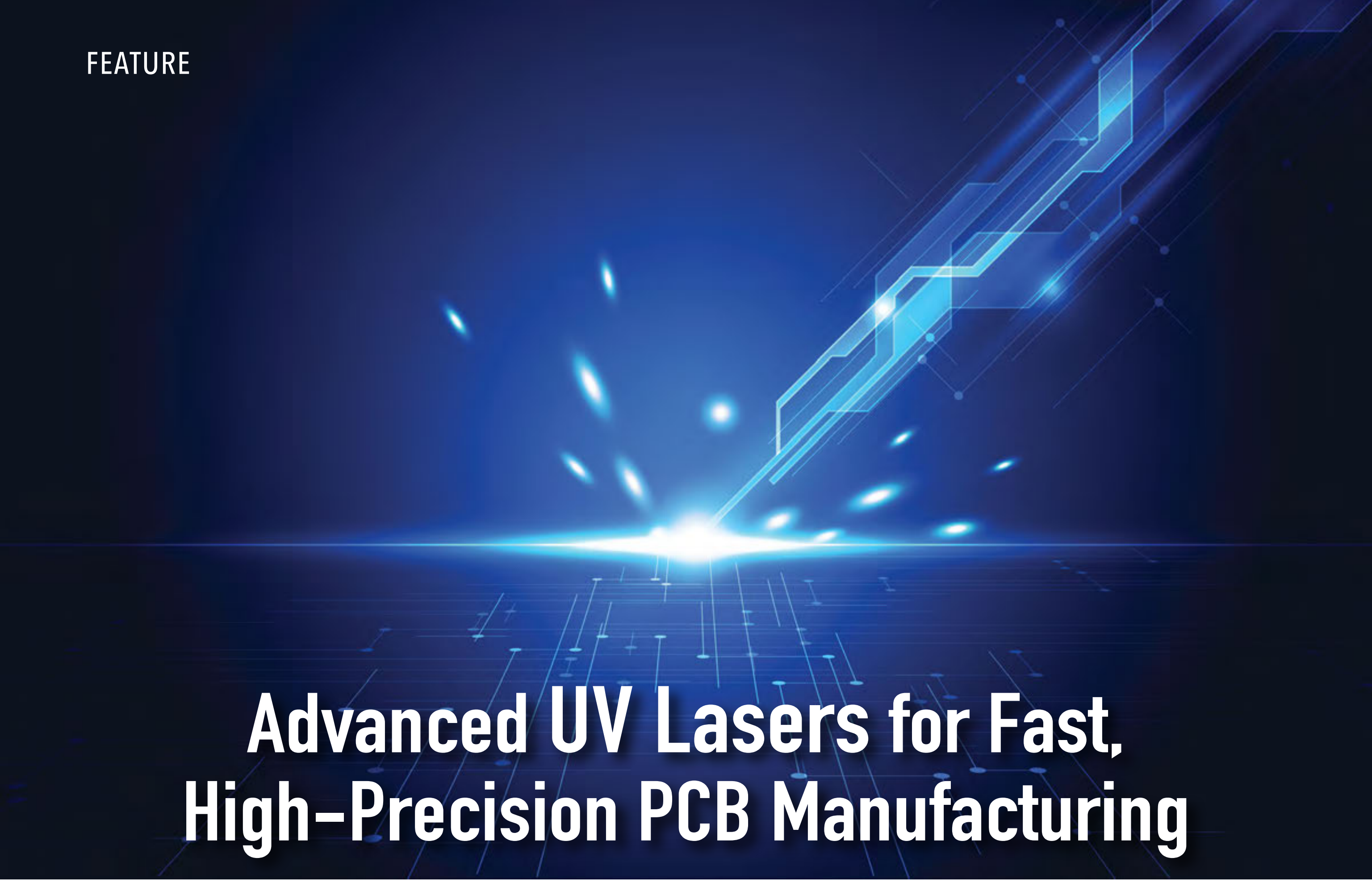


Advanced UV Lasers for Fast, High-Precision PCB Manufacturing

by Jim Bovatsek
SPECTRA-PHYSICS

Introduction

For more than 30 years, lasers have played a significant role in the manufacturing of PCBs. It is not a coincidence that electronic devices have, at the same time, become increasingly miniaturized. The ability to tightly focus a laser beam much smaller than a mechanical tool has been an enabler of such dense, compact circuitry; and the elimination of consumables such as drilling and routing bits has reduced manufacturing costs.

The workhorse laser technology over the years has been the carbon dioxide (CO_2) laser, which has provided manufacturers with reliable, cost-effective power for various applications. The most identifiable laser process in PCB manufacturing is what is referred to as via drilling, which involves laser drilling a hole through an electrically insulating dielectric layer on a copper substrate. Generally, if the substrate is left intact, the hole is a blind via; if it is also drilled through, it is a through via. Very small holes having diameters below about 150 micrometers are commonly referred to as microvias. After a subsequent copper plating step, an electrical interconnection through the dielectric layer is formed. By arranging these vias in various two-dimensional configurations and by implementing additional build-up, drilling, and plating steps to introduce a third dimension, the high-density interconnect (HDI) and packaging needs of today's powerful yet compact electronic devices are satisfied.

Making it Smaller

As always there is a mandate for smaller: smaller mobile devices, smaller microchips, smaller electronics packages, and smaller interconnect vias. Vias drilled with CO_2 lasers are generally limited to diameters of 60–80 μm or larger due to the long (~10 μm) wavelength of the light, which has a direct bearing on how small the beam can be focused. While smaller via sizes can technically be achieved, the business case quickly vanishes due to higher overall process complexity (and therefore cost).

Here is where shorter-wavelength pulsed ultraviolet (UV) diode-pumped solid-state (DPSS) laser technology enters the picture. The short UV wavelength—about 30 times shorter compared to CO_2 wavelengths—can easily be focused to the small sizes necessary for the fabrication of increasingly small microvias. Since the mid-1990s, pulsed UV DPSS lasers with nanosecond (ns) pulse durations have been commercially available for industrial/OEM use. While during the early days of the technology the relatively high cost and troubling reliability issues limited their appeal, today's products are vastly improved in both areas. Indeed, over the past decade, the cost per Watt for such lasers has fallen by an order of magnitude, and product lifetimes have improved dramatically, in some cases surpassing 20,000 operating hours at high power levels.

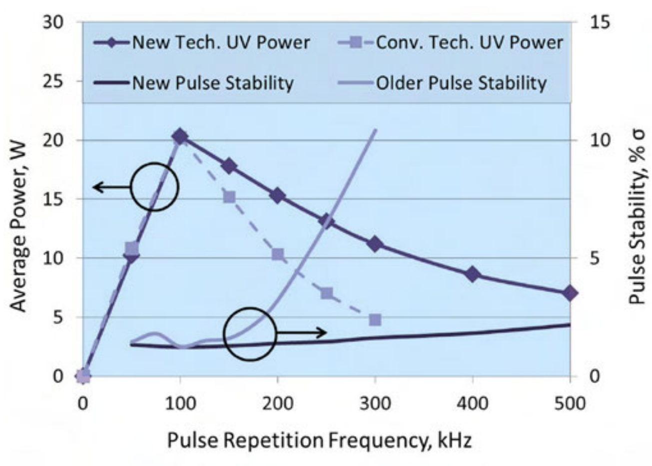


Figure 1: Advanced UV light conversion leads to high power and high-pulse energy stability well beyond the nominal pulse frequency.

Today's UV DPSS Laser Technology

Typically, a UV DPSS laser begins with a high-power laser source at a fundamental infrared (IR) wavelength of ~1 mm which is focused into non-linear optical crystals to generate the UV output, a phenomenon known as harmonic conversion. The IR to UV conversion efficiency is dependent on the IR pulse energy, among other factors. The pulse energy is equal to the laser's average power divided by the pulsing frequency or pulse repetition frequency (PRF).

For IR wavelengths, the average power is relatively constant above some particular frequency, and therefore higher PRFs result in lower pulse energies, and vice-versa. As for the converted UV light, the maximum average power is achieved at some nominal frequency, PRFnom, the specific value of which is determined by the design of the laser. The average power at the UV wavelength decreases with operation at higher PRFs since the IR pulse energy, and hence the IR to UV conversion efficiency, diminishes.

If elevated UV power levels can be maintained for a wide range of operating PRFs through a careful laser design consideration then this offers a high level of machining flexibility for the end user. Higher energies can be used to machine large features and deep cuts, but if lower energies are required for precision drilling, cutting and micromachining, operation at higher PRF levels can be used to proportionally scale up throughput. In short, the ability to have relatively high power levels for an extended PRF range would make for a highly flexible tool with a large application space. And if one laser can operate across this continuum, then tool builders can reap the cost savings inherent in having both a single equipment interface (mechanical, electrical, optical, communication) and a single equipment supplier (higher volume orders reducing cost per unit).

Increasingly, lasers incorporating such advanced design and UV conversion technology (including Spectra-Physics' latest industrial UV lasers) are becoming available on the marketplace. While the exact techniques for achieving this performance are generally proprietary and closely guarded, they typically require strong expertise in harmonic conversion methods as well as access to advanced optical coating technology.

Compared to other UV DPSS nanosecond lasers (including Spectra-Physics' older generation technology), the new harmonic conversion technologies allow elevated power levels to be maintained at an extended range of PRFs—well beyond PRFnom—as shown in Figure 1. Indeed, going beyond 3× PRFnom, the power output advantage approaches a factor of 2. Furthermore, the pulse energy remains remarkably stable (well below 5%) out to 5× PRFnom. More conventional UV laser technologies technically do allow operation at such higher PRF values, but beyond about 2–3× the PRFnom, the pulse energy stability degrades very rapidly.

PCB Microvia Drilling with UV Lasers

A common laser via drilling application is microvia formation in Ajinomoto Build-up Film-

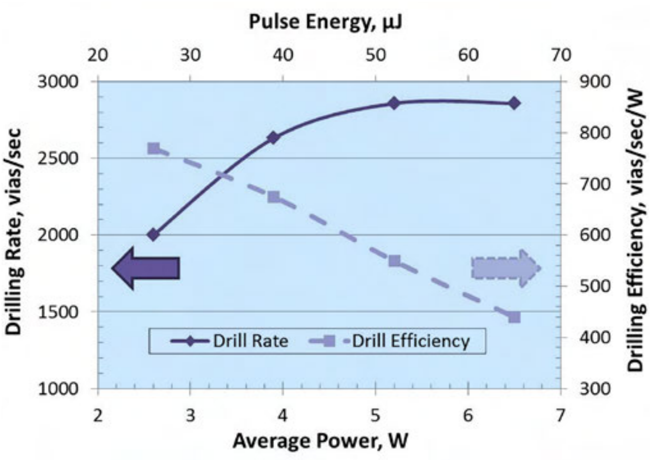


Figure 2: Via drilling rate and efficiency with increasing average power at a fixed PRF. NOTE: This data is at a condition of non-optimized system configuration and process parameter set.

coated thin-rigid copper-clad substrate. The goal is to quickly and cleanly remove the material with minimal copper damage and with a small, controlled amount of sidewall taper angle. Using a pulsed nanosecond UV laser combined with high-efficiency flattop beam-shaping optics, experiments were performed to determine drilling throughput at varying average power levels. The ABF type was GX13 with a thickness of 30 µm, and the targeted via-diameter was in the 50–60 µm range. The power was varied within the range 2–7 W with a fixed PRF of 100 kHz, resulting in a pulse energy window of 20–70 microJoules (µJ). The number of irradiating pulses was varied for each power level, and the minimum count required to cleanly expose the copper substrate was noted. Dividing this number into the 100 kHz PRF generates the maximum theoretical drilling rate in vias per second.

Results of the study are summarized in Figure 2. The rate of drilling is plotted on the left-hand axis and the drill rate per unit Watt of laser power, a measure of efficiency, is on the right-hand axis. As the power and hence pulse energy increases, the drilling rate initially climbs rapidly, approaching 3000 holes per second. Above ~40–50 µJ of energy, however, a saturation regime is encountered and the drilling rate levels off which results in the downtrend in drilling efficiency. This saturation phenomenon is caused by the exponential nature of light extinction in the material, whereby beyond certain fluence (energy per unit area) levels, only marginal increases in ablation depths can be achieved even with large increases in fluence. With UV light and strongly absorbing polymeric materials, this transition can be quite abrupt. A consequence of this phenomenon is illustrated in Figure 2: A doubling of pulse energy from 25 µJ to 50 µJ only resulted in a 1.4× faster drilling/ablation rate, much lower than the 2× one might have expected.

Since the laser used for the tests maintains high power at high PRFs, drilling rates easily exceeding 3,000 vias/sec could be achieved simply by increasing the PRF used for the process. In Figure 3, microscope images of a ~50 µm diameter laser-drilled via show that the ABF is drilled with high quality and with minimal damage to the underlying copper. For this via, 45 pulses at 150 kHz PRF were used, which equates to a drill rate of 3,300 vias per second.

Since small microvias require less energy due to the higher concentration of the beam, it can be a challenge to design a system and define a process that can make efficient use of today's higher power UV sources, which in many cases are designed to operate nominally (i.e., with maximum output power) at lower PRFs and higher pulse energies. One simple way to maximize throughput is to increase the laser's PRF until the optimal combination of pulse energy and pulse rate is en-

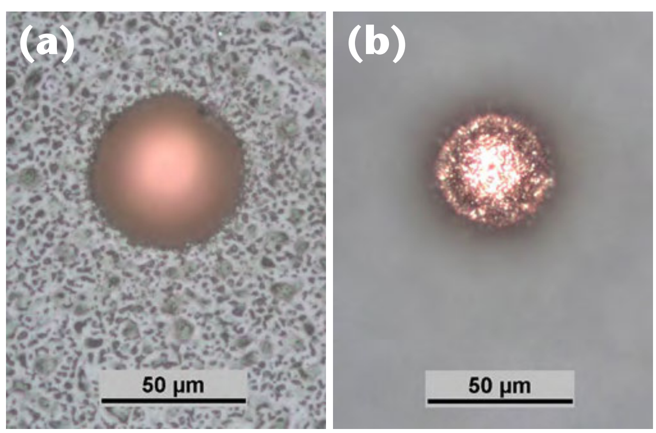


Figure 3: Top ABF surface (a) and bottom copper surface (b) views of a blind microvia drilled with a pulsed UV laser at high PRF with 3,300 holes/sec throughput.

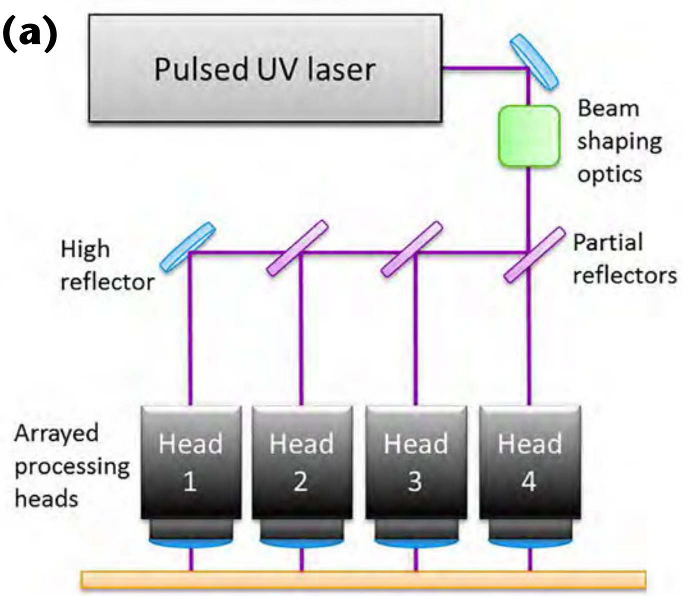
countered, resulting in the most efficient processing and maximum throughput. As an example, consider the case where this optimal combination happens to occur at 200 kHz for a laser having PRFnom of 100 kHz. Both the average power and pulse energy are lower than at PRFnom, but the same number of pulses are emitted in half the time; and although the pulse energy is lower and the per-pulse ablation rate will therefore be lower, the data in Figure 2 indicate it will not be lower by a factor of 2. Hence, a net improvement in the process throughput will be realized. In this fairly common scenario—a mismatch between the design point of a laser and the needs of a specific application—lasers with elevated power levels for an extended range of PRFs are highly advantageous.

There are other ways to maximize the potential of today's higher-power UV lasers. If the optimal energy for efficient processing is significantly lower than the energy at the designed PRFnom for maximum laser average power, then it may make sense to split the beam into multiple lower energy beams and route them to multiple processing heads (as shown in Figure 4a). Using such a configuration, the effective throughput of the processing laser can be further improved compared to the above described approach of simply increasing the PRF. The throughput advantage is greater for smaller vias since they require lower energy and therefore a larger number of beam splits can be made. As an example, Figure 4b contains a table demonstrating the effective via drilling rate for the case of a single beam/high PRF vs. a split beam configuration for drilling ABF blind vias of diameters 50 and 100 µm which using a 15 W UV laser system. With the latest 30 W version of the laser, the throughputs would be about double that of the 15 W model.

Laser Processing for Flex PCB Manufacturing

Not only is packaging becoming smaller, it is by necessity becoming increasingly flexible. Device miniaturization has reached the point where modules can be integrated into very thin items—credit cards, passports, clothing (wearables), even paper—and interconnection and packaging schemes must accommodate the same. In addition, the flex PCBs allow for more versatile and compact arrangements within portable devices, leading to reduced form factors, increased functionality, and design flexibility. With such driving forces, manufacturing of flex PCBs has experienced rapid growth for several years and this is likely to continue.

(a)



(b)

Beam delivery type, efficiency	Drill rate, at via diameter 50-60 µm Ø vias/sec	Drill rate, at via diameter 100 µm Ø vias/sec
Using beam splitting at PRF_{nom} 60% eff.	6000	3300
Single beam, High PRF 75% eff.	3300	2800

Figure 4: Splitting a laser's high-power beam (a) allows higher overall drilling rates (b), especially for smaller diameter vias which require less pulse energy.

A commonly used material in flex PCB manufacturing is the copper/polyimide/copper laminate. The foil thicknesses within the laminates have shrunk over time, with copper and polyimide layers currently down to below 10 and 13 µm, respectively, and likely to trend thinner still. Common flex PCB laser processes include profile cutting and both blind and through via drilling. Compared to ABF resin-on-copper via drilling, flex PCB via drilling has the additional requirement that two very different materials—copper and polyimide—must be processed, ideally with the same laser source. As it turns out, CO2 lasers, with their far infrared (~10 µm) wavelengths, are not suitable because the long wavelength light is strongly reflected by the copper. Hence, UV DPSS lasers are used heavily in flex PCB manufacturing.

Using a high-power 30 W UV laser, processes for drilling both blind and through vias have been developed and characterized for drilling throughput. The flex PCB laminate consisted of 1 mil thick polyimide laminated on both sides with ½-mil copper foil. Since the materials are fairly thin, very small vias of 25 µm diameter or below can be percussion drilled using a very small focus spot. The small spot size and strong coupling of the UV light to both the copper and the polyimide allows for processing with relatively low energy levels, which means the laser can be operated at very high PRFs, thereby achieving high drilling rates. If larger vias are required, a larger focus spot could be used (with more energy per pulse from the laser) and for yet larger vias, high-speed beam scanning optics can be employed to rapidly move the tightly focused beam in a circular pattern—a process technique known as trepanning—while the laser is ablating the material. Typically, the small-circle trepanning process is limited by the speed of the scanning optics, and sometimes operating the laser at very high PRFs can result in undesired heat affects. In such cases, a laser with a lower PRF (and therefore lower average power) is preferred in order to match the speed of the beam scanning equipment, thereby ensuring best quality.

For percussion drilling (Figure 5 a, b), throughputs can be very high because there are no moving parts required to drill, and the laser can be operated at a very high PRF since the focus spot is small and therefore energy requirements are reduced. The percussion drilled blind vias in Figure 5 were drilled with a laser-capable drill rate of about 9,000 vias/sec, while the drill rate for the through vias was more than 5,500 vias/sec. Both drill processes used a higher laser PRF of 300 kHz. The trepan drilled via in Figure 5c involved a 2-axis scanning galvanometer processing head that deflected the beam with small circular motion—an approach that is inherently slower compared to percussion ablation. In this case, three repeat scans at 200 mm/s were used, which resulted in an effective drill rate of >250 vias/sec. In this case, the laser PRF was much lower at 60 kHz in order to match the speed of the beam scanning equipment. The 3D optical profilometer data plot in Figure 5d shows the high-quality, much desired, very low edge burring that can be achieved with careful process optimization. In this case, the 2–4 µm edge burr is not much larger than the native roughness of the copper foil.

Coverlay Patterning

In flex PCB manufacturing, coverlay patterning is an important process for cutting various

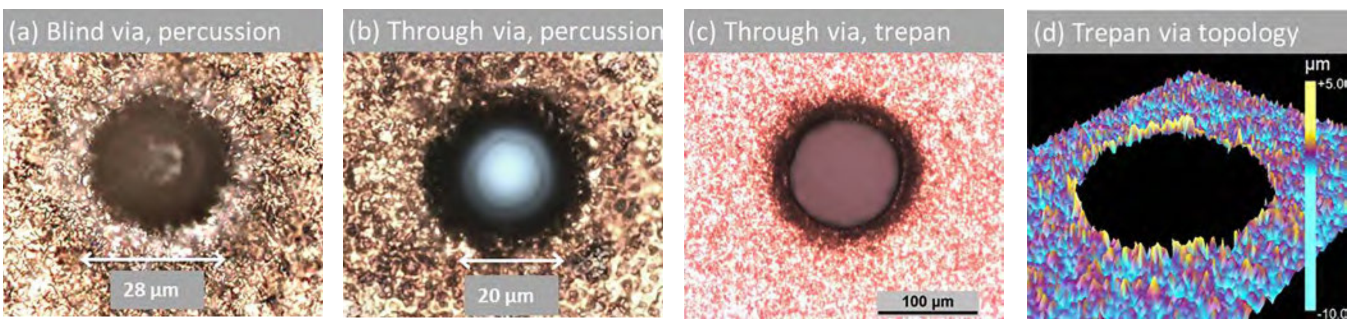


Figure 5: Optical photomicrographs of blind (a) and through (b) vias in Cu/PI/Cu laminate as well as trepanned via (c), and surface topology of trepanned via (d) generated with pulsed UV lasers.

geometric shapes in a thin polyimide sheet which may be loosely adhered to a paper backing. The coverlay itself is then adhered to a flex circuit as a protective layer, and its purpose is functionally analogous to that of solder mask for rigid PCBs. In some cases the polyimide and adhesive are attached to a release paper, and it is important to have non-thermal ablation of a UV laser source to avoid burning the paper. To cut through the materials, high energy levels are not necessarily required because the sheets are very thin which allows a very small focus spot to be used (smaller focus spots are also more divergent and hence less suitable for cutting thicker materials). If this energy can be applied at very high PRFs, then high patterning speeds can be achieved accordingly. As UV laser power is varied from 6 W upwards to 30 W, different patterning speeds can be achieved with either a single beam, high-PRF approach or a more advanced beam splitting tool design.

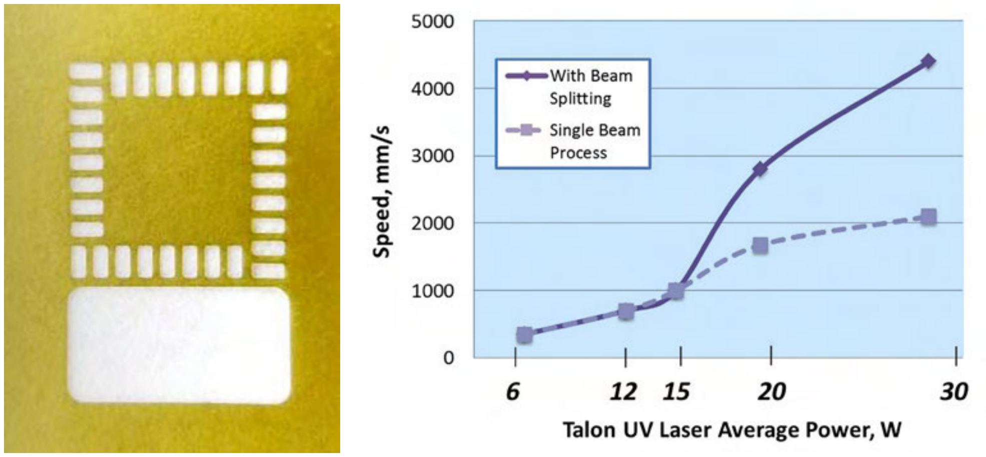


Figure 6: Coverlay patterning—high-speed cutting of thin polyimide, can benefit greatly from a split-beam system configuration.

At lower power levels, the increase in processing speed is approximately linear with increasing average power. However, when transitioning to 20 W UV a stronger throughput advantage is realized. This is because lasers at 20 W UV and higher are typically designed for a higher PRF-nom (100 kHz vs. 50 kHz), which means even higher energy is still available at the very high PRFs. Furthermore, the advantage of beam splitting becomes increasingly significant because several multiples of the required pulse energy are available at the higher powers. Higher power levels allow for more beam splits, such as 2× beams for 20 W and 3× beams for 30 W.

Conclusion

Pulsed ns UV DPSS lasers have been rapidly making inroads into high-volume advanced high-density PCB manufacturing for many years, and the drive to thinner, more flexible PCBs is likely to maintain if not accelerate the trend. For most laser product offerings on the marketplace, however, the output power is sufficiently high for only a small range of pulse output frequencies, which limits the flexibility of the laser and hence narrows its application space. More recently, with new UV laser technology, a substantial broadening of the application space is achieved due to the ability to maintain high power levels at high PRFs. The technology is also conducive to lower cost of manufacturing which can further expand the serviceable application space. With continued technology development for UV DPSS lasers expected to further increase the availability of higher power, low cost, reliable laser products, further miniaturization of electronic circuitry and packaging thereof should lead not only to the improvement of current electronic devices, but may also help accelerate more nascent industries such as the manufacturing of wearables.

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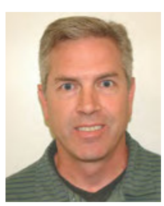

Jim Bovatsek is applications engineering manager with Spectra-Physics, a division of MKS Instruments.