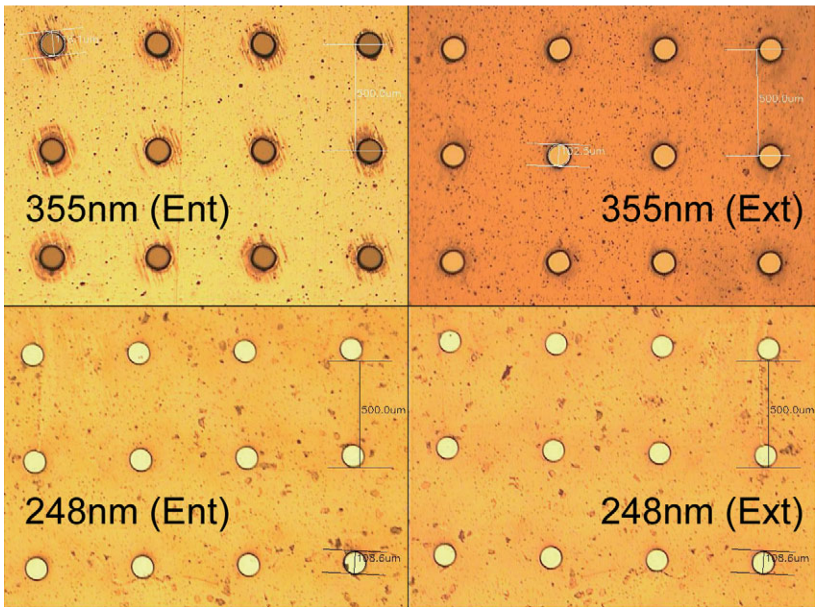
LASER MANUFACTURING

Choosing the Right Laser AND PROCESSING APPROACH



<< Figure 1: Comparison of drilling polyimide with different lasers. >>

NADEEM RIZVI,
LASER MICROMACHINING LTD

People working in laser companies or in the laser machining industry are often asked by prospective users about which laser will be best for their application. This is an almost impossible question to answer in a simple way because it depends on a balance between a very large number of factors — it is the careful mix of these variables that gives the most suitable result and, even then, there is usually more than one answer to achieve the desired result. So, to assess this kind of question, a set of choices has to be made and prioritised to determine which laser process will be selected. Even with such an approach, it has to be said that there is hardly ever a unique solution and usually more than one laser can achieve the desired outcome. This article explores some of the issues in relation to this situation in an effort to explain why it is so difficult to be definitive about laser options and how various processing techniques need to be considered when making decisions.

Which Laser is Best?

Since all micro processing applications require the machining of a material, perhaps the best place to start is to assess how lasers interact with different materials. Table 1 lists some common engineering materials and gives a qualitative guide to how different laser wavelengths machine these materials.

Table 1 shows how different materials can be machined using nanosecond lasers (the most common type of micro machining lasers) and ultrafast lasers (those with sub-nanosecond pulse durations, typically in the range 100fs-20ps). The 'green-orange-red' categorisation of the interactions is purely given as a convenient indicator to show which lasers one might choose as being good candidates for any particular material. It is not always clear-cut which laser will be the 'best' for a micro processing task since the issue of quality is such a difficult one to define — one application may be able to withstand hundreds of microns' worth of damage around a cut edge, which means that an 'orange' category laser may be perfectly acceptable, whereas another application in the same material may need a 'green' category laser due to its higher specification on edge damage; it all comes down to the specific details of the job as to which laser may or may not be a suitable candidate.

In general, there are no hard-and-fast rules on what can be done with lasers in different materials and so Table 1 should be seen in

	NANOSECOND						ULTRAFAST
	193nm	248nm	266nm	355nm	532nm	~1000nm	UV-IR
POLYMERS	Good	Good	Good	Good / Limited	Does not machine	Limited	Good
METALS	Does not machine	Does not machine	Good / Limited	Good	Good	Good	Good
CERAMICS	Good	Good	Good	Good	Good	Good	Good
GLASS	Good	Good / Limited	Limited	Limited	Limited	Does not machine	Good
SILICON	Does not machine	Does not machine	Good	Good	Good	Good	Good
THIN FILMS	Good	Good	Good	Good	Good	Good	Good
QUARTZ/FUSED SILICA	Does not machine	Does not machine	Does not machine	Does not machine	Does not machine	Does not machine	Good
PMMA	Good	Does not machine	Does not machine	Does not machine	Does not machine	Does not machine	Good
PTFE	Does not machine	Does not machine	Does not machine	Does not machine	Does not machine	Does not machine	Good

Good quality machining — *Only machines with limited quality or not at all* — *Does not machine*

Polymers – mainly PC, PI, PE, PET, PEEK but also to include some other common polymers.

<< Table1: Material machining coverage of common laser wavelengths. >>

this context. One example of this is the use of excimer lasers in the aerospace industry; although metals are not traditionally machined with excimer lasers, there is, nonetheless, a very specific application where excimer lasers are used to drill holes in aircraft wings and this is a mature technology (albeit with a very particular set of laser parameters). Hence, Table 1 represents a first-level guide to possibilities rather than excluding particular lasers from a machining task.

Looking at the green categories in Table 1, it might be tempting to make one generalisation: only one type of laser can machine all materials with 'good' quality and that is the ultrafast laser, so why not simply select this type of laser for everything? Although ultrafast lasers can machine all materials rather well, they are much more expensive than nanosecond lasers (being factors of 5-10 more than nanosecond lasers of similar average power, although this price differential is reducing). Price is a big factor in this discussion but quality vs. processing speed is another important one. To obtain really high quality machining, ultrafast lasers often have to be run at very low powers (and pulse energies) and the consequence of this is that the processing speed becomes slow. Hence, the practical penalty for obtaining the best quality of results is that the production time becomes longer and this is something that has to be evaluated carefully. In many industrial (and even development) applications, ultimate best quality is not necessary and so nanosecond lasers become good practical alternatives — if a nanosecond laser can give 90% of the quality of an ultrafast laser but at lower price and faster speed then the case for using ultrafast lasers becomes weaker and this is one of the reasons why the vast majority of industrial applications still use nanosecond lasers. Nanosecond lasers can also give exceptional quality results and so an ultrafast laser is not the only choice when it comes to obtaining high quality results.

Other features which are evident from Table 1 include the fact that quartz and fused silica cannot be machined with any of the common nanosecond lasers, due to the fact that there is such low absorption in quartz/silica from the UV to the near IR. Materials like PTFE and other fluorinated polymers also cannot be machined well with any of the common nanosecond lasers. It is clear that thin films (like nm-thick ITO, TCO and metallic coatings) and ceramics can be processed with any of the laser wavelengths shown and the actual choice which is made will be determined by what features need machining and some of the other issues as discussed later in this article.

A final point to make is that if one material is to be removed from another (e.g. a polymer from a metal or a thin film from glass), then it is helpful if the top material machines easily while the substrate does not machine well with the same laser. Hence removing polymers from metals is efficiently done by a UV excimer laser since metals don't machine well at UV wavelengths; this differential in machining is what makes the selective laser machining possible and so the choice of laser should always be such that it machines one layer strongly while not affecting the other layer.

Comparisons of Speed and Quality

Having seen that there exist options for different lasers to machine a material, it is informative to look at practical examples and compare the results.

Hole Drilling

Many billions of holes are drilled with lasers each year in industrial applications so the efficient production of holes is obviously an important issue. However, how the drilling is approached — and what laser choices are made — plays a huge role in how quickly and cost-effectively the drilling can be accomplished.

Polyimide (especially Dupont's Kapton) is extensively used in many microelectronic, printing, sensor and medical products and it presents a good case study for laser drilling. As can be seen from Table 1, polyimide can be machined well with various laser wavelengths and so we can choose a couple of these wavelengths to examine the pros and cons of using different lasers. The two lasers which have been chosen for this comparison are a 248 nm excimer laser and a 355 nm solid-state laser and the approach we take is to produce 100 µm diameter holes on a pitch of 500 µm in a 50 µm thick film of polyimide. The hole sizes are chosen deliberately to be larger than the typical focused spot size from a solid-state laser which is ~15–20 µm so that percussion drilling cannot be used. Hence, to make the 100 µm holes with a solid-state laser, beam trepanning using a galvanometer scanner is used while mask projection is used with the 248 nm excimer laser. Obviously there are many options for the power of the laser that

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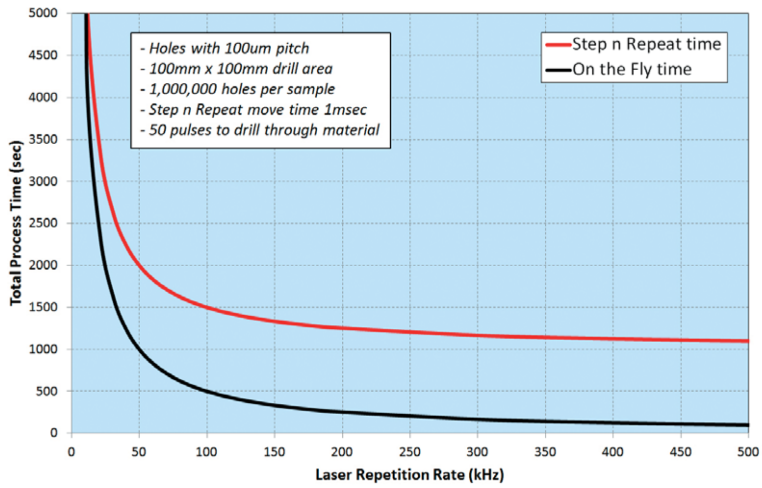
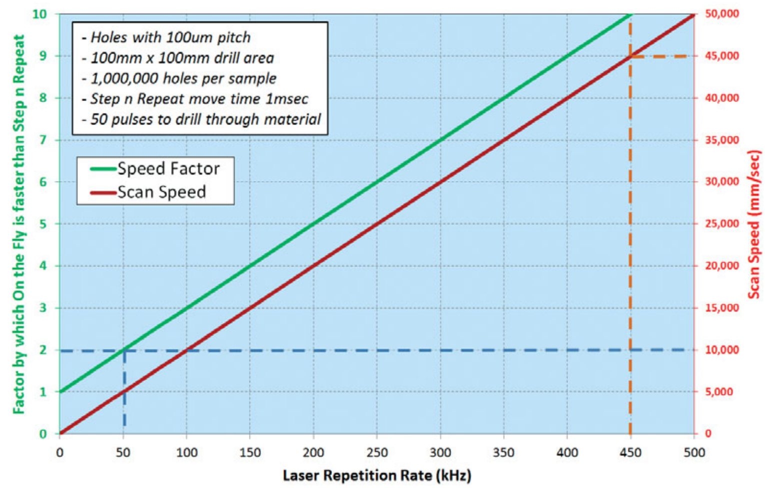


<< Figure 2: Plots of drill time to drill 1 million holes using step-and-repeat and on-the-fly methods. >>



<< Figure 3: Speed factor by which on-the-fly is faster than step-and-repeat (green line) and associated scanner speeds (red line) for the drilling of 1 million holes. >>

can be used for each wavelength so we chose modest power-level lasers in each case where the cost of each laser was about the same (around $50 k). Using standard, commercially-available optics and hardware (i.e. nothing specifically configured to give either laser a particular advantage), hole drilling was optimised so that 'good' quality holes (e.g. round shape, clean sharp edges, lack of damage or debris) were produced over an area of 100 mm x 100 mm.

Figure 1 shows the comparative results of the polyimide drilling with each laser and shows the holes from the laser entrance and exit sides.

It can be seen that the holes are identical with no significant difference in hole size or quality, i.e. there is no practical difference in the results due to the laser wavelength. When comparing drill times, however, there is a big difference in the numbers of holes which can be drilled per second with each laser, at least for the parameters of this particular experiment. The 355 nm holes were drilled at a rate of 96 ms/hole whereas the 248 nm holes took 1600 ms/hole, i.e. the 355 nm drilled holes were x16 faster than the 248 nm drilled holes. So it would appear that since the quality that both lasers can give is the same, it would make sense to choose the 355 nm laser for polyimide drilling due to its much faster drilling speeds.

However, as with most things to do with laser micro processing, there are alternatives which make things less simple. In this case, it is due to how the 248 nm excimer drilling was done. Only one hole was drilled at a time with each laser in our experiment (to give a form of consistency) but also because a small-frame excimer laser was chosen whose spot size at the sample was ~500 µm, i.e. only one hole fitted into the machining area anyway. So, as a direct single-hole drilling comparison, the above drill times are correct but only for the narrow set of laser parameter choices we made. An obvious way to reduce the drill times in both cases would be to use a higher repetition rate of laser so that the required pulses were delivered more quickly to the sample. This would certainly work but may lead to a reduction of quality due to heating effects (due to more pulses arriving quickly on the sample). However, higher repetition rate lasers of the same output power are generally more expensive so this change is not always simple or cost effective. This is where the interplay between the choice of laser, optics and machined area has to be optimised and it is not a trivial matter.

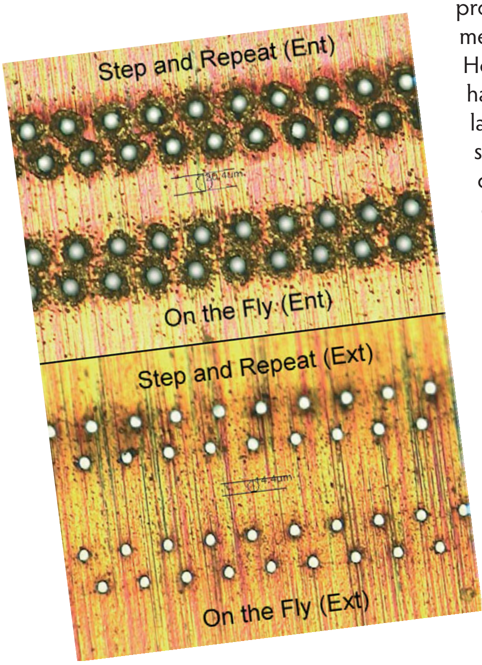
Let's look at the scenario for the Kapton drilling and assess some of the options (see side-box for definitions of the parameters). To maintain a particular quality of hole, the energy density of the laser at the polyimide should be kept the same so, this being the case, having a laser with a higher pulse energy would mean that a larger area of the sample could be covered with the same energy density. In the case of the 355 nm laser and galvanometer scanner system, this does not help because only one hole is drilled at a time and so whatever energy is available from the laser, only the selected amount of energy can be supplied to drill the single hole; having more energy available from the laser does not help as it cannot be used. In the case of the excimer laser, however, having a higher pulse energy means that a larger area can be illuminated at the sample and so many more holes could be drilled as long as the projection lens being used has a large enough field size. If, for example, we used a lens with a field size of 4 mm x 4 mm, then 64 holes on a 0.5 mm pitch would fit into the field size and hence 64 holes could be drilled in the same time as one hole. So instead of a hole every 1600 ms, there would be 64 holes every 1600 ms, i.e. 25 ms/hole, faster than the 96 ms/hole time for the 355 nm hole. This is one of the main attractions of excimer lasers since depending on the laser and optics, a very large area can be covered extremely quickly.

The drilling time can be dramatically reduced with excimer lasers, therefore, by increasing the area over which the drilling is carried out, although this does require a larger-frame, more powerful laser. With the 355 nm solid-state laser, increasing the power is not the best approach since only a single hole is drilled at a time. The use of diffractive optical elements can produce more than one drill site at a time — in which case the higher energy would be beneficial — but such multiple-beam optics have not yet found their way into mainstream production due to a number of issues concerning their ease of use and uniformity.

So what other strategies are there to improve the 355 nm production rate? In our experiment the drilling of the 100 µm trepanned holes was done by a 'step-and-repeat' method, i.e. drilling a single hole statically, moving to the next site and then drilling the next hole. Since each hole requires a trepanning process, the step-and-repeat method suits these holes well. However, for holes which have sizes of the order of the laser beam spot size or smaller, percussion drilling can be used. In percussion drilling, the laser beam is just focused onto the drill site and the number of pulses required to drill the material is applied.

The step-and-repeat method can also be used with percussion drilling. To increase the overall process speed, the drill time can be reduced (using higher repetition rates) and/or the step movement time can be reduced (using a faster move). However, both of these options are limited in how much benefit they can provide — the increased repetition rate has already been stated to affect quality while reducing move times is governed by how fast the galvanometer scanners can be stably accelerated and decelerated. One of the restrictions of the step-and-repeat process is that each move is accompanied by an acceleration and deceleration and these times can add up to significant delays when there are millions of holes to drill. A much more efficient drilling method exists, however, which can overcome this acceleration/deceleration problem and this is known as 'on-the-fly' drilling.

In on-the-fly drilling, the laser is turned on and then moved using the galvanometer scanner to make a line. Since the laser is pulsed, laser pulses arrive periodically at the sample while the beam is moved over it in a line and the distance between the pulses on the sample is given by the speed of the galvanometer motion divided by the laser repetition rate. Hence, if the beam is moved at 1000 mm/sec and the laser is running at 10 kHz repetition rate, the separation between pulses on the sample will be 0.1 mm. The benefit of this technique is that one line (which can contain many



<< Figure 4: Comparison in quality of holes drilled in 20 µm thick titanium foil using step-and-repeat and on-the-fly techniques. The entrance hole sizes are 20 µm and the exit hole sizes are 15 µm. >>

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hole locations) requires only one acceleration and deceleration and so the overall times can be far lower to drill a particular area. Let's assume that, for example, we wish to drill an area of 100 mm x 100 mm with holes on a 0.1 mm pitch and that each hole takes 50 pulses to drill. The sample will contain 1 million holes and so with the step-and-repeat method there will have to be 1 million accelerations and 1 million decelerations of the galvanometer scanner. In the on-the-fly method, we will have to repeat the scanning process 50 times since each pass only places one pulse at each location (and we need 50 pulses to drill the hole). One pass requires 1000 lines to be made (100 mm divided by 0.1 mm) and so has a total of 1000 accelerations and 1000 decelerations. So, over 50 passes, the total accelerations and decelerations is 200,000 as compared with 2 million for the step-and-repeat case. Obviously, if fewer pulses are needed to drill a hole, there will need to be fewer passes in the on-the-fly procedure and hence it will be even faster since there will be fewer numbers of accelerations and decelerations.

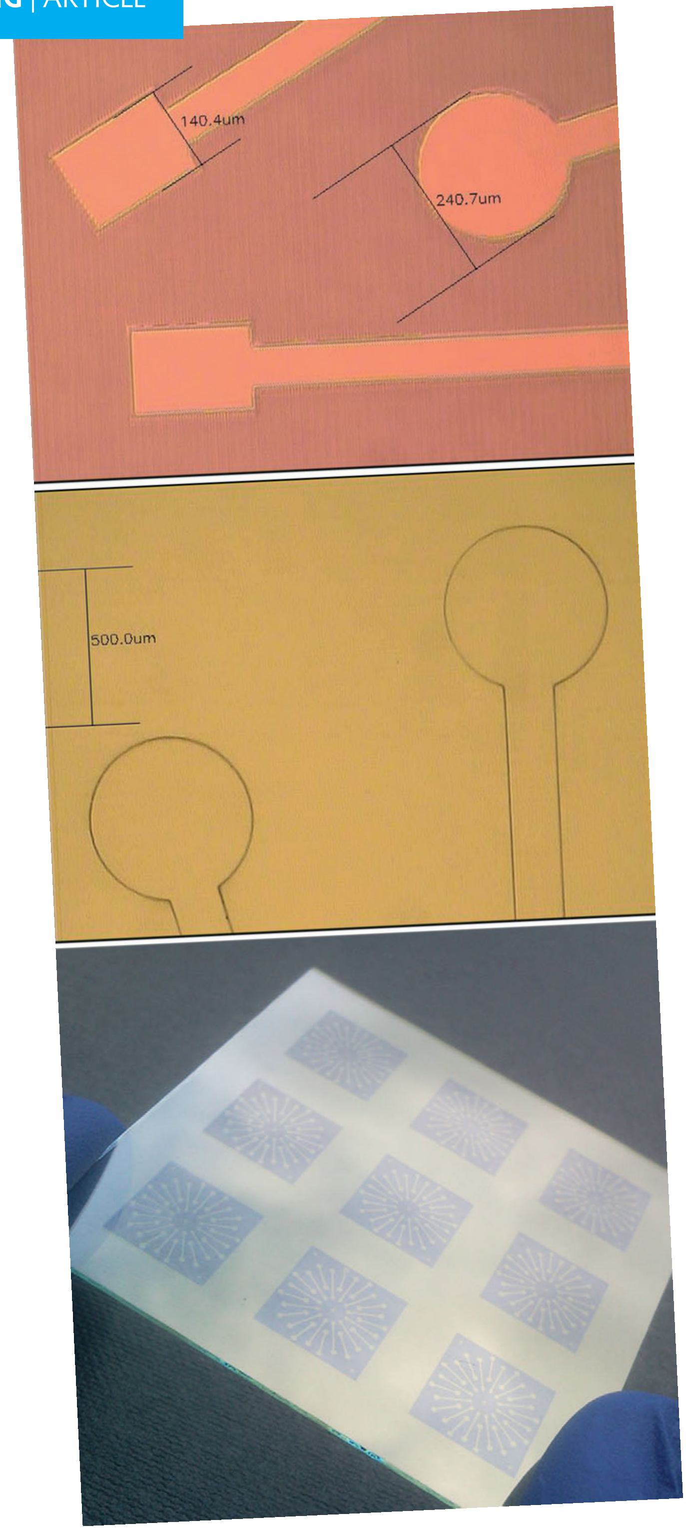
Taking the example above, we can plot the times that the step-and-repeat and on-the-fly methods will take and this is shown in figure 2. We assume that 50 pulses are needed for the drilling, the holes are on a 100 µm pitch, the sample is 100 mm x 100 mm in size and the total move time in the step-and-repeat case is 1 ms. It can be seen that on-the-fly drilling is always faster than step-and-repeat method and that the speed difference increases as the laser repetition rate increases.

Extending the same example, the calculated data can be re-plotted to show the factor by which the on-the-fly drilling is faster than the step-and-repeat method and the associated speeds of the galvanometer scanner. This data is plotted in figure 3. This treatment shows that at 50 kHz repetition rate, for example, the on-the-fly process is x2 faster than the step-and-repeat method and the associated galvanometer scan speed is 5000 mm/sec. This is around the limits of easily-available current scanner technology, although scanners with speeds of around 10,000 mm/sec have been demonstrated. So even though it can be seen from figure 3 that at 450 kHz, for example, the on-the-fly process would be x10 faster, this cannot be achieved because it would require a scan speed of 45,000 mm/sec, something which is impractical at present. So although using a really advanced, ultra-high speed scanner would lead to faster processing, the choice has to be made whether it is a worthwhile investment balanced against the likely benefits. Only a full appraisal of the overall machining task provides this answer.

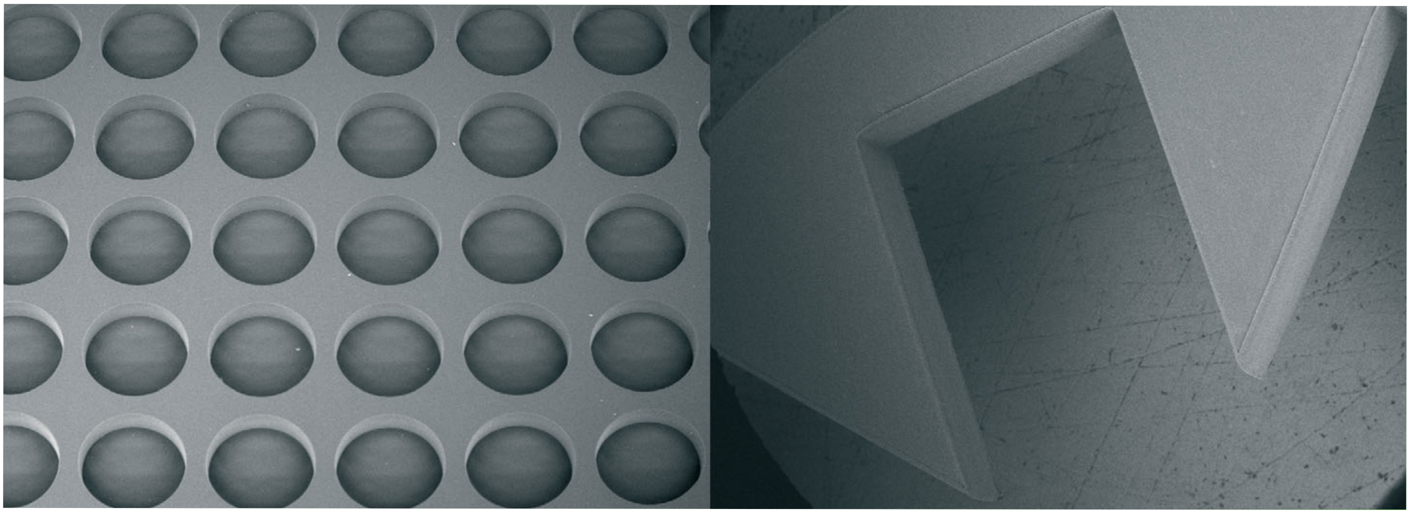
Separate from the processing speed issue, there should be no difference in the quality of the drilling between step-and-repeat and on-the-fly if the process is properly set-up and optimised. Figure 4 shows the comparison of this in the drilling of 20 µm thick titanium foil. The holes were drilled using a galvanometer scanner system at 355 nm using a nanosecond laser. The processing speed of the on-the-fly drilling was more than x3 faster than the step-and-repeat method (~3,300 holes per second being produced by the on-the-fly method as compared with ~1,000 holes/second with step-and-repeat).

Thin Film Patterning

If we now examine a completely different type of processing — the patterning of thin films — we can see again how the selection of processing parameters leads to major differences in the results. Thin film patterning is widely used in the production of solar panels, biotech sensors, microelectronics devices and display products of all kinds. The films are commonly a form of thin conducting oxide (e.g. ITO) or a metallic layer (e.g. gold) with thicknesses in the range of 10-200 nm. The main requirements for the patterning are that the film be completely removed, the edges are clean/sharp and that there is no discernible damage to



<< **Figure 5: Patterning of ITO on glass using 355 nm (top) and 248 nm (middle).** >>



<< **Figure 6: Cutting of polycarbonate: 400 µm diameter holes in 175 µm thick PC (left) and 2 mm wide cut shape in 375 µm thick PC (right).** >>

the substrate (which is usually glass or polymer, sometimes a ceramic). As shown in Table 1, thin films have a very wide process window when it comes to the choice of laser so which route is taken depends a lot on other factors.

A glass plate, 50 mm x 50 mm in size and coated with ~100 nm thickness of ITO, was chosen for comparative tests. A spoke pattern of electrodes was generated which typifies the types of features which are usually produced on thin films and this pattern was machined into the ITO using a 355 nm solid-state laser using a galvanometer scanner and a 248 nm excimer laser using mask projection. Figure 5 shows the results of the patterning with 100 µm-wide electrode and 500 µm diameter pad features.

The 355 nm laser processing used 4 shots/area at 60 kHz with a 20 µm round beam while the 248 nm laser used 4 shots/area at 50 Hz and a 2 mm square beam. Therefore the solid-state laser has a very small spot but runs at a very high repetition rate whereas the excimer laser has a large spot but only operates at a very low repetition rate. It can be seen from figure 5 that the quality of the patterning with both lasers was the same and no practical differential could be found in the processed plates. The process times were 1000s for the 355 nm plate and 50s for the 248 nm plate.

In this example, the low repetition rate excimer laser is far more efficient at patterning the thin film since the number of pulses required for removal is very low (usually 1-4 pulses) and, therefore, having a high repetition rate to deposit lots of pulses quickly adds less benefit than being able to cover a large area. Since the solid-state laser, which is directly focused to ~20 µm spot size, cannot be made much larger in practice (because otherwise it would not provide the feature resolution needed), it cannot compete with the very large beam size of the excimer laser. Since the mask projection optics define the feature resolution, the excimer laser beam can be made as large as possible as long as the energy density at the sample required for pattering remains achievable. In such cases, even though the excimer laser system may be more complicated than a solid-state laser one, the processing speed benefits are so large that it has to be considered as a viable candidate.

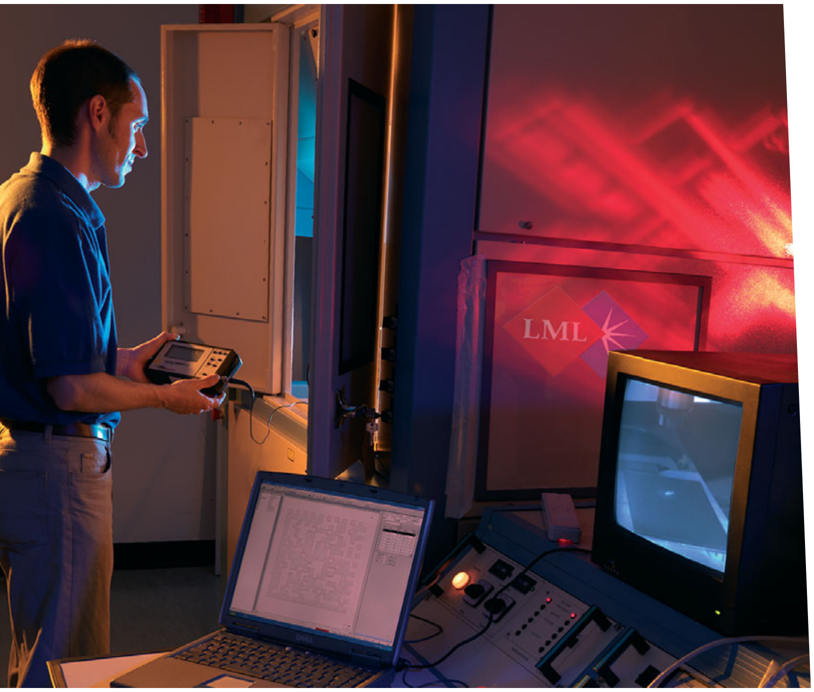
There are particular attributes for an excimer laser that make it very efficient in the patterning case and these are:

- large beam size with high pulse energy giving ability to cover large areas with high energy densities;
- poor beam quality (large number of spatial modes) giving ability to mask project with good fidelity;
- short wavelength allowing high resolution imaging;

This combination of properties from an excimer laser cannot be matched in practice by any other laser and this aspect dispels the assertion that an ultrafast laser is the only laser one may need since an ultrafast laser would not be more efficient in the patterning case above (as its process time would be similar to that of the 355 nm laser). Therefore, it has to be the case that one has to choose a particular laser (and the optimum processes associated with it) to be able to obtain an efficient solution for each application.

Figure 6 shows polycarbonate machined with an excimer laser and an ultrafast laser. Both results display excellent quality of machining and it is difficult to choose between them or even guess which one is which (in fact, the holes were made with the excimer laser and the cut shape with the ultrafast laser).

Although the quality of the results is the same, the speed of machining would be a major factor when deciding which laser to use — in just making one hole or one shape the overall time difference is not great but it would be if there was a large sample with thousands of features to machine. So, if only a smaller number of features were required then either laser could be used, if both lasers were available on equal terms. It would be a totally different matter, however, for larger volumes of material removal — in that case, the entire job would have to be evaluated to see which laser process would be more suitable. This, summarises the dilemma for a potential user: it is simply not possible to choose a laser based purely on the material alone or a small knowledge of the machining to be done; a broader understanding of what is required is always necessary to gain the optimum solution.



Summary
In one sense, the answer to the question posed at the beginning of the article is that there is no single, absolute choice of laser which is best for a particular application; it is only by being selective and prioritising a set of options that a practical solution can be found. This position is more easily reached if the interplay between the competing factors (technical, economic and practical) is understood. As a user who simply wants processed parts, it may not be important, at all, to know how something is done but it usually helps to know why a solution has been selected. It is the job of laser companies to sell lasers — their lasers — so the opinion from them may not be as fulsome or objective as a user may want. Service providers are not selling laser products and so can supply a more independent view to users about which lasers (and laser processes) would be best for their needs. Users should be aware that there is a huge complexity involved in finding the right laser processing solution — once the solution exists then laser processing is unrivalled in the speed, quality, reliability and scalability that it can offer but it should be remembered that the choice of laser processing variables is enormous and generally no single answer exists for a particular application. It is the job of providers and users to work together to adopt the right solution.

Acknowledgement: the laser machining results and data presented in this article were produced at LML by Andy Goater, Gary Owen, Rob Armstrong, Phil Boulton and Julian Burt.

Dr. Nadeem Rizvi is Managing Director of Laser Micromachining Ltd, a provider of laser contract manufacturing services to industry.

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HOW ARE LASER PARAMETERS RELATED?

The main parameters of interest for laser micro processing are: **average power, repetition rate, energy density, wavelength** and **beam quality**. All these parameters have to be suitably addressed to gain the best results.

The average power from a laser, given in Watts, is defined as:
Average power (W) = Pulse energy (J) x **Repetition rate** (Hz)
The **energy density** (also called ‘fluence’) at the material is defined as: **Energy density** (J/cm^2) = Pulse energy (J) / Beam area (cm^2)
The beam area (for round Gaussian beams) at the material is approximated by: Beam area (cm^2) ~ $(1.06\ M^2\ f\ \lambda / D)^2$ where M^2 is the **beam quality** factor, f is the focal length of the focusing lens (cm), λ is the laser wavelength (cm) and D is the laser beam diameter (cm) at the focusing lens.

Hence the beam area is affected by the **beam quality** (the focusability of the laser beam). The **energy density** is affected both by the beam area and the pulse energy (which is linked to the laser **average power** and **repetition rate**).

So, if we have two lasers which each give 2W of output power but Laser A runs at a repetition rate of 100 kHz and Laser B runs at a repetition rate of 1 MHz, then Laser A will have a pulse energy of 20 µJ whereas Laser B will have a pulse energy of 2 µJ. Therefore, if using identical focusing optics for both lasers (assuming that both lasers output at the same wavelength and with the same beam quality), then the fluence with Laser A will be x10 higher than with Laser B. Therefore, even though both lasers are running at the same wavelength, output the same average power and focus to the same spot size, one will ablate at a fluence 10 times higher than the other and this will lead to a big difference in the speed and quality of machining.

Wavelength also impacts on how the material absorbs the laser light and this is critically important for all non-ultrafast lasers. So just having a particular laser is a start but how it is used is vital to the results that are achieved.