

Advanced Laser Microfabrication in High Volume Manufacturing

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There is increased interest in the laser microfabrication of variable shape and size features for a wide variety of materials. Quality and throughput requirements continue to increase, with tighter tolerances regarding dimensional and positional specifications. Consequently, improved laser sources and manufacturing techniques, with advanced system integration and process control need to be developed to be able to address ever increasing industry requirements.

This paper discusses recent advances enabled by a new generation of IPG Photonics fiber lasers that are resulting in systems having greater flexibility, greater reliability and lower operating cost of ownership than their predecessors, and that are producing machining processing rates up to an order of magnitude faster. Examples are given of using high brightness, high pulse energy, pulsed fiber lasers known as quasi continuous wave (QCW) fiber lasers operating in the near infra red (1070 nm) with pulse durations in the micro to millisecond regime, as well as using green (532 nm) fiber lasers in the nanosecond regime. Applications include high speed drilling of ceramics such as alumina and AlN with sub-50um diameter holes machined at 3000, 750 and 300 holes per second in 100, 381 and 635 microns thick substrates, respectively; high speed cutting and scribing of alumina in 381 and 635 microns substrates, high quality cutting of up to 3 mm thick sapphire substrates, as well as high quality cutting & drilling of polymers from PEEK, to silicone, epoxy, and FR4 are presented. Laser machining techniques and their implementation in a new high-volume manufacturing platform are discussed.

Keywords: Ceramics, sapphire, alumina, microfabrication, drilling, cutting, QCW fiber laser, green fiber laser

1. Introduction

Today the application of laser technology in manufacturing is well known in applications such as metal cutting and welding. A subset of this manufacturing field is laser microfabrication or laser micromachining, which typically refers to cases where material thicknesses are less than one millimeter and feature sizes are commonly measured in microns. Compared to typical bulk industrial applications such as robotic welding or sheet metal cutting, the tools and technology required for micromachining applications require an emphasis on high accuracy and process control. Common applications may be very sensitive to thermal input and/or require extremely high precision, and as a result the specifications of the type of laser used, optical system, and equipment hardware configuration are extremely important to developing a robust high volume manufacturing solution.

The choice of laser depends on many factors including materials properties, geometry to machine, process tolerances and desired throughput. A new generation of fiber lasers has led to improved and more flexible laser sources at lower cost of ownership.

A major drawback of rod type solid-state lasers is their limitation on average power due to thermal lensing. Rod type lamp- or diode-pumped solid state lasers are being replaced by IPG Photonics (IPGP) quasi continuous wave (QCW) Ytterbium fiber lasers that combine high bright-

ness/high beam quality with high pulse energy, high peak and high average power. These are air cooled, compact lasers, with high wall plug efficiency above 30%, and maintenance free operation. The lasers operate in the near IR at 1070 nm, in a 'long pulse' operation mode with pulse lengths in the micro to millisecond regime, and also in CW mode.

If shorter pulses are needed (i.e., nanosecond regime or shorter), a variety of fiber lasers are available to cover a large range of wavelengths, pulse energies and average/peak powers. While q-switched fiber lasers operating at near IR (1064 nm) have been around for a while, a new generation of green (532 nm) pulsed fiber lasers has recently been introduced. IPGP's pulsed green fiber lasers provide a high peak power with scalable average output power up to 50 W and a constant pulse duration of 1 ns at 10 to 300 kHz. The all fiber format allows adjustment of pulse energy and/or change of repetition rate without affecting any of the output beam parameters. Featuring an M^2 of <1.2 , this novel fiber laser is much more efficient and compact than conventional lasers now on the market, at a lower cost.

While IPG Photonics has a range of lasers that cover wavelengths from UV to mid IR this paper will focus on examples of applications that are covered using the QCW and green pulsed fiber lasers. Examples of applications and machining techniques with these lasers, and their imple-

mentation in a new high-volume manufacturing platform are discussed.

For QCW fiber lasers, applications results were obtained for ceramics such as alumina and aluminum nitride, and sapphire. Alumina (polycrystalline Al_2O_3) and aluminum nitride (AlN) are considered high performance thermal conducting substrates, and are used on a large number of industries such as the LED industry, RF, and microwave packaging. High speed hole drilling and singulation of these materials is therefore very important to achieve needed cost reduction. On the other hand, mono crystalline Al_2O_3 also known as sapphire has outstanding characteristics such as high hardness, second only to diamond. Compared to typical optical glass, sapphire is much stronger and more scratch resistant, has a wide optical transmission ranging from UV to near infrared, and has a high thermal conductivity. Sapphire is widely used in the LED industry as a substrate to grow light emitting epitaxial layers by MOCVD. Its use has increased dramatically in the last few years due the fast expansion of LEDs in applications such as back lighting on displays and more recently general lighting. In addition, its use has recently expanded to the consumer electronics markets, where it is being used in mobile phones as the camera lens, the home button, or the entire display.

The green fiber laser complements the QCW fiber laser since it can process materials typically not easily processed at longer near IR wavelengths, such as polymers (e.g., PEEK, silicone, epoxy or FR4). As a result of its shorter pulse duration fine structuring of metals and ceramics is also possible. Various applications results on these materials will be presented.

2. QCW fiber laser Results

For these experiments a YLM-150-1500-QCW laser was used with a single mode core fiber (14 microns), allowing for a maximum peak power of 1.5 kW and average power of 150 W (up to 250 W in CW mode only); also a YLR-300-3000-QCW laser was used with a multimode fiber (50 microns), allowing for a maximum peak power of 3 kW and average power of 300 W, both operating at 1070 nm. The pulse duration is adjustable between 10 microseconds and 50 ms, with exact range depending on laser model and parameters used.

With these relatively long duration pulses a thermal machining process is often used where the material temperature is locally raised above its melting point and an assist process gas (e.g., air, N_2 , oxygen or argon) is used to mechanically expel the molten material. On a typical workstation setup the beam/fiber enters a collimator with a focal length typically in the range of 50 to 150 mm, then is guided into a cutting head, where a focusing objective is used, with a focal length adjusted to the application at hand, typically in the range of 50 mm to 200 mm. Assist gas is flowed through the cutting head exiting a nozzle concentric to the beam. The diameter of the nozzle and the distance from the nozzle to the part is application specific but is typically around 0.5 to 1 mm for nozzle diameter and 0.5 to 1 mm for nozzle-part offset. By controlling process parameters such as pulse duration, repetition rate, peak and aver-

age power (duty cycle), cutting speed, and gas type and pressure the heat affected zone can be controlled and minimized.

QCW fiber lasers allow for a variety of peak powers, average powers, and pulse durations. They can be single or multi mode which allows adjustment of the focused beam size as needed for the process. With a single mode fiber the beam quality is very fine with an $M^2 < 1.05$. Since the beam can be tightly focused nearly to its diffraction limit, spots sizes below 20 microns diameter are possible allowing for power densities to reach $10^7 W/cm^2$. This is typically enough to induce coupling and localized melting on most materials even those that have poor linear absorption at this near IR wavelength (e.g., sapphire and alumina). While alumina has much less optical transmittance than sapphire because of its grain boundaries, pores and impurities causing absorption, reflection and scattering of incoming radiation, the bulk alumina is still a poor absorber in the near IR.

2.1 Drilling with QCW fiber laser

The QCW laser allows for high speed drilling since drilling can be done using 1 laser pulse per hole. Holes were drilled on alumina (96%) 635 microns thick, at the rate of 300 holes per second, and a pitch of 150 microns, with the part moving under the beam at a linear speed of 45 mm/sec. This was done using the single mode process fiber, with pulse duration around 200 microseconds. The shorter the laser pulse duration the higher the maximum drilling rate can be. That said there is an optimum peak power that leads to best hole quality, with optimum pulse energy and pulse duration, typically with higher pulse energy and/or longer pulses needed to drill through thicker material. Figure 1 shows the entrance and exit of the holes. The exit of the holes was manually measured under microscope as $22 \pm 3 \mu m$, and the entrance was $49 \pm 3 \mu m$. The part was coated prior to machining, and a cleaning/polishing step was performed after processing.

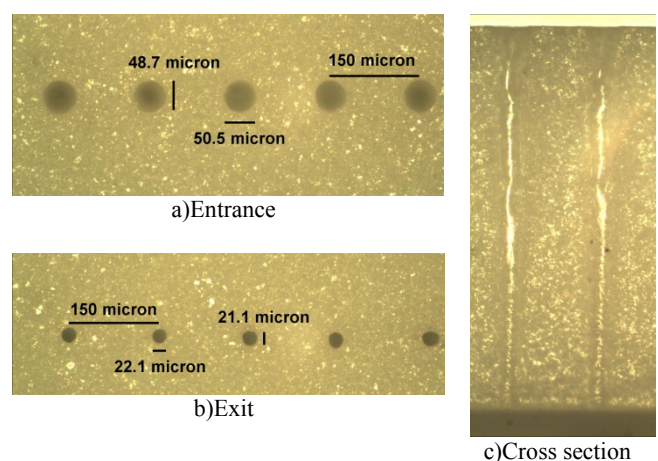


Fig. 1 Alumina (96%) 635 microns thick, drilling at 300 holes/sec.

Drilling requires good coupling but also the ability to adjust the size of the holes drilled. High power densities typically result in consistent coupling and subsequent hole drilling in alumina. However, when machining materials

that couple poorly, such as alumina, coupling cannot be achieved only by relying on very high power densities, for example when focusing to very small spots below ~ 30 microns, since often larger hole sizes are desired. On the other hand, significantly increasing peak power simply to promote coupling typically will impact hole quality. Traditionally, absorbing coatings are frequently used to enhance surface coupling on alumina. IPG Microsystems has developed new methods where enhanced coupling can be achieved by use of modified laser techniques, where no coating is needed to achieve coupling enhancement. However, depending on the particular situation coatings might still be used to help overall quality minimizing splatter and dross accumulation.

Figure 2 shows individual holes machined in 381 microns thick alumina (99.6%) at a rate of 750 holes/sec. They were measured at ~ 37 microns for the entrance and ~16 microns for the exit, and were drilled using a single mode fiber.

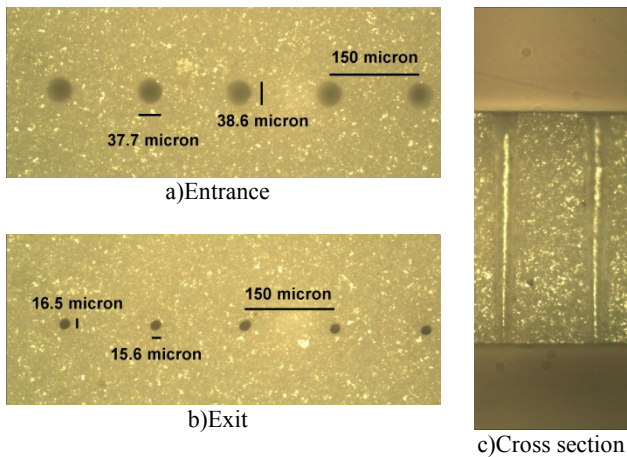


Fig. 2 Alumina (99.6%) 381 microns thick, drilling at 750 holes/sec.

Figure 3 shows individual holes machined in 381 microns thick AlN at a rate of 300 holes/sec. They were measured at ~ 42 microns for the entrance and ~31 microns for the exit. A higher peak power and longer pulse duration was used when compared to holes drilled on alumina with the same thickness.

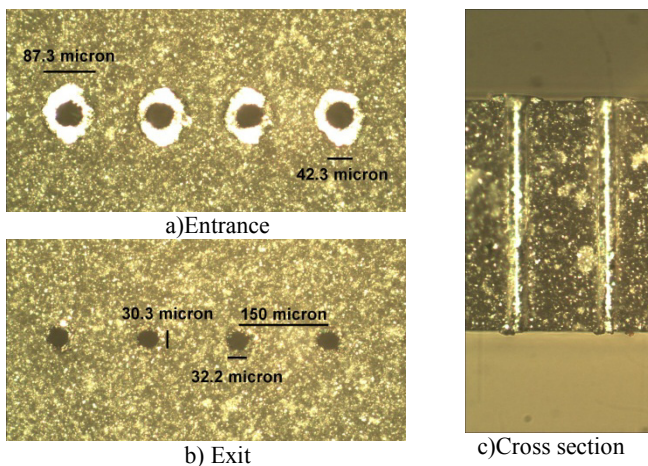


Fig. 3 Aluminum nitride 381 microns thick, drilling at 300 holes/sec.

Figure 4 shows individual holes machined in 100 microns thick alumina (99.6%) at a rate of 3000 holes/sec. They were measured at ~33 microns for the entrance and ~22 microns for the exit.

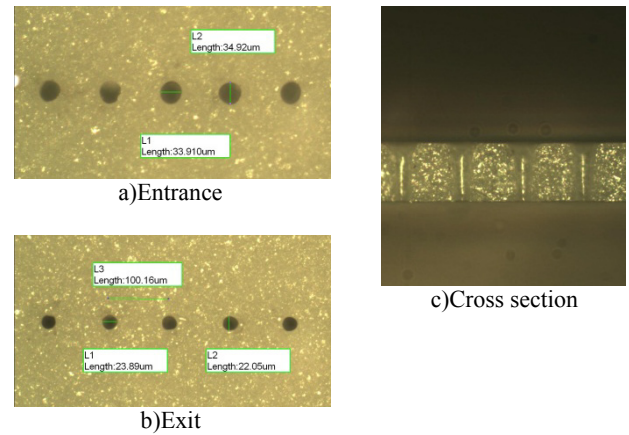


Fig. 4 Alumina (99.6%) 100 microns thick, drilling at 3000 holes/sec.

By changing the diameter of the process fiber (for example by changing laser and its fiber, or by using a beam switcher/coupler connecting the laser feed fiber to a larger process fiber), the beam delivery (varying the collimator and/or objective focal lengths), or process parameters (typically pulse duration and/or pulse energy, i.e. peak power) one can adjust the hole size machined.

Figure 5.a shows 'larger diameter holes' drilled using a multimode process fiber with an exit ~73 microns diameter in 320 microns thick alumina, drilled at a rate of over 100 holes/sec. Figure 5.b shows holes drilled in 320 micron thick aluminum nitride with a pitch of 325 microns along the scanning direction, also above 100 holes/sec. The dimensions of individual holes were measured at ~105 microns for the entrance and 65 +/- 9 microns for the exit for over 20,000 holes.

For all cases shown above positional accuracy achieved is within +/- 5 microns over an area 150 mm by 150 mm, with the hole diameter variation within +/-15 % of nominal hole size for 100% of the holes. This hole diameter variation can often be better depending on application specifics.

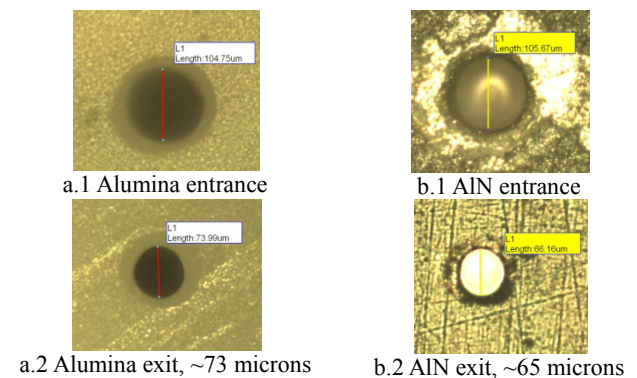


Fig. 5 'Larger holes' drilled in 320 microns thick a) alumina and b) aluminum nitride.

2.2 Scribing with QCW fiber laser

A similar setup used for drilling can also be used for high speed scribing on these ceramics, where a single pulse is used to machine a blind hole into the material, with an appropriate pulse-to-pulse spacing needed to allow for a follow on breaking operation.

Figure 6 shows scribing of alumina (96%) 635 microns thick, at a speed of 200 mm/sec with individual shots to a depth over 350 microns, and a spacing $\sim 150\mu\text{m}$. A pulse duration below 100 microseconds was used.

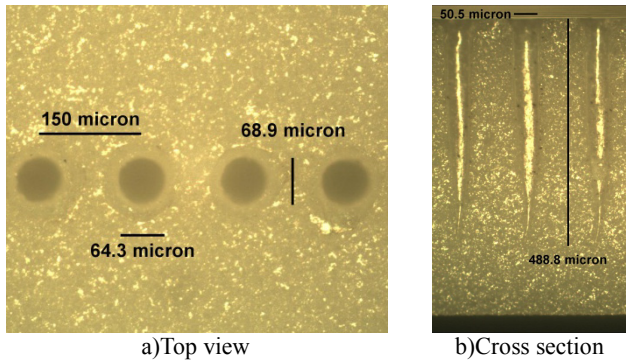


Fig. 6 Scribing of 635 microns thick alumina (96%) at 200 mm/sec.

Figure 7 shows scribing of alumina (99.6%) 381 microns thick, at a speed of 300 mm/sec, while figure 8 shows scribing of aluminum nitride 381 microns thick also at a speed of 300 mm/sec. A pulse duration below 50 microseconds was used.

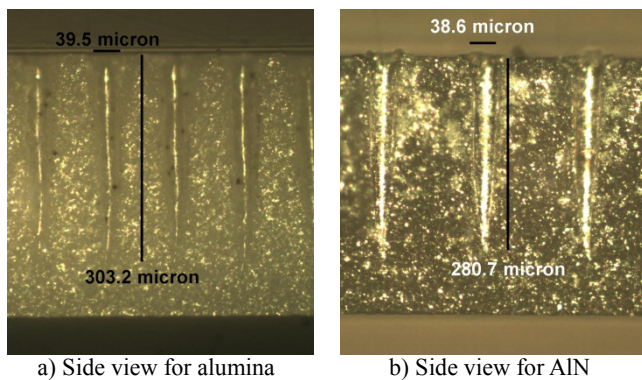


Fig. 7 Scribing at 300 mm/sec for both alumina and aluminum nitride (381 microns thick).

2.3 Cutting with QCW fiber laser

High speed cutting of 96% alumina with a thickness of 635 microns was demonstrated at 140 mm/sec using a single mode QCW laser (Figure 8). A coating was applied prior to the process and removed afterwards, helping to protect from spatter and recast. A high quality cut was achieved with no dross or chip out. Thinner alumina at 381 microns thick was cut at a linear speed of 250 mm/sec (Figure 9).

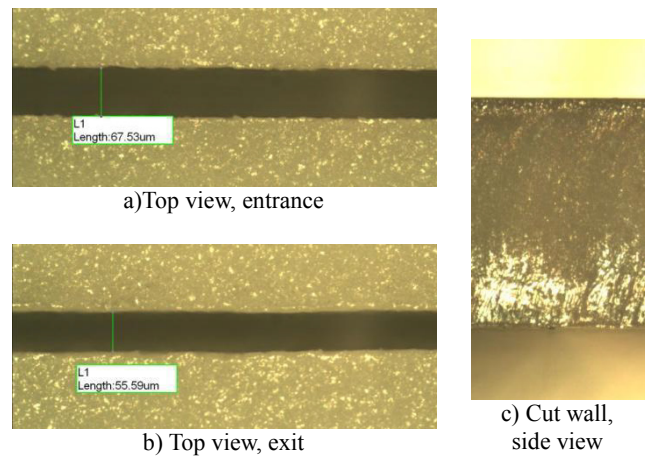


Fig. 8 Cutting of alumina (96%) with a thickness of 635 microns at 140 mm/sec.

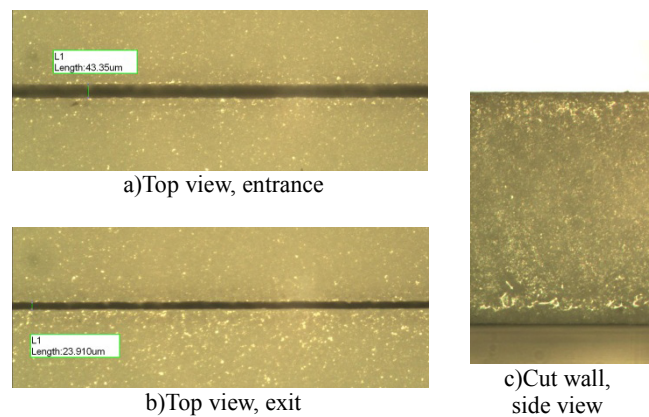


Fig. 9 Cutting of alumina (99.6%) with a thickness of 381 microns at 250 mm/sec.

QCW lasers were also used for high quality cutting of sapphire. Figure 10 shows some of the typical shapes cut for the consumer electronics market.



Fig. 10 Examples of various part geometries cut in sapphire with QCW fiber laser as used for consumer electronics.

Thicknesses up to several mm thick can be cut at reasonably high speeds with good cut quality, avoiding cracks and chip out, and with a surface roughness R_a typically below 2 microns (Figure 11). Sapphire parts with thicknesses of 0.4, 1 and 3 mm thick were cut at speeds around 12, 9 and 3 mm/sec, respectively, with final speeds depending on geometry and quality requirements.

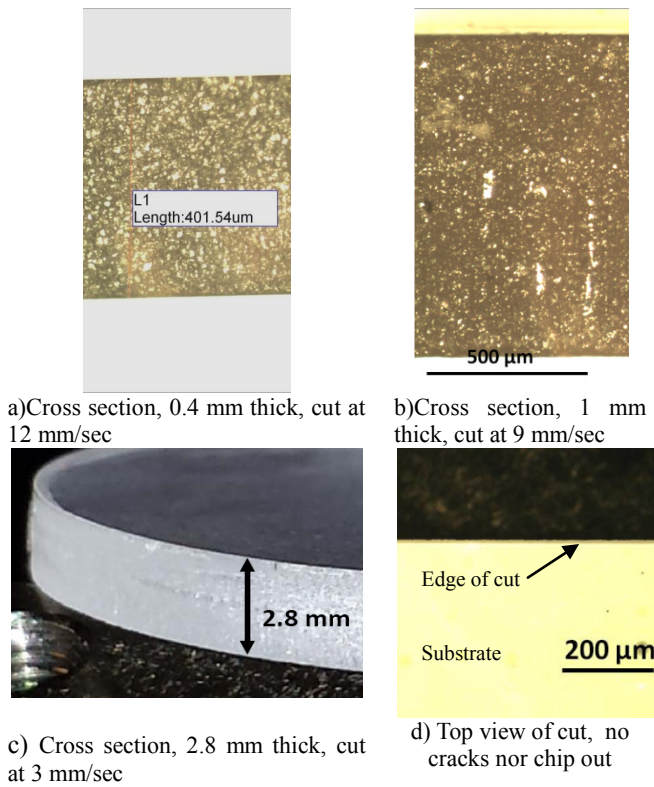


Fig. 11 Examples of cut quality on sapphire for various thicknesses when using QCW fiber laser.

3. Green 1ns fiber laser Results

A new type of fiber laser operating at 532 nm with pulse duration of 1 ns was used for these experiments. The lasers used were the GLPN-100-1-10-R (100 microJ/pulse at 100 kHz, 10W), and the GLPN-200-1-20-R (200 microJ/pulse at 100 kHz, 20W).

With these relatively short pulses, below 100 ns, machining is typically an ablative process, where each pulse leads to the removal of a particular volume of material. When used for conventional laser machining, a simple far field imaging technique is used, wherein the laser beam is sharply focused onto a small spot on the target part, and machining occurs using a ‘direct writing technique’.

For some applications a ‘fixed beam’ is used with the part moving under the beam to create the desired machining pattern. The part handling stages can have various axes of motion (X, Y, Z, theta, spindle, etc) coordinated with laser triggering to allow highly complex machining patterns. Typical positional accuracies are better than 3 microns per 150 mm of stage travel, for stage linear speeds up to about 1 meter/sec.

Galvanometers are typically used for applications that benefit from moving the beam at higher speed over the part. Typically the positional accuracy achieved with galvanometers is not as high as that achieved with linear stages, but recent advances with the galvanometer and their controllers continue to improve their accuracy and repeatability. Typical writing speeds are within 1-5 meters/sec, with short settling times.

High quality micromachining depends on good coupling between laser light and the target material. Typically reducing the wavelength improves coupling due to the

higher photon energy. An optical penetration depth L_o can be established as $L_o=1/\alpha_{opt}$, where α_{opt} is the optical absorption coefficient, containing both linear and nonlinear terms, which is dependent on wavelength, temperature and intensity, also often referred to as power density [$J/(sec.cm^2)$, or W/cm^2]. Non-linear multi-photon absorption of high intensity laser pulses can significantly increase coupling, even if the linear (single photon) absorption is low. Using high pulse energy, short pulses and/or tightly focusing radiation can generate high laser intensities on the target material. In addition to optical properties, the material’s thermal properties (e.g., thermal diffusivity) are also very critical since those dictate how the absorbed light/energy is transferred to the bulk material in the form of heat. The heat penetration depth (L_t) is given by $L_t \approx 2(\kappa\tau)^{0.5}$, where κ is the thermal diffusivity [m^2/sec], and τ is an appropriate time duration, typically the laser pulse duration if longer than the electron-lattice relaxation times ($\sim 10^{-12}$ sec). On a first order approximation, it can be assumed that the light and heat distributions are independent from one another in the material, in order to define an energy penetration depth $L_e \approx L_o + L_t$. While this equation is a simplification, this concept can often be used to understand the laser machining behavior of a wide range of materials. In particular, it explains how increased radiation absorption, often leads to improved machining quality at the expense of reduced removal rates for identical pulse duration. This equation also helps explain why reducing the pulse duration typically means a reduction of the material removal per pulse for identical wavelength. Achieving both quality and throughput requirements often needs a compromise between laser wavelength and pulse duration.

The 532-nm 1-ns fiber lasers were used to machine a number of materials that are typically difficult to machine at near IR wavelengths to demonstrate capability, as well as to show how such a laser can complement the QCW fiber laser. Comparative testing against other lasers with distinct wavelengths and pulse durations was also performed.

PEEK is a semi crystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained at high temperatures. Good cut quality was achieved (Figure 12) with speeds around 20 mm/sec for 50 microns thick material, also demonstrating high speed percussion drilling at >100 holes/sec. The cut quality was similar to that achieved with a laser operating at a shorter 266-nm wavelength and longer >10 ns pulse duration.

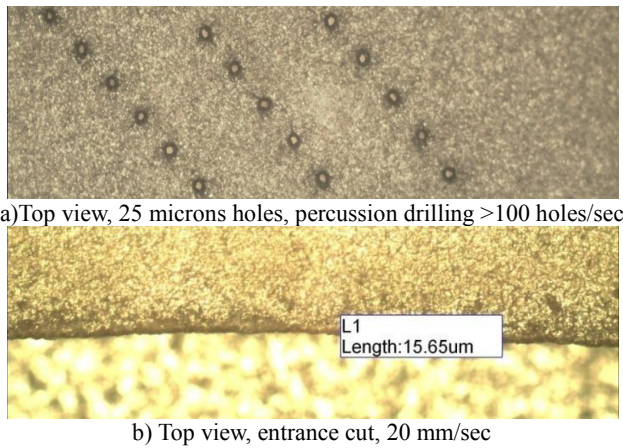


Fig. 12 Drilling and cutting of PEEK (50 microns thick) with green 1 ns fiber laser.

Silicone is a difficult to machine material since it melts considerably. The cut quality obtained with the green 1 ns fiber laser was good, with a well defined, high aspect ratio, cut through 1 mm thick silicone at a rate of ~ 4 mm/sec (Figure 13). Machining tests performed with a laser also operating at 532 nm, but with a shorter pulse duration of ~ 10 ps showed similar cut quality but reduced ablation rates. This indicates that the 1 ns pulse duration is short enough to limit thermal affectation, while leading to improved throughput.

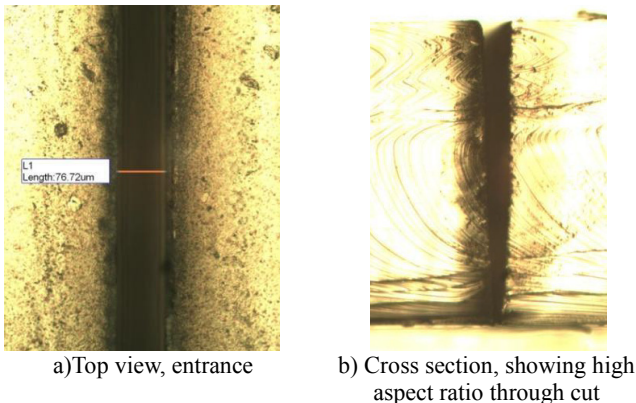


Fig. 13 Cutting of silicone 1 mm thick with green 1 ns fiber laser.

Epoxy 1.3 mm thick with a top copper layer of ~100 microns was also cut with high quality at an effective cutting speed of about 5 mm/sec (Figure 14). In this case, comparison against longer pulse duration green lasers (>10 ns) showed improved cut quality. Typically standard DPSS lasers experience increased pulse duration with increasing repetition rate. That is not the case with this fiber based green laser – it keeps a constant 1-ns pulse duration across the wide range of repetition rates available, making it easier to match the laser average power to the throughput needed.

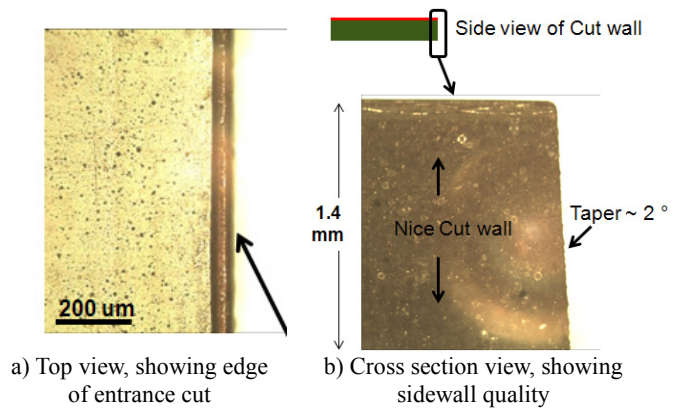


Fig. 14 Cutting of epoxy 1.3 mm thick (+ top 100 microns copper layer) with green 1 ns fiber laser.

High cut quality of FR4 material was demonstrated on 300 microns thick material, with a very clean edge, no carbonization and a narrow kerf below 15 microns (Figure 15.a). Speeds of several mm/sec were demonstrated typically depending on thickness of embedded copper traces. The quality achieved was comparable or better than that achieved with 355 nm laser radiation, operating at longer pulses durations (> 30 ns).

Holes ~100 microns diameter were cut in 200 microns thick FR4 at a rate of 50 holes/sec (Figure 15.b). With this green laser much smaller vias can be obtained, below 20 microns, which for example opens up the path for replacement of CO₂ lasers by this green 1 ns laser on FR4 laser applications that demand very small feature sizes.

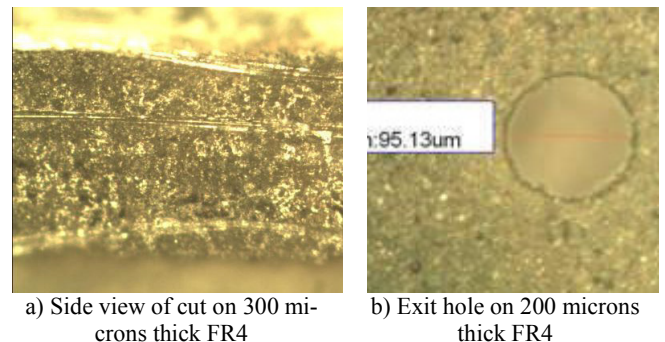


Fig. 15 Cutting and drilling of FR4 substrates with green 1 ns fiber laser.

While the QCW laser also allows for high quality machining of metals, certain complex cut geometries, or part handling considerations may favor a high speed galvo machining vs. a thermal cutting approach. Metals such as brass, copper, Mg and FeCo were cut with high quality using the green 1 ns fiber laser, comparable to that achieved with shorter pulses in the ps regime (Figure 16).

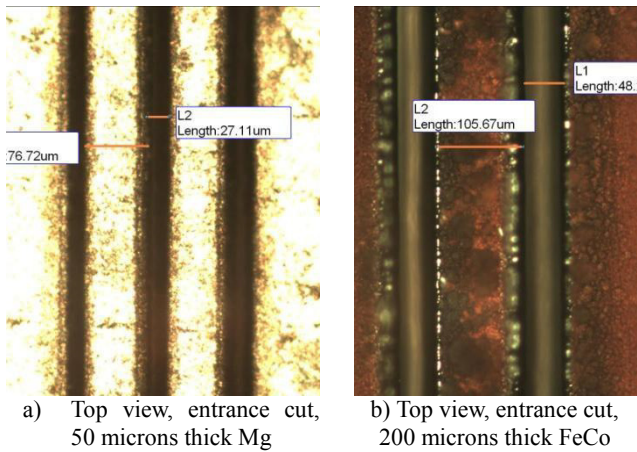


Fig. 16 Cutting of metals with green 1 ns fiber laser.

The short pulse duration of the green fiber laser also is ideal for high quality micro milling, which is achieved with a layer by layer removal (e.g., alumina in Fig. 17).

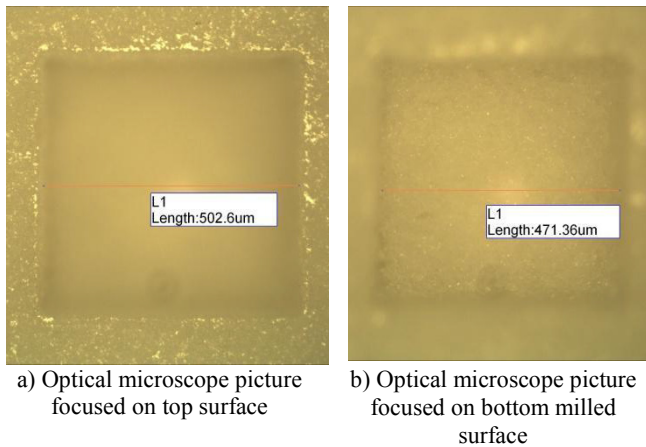


Fig. 17 Micro milling of a 150 microns deep pocket in alumina within a 500 by 500 micron area using the green 1 ns fiber laser.

These results show that the green 1 ns fiber laser can be used with a wide range of materials, allowing for a better or similar quality in several materials than that achieved with lasers with lower wavelengths but longer pulse duration. For some materials the pulse duration is short enough that comparable quality is achieved versus even shorter pulses at ~ 10 ps, but with higher removal rates. The green 1 ns laser with its 'short pulse duration' and high repetition rate is ideal for ablative high speed processing, and complements the 'long pulse duration' QCW fiber laser well. When compared with other short pulsed lasers operating in the ns regime, often operating at 532 nm offers the best tradeoff between improving coupling, by frequency doubling of the fundamental 1064 nm wavelength, and highest pulse energy/power, which can further be reduced by using higher harmonics (i.e., 355 nm and 266 nm).

4. Laser System

The prior results illustrate that depending on the material and the application, process development establishes which laser and laser technique is better suited to meet manufacturing goals, thus allowing for specification of equipment options. In addition to required machining quali-

ty, including dimensional and positional specifications, additional considerations for high volume manufacturing include throughput needs as well as cost of ownership. To address these requirements while allowing for machining complexity and versatility IPG Photonics - Microsystems Division is introducing a series of workstations in which multiple laser types and beam delivery systems can be installed and are available for immediate sequential use. Examples of lasers include the QCW and green fiber lasers discussed, but other lasers (e.g. DPSS, excimer, etc) are possible. A part can be processed with the green fiber laser using a galvo-based machining approach, followed immediately with processing using the QCW fiber laser coupled to a high pressure cutting head.

These workstations are available in manual load, semi automatic configuration, or with optional Integrated Automation Platform cassette loaders, allowing for high volume manufacturing in a fully automatic configuration. Configurations with up to four cassette load/unload ports are available with a wide variety of integrated metrology and process control functions to ensure a highly robust production process.

For mechanical and thermal stability the workstations feature a granite support structure to which the optical components and precision part handling stages are mounted. Process and high magnification alignment cameras are available, that can be configured to automatically align the part and beam(s) to micron precision using machine vision. Additional advanced features such as computer controlled illumination and automatic focus subsystems are also available. Integrated power and pulse energy monitoring allows the system to automatically check and adjust laser power and/or energy levels. The system can also check and correct for any drift in spot placement and variation in beam size over long production runs. The integrated software allows for ease of setup and operation, while also providing extensive data logging capabilities.

5. Conclusions

We have shown a variety of applications results using a new generation of IPG Photonics QCW and green fiber lasers.

The QCW laser enables high quality cutting, scribing and drilling of materials up to several millimeters thick using a thermal cutting technique. The high beam quality allows for small spots on target (<20 microns diameter) with high power densities leading to coupling in materials that are typically transparent at near IR. If larger spots are required then there are processing techniques that still allow for 100% coupling to materials such as alumina and sapphire. High drilling rates of 300, 750 and 3,000 holes/sec were achieved on 635, 381, and 100 microns thick alumina respectively. High speed scribing at 200 and 300 mm/sec was demonstrated for 635 and 381 microns thick alumina, respectively. High cutting speeds were demonstrated on 635 and 381 micron thick alumina at 140 and 250 mm/sec respectively, with negligible dross and no chipout. Similar results were shown for aluminum nitride but typically with a relatively lower throughput. Sapphire with thicknesses of 0.4, 1 and 3 mm thick were cut at

speeds around 12, 9 and 3 mm/sec, respectively, with final speeds depending on geometry and quality requirements.

In contrast, the green fiber laser enables ablative micromachining which allows for cutting, drilling and milling of heat sensitive materials such as polymers, and also ceramics and metals. The short 1-ns pulse duration minimizes

heat penetration, while high average power at high repetition rates allows for fast throughput.

These two types of fiber lasers complement each other well to allow for a wide range of laser processing capabilities. A laser workstation that can use both these lasers simultaneously has recently been introduced by IPG Photonics – Microsystems Division for high volume manufacturing.