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INTERVIEW INSIDE

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Lasers Make the Cut for **SiP Manufacturing**

Laser cutting and drilling can be key to reaching the higher levels of miniaturization required for advanced packaging methods, including System-in-Package (SiP) technology.

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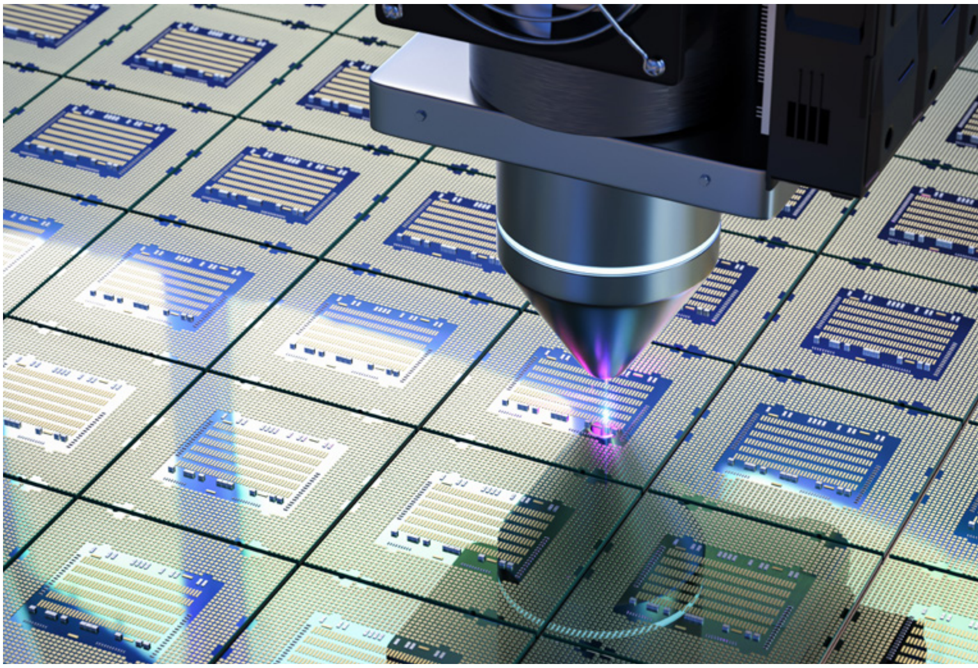
Advanced packaging methods involve smaller, higher-density layouts, reduced feature sizes, and thinner substrates, often incorporating innovative materials. Together, these characteristics place greater demands on the various material processing tasks performed during manufacturing, such as cutting and drilling. Specifically, these requirements include increased dimensional accuracy and higher precision to support the creation of smaller features, as well as smaller Heat Affected Zones (HAZ) to enable closer feature placement. All of this must be achieved while maintaining throughput, quality, and cost-effectiveness

In response to these demands, lasers have emerged as an attractive alternative to traditional mechanical cutting and drilling methods. They're also gaining ground over other non-mechanical techniques such as plasma etching, ElectroChemical Machining (ECM), ultrasonic machining, and Ion Beam Milling (IBM). However, it's important to note that there are actually a variety of different laser technologies and implementations currently in use, each with its own strengths and applications.

This diversity in laser solutions is both advantageous and challenging for manufacturers. While it offers the potential for highly optimized processes, it also requires careful consideration to ensure selection of the best technology for a specific application.

This article explores the necessity for these different laser technologies and presents cutting data to demonstrate the outcomes achievable for some specific SiP materials and processes. The goal is to help readers navigate the wide array of laser-based cutting systems available, and confidently choose a solution that will meet both current and future demands.



Laser processing has become a key enabler for the development and manufacturing of increasingly powerful, yet more compact, printed circuit boards and packaging architectures.

Laser Materials Processing Basics

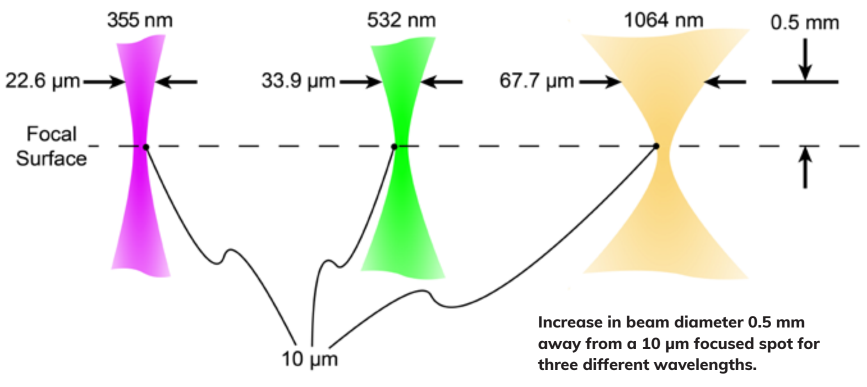
To understand the need for different laser types, it's essential to first grasp how lasers interact with materials. Broadly speaking, there are two basic mechanisms by which lasers can remove material from a solid substance.

The first are thermal methods in which the material absorbs the laser light, thus heating the substance it melts or vaporizes. Often a gas jet is used to remove molten debris to create a cut, trench, or hole. Plus, the chemical reaction caused by laser heating can be modified using various process gasses. This processing regime is typically associated with the use of longer InfraRed (IR) wavelength lasers having longer pulse durations.

The second approach involves using a laser with a large enough photon energy to directly break atomic or molecular bonds within the material. Thus, material is removed nearly instantaneously because the bonds holding it together are directly dissociated.

The chemical bond energies in most solid materials have a dissociation energy that corresponds with

Wavelength	Spot Diameter	Rayleigh Range	Beam Diameter at:		
			0.5 mm	1 mm	2 mm
355 nm	10 µm	0.22 mm	22.6 µm	45.2 µm	90.4 µm
532 nm	10 µm	0.15 mm	33.9 µm	67.7 µm	135.5 µm
1064 nm	10 µm	0.07 mm	67.7 µm	135.5 µm	270.9 µm



Shorter wavelengths have a longer depth-of-focus. If three different lasers are all focused to a 10 µm spot, they will have each spread a different amount 0.5 mm away from the focal plane.

UltraViolet (UV) photons, or even shorter wavelengths. Keep in mind that photon energy increases with the frequency of light, so shorter frequency photons (UV, as opposed to visible or infrared light) have higher energy. Thus, direct ablation of most materials through linear absorption of light typically requires a UV laser. Lasers with UV wavelengths typically emit pulses of light with nanosecond (ns) or shorter time durations.

Both the heating and bond breaking mechanisms just described depend on linear absorption of the laser light. However, it's also possible to drive direct ablation through non-linear absorption. In this case, a single chemical bond absorbs the energy of two or more photons simultaneously. Although the energy of each individual photon might be insufficient to break the bond, their combined energy can. This is called "multiphoton" absorption. It requires very high laser peak power levels to produce multiphoton interactions.

UltraShort Pulse (USP) lasers are typically needed to reach the high peak power levels necessary to efficiently drive multiphoton processes. Specifically, laser pulses in the picosecond (10^{-12} second) or femtosecond (10^{-15} second) regime can (briefly) achieve the peak power levels required.

Laser Wavelength

From the previous discussion it can be seen that linear absorption of the laser wavelength is a significant driving factor for matching a laser type to a particular material and process. Stronger absorption equates to increased processing efficiency. This is why Carbon Dioxide (CO2) lasers can process organic materials well but perform poorly with metals such as copper. Their wavelength is strongly absorbed by the former and mostly reflected by the latter.

Visible and infrared wavelength lasers are compatible with most materials that appear opaque to the eye, but less useful with those that appear transparent (like glass or sapphire). However, most everything absorbs UV light.

In contrast, the non-linear absorption involved in ablative processing makes it applicable to virtually every material regardless of wavelength. Specifically, USP lasers can typically process a substance that is nominally transparent at the laser wavelength. For example, a USP laser with a green output wavelength can readily cut glass.

Another important factor relating to wavelength is how it affects the focused spot size. Simply stated, light diffraction effects dictate that shorter wavelengths can be focused to smaller spot sizes than longer wavelengths. This means that shorter wavelength lasers can, in general, produce smaller, more intricate features. Thus, the long infrared wavelength of the CO_2 laser prevents it from being focused to small enough spot sizes to deliver smaller via diameters.

A more subtle effect related to light diffraction is the Rayleigh Range, or depth-of-focus. This refers to how rapidly the spot size increases away from the plane of best focus. At a given focused spot size, a shorter wavelength laser produces a longer depth-of-focus.

This can have a rather significant impact in a real-world laser cutting or drilling system. First of all, a longer depth-of-focus makes the system less sensitive to variations in material surface height or slight misalignments. This increases the process stability and consistency, and also reduces the need for system focus adjustment.

A longer depth-of-focus also allows the creation of cuts or holes with high aspect ratios (depth-to-width ratio), which is beneficial for drilling deep vias or other high-precision features required in advanced packaging. Such features will have lower sidewall taper, which reduces the amount of precious real estate that must be reserved for them. In the end, higher densities and smaller devices are achieved.

Nanosecond Laser Singulation Test Results

To evaluate how these factors come together in real-world singulation applications, MKS Spectra-Physics applications engineers conducted a series of cutting tests on substrates commonly used in SiP and other advanced packaging techniques. The objective was to determine the effectiveness of these lasers in cutting the materials and to quantify the differences in cut quality and overall system performance between nanosecond pulse lasers and ultrashort pulse (USP) lasers.

The nanosecond pulse laser (Spectra-Physics Talon GR70) used provides 70 W of output at 532 nm (green). In the first set of tests, it was used to make through cuts in a SiP material comprised of thin FR4 with embedded copper traces and solder mask layers on both sides. Total thickness of this material was 250 µm, 150 µm of which was the FR4 board, with the remaining 100 µm being the polymeric solder masks.

The cutting setup utilized a high-speed, multi-pass processing technique based on a 2-axis scanning galvanometer. In order to avoid thermal effects and minimize the HAZ, a high scanning speed of 6 m/s was employed.

Since the material is relatively thin, a small focus spot size (~16 µm) was combined with a high laser Pulse Repetition Frequency (PRF) of 450 kHz. This combination of parameters takes advantage of this laser's unique ability to maintain high power at high repetition rates (67 W at 450 kHz in this case). This is beneficial for maintaining proper energy densities and spot-to-spot overlap at the higher scanning speeds, which means faster cutting. Because multiple passes over the cutting path were made to achieve a through cut, the so-called net cutting speed (scanning speed divided by number of scans) was 200 mm/s.

Photographs taken through an optical microscope (Figure 1) show entry and exit surfaces of the cut as well as a subsurface area where the cutting path crossed over a buried copper trace. Both the entry and exit surfaces are cleanly cut with little evidence of HAZ, although there is some surface debris. In addition, the presence of the copper trace did not significantly affect the cutting process.

Greater detail is seen in the next image (Figure 2) which shows a cross-sectional view of the cut sidewall. Cut quality is good, with a small HAZ and limited carbonization. The individual fibers in the FR4 layer are clearly discernible, with melting limited to the cut fiber end faces oriented outward from the sidewall (i.e. perpendicular to the fibers running along the face of the cut). Importantly, no delamination amongst the layers is seen. Furthermore, this closer view confirms that the Cu trace line cut is of good quality and did not suffer detrimental thermal effects, such as outflow of molten copper or delamination

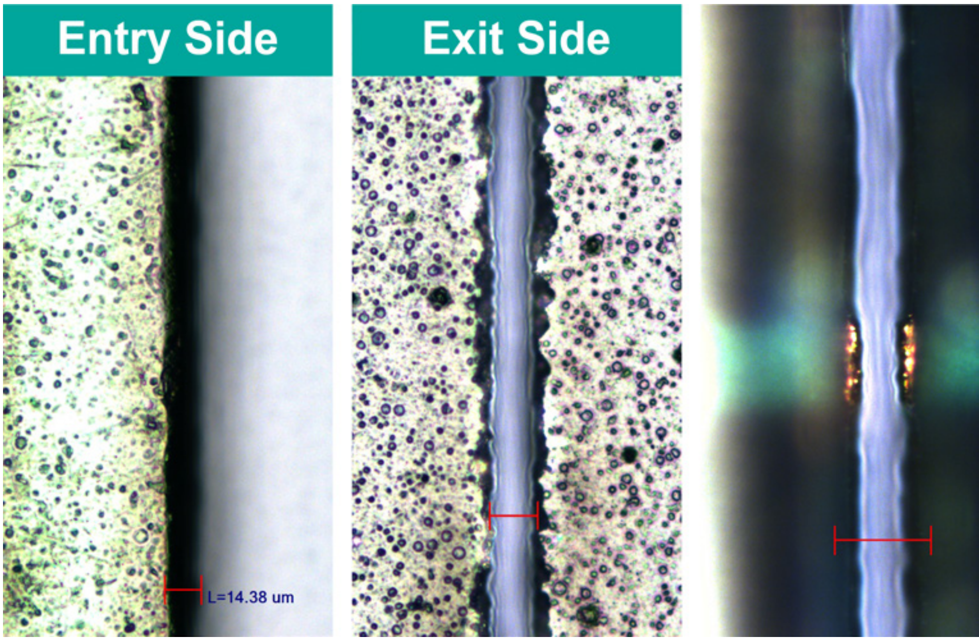


Figure 1. Cutting results for the 250 µm thick SiP substrate using a green nanosecond laser. These microscope photos show the entry and exit sides of the cut, plus the cut through the copper trace.

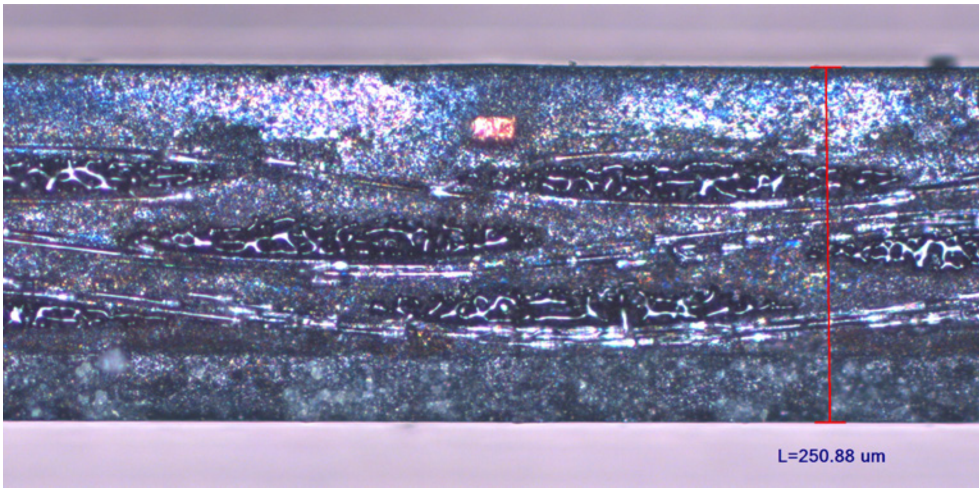


Figure 2. This sidewall view of a green nanosecond laser-cut, 250 µm thick SiP substrate demonstrates good quality, with minimal glass fiber melting and no HAZ adjacent to the buried copper trace.

While the cutting result using the green wavelength ns pulse laser is of quite good quality – and is very fast – close inspection of the sidewall does reveal minor melting of glass fibers. The significance of this will depend on specific application requirements.

USP Laser Singulation Test Results

To explore cutting with a USP laser, testing was performed with a 13 ps pulse width laser having an average output power of 50 W at 532 nm and

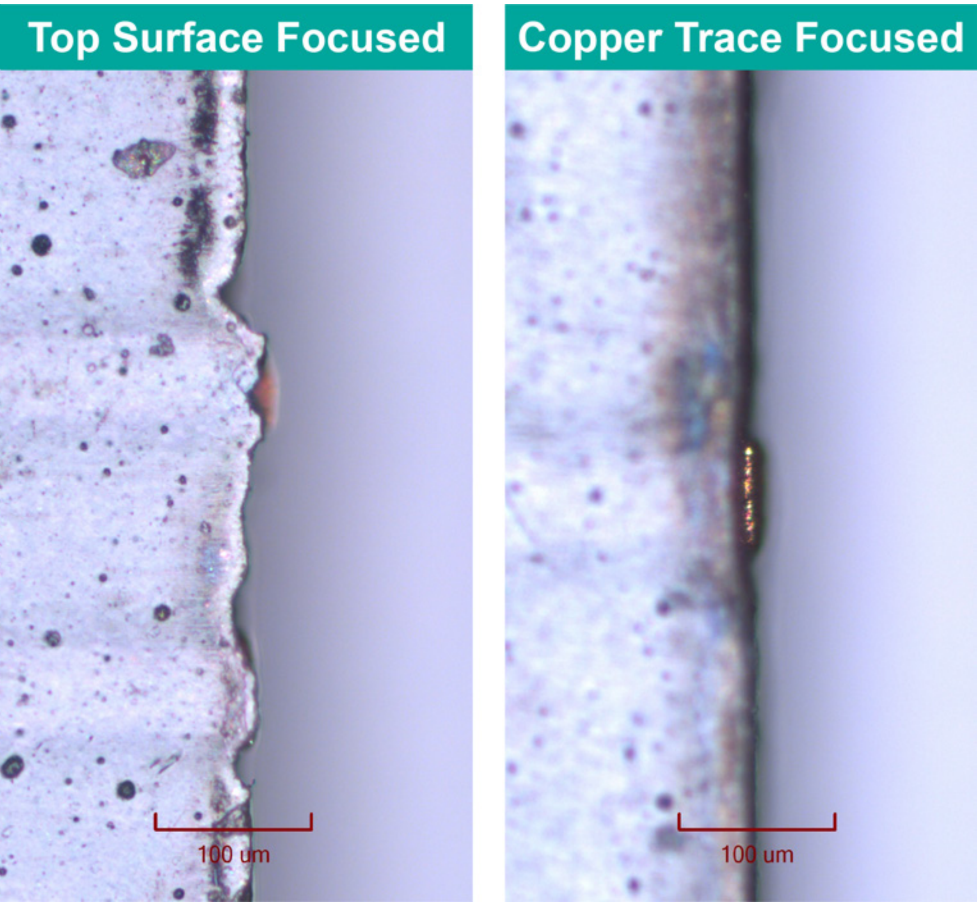


Figure 3. Cutting results for the 200 µm thick SiP substrate using a green USP laser operating at 40 W. These microscope photos both show the entry side of the cut, with one focused to emphasize the slightly protruding edge of the copper trace. While cut quality is good, there is some HAZ around the copper trace.

500 kHz (Spectra-Physics IceFyre GR50). Because it is expected that the USP laser will be reserved for the most demanding and delicate processing tasks, this testing used a thinner substrate. In this case, a 200 µm thick FR4 substrate having polymer solder mask protective layers on both sides, plus intermittent embedded copper trace lines layered along the intended cutting path. The FR4 itself was about 100 µm thick.

Initial process efforts found best results with the laser operating at 40 W and a PRF of 400 kHz. Multi-pass scanning was again employed so that the scanning speed of 4 m/s resulted in an effective cutting speed of 57 mm/s.

The microscope photographs (Figure 3) show the entry surface which includes a cut through a copper trace. The surface quality is excellent overall, with better cut edge quality and significantly less debris than with the ns laser cut. However, there is evidence that excess heating around the copper layer has caused a slight erosion of the polymer/FR4 material around it. This has produced a minor protrusion of the copper from the sidewall. Importantly, the laser-cut feature in this image is shown as-processed, with no post-cleaning step, in contrast to the previous result obtained with the ns pulse laser.

To see if results could be improved, the laser power was reduced 50% (20 W), along with other parameter adjustments. The scanning speed was increased to 6 m/s, resulting in a net cutting speed of 38 mm/s. If a 50% power reduction delivers acceptable results, the laser could instead be split into two processing beams executing the same process. This would double the overall system cutting speed to 2×38 = 76 mm/s, which is 33% greater than that with a single high-power beam.

The microscope photos (Figure 4) clearly demonstrate that these process parameters delivered better cut quality with an even greater reduction in debris. Once again, no post-process cleaning step was performed. There is virtually no HAZ around the copper trace in this cut and no significant protrusion of the copper post cut. Thus, in this case, using reduced laser power clearly delivered increased quality; and the overall throughput gain with a two-beam split configuration demonstrates a more efficient use of the laser's available power.

Scanning Electron Microscope (SEM) imagery (Figure 5) provides more information on cut quality. It shows a cleanly-ablated sidewall, and individual fiber end faces exhibiting no or low melting. There is no delamination between layers. Importantly, the copper trace has been cleanly ablated with no melting or deformation in and around the copper.

Discussion and Conclusion

Based on the technical considerations of the light/material interaction and the limited test results presented here, it should be clear that there is no "best" laser for the demanding materials processing needs of advanced packaging.

Clearly, there is an improvement in feature quality as pulse width is decreased, but at the cost of reduced processing speed. However, if the improvement in quality is sufficient to eliminate the need for additional cleaning steps, the overall manufacturing throughput may in fact not be reduced. And, while this testing has not explored the parameter of wavelength, it can be stated almost categorically that UV lasers will produce better results than longer wavelengths.

None of this is surprising. In general terms, photothermal material removal – which usually occurs with CO_2 lasers and nanosecond pulse regime fiber and solid-state lasers –

delivers higher material removal rates. But these lasers produce a larger Heat Affected Zone (HAZ) and also require short wavelengths to achieve the very smallest feature sizes.

The converse is true for pure USP photoablative processes. They typically operate at lower material removal rates but minimize (or in some cases virtually eliminate) the HAZ and need for post-processing. In fact, since ablation with USP lasers doesn't introduce much heat into the material, it is often termed a "cold" process. Although it should be noted here that USP lasers rarely operate exclusively through ablative means and usually remove material through a mix of thermal and ablative processes.

But besides the speed tradeoff for increasing quality, there is another important practical consideration. Namely, the USP lasers required for ablative processing are usually more expensive than those used for purely thermal processing methods. They're also more complex, which can impact reliability and maintenance costs.

Similarly, UV lasers (both nanosecond and USP) are invariably more costly than their visible or IR counterparts, and also produce lower output power. This typically results in higher capital cost and lower throughput. From this perspective, nanosecond green wavelength lasers can offer an optimal balance.

In conclusion, laser technology offers a versatile and precise solution for the demanding material processing requirements of advanced packaging, including SiP. While both nanosecond and ultrashort pulse lasers can deliver exceptional results, the optimal choice depends on specific application needs. Factors such as feature size and heat-affected zone must be balanced against throughput, capital expense, and ongoing cost-of-ownership. Successfully moving forward with laser-based SiP and advanced packaging solutions will be contingent on working with suppliers offering a full range of different laser technologies – from ns to USP, and wavelengths from IR to green to UV – as well as the knowledge and expertise for applying them. G

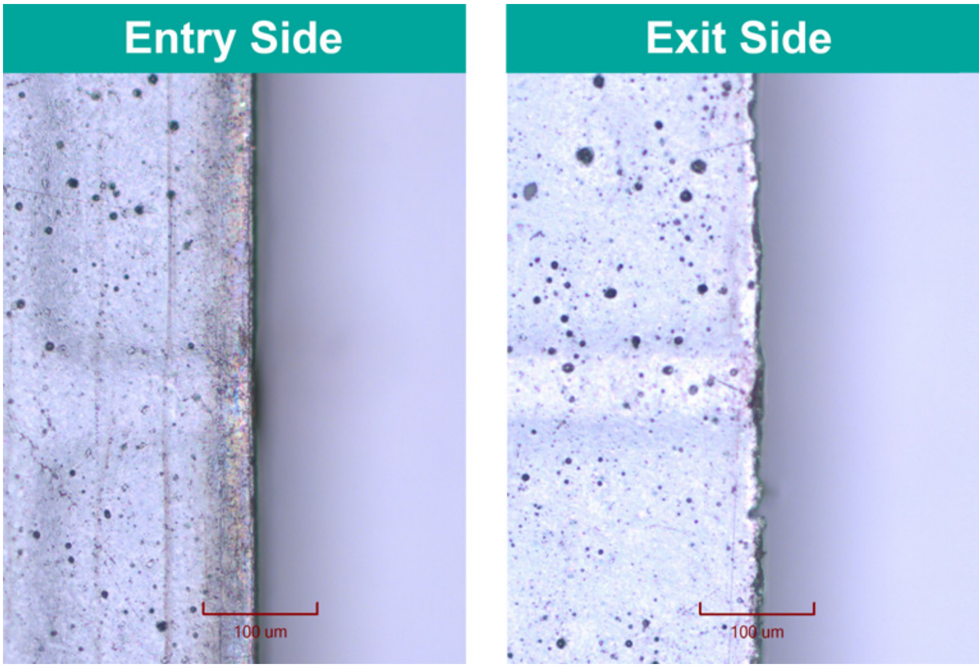


Figure 4. Cutting results for the 200 µm thick SiP substrate using a green USP laser operating at 20 W. These microscope photos show the entry and exit sides of the cut around the copper trace. There is a clear improvement over the results obtained at full power operation. Specifically, the HAZ surrounding the copper has been essentially eliminated. The speed in this case can be increased significantly by using a higher power ps UV laser and splitting the beam.

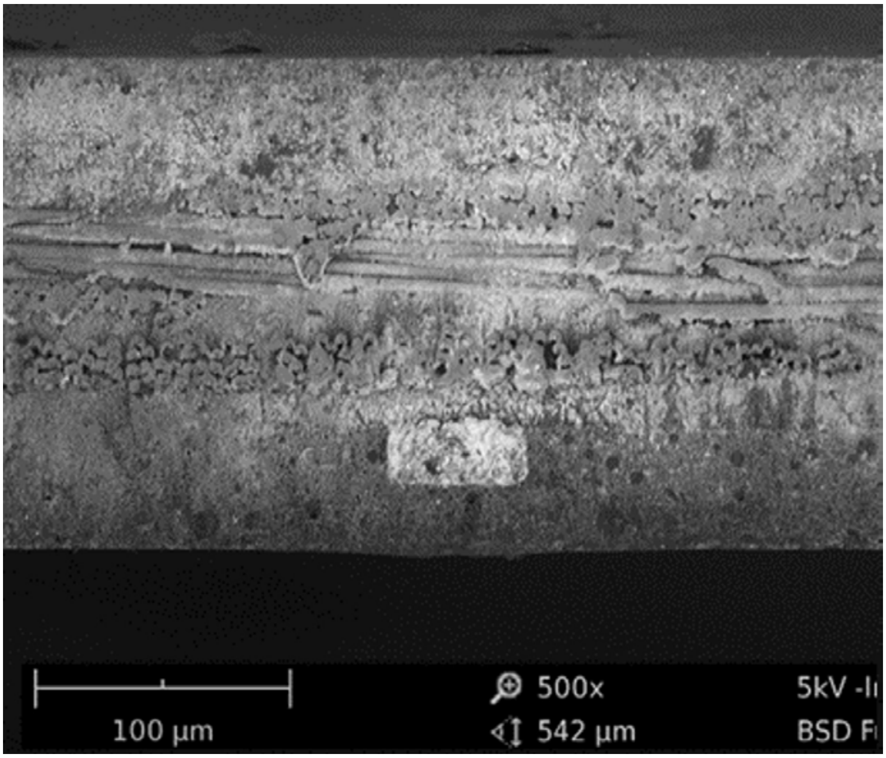


Figure 5. Sidewall view of a 200 µm thick SiP substrate cut with 20 W of green USP laser power. The substrate demonstrates excellent quality, particularly within the glass fiber weave and adjacent to the buried copper trace.