Advanced Laser Microfabrication of Ceramics and Sapphire in High Volume Manufacturing

Marco MENDES, Cristian PORNEALA, Xiangyang SONG, Mathew HANNON, Rouzbeh SARRAFI, Joshua SCHOENLY, Dana SERCEL, Sean DENNIGAN, Roy VANGEMERT, Heath CHAPLIN, John BICKLEY, Jeff SERCEL

IPG Photonics–Microsystems Division, 220 Hackett Hill Road, Manchester, NH 03102,USA

Processing techniques are discussed covering laser microfabrication using near IR "long pulse duration" (microsecond range) Quasi Continuous Wave (QCW) fiber lasers, as well as using shorter wavelength (UV) and shorter pulse duration (nanosecond range) lasers.

Results are shown for QCW laser processing of materials that are difficult to machine at near IR wavelengths (1070 nm), namely ceramics such as alumina and aluminum nitride, and crystalline sapphire. Alumina and AlN are used in industries such as LED packaging as well as RF and microwave device packaging. High speed drilling up to 3,000 holes/sec is shown with hole diameters ranging from 100 to 15 microns, in material thicknesses ranging from 635 to 100 microns. Examples of high speed cutting and scribing are also presented. Sapphire has received increased attention in the consumer electronics industry. Results are shown for high quality cutting of sapphire up to 3 mm thick using QCW fiber lasers.

Results are also shown using shorter wavelength 355 nm lasers operating in the nanosecond pulse duration regime in the microfabrication of shaped (rectangular) micro holes in ceramic substrates such as silicon nitride and alumina for guide plates used for the probe card industry.

Laser systems requirements for high accuracy and high volume processing are discussed.

Keywords: ceramics, alumina, AlN, silicon nitride, sapphire, QCW fiber laser, laser micromachining, probe cards, UV pulsed laser

1. Introduction

Laser microfabrication or laser micromachining 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 laser 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 lead 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 (DPSS) lasers are being replaced by IPG Photonics (IPGP) QCW Ytterbium fiber lasers that combine high brightness/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), IPGP has a variety of fiber lasers 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 near IR, green (532 nm) and UV (355 nm) pulsed fiber lasers from IPGP has recently been introduced providing a variety of pulse durations from hundreds of nanoseconds to sub nanosecond. 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, these novel fiber lasers are more efficient, compact and lower cost than conventional lasers now on the market. At IPG Microsystems extensive comparison work is being done to understand the impact of laser pulse parameters on various applications.

While IPG Photonics has a wide 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 fiber laser and UV lasers. Examples of applications and machining techniques with these lasers, and their implementation in high-volume manufacturing platforms are discussed.

Applications results with the QCW fiber laser were obtained for ceramics such as alumina and aluminum nitride, and sapphire. Alumina (polycrystalline Al_20_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 cover, the home button, or the entire display.

Additionally, results obtained with UV lasers operating at 355 nm in the nanosecond pulse duration regime are also discussed namely drilling of micro holes in silicon nitride (Si_3N_4) and alumina ceramic substrates for fabricating guide plates for the probe card industry. This precision drilling application usually requires holes less than 100 μm in size, rectangular or round, with tight specs on the size, location, edge quality, shape, and taper. These ceramics are used because they are very stable mechanically, allow for high density drilling, enable guiding and sliding of the probe pins, and provide appropriate thermal and electrical properties.

Nanosecond UV pulsed lasers can complement the QCW fiber lasers well since the shorter wavelength allows for machining of smaller features, and the short pulse duration leads to an ablative type machining that is useful when looking for controlled layer by layer removal, with high accuracy and high repeatability machining of shaped features.

2. QCW Fiber Laser Results

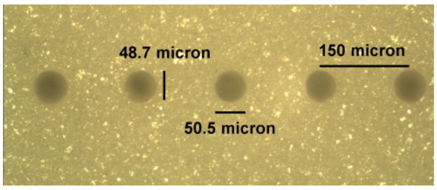
For these experiments a YLM-150-1500-QCW laser was used with a single mode core fiber (14 microns), allowing for a maximum peak power of 1.5 kW and average power of 150 W (up to 250 W in CW mode only); also a YLR-300-3000-QCW laser was used with a multimode fiber (50 microns), allowing for a maximum 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 flows 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 average power (duty cycle), cutting speed, and gas type and pressure the heat affected zone can be controlled and minimized.

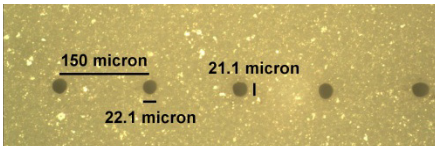
QCW fiber lasers allow for a variety of peak powers, average powers, and pulse durations. They can be single or multi mode which allows adjustment of the focused beam size as needed for the process. With a single mode fiber the beam quality is very high with an $M^2<1.05$. Since the beam can be tightly focused nearly to its diffraction limit, spot 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 (single photon) 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 of Ceramics with QCW Fiber Laser

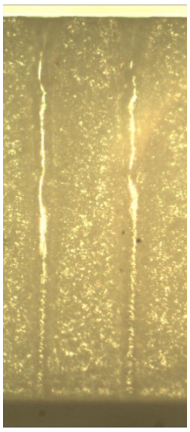
The QCW laser allows for high speed drilling since drilling can be done using 1 laser pulse per hole. Figure 1 shows holes drilled on alumina (96%) 635 microns thick, at the rate of 300 holes per second, and a pitch of 150 microns, with the part moving under the beam at a linear speed of 45 mm/sec. The exit of the holes was manually measured under optical microscope as 22 ± 3um, and the entrance was 49 ± 3 um. The part was coated prior to machining, and a cleaning/polishing step was performed after processing. The single mode fiber laser was used with pulse duration around 200 microseconds. The shorter the laser pulse duration used, the higher the maximum scanning speed can be without hole elongation, and therefore 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.



a)Entrance



b)Exit

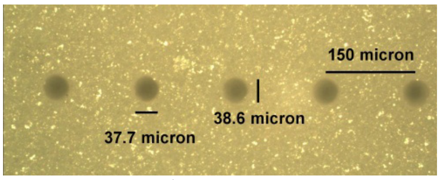


c)Cross section

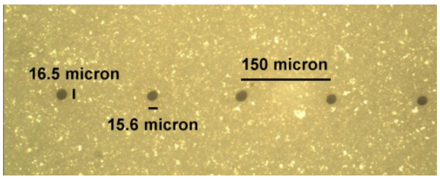
Fig. 1 Alumina (96%) 635 microns thick, drilling at 300 holes/sec.

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 by minimizing splatter and dross accumulation.

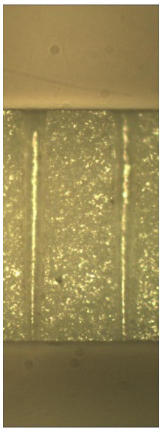
Figure 2 shows individual holes machined in 381 microns thick alumina (99.6%) at a rate of 750 holes/sec. They were measured at ~ 37 microns for the entrance and ~15 microns for the exit, and were drilled using a single mode fiber.



a)Entrance



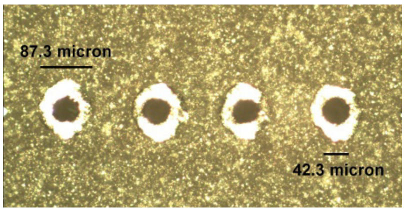
b)Exit



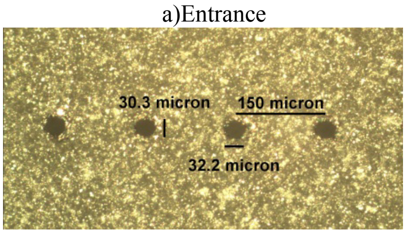
c)Cross section

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

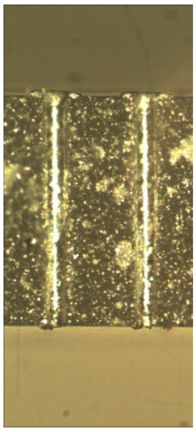
Figure 3 shows individual holes machined in 381 microns thick AlN at a rate of 300 holes/sec. They were measured at ~ 42 microns for the entrance and ~31 microns for the exit. A higher peak power and longer pulse duration was used when compared to holes drilled on alumina with the same thickness.



a)Entrance



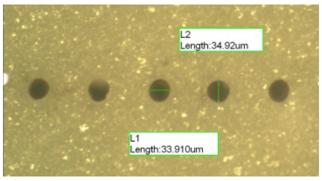
b) Exit



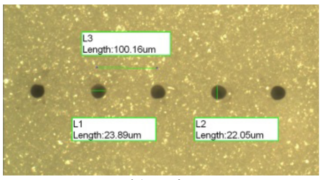
c)Cross section

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

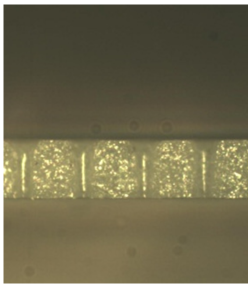
As the material thickness is reduced, shorter pulses can be used, thus allowing for higher drilling rates. Figure 4 shows individual holes machined in 100 microns thick alumina (99.6%) at a rate of 3000 holes/sec. They were measured at ~33 microns for the entrance and ~22 microns for the exit.



a)Entrance



b)Exit

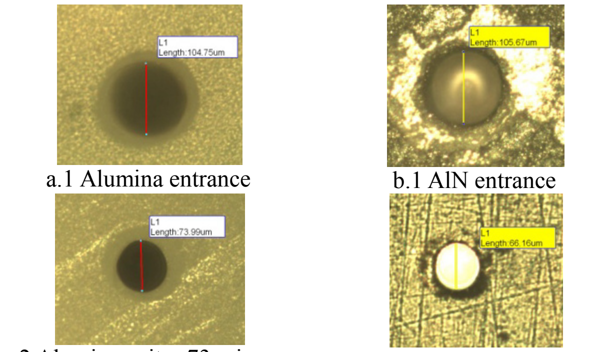


c)Cross section

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.



a.1 Alumina entrance b.1 AlN entrance

a.2 Alumina exit, ~73 microns b.2 AlN exit, ~65 microns

Fig. 5 'Larger holes' drilled in 320 microns thick a) alumina and b) aluminum nitride both at > 100 holes/sec.

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 (Figure 6). This hole diameter variation can often be better depending on application specifics. Both periodic and non periodic hole patterns can be machined at high speed with high positional and dimensional accuracy, by using external encoder based laser triggering.

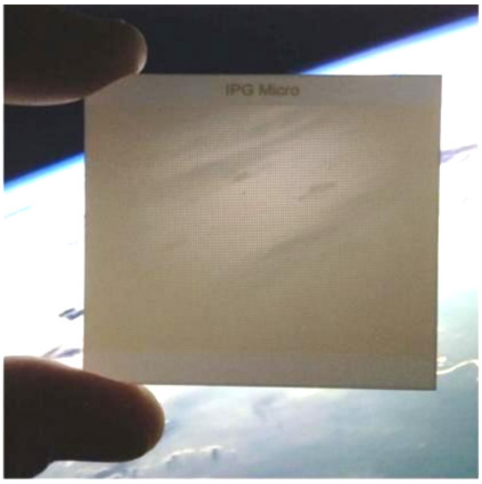
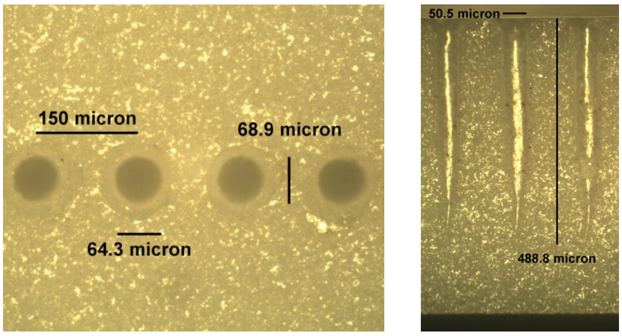


Fig. 6 Drilling of 20,000 holes in 50 mm by 50 mm alumina substrate 320 microns thick at >100 holes/sec using the QCW fiber laser. Positional accuracy within ± 5 µm, dimensional accuracy 100 µm entrance, and 70 ± 10 µm exit for 100% of the holes.

2.2 Scribing and Cutting of Ceramics 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.

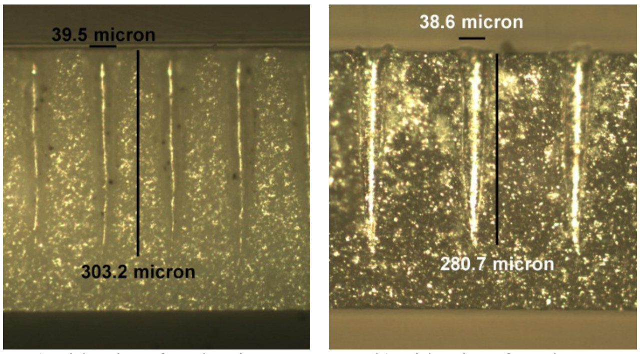
Figure 7 shows scribing of alumina (96%) 635 microns thick, at a speed of 200 mm/sec with individual shots to a depth over 350 microns, and a spacing ~150µm. A pulse duration below 100 microseconds was used.



a)Top view b)Cross section

Fig. 7 Scribing of 635 microns thick alumina (96%) at 200 mm/sec.

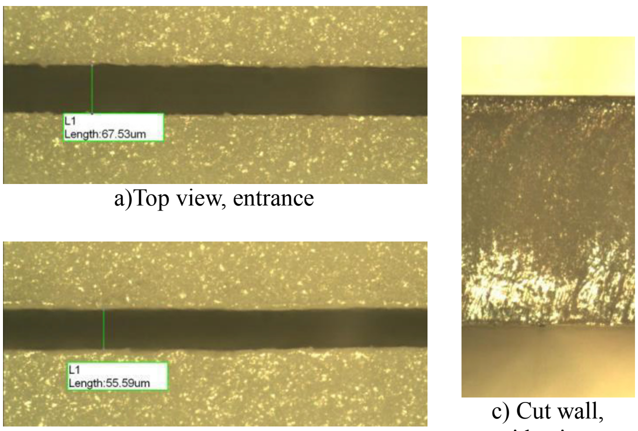
Figure 8.a shows scribing of alumina (99.6%) 381 microns thick, at a speed of 300 mm/sec, while figure 8.b shows scribing of aluminum nitride 381 microns thick also at a speed of 300 mm/sec. A pulse duration below 50 microseconds was used.



a) Side view for alumina b) Side view for AlN

Fig. 8 Scribing at 300 mm/sec for both alumina and aluminum nitride (381 microns thick).

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 9). 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 10).

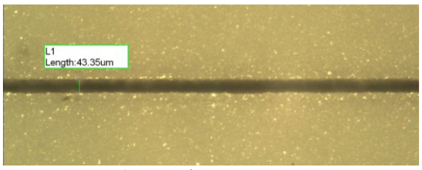


a)Top view, entrance

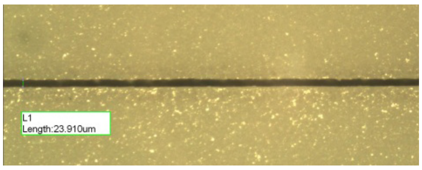
b) Top view, exit

c) Cut wall, side view

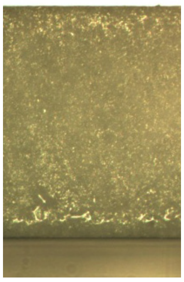
Fig. 9 Cutting of alumina (96%) with a thickness of 635 microns at 140 mm/sec.



a)Top view, entrance



b)Top view, exit



c)Cut wall, side view

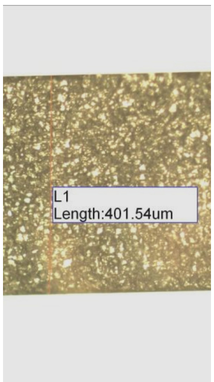
Fig. 10 Cutting of alumina (99.6%) with a thickness of 381 microns at 250 mm/sec.

2.3 Cutting of Crystalline Sapphire with QCW Fiber Laser

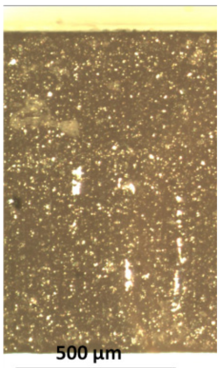
QCW lasers were also used for high quality cutting of sapphire. Figure 11 shows some of the typical shapes cut for the consumer electronics market.

Fig. 11 Examples of various part geometries cut in sapphire with QCW fiber laser as used for consumer electronics.

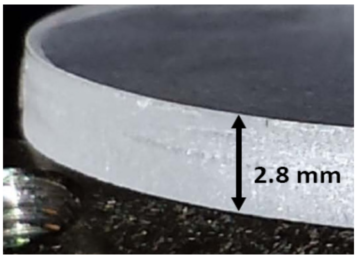
Sapphire up to several mm thick can be cut at reasonably high speeds with good cut quality, avoiding cracks and chip out, and with a surface roughness Ra typically below 2 microns (Figure 12). Sapphire parts with thicknesses of 0.4, 1 and 3 mm thick were cut at speeds around 12, 9 and 3 mm/sec, respectively,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



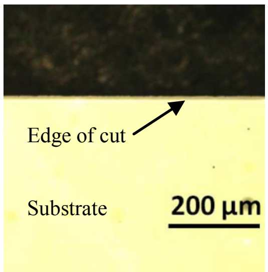
a)Cross section, 0.4 mm thick, cut at 12 mm/sec



b)Cross section, 1 mm thick, cut at 9 mm/sec



c) Cross section, 2.8 mm thick, cut at 3 mm/sec



d) Top view of cut, no cracks nor chip out

Fig. 12 Examples of cut quality on sapphire for various thicknesses when using QCW fiber laser.

3. UV Laser Results

With 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. 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, lathe, 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.

For drilling of micro holes in guide plates for vertical probe cards a special beam delivery with optimized drilling techniques was used that allowed for adequate control of entrance and exit dimensions, and machining of near taperless holes with high accuracy and repeatability. The same system can also be used for engraving/marking and cutting larger features in addition to drilling micro holes.

A typical example of specifications for the rectangular holes needed would be ±2 µm hole size variation (for size length varying from 30 to 100 microns typically), 3 µm maximum error in radial true position across 50 mm by 50 mm, total taper < 5% of the thickness, to be held within 3σ limits for >20,000 holes.

Figure 13 shows the high quality of the holes achieved. Figure 14 shows holes with a slight curved opening at the entrance (which acts as a guide for inserting probes) quickly followed by a straight and smooth hole wall and ending up in a well-resolved exit shape.

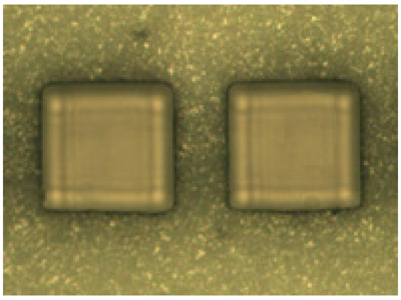


Fig. 13: Exit of 65 by 60 microns holes machined in 200 microns thick silicon nitride, <1 sec/hole, with a UV pulsed laser and a special drilling technique.

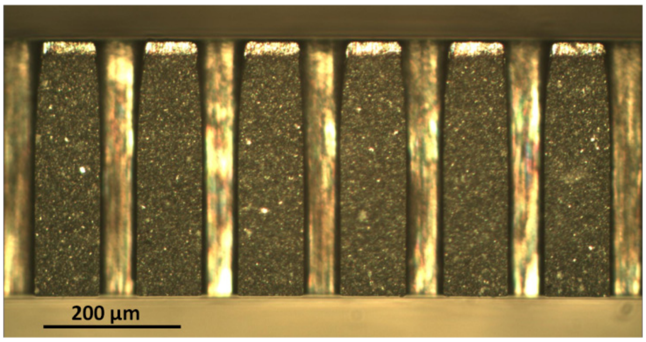


Fig. 14: Cross section showing near taper less rectangular holes in 380 microns thick silicon nitride.

In order to achieve the highest hole density which is driven by the probe card industry needs/roadmap one is required to machine near taperless holes bringing these as close as possible while still maintaining part integrity and functionality for guiding/sliding of the test pins through each micro hole. Figure 15 shows reduced side wall to 10 microns, on center to center pitch of 80 microns. Typical minimum center to center pitch is around 40 microns for 200 microns thick silicon nitride substrate, although even shorter can be achieved.

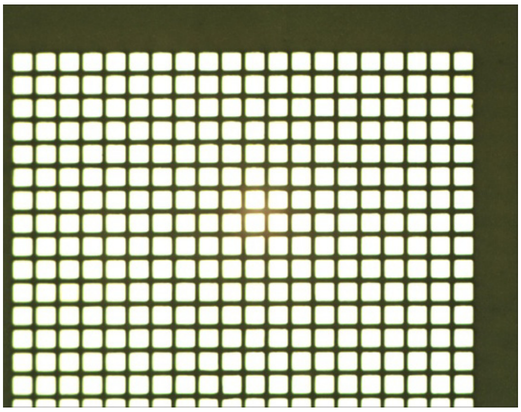


Fig. 15: Array of holes machined with UV laser in 200 microns thick silicon nitride with center to center pitch 80 microns, 10 microns side wall.

Very tight specifications regarding positional and dimensional tolerances are needed for guide plates that typically have in excess of 20,000 holes. With this many holes reducing time/hole is crucial, but cannot be achieved at the expense of specifications needed. Moreover, yield needs to be extremely high since the complete part needs to be "right the first time". IPG Microsystems provides a highly repeatable drilling process, with excellent process stability, at the highest throughput for guide plates needing such specifications, at <1 sec/hole for up to 250 microns thick silicon nitride. Typical results on silicon nitride obtained by the IPGM's precision drilling system are shown in Table 1.

Thick-ness	Typical hole size side	Dimen-sional accuracy	Posi-tional accuracy	Drilling time (per hole)
200 µm	≥ 30 µm	< 2 µm	< 3 µm	< 1 sec
250 µm	≥ 40 µm	< 2 µm	< 3 µm	~ 1 sec
380 µm	≥ 50 µm	< 2.5 µm	< 5 µm	< 2 sec

Table 1: Typical characteristics of rectangular micro holes (up to 100 microns wide) drilled in *silicon nitride* with UV laser using IPGM's system; typical number of holes drilled >20,000 for probe card guide plates, over 50 mm by 50 mm substrate, showing 3sigma numbers.

Other ceramic materials that can yield high quality precision holes with laser drilling include (but are not limited to) alumina, aluminum nitride and Photoveel. Figure 16 shows an array of 50µm rectangular holes made in 300µm thick alumina. Table 2 summarizes typical results obtained for drilling micro holes in alumina.

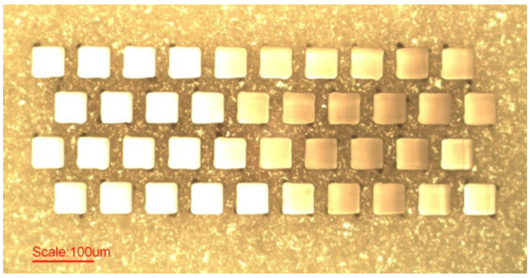


Fig. 16: 50µm rectangular holes made in 300µm thick alumina, 75 microns pitch center to center.

Thick-ness	Typical hole size side	Dimen-sional accuracy	Posi-tional accuracy	Drilling time (per hole)
200 µm	≥ 30 µm	< 2.5 µm	< 3 µm	< 2 sec
300 µm	≥ 40 µm	< 2.5 µm	< 3 µm	< 2.5 sec
400 µm	≥ 50 µm	< 2.5 µm	< 5 µm	< 3 sec

Table 2: Typical characteristics of rectangular micro holes (up to 100 microns wide) drilled in *alumina* with UV laser using IPGM's system; typical number of holes drilled >20,000 for probe card guide plates, over 50 mm by 50 mm substrate, showing 3 sigma numbers.

4. Laser Workstations

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 quality, including dimensional and positional specifications, additional considerations for high volume manufacturing include throughput needs as well as cost of ownership.

To address these multiple and at times very distinct requirements, IPG Photonics - Microsystems Division has distinct workstation series available that can be tailored to the final specifications needs.

For example, it has been shown that drilling micro holes in ceramics can be done using very different lasers and machining techniques, to meet very different positional and dimensional specifications and throughputs. While the series of workstations share the same concepts and general building blocks, they can be specifically designed to meet the needs of high throughput drilling in large ceramic substrates using a QCW fiber laser and a thermal machining technique; or specifically designed to meet the tight positional and dimensional specifications of guide plates for the probe card industry using UV nanosecond pulsed lasers and an advanced drilling technique. At times users are interested in both complexity as well as versatility and IPG Microsystems also provides 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 fiber laser and UV pulsed lasers discussed, but other lasers are possible, such as picosecond or excimer lasers. A part can be processed using the QCW fiber laser coupled to a high pressure cutting head, followed immediately with processing with a pulsed UV laser using galvo-based or fixed beam machining approaches. As an example of such approach Figure 17 shows beveling of sapphire using a pulsed UV laser after cutting it with a QCW fiber laser.

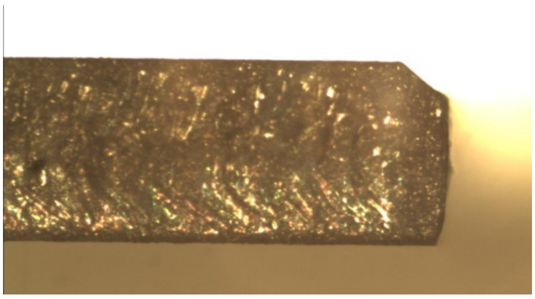


Fig. 17: Side view showing beveling/polishing of 1 mm thick sapphire with pulsed UV laser after cutting it with QCW fiber laser.

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 set-up and operation, while also providing extensive data logging capabilities.

5. Conclusions

A variety of applications results covering advanced laser microfabrication of ceramics and crystalline sapphire have been shown.

The IPG Photonics QCW fiber 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 such as alumina and sapphire. If larger spots are required then there are processing techniques that still allow for 100% coupling to these materials. High drilling rates of 300, 750 and 3000 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 was cut at speeds around 12, 9 and 3 mm/sec, respectively, with final speeds depending on geometry and quality requirements.

High accuracy and high repeatability machining using UV pulsed lasers and advanced drilling techniques were shown machining guide plates for the probe card industry. Shaped rectangular micro holes were machined in silicon nitride and alumina up to ~ 400 microns thick. In 250 microns thick silicon nitride holes up to 100 microns side were drilled with ±2 µm size variation, 3 µm maximum error in radial true position across 50 mm by 50 mm, >20,000 holes all within 3σ limits, and at <1 sec/hole which is believed to be the highest throughput commercially available in a laser workstation meeting such specifications. Similar specifications were obtained for shaped micro holes in 200 microns thick alumina, although at a lower drilling rate of < 2 sec/hole.

The processing techniques used were discussed as well as laser workstations requirements for high volume manufacturing.