# MICRO-ENGINEERING APPLICATIONS OF PULSED LASERS

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## INTRODUCTION

Lasers are currently being used world-wide in a wide variety of applications. This upsurge in the use of laser systems is constantly being fuelled not only by the increase in the performance of the lasers themselves but also by the rapid developments in microprocessing techniques which are taking place. In particular, many pulsed lasers have become the lasers of choice in the manufacture of numerous microsystems technology (MST) devices.

This paper reviews some of the micro-processing techniques which have been developed recently for micro-engineering and highlights various laser-based micro-engineering applications.

## LASER MICROPROCESSING TECHNIQUES

The choice of laser or the technique by which a particular application is accomplished is usually determined by the exact details of the application. In general, the most important parameters to consider when choosing a laser micro-processing route are:

- Material
  *This largely determines the laser which can be used since most laser applications are fundamentally reliant on absorption of the laser light by the sample material.*
- Features
  *Whether exposure, surface modification, ablation etc. and 2D or 3D – these impact on the processing approach undertaken.*
- Resolution
  *The required minimum feature sizes govern the choice of laser, the processing technique and the optical system which are used.*
- Size
  *The area of the samples to be processed is a large factor in the system design.*
- Speed
  *Normally, economic constraints also decide if a particular laser approach is feasible and the most important criterion is the time taken per unit sample.*

Bearing the above factors in mind, a processing method also has to be chosen and this can fall into two basic categories: *focussing* or *projection*. Beam focussing relies on directly focussing the laser beam at the sample and using the focussed light to micro-structure the sample. In contrast, projection techniques use the laser beam to illuminate an object (usually a mask of some kind) which is then imaged, or projected, onto the sample to perform the micro-processing. These fundamentally different approaches are currently both used in industrial applications world-wide but care has to be taken to utilise each method appropriately.

### Direct Writing

The beam focussing technique is often called “direct writing” or “serial scribing” (as shown in figure 1) since the laser beam is focussed to a small spot to define the feature dimension and then directed over the sample to machine the desired structure.

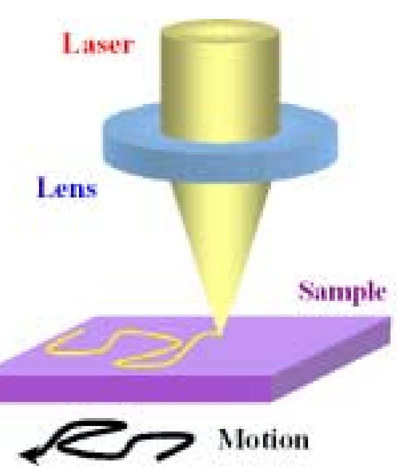


*Figure 1. Schematic diagram of a laser direct write system for micro-machining applications.*

Direct writing is widely used with many solid-state lasers (such as Nd:YAG) or with carbon dioxide lasers. The fundamental reason why this technique works well with these lasers is that they generally exhibit a very good beam profile and that the beam propagates in a well-defined Gaussian mode with low divergence. This enables the beam to be focussed to a small, well-defined spot. A typical beam profile from a Nd:YAG laser is shown in figure 2 together with a beam profile from a standard excimer laser.

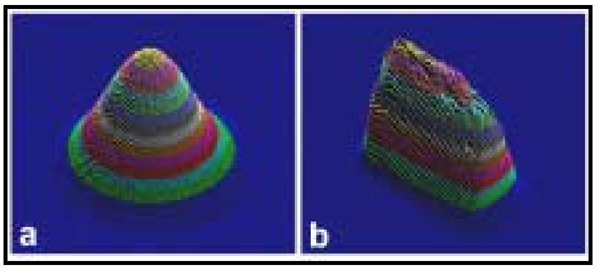


*Figure 2. Typical beam profiles showing differences in mode structure from (a) Nd:YAG laser (b) excimer laser.*

One of the main advantages of direct write systems is that they offer great flexibility in the structures they can be used to produce. The majority of direct write systems maintain a fixed beam position with the sample being moved by using XYZ tables and so the features to be produced can be simply controlled by the motion of the sample. This can easily be accomplished by CAD data input to the system to define the pattern to be machined. Hence, the same system can be used to machine any structure so as long as the sample can be moved appropriately.

One extension of direct writing is the technique of beam scanning. In this case, the laser beam is moved rapidly over a small sample area by galvanometer XY scanning mirrors and the control of the scanning mirrors determines the features to be produced.

The scanner mirrors can be controlled by CAD data files in the same way as the sample tables in direct writing. The principle of beam scanning is shown in figure 3. Specially-designed “flat field” lenses are used in beam scanning systems and these lenses, as their name suggests, have flat image fields to allow the beam to be scanned over an area while maintaining a good beam focus. Lenses with scan field sizes of many tens of millimetres are commonly available.

Direct writing or beam scanning, or combinations of both, are used widely in industry where cutting, drilling or profiling operations need to be performed.

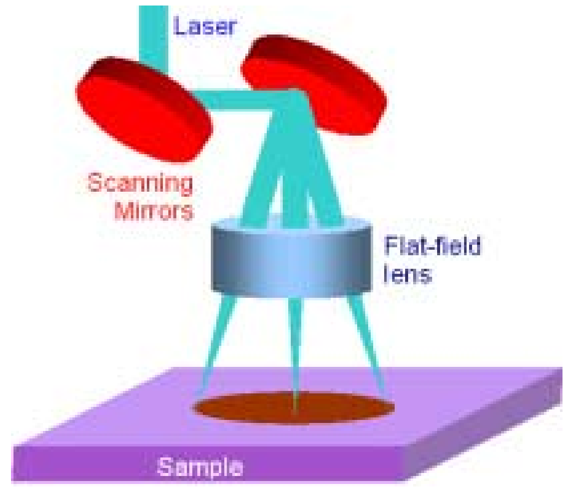


*Figure 3. Schematic diagram of beam scanning technique where galvanometer-driven mirrors deflect the laser beam to the desired locations for micromachining.*

One of the most common applications or direct writing is the drilling of micro-via holes for applications such as PCB boards or micro-circuit devices. If the hole to be drilled is larger in diameter than the size of the focussed beam (as is usually the case), then the sample can be trepanned around the beam to define the circumference of the hole and therefore to drill it out. Since the drilling of metallic layers in PCB boards can be efficiently carried out by Nd:YAG lasers, the hole trepanning can be performed very rapidly as Nd:YAG lasers can operate at pulse repetition rates of many tens of kilohertz. Figure 4 shows a hole drilled into copper by trepanning using a Nd:YAG laser where direct writing has been used.

Rapid processing is possible using direct writing since the high repetition rate lasers enable very high machining speeds. These speeds are still not fast enough for some areas, however, and direct writing can to be combined with beam scanning to reduce the processing time further. This is achieved by processing an area covered by the scan field and then stepping the sample laterally by using XY tables. Adjacent fields of the scanning mirrors have to be joined or "stitched" together to form the complete pattern. The ultra-high speed scanner processing, albeit in a restricted area, coupled with the large sample area provided by the XY tables means that large numbers samples can be processed in a very short time.

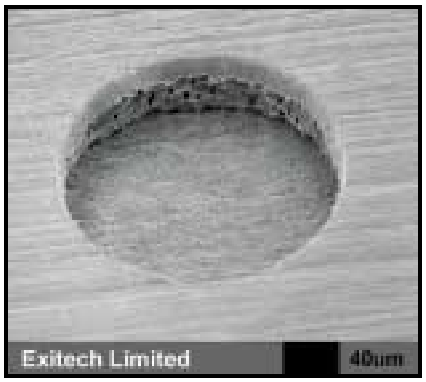


*Figure 4. Hole trepanned into top copper layer using a Nd:YAG laser. Also visible is a central polymer layer which has been machined with a $CO_2$ laser and the base copper layer which is undamaged.*

Applications of direct writing include areas as diverse as the cutting of automotive panels, the scribing of solar panels and the marking of electronic components.

Beam scanning is usually only combined with direct write systems where discrete scan fields are feasible, i.e. where separate scan fields can be stitched together, such as in PCB boards where individual hole positions can be easily defined in each scan field. Systems are now available [1] however, where the discrete nature of this approach does not have to applied and where a continuous pattern can be micromachined using combinations of scanning and XY motion. This new development should allow the speeds associated with beam scanning to still be maintained but with the added advantage that virtually any pattern (whether regular, repeating, irregular or continuous) can be machined into the sample at high speeds. This should find application in areas such as the production of display panels, micro-via drilling and circuit patterning and profiling.

**Mask Projection**

If the application requires the use of an excimer laser, then it may not be advantageous or even possible to use direct write methods. As shown in figure 2, the beam profile from standard excimer lasers does not lend itself easily to direct writing but the multi-mode nature of the excimer laser output does mean that it is a very good source for mask projection systems. Hence, the vast majority of MST applications of excimer lasers use mask projection methods.

The basic concept of mask projection [2] is shown in figure 5. The laser beam from an excimer laser is shaped and homogenised to make the energy distribution uniform to within around ±5%.

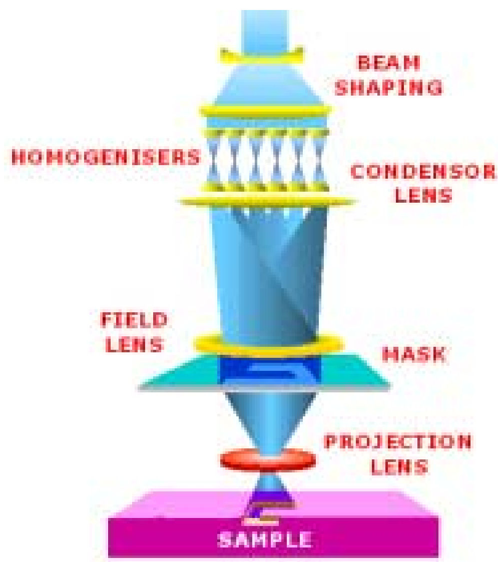


*Figure 5. Schematic diagram excimer laser mask projection system.*

The plane of uniformity of this beam is then made coincident with the plane in which a mask is positioned. This mask is usually either made from metal or from chrome-on-quartz.

The mask is imaged, or projected, onto the sample by a high resolution lens which also de-magnifies the mask pattern. The mask is normally held on XY positioning tables and the sample can also be moved by in four axes (XYZθ) but the laser beam is normally kept fixed in position.

One of the main advantages of mask projection is that the mask and workpiece can be moved independently of each other and this allows great flexibility in the range and types of features which can be micro-machined.

Mask projection systems can be used in the following ways to produce a variety of micro-structures [3]:

- Mask and workpiece stationary
  This is most commonly used for step-and-repeat processing where a single feature, e.g. a hole, needs to be produced repeatedly at different sample sites. The beam area at the mask can illuminate many shapes at the same time and all of these can be machined at the same time on the sample and then the entire pattern stepped and repeated. It should also be noted that where a small aperture is used as the mask and this is then imaged onto the sample, this technique resembles direct writing since this projected shape mimics a focussed laser beam.

  Applications areas include PCB via hole drilling, printer nozzles and cutting.

- Moving mask
  This allows ramped and contoured structures to be produced by control of the mask position during laser firing.

  Applications include micro-fluidic systems and 3D micro-machining.

- Moving workpiece
  This can be used to produce slots or micro-channels in the sample. A fixed shape at the mask defines the cross-section of the channel and the sample is moved to produce the structure with a defined path. Straight, curved or arbitrarily-contoured channels can be produced.

  Application areas include micro-fluidic systems and biomedical devices.

- Synchronised scanning
  Any large, non-repeating pattern can be transferred to the sample by scanning both the mask and sample under the laser beam in synchronism. In this manner, high resolution patterns can be produced over large areas.

  Applications include large area circuit patterning and printing.

- Synchronised overlay scanning
  An additional aperture aswell as a mask is used in the projection system. This imparts varying depth information on the sample and adds dimensionality to the micro-structure. It is usually used with synchronised scanning but can also be applied to the other mask and workpiece moving techniques to produce multi-dimensional features.

Figures 6-10 show examples of structures produced by each of the mask projection techniques described above.

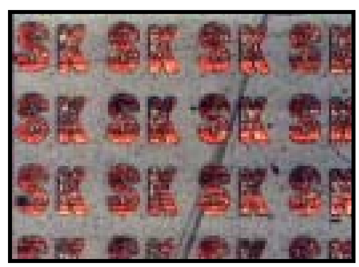

*Figure 6. Polymer layer on copper selectively removed by laser ablation. The 120μm high "SK" characters are produced by step-and-repeat processing.*

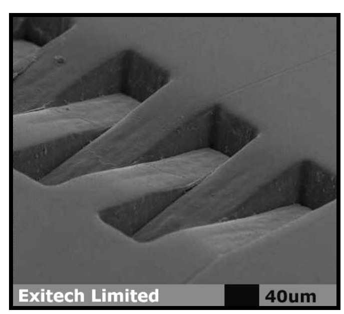


*Figure 7. Multiple ramp structures produced in polymer by moving mask technique. The ramps of one direction are produced at the same time followed by the ramps of the other direction.*

It should be noted that the same system can be used to produce all these features, highlighting the great flexibility of mask projection techniques.


*Figure 6. Curved micro-channels produced in polymer by moving the workpiece during laser firing. The shaped cross-section is determined by the mask while the sample motion defines the path of the channels.*

*Figure 9. Pattern produced by synchronised scanning where a metal-coated polymer sample has been selectively de-metallised by the projection of a complex mask pattern onto the sample.*

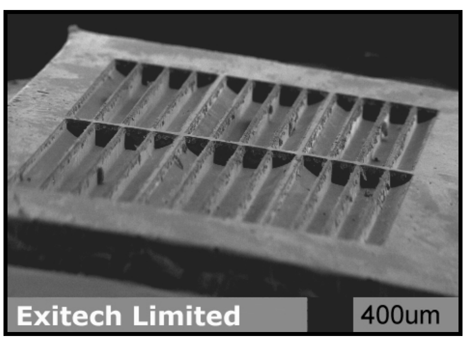


*Figure10. Microchannels produced inside curved wells by synchronised overlay scanning.*

The techniques described above are available in industrial, production-worthy laser tools and enable many high specification processing jobs to be accomplished. The following section highlights some applications of laser micro-engineering where these techniques are being applied and which are at the forefront of laser-based micro-engineering applications.

## INDUSTRIAL APPLICATIONS OF LASERS

### Annealing of Display Panels

Flat-panel displays (FPDs) are in great demand for a wide variety of imaging and display applications ranging from small viewfinders in video cameras to giant screens for advertising and television systems.

The crucial element in modern FPDs is the thin film transistor (TFT) which switches and controls the light transmission properties of each pixel in the display. The TFT requires a high carrier mobility, amongst other attributes, to be able to generate high switching speeds but the method of manufacture of the thin silicon films (usually a form of chemical vapour deposition) yields amorphous silicon. This has a relatively low carrier mobility. To increase the mobility and therefore increase the switching speed of the TFT, the *a*-silicon can be annealed – the process whereby the silicon is melted and then recrystallised to from poly-crystalline silicon.

Thermal annealing requires the panel with the thin film to be heated to temperatures of the order of ~1000°C in an oven and substrates such as borosilicate glass tend to deform. Materials like quartz or high-temperature glasses can withstand the heating cycle but are much more expensive. Thermal annealing can increase the mobility by factors of about 30 or so as compared to that of untreated *a*-silicon.

Excimer laser annealing does not significantly heat the panel substrate and so offers an attractive low-cost option for TFT production since cheap glass substrates can be used.

The UV excimer laser light is fully absorbed in the thin films and the heat-affected zone is also very small (~100nm). Usually, either 248nm or 308nm excimer lasers are used for annealing and typical single pulse energy densities of ~200mJ/cm$^2$ can produce mobility increases of more than two orders of magnitude over the *a*-silicon values.

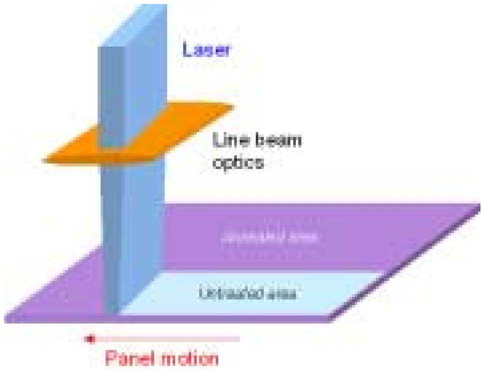


*Figure 11. Excimer laser annealing where the panel is moved in a raster fashion across a line beam.*

In practical systems, as depicted in figure 11, the excimer laser beam is shaped to be in the form of a line beam which may be 200-300mm in length and tens or hundreds of microns in width. This panel is then traversed across this beam in a XY raster scan, enabling panels as large as 500mm x 500mm to be annealed. Since the carrier mobility is critically dependent on the crystallisation process, extreme care has to be taken in maintaining a uniform beam energy distribution across the entire area of the laser beam and the processing has to be very tightly controlled in order for the sample to receive a uniform total dose per unit area over the entire panel.

Excimer laser annealing is already used in the full production environments and offers a far greater yield than thermal annealing together with other economic and technical benefits.

### Drilling of Nozzles

The production of micro-holes is a key micro-machining process in a multitude of industries including the manufacture of ink-jet printers, micro-fluidic systems, multi-level sensors or medical devices. As already described, hole drilling can be achieved by direct writing or by mask projection methods.

The majority of ink-jet printers produced in the world at present contain excimer laser-drilled nozzle holes and these are made using mask projection techniques.

The standard resolution of 600dpi (dots per inch) means that each nozzle plate has to have holes of ~28µm diameter and although this is sometimes achievable by other techniques such as electroforming, the yield is so low with these other processes that laser drilling is now the only economical option. Excimer laser drilling of nozzles produces production yields of >99% so not only can reliable and reproducible devices be made [4] but they can still be improved further as laser machining is not at its limits in this application.

Different designs of printers have varying types of holes – dimensions, shapes, additional features, special material effects etc. can all differ but all can be incorporated into the nozzle designs and produced by laser micromachining. Figure 12 shows two types of printer nozzle structures machined using excimer laser projection techniques.

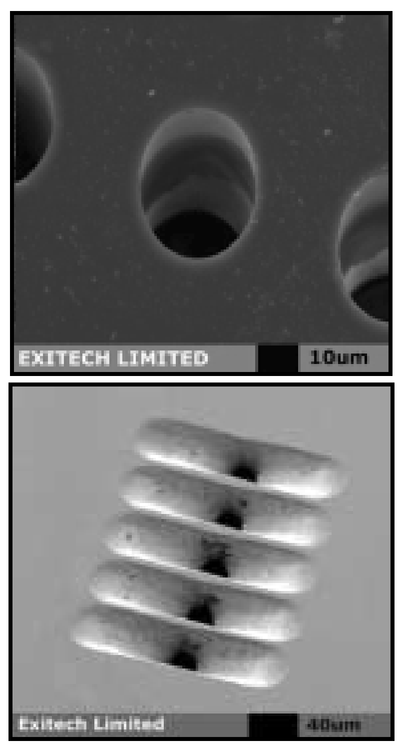


*Figure 12. Nozzle holes in polyimide made with excimer lasers*

Other devices such as micro-fluidic mixers and separators or bio-medical products can also require holes. In these areas, materials such as silicon, ceramics or piezoelectric materials are of interest as well as polymers.

Depending on the exact nature of the application, the holes may need to have some form a taper or be incorporated into other functions of a device. Excimer laser mask projection can again be used effectively to produce these multi-functional devices incorporating such holes. Figures 13 and 14 show an example of a tapered hole and of an array of holes inside a fluid reservoir, respectively.

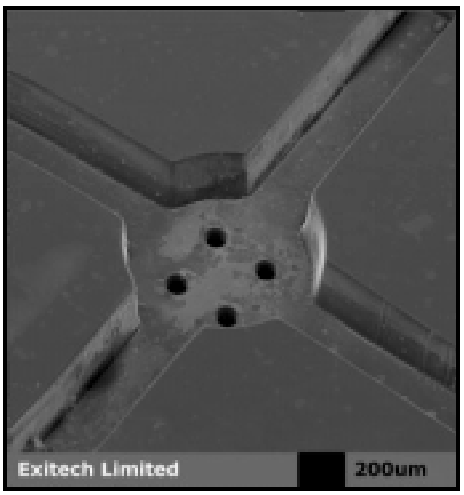


*Figure 13. Micro-holes drilled into polymer reservoir for a micro-fluidic device.*

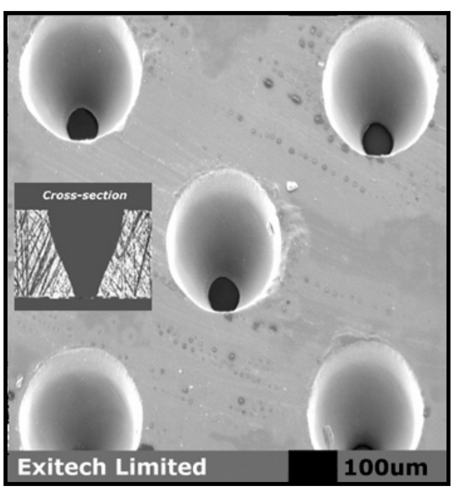


*Figure 14. Tapered holes produced by excimer laser mask projection with sample motion. A cross-section of the holes is shown in the inset.*

**Production of Micro-Optical-Electro-Mechanical Systems (MOEMS)**

Many devices are now being produced or designed which bring together multi-functional elements on a single chip or discrete element. These devices aim to integrate mechanical, optical and electrical processes on a miniature scale and so are generically known as micro-optical-electrical-mechanical systems, or MOEMS.

The main advantage that laser processing has over other “conventional” techniques such as mechanical machining or chemical etching is that laser systems can produce very small, high resolution structures in many materials and combine different types of structures on compact single substrates. In this way, laser micro-engineering is likely to be the key enabling technology in many areas which require some or all of MOEMS functions.

There is much interest in the production of micro-structures which have more than two dimensions and excimer laser projection systems allow these avenues to be explored. Examples of such structures are shown below.

Figure 15 shows an array of square pyramids machined using workpiece motion.

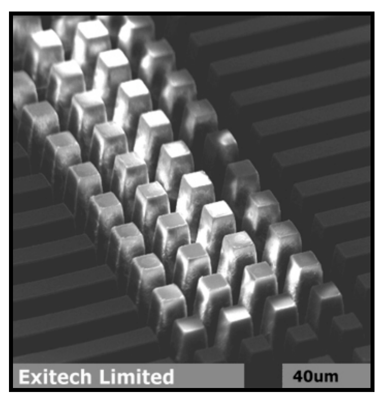


*Figure 15. Micro-optical structures produced by excimer laser mask projection and workpiece motion technique.*

These types of structures are used in many optical applications where they control or enhance various properties of light, e.g. acting as anti-reflection structures for incoming light.

Figure 16 shows a type of structure which can be incorporated into chemical and biomedical systems where fluidic interchanges can be monitored and controlled. Such structures can be used to effect the passage of a fluid from one level to another, where each level may serve a particular purpose such as micro-reaction, micro-mixing or micro-separation.

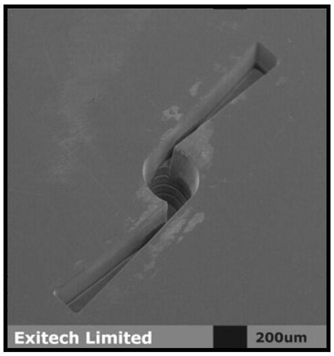


*Figure 16. Micro-fluidic device incorporating multi-level excimer laser micro-machined structures.*

## FUTURE TRENDS

In terms of lasers, much rapid progress is currently being made with various solid-state lasers on diode-pumping, high repetition rate operation and wavelength accessibility. This should enable the laser applications to benefit from compact, efficient, reliable, low-maintenance and cheap sources of laser light which run at ultra-high repetition rates and can cover the desired spectral regions. These sources should enable many more applications and industries to benefit from the advantages offered by laser micro-processing.

Another aspect of laser systems which will play a major role in future laser-produced micro-products is that of pulse duration. Current ultra-short pulse lasers (where pulse duration is in the region of picoseconds or femtoseconds) are already being used for micro-machining applications and there appear to be significant benefits in using such short pulses as compared to the conventional regime of nanosecond-millisecond pulses. Much work has already been performed to address the various issues of ultra-short pulse micromachining.

Laser processing techniques are constantly being developed and improved and these developments are partly the result of new user needs or the lack of conventional alternatives. Areas of interest which will continue to be developed in the future include that of laser processing with chemical fluid assistance and the production of fully three-dimensional, free-standing micro-parts. Many strands of MST should benefit from these advances.

## SUMMARY

Some of the most important techniques used in laser micro-engineering have been described. In particular, detailed descriptions of excimer laser mask projection systems have been presented together with novel advances in the production of multi-dimensional structures. State-of-the-art industrial applications of these techniques have been outlined where the particular advantages of laser micro-processing are not only producing modern, competitive micro-products but also guiding these fields into exciting new areas.

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