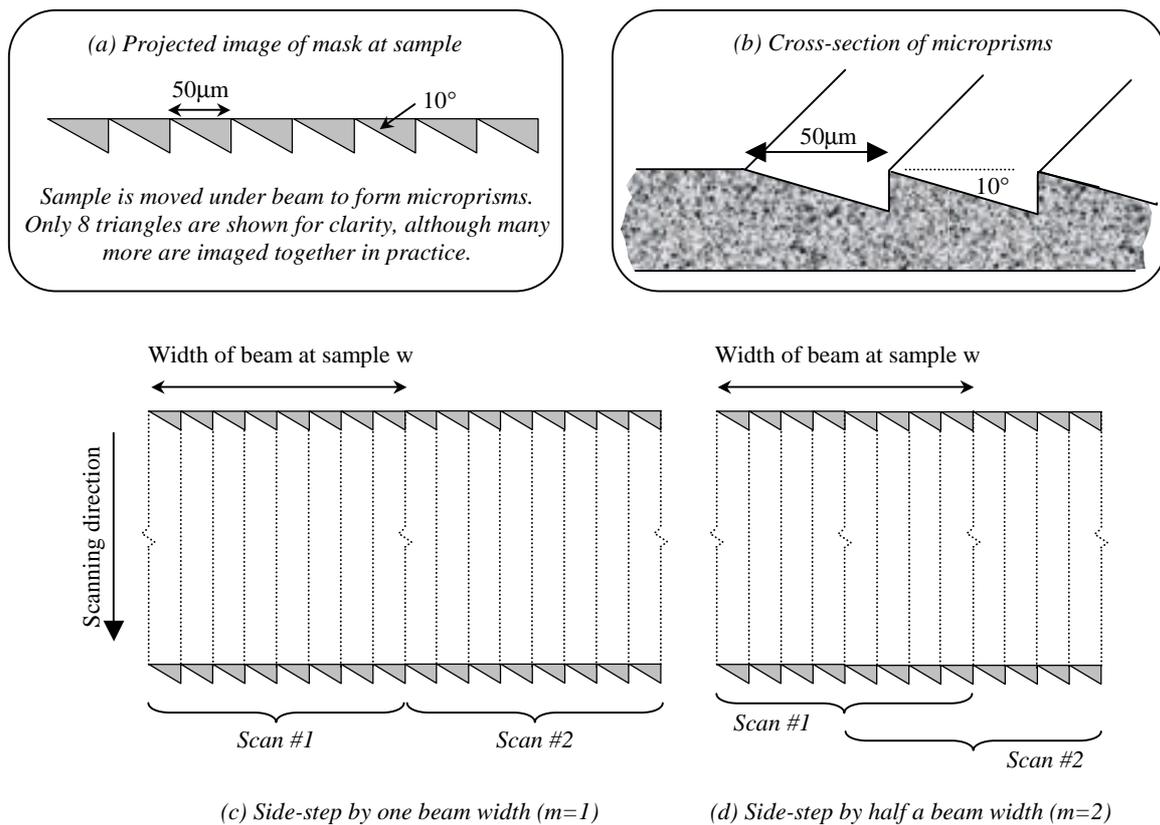


Figure 2. Representation of the workpiece dragging and processing method for the formation of microprisms with (a) projected image, (b) transformation of triangles into microprisms, (c) zero beam overlap in processing and (d) overlap by a factor of 2 in processing.

If we assume that  $N$  shots are required in total by any unit area for that area to be ablated to a depth of  $8.8\mu\text{m}$ , then it can be seen with reference to figure 2 that there are many ways in which those  $N$  shots can be deposited onto the sample. Since the sample is machined by scanning a pattern in one axis and then repeating the scan in adjacent positions on the sample, the simplest way to achieve a total of  $N$  shots is by using  $N$  shots/area in the scanning direction and then stepping sideways by one complete beam width (i.e. side step =  $w$ ). If the beam is stepped sideways by half a beam width (i.e. by  $w/2$ ), then  $N/2$  shots/area have to be used in the scanning direction. In general, if the beam is stepped sideways by  $1/m$  of the beam width, then the number of shots per area in the scanning direction has to be  $N/m$ . Of course, the entire process can be repeated a number of times so that a single cycle of the process machines to a smaller depth than required and the whole procedure is repeated successively until the desired depth is achieved. Therefore,

$$\text{Total Shots } N = L S m$$

where  $L$  is the number of processing loops,  $S$  is the number of shots per area in the scanning direction  $m$  is the fraction of the beam width  $w$  by which the sample is stepped sideways (e.g. stepping by a  $1/3$  of the beam width gives  $m=3$ ).

The combination of the three parameters  $L$ ,  $S$  and  $m$  affects the quality of the micromachined features, especially the smoothness of the "faces" of the microprisms. In particular, if  $S$ , the number of shots per area in the scanning direction, is too large, then the smoothness of the prism faces degrades because the sample moves a greater distance in between pulses. This is illustrated in figure 3 which shows a scanning electron micrograph (SEM) of microprisms machined into polycarbonate where significant "steps" can be seen on the faces of the prisms.

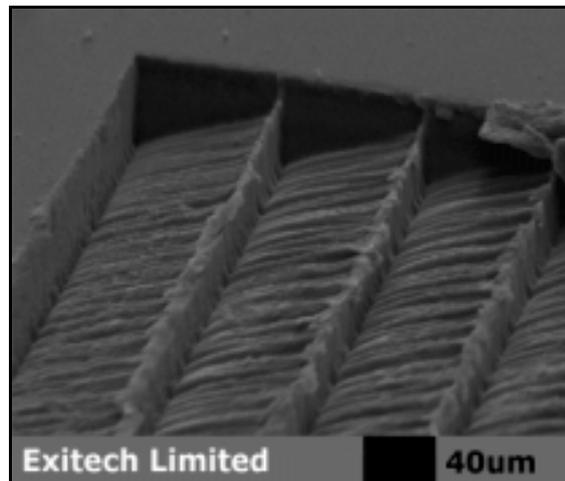


Figure 3. SEM of microprisms showing stepping effects of non-optimum machining conditions.

It was found that high quality microprisms were produced using a laser fluence of  $1\text{J}/\text{cm}^2$  with 80shots/area at a laser repetition rate of 150Hz. The effects of oxygen, nitrogen, helium and air assist gases were also compared and this is described in section 2.2.5.

## 2.2 Analysis of Laser-Machined Structures

Polymer samples of  $\sim 50\text{mm} \times 50\text{mm}$  in size were laser machined with  $10^\circ$  microprisms and then analysed using optical microscopy, scanning electron microscopy, interferometry and diffraction analysis. These samples were evaluated both qualitatively and quantitatively - since the end products for these structures are optical display devices, the qualitative appearance to the eye is a very important measure of their quality.

### 2.2.1 Reflective Structures

Figure 4 shows a SEM picture of  $10^\circ$  microprisms micromachined into polycarbonate showing the regular and reproducible nature of the optimised laser machining. It should be noted that a 50mm wide sample contains approximately 1000 microprisms and dimensional changes of the order of  $\sim 2\mu\text{m}$  are readily discernible by the change in regularity they cause.

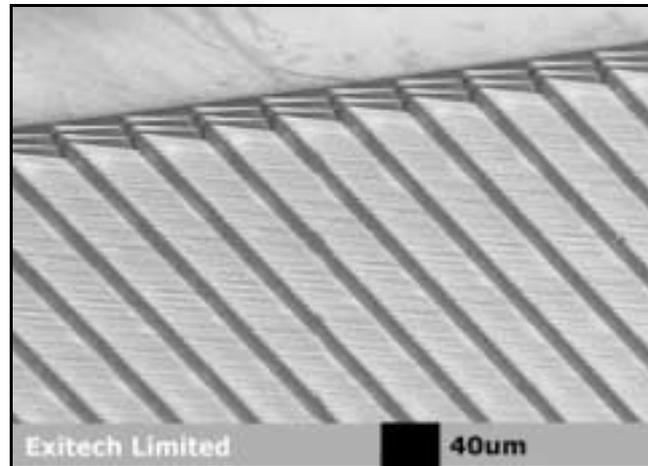


Figure 4. SEM of  $10^\circ$  microprisms laser machined into polycarbonate.

A Zygo interferometer was also used to measure the surface relief at the centre of one of the samples and the 3D and cross-sectional data obtained is shown in figure 5. It can be seen that the depth from the cross-sectional analysis of  $\sim 8.8\mu\text{m}$  agrees precisely with the desired value and the smoothness and regularity of adjacent microprisms is also clearly evident.

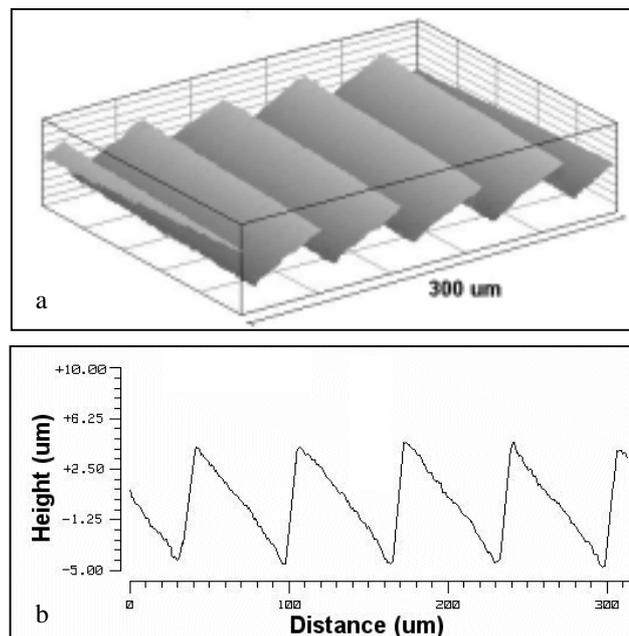


Figure 5. Interferometer data from a laser-machined polycarbonate sample showing (a) the 3D profile and (b) the cross-section of the microprisms.

The main role of the reflective prismatic structure, as shown in figure 1, is to re-direct light from the specular reflectance angle into a more convenient direction and it can easily be shown that light incident at  $\sim 30^\circ$  to the normal will be redirected towards the normal if  $10^\circ$  prismatic structures are used. This was verified by measuring the angular sensitivity of the

reflection from the laser-machined samples using a white light source. Figure 6 shows a polar plot and cross-section of the light intensities measured as a function of angle. The input light was incident at an angle of  $30^\circ$  to the normal and two reflection peaks can be seen. The broader peak on the left (peak "A") is from the  $10^\circ$  microprisms re-directing the light towards the normal while the narrower peak on the right-hand side (peak "B") is caused by the specular reflection from the front surface of the polycarbonate.

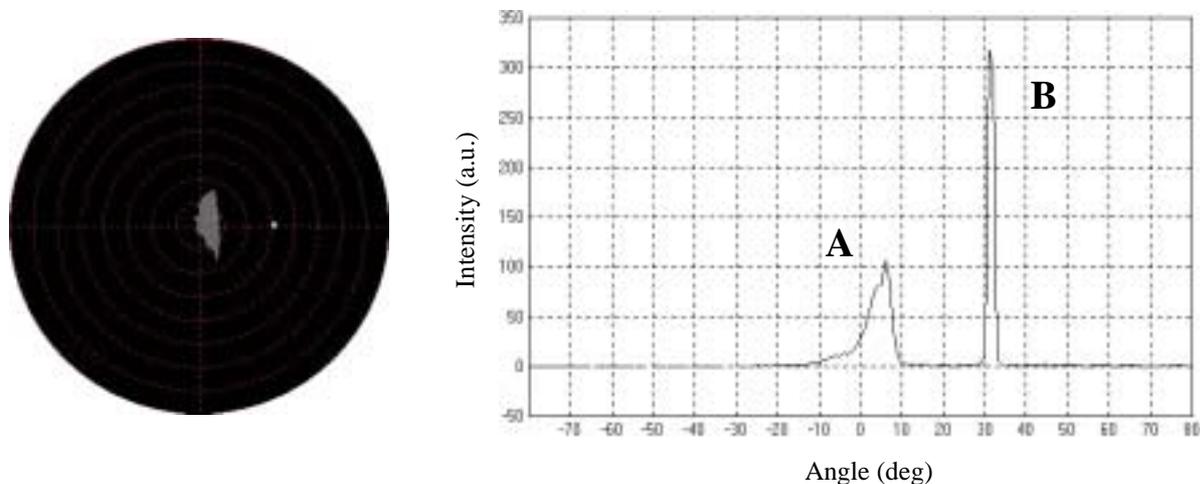


Figure 6. Plots of the reflected intensity from a laser-machined prismatic structure with light incident at  $30^\circ$ . Peak A is from the prismatic structures and peak B is the specular reflection from the surface of the polymer.

### 2.2.2 Reflective Structures with a Diffuser

As can be seen from figure 1, a typical display device usually also has a diffuser element in front of the prismatic structure and the addition of this was also measured using the same method. Figure 7 shows the results from the reflection of light from just a diffuser sample and from the combination of a diffuser and prismatic structure.

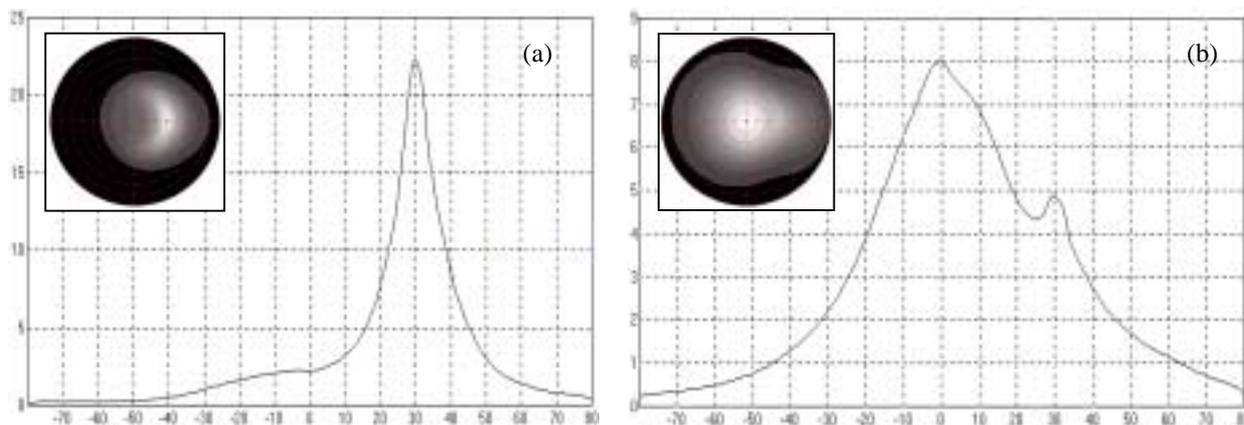


Figure 7. Plots of the reflected intensity from (a) a diffuser element alone and (b) the combination of the diffuser and  $10^\circ$  prismatic structures, both with light incident at  $30^\circ$ .

It can be seen that, as expected, the diffuser sample by itself purely scatters the light over a wide cone of angles while maintaining its peak around the  $30^\circ$  specular reflection angle. The addition of the  $10^\circ$  microprisms concentrates most of the light around the normal to the sample, thereby giving the conveniently-viewable range of angles for the display.

Although the use of prismatic structures usually means that light is redirected principally in one axis, the display applications under discussion here also benefit from light being available in the other axis as well so the broadening of the light distribution in both axes is not necessarily a detrimental effect. This is also the reason why a small amount of non-uniformity on the faces of the prisms, as seen in figure 4, is desirable.

### 2.2.3 Transmissive Structures

If the microprisms are to be used in a purely transmissive mode, i.e. with the backlight option as shown in figure 1, then it is expected that the light should be transmitted by the sample at  $\sim 10^\circ$  to the normal with normal incidence illumination. This has been confirmed by measuring the transmitted intensity as a function of angle for normal incident light and the result is shown in figure 8.

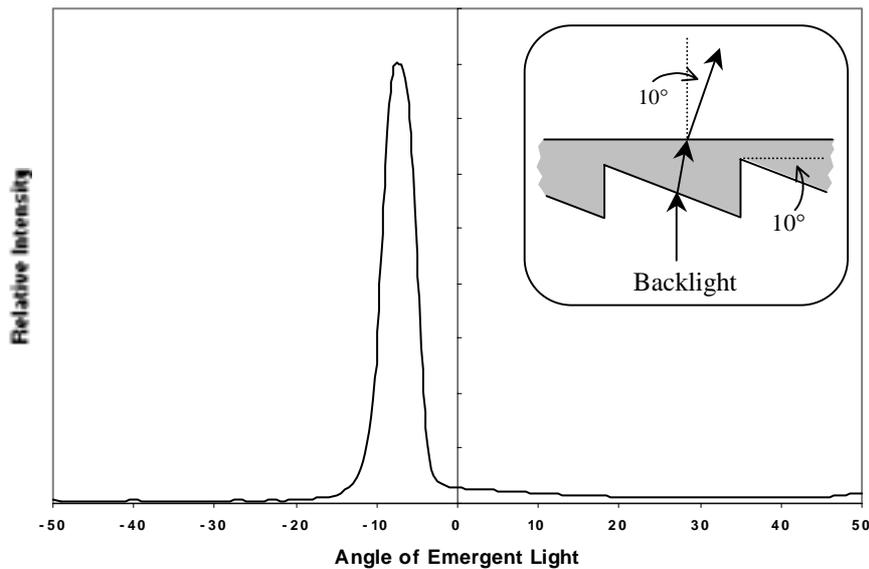


Figure 8. Transmitted intensity as a function of angle for the  $10^\circ$  microprisms with normal incidence backlight illumination.

### 2.2.4 Micromachining Optimisation

As has already been mentioned, the sensitivity of eye to non-periodic structures makes the entire machining process relatively intolerant to errors in positioning or focus. If, for instance, the beam overlap or side-step (as discussed in section 2.1) is incorrect, then even a slight mis-positioning of one set of triangles will interfere with another set of patterns, causing the quality of the microprisms to degrade. This can be seen in figure 9 which shows a SEM of an overlap region where, as shown in figure 2(d), the edge of scan #2 is super-positioned on an existing scan #1.

It can be seen that the sharpness of the corners of the triangles is worse in the section where both scans #1 and #2 have been performed and this effect results in the edges of the prisms not being as good. Small variations such as this need to be controlled carefully to achieve the best results.

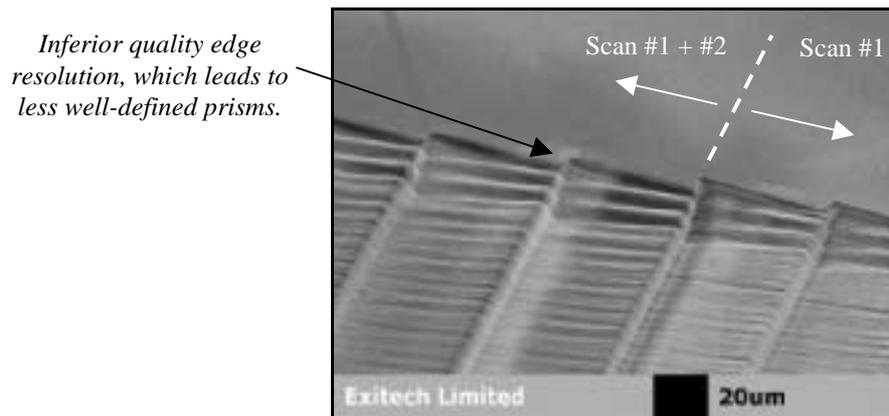


Figure 9. SEM of micromachined structures showing positioning errors which cause deformation of the microprisms.

### 2.2.5 Gas Assist

Four samples were machined with identical conditions with only the assist gas being changed in between. Air, oxygen, nitrogen and helium were used and the angular reflectivity response of each of the samples was then measured. By eye, it was clear that the main effect of the different gases was the amount of diffusion and optical scatter which was caused by the sample and this was borne out by the reflectivity data. Figure 10 shows polar reflectivity plots of the best and worst assist gases for the prismatic structures.

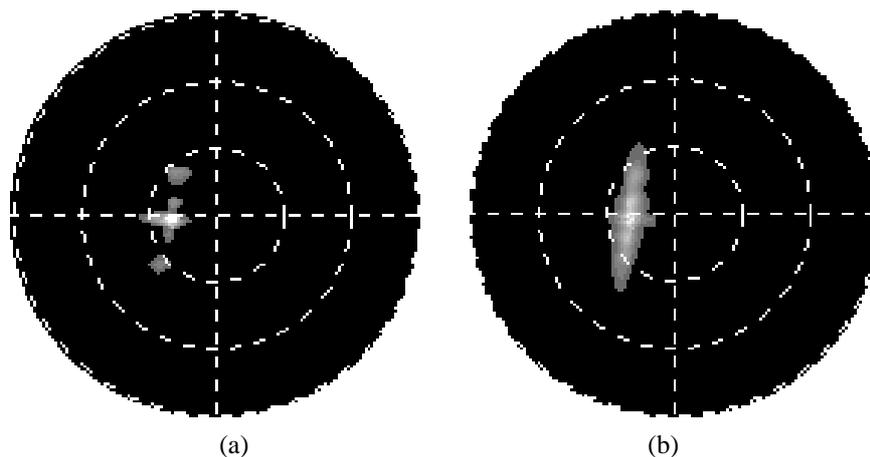


Figure 10. Reflectivity plots of microprism samples with (a) nitrogen and (b) helium assist gases.

The sample machined under nitrogen assist shows quite distinct diffraction as opposed to the helium assist sample where a broad diffuse region is observed. The main cause of this difference appears to be the amount of re-deposited material on the sample during the laser ablation which causes light to be dispersed by varying amounts. These tests showed clearly that nitrogen assist gas was by far the best in terms of causing least disruption to the effects of the microprisms.

### 3. FUTURE DEVELOPMENTS

One of the advantages of the laser micromachining is the inherent flexibility which it provides and the large range of possibilities it offers for the production of various microstructures. In display device applications, for example, an excimer laser micromachining system can be used in many ways:

- patterning of transparent conducting oxides (e.g. ITO) with electrode or other features
- machining of layers in polymer and organic LED devices
- drilling of interconnects and vias for multi-layer systems
- production of microstructures such as microlenses for optical components

Figure 11 shows two examples of optical microstructures - micromachined cylindrical lenses and optical channelling "pyramids", both of which have been developed to guide and control light for LED and LCD display devices. In applications such as those discussed in this paper, the use of laser micromachining offers the ability to tailor the shape of the microprisms, for example, to suit different reflective/transmissive geometries where, for instance, prisms with multiple-angled or continuously-varying facets may be used. Such structures are not possible with precision mechanical tooling machines.

Other lasers such as infra-red, visible or ultra-violet solid-state lasers are also finding increasing use in display device manufacturing, particularly for ultra-high speed patterning. Apart from the versatility element of direct laser processing, the other main benefit of laser machining is that it is usually a single-stage dry process, i.e. lithographic patterning and chemical etching steps can be avoided. This not only reduces the costs associated with wet processing stations but also enables very large sizes to be handled which are beyond the capabilities of current exposure and etching systems.

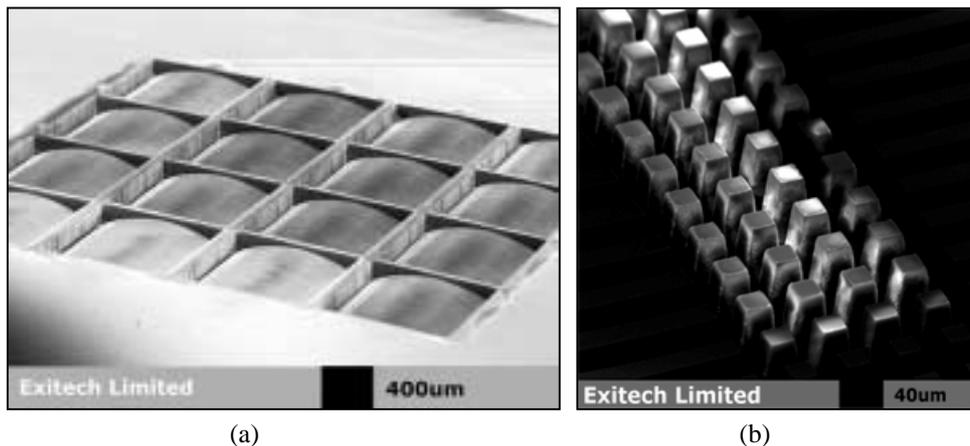


Figure 11. (a) Cylindrical microlenses and (b) light-guiding structures, both micromachined using excimer laser micromachining.

Increasingly, more systems with multi-functional units are being designed and developed and these may include elements such as optical devices, micro-mechanical systems, electrical circuits and interconnects. As this advanced device technology matures, laser micromachining will play a vital role in their manufacture, allowing unprecedented performance specifications to be realised.

### 4. SUMMARY

Excimer laser micromachining has been used to produce prismatic structures in polymers for use as selective optical elements in display devices. The processing conditions have been optimised to produce high quality, large-area samples which have been tested using optical methods. The evaluation has confirmed that the micromachined structures have the attributes expected from the samples and have demonstrated their applicability for display devices.

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