New Developments and Applications in the Production of 3D Micro-structures by Laser Micro-machining

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ABSTRACT

Micro-machining techniques using pulsed lasers are currently being applied world-wide in many diverse industrial application areas including biomedical devices, printers, flat-panel displays, semiconductors devices and telecommunications systems. In particular, the use of excimer lasers has been at the forefront of the new developments in the manufacture of complex micro-structures for the production of micro-optical-electro-mechanical-systems (MOEMS) units such as nozzles, optical devices and sensors. This paper reviews the fundamentals of excimer laser micromachining techniques and details recent developments which have enhanced the capabilities of these approaches. Application areas where these techniques are of interest are highlighted.

Keywords: excimer lasers, micro-machining, ablation, mask projection, MOEMS, micro-structures.

1. INTRODUCTION

Laser micro-engineering techniques are currently revolutionising many industries, both in terms of allowing previously-unattainable product specifications and in the way new manufacturing methods which can be adopted. These changes are being driven by rapid technical advances in the available laser-based systems and also by the economic benefits that laser micro-engineering techniques bring.

Pulsed laser micromachining, especially, has led the way in the development of innovative solutions in numerous industrial micro-engineering applications. The use of pulsed laser systems in these fields offers many advantages which include:

- Quality
- Resolution
- Precision
- Speed of processing
- Low thermal damage
- Single-stage “dry” process
- Large range of materials
- High production yields
- Good tolerances
- Reproducibility
- Flexibility
- Cost

In certain areas such as, for example, the production of electrode structures for display panels or the manufacture of channels for micro-fluidic devices, laser techniques compete with existing conventional processing methods such as photolithography. Such routes involve multiple steps where exposure, wet development and chemical or plasma etching are required – even if the achieved end result is similar in terms of quality, then the attractiveness of a laser-based method often lies primarily in it being a single-stage, “dry” process. Lasers also offer great flexibility in prototyping and rapid evaluation of new micro-products and laser systems also usually allow many different processes to be evaluated with the same tool.

In other areas such as the production of ink-jet printer nozzles, for example, lasers offer unrivalled technical benefits and device attributes like nozzle hole size, reproducibility and centricity are not available with competing techniques like electro-discharge machining. As such, lasers not only allow great advances to be made in these fields but also enable development to continue to produce higher specification products.

Many high-power systems using Nd:YAG or CO_2 lasers are used widely for the drilling, cutting or profiling of thick metals at average power levels of many kilowatts or above. These applications fall outside the remit of this article. Instead, the systems which will be addressed operate at typical power levels of a few tens to hundreds of watts of average power and, importantly, make use of the micro-processing capabilities of lasers. In particular, excimer laser systems using mask projection methods will be detailed.

2. EXCIMER LASER MICROMACHINING SYSTEMS

As a result of the nature of excimer lasers, particularly with regard to the beam divergence and spatial incoherence, the technique of mask projection is most commonly used in excimer laser micromachining systems. Excimer lasers, which are pulsed laser sources emitting in the ultra-violet (UV) region of the spectrum, are relatively broadband sources. They usually have a rectangular beam output shape of the order of 20-30mm in length and 5-10mm in width and typically have beam divergences of ~1-5mrad. The divergence is also different in the two orthogonal beam dimensions. Due to this large divergence, and the fact that the divergence is different in the two beam axes, the direct focussing of excimer lasers is generally unattractive.

The energy distribution of the laser output is also not uniform as shown figure 1(a). This can be problematic since the varying energy density across the beam would manifest itself in the sample as varying depth of the microstructure being machined. To overcome this, the excimer beam is usually homogenised in some fashion to enable high quality ablation micro-structures to be produced. One method of beam homogenisation uses multiple lens arrays to split and recombine portions of the beam, which has the effect of making the re-combined beam more uniform in energy distribution. An example of an homogenised beam is shown in figure 1(b).

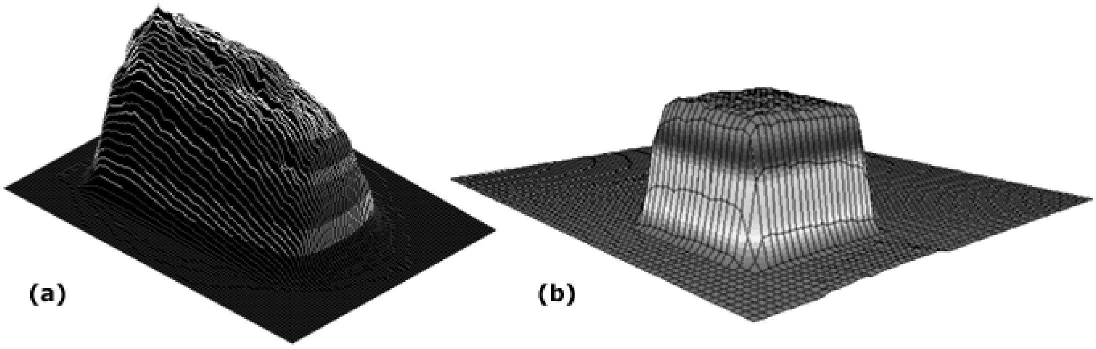

Figure 1. Beam profiles of an excimer laser, (a) directly at the output of the laser and (b) after beam homogenisation

Unlike lasers which have a Gaussian beam profile and a TEM_{00} transverse mode – and hence have a single phase across the beam front - standard excimer lasers have poor spatial coherence due to the fact that many transverse modes are present. This property, however, can be used advantageously since it allow an excimer beam to be used in projection systems without unwanted interference effects being present.

2.1 Mask Projection

In mask projection systems, the excimer laser beam is used to illuminate a mask. Typically, the mask is either made of chrome-on-quartz or from a thin metal sheet. In whichever case, the mask defines a pattern which is used to produce the desired microstructure. The illuminated mask pattern is imaged onto the sample with a high-resolution projection lens. 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 2.

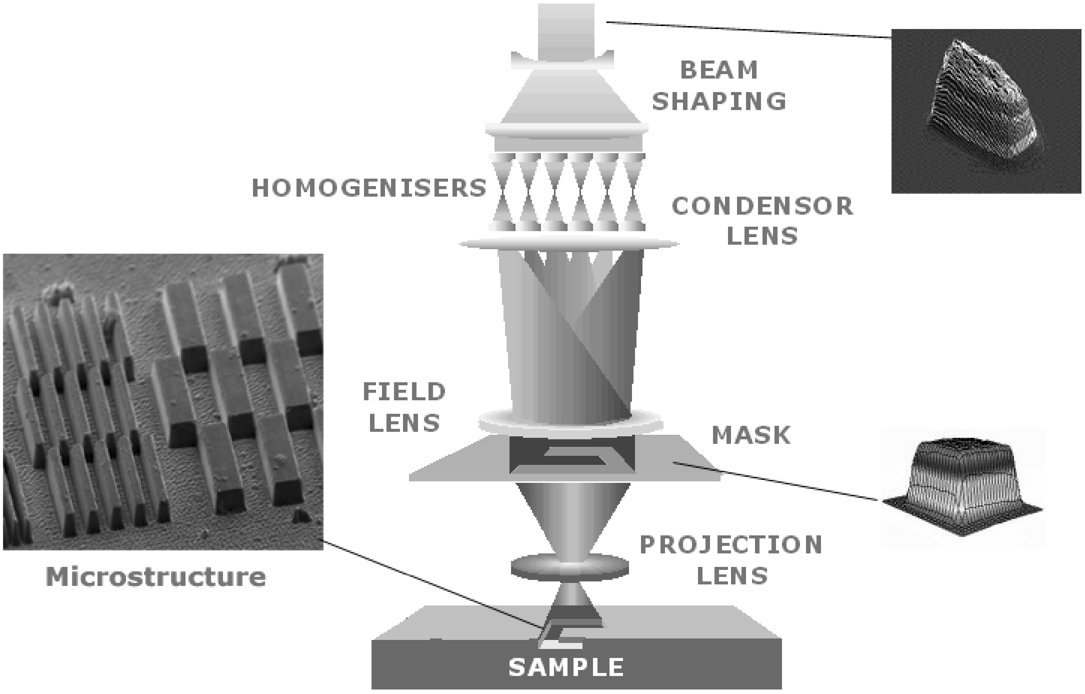

Figure 2. Representation of typical excimer laser mask projection system.

There are numerous aspects of mask projection which can be utilised when considering industrial micro-machining applications. These include:

- <u>Mask dimensions</u>

  Since the projection lens usually de-magnifies the mask pattern onto the workpiece, 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 it's complexity and cost of manufacture.

- <u>Mask Damage</u>

  Also 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.

- <u>Separation of Mask and Workpiece</u>

  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.

- <u>Independent Control</u>

  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.

- <u>Resolution and Depth of Focus</u>

  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 λ 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.

One of the biggest advantages of a mask projection systems is the great flexibility they provide in the range of micro-engineering tasks that can be performed - the same system can be used for the production of diverse micro-structures for many applications. The following section provides details of the types of techniques which have been developed for the production of different types of features with excimer laser mask projection systems.

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 two 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

If the structure to be produced is small and simple, or made-up of regular repeating patterns, then it is possible to use the techniques 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 but any discrete feature can be produced. Some examples are shown in figure 3. A single feature or multiple features can be produced, as long as they can all be contained within the area of the beam at the mask. This area can be as large as many tens or hundreds or square millimetres.

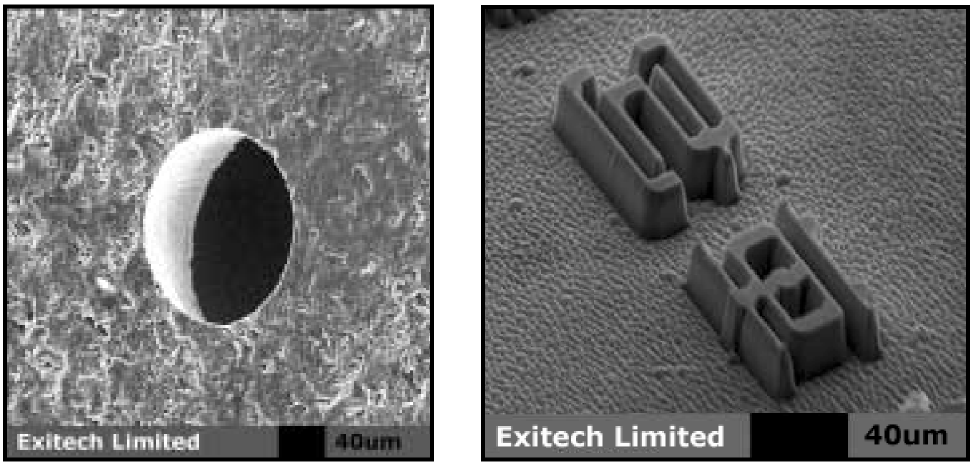

Figure 3. Examples of micro-structures produced with static mask projection method showing a hole drilled into ceramic and some features machined into polymer.

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 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 id called indexed mask projection.

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 wither the mask or workpiece are moved in between the processing. Example of step-and-repeat and indexed mask projection are shown in figure 4, where a 3x3 array of holes have been drilled in figure 4(a) and then step-and-repeated across the sample and 5 square holes have been machined on top of one another in figure 4(b).

Step-and repeat processing is now commonly used world-wide 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.

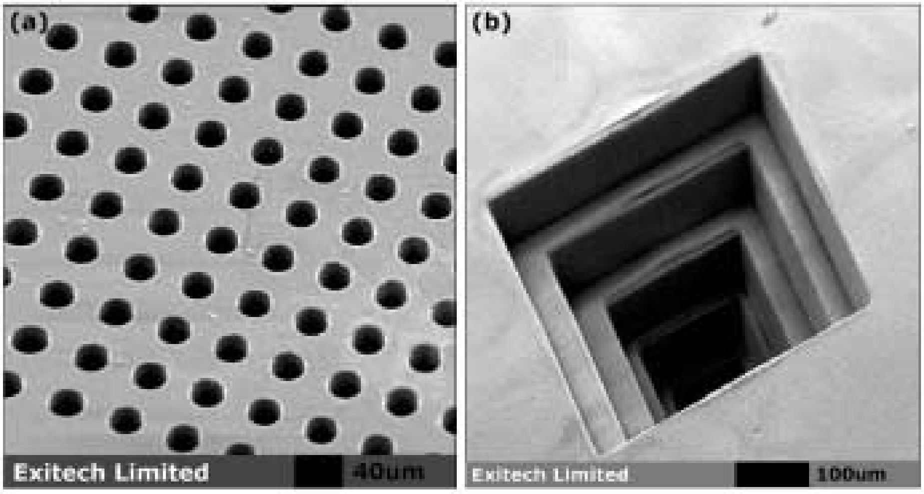

Figure 4. Micro-structures produced by (a) Step-and-repeat mask projection. (b) Indexed mask projection.

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 5 shows the concept of machining using a moving mask together with an example of a simple linear ramp produced with this method in a polymer material.

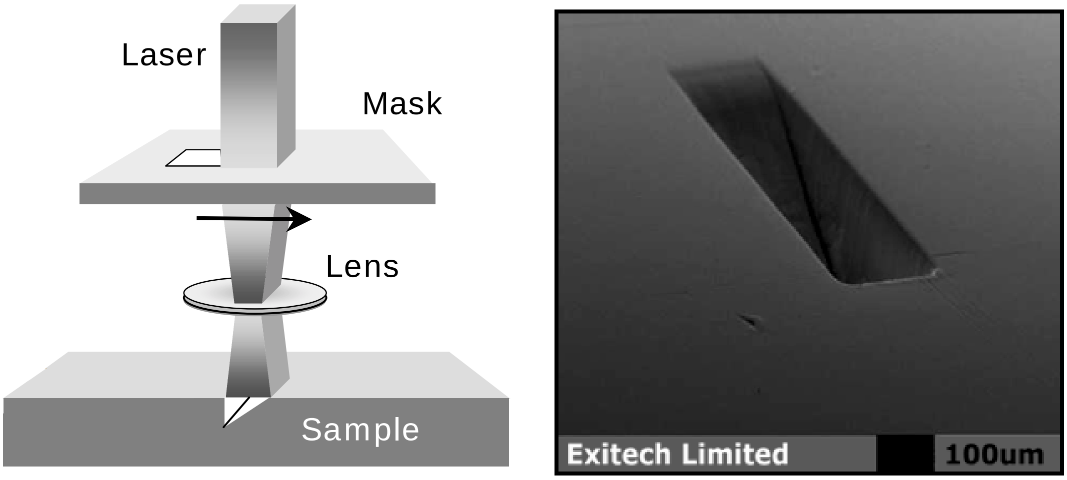

Figure 5. (a) Technique of moving mask micro-machining
(b) a simple linear ramp produced in PET at 248nm.

The relatively simple micro-structure shown in figure 5(b) can, of course, be elaborated upon for different applications, using the basic technique represented above for the production of more complicated features. Three examples of these features are shown in figure 6 where multiple ramped structures have been produced in a polymer.

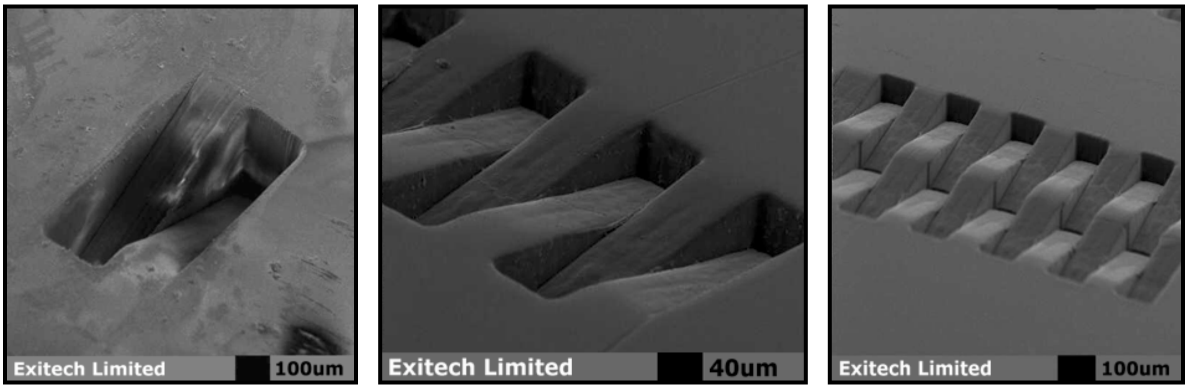

Figure 6. Multiple ramps produced in PET by moving mask technique.

Some MOEMS applications require the referencing of two separate pieces with respect to each other and such positioning can be accomplished with the types of interlocking features shown in figure 6. 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 the 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. The concept of workpiece dragging is shown in figure 7(a) with 20µm wide micro-channels produced with this method shown in figure 7(b).

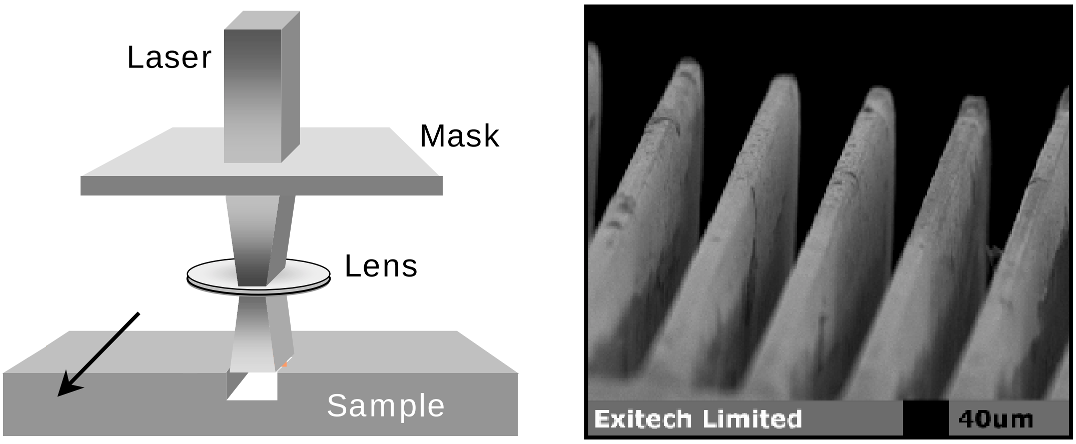

Figure 7. Technique of workpiece dragging and micro-grooves produced in polymer at 248nm.

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 micro-structures produced with 2D workpiece dragging are shown in figure 8.

Many applications require the types of structures shown in figure 8. These areas include optical technologies where light guidance or control is required, for example, 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.

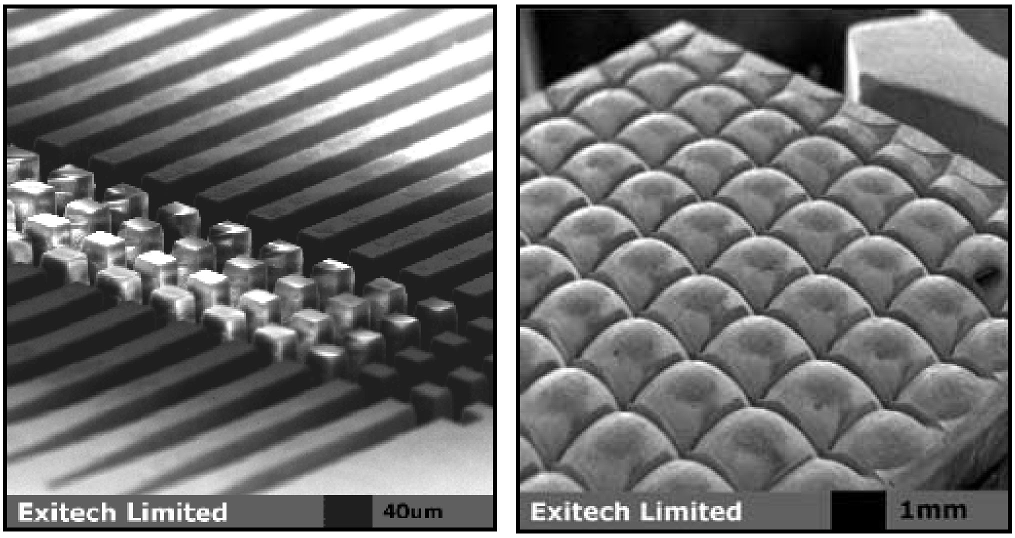

Figure 8. Microstructures produced in polymers using 2D workpiece dragging.

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. 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 but they also rely on an intermediate resist layer exposure 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. This motion is also carefully synchronised with the firing of the laser. Since mask projection usually involves a de-magnification (say by a factor M), it means that the mask has to travel M times farther than the sample in the same time during synchronised scanning. All this has to be accomplished with high precision and while maintaining the desired number of shots over the entire exposure area, even taking factors such as the acceleration and deceleration of the mask-workpiece stages into account.

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. Figure 9 shows the concept of synchronised scanning with an example of a micro-machined pattern produced in aluminised polyester.

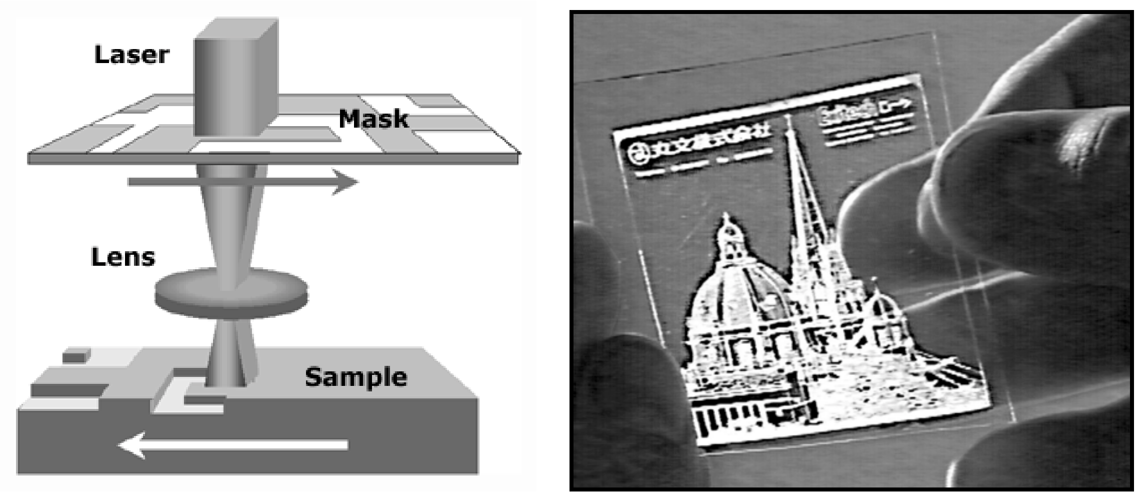

Figure 9. (a) Technique of synchronised scanning
(b) Pattern produced on metallised polymer sheet at 248nm.

The main disadvantage of synchronised scanning is that the entire pattern to be produced has to be contained on the mask Otherwise, all the 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. This concept is shown in figure 10.

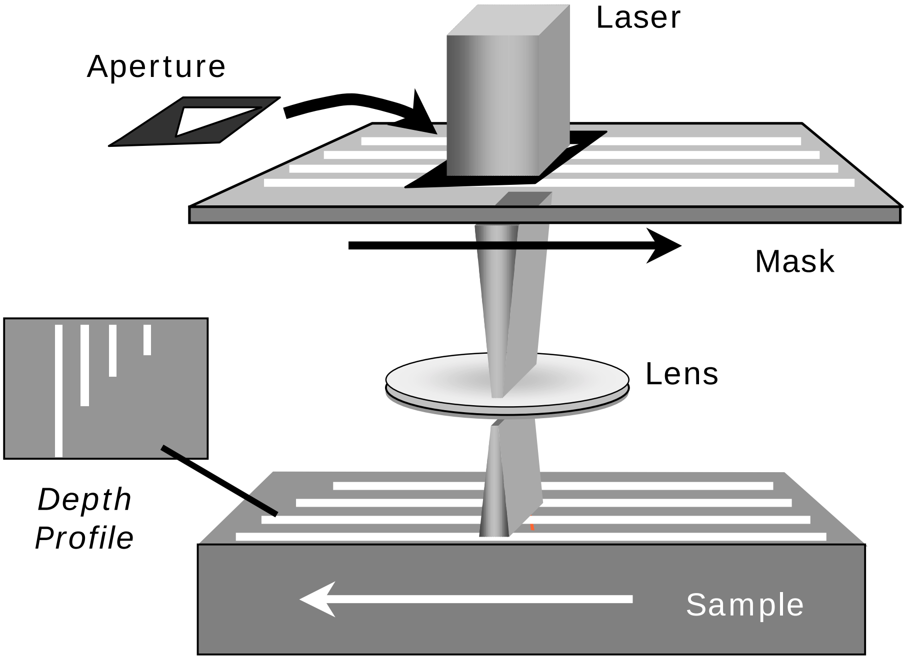

Figure 10. Technique of synchronised overlay scanning. A triangular-shaped beam is shown as an example to define a triangular depth contour.

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. Some examples of the types of multi-dimensional micro-structures which can be produced with synchronised overlay scanning are shown in figure 11.

3. FUTURE TRENDS

It appears likely that the increase in demand for multi-dimensional micro-structures will continue as more application areas emerge. Inter-disciplinary devices incorporating optics, mechanics, electronics and bio-medicine are already in production and this field is likely to expand explosively as more bio-technological sensors and chips become commercially available for mass consumer markets. These market-led forces will drive the technology of production into new regimes of automation and higher specifications. Economics will, as always, play a crucial role in determining the feasibility of the emerging products but laser micro-engineering is likely to offer an unrivalled set of attributes such as high specifications, flexibility and attractive production yields.

Other avenues which will need to be addressed include the use of different laser characteristics such as wavelength and pulse duration to access a wider array of materials. Such systems using fluorine lasers operating at 157nm, for example, are already being actively researched as are ultra-short pulse systems with pulses in the femtosecond regime. Another area which will find industrial interest is the micro-machining of arbitrary-shaped products such as the housings of mobile telephones. This ability to micro-structure contoured surfaces could then replace bulky electronic elements such as planar circuits with electronics directly printed onto the actual bodies of these small products, thereby providing benefits in weight, size and cost.

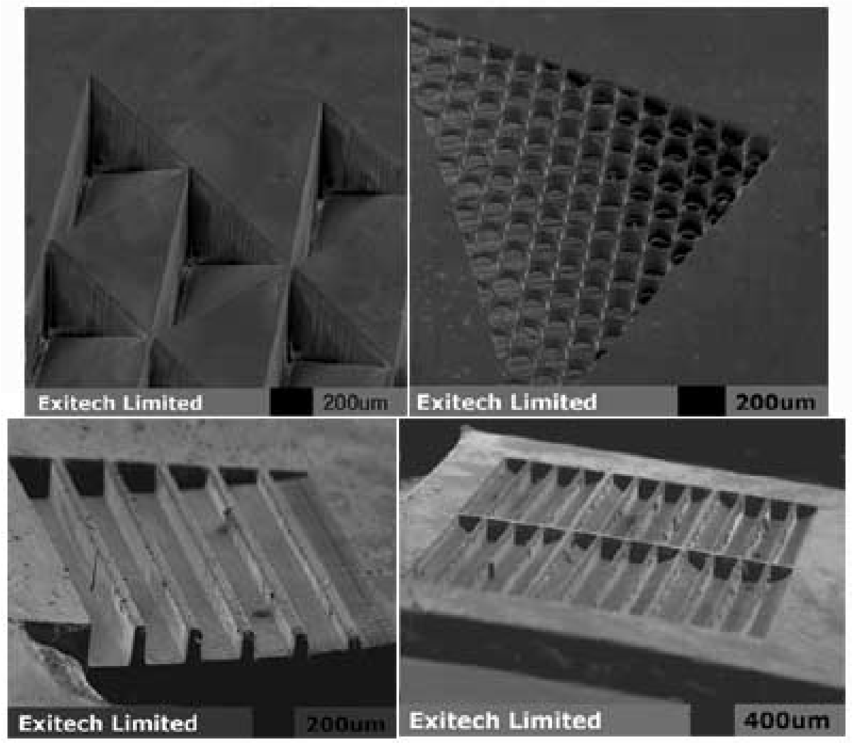

Figure 11. Micro-structures produced in polymer using synchronised overlay scanning

4. SUMMARY

Laser micro-engineering techniques which have been developed for excimer laser micro-machining systems have been detailed to provide an overview of the current state-of-the-art of this rapidly-expanding field. The production of a variety of micro-structures has been outlined together with relevant applications.

5. ACKNOWLEDGEMENTS

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