# Laser Micromachining - New Developments and Applications

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## ABSTRACT

Excimer laser micromachining has developed into a mature production method and many industrial applications such as the drilling of ink-jet printer nozzles, production of sensors and the manufacture of display panels now routinely use excimer laser microprocessing in production environments. The important concepts of excimer laser micromachining systems are described and the novel methods which have been developed in this area are presented. In particular, techniques for the production of complex, multi-level 3D microstructures are described and examples of such features are used to illustrate the relevant applications. Furthermore, some initial micromachining results from a sub-nanosecond, solid-state fibre laser are presented to highlight the rapidly-growing area of laser microprocessing using ultra-short pulse lasers.

**Keywords**: lasers, micromachining, excimer, ablation, MST devices, ultrashort pulses.

## 1. INTRODUCTION

Lasers have been in use in various industrial sectors such as the automotive and aerospace industries for many years performing cutting, welding and materials processing tasks [1]. More recently, there has been an upsurge in the micro-engineering applications of lasers where pulsed lasers, in particular, have played a major role in the development of numerous micro-systems technology (MST) areas. In some cases such as ink-jet printer nozzles, for example, the transfer of the production methods to laser-based systems has provided an improvement in the technical specification of the devices together with higher production yields as well [2]. In other fields (e.g. biomedical analysis "chips"), totally new forms of devices have been developed [3] as a result of the unique properties offered by laser micromachining techniques.

In general terms, the most important qualities provided by pulsed laser micromachining include:

- Good quality
- High resolution
- High precision
- High processing speeds
- Low thermal damage
- Excellent reproducibility
- Use with many materials
- High production yields
- Good tolerances
- Single-stage “dry” process
- High flexibility
- Economically attractive

Some or all of the above may be applicable at any one time but this is largely determined by the application, the choice of laser and the method of its use. One of the main attractions of laser microprocessing is that lasers offer great flexibility in the rapid prototyping and evaluation of different designs. Many different process routes can also be tried out with the same laser tool in a relatively short time so the developmental cycle is also much faster than with many conventional techniques.

Many different pulsed lasers have been used in micromachining trials world-wide and these have ranged in wavelength from the infra-red to the deep UV, in pulse duration from milliseconds to femtoseconds and in repetition rate from single pulses to many tens of kilohertz. The work described in this article concentrates on the use of UV excimer lasers since these have been at the forefront of many innovative developments in different applications areas. Some preliminary research on the use of a new type of solid-state laser is also presented since this may be of interest in some fields.

## 2. EXCIMER LASER MICROMACHINING

Excimer lasers are pulsed laser sources emitting in the ultra-violet (UV) region of the spectrum. They are relatively broadband sources and usually have a rectangular beam output of the order of ~25mm x ~10mm. The beam divergence is usually ~1-5mrad and it is different in the two orthogonal beam directions. Due to this relatively large and non-uniform beam divergence, and the fact that the beam has poor spatial coherence, the direct focussing of excimer lasers is generally unattractive. Hence, the technique of mask projection is commonly used in a large number of applications.

### 2.1 Mask Projection

The output beam from the excimer laser is not uniform and so usually some form of beam homogenisation is used to make a "flat-top" beam. This homogenisation is normally important since the ablated depth of the sample depends on the energy density of the beam at any point. A mask, which is used to define a shape or pattern which is required for the formation of the desired microstructures, is placed at the plane of optimum uniformity of the beam. It is then imaged onto the sample by appropriate high-resolution optics. The mask is typically either made from chrome-on-quartz or from a thin metal sheet.

In mask projection systems, the laser beam usually remains fixed and the mask and the workpiece can both be moved across it in a precisely controlled manner. The concept of mask projection is depicted in figure 1.

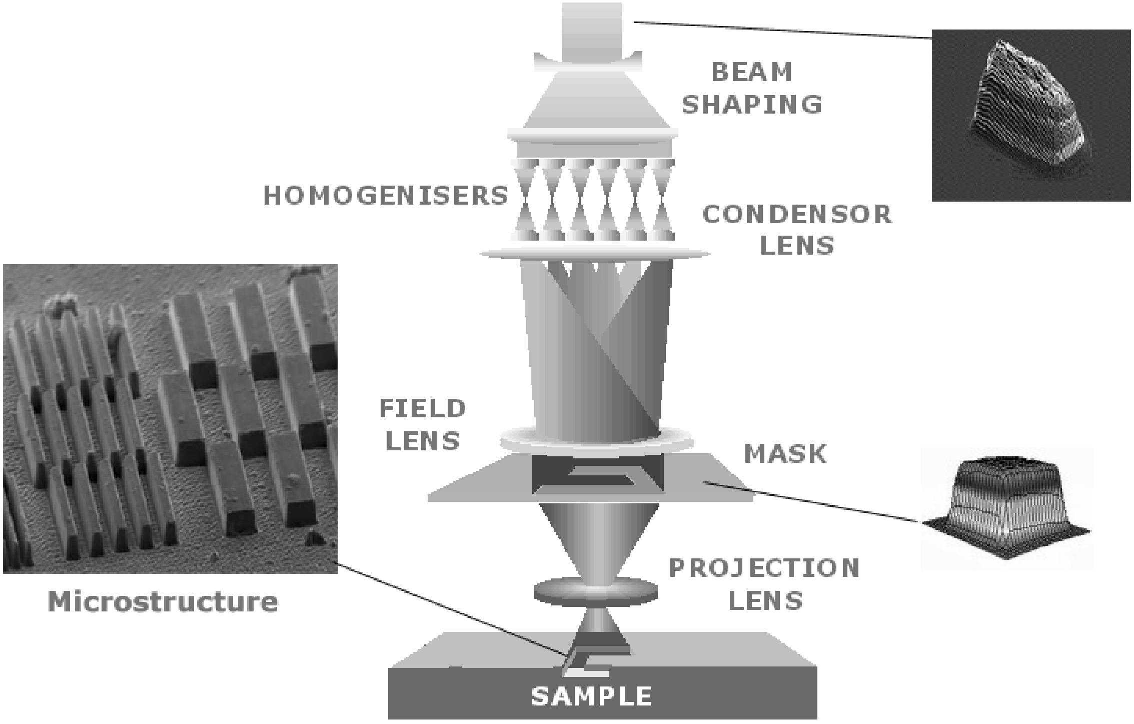

Figure 1. Representation of typical excimer laser mask projection system.

The mask projection method offers great flexibility and there are numerous features which can be utilised when considering micro-machining applications. These include:

- Mask dimensions
  The projection lens usually de-magnifies the mask pattern onto the workpiece and so the features on the mask do not need to be as small as the micro-structures to be produced. Typically, de-magnifications of x4, x10 or x30 are used so the mask does not have to be made of ultra-high resolution features, thereby reducing its complexity and cost of manufacture.

- Mask Damage
  Due to the de-magnification which is used, the energy density of the laser beam is much lower at the mask than at the sample. This reduces the risk of damage to the mask and increases the mask lifetime as well.

- Separation of Mask and Workpiece
  Because the mask and workpiece are not in close proximity, the mask does not suffer from any debris or particulate damage from the sample ablation.

- Independent Control
  Mask projection allows independent control of the motion of the mask and workpiece and this allows many different processing techniques to be used depending on the desired micro-engineering application.

- Resolution and Depth of Focus
  The smallest feature resolution R which can be obtained is fundamentally governed by the projection lens being used and can be expressed as $R \alpha k_1\lambda/NA$, where $\lambda$ is the laser wavelength and NA is the numerical aperture of the optical system and $k_1$ is a constant which depends on the sample material and processing conditions. The depth of focus (DoF) is similarly given by $DoF \alpha k_2\lambda/NA^2$ where $k_2$ is another optical/process-related constant.

Mask projection systems provide great flexibility in the range of micro-engineering tasks that can be performed with them - the same system can be used for the production of many diverse micro-structures for different applications.

## 2.2 Production of Microstructures

There are certain variables which can be adjusted in mask projection systems and the proper control of these parameters enables a variety of different effects to be accessed. The processing variables include the laser wavelength, the optical system design, the sample material, the laser energy density and repetition rate but the most important parameters in determining the *type* of micro-structure which can to be produced are the positions and motion of the mask and sample during the firing of the laser. Therefore, the accurate control of the mask and the workpiece, together with precise synchronisation of these two elements to the laser pulses, is vital in the production of micro-machined structures.

### 2.2.1 Static Mask and Workpiece

Typical projection lenses have image field sizes which can range from hundreds of microns to many millimetres. Since the image is smaller than the mask by some factor (e.g. x10), the laser beam at the mask is usually up to tens of millimetres in size. If the structure to be produced is small and simple, or made-up of regular repeating patterns, then it is possible to use the technique of *static* mask projection, providing the basic “unit cell” of the pattern can be fully illuminated by the laser beam. This technique is most commonly applied in the production of holes - ink jet printer nozzles, for example - but any discrete feature can be produced. Figure 2 shows some 100μm diameter holes which have been drilled through a 50μm thick piece of ceramic.

There are two extensions of the basic process which can enhance the applicability of static projection. One involves the lateral motion of the sample in between the production of structures: the laser is fired with a static mask and workpiece to produce a structure; the laser is turned off; the sample is moved laterally in X or Y; the laser is fired again to produce the same structure again. By repeating this procedure, large areas can be covered with the same structure. This technique is called *step-and-repeat* processing.

The second extension of static projection involves the positioning of a new mask pattern in between production of the structures: the laser is fired with a static mask and workpiece to produce a structure; the laser is turned off; the mask is moved laterally to position another mask pattern under the laser beam; the laser is fired again over the same workpiece area to superimpose the new mask pattern over the previous one. This techniques is called *indexed mask projection*.

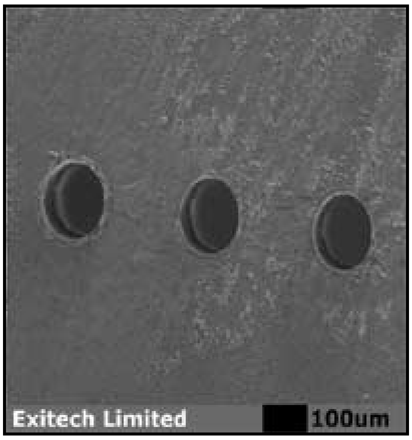

Figure 2. Holes drilled into a ceramic using an excimer laser.

These two methods can be considered extensions of the static projection technique since the mask and workpiece are stationary during the production of the micro-structures, even though the mask or workpiece are moved in between the processing steps. Examples of step-and-repeat and indexed mask projection are shown in figure 3.

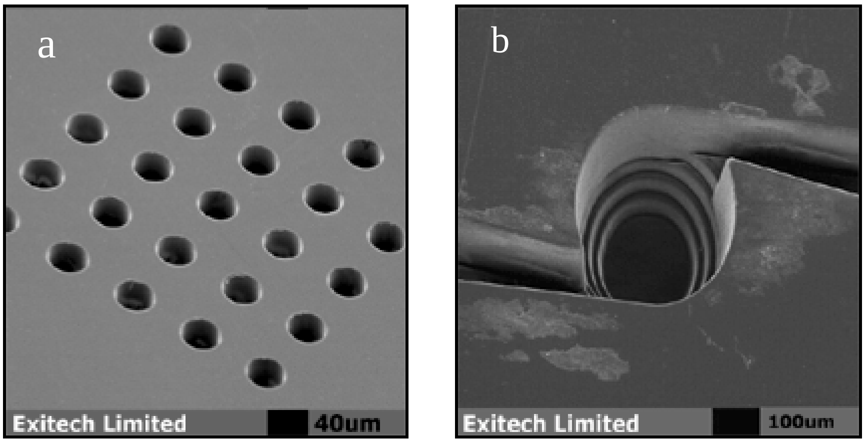

Figure 3. Micro-structures produced by (a) Step-and-repeat mask projection. (b) Indexed mask projection.

The holes shown in figure 3(a) were produced individually with the sample being moved in between each drilling step. Two points to note are the positioning accuracy of the holes (governed buy the workpiece stages) and the reproducibility of the quality of the holes (determined mainly by the laser stability). Figure 3(b) shows a nozzle device where the central section contains a stepped structure leading down to a small hole. The steps inside the central well were produced by using different diameter apertures to define the different steps - a particular diameter circular section was machined to a specified depth, the mask changed for another one and the machining repeated for the new diameter and depth. In both cases, the sample material was polyester and a krypton fluoride (248nm) laser was used. Typical laser energy densities used for the structures in figure 3(a) and (b) were ~300mJ/cm$^2$.

Step-and repeat processing is now commonly used in applications such as the micro-drilling of ink-jet printer nozzle heads. In this case, the entire nozzle head (consisting of hundreds of holes) is drilled at the same time followed by the motion of the same to the next position for drilling. In industrial production of such nozzle plates, the sample is usually in the form of polyimide tape and the laser system automatically winds the tape, drills the holes and then winds the tape further. This tape handling has to be accomplished with high speed and precision to ensure that the tolerances in the nozzle diameters (typically ±1µm) are maintained and that the nozzles are also positioned correctly on the tape.

### 2.2.1 Moving Mask

If the mask is moved during the firing of the laser, then structures can be produced which have varying depth profiles, thereby introducing simple depth information into the features. This can be achieved by ensuring that an aperture moves across the laser beam in a precisely controlled manner during the laser firing – hence, the static workpiece is exposed to a continually-varying amount of energy across it’s exposed area which produces a depth gradient in the sample. This technique is also known as *mask dragging*.

Figure 4(a) shows an example of a simple linear ramp produced with this method in a polymer material. The relatively simple micro-structure shown in figure 4(a) can, of course, be elaborated upon for different applications, using the basic technique for the production of more complicated features. Examples of such features are shown in figures 4(b) and 4(c) where multiple ramped structures have been produced in a polymer - these have been produced by careful combination of mask aperture, mask motion, workpiece positioning and laser firing sequence.

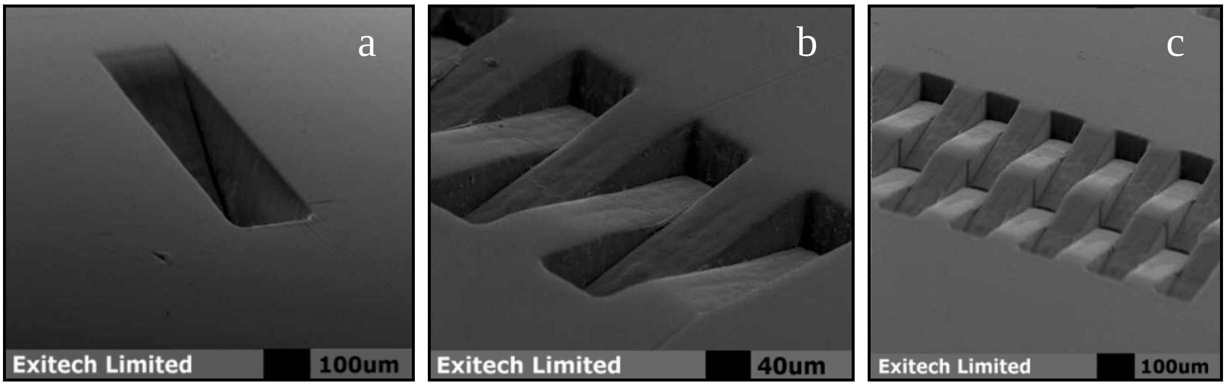

Figure 4. Linear ramps produced in PET at 248nm.

Some micro-optical- electro-mechanical-systems (MOEMS) applications require the referencing of two or more separate pieces with respect to each other and such positioning can be accomplished with the types of interlocking features shown in figure 4(b) and 4(c). Other areas, such as multi-functional sensor devices or multi-level micro-fluidic systems, often require the transfer of fluids from one area or plane to another. Such controlled guidance of fluids, for example, can also be achieved with these structures, particularly since other features such as nozzle holes can also be incorporated into these ramps or sloping channels.

### 2.2.2 Moving Workpiece

This is one of the most common extensions of the mask projection technique and involves the movement of only the sample during the laser firing. It is usually associated with the production of micro-channels or micro-grooves which may be used in various biomedical or optical applications. The concept of *workpiece dragging*, as this technique is also often called, involves using a static mask while moving the sample under the laser beam during firing. The laser processing conditions such as fluence and number of shots define the depth of the feature (as with all other mask projection methods) but the mask *shape* determines the depth profile of ablated structure. Therefore, the 2D layout of the channels can be defined by the motion of the workpiece and their cross-sectional profile by the mask shape – since these two aspects can be chosen independently, the technique allows a great deal of diversity in the details of the micro-structures which can be machined. Micro-channels of different cross-sections are shown in figure 5 where each of the cross-sections shown was produced using an appropriate mask (i.e. (a) triangle, (b) 'T' shape and (c) circle).

Figure 6 shows some micro-fins which have been produced using the workpiece dragging method for a gas pressure sensor application. These features were machined in a ceramic material as a demonstration for a prototype device using 248nm laser. All the fins were produced at the same time by using a mask with 5 rectangular slots in it.

The production of straight channels or grooves can be considered as workpiece dragging in one dimension (along the length of the channels). One of the reasons why workpiece dragging is an important technique is because it can be used for the production of controlled, multi-shaped 3D micro-structures. This is achieved by using workpiece dragging in two dimensions – making channels or shapes in two directions on the same sample. This can produce features such as pyramids, cones, pillars, lenses etc. and some typical pyramidal micro-structures produced with 2D workpiece dragging are shown in figure 7.

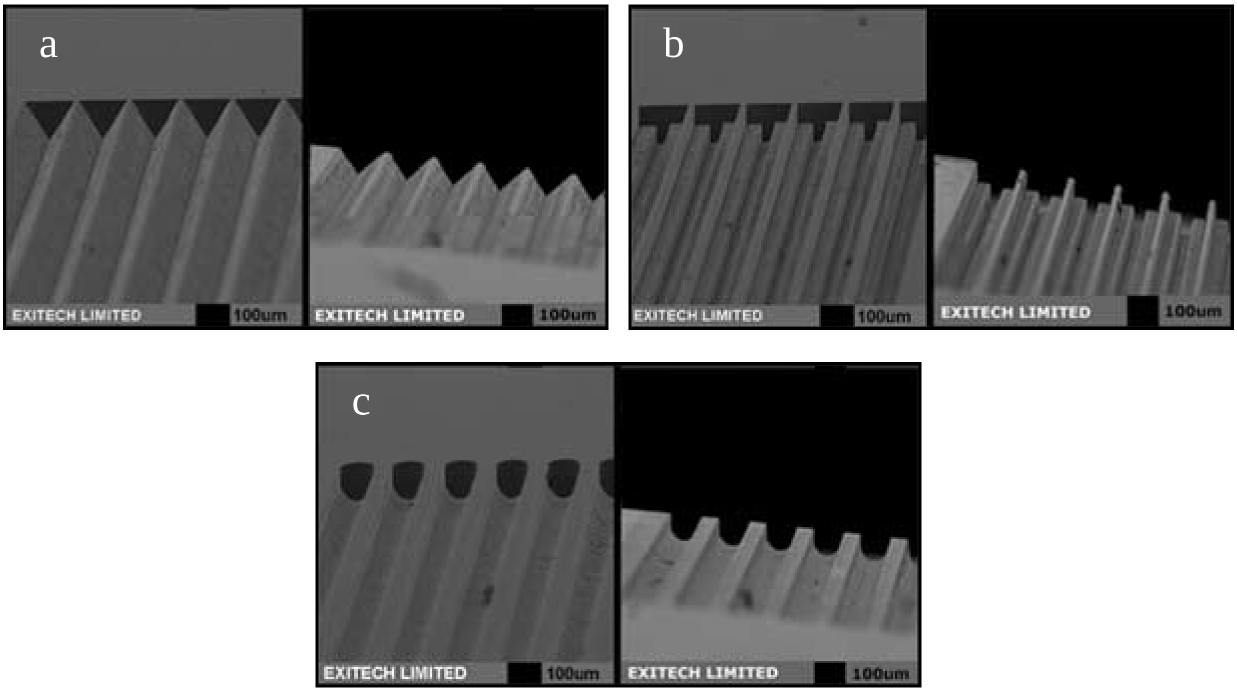

Figure 5. Shaped cross-section micro-channels produced using workpiece dragging technique.

Many applications require the types of structures shown in figure 7. These areas include optical technologies where light guidance or control is required for display panels and sources/detectors for micro-chip devices. The ability to micro-machine these structures directly onto the optical devices is a major factor in the development and viability of these systems. Such 3D pyramidal features can also act as anti-reflective (AR) structures for optical elements in the infra-red optical region where they mimic the response of multi-layer dielectric AR-coatings.

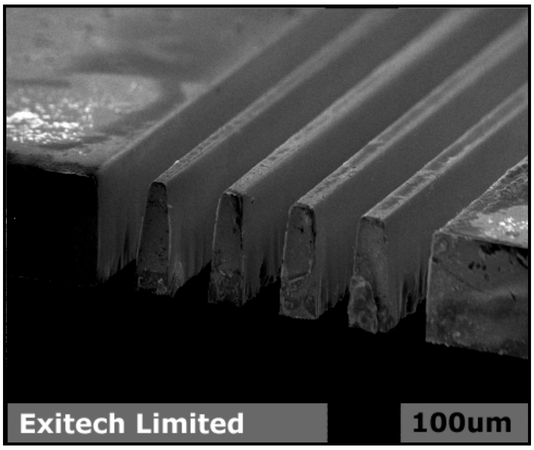

Figure 6. Micro-fins produced in ceramic at 248nm using workpiece dragging.

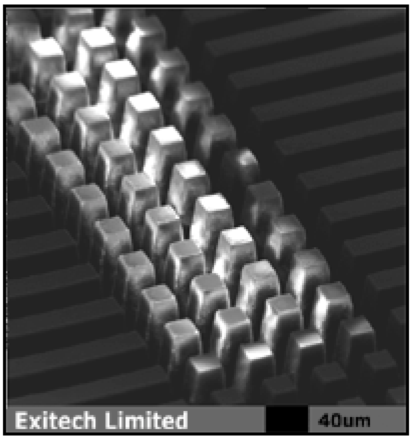

Figure 7. Microstructures produced in polymers using crossed workpiece dragging

The advantages of directly machining these AR structures on to the optics are that (i) they do not have any optical mismatch problems (since they are made of the same material), (ii) there is no issue of coating contamination or ageing and (iii) there is no damage constraint imposed by a coating. There are other interferometry-based methods by which these features can also be produced [4] but pulsed laser micro-machining can produce these structures directly in a single procedure.

### 2.2.3 Moving Mask and Workpiece

This technique is also referred to as *synchronised scanning* since both the mask and workpiece are moved in synchronism with each other during the machining process. Synchronised scanning is used where the pattern to be produced is large, non-repeating and cannot be produced by any of the three techniques detailed above. It has applications in printing (where the plates used to transfer the ink to the print medium can be laser-engraved), printed-circuit-board industries (for the definition of the electrode patterns) and display panels (for the electrodes), amongst other areas.

The motion of the mask and sample (which move at different speeds since there is a de-magnification involved) and the firing of the laser (taking the acceleration and deceleration of the stages into account) needs to be accomplished with high precision. If the pattern to be ablated requires a uniform depth, then care also has to be taken to fire the same number of laser shots over the entire sample.

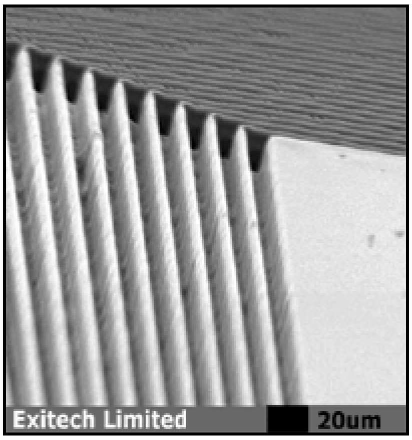

Figure 8. Pattern produced by synchronised scanning in polymer at 248nm.

Figure 8 shows an example of a micro-machined pattern produced in polyimide by synchronised scanning where the uniform depth of the ablation is apparent. The structure shown is part of a micro-coil device which is made from the polymer part produced by the laser system. Following the laser ablation, the sample can be metallised to form an inverse metal master from which multiple copies can be produced. This approach - known as *Laser LIGA* - is currently being pursued actively as it allows the mass reproduction of micro-products from a small number of high quality laser-produced masters.

The main disadvantage of synchronised scanning is that the entire pattern to be produced has to be contained on the mask. Otherwise, all the previously-listed benefits of laser micro-machining apply equally well to this method as well. It is usual with synchronised scanning to maintain the same depth in the micro-machined sample but another variation of this techniques can also allow the depth to be varied across the sample. This is called *synchronised overlay scanning* and uses an element of workpiece dragging to add the depth information to the synchronised sample.

As was explained above, workpiece dragging uses the shape of the mask to define the cross-section of the micro-machined channels, i.e. the shape of the beam at the mask can be used to define the form of the machined depth. In synchronised overlay scanning, both the mask and the workpiece are scanned together as normal but, in addition, an aperture is introduced into the beam to shape the beam. The combination of the beam shaping and the scanning then gives the ability to pattern large, non-repeating patterns but with the added depth control offered by the beam shape. Figure 9 shows two examples where micro-structures have been produced where the depth varies across the machined areas - (a) where one side of a set of triangles has a 45° slope and (b) where some micro-channels have been produced on a linear ramp.

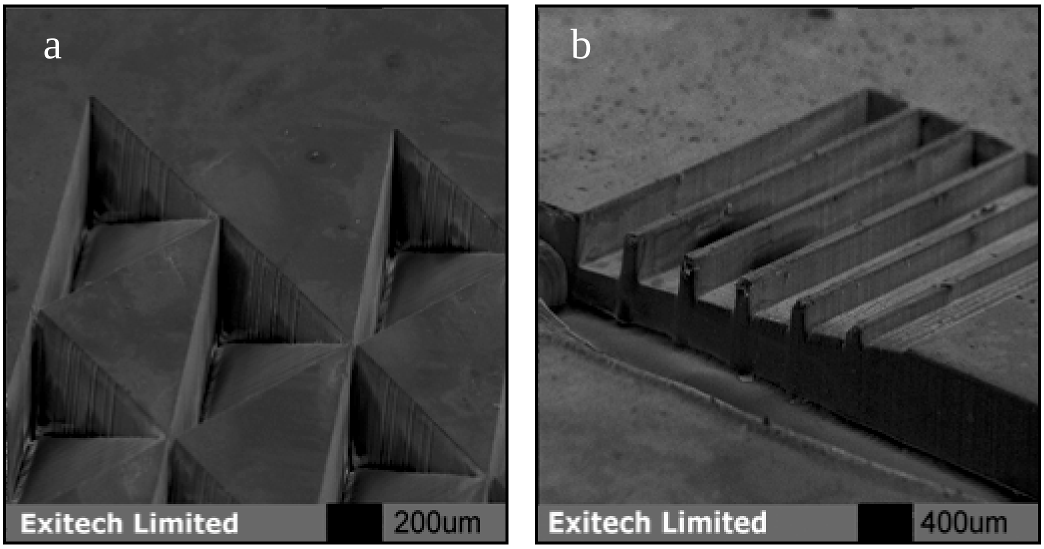

Figure 9. Microstructures produced by synchronised overlay scanning giving depth variation across the sample.

Synchronised overlay scanning also enlarges the areas where laser micro-machining techniques may be applied. Areas in fluid dynamical systems, for example, where parts in bearings and seals are required can be structured with special shapes for fluid flow requirements. Alternatively, various “chips” for bio-technology applications where multi-functional units need to assembled on a single discrete package can incorporate different micro-features with varying depths.

### 2.3 Direct Writing using Mask Projection

Direct writing is a technique which is normally used with Nd:YAG or $CO_2$ lasers (which usually have good beam propagation characteristics) where the laser beam is focussed down to a small spot. The motion of either the laser beam or the sample (or sometimes both) is then used to produce the microstructures in the sample.

The two main advantages of direct writing are that:

(i) it does not require a mask.
(ii) the path to be machined can be fed directly into the control of the machining system (i.e. the laser system can be directly interfaced to the CAD generation of the pattern).

As was stated earlier, excimer lasers are generally not focussed directly but a mask projection system can be used in the manner of a direct writing tool if required. This is achieved by using a circular mask which defines a beam spot at the workpiece. By keeping this mask stationary, the system appears as a conventional direct write tool and design data can then be fed to the workpiece stages to control their motion across the laser beam. One big advantage that this method has over the conventional direct systems is that with the mask projection approach, changing the spot size of the beam is only a matter of changing the mask and does not involve changing lenses.

Figure 10 shows a demonstration of direct writing using a mask projection system where "Exitech" has been written in a polymer sample by moving it across a fixed excimer laser beam and figure 11 shows the use of this technique in a biomedical application where some micro-channels of different radii have been machine into a PET sample.

The use of direct writing using excimer laser mask projection systems is finding increasing use in the manufacture of complex structures in polymers for sensors and biomedical devices. This combines the benefits of excimer laser machining of polymers with the advantages of direct writing of contoured paths where the use of masks to define the patterns is not attractive.

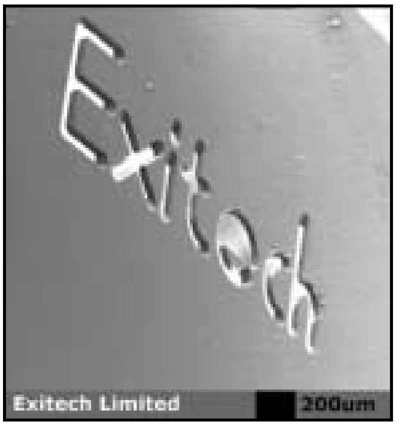

Figure 10. Direct writing using an excimer laser.

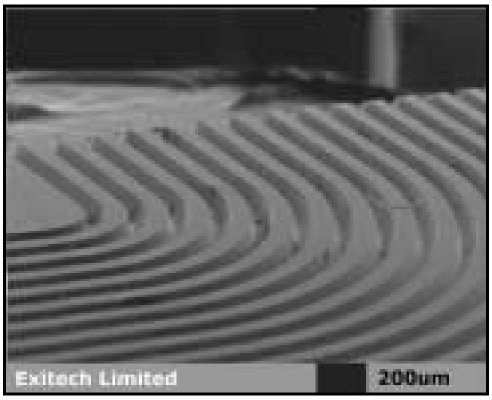

Figure 11. Production of micro-channels using excimer laser direct writing.

## 3. ULTRASHORT PULSE LASER MICROMACHINING

There has been intense interest recently in the use of ultrashort pulse lasers for various applications [5], especially in the use of femtosecond solid-state systems such as titanium sapphire lasers. Some of the areas which are already being researched include medical applications (e.g. eye surgery, medical imaging, cosmetic surgery), telecommunications, high-speed electronics and micromachining (e.g. printer nozzles, production of MEMS devices etc.) and the number of potential uses is growing rapidly [6]. Almost all of the work carried out so far in femtosecond micromachining has used amplified Ti:sapphire lasers where the pulse duration has been of the order of a few tens to a few hundreds of femtoseconds.

The main drawback of the titanium sapphire systems is that they are invariably bulky, relatively complex, expensive and often require some form of expert laser knowledge in obtaining optimum performance. Although major advances have been made in making these systems user-friendly, their uptake in industrial environments is still likely to be slow due to their perceived drawbacks, irrespective of whether these are real or not. There exists a real need for simple, compact lasers which can provide sufficient power to be useful in micro-processing applications and which can be integrated easily and reliably into industrial situations.

There exists a situation at present where laser micromachining is being performed with lasers with pulse durations in the nanosecond regime or longer (Nd:YAG or $CO_2$ lasers) and in the femtosecond regime (Ti:sapphire lasers). The former field is well-advanced and already at a mature level whereas the use of femtosecond pulses is gaining in importance. There has, however, been little work done on assessing the viability of lasers with pulse durations less than tens of nanoseconds but significantly above the femtosecond domain.

We have used a prototype Q-switched fibre laser which has been developed by IMRA America Inc. (Ann Arbor, Michigan, USA) to address some of the issues of laser micromachining. This laser - known as the *Picowatt laser* -operates at a wavelength of 1064nm and produces a linearly polarised output beam with a beam quality factor $M^2 < 1.2$. The laser produces an output pulse duration of 750ps and the maximum pulse repetition rate is 10kHz. Typical pulse energies are ~150μJ @ 1kHz and ~80μJ @ 10kHz which gives average powers of 150mW @ 1kHz and 800mW @ 10kHz. This laser, therefore, has peak powers of 200kW @ 1kHz and 106kW @ 10kHz. This peak power is, in fact, higher than most diode-pumped solid-state lasers available currently. The laser head is compact (approximately 21"x12"x4.5") and sealed with no external adjustments and the power supply (~21"x24"x12") plugs directly into a mains power point. The laser required no system warm-up and could be set-up ready for machining in a matter of minutes.

Using this IMRA prototype laser, we focussed the beam down to spot size of ~15μm using a microscope objective (x10, 0.25NA) onto samples which were held on XY translation stages. The objective was mounted on an elevator stage to allow focal positioning to be accomplished and the stages were controlled via a CNC interface to allow programmed direct writing to be performed. A number of materials were machined to gain an overall qualitative picture of the effects of this *Picowatt* laser. These samples included borosilicate glass, stainless steel, silicon and CVD diamond.

The best results were obtained with the CVD diamond and the stainless steel samples. Figure 12 shows both sides of a CVD diamond wafer which was ~100µm thick. The laser beam was trepanned over the sample in a square and circular fashion and the excellent quality of the cuts is clearly evident. Also, there appears to be no graphitisation of the surrounding areas as is often observed with the excimer laser or Nd:YAG laser cutting of diamond. The average cutting speed was ~0.2mm/sec and so the holes shown in figure 12 only took a few seconds to cut out.

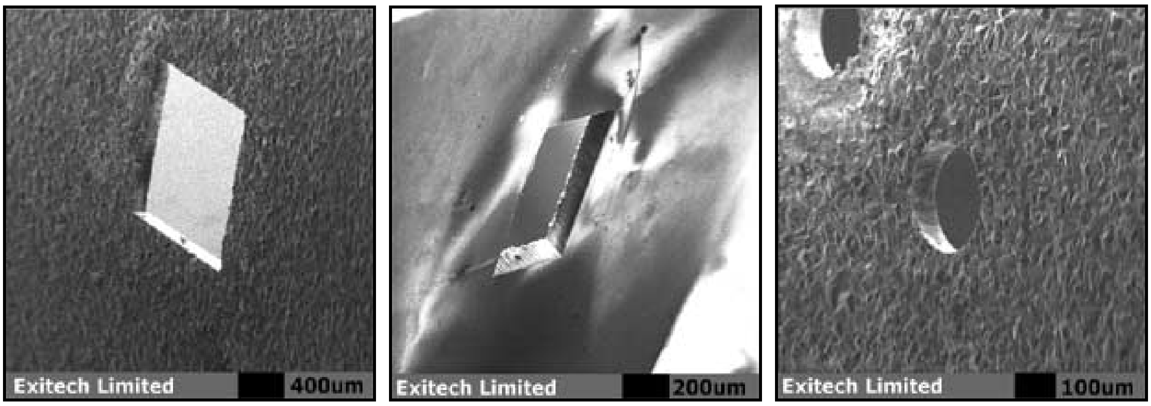

Figure 12. CVD diamond cut using a 750ps fibre laser.

As CVD diamond becomes available in larger sizes and with better quality, its unique set of properties is becoming more in demand for a range of uses such as optical components (laser optics, windows, lenses etc.) or thermal management devices for MEMS products. Laser microstructuring or smoothing can be achieved already with good results using excimer lasers but systems such as the Picowatt laser may offer an attractive alternative. These lasers appear to be effective in the machining of CVD diamond and this, combined with the small size, efficiency, running costs and ease of use, may make this type of laser extremely useful for these applications.

Similar cutting was tried with the stainless steel samples which were 50-75µm thick and a typical cut hole is shown in figure 13. The sample was trepanned under the laser using a stage speed of 10mm/sec and the total time taken to cut out the hole was ~12 seconds. The laser was used at 10kHz for both the diamond and the steel.

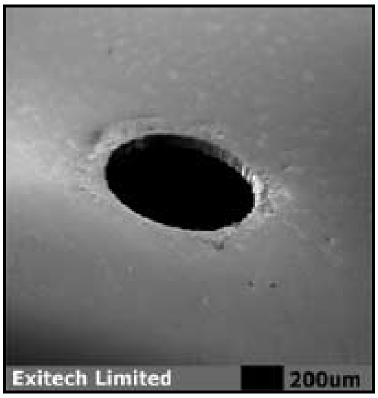

Figure 13. A thin sheet of stainless steel machined with a short pulse laser.

The results with the glass samples showed a lot of damage in the interaction sites and it seems clear that the peak intensity of the Picowatt laser is insufficient to machine glass cleanly. The silicon machined well for a certain depth but the ablation appeared to be self-limiting. This effect needs to be investigated further.

More quantitative work still needs to be done on different materials to measure the effects (e.g. etch rates, smoothness, debris issues) of these types of lasers and this work will continue in tandem with the development of the laser sources.

## 4. SUMMARY

The use of excimer lasers for the production of different multi-dimensional micro-structures has been described in detail with particular emphasis on the flexibility offered by mask projection systems. Some of the diverse applications where these features are used have been presented to highlight how technical advances in the laser techniques are helping in the development of some new MST fields.

Some initial trials using a sub-nanosecond fibre laser have also been detailed. It appears that ultrashort pulses in the femtosecond domain are not necessarily required for the micromachining of certain materials such as CVD diamond or stainless steel and that such lasers may find a niche in some areas as an alternative to excimer or Nd:YAG lasers.

## 5. ACKNOWLEDGEMENTS

The authors would like to thank their colleagues at Exitech Limited for technical assistance in the production of the microstructures described in this article, especially Dominic Ashworth, Tim Willford and Ben Simmons. We also gratefully acknowledge the loan of the Picowatt laser from IMRA America Inc. and thank Don Harter and Heinrich Endert for their helpful advice and co-operation.

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