Coherent White Paper

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High Repetition Rate USP Lasers Improve OLED Cutting Results

High power ultraviolet, picosecond industrial lasers are widely employed because of their proven ability to perform cost effective processing of a wide range of materials with high precision and minimal heat affected zone. This paper reviews application results showing that for sensitive materials with a low ablation threshold, increasing laser repetition rate can increase process throughput and improve quality simultaneously.

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Increasing demand for displays based on organic light emitting diode (OLED) technology puts pressure on manufacturers to simultaneously increase production throughput, while improving process utilization and maximizing yields. However, the complex composition of OLED display layer structures, together with the level of precision at which they are fabricated, makes achieving these goals challenging. Device singulation and trimming are processes in which accomplishing these objectives are critical because they are performed on nearly finished devices where a substantial amount of value is already built in. Ultra-short pulse (USP) lasers have already proven a useful tool for these processes, and recent work shows that operating them at higher pulse repetition rates further improves both throughput and quality. This document reviews the basics of USP laser cutting and the most recent results on high repetition rate cutting of OLED materials.

Flexible OLED Cutting Requirements

OLED displays comprise a relatively thin but complex stack of heterogeneous materials, most of which are highly heat-sensitive, all deposited on a polymer substrate. Specifically, components mmay include a silicon based thin film transistor (TFT) layer, several layers of active organic materials, a conductive transparent indium tin oxide (ITO) layer, and other semiconductor and polymer materials like PET or polyimide.

Figure 1. Simplified schematic (not to scale) of typical flexible-OLED structure. The glass carrier is removed at some point during fabrication.

Flexible OLED displays, which have become popular for smartphones and smart watches, present unique fabrication requirements and are produced differently than rigid glass-based displays. In particular, while flexible OLEDs are also produced on glass substrates, at some point in the process flow the OLED display is removed from the temporary glass carrier. Typically, this is accomplished using an excimer laser-based technique called Laser Lift-Off.

While the details of where and how the OLED display is separated from the carrier vary among manufacturers, all flexible OLEDs must eventually be precision trimmed to their final shape. Often this occurs after additional functional layers – polarizer, touch sensor – have been added to the finished display circuitry. Increasingly, this final shaping includes rounded cuts and contours, and even cutouts.

Typically, these requirements translate into a cutting kerf width of only 25 μm, and a process affected zone in the tens of micrometers range. This level of precision precludes virtually all traditional mechanical cutting methods. Moreover, from a practical standpoint, economics require that any cutting method deliver 24/7 reliability, with high throughput and a yield above 99.9%. Laser cutting has emerged as the only method for flexible OLED trimming that can meet all these requirements.

To implement laser cutting, the laser beam is directed through a pair of galvanometer scan mirrors and then a scan lens which focuses it to a spot size in the 10 to 20 μm range on the surface of the OLED. Because the field of view of the scan lens is relatively limited – typically a few hundred millimeters – a motorized xy stage can provide additional part motion in conjunction with this beam scanning. Alternative setups feature translation stages moving the sample under a fixed laser beam.

Laser Ablation

Lasers can process material photothermally or photoablatively. Traditional industrial lasers produce either continuous output, or pulsed output with pulsewidths in the tens of nanoseconds range. For these lasers, material removal occurs through a photothermal interaction, i.e., intense spatially confined heating. This allows relatively high material removal rates; however, for the most demanding tasks, peripheral heat affected zone (HAZ) damage can be a significant problem. For multilayer targets such as OLED's, this undesirable damage can lead to delamination of surface coatings, microcracking, changes in the bulk material properties, and/or the presence of recast material.

The second mechanism for laser material removal is based on photoablation, typically accomplished using ultra-short pulse (USP) lasers with very high peak power. This high peak power is sufficient to directly break the molecular or atomic bonds which hold the material together, rather than simply heating it, resulting in inherently "cold" material removal. Plus, the material is exposed to the laser light for such a short time that the energy isn't carried beyond the area of impact. This minimizes the heat affected zone, and leaves no recast material that could require post-processing.

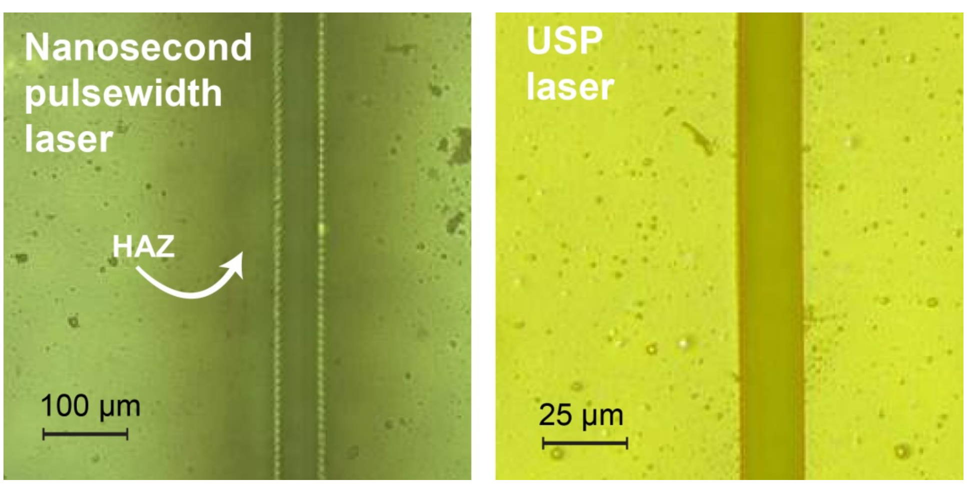


Figure 2. 30 µm thick polyimide sheets cut with a nanosecond and USP laser (in the UV). The nanosecond laser processed at 66 mm/sec, while the USP laser cut at 193 mm/sec. The nanosecond laser produced a

substantial HAZ – seen as a darkening in this image – while the USP laser produced none, and also delivered a substantially smaller cut width. Note the difference in scale between the two images.

Flexible OLED cutting represents an excellent example of where the reduced kerf width and smaller HAZ of USP laser processing delivers a unique advantage. Even nanosecond pulsewidth lasers with ultraviolet (UV) output, which are widely employed in challenging applications throughout microelectronics manufacturing (e.g., for high precision wafer cutting, scribing and marking), cannot reach the required level of accuracy for this application (see figure 2).

UV Benefits

USP lasers are commercially available with emission wavelengths in the near infrared, green and UV. In the case of OLEDs, operation in the UV is particularly advantageous because virtually all of the materials used (both semiconductors and polymers) absorb well in this part of the spectrum. Strong UV absorption limits the penetration depth of the light into the material, providing fine process control and further minimizing the HAZ. Furthermore, since process quality (specifically kerf width) generally improves in virtually all materials as wavelength decreases (see figure 3), the USP ultraviolet laser is the ideal choice for this application.

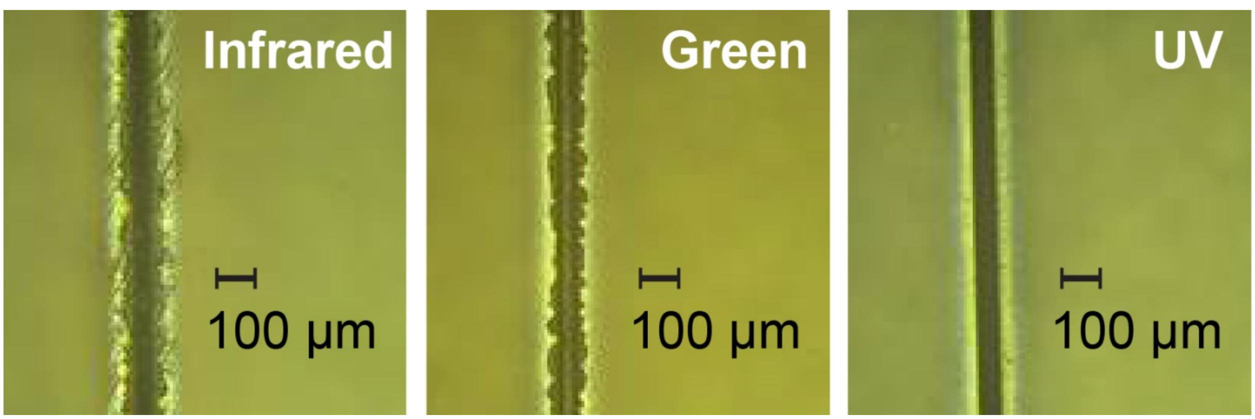


Figure 3. A 220 µm thick simulated display layer on glass scribed with a Coherent HyperRapid NX laser with output in the infrared, green and ultraviolet. This clearly demonstrates the improvement in cut quality with decreasing wavelength.

In addition to these factors, a laser must produce a high quality, Gaussian beam, which is usually focused down to a spot size of 10 – 20 µm at the workpiece in order to yield a sharp and clean cut. Plus, this beam should ideally be highly symmetrical so that the kerf and HAZ don't vary as cut direction changes.

Figure 4 shows that the Coherent HyperRapid NX operating at 355 nm delivers a beam symmetry of >90% over a depth of focus of more than 500 µm when focused to a beam waist of 15 µm. This ensures optimal cut quality when cutting through OLED stacks of typical thickness (in the 200 – 400 µm range), regardless of how complex the actual display shape. Finally, the laser must exhibit industrial-grade stability and reliability to maintain the expected yield over 24/7 operation.

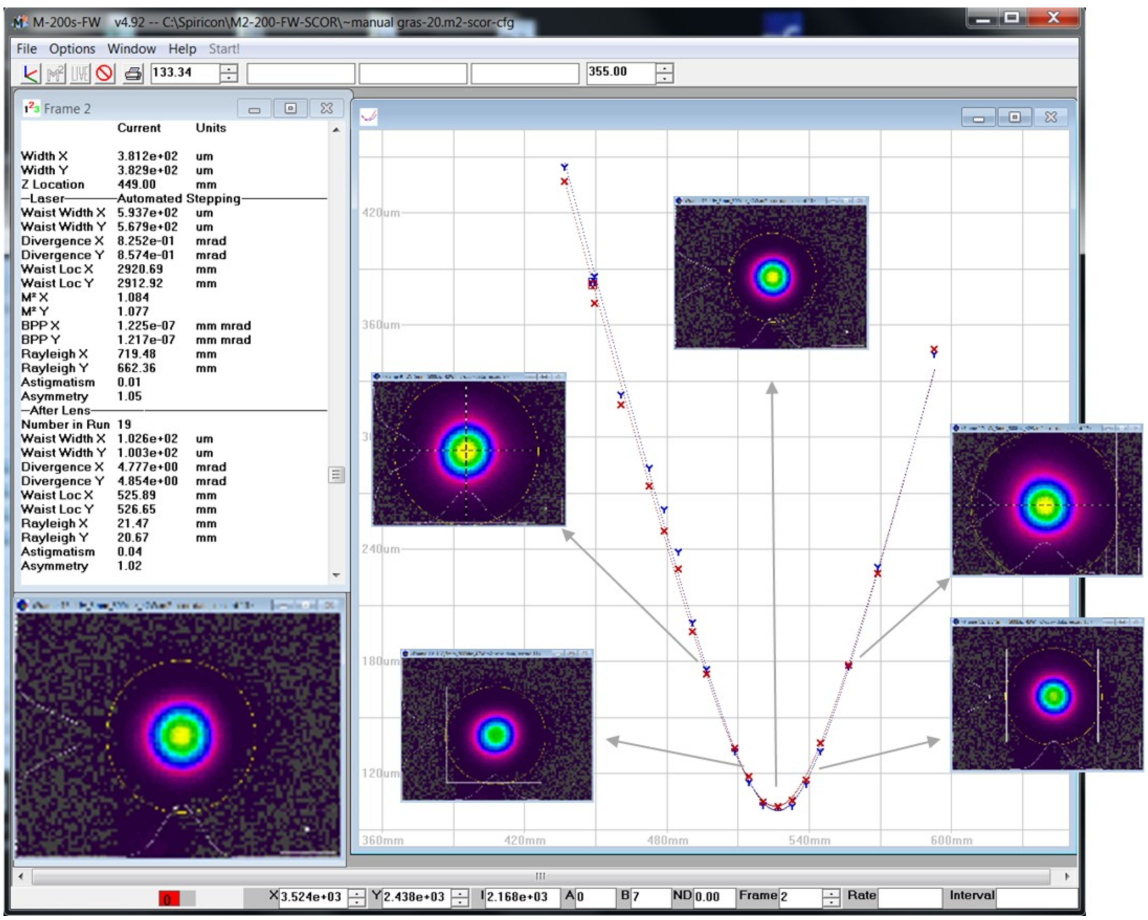


Figure 4. The Coherent HyperRapid NX operating at 355 nm delivers a beam symmetry of >90% over a depth of focus of more than 500 µm when focused to a beam waist of 15 µm.

Increased Repetition Rate for Optimum Process Performance

The 30 W UV picosecond laser has become widely adopted as the standard for OLED cutting because it meets all the criteria just outlined, and also delivers a high level of value in terms of cost per watt. Until recently, commercially available products of this type topped out at 400 kHz repetition rate for 30W UV output. With the recent market introduction of higher repetition rate lasers, Coherent applications engineers investigated if these higher repetition rates could be utilized to further optimize or improve the process.

Specifically, the Coherent team performed a thorough application study to determine the best process conditions for cutting OLED displays. Interestingly, this study shows that the high energy processes used in production today are sub-optimal. More specifically, these results show that increasing repetition rate, while maintaining the industry standard 30 W average power, simultaneously improves both throughput and quality.

To understand why this is true, it's useful to examine the typical relationship between ablation rate and peak pulse fluence for a micromachining process.[1] A generic curve of this relationship is shown in figure 5 (without specific units). Experiments prove that this type of relationship applies to the cutting of sensitive materials, such as OLEDs, as well as "tough" materials, including glass and ceramics. All that changes is the actual numeric values for ablation rate and fluence (with the optimum ablation rates for more delicate materials occurring at lower absolute vales for peak pulse fluence).

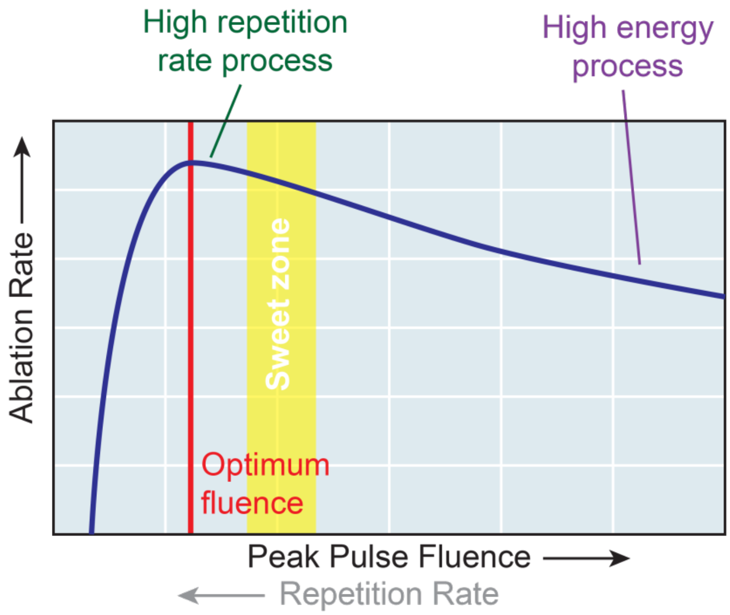


Figure 5. Typical relationship between ablation rate and peak pulse fluence for micromachining processes.

Peak pulse fluence is a function of pulse energy, focused spot size and pulse duration. However, assuming the focused beam characteristics don't vary for a given laser and optical setup, then peak fluence is mainly a function of pulse energy. And, if the average power of the laser is kept constant, then peak pulse fluence is inversely proportional to repetition rate (because average power = pulse energy x repetition rate). Therefore, the x-axis of this graph could just as well be "repetition rate," with the values *decreasing* from left to right, since this directly corresponds to increasing pulse energy/peak pulse fluence (all other factors being fixed).

This typical curve has the peak ablation rate occurring at an optimum fluence that is usually equal to 5 to 10 times the fluence required to begin ablating the material. Above the optimum fluence, despite the higher energy available to process the material, the process is less efficient and the wasted energy is transferred into the material as heat, which degrades cut quality. Unfortunately, this non-optimized regime is representative of the OLED production processes in factories today! Operating above the optimum fluence simply reduces throughput, without improving any other parameter.

In practice, it's usually best to operate a process in the "sweet zone" located just to the right of the peak ablation point on the graph. That's because this part of the graph is relatively flat, so minor deviations from this point, which are inevitable due to slight variation in material quality, beam delivery, machine-to-machine differences or environmental factors, don't push the process on to the steeper part of the curve, where results would be dramatically affected.

Experimental results

The testing that confirmed these hypotheses and quantified the results was performed on two different sets of sample materials, both representative of current display technologies.

The first was a 400 µm (total) thickness substrate consisting of PET | *OCA adhesive* | *Polarizer* | *OCA adhesive* | PET. The second was a 230 µm (total) thickness sandwich of PET | *OCA adhesive* | PI | PET. In both cases, the most heat-sensitive layers in the display structure are indicated in *italics.*

Figure 6 & Figure 7 summarize the overall results for the 400 µm and 230 µm samples, respectively. Clearly, higher repetition rates produce a much higher cut quality, notably thanks to a shallower heat affected zone (HAZ).

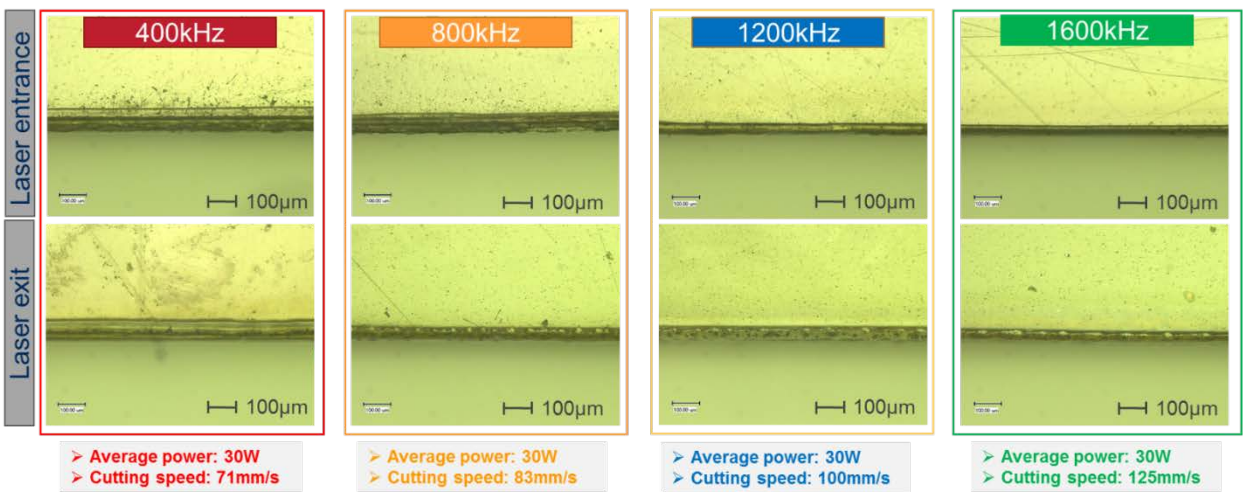


Figure 6. Photos of the laser cut (scan rate= 0.5 m/s) in sample material 1 show a clear improvement in cut quality with increasing repetition rate.

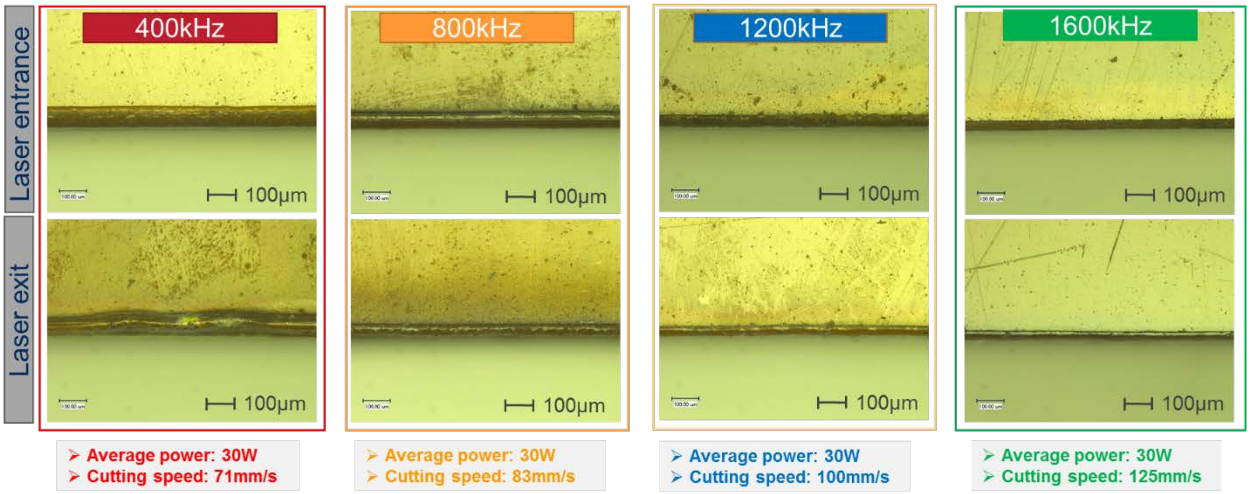
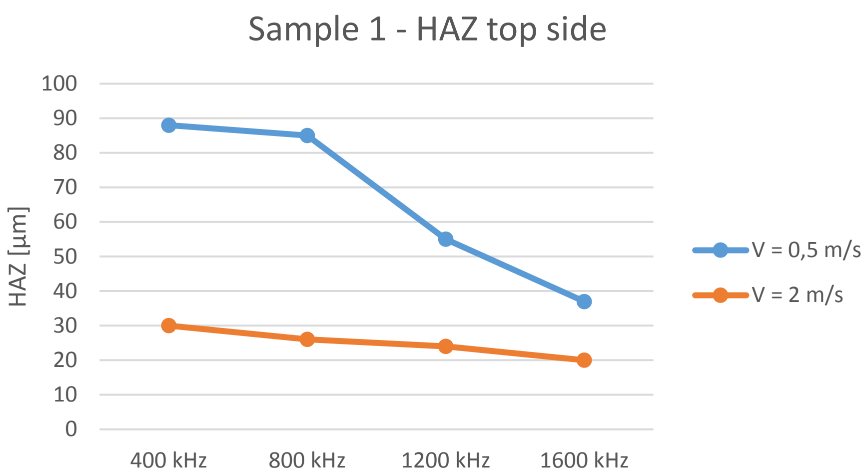


Figure 7. Photos of the laser cut (scan rate= 0.5 m/s) in sample material 2 also show a clear improvement in cut quality with increasing repetition rate.

Figure 8 quantifies these results. The graphs show results for two scan speeds: the lower 0.5 m/s scan speed is representative of a setup where translation stages move the sample under a fixed beam delivery; the higher 2 m/s scan speed is representative of beam delivery using a commercial scanner. Specifically, the first two show that the HAZ decreased steadily as repetition rate increased for both materials tested, with the most dramatic improvement occurring at the lower of the two scan speeds (0.5 m/s). Reduction of HAZ for sample 1 nears a factor of 2.5 under these operating conditions.

Figure 9 demonstrates that this improvement in cut quality also corresponded with an increase in effective cutting rate. For the second sample (PET | OCA adhesive | PI | PET), cutting speed can be improved by a factor of 2 simply by increasing repetition rate, for the same 30W output power.



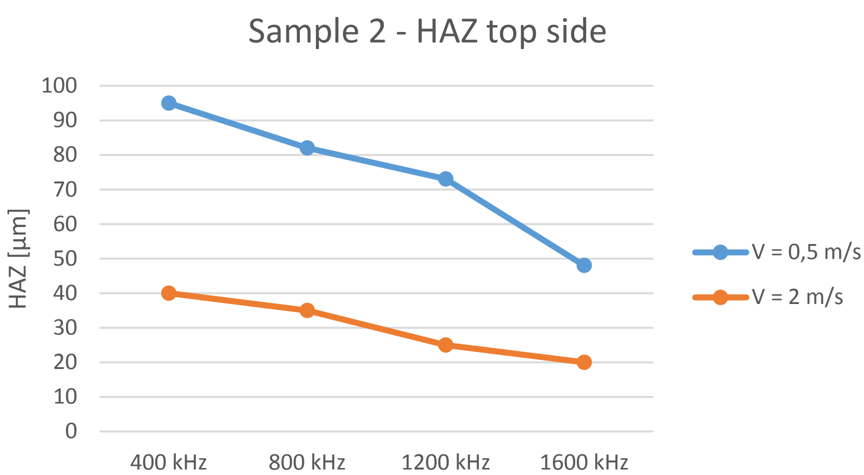
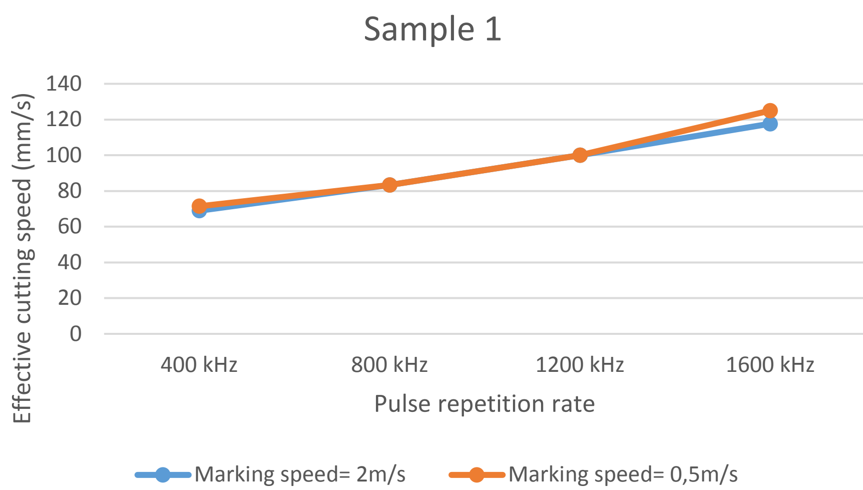


Figure 8. Plots of measured HAZ vs. repetition rate for both sample materials at two different scan rates.



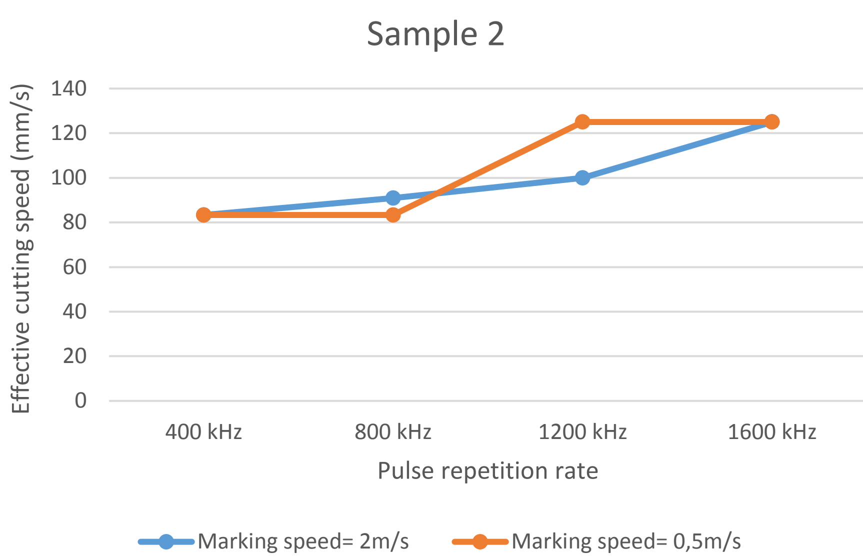


Figure 9. Plots of measured "cutting speed vs. repetition rate" for both sample materials at two different scan rates.

The exact numerical values for the quality and speed improvements derived from this testing are specific to the particular materials and testing conditions used. However, given the broadly applicable relationship between laser fluence and ablation rate presented earlier, it is reasonable to assume that they will apply to virtually any integration scheme, regardless of the motion stage or scanner speed. Also, it is likely that most current applications for processing of delicate materials which utilize the widely employed 30 W, UV USP laser can be improved in this same manner.

Conclusion

The newest HyperRapid NX offers 30 W of UV average power at repetition rates of up to 1600 kHz, with the same market leading beam quality that made its predecessor the benchmark for OLED cutting applications. This new high power picosecond laser product is built on the identical platform as current standard models, making it a drop in replacement for the standard lasers.

Those building new OLED displays production lines can choose to operate at the current industry standard quality level, and benefit from increased throughput. The precise improvement that can be leveraged from this throughput reserve depends on the entire production line design. According to the results presented here, the laser cutting process step has potential for a two-fold speed increase. But, whatever the particulars, the potential savings in terms of cost per part are simply tremendous, with typical factories producing more than 15,000 panels per month.

For those with an existing production line, embracing this improved OLED cutting process offers a straightforward path towards immediately achieving a multi-fold improvement in quality (while maintaining the existing production speed). Again, the actual quality improvement potential is dependent on the OLED stack structure and the tool design. This is clearly an enabler for the next generation of screens where there is a consumer expectation of increased quality due to the elimination of the display bezel.

On a more general level, the process optimization method described and illustrated here could be applied to many others materials than OLED displays. Potentially all the materials with low ablation threshold – typically polymers and/or organics based structures – could benefit from being processed at higher pulse repetition rates rather than the few 100’s kHz used in micromachining processes today.

Side-Bar
Practical USP Lasers

Coherent has responded to the needs of OLED manufacturers with a new generation of USP products specifically engineered to produce the optimum output characteristics for fine micromachining, while retaining an attractive cost of ownership. The Coherent HyperRapid NX series of USP lasers incorporate a number of output control options that enable a high degree of process optimization and process flexibility, therefore maximizing customers' return on their capital investment.

Particularly important features in this context are pulse gating, continuous energy control of individual pulses, and the ability to alter repetition rate on the fly. These are necessary to support a high degree of synchronization between the scanner, motion stage, and the laser pulses. Specifically, when cutting curves or contours, the laser beam travels slower around the curves than it does when cutting straight lines (because the stage or galvanometer mirrors must decelerate/accelerate). So, the time spacing between pulses must be varied on the fly in order to maintain constant laser power delivery at any given point, and therefore a consistent laser/material interaction. The alternative is to work at a constant speed, equal to the minimum speed imposed by the shape of the display. This is becoming an increasingly critical requirement for maximizing throughput for next generation displays which often have complex shape contours. The architecture of Coherent HyperRapid lasers, which feature a pulse jitter of ~10 ns, supports this functionality well.

The Coherent HyperRapid NX represents the new generation of USP lasers that deliver the performance and reliability necessary for cost sensitive, high throughput manufacturing applications.

USP laser technology is more complex than older laser technologies. With complexity comes potential failure modes. Coherent has successfully mitigated this complexity downside by focusing on product reliability and lifetime, which is critical in cost-sensitive consumer product manufacturing. The application of Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screening (HASS) protocols is novel– Coherent is currently the only company in the laser industry to invest in this. HALT is a proven approach that takes initial component and system designs and makes them better through pushing components and systems to failure, analyzing the failure mechanism(s), designing out the failure cause, and then iteratively repeating the harsh testing until all identifiable failure mechanisms are eliminated. HASS is a complementary screening protocol that identifies product manufacturing weaknesses or errors before delivery, therefore dramatically improving the product reliability for the end user.

Finally, operational flexibility is important because OLEDs are still an emerging technology, and device structure is both diverse and fast evolving. Operational flexibility enables display manufacturers to adapt seamlessly as device structure changes, as well as to address different market segments. A laser which supports a wide range of operating modes can more readily deliver the right process recipes for these various needs.

References

[1]: B. Neuenschwander & al., *Surface structuring with ultra-short laser pulses: Basics, limitations and needs for high throughput,* 8th International Conference on Photonic Technologies LANE 2014