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Advances in Femtosecond Micromachining and Inscription of Micro and Nano Photonic Devices

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1. Introduction

Femtosecond micromachining and inscription uses focussed femtosecond laser pulses to fundamentally change materials through the interaction of the pulse and material. The fabrication of intricate microstructures on the surface of opaque materials, or within the bulk volume of optically transparent glassy or polymeric materials, is widely recognized as an important development in the innovation of advanced components in fields such as medicine (stent production) and photonics (micro-devices, sensors). This chapter sets out to introduce the topic of femtosecond laser micromachining and inscription of different materials and will focus on the practical considerations of the subject.
A femtosecond, often shortened to fs, corresponds to 10^{-15} of a second and in femtosecond laser machining specialised lasers generate extremely high intensity pulses, where each pulse has a temporal duration that typically ranges between 50 to 500fs, which subsequently interact with materials. This interaction has a number of interesting properties that can be utilised in shaping and permanently changing the physical, chemical and optical properties of the material. Recent advances in the development of femtosecond laser sources have accelerated the growth of this field resulting in many exciting novel applications.
The extremely short temporal profiles of femtosecond laser pulses, when combined with tightly focusing optics, produce sub-micron scale material changes that are associated with the parts of the beam where the optical intensity is extremely high, typically reaching 10^{13}W/cm^2. Under such conditions, intensity-dependent non-linear absorption processes, such as multi-photon absorption and avalanche ionisation take place, leading to permanent structural and chemical changes in a myriad of materials (N. H. Rizvi, nd). This is particularly important for transparent materials since they have electronic band gaps too large to bridge with a single photon process and therefore the linear absorption of laser light does not occur. As a result of this there is minimal interaction between the laser and material; however, with a tightly focused femtosecond laser beam the interaction can be triggered and the non-linear effects dominate. Any structuring therefore only occurs around the laser focus and has strong spatial confinement. The induced structural changes can take many forms; index change and void creation are two common examples and can be used to

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form true 3-dimensional structures. This is only possible because of the non-linear behaviour of the pulse-material interaction at the focus.
In this chapter we discuss the following subject areas: the key concepts of femtosecond pulse and material interaction; the materials that are used as machinable substrates; we offer a review of the types of femtosecond lasers that are commercially available; we introduce some techniques applied in the field to date and a review of some of the current applications for this type of technology.

2. Fundamental considerations

Having first looked at the fundamentals of how femtosecond lasers interact with materials, we will look at the properties of a femtosecond laser beam and discuss a number of parameters that strongly affect the micromachining process.

2.1 Pulse energy deposition mechanisms

The nature of the interaction between a material and a femtosecond pulse is largely dependent on the energy bandgap of the material and the energy of the incident photons. This determines whether single or multiphoton (figure 1) absorption will dominate. If the photon energy is greater than the bandgap then single photon absorption dominates. In this instance a photon is absorbed and an electron in the valence band is promoted to the conduction band leaving a hole. It is worth noting that in some indirect bandgap semiconductors single photon absorption can also occur but this process requires assistance from phonon interactions. When the bandgap is greater than the photon energy then multiphoton absorption becomes important. Multiphoton absorption relies on a number of photons arriving and being absorbed by the electron within a short space of time and is the key absorption mechanism in transparent insulating materials such as fused silica (amorphous SiO_2), where the band gap is large. Multiphoton absorption can also be important for laser absorption in materials where single photon absorption is inhibited by band filling, for example in indirect gap semiconductor materials such as silicon (Sundaram & Mazur, 2002; J. P. Callan et al., 2001).

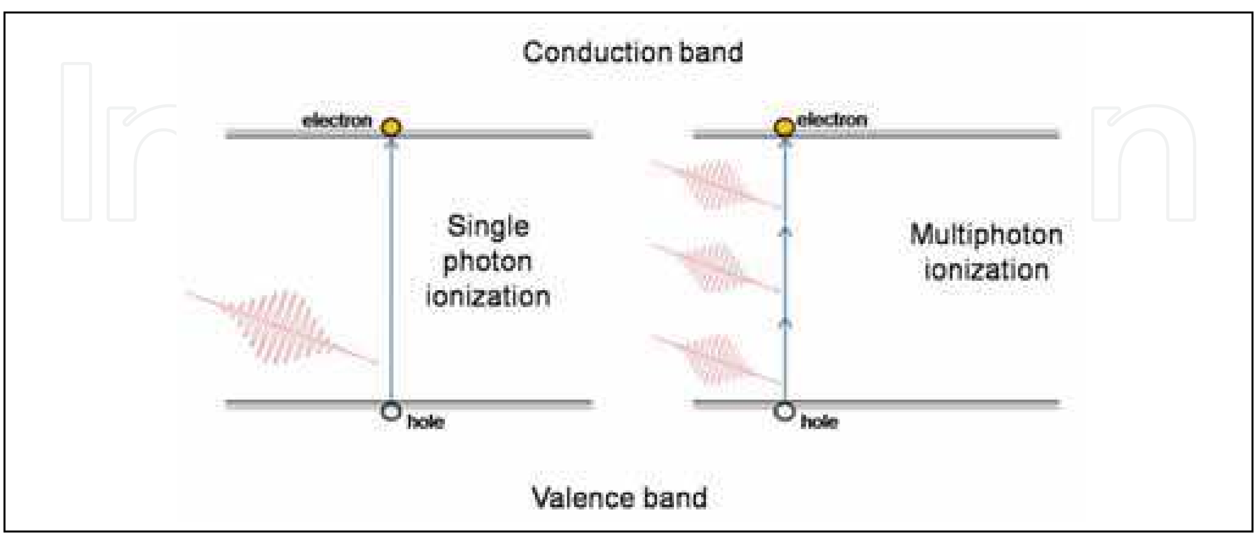

Fig. 1. A schematic of single and multiphoton absorption of incident photons (shown in red) causing electrons to be promoted to the conduction band from the valence band.

When a femtosecond laser beam is focussed onto a transparent material very little absorption occurs until the light intensity is high enough for multiphoton absorption to occur. The multiphoton ionisation that triggers the multiphoton absorption results from several photons being resonantly absorbed causing an electron to be promoted from the valence band to the conduction band.

In solids, scattering effects cause a loss of phase coherence between the excitation and incident photons. This means that the coherence dependent effects (i.e. ionisation) are observed in timescales of between 10-100 fs. It is only after this time that any created carriers become free. These carriers are then able to absorb more energy through free carrier absorption. This process does not increase the free carrier population only the energy although in extreme cases impact ionization can be triggered creating additional excited carriers.

Once excited the electrons and holes, through carrier-carrier and carrier-phonon scattering, spread and re-organise themselves in the conduction and valence bands. The two processes involved in the redistribution of carrier energy vary significantly in their mechanisms. Carrier-carrier exchange is a two body electrostatic interaction between two carriers. In this process there is no loss or gain in the total energy in a given system. This type of scattering takes 100s of femtosecond to reach an even distribution (the Fermi-Dirac state) through dephasing. Carrier-phonon scattering involves the free carriers losing and gaining energy and momentum through the emission and absorption of phonons. This transfer can be both inter and intra valley as well as within the bands themselves. The interaction does not change the number of carriers, however, their energy decreases due to spontaneous phonon emission with the energy being transferred to the substrate lattice. The two processes also have different timescales, although they can scatter concurrently. The carrier-phonon scattering lasts several picoseconds as the individual phonons carry limited energy and thus to dissipate the energy to thermal equilibrium takes longer.

Once the electrons, holes and lattice are in thermal equilibrium there will still be an excess of free carriers, as compared to when the entire material is in thermal equilibrium. These excess carriers are removed through either recombination (Auger and radiative) of electron-hole pairs or by carrier diffusion from the region of exposure. These processes take 10-100s of nanoseconds to occur. Once both thermal equilibrium is restored and the excess free carriers have been removed the material is often changed structurally and or thermally. If the material threshold has been exceeded, in other words if taken to temperatures above melting/boiling points, then melting and vaporization can occur. This occurs in the ns to μs timescale after initial exposure. The material becomes extremely hot but is still solid until a form of nucleation occurs and it can locally turn into a liquid or gaseous state. At this point there is an expansion into the surrounding media. The remaining energy, from the trailing edge of incident pulse(s), is converted to kinetic energy creating ions and allowing atoms and molecules to gain sufficient energy to break bonds. If this occurs on the surface and the particles leave the surface of the substrate this is called ablation. If this occurs within a transparent material it is often referred to as void creation where there is an absence of material often with compacted areas surrounding it. The extent to which the expansion occurs is dependent on the thermal diffusion rate of the material as it determines the rate of cooling of the exposed area. If melting or other processes have occurred resolidification and condensation are the mechanisms for returning the material to thermal equilibrium. This, however, may not leave the material in its' original state and this is where femtosecond micromachining comes in with the aim of manipulating the modification to create useful devices in a highly controlled manner.

To look at multiphoton absorption in a little more depth let us consider the inscription of dielectric crystals. As in the case of most glasses, the material bandgap is significantly greater than the incident photon energy. This ratio between the two is known as the multiphoton absorption order, K and for glass exposed with a femtosecond laser in the IR spectrum is typically 4-6. It is possible to reduce this value to 2 by using a source operating in the UV range thus obtaining two-photon absorption. This happens because of the relative increase in the individual photon energy that occurs at the lower wavelength. The dependence on having a sufficient flux of incident photons to initiate multiphoton absorption and ionisation implies a non-linear process. This is due to its' energy loss rate being proportional to the K^{th} power of the peak pulse intensity. This leads to the threshold pulse intensity being given by:

$$I_{MPA} = \left(\frac{\mathrm{K}\hbar\omega\rho_{cr}}{t_{\mathrm{p}}\beta_{\mathrm{K}}}\right)^{1/\mathrm{K}} \tag{1}$$

where ρ_{cr} is the plasma breakdown intensity, t_p is the pulse width, β_K is the multiphoton absorption co-efficient and ω is the laser frequency. It should be noted that as K increases the influence of the other parameters decreases. It is also only the section of the plasma field induced by multiphoton absorption that creates a modified region. This region is typically half the size of that which is heated. This can be exploited to give sub diffraction limited nanoscale modulations in index and ablation (S. K. Turitsyn et al., 2007).

2.2 Typical pulse properties

Each femtosecond laser has its' own characteristic pulse properties; however, there are some fundamental properties that they share. Most are Gaussian in both the temporal and spatial domain although it should be noted that $sech^2$ is most common for mode-locked lasers. The pulses typically have a low M^2 factor (ISO Standard 11146, 2005); more details on this are covered in section 4. This allows the pulses to be shaped easily through a number of techniques (N. Sanner et al., 2005). However, complex pulse shaping is not typically applied in most systems. Most pulse shaping is done with the use of spatial light modulators. These are typically 2D liquid crystal displays that are adjusted in the Fourier domain, although they are progressing to the use of micro-mirrors, which modulate the beam. In the case of the displays often the pulses are monitored and the liquid crystal programmed to act as a filter for certain areas until the desired pulse shape is achieved. These systems are usually attached to the lower repetition rate amplified laser systems although technological progress means that refresh rates towards the MHz range are close to being achieved (E. Frumker & Y. Silberberg, 2007).

2.3 Control of ablation area

When a pulse passes through an objective lens it becomes a stretched Gaussian profile in the spatial domain. Through the correct choice of lens it is possible to control the energy profile of the pulse and its spatial footprint. The spot diameter is given by:

$$\text{Spot diameter} = 1.22 * \frac{\lambda}{\mathrm{NA}} \tag{2}$$

where λ is the wavelength and NA is the numerical aperture of the focusing lens objective.

At the focus, if the material's threshold energy is exceeded, the pulse will interact with the material and be absorbed. The use of lenses to focus and control the laser induced plasma is a very effective method of spatially shaping the resultant profile. Also by changing the pulse energy it is possible to control the spatial dimensions of the pulse-material interaction, figure 2. This allows the pulses to be spatially confined to a sub micron focal spot under the right conditions enabling a range of complex structures to be micromachined. (R. W. Applegate et al., 2006; P. Bado et al., 2006; S. Kawata et al., 2001; B. Yu, 2008).

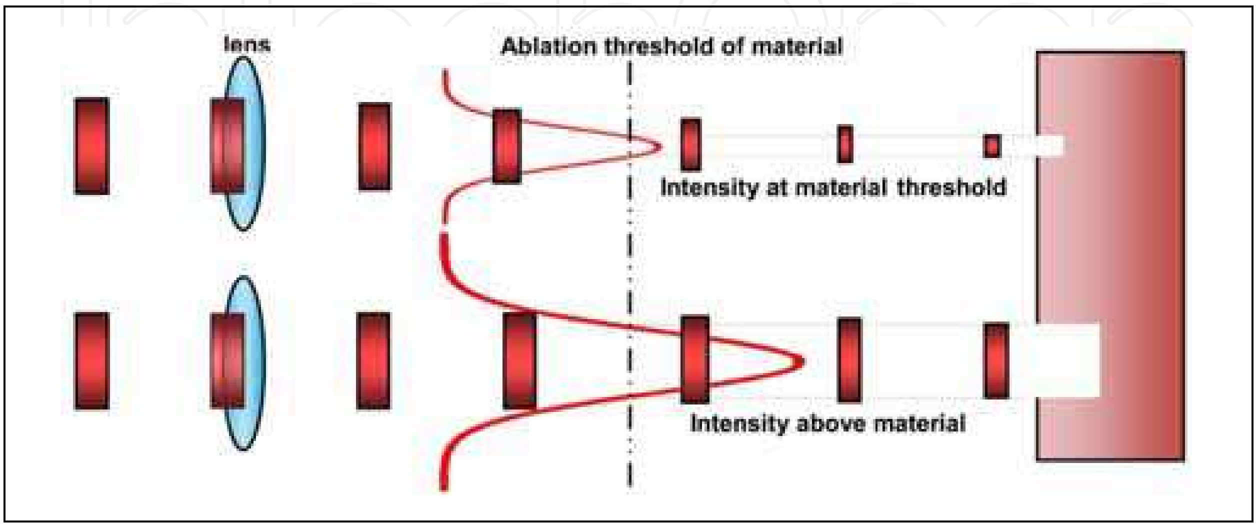

Fig. 2. A schematic showing that control of the laser pulse energy, relative to the material ablation threshold, can spatially control the structural change, in this case ablation.

Focussing can occur through the use of lenses and /or by using a low numerical aperture (NA) lens and allowing the material to self focus. The most common approach is to use an objective lens to create a focal spot because it is a more controlled process and works for lower power laser pulses. The threshold for the Kerr self focusing effect, where the refractive index seen by the beam is intensity dependent and is given by $n = n_0 + n_2 I$, is sufficiently high that for most materials this technique requires a significant amount of energy incident to create the fluence levels required (M. Sheik-Bahae et al., 1990; G. P. Agrawal, 2006). Above the threshold the Kerr effect occurs and the pulse experiences self focusing until it collapses. This effect at most energy levels is balanced by multiphoton absorption, plasma absorption and the plasma self-defocusing, due to the lower refractive index it creates. It is often considered preferable to avoid the Kerr effect when micromachining as it causes the laser focus to be deviated from its point of intended path. Self focusing occurs when the power, P, becomes greater than the critical power, P_{Cr} which can be calculated from the equation:

$$P_{Cr} = \frac{\lambda_0^2}{2\pi n_1 n_2} \tag{3}$$

where λ_0 is the laser wavelength, n_1 is the linear refractive index and n_2 is the nonlinear refractive index.
The time between pulses is a function of the repetition rate of a laser. The time between subsequent pulses interacting with the media makes a significant difference to the heating and subsequent cooling of the focal volume. The two forms of sources, oscillators and

amplifiers, have very different repetition rates and so have quite different heat accumulation and diffusion characteristics.

The average power of a laser is determined by the pump source, this then produces either large amplified pulses separated by ms or smaller oscillator pulses with pulse separations of tens of ns, see figure 3. This range in repetition rates has a significant effect on the interaction with the material. The heat from a typical focal spot in a femtosecond micromachining system has a diffusion time of a μs in the case of fused silica. This means that in high repetition rate systems, when the repetition rate is such that the pulse separation is of the order of ns, the material in the focal region gains heat and is thermally loaded by successive pulses. If this thermal loading causes the focal volume to be above the temperature of the material melting point then permanent structural changes take place.

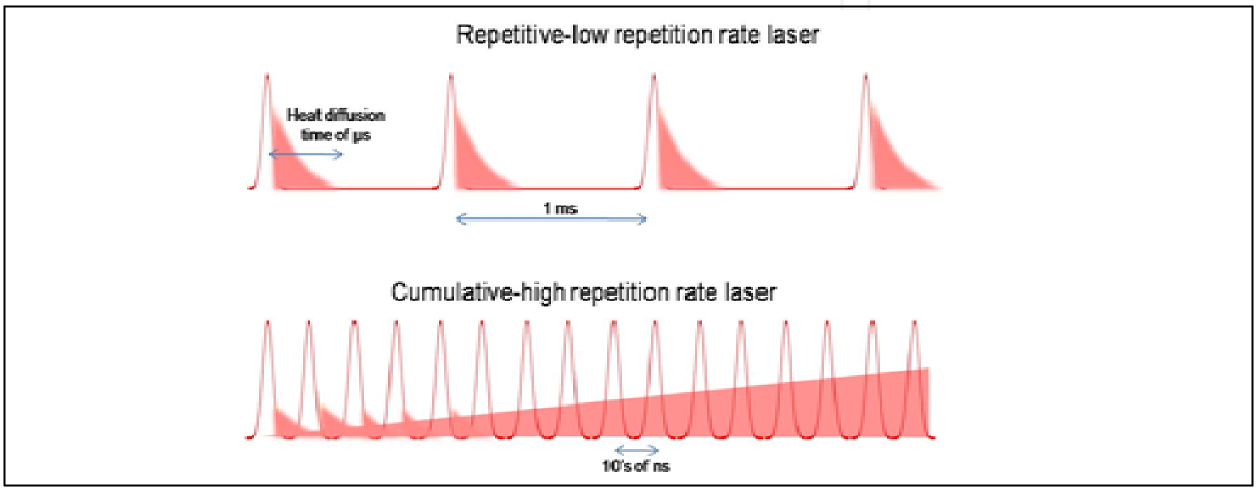

Fig. 3. A schematic showing the difference in low and high repetition rate lasers effect on the focal spots thermal accumulation and diffusion.

In contrast, amplified sources have much lower repetition rates and as such the heat has time to diffuse from the focal volume before the next pulse arrives. This tends to make the regions of change more confined to the focal volume than with oscillator laser sources. This dependence can be manipulated through the use of different lenses or combination of lenses but often the resultant structure has a shape associated with the focal spot. This fine dependence on the lens focussing is less stringent with high repetition rate sources as the thermal effects tend to impose a more spherical shape.

3. Materials

One of the least understood, yet most crucial aspects of femtosecond micromachining, is the precise nature of the interaction of the laser pulses with the substrate materials. The material properties affect the plasma as it interacts with it. Materials can be divided into two groups for classification, transparent and non-transparent. Figure 4 shows a range of both types of materials and their ablation/damage thresholds. The values for the material thresholds are taken from published work and are for a number of different wavelengths and pulse durations (P. Mannion et al., 2002; K. Nagashima, 2004; T. V. Kononenko et al., 2008; S. Baudach, 2000; G. Olivié et al., 2008; J. Kim & S. Na, 2007; A. Baum et al., 2007; J. Kruger et al., 2007; J. S. Yahng et al., 2009; N. Sanner et al., 2009). The values can be used to illustrate the general trends but should not be taken as finite points.

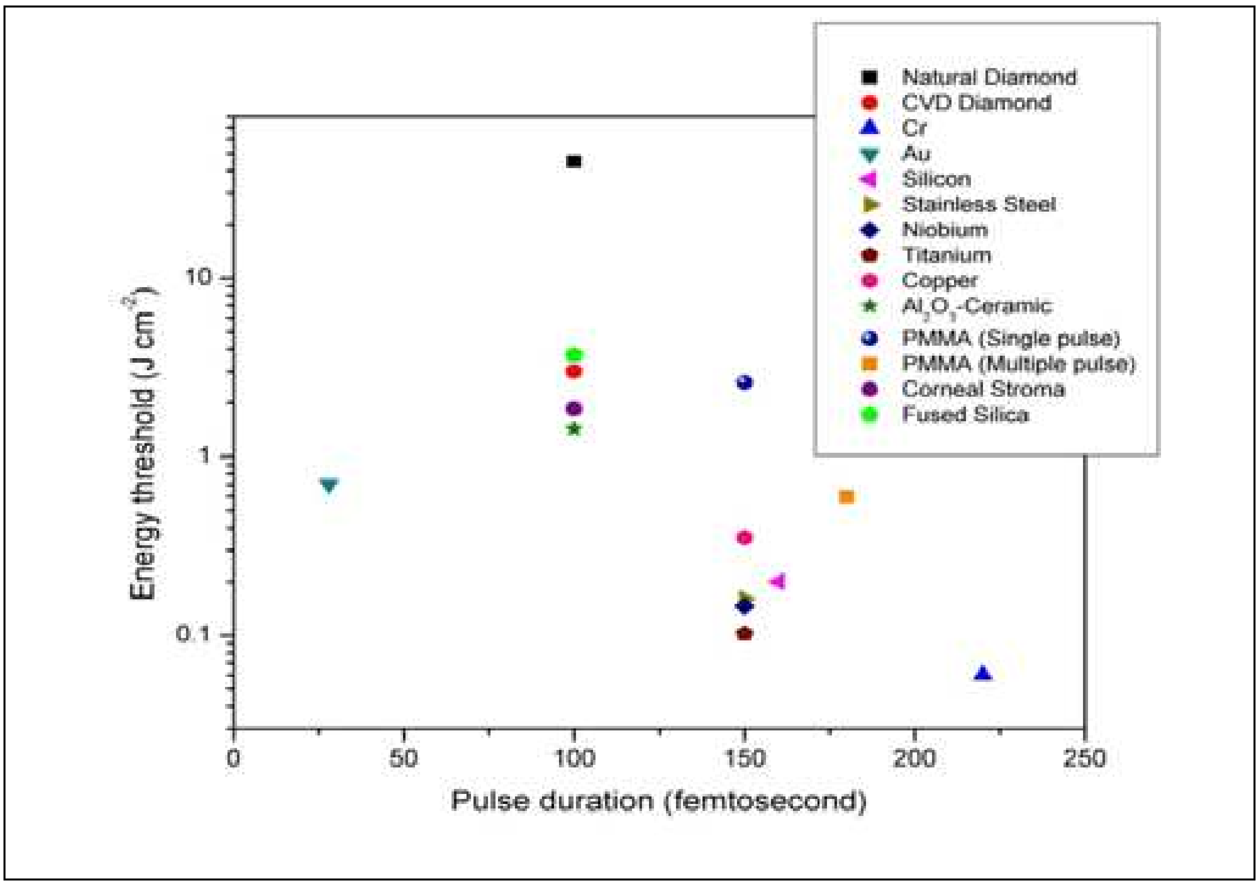

Fig. 4. A plot of the energy thresholds for modification vs pulse duration, for a range of materials, with the values taken from a literature survey.

Most material thresholds have a small range of values attributed to them arising from the laser parameters and techniques being applied being different between groups conducting the research. A good example of this is given in the paper by Sanner et al (N. Sanner et al., 2009), where the range of values quoted for the ablation threshold for fused silica is given as 2-12 J cm^{-2}. This range is by no means an anomaly or the widest range published, for example the value for natural diamond is given as 10-80 J cm^{-2} (T. V. Kononenko et al., 2008) where the value fluctuates widely across a specimen surface. The reason for the range in values can be explained by considering that there are a number of ways of measuring the thresholds and even defining them (N. Sanner et al., 2009), there are also differences in the exact composition of the materials used and their source, as well as differences in the experimental set-up. The variation in material and the dependence on small variations of impurities and dopants can lead to significantly different thresholds. The values also do not reflect the range of repetition rates that are available and the subsequent change in energy threshold (S. M. Eaton et al., 2005; C. B. Schaffer, 2003). There is also a dependence on the wavelength of the laser as this will determine the physical mechanisms involved from multiphoton absorption, impact ionization, free carrier absorption and many others.
It should be noted that the chart also reflects the work carried out using the lasers that have been practically available in laboratories around the world. The vast majority of these systems have a repetition rate of about 1kHz and are Ti:Sapphire amplifier lasers. This will potentially bias the results of the plot as the lasers that may be best suited to a given material may not be reflected in the work carried out to date. A good example of this may be

Poly(methyl methacrylate) (PMMA) where at the correct wavelength a particularly short pulse may suit the material in which the chain length of the molecules is long and the thermal sensitivity is high. The short pulse duration would potentially enable the confinement of the resultant shockwaves to be significantly greater.

3.1 Non-transparent materials

As one would expect, the use of femtosecond lasers with non-transparent materials is typically limited to working on the surface in either ablation or modification (E. D. Diebold, 2009). There are a number of non-transparent materials that have been studied as shown in figure 4. Each material has a number of different properties that affect the energy threshold. For non-transparent materials, the band gap is the most important contributor when looking to determine the energy threshold. This will, as detailed in section 2.1, determine the process by which the photons interact with the material. The interaction of femtosecond pulses with non-transparent materials causes excitation of the majority of electrons, formally in bound states, creating a plasma-like state which immediately creates disorder in typical lattice structures. This means that the process is typically considered to be athermal as it occurs before the lattice has come to an equilibrium state through the carriers. There is some debate as to exactly how athermal the process is but there is little disagreement that the reduction of the heat affected zone (often abbreviated to HAZ) is significant as compared to the longer pulse durations that had previously been studied (S. Valette et al., 2005). The potential for the use of non-transparent materials, either on their own, in multi-layered combinations or, in combination with dielectric materials, for a range of applications holds a great deal of future development capacity and will be a subject of continued research for a number of years to come.

3.2 Transparent materials

Transparent materials also rely on non-linear absorption and subsequent ionization to create either ablation at the surface or index modification within the bulk. The exact mechanisms are not fully determined. However, work on modelling the processes involved is beginning to compare well with practical results and illuminate the mechanisms (J. S. Petrovic, 2007). The mechanism for the energy transport from pulse to material is commonly thought to be through nonlinear absorption. A femtosecond pulse of sufficient energy when focused inside a material will optically breakdown. At this point a proportion of the energy is transferred to the lattice via excitation of the electrons in a multiphoton absorption process. These electrons reach thermal equilibrium within several femtoseconds and seed the subsequent avalanche ionisation which absorbs the energy in the tail of the pulse. It is assumed that the energy that does not go into the ionisation is stored as kinetic energy in the electrons. The recombination time for electrons in fused silica is of the same order as most of the pulse durations as shown in figure 4 at 170fs (Q. Sun et al., 2005). It is commonly assumed that the mechanical and thermal changes on the time scale of a pulse are negligible. In the next picosecond a proportion of the energy in the electrons is transferred to the lattice. During this time there is plastic deformation occurring which propagates at the speed of sound covering about a micron in 0.1ns. This pressure or shockwave separates from the hot focal volume in a matter of nanoseconds. This is then followed by thermal diffusion acting in the microsecond timescale where the thermal energy diffuses out of the focal volume. Beyond critical energies these processes give rise to permanent changes in structure that creates one of two commonly accepted forms in the shape of voids (A. Martinez et al., 2006) or smooth index changes (N. T. Nguyen et al., 2006). The difference between the two depends on whether the pulse is above or below the damage threshold of the material concerned.

Void creation is achieved when the focusing is very tight and the pulse energies used are high. This has the effect of creating huge pressures at the point of focus and subsequently on the surrounding material. The surrounding material experiences a pressure wave moving away from the peak intensity forming a rarefied region of material followed by a region of densification. When the pressures created, through the focusing and pulse energy, are great enough a void may be created (E. N. Glezer & E. Mazur, 1997).

Smooth index changes are achieved with pulses below the structural damage threshold. They too create rarefied areas; however, as the pressure exerted by the focal volume is much smaller the resultant index change gradient is smoother leading to structures that can be used for waveguiding. The effect of the pulse repetition rate on the material-pulse interaction is shown to have a significant effect on the profile of the index change at higher repetition rates (typically in the MHz region). This is shown to be due to the thermal diffusion of the material being longer than the pulse to pulse separation (C. B. Schaffer et al., 2003). This means that the material is thermally loaded when the next pulse is incident at the focal region. This effect has not been observed at lower repetition rates in the kHz range.

It should be noted that there are competing mechanisms for explaining the effects of pulse material interaction such as tunnelling ionization; however, work by Keldysh has shown that they are just two boundaries of the same process under different conceptual approaches (L. V. Keldysh, 1965).

3.3 Ablation in transparent materials

When the conditions for void creation are met and the energy incident in the focal region is sufficient to create a plasma with sufficient energy for Coulomb repulsion to create voids, ablation may occur. The only difference is the depth at which the changes occur. If near enough the surface the plasma will inevitably weaken the surface wall allowing the pressure on the side walls to be reduced in due course. This causes the removal of material from a substrate and is characterised as ablation.

3.4 Heat affected zone

The nature of the timescales involved in both transparent and non-transparent material interactions with femtosecond pulses, and the subsequent structural changes, offer up insight into the advantages of micromachining with ultrashort pulsed lasers. The electron-phonon scattering time, of approximately 1 picosecond, is greater than the pulse duration and so the pulse has ended before the excitation of the ions has begun. This means that theoretically the heat diffusion outside of the focal area is minimized (S. Valette et al., 2005). This extra control on the locale of micromachined change adds a level of precision not afforded to lasers of sub-picosecond pulse duration. This reduction in the heat affected zone is often important in many applications. The reduction can lead to fewer, if any, micro-stress fractures being created when machining materials which, for example, are used for heavy strain loading thus reducing the chances of fracture. Also, to induce changes in a material using a femtosecond laser it is not necessary to have dopants to seed the absorption process. The effect of the nonlinear ionization can be used, with great care and refined technique, to produce a confined and reproducible material change that can be put to practical use.

4. Types of femtosecond laser

The results of a market survey on femtosecond laser sources are presented in table 1 (Amplitude Systemes; Coherent; High Q laser; Kapteyn-Murnane Laboratories; Raydiance). There are a number of ways of evaluating femtosecond lasers, each parameter set leading to a different profile of applications that they suit. The parameters chosen for this summary are wavelength, energy per pulse, pulse width, repetition rate, average power and the key amplification medium of the source. There are, of course, other parameters that are also fundamental but for reasons of space have not been included for example, the M^2 value, peak power, beam diameter and polarization. These parameters should not be overlooked, however, when considering which laser source is applicable to a given task.

The M^2 factor, also known as the beam quality or beam propagation factor, is commonly used as a measure of the beam quality (ISO Standard 11146, 2005). For diffraction limited Gaussian beam the divergence is thus given by:

$$\Theta = M^2 \left(\frac{\lambda}{\pi\omega_0}\right) \tag{4}$$

where Θ is the half angle beam divergence, λ is the wavelength and ω_0 is the beam radius at the beam waist. A diffraction limited beam has an M^2 of 1 and is considered Gaussian. The level of divergence that a beam has will limit the degree to which it can be focused and since the M^2 factor is a measure of this it is a good indication of how a laser beam will focus given a certain numerical aperture objective lens. When combined with the optical power of a laser it determines the laser fluence achievable. Typically femtosecond lasers will have an M^2 value of between 1 and 1.5, in most applications a value closer to 1 is usually preferable.

The peak power is a parameter that is typically considered when deciding what material you wish to ablate or into which you wish to inscribe a structure. The key being that the peak power must exceed the material threshold energy so that work may be carried out. This can be done by comparing the many sources of material thresholds (see figure 4 for published results) against the specifications of the systems supplied. The peak pulse power, ppp, is given by:

$$ppp = F.\frac{Average\ power}{Repetition\ rate.\tau_p} \tag{5}$$

where τ_p is the pulse duration and F is a factor determined by the shape of the pulse; for a $sech^2$ pulse the factor is 0.88, for a Gaussian it is 0.94.

The beam diameter needs to be taken into consideration when designing the optics that a femtosecond laser system will require or, of course, vice versa. It is important to control the beam divergence and aperture size of the lens as through miscalculation of these much of the beam quality, wavefront, energy profile and peak energy may be lost or reduced.

Most of the sources in table 1 are linearly polarised. Although the polarisation is not generally an issue, care should be taken when designing the system to make sure that the polarisation for any beam is known at any given point. As an example, when using an autocorrelator to monitor the laser, an orthogonal polarisation state may be required to that which your laser outputs. There is also work on the polarisation state relative to the direction of beam-substrate translation; this is covered in more detail in section 5.3.

There are currently two key types of femtosecond laser commonly commercially available. They may be grouped into amplifier and oscillator systems. The details as to how they work

will not be covered here but may be found in references (T. Südmeyer, 2008; S. Backus, 1998), however, differences in terms of the output pulses will be discussed.
The wavelength ranges of the types of laser are determined by a number of factors. There are two main bands covered by the fibre lasers at 1030-1045nm and around 1550-1560nm. The two bands correspond to the dopant used in the lasers cavities. The conventional C-band erbium window is at 1530-1565nm and ytterbium sources operate at around 1030-1050nm (S. B. Poole, 1985). There is a third much smaller group of fibre lasers operating at around 800nm. Bulk amplifiers and oscillators, are also governed by the amplification material chosen. They typically use Ti:Sapphire and ytterbium and as such commonly operate at wavelengths around 800nm and 1030-1050nm.
The energy per pulse is a parameter to be considered in a similar way to the peak power. The pulse energy required will depend on both the material and the chosen application. Machining of a crystal for instance will typically require a much greater energy per pulse, for example energies up to and above 80 Jcm^{-2} (T. V. Kononenko et al., 2008) for natural diamond, while for index change in PMMA energies above 0.6 Jcm^{-2} (A. Baum et al., 2007) cause permanent change. The energy per pulse of the types of laser are detailed in table 1. The oscillators typically have energies in the range of 1-100s nJ per pulse, whereas the fibre lasers offer energies in the μJ range and amplifier pulse energies typically fall in the mJ range. The choice of pulse energy for a given application is critical as most materials have a small window of energies between the desired effect, say index change, and damage. The other consideration is that to control the energy, and other parameters, incident on a sample is significantly easier when not having to operate at the extreme limits of attenuators or with insufficient laser energy after the losses experienced through the system.

Type	Wavelength (nm)	Energy per pulse	Pulse width (fs)	Repetition rate	Average power (W)	Key material	Company
Amplifier	800	0.3-6mJ	25-130	1 or 5 kHz		Ti:Sapphire	Coherent
Amplifier	1030	10μJ-1mJ	400-300	0-100kHz		Diode pumped	Amplitude
Amplifier-multi pass	Tuneable	0.25-20mJ	<25-100	1-20 kHz	3.0 to 50	Ti:Sapphire	Kmlabs
Amplifier-Regen	1035	0.4-1mJ	350-500	1-100kHz	1.0 to 2.0	Ytterbium	High Q
Amplifier-Regen	1055	1mJ-5μJ	650	10-100kHz	0.100 to 0.200	Nd:Glass	High Q
Amplifier-Regen		3mJ	60-160	100/250	0.3 to 0.75	Ti:Sapphire	Coherent
Fibre	780		100	50MHz	0.02	Erbium doped	IMRA
Fibre-Amplifier	810		<150	75MHz	0.1	Erbium doped	IMRA
Fibre	1030	0.5-10 μJ	100-700	30-25MHz	20		Amplitude
Fibre	1043	2μJ	500	200KHz	0.4	Ytterbium doped	IMRA
Fibre	1043	10	700	200KHz	3W	Ytterbium doped	IMRA
Fibre	1045	10μJ	700	100kHz		Ytterbium doped	IMRA
Fibre	1552	1-10 μJ	<600	1Hz-300kHz	3		Raydiance
Fibre	1552	5-50 μJ	<800	1Hz-100kHz	5		Raydiance
Fibre	1560		100	50MHz	0.06	Erbium doped	IMRA
Oscillator	800	3-10nJ	<12	80-100MHz	0.250 to 0.900	Ti:Sapphire	Kmlabs
Oscillator	800		<20	80MHz	>0.300	Ti:Sapphire	Coherent
Oscillator	1030	20-300nJ	200-500	10-30MHz	1 to 5	diode pumped	Amplitude
Oscillator	1060	1.4nJ	<150	72MHz	>0.100	Nd:Glass – diode pumped	High Q
Oscillator	1030-1053	2-300nJ	~350	10-80MHz (fixed)	0.150 to 3	Ytterbium	High Q
Oscillator	790-870		100-300	73MHz	>0.200	Ti:Sapphire	High Q
Oscillator-Cavity dumped	800	>60nJ	100	0.5-1MHz	0.06	Ti:Sapphire	High Q
Oscillator-Cavity dumped	1040	>500nJ	<400	0.5-1MHz	0.5	Ytterbium	High Q
Oscillator-Cavity dumped	800	30nJ	<15	1kHz-4MHz			Kmlabs

Table 1. Table showing the market survey of femtosecond sources and basic properties

Femtosecond pulses are considered ultrashort and as table 1 shows they range greatly in practical terms. There are effectively two or three classifications of pulse duration. There are the extremely short pulsed lasers, with pulses typically in the 10s of femtosecond duration which are most commonly, although not exclusively, oscillator lasers. The next region is about 100-350 fs that are often amplifier lasers. The final group is from 350-800 fs and is largely occupied by fibre and amplifier lasers. The pulse duration makes a significant difference to the pulse-material interaction and the pulse energy required.

Repetition rates of commercially available systems range greatly from single kHz through to 100MHz. The range leads to a significant difference in the applications of each. There is some evidence to suggest that better quality waveguides, for instance, are written with lasers operating in the MHz regime rather than kHz (S. M. Eaton et al., 2005). On the contrary often for micro-machining ablation lower repetition rates in the 1-300 kHz range tend to be chosen because they have higher pulse energies which are above the ablation threshold. For these lower repetition rate systems there is also less thermal loading due to the pulse train spacing. Repetition rates and the resultant thermal loading, or absence, offers clear advantages of one repetition rate over another for a specific task.

In conclusion the parameters of a chosen laser will strongly influence the effectiveness of work in particular area. The parameter windows are relatively small for high quality results in any given application.

5. Techniques employed

There are several different techniques employed when making micro-machined devices through inscription and ablation. Some of them are techniques applied to both regimes and others are applied more specifically to one or the other. Typically using a laser to perform micro-machining involves complex physical processes and is dependent on fine parameters of the material and laser. Theoretical models exist and are touched upon in other sections of this chapter, however, they are often considered to be only a guideline and require refinement for optimal processing when using a practical system. In this section some of the basic methods and techniques applied to micro-machining are explained.

5.1 The basic system

Systems tend to either operate by having the sample fixed and the laser beam moving or by fixing the sample to a moving stage, or set thereof, and having a fixed objective lens, figure 5. There is also the option to use galvanometric systems where the beam is manipulated using mirror(s) and obviously a combination of all three. Each of the layouts has its own pros and cons depending on the main purpose of use, for instance when the desired sample is small and is required to be machined quickly then galvanometric systems can be most advantageous, however, when operating over a larger area these systems suffer from spherical plane effects and correcting for these often leads to a loss of sharpness in the focusing. This is especially important for femtosecond work where the depth of focus, due to the nonlinear nature, is so small.

Often the most practical systems use a partially fixed objective, where the objective is also on a stage but often remains stationary when working at a given depth in the sample, and use mechanical or air bearing stages to move the sample. These are often programmed by computer linked drive control units. The majority of stages operate some version of CNC (Computer Numerical Control) system (Smid, 2005) each of which have their own protocols, however, the techniques used are applicable to most if not all systems of this sort.

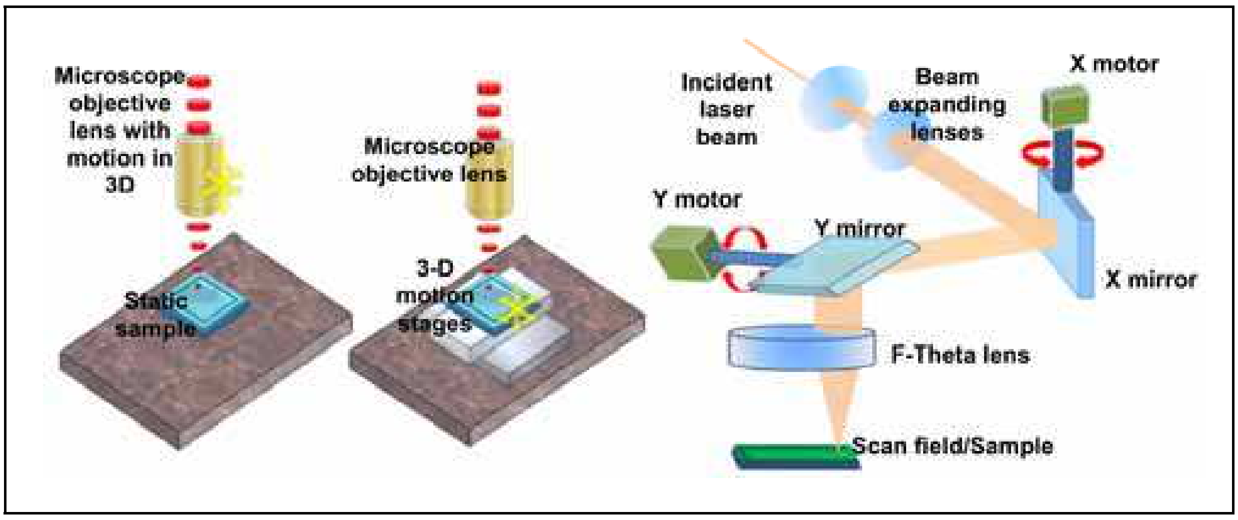

Fig. 5. A schematic of three types of focusing arrangement from left to right a static sample with moving objective, a moving stage with static objective lens and a galvanometric set up with motion controlled by mirror angle.

5.2 Common terminology & basic techniques

There are a number of terms applied to certain types of machining that describe the fundamental technique applied to working on a work piece and these are defined in table 2. The first of which we will consider is percussion drilling. This is a process of firing a number of pulses on a given area, each pulse removing a very small volume of material, thus leading to the creation of a hole. Typical laser repetition rates over 1kHz allow removal rates to be viable for use. This technique is used for the creation of small holes through or in materials. In general the material removal rates are relatively constant for small depths (to ~100 µm) after which the removal rate operates as the square root of the depth. Thus the time taken to double the depth is typically in excess of four times that of the initial hole. This occurs because as the beam penetrates to the bottom of a hole energy is lost to the material and the nature of Gaussian beam paths, after focusing, means that the energy available at the bottom decreases as the wing that is clipped is inversely proportional to the aspect ratio increase. Typically helical trepanning produces some of the smoothest side walls and most uniform holes but takes longer and tends to be best applied to smaller artefacts.

5.3 Other considerations

There are a number of other parameters and components to be aware of that can be critical to the finish and quality of a desired object. It is important to consider the desired aspect ratio or etch depth, the NA and working distance of the lens, the position of the focus in the sample, the beam polarisation, the speed of the moving parts and an inspection mechanism.

The aspect ratio is defined by the ratio of depth to width of an artefact, for example, a microfluidic channel or hole through a ceramic. The etch depth is the effective write depth of an inscribed feature such as a waveguide or diffractive element inside the bulk of the material. To optimise both of these parameters the choice of lens, power and beam shaping are fundamental. If aiming to write a deep slot into a substrate one would typically choose a lens with a low NA and long working distance so that it could operate at a distance and over a range of positions without being coated with the debris created by the plasma and

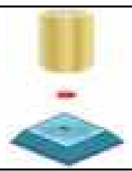	**Single shot drilling -** The process of using a single laser pulse to drill, this is rarely used.
	**Percussion drilling -** The use of a number of laser pulses at a repetition rate spacing above that of the length of the pulse used to remove material. Can lead to surface spatter which can lead to micro-cracking, deformation of hole shape and achieving high aspect ratios is often difficult.
	**Trepanning -** This is essentially percussion drilling with circular motion, often a pilot hole is drilled and then a spiral motion followed by circular finishing. The technique suffers from the same drawbacks as percussion drilling. The hole size formed by this motion is, to within the radius of the plasma, the diameter of motion. The holes produced by trepanning are generally more circular and accurate than a percussion drilled hole, however, they are larger in size.
	**Helical drilling -** The process of quantizing the ablation steps reaching breakthrough only after a number of passes described by a spiral motion. This often has a more circular geometry than trepanning and also minimises the load placed on the opposite face to that of the focus. It tends to also give less recast, however, takes significantly longer to process.
	**Cutting -** Cutting through a sample using a series of pulses through motion of the beam or sample, often multiple passes are required. **Etching / Milling -** Removing a defined depth of material through control of pulse energy and/or number of pulses per location.
	**Rastering -** The motion of moving back and forth over an area with lines separated by a given pitch. By varying the pitch this can lead to the removal of material from an area or in trenches. Typically these form square wave patterns although other forms are also used.

Table 2. A Table of the common techniques and a brief description of their mechanism.

avoiding contact with the material. Ideally most of the work should be done with a static z component and the right choice of lens, however, there are times when stepping the lens towards the sample is necessary to achieve a specific depth or profile. The position of the focus required to ablate a slot, when scanning, is typically not at the midpoint of the desired slot depth. Through experience it comes out at typically 1/3 of the depth but the exact position will change depending on the sample and other parameters. There are also issues to do with shielding by the walls when looking to achieve high aspect ratio side walls. This is because the pulses wings are clipped reducing the power of the pulse.
The speed of any scanned motion, as with repetition rate, will affect the rate of removal of material. This is because the fluence will be varied by the change in the speed of motion as the number of pulses per unit volume will be less. A variation in the repetition rate would have the converse effect. That is to say that if the pulse rate increases by a factor of 2 that the removal rate would increase linearly, assuming constant pulse energy. Whereas a doubling of the speed would half the removal rate or create a series of dots rather than a line.

There are two types of polarisation that can be used, linear and circular polarisation. The polarisation is believed to affect the write quality of inscribed lines such as waveguides. The current thinking is that a polarisation orthogonal to the direction of write for straight waveguides, or circular for curved ones, is preferable and results in smoother tracks (M. Ams et al., 2006). Polarisation parallel to the direction of write is not favourable since it produces less smooth tracks. There are other techniques employed such as combining cylindrical lenses with the regular microscope objectives to refine the width of written lines.

The ability to fully inspect and align a sample pre- and post-inscription or ablation is of fundamental advantage to any system. The use of confocal systems and inspection methods to inspect during writing has also developed considerably in recent years (J. Li, et al., 2008). A standalone camera can also be used to monitor the sample. The exact design and components used will not be uniform across all systems but the importance and advantage gained by their inclusion are extremely significant to the complexity of the fabricated devices.

Some examples of femtosecond micromachining are shown in figure 6. The images illustrate some of the common effects observed, both good and bad, from femtosecond micromachining. By reducing the separation between the slots it is possible to reduce the wall thickness and create extremely high aspect ratio structures. Figure 6 also shows entry and exit holes. The entry holes in this example are slightly rounded which can be corrected for by adjusting the focus position. The third image shows how both good and bad set up parameters affect the resultant finish quality.

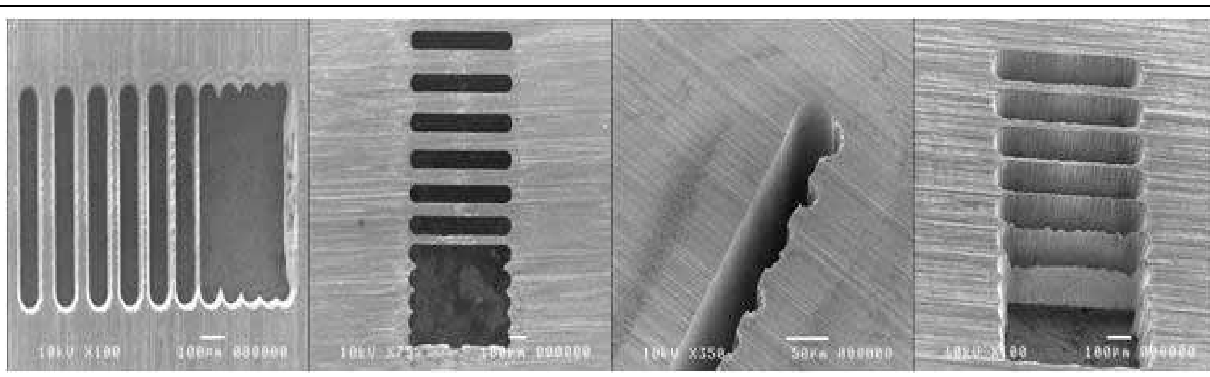

Fig. 6. Slots machined in stainless steel shim 0.178 mm thick; (LHS) entry side showing gradual reduction in slot separation, (left middle) exit of the same slots, (right middle) slot showing what happens when the parameters and finishing are correct and wrong, (RHS) showing the high aspect ratio structures remaining after ablation.

5.4 Computer Aided Design (CAD) & rapid prototyping

There are a number of applications of femtosecond micro-machining where the complexity and rapid prototyping required are less suited to programming the motion line by line. This is clearly shown in the complexity of the microfluidic device illustrated by figure 7 below.

To code this line by line would be extremely time consuming and to change something like the machining pitch could take considerable effort going through the code line by line. In these situations the use of CAD software packages can be a significant advantage in being able to vary the parameters (such as pitch, write speed and scaling) quickly and design complex structures that would otherwise take significantly longer. Although it is not impossible to code some of the more complex structures the plausibility and economy of doing so when the software packages are available becomes more weighted in favour of the automated approach (G. Smith, 2008).

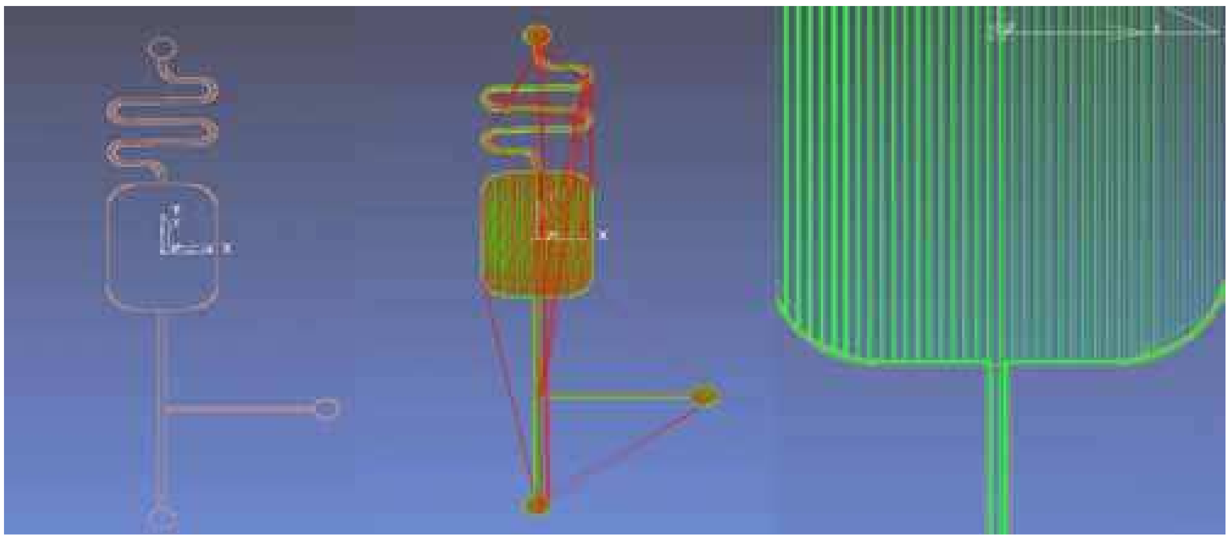

Fig. 7. Computer Aided design images, from left to right 1) An plan view of a computer designed microfluidic device, 2) the machine path lines shown for workpiece with green representing the path of the laser ablation and red being the skimming non ablation transit, 3) a close up of the tool path for ablation showing rastering and a finishing edge pass.

5.5 Post processing

There are a few post processing techniques that are important in relation to femtosecond micromachining. The most common technique is to wet etch using either hydrofluoric acid (commonly abbreviated to HF and is hydrogen fluoride in water solution) or ammonium bifluoride (ABF is chemically NH_4HF_2 and a diluted version of HF in a salt form, although used in water solution). The whole process involves inscribing the material (below the ablation threshold) using the laser focal spot then placing the substrate in the acid. The acid preferentially etches the inscribed areas at a rate of 50:1 in fused silica (K. Sugioka et al., 2007) and as such removes the inscribed area selectively. This technique offers the ability to make smoother structures in transparent materials with smaller features and higher aspect ratios. It is also possible to fabricate subsurface channels that would otherwise take a sequence of layer deposition stages or lithographic techniques. There is a downside, in that the use of these chemicals adds additional processes and time over direct ablation and involves the handling of hazardous chemicals. Figure 8 shows work done in optical fibre. The fibre has been exposed by femtosecond laser inscription below the damage threshold then wet etched using HF producing very narrow, high aspect ratio channels through the fibre core.

The use of heat treatment, cycled and constant, may be important for femtosecond micromachined structures. In theory, the thermally induced stresses created by the shockwaves propagating in the material around the plasma can be thermally annealed out through heating the substrates post inscription. Heat treatment thermally relaxes the material such that the stress is released and the permanent change of the inscription is all that is left. This effect is still the subject of study and its ability to offer further understanding of the plasma-material interaction will most likely be of fundamental impact (S. Juodkazis et al., 2004).

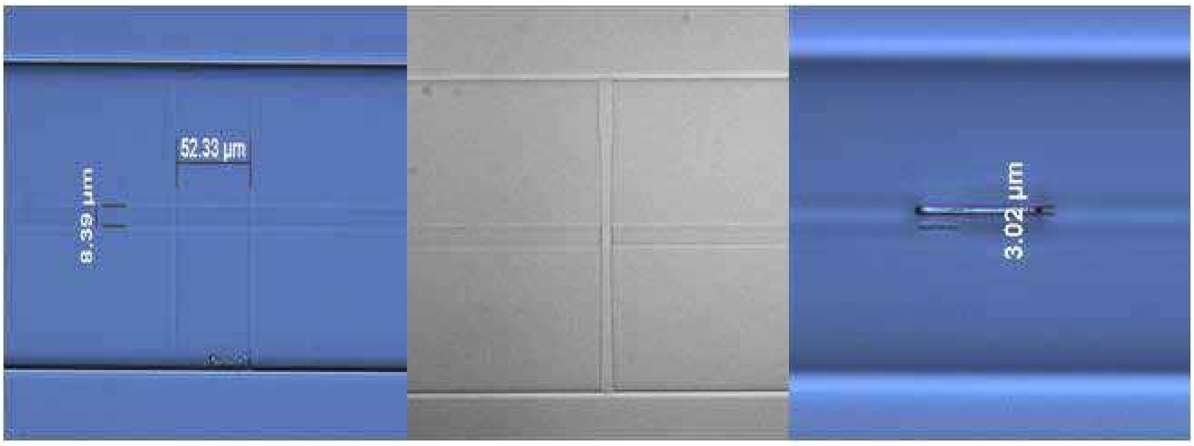

Fig. 8. Micro-channels fabricated in standard fibre using fs inscription and chemical etching (Y. Lai et al., 2006).

6. Applications

The numerous properties of femtosecond pulse interactions with a range of materials have led to a diverse range of novel applications. For example, the ability to micromachine in 3 dimensions in transparent media due to the nonlinear interaction has opened up possibilities that were previously not available without the addition of dopants and short wavelength laser exposure. There are also a number of applications that would simply not be possible without the use of femtosecond lasers for micromachining. Having said this there should be a note of caution as while there are numerous advantages to the technology it should not be considered as the only solution to all applications. Instead the advantages should be utilised for specific purposes.

6.1 Periodic structures

Because of the short pulse duration and the high refractive index changes that can be induced femtosecond lasers can be used to produce period structures in transparent materials. More specifically, they have been used to fabricate fibre Bragg gratings (Y. Kondo et al., 1999). These structures are written into or near the core of an optical fibre and reflect light at a wavelength determined by the periodicity of the structure.

Two approaches to the fabrication of these structures have been optimised over the last few years in the femtosecond domain: the point-by-point method (E. Wikszak et al., 2004; A. Martinez et al., 2004, K. Kalli et al., 2009) and the phase mask method (K. A. Zagorul'ko et al., 2003). Both methods had previously been used for the UV fabrication (with either CW or conventional pulsed lasers) of fibre Bragg gratings however the femtosecond regime provides some key differences due mainly to the localisation of the fringes which allows, for example, multiple gratings to be positioned in unique positions around a single core, as shown in figure 9. This can be highly advantageous from a device design point of view as, for example, it enables the production of a single fibre Bragg grating device that can be used as a directional bend sensor. Gratings can also be inscribed through the hole structure of microsctructure optical fibres using femtosecond lasers. Kalli et al have shown that with a suitable fibre design it is possible to use femtosecond pulses to penetrate the holes of the microstructure fibre without significant breakup of the femtosecond laser pulse during inscription.

In planar samples femtosecond lasers have been used to inscribe diffraction gratings which can in turn be used to fabricate fibre Bragg gratings (G. N. Smith et al., 2009). A photograph of one of these is shown in figure 9 showing first, second and third order phase masks. The work to date demonstrates the proof of concept and flexibility for the use of femtosecond lasers to make complex and reproducible phase masks. This approach has the potential to rival e-beam fabrication of phase masks and has the advantage of being a single step fabrication process that uses no chemicals.

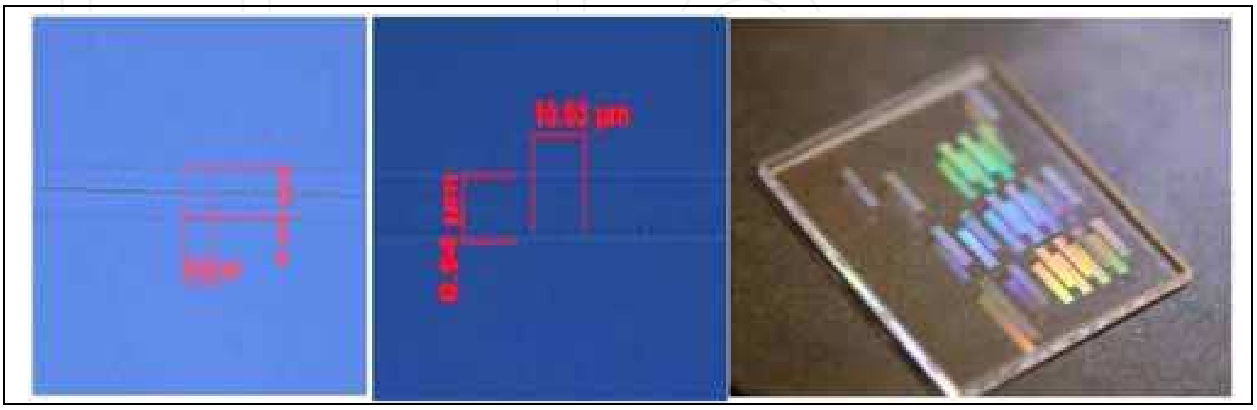

Fig. 9. Femtosecond inscribed fibre Bragg gratings in (LHS) the centre of the fibre core and (middle) on the edge of the fibre core, (RHS) photograph of a femtosecond phase mask inscribed with fs laser underneath the surface of the UV grade fused silica (G. N. Smith et al., 2009).

6.2 Micromachining of planar glass

Microfluidic device, incorporating high aspect ratio micron scale channels, can be directly machined. These devices are developed as lab-on-chip devices for purposes such as measuring a specific particle to particulate sorting and counting (D. N. Schafer, 2009). The advantage is that they only require tiny amounts of a fluid to function thus reducing costs of development of chemicals, allowing more information to come from smaller samples at increased speed of prototyping and development. Some of typical structures that are employed are shown in figure 10. They show bends, micropump holes, joints and high aspect ratio structures in both planar and fibre samples all of which can be easily adapted and machined using femtosecond micromachining giving advantages for rapid prototyping (G. Smith et al., 2008).

There are a number of methods for making these devices. The most common is to inscribe a structure in the material and then expose it to hydrofluoric acid. Another is to ablate structures or create voids in the presence of what are known as wetting fluids (Y. Iga et al., 2004). This works in the same way as you would use fluid with a standard milling process to remove the debris from a machined area. A third method is dry ablation, however, the results often lead to sidewalls that suffer from turbulent flow (rather than the ideal lamina flow) due to the surface roughness.

6.3 Waveguiding

There has been a great deal of interest in the use of femtosecond lasers to make waveguides. They have been used to make a number of things from straight connectors and curved waveguides to more complex structures like splitters, beam shapers, amplifiers and

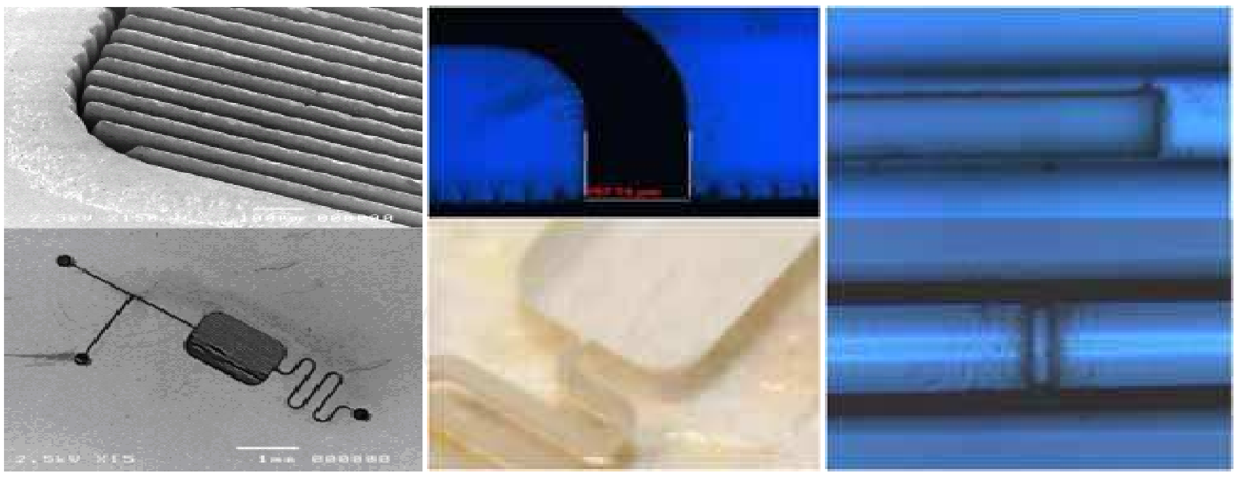

Fig. 10. Microfludic devices - (top LHS) SEM image of micro-groves to enhance fluid mixing (bottom LHS) SEM image of test structure, (top middle) microscope image showing smooth channel bend from microfluidics device, (bottom middle) photograph of larger scale structure showing high aspect ratio of fluid guides, (top RHS) slot ablated along the fibre axis in optical fibre using fs laser to within 5µm of the fibre core, (bottom RHS) slot ablated perpendicular to the fibre axis.

interferometers (A. A. Said, 2004; A. Szameit et al., 2006; A. M. Kowalevicz et al., 2005; K. Minoshima et al., 2001). There have been other avenues where the properties have been utilised such as the image reconstruction using a waveguide array (A. Szameit et al., 2009). This and other applications rely on the 3D write capability of femtosecond lasers allowing the creation of complex structures that are otherwise typically built layer by layer. The only pre-requisite is to create permanent index change localised to the area of write, typically the desired effect is a positive index change although other structures are also possible, thus forming a guide for the light to travel along. There are normally areas around the waveguides where the pulses have interacted with the media through the wings of a pulse or through heat shockwaves etc. These are best reduced through optimisation of the material and laser parameters used. Waveguides have typically been written in planar glass or crystalline samples, however, using femtosecond laser it is possible to inscribe waveguide structures in optical fibre. Figure 11 shows an example of this written at Aston University using a femtosecond laser in standard single mode optical fibre. The guide ends close to the edge of the fibre core and couples light from the evanescent field out of the fibre. This shows the potential to include complex waveguide based structures in fibres which could have a range of telecommunications and sensing applications.

6.4 Other applications

Femtosecond lasers have been used for numerous other applications, some of which are briefly described here to provide an illustration of the scope and potential of femtosecond lasers.

Optical data storage uses micron sized defects, typically index variations, in substrates used for the storage of data in a highly dense arrangement. This has now been accomplished in 3 dimensions and in a rewriteable format (K. Miura et al., 2002). The ability to write the points in 3 dimensions is something that can only be achieved through the use of the nonlinear femtosecond processing. The other key advantage of using a femtosecond laser process is

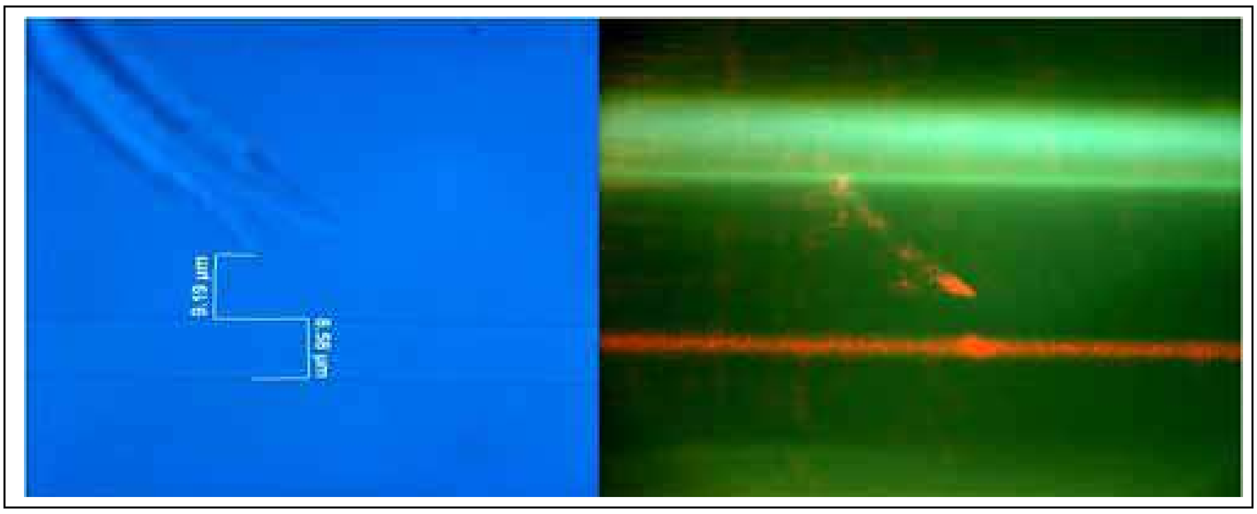

Fig. 11. (LHS) microscope image showing the separation of the fibre core and start of written guiding structure, (RHS) dark field microscope image of light being outcoupled from fibre core by a waveguide/lightpipe structure written with a femtosecond laser.

that the high point density that can be achieved through the spatial confinement of the femtosecond pulse-material interaction. This more localised index change means that the point defects can be more closely arranged giving higher density data storage without undesirable, peripheral modified regions that would otherwise make data recovery impossible.

Photopolmerisation exploiting the two photon polymerisation affect using femtosecond lasers has been used to create submicron features in polymer after chemical rinsing (R. Guo et al., 2006). This has produced a range of intricate structures that have a wide range of applications from terahertz lenses and photonic crystal structures and to non-photonics applications for example to produce medical stents. The femtosecond lasers unique ability to polymerise liquids and resins allows more intricate and complex artefacts than any other source to be produced. This ability to form fine structures is due to the small volume of interaction and spatial confinement femtosecond lasers.

There are a number of medical applications for femtosecond micromachining ranging from eye surgery and dentistry to cell transfection (C. T. A. Brown et al, 2008; C. McDougall et al., 2009; S. H. Chung & E. Mazur, 2009). Femtosecond lasers are used to perform submicrometer resolution surgery with minimal invasion and also use multiphoton absorption processes initiated by the femtosecond pulses to permeate cell membranes in a transient manner. One example of this is the injection of gold nanoparticles into mammalian cells using optical transfection combined with optical tweezing techniques. Interest in the use of femtosecond lasers in dental surgery has been generated because of a few key qualities. The short pulse durations provide crack free machining (an important attribute for successful cement fillings), the removal rates are comparable to those of mechanical drills and much improved over picoseconds lasers and reduced pain levels incurred are all fundamental reasons for ongoing development in this field.

Laser assisted in-situ keratomileusis (LASIK) is the surgical manipulation of the cornea (keratomileusis is Greek for cornea flap cutting). Using lasers to do this has become a common surgical procedure with high success rate and is now the most commonly performed refractive surgical procedure. The unique nature of the femtosecond pulse-matter interaction and the lack of damage caused to surrounding areas, due to better spatial confinement and lower thermal loading, has led to femtosecond lasers being developed to replace the other lasers and perform as minimally invasive, accurate and precise scalpels on a daily basis (J. F. Bille, 2008).

7. Conclusions

The use of focussed femtosecond laser pulses to fundamentally change materials through the interaction of the pulse and material offers new opportunities in device design. This is especially true for fabrication of intricate microstructures within the bulk volume of optically transparent glassy or polymeric materials. But it also can give significant advantages for the micromachining of surface structures in opaque materials in terms of feature size and aspect ratio.

Although femtosecond laser micromachining and inscription has been studied for several decades recent significant improvements in the range of lasers available have accelerated the technology into a range of diverse fields. The lasers available today offer vastly improved peak powers and reliability making commercial exploitation more viable. The advantages of using the nonlinear interaction of light with solid materials are being explored in a number of exciting ways, both in science and engineering, with new avenues opening up as new materials, sources and techniques are developed.

The capacity for making use of the short pulse durations, nonlinear absorption and other characteristics discussed above to create complex three dimensional structures both on the surface and within materials has attracted much recent research effort. However, there is much more potential through the combination of techniques and the development of further knowledge, simulation and modelling that will likely lead to future applications and fields that are only in their infancy at present.

The unique capabilities of femtosecond micromachining make it preferential in a great number of applications. The capacity to locally modify and create permanent change in a range of both transparent and non-transparent materials is of fundamental importance not only to photonics but to a growing number of manufacturing processes. The industrialisation of micromachining processes will be of great significance in the future success of solar cell and flexible organic light emitting diodes (OLEDs) in the manufacture of large sheets that need highly localised and complex machining patterns cut at speed. The most prominent current technology that will be able to facilitate this is the use of femtosecond lasers.

The reliability of the current generation of femtosecond sources compared to earlier models means that these lasers are rapidly being accepted as an option for commercial fabrication. With the continued development in the supporting technologies associated with femtosecond lasers such as the improvement in pump sources, development and commercialisation of more efficient glass compounds, the pulse-material interaction being more fully understood and the delivery systems and techniques being refined, there is a promising future for femtosecond micromachining to expand into more fields and become a common part of manufacturing and photonics industries.

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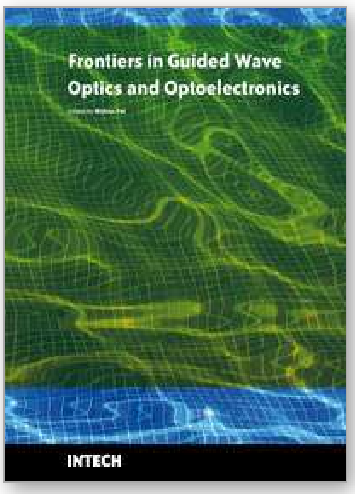
8.1 Laser suppliers

For details of the laser specifications go to the links below;

Amplitude systemes: http://www.amplitude-systemes.com/

Coherent: http://www.coherent.com/Lasers/
High Q: http://www.highqlaser.at/en/products/
IMRA: http://www.imra.com/
Kapteyn-Murnane Laboratories: http://www.kmlabs.com/
Raydiance-Inc: http://www.raydiance-inc.com/our-products



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As the editor, I feel extremely happy to present to the readers such a rich collection of chapters authored/co-authored by a large number of experts from around the world covering the broad field of guided wave optics and optoelectronics. Most of the chapters are state-of-the-art on respective topics or areas that are emerging. Several authors narrated technological challenges in a lucid manner, which was possible because of individual expertise of the authors in their own subject specialties. I have no doubt that this book will be useful to graduate students, teachers, researchers, and practicing engineers and technologists and that they would love to have it on their book shelves for ready reference at any time.