# Micromachining of Industrial Materials with Ultrafast Lasers

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## Abstract

The use of femtosecond-pulse titanium sapphire lasers for micromachining applications is described, with particular emphasis on the advantages and disadvantages of this technology for existing and emerging microfabrication applications. The effects of micromachining in different materials such as silicon, diamond and glass are presented and the results are compared with those from other laser sources. The relevance to emerging applications is discussed.

## Introduction

Femtosecond laser technology has been in use in a wide range of disciplines for more than thirty years and significant developments have been made in many fields of physics, chemistry and medicine. Materials processing is one of the areas where ultrashort pulses offer many unique advantages but the widespread use of ultrashort pulse micromachining has been somewhat slow to develop, mainly due to the lack of suitable, user-friendly laser systems. In the past couple of years, however, high repetition rate, amplified, femtosecond pulse laser systems have become commercially available and these new sources have again given fresh impetus to ultrashort pulse micromachining studies.

Laser micromachining applications generally require a number of particular attributes from the laser, which include:

- Good beam quality ($M^2$ ~1.5)
- High pulse energy (~millijoules per pulse)
- High repetition rate (~few kHz)
- Reliable, simple operation
- Easily controllable system parameters

A number of "single-box" ultrashort pulse laser systems - where the oscillator, amplifiers, pulse expansion/compression gratings and pump lasers are housed in a single mechanical unit - are now available from companies such as Spectra Physics (USA), Clark (USA), Thales (France) and Quantronix (USA) and these systems provide the potential for the use of femtosecond lasers in industrial micromachining applications. The ease-of-use and consistent operation of these laser systems is an important parameter for industrial users and major advances have been achieved in this respect recently.

In this article, we present data derived from the use of two commercial femtosecond laser systems with different materials to present an overview of ultrashort pulse micromachining. The industrial relevance of such work and the issue of integration of such systems into industrial environments is addressed. Comparative results from laser micromachining with nanosecond-pulse solid-state lasers is also included to enable a fuller picture of current options to be presented.

## Femtosecond and Nanosecond Laser Micromachining

Much work has already been conducted in the use of solid-state lasers for micromachining tasks and it is useful to compare what these different sources offer for different applications. The new femtosecond laser systems provide another excellent option for the laser applications engineer but it is important to remember that femtosecond pulses cannot provide the best results in all cases and that other longer-pulse lasers may give a more complete solution in specific applications.

All the work reported here using femtosecond pulses was carried out using either of the following two laser systems:

- "Hurricane" laser system from Spectra Physics (~0.75W, 1kHz, ~800nm, 130fs)
- "Brite" laser system from Thales Laser (~1.5W, 3kHz, ~800nm, 130fs)

Both these systems are commercially available and have similar output characteristics, offering a single-unit source of amplified, high repetition rate, femtosecond pulses. Both systems offer the ability to adjust the pulse duration from ~100fs to ~1ps but this facility was not used in the trials reported here and all work was performed at the shortest available pulse duration of ~100fs.

The laser pulses were steered from the laser to the sample using broad-bandwidth, multi-layer, dielectric-coated turning mirrors. A thin singlet lens made from fused silica was used to focus the laser onto target and focal lengths ranging from 50mm to 150mm were used. High precision XYZ stages were used to control the position of the sample and the focal position of the laser beam.

All samples were machined in air and the only post-processing which was conducted was immersion in a ultrasonic bath of isopropanol for a few seconds to remove any loose debris. Assist gas was sometimes employed to stop debris and re-deposition of ablated materials from collecting on the sample surface.

### Silicon

The processing of silicon using chemical or plasma etching techniques is an extremely mature technology and has been developed over many years mainly for the microelectronics sector. These "conventional" processes produce exceptional results but only with a relatively small number of options for the shapes and geometries which are possible - there are an increasing number of applications where standard techniques cannot provide the desired results and where other methods are required. In photonics applications, for example, where sensitive optical devices are integrated onto silicon wafers, the use of etching is often not desirable or possible. In such cases, the use of direct laser microprocessing provides the means to produce different machined features.

The simplest requirement in silicon-related work is for the dicing of wafers, which is easily done by the machining of straight lines using nanosecond-pulse Nd:YAG lasers operating in the near infra-red spectral region. Apart from this dicing work, however, all other current silicon applications usually require the precise, high quality micromachining of wafers with good cut-edge quality, little taper, no debris and no thermally-affected zones. This means that, in general, new laser sources are required with good energy stability and higher average powers which emit at shorter wavelengths with short pulses.

Femtosecond pulses have been shown to produce damage-free micromachining in silicon and many other materials [1]. Figure 1 shows an example of a rectangular slot etched in a silicon wafer with sharp edges and totally free of thermal damage surroundings.

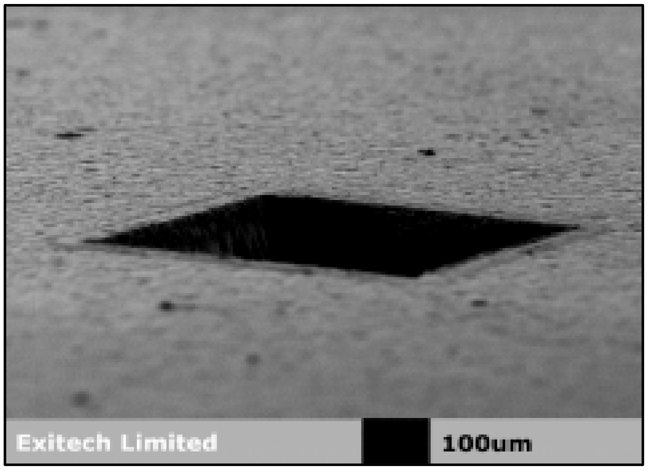


Figure 1. Silicon machined with femtosecond pulses from a titanium sapphire laser.

With the continuing advances in the development of industrially-robust, diode-pumped, solid-state (DPSS) lasers, the higher harmonics of the Nd:YAG laser (532, 355 and 266nm) have attracted great interest for many micromachining applications. In particular the third harmonic of DPSS Nd:YAG lasers emitting at 355nm with several watts of average power obtainable from commercial suppliers is already a proven tool for drilling microvia holes in printed circuit boards [2].

Apart from the relevant production quality issues, the speed of processing is another major requirement in order for a laser to be considered as a manufacturing tool. In many cutting and drilling applications of silicon an important concern is for the laser process to be cost-effective, offering production volumes that reduce the part manufacturing cost.

Ablation studies were carried out using a Lightwave Electronics diode-pumped 3rd harmonic Nd:YAG laser (model 210P-355-5000) to compare with micromachining of silicon with that using ultrashort pulses. The laser produced a maximum output pulse energy of 600µJ at 10kHz corresponding to average power of 6W with pulse-to-pulse energy stability of better than 0.3%. At this repetition rate the pulse duration was 38ns.

In figure 2, comparative etch rate data of silicon is shown as a function of incident laser fluence using a nanosecond Nd:YAG laser at 355nm and a femtosecond Ti:sapphire laser at 800nm. Each laser beam was focussed on the silicon surface using thin singlet fused silica lenses to spot sizes of 15 μm and 30 μm respectively. The morphology of the craters was measured with a high resolution optical microscope. Five pulses were used in the case of the Nd:YAG laser and 100 pulses for the Ti:sapphire laser.

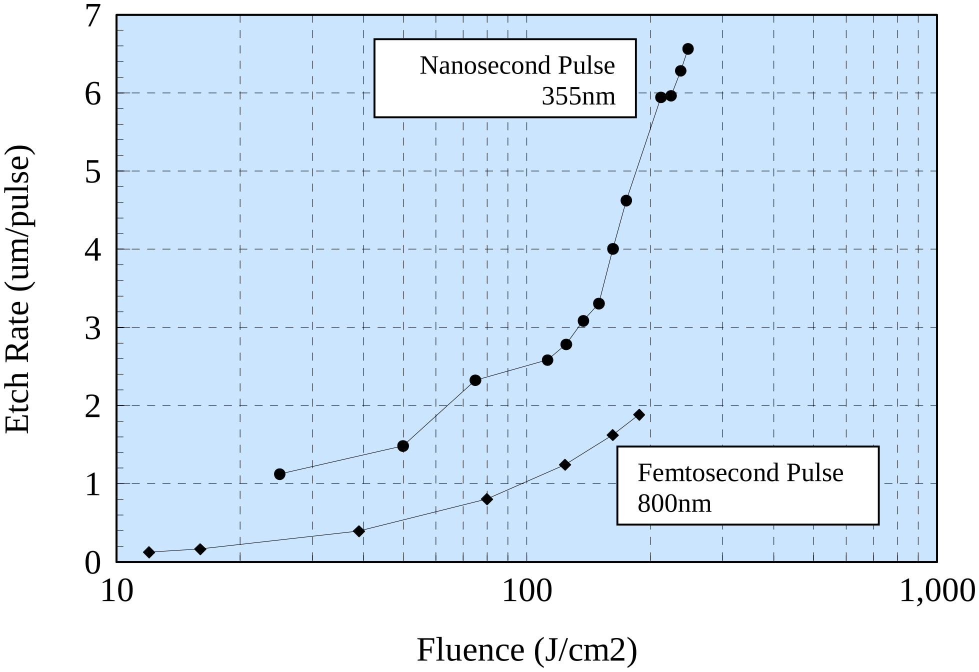


Figure 2. Etch rate data for silicon using a nanosecond-pulse Nd:YAG laser and a femtosecond-pulse titanium sapphire laser.

The shape of the ablated crater closely resembled the spatial profile of the beam, which was very close to a Gaussian ($M^2$=1.2 and 1.5 for the Nd:YAG and Ti:sapphire lasers, respectively). Although etching is not spatially uniform using these lasers, the depth of the crater can provide a good indication of the etching efficiency in each case. It can be seen that in the case of the nanosecond laser, the crater depth increases gradually as the fluence increases from 10 J/cm$^2$ to 100J/cm$^2$ resulting to etch rates between 1-2.5μm per pulse. Above ~110J/cm$^2$ a different regime is observed where the crater etch rate increases rapidly from ~2.5μm/pulse to 6.5μm/pulse (at 250J/cm$^2$) indicating a different ejection mechanism. In contrast the femtosecond laser machines silicon at a lot lower etch rate for similar fluence range. In this case as the fluence increases from 6J/cm$^2$ to 94J/cm$^2$ the etch rate gradually increases from 0.1 to 1.27μm per pulse, almost half that achieved with the nanosecond laser. Also, the two sets of data have been averaged using different numbers of laser pulses and therefore they are blind to any discrepancies arising from a possible difference in the ablation mechanism in multi-shot experiments.

There is qualitative agreement between the data shown here and previously reported ablation studies of Si with Nd:YAG solid-state laser at 266nm [3] and also with femtosecond laser ablation experiments at 800nm [4]. It is generally observed that femtosecond lasers ablate Si in a more controlled manner and therefore offer a great advantage as a tool for the precise micromachining of miniature devices. This benefit is offset by the fact that femtosecond micromachining is performed at slower ablation rates and therefore can appear less attractive when throughput and cost considerations are taken into account.

The use of solid-state lasers in Si micromachining industrial applications is a more viable solution at present especially because the quality offered is directly comparable to that obtained with the current femtosecond technology. Figure 3 shows a micromachined section from a 4" silicon wafer which was produced using a nanosecond-pulse 355nm laser (Spectron Laser, 60nsec, 1.5W, 3kHz). No post-processing was used on the sample. The sharp edge quality, small taper angle and complete lack of thermal damage to the surrounding areas are all clearly evident from the SEM.

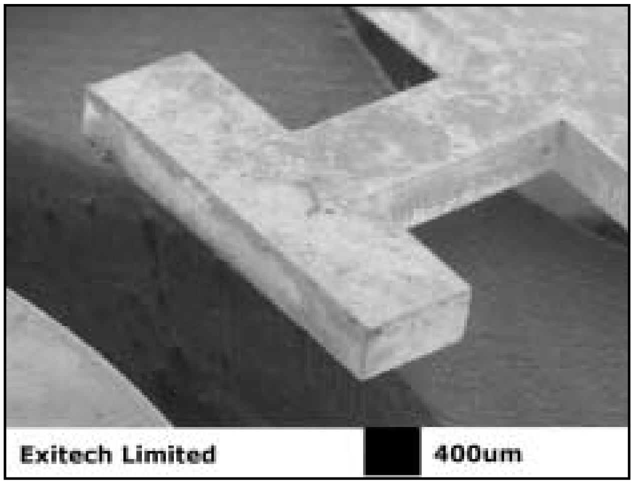


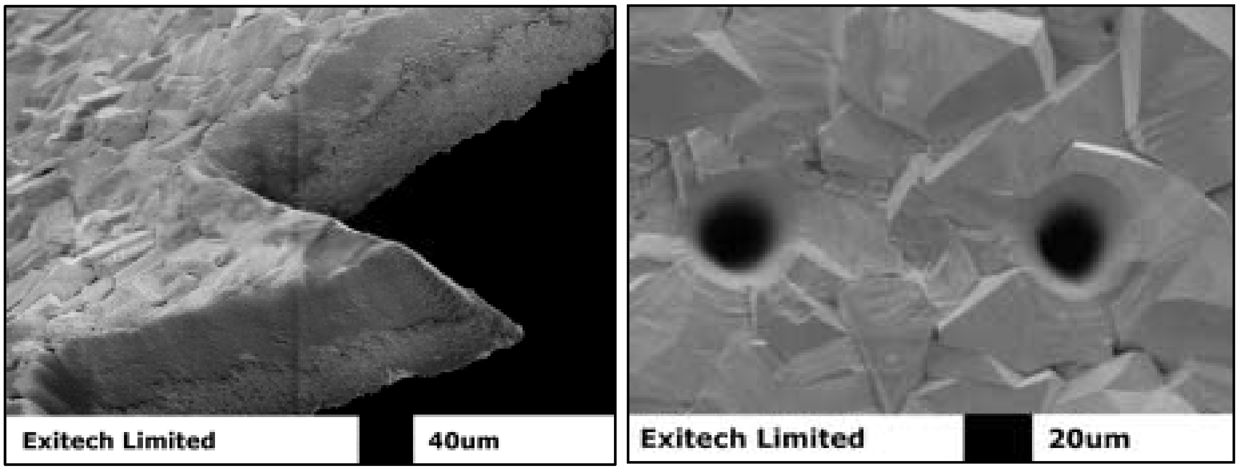
Figure 3. Silicon wafer machined using a Nd:YAG at 355nm.

### Synthetic Diamond

CVD diamond is becoming an important material in a growing number of optical and opto-electronic applications, mainly due to its unique set of physical, thermal and optical properties [5]. Laser processing options for CVD diamond include cutting, drilling, smoothing and machining (e.g. microlenses). Various lasers have been used for diamond applications including nanosecond-pulse infra-red Nd:YAG lasers and UV excimer lasers. With both these lasers, cutting or machining is possible but there is always an issue with graphitisation of the areas adjacent to the machined sites. In high resolution applications, this is often unacceptable.

We have used femtosecond pulses to laser smooth and cut wafers of CVD diamond with no evidence of this graphitisation problem. Figure 4(a) shows a SEM of a diamond wafer which has been cut using the "Brite" femtosecond laser and the excellent edge quality, sharpness of the feature and the lack of any surrounding damage are all easily seen.

Figure 4(b) shows holes drilled through the same wafer of diamond using a 355nm laser (Lightwave Electronics 210P-355-5000). The quality of the drilled holes is again evident with no damage to the adjacent diamond grains.



(a) (b)

Figure 4. Micromachining of CVD diamond with (a) femtosecond titanium sapphire laser and (b) 355nm Nd:YAG laser.

## Metals, Glasses, Ceramics and Optical Materials

Many other materials are also of interest in different laser applications, particularly in the MEMS/MOEMS field. The unique attraction of using femtosecond pulses was either the excellent quality of the results (especially the lack of thermal effects) or the fact that other lasers could not machine the materials (e.g. silica, fluoro-polymers). These two criteria have now largely been removed as other laser sources have developed sufficiently to allow other options: UV solid-state lasers can achieve excellent quality and fluorine ($F_2$) lasers can access the "difficult" materials such as silica [6].

An etch rate of a variety of materials is shown in figure 5 using a femtosecond Ti:sapphire laser. In this case the data shows the average etched depth as a function of incident laser fluence normalised to the maximum fused silica value. The femtosecond laser was focussed onto the material surface which was moving in a straight line at a constant speed by means of sophisticated motion system ensuring that each individual point in the ablated area received the same number of laser shots. The machined depth of the resultant slot was measured and averaged over the number of passes over the machined path.

It can be seen that all materials exhibited a similar response and that the etched rate showed a linear dependence against the logarithm of fluence, even at very high irradiation levels of the order of $100J/cm^2$. This suggests that there is no plasma screening observed as expected and most of the incident energy will be deposited in the material.

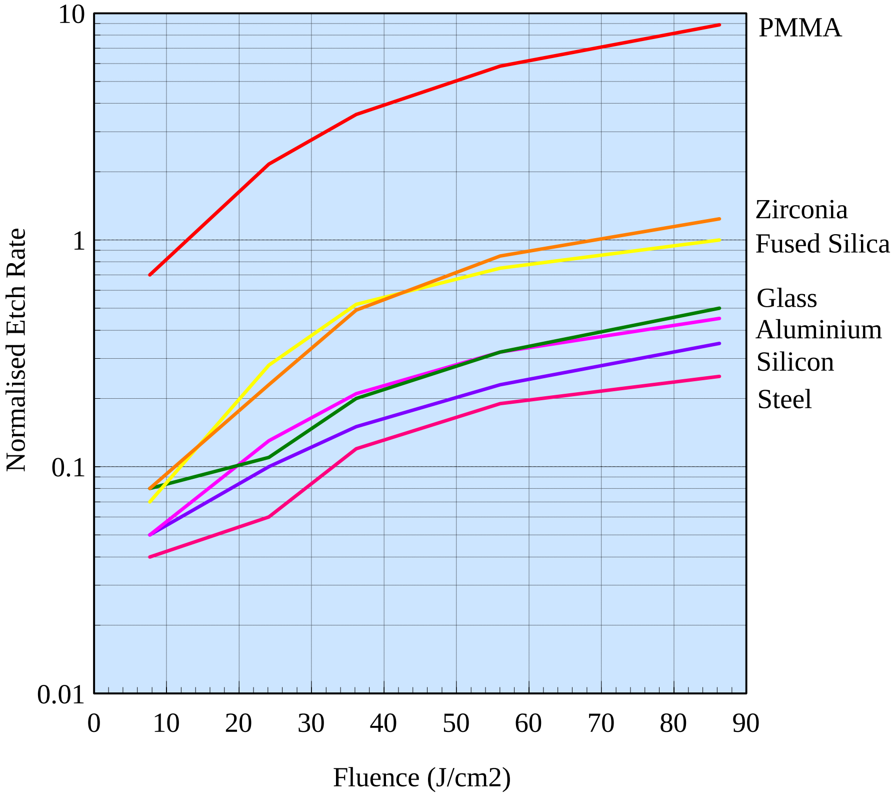


Figure 5. Comparative femtosecond laser etch rates normalised to fused silica.

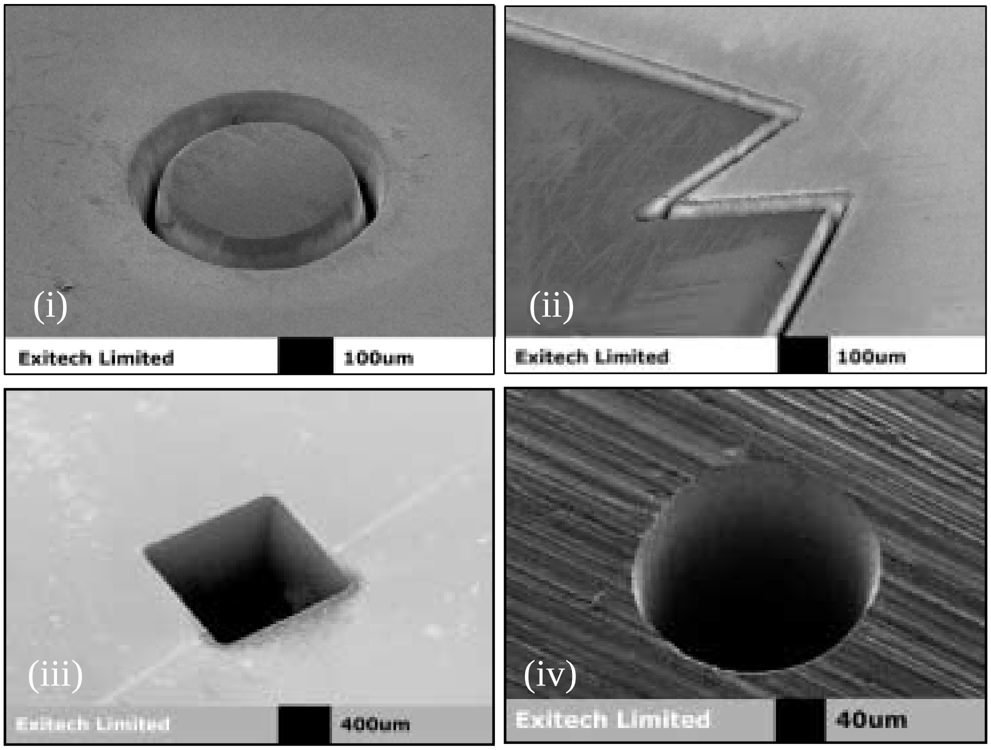


Figure 6. Femtosecond micromachined structures in (i) glass, (ii) silica, (iii) FEP and (iv) steel.

## Steel

The importance of steel in industry has attracted a lot interest for laser micromachining applications. Despite all the effort difficulties remain to laser micromachine at micron scale level to high quality standards. Femtosecond laser micromachining of steel has been recently demonstrated and provides exceptional quality.

Despite the high quality achieved with femtosecond micromachining the laser technology is not mature enough to allow integration in industrial environments yet and other solutions have been put forward such as the use of powerful diode-pumped solid state lasers that can remove material at higher rates.

An etch rate is shown in figure 7, using a Lambda Physik Starline diode-pumped 355nm Nd:YAG providing 3W at 3 kHz. The etch depth has been averaged over 30 incident pulses.

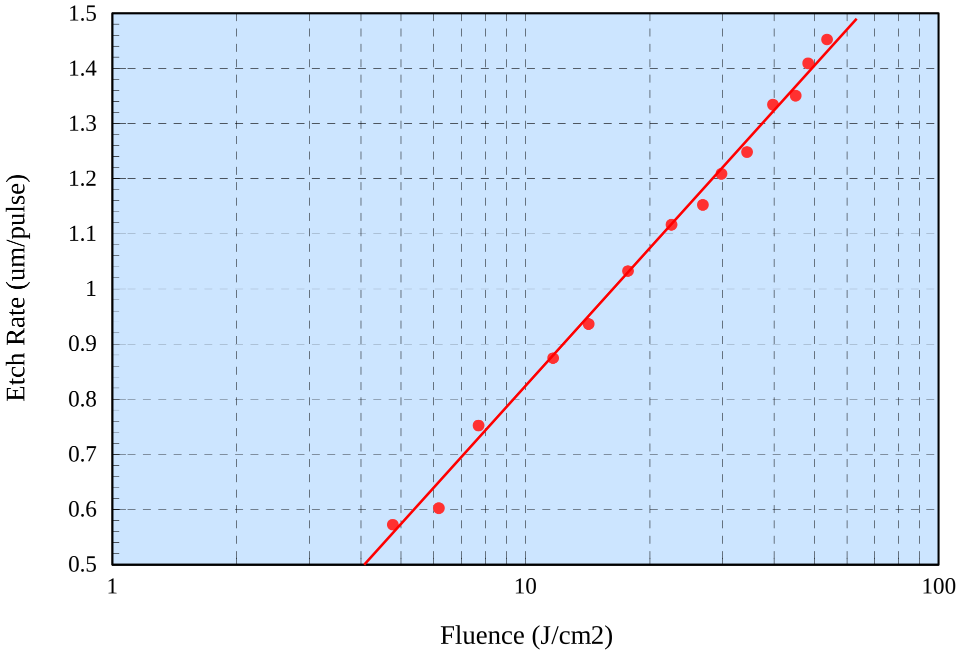


Figure 7. Etch rate for steel with a nanosecond pulse Nd:YAG laser.

## Discussion

Many new applications are emerging to take advantage of laser processing techniques. Two examples of sectors where such work is underway are medicine and photonics. In the medical field, the use of polymer bio-degradable stents for use in heart surgery is opening up the possibilities of implantable devices which do not suffer from incompatibility problems inside the body and which eventually degrade naturally, thereby removing the need for additional surgery for their removal. These polymer stents can be considered for production since the use of femtosecond lasers in their manufacture avoids thermal changes in their composition and so they are able to retain all their beneficial elastic and strength properties even though they have been micromachined. In the photonics area, one of the most important advances being made is the direct production of optical waveguides inside bulk media such as silica by femtosecond pulses. This not only avoids other, more complicated, methods but also gives incredible flexibility in the geometries which can be achieved. Such directly-machined waveguides can also be combined with other structures machined directly with lasers which might be located on the same chip or wafer.

Rapid advances are currently taking place in laser technology and a variety of competing laser sources now offer exciting processing options. In the machining of certain materials such as steels, silicon, silica and PTFE, for example, the situation has completely changed in the past couple of years - materials which were extremely difficult (if not impossible) to machine well previously can now be addressed with femtosecond Ti:sapphire lasers and, in some cases, with DPSS lasers. These major laser advances have been accompanied by another feature: femtosecond pulses are no longer the sole option when considering the machining of "difficult" materials but other sources are also at least as viable. In industrial applications where equipment costs and speed of processing are important factors, the femtosecond laser systems can appear relatively immature and expensive options when compared to other solid-state lasers and a careful choice needs to be made as to which system offers the best combination of micromachining quality and economic viability.

## Summary

A variety of materials which have increasing relevance in industrial applications have been micromachined using femtosecond and nanosecond laser pulses. It seems to be clear that although the results with femtosecond lasers are exceptional in many cases, similar effects can also be produced by the use of other, longer-pulse lasers if sufficient care is taken in optimising the use of those systems. Instead of excluding other solid-state lasers, it looks more likely that femtosecond lasers will find specific niche applications where they are unrivalled but that they will be just one of the lasers of choice in the majority of industrial micromachining sectors.

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