

# Laser micromachining of optical biochips

Andrew D. Goater<sup>2,1</sup>, Julian P.H. Burt<sup>1,2</sup>, David J. Morris<sup>1</sup>, Anoop Menachery<sup>1</sup>, Nadeem H. Rizvi<sup>2</sup>,  
Daniel R. Matthews<sup>3</sup>, Huw D. Summers<sup>3</sup>

<sup>1</sup>School of Electronic Engineering, University of Wales, Bangor,  
Dean Street, Bangor, Gwynedd LL57 1UT, United Kingdom

<sup>2</sup>UK Laser Micromachining Centre, Dean Street, Bangor, Gwynedd LL57 1UT, United Kingdom

<sup>3</sup>School of Physics and Astronomy, Cardiff University,  
The Parade, Cardiff CF24 3YB, United Kingdom

## ABSTRACT

Optical biochips may incorporate both optical and microfluidic components as well as integrated light emitting semiconductor devices. They make use of a wide range of materials including polymers, glasses and thin metal films which are particularly suitable if low cost devices are envisaged. Precision laser micromachining is an ideal flexible manufacturing technique for such materials with the ability to fabricate structures to sub-micron resolutions and a proven track record in manufacturing scale up.

Described here is the manufacture of a range of optical biochip devices and components using laser micromachining techniques. The devices employ both microfluidics and electrokinetic processes for biological cell manipulation and characterization. Excimer laser micromachining has been used to create complex microelectrode arrays and microfluidic channels. Excimer lasers have also been employed to create on-chip optical components such as microlenses and waveguides to allow integrated vertical and edge emitting LEDs and lasers to deliver light to analysis sites within the biochips.

Ultra short pulse lasers have been used to structure wafer level semiconductor light emitting devices. Both surface patterning and bulk machining of these active wafers while maintaining functionality has been demonstrated. Described here is the use of combinations of ultra short pulse and excimer lasers for the fabrication of structures to provide ring illumination of in-wafer reaction chambers.

The laser micromachining processes employed in this work require minimal post-processing and so make them ideally suited to all stages of optical biochip production from development through to small and large volume production.

Keywords: Laser Micromachining, Optical Biochip, Excimer, Electrokinetics, Femtosecond, Ultra Short Pulse.

## 1 INTRODUCTION

Biochips bring together the accuracy and flexibility of microfabrication processes and biological or chemical assays to create an integrated environment for biotechnological processing. The potential of biochip technology extends over a wide range of market sectors dominated by the benefits in healthcare and drug discovery but also including sectors such as food and environmental monitoring and analysis. Optical biochips extend the fundamental biochip concept to include optical principles either as part of a monitoring process such as absorbance or fluorescence measurement or as an essential part of a reaction chain or assay such as in photosynthesis and similar processes. Optical biochips can make use of either external or integrated light sources and detectors but typically contain integrated optical delivery components such as light or waveguides, reflectors and lenses. While there are many examples of optical integration within biochip devices, the development challenges in optical biochips are moving towards the integration of optical systems typically associated with complex optical bench configurations and high costs. To meet such challenges advances in biotechnology for assay formatting, physics and electronics for semiconductor laser development and microfabrication are required.

While many of the components of optical biochips can be manufactured using surface and bulk micromachining processes of varying formats, there is a growing necessity to create optical biochips that are easy to mass produce and hence of low cost and, for use in biomedical applications, able to be disposable. Such demands place significant restrictions on the range of materials and manufacturing processes that can be used to produce optical biochips. Typically, it is desirable to produce devices entirely from polymers. However, the need for mechanical stability often requires the use of glasses and other substrates. Additionally, if integrated sources and detectors are to be used, polymer processing must integrate with embedded semiconductor materials and associated electrical connections. This often gives rise to issues of thermal compatibility. In this work the use of laser micromachining to produce a range of optical biochip components is described.

## 2 LASER MICROMACHINING

Laser micromachining as a manufacturing technique, has emerged from the development of micro and nanotechnologies over the past two decades. While laser micromachining is still considered a new process in many areas of microengineering, it has become an established manufacturing method in niche application areas such as inkjet printer nozzle drilling [1] and flat panel display patterning [2]. Accurate laser micromachining tends to use pulsed lasers at wavelengths where heating and melting-based surface disruption is minimal. By controlling the number of laser pulses, and hence the total incident radiation, precise machining depths can be achieved while minimal thermal distortion occurs at the edge of the exposed region. In this work laser micromachining using nanosecond pulsed, ultra-violet (248nm) KrF excimer and femtocond pulsed infrared (800nm) Ti:Sapphire lasers have been used to create a range of optical biochip components and were configured to produce microstructures using either a direct write or a mask projection machining process.

### 3.1. Direct write

Direct write laser micromachining, as illustrated in figure 1a, makes use of a laser beam tightly focused to a small spot which is moved over the surface of the workpiece during machining. Typically direct write machining uses a laser with a Gaussian beam profile. Good beam quality and a low  $M^2$  factor allow the beam to be focused to a small spot using simple optical components and to give a beam fluence at focus that is above the ablation threshold of the workpiece material. Control of the beam movement over the surface of the workpiece allows arbitrary 2D patterns to be machined. By overlaying machining runs it is also possible to create 3D structures. Machining depth control during workpiece movement is achieved by synchronizing laser pulse or power output with workpiece stage position. The direct write machining system used in this work was an Exitech M2000F Laser Micromachining Workstation (Exitech Ltd., UK) incorporating a Spectra Physics Hurricane Ti:Sapphire laser with a pulse duration of 120fs and a beam power density of up to  $3.5\text{Wcm}^{-2}$ . In this system beam delivery components allowed CNC control of beam power density and focusing. Typically the beam was focused to a  $20\mu\text{m}$  spot delivering power densities of up to  $0.3\text{MWcm}^{-2}$ . The workpiece was held on a micropositioning stage with  $1\mu\text{m}$  resolution (Aerotech Inc., USA). Movement of the workpiece and beam on/off control was through a PC based motion controller (Unidex 500, Aerotech Inc. USA).

### 3.2. Mask projection

Mask projection laser micromachining, as illustrated in figure 1b, uses a large area uniform intensity laser beam at a mask plane. The mask pattern is subsequently imaged onto the workpiece using a projection lens. Typically the projection lens will provide some form of demagnification to allow a low fluence beam at the mask plane and a smaller, high fluence, beam at the workpiece. Large area multi mode beams are often used for mask projection laser micromachining. Homogenizing optics are used to produce a uniform intensity over the beam area. Large area mask pattern transfer can be achieved by the synchronized movement of both the mask and workpiece using micropositioning stages. As with direct write laser micromachining, machining depth control during pattern transfer is achieved by synchronizing laser pulse output with mask or workpiece position. In this work an Exitech S8000 Laser Micromachining Workstation (Exitech Ltd., UK) was used for mask projection machining. This system incorporates a Lambda Physik Compex 110 excimer laser configurable for operation at either 248nm or 193nm and beam delivery components allowing beam shaping and homogenization to produce a uniform intensity  $10\text{mm} \times 10\text{mm}$  beam at the

mask plane. Using a 0.1NA projection lens with a demagnification of  $\times 10$  a 1 mm  $\times$  1 mm image of the mask plane was created at the workpiece. Micropositioning stages (Aerotech Inc., USA) were used to control the position of both the mask and workpiece while beam fluence was controlled using a motorized (Aerotech Inc. USA) attenuator based on contra rotating dielectric coated quartz plates.

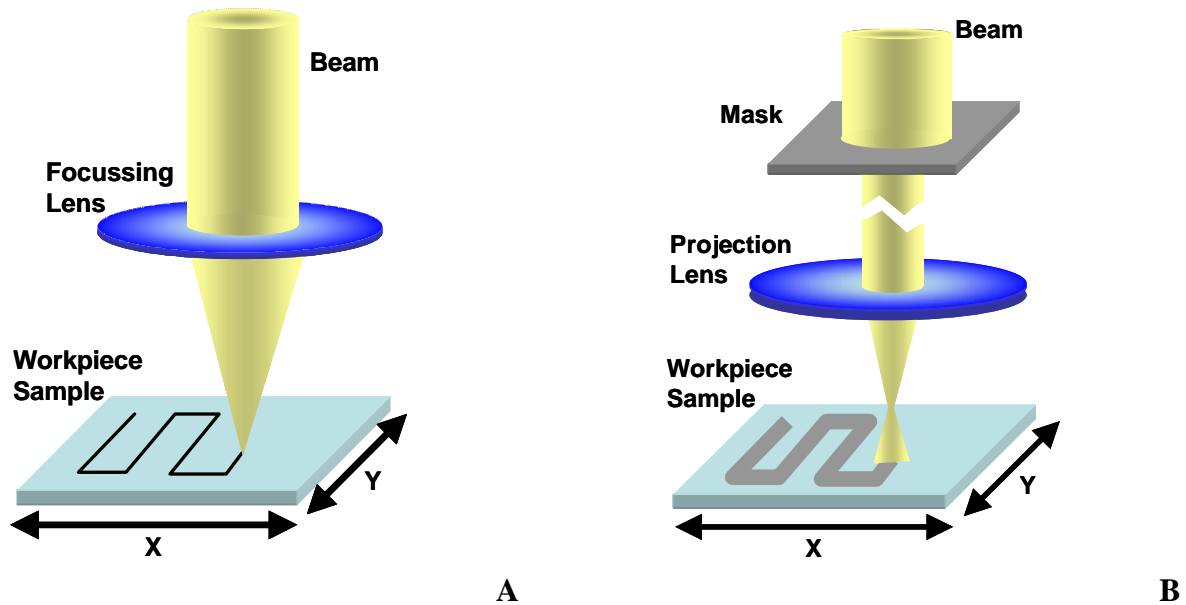


Fig. 1 (A) Illustration of direct write laser micromachining. (B) Illustration of mask projection laser micromachining.

### 3 OPTICAL BIOCHIPS

Figure 2 shows a conceptual diagram of a simple optical biochip device for the analysis and subsequent separation of a mixed population of biological cells. The diagram divides the key processing steps into unit block. Several different technologies can be used in each block. For instance, in this work, the particle direction switch on the main inlet channel is an electrokinetic module which uses microelectrode generated electric fields to direct cells within the sample along either outlet branch. However, such direction switching could be implemented using mechanical valves, additional fluid flows or even magnetic fields if the cells are labeled with magnetic beads. The device outlined in figure 2 analyses a mixed population of cells which are introduced through the inlet channel. Cells are focused into a narrow stream at a defined lateral position within the channel. This stream corresponds to the optimum position of a sensor which detects a specified sub population of the cells entering the device. Knowledge of the cell velocity allows the switching unit to direct cells within the detected sub population along one outlet branch while other cells are directed along the second outlet branch. Within these branches, secondary sensing units can undertake further analysis of the cell population while corralling chambers can be used to collect and hold further sub populations identified in the secondary sensing processes.

#### 3.1. Microelectrodes

Microelectrodes are increasingly used in biochips for sensing and actuation. Electrokinetic actuation employs a range of typically AC electric fields to induce a force, and hence motion, on particles suspended in a sample medium [3,4]. The simplest AC electrokinetic principle is dielectrophoresis where particles exposed to a non-uniform AC electric field experience a force either towards or away from the regions of highest field intensity. The speed and direction of motion is a function of the dielectric properties of the cell and suspending medium, the electric field geometry and the magnitude and frequency of the electric field. In the concept optical biochip shown in figure 2 the particle focusing and particle switch units use negative dielectrophoretic forces, which push cells away from regions of high field intensity, to

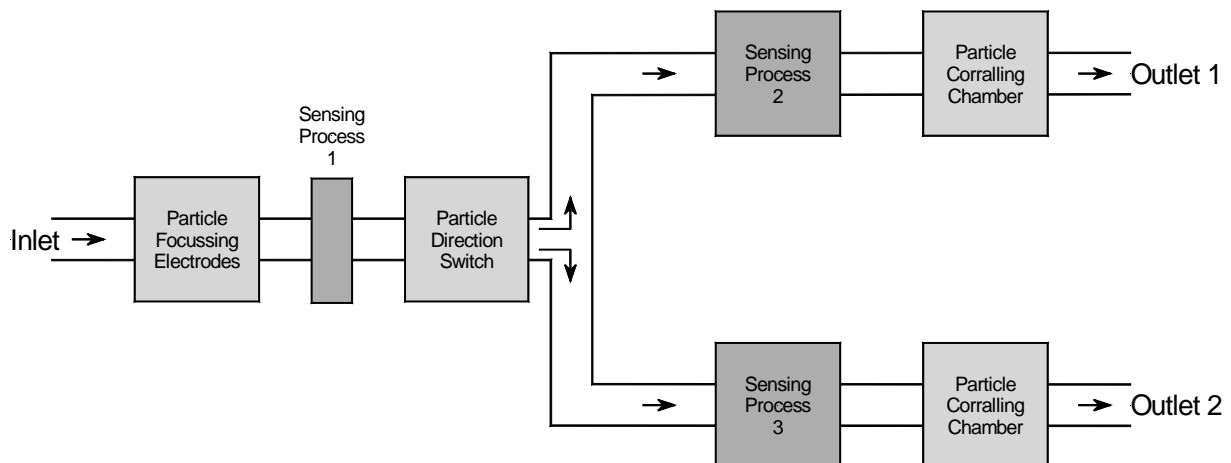


Fig. 2 Conceptual diagram of a simple optical biochip for biological cell analysis and subsequent separation

direct cells. A second electrokinetic process is that of electrorotation. Here electrodes are typically arranged in a quadrature geometry and energized with quadrature sinusoidal voltages to provide a uniform rotating electric field. In this case, cells experience an electric field induced torque. As with dielectrophoresis, the direction and magnitude of the subsequent particle rotation is a function of the dielectric properties of the cell and medium along with the electrode geometry and electric field magnitude and frequency. Electrorotation is a sensitive technique capable of detecting physico-chemical changes within cells. In the conceptual optical biochip it is used for secondary sensing as in sensing process 2.

The laser microfabrication of microelectrodes is a process of demetalizing a thin (typically  $<1\mu\text{m}$ ) metal film from a substrate [5]. Excimer lasers are particularly well suited for the production of microelectrodes. Figure 3a shows examples of particle focusing electrodes formed in a thin film of 100nm gold with a 5nm chrome adhesion layer on a glass substrate. Figure 3b shows transparent indium tin oxide (ITO) electrodes used for electrorotational sensing [6]. For electrokinetic applications, such electrodes should be fabricated to a high resolution with electrode edge smoothness a key quality measure since any significant roughness will generate localized dielectrophoretic forces. Typically the active

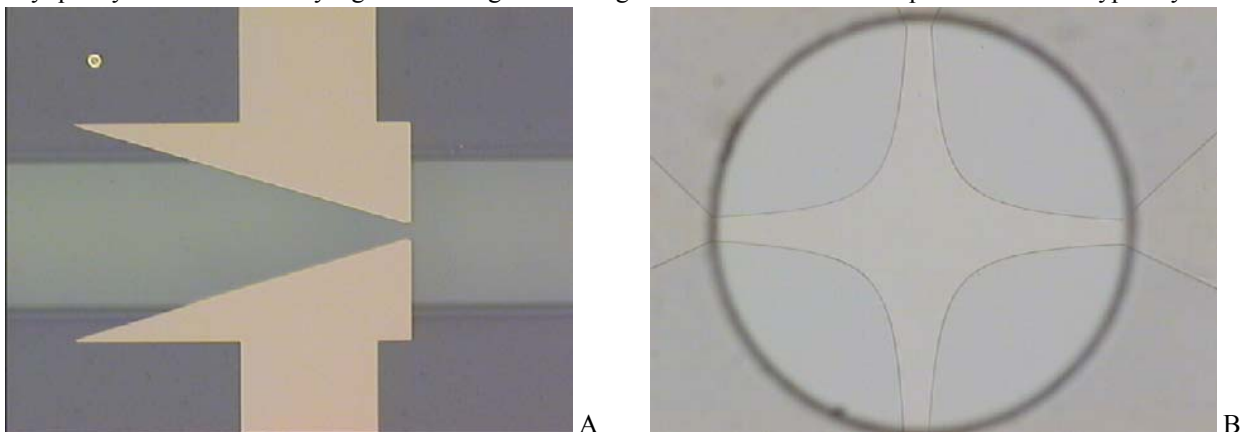


Fig. 3 Electrokinetic microelectrodes. (A) Particle focusing electrodes. The gold microelectrodes generate a negative dielectrophoretic force to concentrate cells into the stream along the centre of a microfluidic channel visible under the electrodes. (B) Indium tin oxide electrorotation electrodes on a glass substrate. Visible above the electrodes is the outline of a  $50\mu\text{m}$  thick polymer containment chamber to constrain cell to a defined volume above the electrode.

region of electrokinetic electrode arrays are fabricated using a mask projection based machining process. In this situation the electrode pattern is held on a mask to a suitable resolution and demagnified as it is projected onto the workpiece. The ablation process is achieved by the raster scanning of a large area beam over the mask so dynamically changing the geometry of the ablating beam and reducing pulse to pulse overlap errors that would occur from direct writing of patterns using an apertured beam. The requirement to remove significant areas of the thin film to produce inter-electrode regions is automatically achieved with zero machining time penalties whereas a direct write approach would take a substantially longer time. For creating metal microelectrodes such as those in figure 3a, single laser pulse metal removal at a wavelength of 248nm and fluence of  $200 \text{ mJ cm}^{-2}$  is used. The ablation of gold/chrome thin films from glass substrates can leave a slightly discolored surface due to chrome diffusing into the glass. To overcome this, microelectrodes have also been fabricated by the ablation of gold/chrome films from the surface of a polymer film spin coated over the glass substrate. In such cases a fluence of the order of  $100 \text{ mJ cm}^{-2}$  is used to remove the gold film by disrupting the underlying polymer surface. Should the optical quality of the glass substrate be required, the inter-electrode polymer can be cleanly removed by further machining at a fluence of  $100 \text{ mJ cm}^{-2}$  or greater. ITO films can be cleanly removed from glass substrates by single pulse excimer laser ablation. For the electrodes shown in figure 3b, ITO with a resistance of  $10\Omega/\text{Sq}$  was machined using a wavelength of 248nm and a fluence of  $1.5 \text{ J cm}^{-2}$ . Electron micrograph inspection of the edge roughness of mask projection machined microelectrodes revealed an overall edge roughness in the plane of the electrode of the order of 100nm whereas direct write laser micromachining produced an edge roughness of approximately  $2\mu\text{m}$  when measured over extended distances. This increased edge roughness is largely due pulse to pulse overlay errors when using a circular beam or small errors in the alignment of the edges of a square beam with the X and Y axes of the workpiece micropositioning stages. Figure 4 shows particle focusing electrodes and the direction switching electrodes of the conceptual optical biochip actively manipulating the flow of cells in a microchannel.

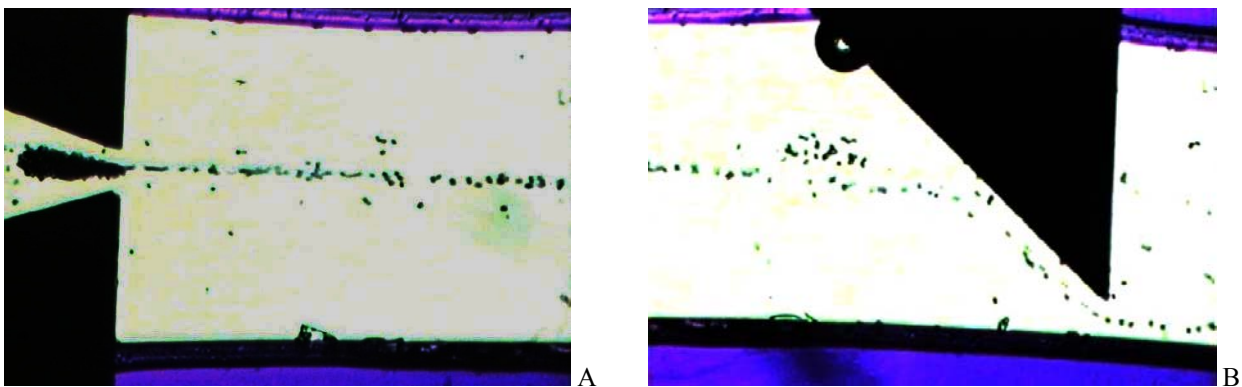


Fig. 4 Active control of cell movement using negative dielectrophoresis to (A) focus cells into a narrow stream along the centre of a microfluidic channel and (B) to switch cells to one side of a channel prior to a divide in the channel, and hence a division in the fluid flow.

### 3.2. Light Guides

Light guides, including waveguides, are important tools for the delivery and collection of light from optical sensing components. The particle direction switch in figure 2 relies on knowledge of the fluid flow within the channels to direct cells towards the correct outlet channel. However, detection of subpopulation cells within the channel must be synchronized with the energizing of the switch. Undertaking a cell measurement at a precise location upstream from the switch and combining this with fluid velocity profiles allows such synchronization to be achieved. In figure 2 this is shown as Sensing Process 1. The sensing process could be as simple as an optical absorbance or transmission measurement but may involve measurement of scattered light or fluorescence. Laser micromachining can be used to directly or indirectly manufacture light guide structures. For instance, excimer laser micromachining can be used for the direct patterning of thin transparent polymer films to form isolated light and wave guide structures. Such patterning can be achieved by ablation based machining or, with greatly attenuated beam fluence, by photo exposure of deep UV sensitive materials. Such structures are typically coated with a suitable cladding material that is also used to define other

structures such as microfluidic channels. Whilst the creation of light guide structures only requires the isolation of the guide itself from a continuous film, coating a substrate, it is often desirable to remove all unwanted guide material. This can be a time consuming process and it is often preferred to selectively deposit guide material only where it is to be used. Figure 5 shows a series of images showing the creation of molded light guide structures for guiding 650nm light from embedded semiconductor LED or laser chips and can illustrate both direct and indirect light guide manufacture. Figure 5a shows the directly excimer laser machined mold. In this case the mold material is a dry film laminate photoresist which has been laminated onto a glass substrate and then baked to form a hard, inert, film. Structures remaining in the mold will convert to indentations in the molded duplicate. Figure 5a shows a linear fluidic channel extending diagonally across the mold with two light guide structures orthogonal to the channel. One guide collects light from an embedded source a short distance from the channel and delivers it to the channel while the other collects transmitted light from the channel and delivers it to an embedded detector a similar distance away on the other side of the channel. The source and detector locations are shown by the dome structures in figure 5a. To allow efficient delivery and collection of light, the ends of the light guides have been shaped to form cylindrical lens structures which focus the light to a defined point within the channel. While figure 5a shows a mold for creating duplicate light guide devices, it also demonstrated that ability to create light guide structures directly. For instance, if the dry film laminate were replaced with an appropriate transparent material such as SU8 photo resist, excimer laser micromachining could be used to directly create the guide and lens structures. In the case of figure 5a, a direct write laser micromachining process was employed using a range of square and semicircular beam apertures to create the mold. The light guides in figure 5a are designed to operate as hollow guides with light transport guided by internal reflection from the guide walls. A suitable material to form such guides is the two part elastomer polydimethyl siloxane (PDMS). The structure in figure 5b is the cast PDMS duplicate of the mold in figure 5a. Both the channel and light guides are clearly visible. The dome structures translate to large indentations in the PDMS which house the wire bonded contacts for the embedded source and detector. Following oxygen plasma treatment, PDMS can form an irreversible bond with a glass substrate to form enclosed, sealed, channels and light guides. Figure 5c shows images of the active region of a PDMS hollow light guide from an excimer laser micromachined mold. 650nm light is delivered from the upper, vertical, guide, and focused by the lens structure at the end of the guide to a point within the channel. In the case of figure 5c, the focal point is close to the lower wall of the fluidic channel. Light is then collected by the lower guide and delivered to the embedded detector. The light path can be seen by the scattered light from each interface in the image.

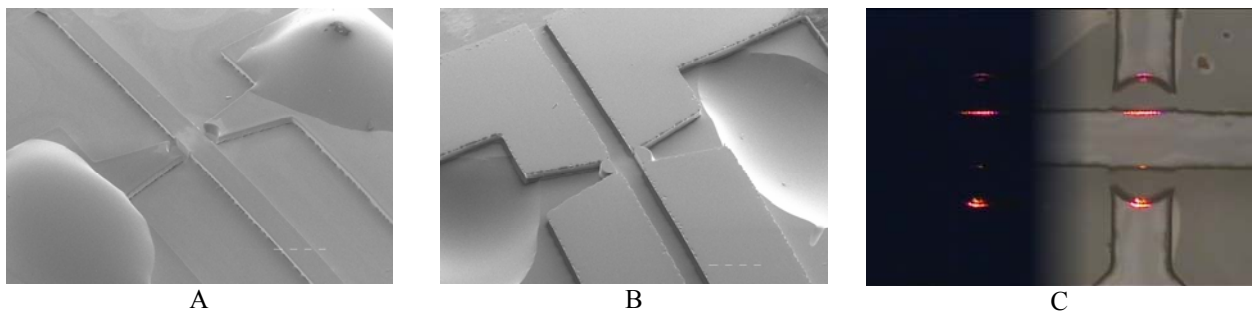


Fig. 5 (A) Hollow light guide mold and (B) polydimethyl siloxane (PDMS) cast duplicate. (C) dark and light field images of the hollow light guide in operation. Note the focusing of the light delivered by the upper, vertical, guide on the lower wall of the horizontal fluidic channel.

The mold shown in figure 5b could also be used to fabricate cored light guides by filling the mold with an appropriate guide material in a liquid form then holding the mold against a substrate and curing the core material while still in the mold. The flexible PDMS mold is then peeled off to reveal the solid light guide core. Excimer laser micromachining is a versatile tool for prototyping light guide structures. Direct write machining processes allow the rapid implementation of design iterations while more advanced machining processes allow variable depth and even 3D contoured guide structures to be produced [7].

### 3.3. Microlenses

Conventional optical components such as lenses, prisms and flat or curved mirrors can also be used within optical biochips for directing and focusing light. In many cases such components can be created using laser micromachining. Consider a wafer containing vertical emitting LED devices. Such devices have a typical beam divergence of the order of  $12^\circ$ . Therefore, the beam from a  $50\mu\text{m}$  LED aperture would be significantly larger than  $50\mu\text{m}$  after just  $100\mu\text{m}$  of travel. To allow such devices to be used effectively in optical biochips, beams can be collimated or coupled into light guides using laser micromachined microlens structures as shown in figure 6. Here a concave microlens structure has been machined into a polycarbonate substrate. This structure could be used as a lens itself. However, it is more common to use convex lenses in a material compatible with other fluidic systems. Figure 6b shows a section of an array of  $50\mu\text{m}$  diameter convex PDMS microlenses created by casting liquid PDMS over a concave structure similar to that of figure 6a.

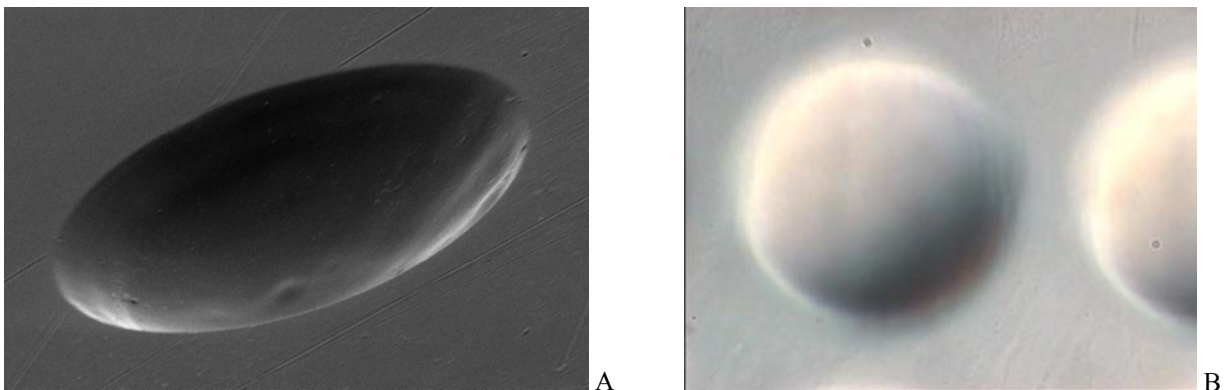


Fig. 6 (A) Electron micrograph of  $50\mu\text{m}$  diameter concave microlens structure in polycarbonate. The structure can be used as a stand alone lens or as a mold for lens duplication by casting. (B) PDMS cast  $50\mu\text{m}$  diameter convex microlenses taken from a concave master.

Microlenses can be produced using grayscale or halftone based laser micromachining [8]. However, such mask design is complex and the mask resolution can be a limiting factor on the size of the final structure. The lenses shown in figure 6 were created using an advanced form of mask projection-based excimer laser micromachining. In conventional mask projection machining extruded 2D structures are typically produced, where the extrusion distance is a function of the beam fluence and the number of incident laser pulses. In creating microlenses an overlaid mask projection process is used as illustrated in figure 7 where the stages of creating a concave microlens similar to that of figure 6a are shown.

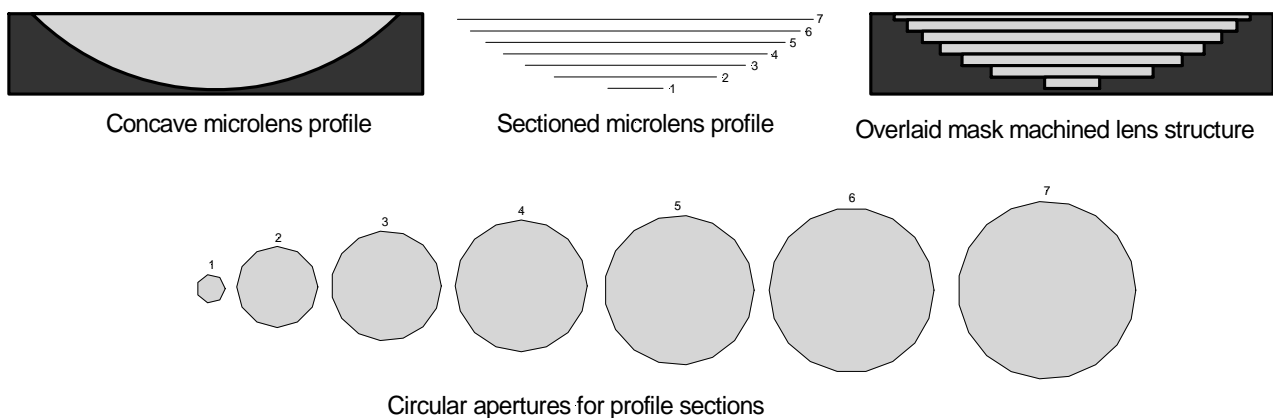


Fig. 7 Illustration of the laser micromachining of a microlens using an overlaid mask projection machining process

The overlaid mask process can be applied to most 3D shapes that do not have overhanging features. The starting point for the process is a 3D computer aided design drawing of the shape to be created. The next stage is to determine the vertical resolution of the final micromachined structure and slice the 3D drawing to obtain a series of 2D cross sectional drawings of the structure. These sections describe the outline of the structure at the given slice height and hence the machining profile at that height which, in turn, is the same as the mask outline for machining at that slice height. The sections are translated into mask patterns to create a sequence of masks describing the machining outline at each slice height. The masks are used sequentially in a conventional mask projection machining process to create the final 3D structure. The surface quality of the finished micromachined structure is generally determined by the depth of each slice and the order in which masks are used. For small structures such as individual lenses each mask can be used as an aperture within a static beam with a static workpiece. Larger area structures such as lens arrays may require synchronized mask and workpiece scanning with laser output triggering on mask or workpiece incremental position. In all cases alignment of each mask to previously machined structures is critical for accurate replication of the 3D CAD drawing structure. The microlenses shown in figure 6 used 20 masks to create the 9 $\mu\text{m}$  deep lenses. Processing of the CAD drawing was carried out using AlphaCAM (Licom Systems, UK).

### 3.4. Light wells

The accurate quantification of fluorescence can only be achieved if the exciting radiation is quantified and illumination is optimized. In the concept optical biochip, cells travel through a series of microfluidic channels. Cells could be positioned anywhere in the cross sectional area of the channel and, due to the laminar flow regime, may only move slightly from that position as they flow through the channel. Whereas the light guides described previously have the ability to deliver directional light to a defined point in the channel, optimally cells undergoing fluorescence measurements should be illuminated from all directions. This form of illumination can be achieved by integrating precisely patterned active semiconductor light emitting substrates into the fluid flow path. Using femtosecond laser micromachining it is possible to machine semiconductor diode and laser wafers in a manner that allows arbitrary shaped 2D light sources to be created.

The delivery of high energy laser pulses in time periods close to 100fs leads to an ionizing ablation process capable of cleanly removing only the region of the workpiece illuminated by the tightly focused laser beam. In the case of light emitting semiconductors where light emission occurs in a defined junction region typically located within 1.5 $\mu\text{m}$  of the surface of the wafer, the ionizing ablation process allows the junction to be cleanly machined without disturbing the illuminating nature of the junction. The lack of large physical debris from the machining process reduces the likelihood of the semiconductor junction being short circuited and the tightly focused beam restricts machining to a highly defined area or path. Figure 8a shows a series of cross-shaped light sources formed by machining the upper 10 $\mu\text{m}$  of a wafer. Figure 8b shows a laser machined circular source used to provide ring illumination to latex microbeads held in a laser micromachined well within the surface of the wafer.

The wafer used here is a commercially available semiconductor laser material (IQE plc, UK) The light emitting structure was grown by metallic organic vapor phase epitaxy (MOVPE) on a silicon doped  $\langle 100 \rangle$  n-type substrate misorientated at  $10^\circ$  to the  $\langle 111A \rangle$  plane. The light generating region consists of three undoped GaInP quantum wells surrounded with 0.2  $\mu\text{m}$   $(\text{Al}_{0.7}\text{Ga}_{0.3})_{0.51}\text{In}_{0.49}\text{P}$  barrier layers. When processed into laser devices the material nominally generates stimulated emission at 650nm. Using a solid state Ti:Sapphire femtosecond laser operating at 800nm and 5kHz, the wells were machined using a direct write machining process with a pulse fluence of 3.2  $\text{J cm}^{-2}$  at the wafer surface. Wells were formed by trepanning the final well diameter starting at the centre of the upper surface entrance circle. Control of the workpiece velocity was used to produce wells of different depths. A typical well 100 $\mu\text{m}$  deep and 100 $\mu\text{m}$  diameter took approximately 6 seconds to machine.

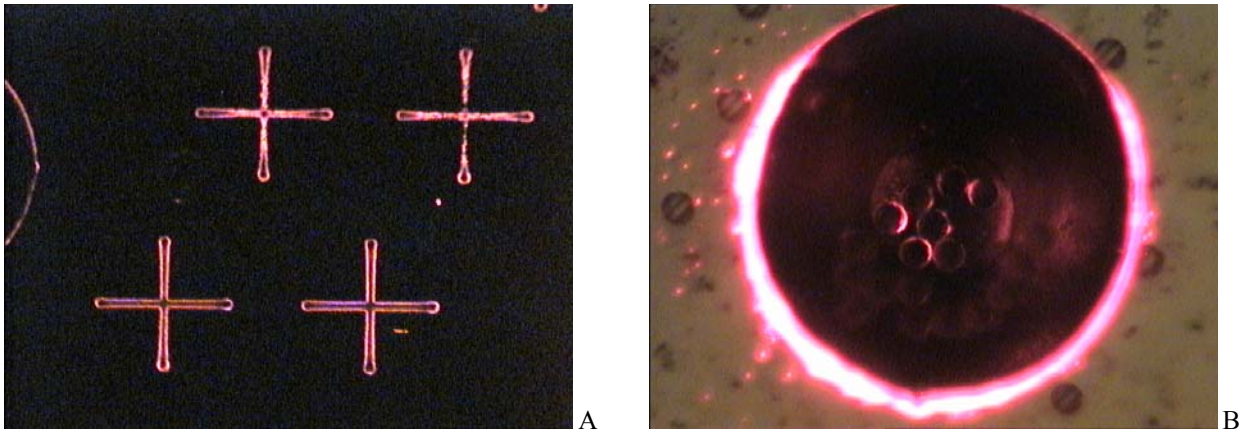


Fig. 8 Light wells created within the surface of a semiconductor laser wafer. (A) Cross-shaped illumination sources machined directly into the wafer. (B) Electrically isolated microfluidic in-chip wells with integrated ring illumination used to quantify latex microbeads.

To use the light well structures within an optical biochip, the exposed wafer junction must be electrically isolated from the biochip sample fluid to prevent short circuiting of the junction. Figure 9 illustrates the electrical isolation and integration of femtosecond laser micromachined light wells into the microfluidic channel system of an optical biochip. Light well wafers are first encapsulated by spin coating an SU-8 epoxy resist layer over the surface of the machined wafer to a thickness of typically 20 $\mu$ m. The SU-8 is blanket exposed using a mask aligner and baked to produce a hard, electrically insulating, film over the surface of the wafer. During the spin coating process the laser machined well structures become planarized. Electrically isolated light wells are reformed to a diameter less than that of the original well using an excimer laser at a wavelength of 248nm and a pulse fluence of 150 mJ cm<sup>-2</sup>. Using a mask projection machining approach to aperture the workpiece beam to the diameter of the desired well, multiple low energy pulses can be used to precisely control the depth of the final well. Fluidic channel structures can be created over the integrated light wells using cast polydimethyl siloxane (PDMS). Efficient sealing between the SU-8 and the PDMS was achieved by mechanically clamping the composite structure.

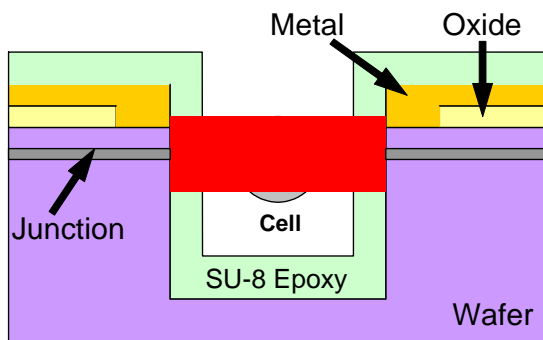


Fig. 9 Illustration of the integration of light well structures into microfluidic channel systems.

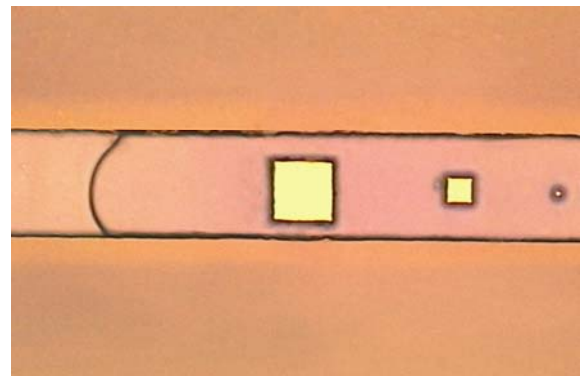


Fig. 10 Excimer laser micromachined microfluidic channel in baked dry film laminate. The channel is sealed with a second laminate layer into which 50 $\mu$ m, 25 $\mu$ m and 5 $\mu$ m square holes have been machined. The fluid meniscus is visible within the channel.

### 3.5. Microfluidics

Laser micromachining is a flexible microfabrication process with the ability to machine a wide range of materials to a high quality. Changing from one material to another often only requires re-establishment of the fluence vs machining depth parameters for the new material. As such, laser micromachining is an ideal technology for the manufacture of microfluidic structures both in prototyping and production environments. The use of direct write machining methodologies using either a focused or apertured beam coupled to Computer Aided Machining software with the ability to translate CAD drawings to machine movement and synchronized laser commands allows rapid realization of device design iterations. Mask projection machining methodologies also allow complex channel layouts to be machined by simple raster scanning the beam over a mask. Figure 10 shows an encapsulated microfluidic channel formed by the excimer laser micromachining of a baked, exposed, dry film laminate resist of the order of 60 $\mu$ m deep. The channel is encapsulated by applying a second layer of resist over the laser machined channel. Figure 10 shows the fluid meniscus within the channel and a series of square outlet holes excimer laser micromachined in the encapsulation layer. Variable width or depth channels to control environmental parameters such as pressure and fluid velocity or process parameters such as diffusion time can easily be created. In a direct write process width is controlled by one or more of either spot size, beam path or aperture size depending on the beam configuration in use. Changing the depth of a channel can be achieved by varying the total exposure fluence which, in turn, can be controlled by pulse fluence, machining velocity or beam path.

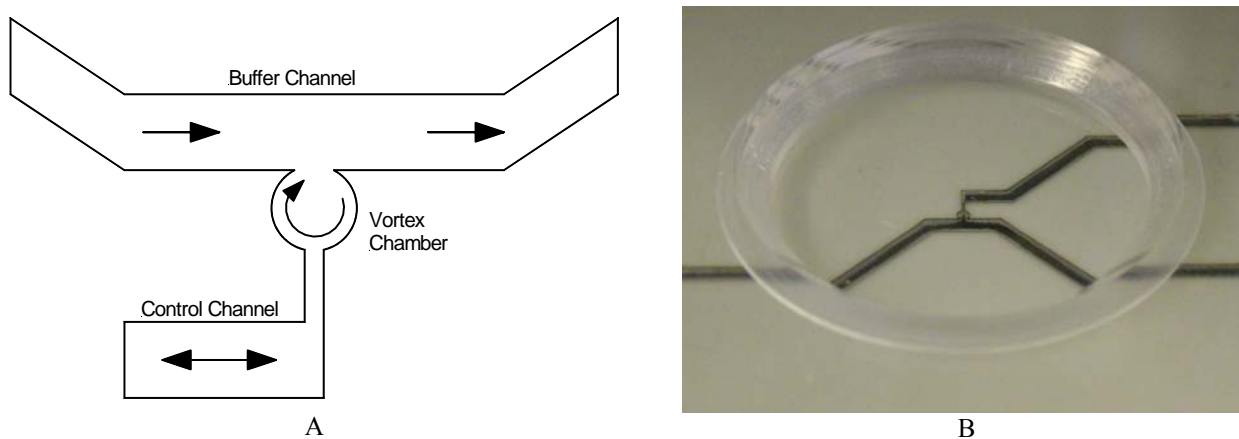


Fig. 11 Femtosecond laser micromachined of composite laminate for the creation of microfluidic channels for vortex based media exchange. (A) Diagram of the channel layout including a buffer channel used to drive the vortex, a chamber in which the vortex is produced and a control channel to allow sample loading and extraction. (B) Laser machined laminate assembled into a working unit and held within a microscope based universal microfluidic platform

Figure 11 illustrates the flexibility of ultra short pulse laser micromachining in the fabrication of microfluidic channel systems for optical biochips. The structure shown in figure 11a could be used as the particle corraling chambers in the conceptual diagram of figure 2. By control of the fluid flow through the control channel particles within the buffer channel can be directed into the circular chamber. Closing the control channel will cause the fluid within the chamber to rotate due to the influence of fluid flow in the buffer channel. Particles within the chamber will rotate and move towards the centre of the chamber while diffusion processes allow ions within the buffer and chamber to be exchanged over time. This microfluidic structure was fabricated using an adhesive backed laminate sheet (Melinex A, Katco Ltd, UK). The benefits of femtosecond laser micromachining are an extremely high cut edge quality with no significant machining debris. The lack of debris is of benefit when micromachining composite materials such as the adhesive backed laminate. The laminate comprised of a 250 $\mu$ m thick polymer sheet coated on both sides with a 50 $\mu$ m thick layer of acrylic-based adhesive which, in turn, was coated with a protective cover. Machining beam paths were derived from a CAD file using AlphaCAM (Licom Systems, UK) computer aided machining software. Machining was carried out with a beam power density of 30kW cm<sup>-2</sup> and an effective workpiece velocity of 5mm min<sup>-1</sup>. The ionizing nature of the femtosecond laser ablation process meant that all materials had similar machining characteristics and could be machined in a single

process step. In addition, the small amount of debris produced in the machining operation was non-adhesive and could be fully removed prior to use. Complete fluidic devices were formed by removing the protective coating from one side of the laminate and bonding to a glass substrate at 80°C followed by repeating the process with a second glass sheet on the other side of the laminate. Fluid entrance holes were machined in the lower glass sheet using a beam power of 60kW cm<sup>-2</sup> and an effective workpiece velocity of 0.22mm min<sup>-2</sup>. The completed device was mounted in a microscope-based microfluidic platform which allowed accurate control of fluidic delivery and flow rates.

### 3 CONCLUSIONS

The microfabricated optical biochip components described here demonstrate the flexibility of laser micromachining for the development of biochip devices. The processing used in this work has made use of the unique machining properties of two different types of lasers to produce components of an integrated device. While other manufacturing processes may be used to create parts of the devices, only laser micromachining has the ability to produce all components described here. Laser micromachining has been demonstrated to operate with a broad range of materials and has the ability to cope with changes in component materials. The high quality of mask projection laser micromachining has also been demonstrated to produce surface qualities suitable for optical components. The ability to directly write structures at high speed with laser micromachining allows it to be used as a cost effective microfabrication tool capable of all stages of fabrication from prototype development to large scale production.

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