HIGH-POWER, NANOSECOND-PULSE Q-SWITCH LASER TECHNOLOGY WITH FLATTOP BEAM-SHAPING TECHNIQUE FOR EFFICIENT INDUSTRIAL LASER PROCESSING
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Abstract

High-power, nanosecond-pulse Q-switch laser processing has become commonplace in both existing and emerging high-tech industries. As these industries grow and mature, there is increased need for low-cost, high-quality manufacturing techniques. This translates to a need for increasingly precise and efficient laser processing capabilities. In this work, Newport/Spectra-Physics' latest Q-switch diode pumped solid state(DPSS) laser technology is combined with optical beam-shaping techniques to explore the role of intensity distribution in improving efficiency of laser machining processes. Results for laser micro machining processes in technical materials are compared for the case of Gaussian and uniform ("flat top") beam intensity distributions. The affects of beam intensity distribution on both the resulting feature geometry and overall processing efficiency are characterized, with the underlying goal of maximizing the benefits of Q-switched DPSS laser technology to industrial manufacturing processes.

Introduction

The use of Diode-Pumped Solid State lasers for industrial applications continues to grow worldwide [1]. To accommodate such growth, Newport-Spectra Physics continues to provide new products to the marketplace. In particular, the new Pulseo™ 20-W Q-switch laser system was designed and introduced in the field to provide the advantages of short-pulse width/short-wavelength processing to existing – as well as new – industrial applications.

The laser, however, is only one part of the equation for a successful industrial processing application. Assuring that the light is delivered to the target material in the appropriate and efficient manner is just as critical. To that end, researchers are continuously pursuing alternative beam shapes to achieve most efficient micromachining. A well-known alternative is to laser micro machine material using a uniform, or "flattop", beam intensity distribution [2]. Historically, flattop beam generation has been optically inefficient, and therefore has generally been used only with high-power, multi-mode laser systems [3]. However, with recent design and manufacturing technology developments, there are now more flattop beam options for (relatively low-power) single mode laser systems [4]. These so-called Gauss-to-flattop beam conversion optics are now readily available with efficiencies in the range of 80-90%. These developments provide more incentive today to use flattop beam processing techniques with lower power lasers.

The use of a flattop beam for material processing allows for optimal and precise spatial control of the irradiating laser intensity. For every material there exists a threshold laser fluence value that must be achieved for ablation to begin. In the Gaussian beam machining; the center of the focused beam spot has a much higher intensity than those areas near the edge of the beam. Thus the center of the beam will ablate at a much higher fluence than the outer regions of the beam, resulting in inefficient use of the pulse energy. This also results in a spatially non-uniform ablation depth. In addition to the non-uniform ablation depth, the Gaussian beam profile has other consequences that must be considered. A significant HAZ (heat-affected zone) can be generated at the outermost regions of the exposed material, where the fluence is just below the ablation threshold and only gradually decays (see Figure 1). In the flattop beam machining the center of the beam has same intensity as it has at the edge. Thus the center of the beam ablates the same amount of material as the edge of the beam does and hence laser energy is utilized more efficiently.

In order to demonstrate the capabilities of Pulseo™, high-energy, high-peak power pulsed UV laser machining combined with a flattop beam profile, we have performed two different laser micromachining experiments: removal of thin film ITO (thickness = 150-180nm) deposited on a borosilicate glass and volume laser ablation of 75μm thick polyimide sheet. In each case, flattop beam machining was compared to

Gaussian beam machining in terms of efficiency and feature quality. Thin film ITO laser ablation is commonly performed in the flat panel display and other industries, including the rapidly-growing thin film solar cell industry; and UV ablation of polyimide is commonly performed in various industries, including microelectronics.
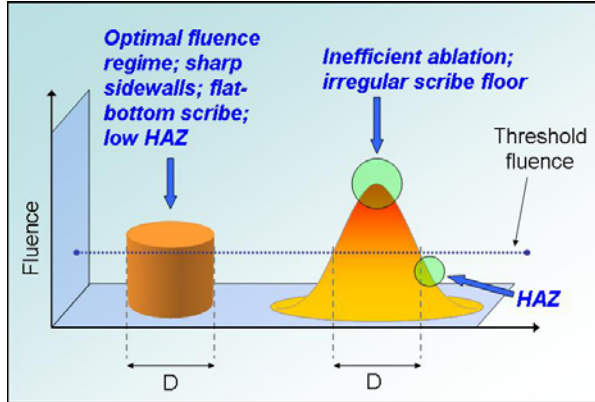

Figure 1: Schematic illustration of flattop beam benefits compared to Gaussian beam.

Experiment Details

General

All laser processing experiments were performed in air-ambient environment using a beam scanning galvanometer system combined with an f-theta lens. The laser output was routed to the scanner system using beam-steering mirrors. The maximum aperture of the optical setup was limited to 10 mm by the scanner head. To maximize the available pulse energy, the laser was operated at 100 kHz repetition rate; and to minimize HAZ formation, high scanning speeds were used throughout, resulting in low pulse overlap on the material. For ITO ablation experiments, beam scans were executed at 3, 4, and 5 m/s. For polyimide ablation tests, only 5 m/s scan speed was used, but multi-pass processing was performed, with number of passes, N = 1, 2, 5, 10, 20, and 50 scans being executed. For both materials, features were machined at various power levels ranging from very low (minimal ablation) to the maximum available.

Laser System

The experiments were performed with Newport-Spectra's Pulseo™ laser system. The laser outputs 20 Watts of 355-nm power in 20-ns pulses at 100 kHz. Detailed laser specifications can be seen in Table 1.

Table 1: Performance parameters of Newport-Spectra Physics Pulseo™ laser system.

Parameter	Value
Wavelength	355 nm
Power	20W at 100 kHz
Repetition Rate	1 Hz – 250 kHz
Pulse Energy (maximum)	200 µJ
Pulse Duration (100 kHz)	20 ns
Beam diameter, $1/e^2$	3.5 mm

Gaussian Beam Machining

For Gaussian beam machining, the 3.5-mm diameter Pulseo™ laser beam was focused with a 160-mm focal length f-theta scan lens. At the focal plane, this created a ~35-µm beam diameter ($1/e^2$). In order to match the larger diameter flattop beam size, the system was de-focused, resulting in a ~65-70 µm spot size incident on the target material.

Flattop Beam Machining

The flattop beam setup used a diffractive optical element (DOE) combined with conventional optics to create a ~70-µm diameter flattop intensity distribution at the work piece. The DOE is a diffractive remapping-type optic, in which the intensity distribution of an inputted Gaussian beam is re-mapped to a uniform intensity distribution. Theoretically, a near-perfect flattop beam can be generated; in practice, however, since the input laser beam is usually not a perfect ($M^2 = 1$) Gaussian beam, the uniformity of resulting flattop beam reflects this. Therefore, a high quality laser beam is very important for achieving a good uniform flattop beam.

A schematic illustration of the optical setup is shown in Figure 2. A 1-mm diameter flattop field is reduction-imaged with a 103-mm focal length telecentric scan lens located ~1.5 meters from the object plane. The magnification factor (image size divide by object size) was ~0.07. The flattop optical element had an optical efficiency of ~87%. Additional losses were incurred by various beam steering mirrors, the galvo scanner head, and the telecentric scan objective, resulting in total optical efficiency of 80% from laser output to target material.
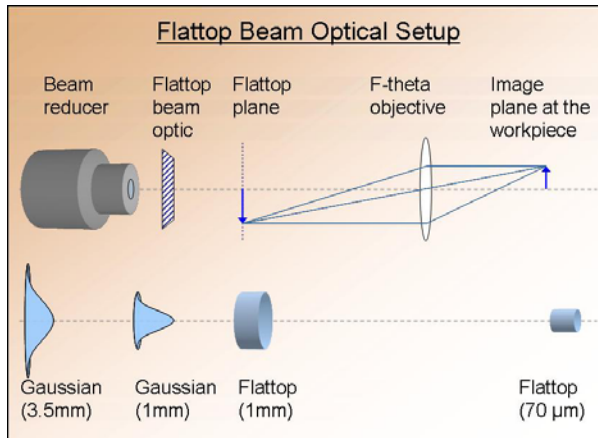
Figure 2: Diagram of optical components and corresponding intensity distribution for the flattop beam setup.

Results and Discussion

Thin Film ITO Removal

Gaussian Beam Processing ITO scribe features were machined with the Gaussian beam distribution at 3, 4, and 5 m/s at 100 kHz pulse repetition frequency. Using the full 20-W output of the laser, the largest spot size that could be fully cleared of the ITO was ~65 μm. This is the clearance generated by a single focused pulse, and is also roughly the width of an ITO scribe when scanning the beam at high speeds (low pulse overlap). Reduction in power/energy resulted in a reduced clearance spot size, as expected with the gradually decreasing fluence of the Gaussian beam profile. Figure 3 shows an optical microscope image of ITO removed with the Gaussian beam.
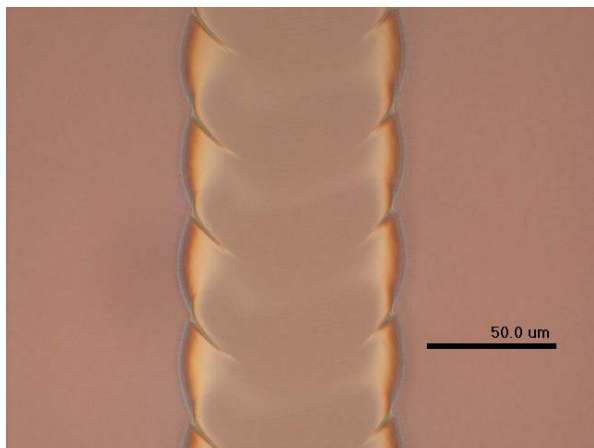

Figure 3: Optical micrograph showing Gaussian beam ablation of ITO on glass at 4 m/s scan speed.

Quick inspection of the feature in Figure 3 clearly shows that a large partially-ablated region exists at the edges of the scribe. As the scanning speed is increased

(thus decreasing pulse overlap on the material), these partially-ablated regions would eventually connect across the scribe, resulting in an electrical short.

Flattop Beam Processing Using the Pulseo™ laser combined with a flattop beam intensity distribution, efficient, high-quality ITO removal from glass was achieved. With the same process conditions (20 W laser power and 4 m/s scribe speed) that were used for Gaussian beam processing, scribes obtained using flattop beam are shown in Figure 4. As can be seen in Figure 4, the scribe features appear very clean, with no observable boundary region (i.e. partially-ablated or otherwise laser-affected) separating the completely removed ITO material and the completely unaffected ITO material. Thus, a highly improved quality of scribe is obtained using flattop beam.
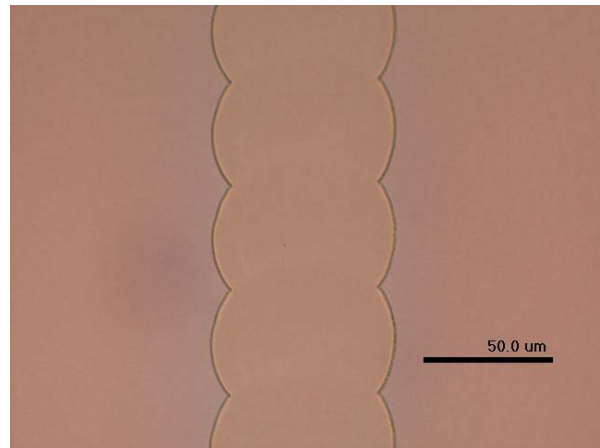

Figure 4: Optical micrograph showing flattop beam ablation of ITO on glass using 4 m/s scan speed.

Differences in Gaussian and Flattop Beam Processing The clean, high-quality removal resulting from the flattop beam profile is visually apparent in the microscope picture (Figure 4).

The differences between flattop and Gaussian beam machining of ITO on glass are further illustrated with scribe depth measurement data. Figure 5 shows line profile data for both types of features, obtained using a mechanical stylus profilometer.

The depth profile data nicely illustrates the sharp sidewalls and relatively flat bottom that result from flattop beam machining, although the edges do indicate the presence of a burr structure. Also of note is that the Gaussian beam resulted in some ablation/modification of the glass substrate near the center of the beam, where the intensity is highest. Because optical absorption in glass begins to increase as the wavelength decreases towards the UV end of the spectrum, this becomes a concern when machining

with 355-nm (compared to 532-, and 1064-nm). In contrast, the well-confined intensity distribution of the flattop beam allows for machining of large areas of slightly lower-threshold material without exceeding the threshold for damaging the glass.
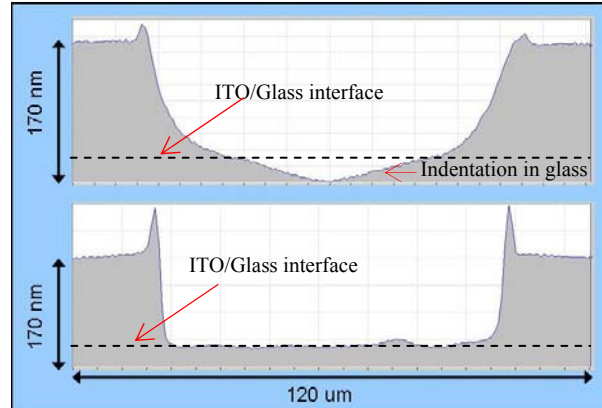

Figure 5: Cross-sectional profile of ITO scribes using Gaussian (top) and flattop (bottom) beam profiles.

A brief analysis of single pulse material removal illustrates the quantitative benefits, in terms of material removal efficiency, of the flattop beam over the Gaussian. With the Gaussian beam profile and ~16 W of on-target laser power, the largest fully-cleared spot generated with a single laser pulse was found to be 65 μm in diameter – a material removal area of ~3300 $μm^2$. Using a flattop beam, only ~8 W of power was required to clear a 70-μm diameter region of ITO – an area of ~3850 um^2. Therefore with full utilization of the available ~16 W of power (either with a larger flattop spot, or beam splitting to simultaneously machine (2) 70-μm spots), then the cleared area per laser pulse of 2 X 3850 = ~7700 um^2 can be achieved. Therefore, flattop beam machining results in 7700/3300 = ~2.3 times more area cleared per unit time. This analysis clearly shows the significant advantage of using a flattop beam for scribing thin ITO film from the glass substrate.

Polyimide Volume Ablation

Gaussian Beam Processing Ablation of polyimide with the Gaussian beam distribution was performed at 5-m/s scan speed and with various number of overlaying scans (1, 2, 5, 10, 20, 50 passes) and 100-kHz pulse repetition rate. The use of multiple, high-speed passes allowed for deep groove machining without incurring significant HAZ. Furthermore, the multiple pass approach allowed for more accurate ablation depth measurement for the case of low-fluence processing (due to the averaging effect of multiple ablation passes). A range of power levels was also explored.

Depth profile data was obtained with a mechanical stylus profilometer, which was programmed to execute multiple adjacent scans (i.e. "step-and-repeat"), resulting in the generation of 3-dimensional topographical data. Figure 6 contains a 3D graphical image composed of this depth data for Gaussian beam machining in polyimide (Power = 16W; N = 1, 2 passes at 5 m/s scan speed).
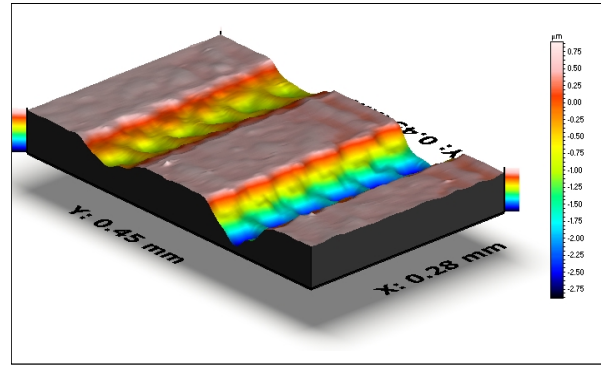

Figure 6: 3-dimensional depth profile showing tapered sidewalls in polyimide using a Gaussian beam shape.

The graphical data in Figure 6 clearly shows the gradual, sloping sidewalls resulting from the Gaussian intensity distribution. For the case of N = 2 passes, the maximum depth achieved is approximately 2.5 μm.

Flattop Beam Processing Using the flattop beam, features were machined in polyimide with processing conditions identical to those used for machining using the Gaussian beam (100 kHz PRF; 5-m/s scan speed; N = 1, 2, 5, 10, 20, 50 passes). This resulted in grooves with steep sidewalls and a relatively flat bottom, as illustrated by the 3D depth profile scan in Figure 7 (Power = 16W; N = 1, 2 passes at 5 m/s scan speed). The maximum depth achieved is approximately 2 μm.
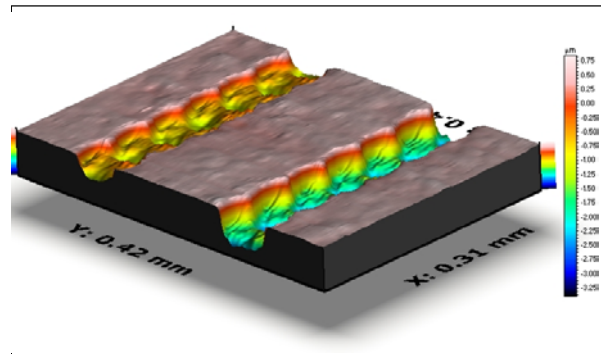

Figure 7: 3-dimensional depth profile showing steep sidewalls in polyimide using a flattop beam shape.

Difference in Gaussian and Flattop Beam Processing The data used to generate the 3D topographical images can also be used to calculate the ablated volume of the

scribe. Dividing the total ablated volume by the number of exposed pulses gives a volume per-pulse ablation rate, which can be useful for determining the efficiency of the ablation process. In Figure 8, this per-pulse volume ablation data is plotted vs. the average power (for N=5 scans) for the flattop and Gaussian beam profiles.
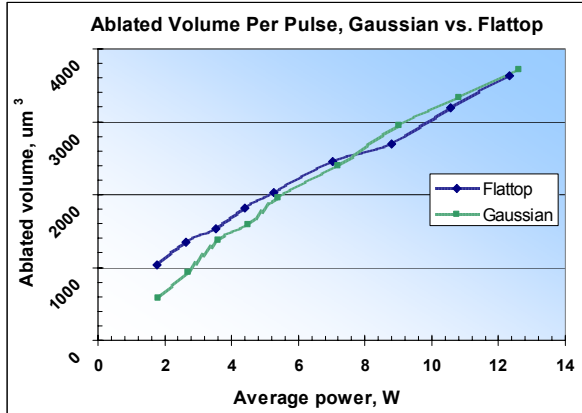

Figure 8: Per-pulse volume ablation rate vs. average power for flattop and Gaussian beam profiles.

Figure 8 shows a trend of increased drilling efficiency with the flattop beam shape as the average power (and therefore incident fluence) decreases. Taking the ratio of the data in Figure 8 (flattop volume divided by Gaussian volume) and plotting it vs. average power clearly illustrates this trend (Figure 9).
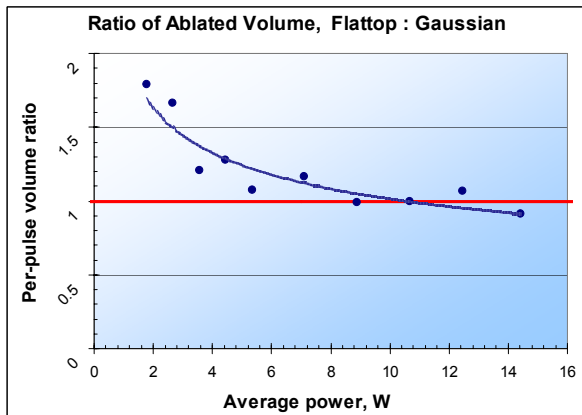

Figure 9: Ratio of ablated volume (flattop over Gaussian) vs. average power.

For higher average power, the flattop and Gaussian beams ablate with a very similar efficiencies (ratio = ~1), with a slight tendency towards higher efficiency with a Gaussian beam shape. However, at lower power levels there is an obvious trend of improved ablation efficiency (ratio > 1) using the flattop beam profile, with a >50% advantage in ablated volume per pulse for power levels approaching the 2-W level.

This indicates that there is an optimal fluence level (relative to the threshold fluence) for which the volume removal rate is the highest. With Gaussian beam fluence distribution, only a limited portion of the beam will have this optimal fluence value. On the other hand, the flattop beam allows for the entire beam to be set to this optimal fluence (through power or spot size tuning), resulting in the most efficient use of the laser pulse energy. With this logic, it can be argued that the Gaussian beam trends higher in efficiency (compared to the flattop beam) with higher incident laser power because (1) for higher powers the flattop beam fluence is *above* the optimal fluence level, and (2) significant portions of the gently-sloping tails of the Gaussian beam are at or very near to the optimal fluence levels, resulting in enhanced efficiency.

One other key advantage of processing polyimide using a flattop beam is the ability to maintain the same feature size (area, not depth) while changing the incident power level. With a Gaussian beam shape, the size of the ablated region increases and decreases as the incident power level increases and decreases; and the extent of the change depends on (1) the spot size of the focused Gaussian beam, and (2) the ablation threshold of the material. For the case of a flattop beam, however, as long as the applied fluence is above the ablation threshold, the feature size remains approximately the same. This advantage of the flattop beam is illustrated in Figure 10, which shows features scribed in polyimide at various power levels using the Gaussian and flattop beam profiles (N = 50 scans at 5-m/s scan speed).
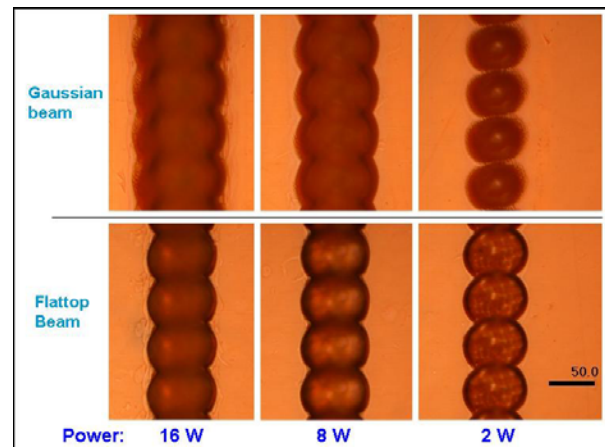

Figure 10: Features machined in polyimide at various power levels using Gaussian and flattop beam profiles.

Figure 10 shows that, even for an increase in power by a factor of 8X, the feature size machined with the flattop beam is relatively constant. Conversely, the width of the Gaussian beam-machined feature nearly doubled in size for the same range of powers. This

intrinsic property of features machined with a flattop beam can offer a distinct advantage for those applications in which feature size must remain constant but feature depth is adjusted by varying laser power.

A closer look at the features also reveals the sharpness of the edge when using a flattop beam (Figure 11).
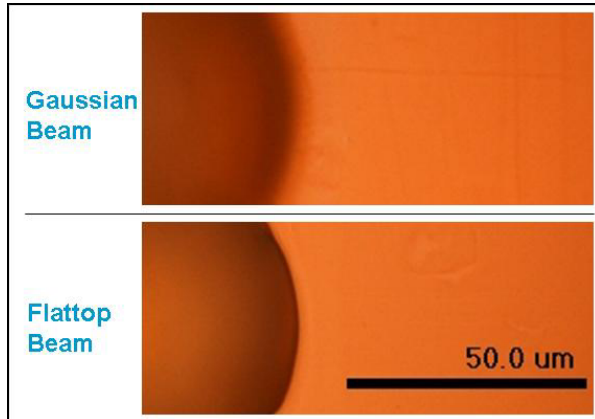

Figure 11:   Close-up view of sharp edge of features machined with flattop beam.

The sharpness of the edge produced with the flattop beam profile reflects the very abrupt transition from near-zero to very high optical intensity; this reflects both the high design quality of the flattop beam optic and the high beam quality of the Pulseo™ laser system.

Conclusions

In this work, we have illustrated that high-quality; high-efficiency machining can be achieved using the new Pulseo™ industrial q-switched 355-nm laser system combined with state-of-the-art flattop beam shaping technology.

In the case of thin (~150nm) film ITO removal, it was demonstrated that the flattop beam shape can improve the area removal rate by a factor of 2.3. For a given desired scribe width, this means that ITO scribing with a flattop beam can be executed at greater than twice the scanning speed compared to a Gaussian beam. Also flattop beam machining produced very clean and sharp edged scribe without any unablated area left behind near the edges of the scribe. Furthermore, the "fluence-containment" offered by the flattop intensity distribution resulted in less collateral damage to the underlying glass substrate.

Similar improvements in quality and efficiency were seen when the flattop beam was applied to volume ablation of polyimide. The steep sidewalls, relatively flat-bottom, and consistent scribe width (relative to

changes in laser power) that are achievable with the flattop beam were clearly demonstrated. Furthermore, it was shown that at lower fluence levels of ~2W or lower, the flattop beam offered an improvement in volume drilling efficiency of more than 50%. So with a flattop beam profile, this "optimal fluence regime" can be utilized to it fullest potential by parallel processing of the material using beam splitting (or processing with a larger spot size).

With its attractive combination of good beam quality, short wavelength, short pulse, and 200 μJ delivered at 100 kHz repetition rate, the Pulseo™ laser system coupled with flattop beam processing can offer exceptional quality and efficiency improvements for numerous laser machining applications spanning a variety of industries.

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