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Pulse bursts in ultrashort-pulsed lasers

FlexBurst™ technology

Ultrashort-pulsed (USP) lasers have come a long way from bulky, sensitive laboratory devices, emitting a few hundred milliwatts of output power, to compact, robust, and reliable workhorses used for industrial applications. Peak powers in the megawatt- to gigawatt-regime at moderate pulse energies together with the ultrashort pulse duration in the picosecond to femtosecond regime enable localized vaporization of solid materials without extensively affecting the surrounding matrix, promising precise machining of materials with pristine quality.

Many micromachining applications using USP lasers have demonstrated high quality results but often produced at low average output power. With USP lasers now emitting hundreds of watts of average power, the major challenge for material processing engineers is scaling processes to higher average power levels, thereby increasing the throughput, while maintaining the quality of the result.

A fundamental requirement for producing high-quality results is usually to keep the local process temperature below the melting point of the processed material. A key aspect for ultrashort-pulsed laser processing is therefore appropriate heat management. This includes a well-controlled pulse overlap, to avoid local heat accumulation as well as an energy-efficient process to start with. Every ablation process only has a finite efficiency. Energy not used for the process itself will ultimately be transformed into heat. The more efficient the available energy is used in the process the less heat is produced.

Process efficiency

Usually the efficiency of an ablation process is not constant with respect to the fluence that is applied, but shows a distinct maximum [1] as it is shown in Figure 1 for the example of copper (other materials show a similar behavior, with varying numerical values).

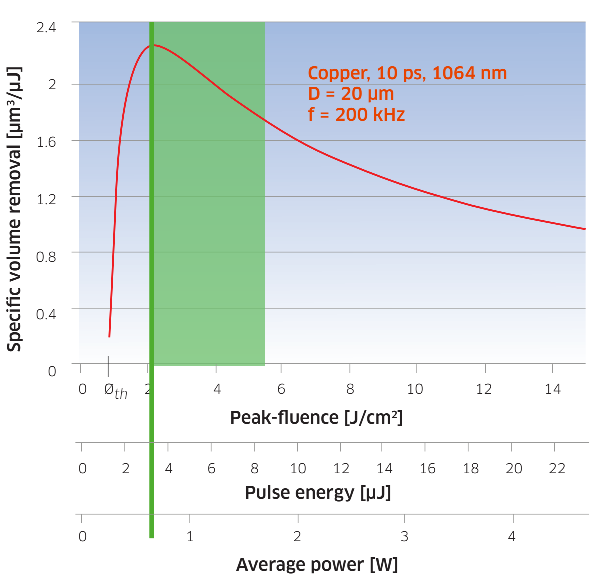


Figure 1: Process efficiency plotted over applied peak fluence, pulse energy and average power for given process parameters. There is a distinct maximum for the efficiency of the process (green line). For a stable and efficient process, parameters should be chosen to be in the green area.

It is obvious that for the given parameters (pulse repetition rate of 200 kHz and focus diameter of 20 µm) this optimum efficiency is obtained at very low average power.

Power scaling

For industrial adoption, a laser process must provide a specific throughput. Usually low-power processes are not economical by today's standards such that they need to be scaled to higher average power. Standard approaches for such a power scaling are either to keep the pulse repetition rate constant (since some laser architectures do not allow altering the pulse repetition rate in the first place) thereby increasing the pulse energy, or to keep the pulse energy constant while increasing the pulse repetition rate. In the latter case, it is easier to set the applied fluence to the optimum point, but a controlled pulse overlap at high pulse repetition rates might quickly exceed the maximum speed capability of a beam delivery system. In the example of Figure 1, using a pulse overlap of 75% (which is equal to a pulse-to-pulse pitch of 5 µm), scaling the repetition rate by a factor of ten would already require a lateral moving spot velocity of 10 m/s. For typical galvanometer scanners such a velocity is feasible for straight lines, but difficult to obtain for smaller geometry features often required in micromachining applications. A potential solution for specific applications can be high-speed beam deflection systems such as polygon scanners.

When scaling a laser's output power to high pulse energies, a single-beam approach quickly reduces the efficiency of a process, resulting in undesired heat accumulation. A common approach to maintain high efficiency is to split the energy of individual pulses and distribute it to multiple processing sites. Drawbacks are increased complexity on the tool side or limited applicability (e.g. in the case of massive parallel processing to produce highly repetitive patterns).

[1] H. Pantsar et al., "Material removal rates of metals using UV and IR picosecond pulses", proceedings of 4th Intl. WLT-Conference on Lasers in Manufacturing (LIM) 2007, Munich, 613-618

Bursts of pulses
An interesting scaling approach uses pulse bursts. The burst can be seen as a combination of both approaches mentioned above: the burst combines high burst energy with high pulse repetition rate within the burst. The underlying fundamental concept is shown in Figure 2.

The energy of one single, high-energy pulse is split and distributed in time over multiple sub-pulses, bundled into a burst of pulses with tight temporal spacing (Figure 2, left). With this, the energy of a single high-energy, low-efficiency pulse is transformed into a group of low-energy, high-efficiency pulses, especially if the energy of individual pulses inside the burst is set close to the optimum efficiency point (Figure 2, right).

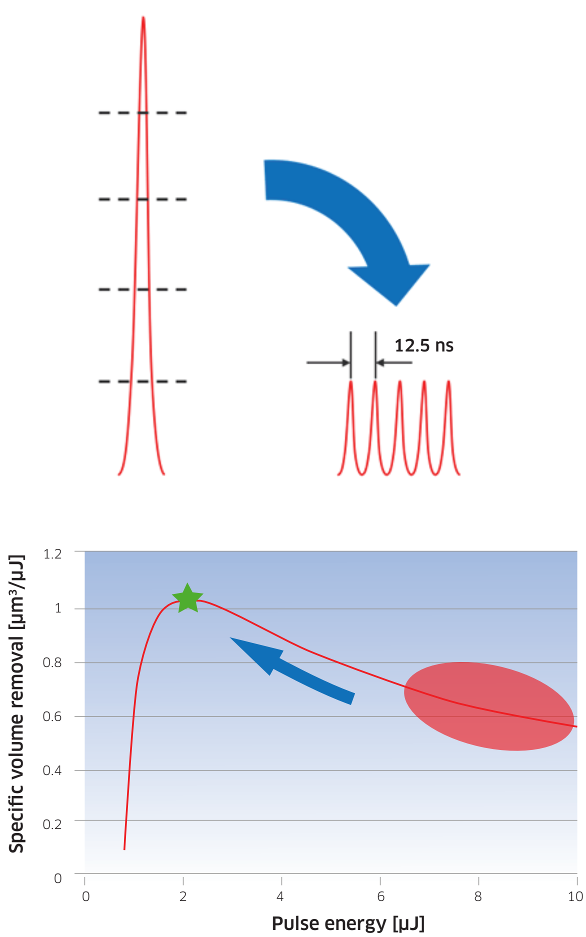


Figure 2: Working principle of pulse bursts. The energy of a single high-energy pulse is distributed over multiple pulses with tight temporal spacing. With this the process can be shifted from reduced efficiency (for the high-energy pulse) to maximum efficiency (for the burst of pulses).

Burst envelope
Today, many commercially available USP lasers offer some kind of burst mode. In most cases, the implementation of the burst feature is rather simple: multiple subsequent pulses from the laser's oscillator are sent without specific control mechanism through an amplifier or a chain of amplifiers. As a consequence, the envelope of such amplified bursts looks as shown in Figure 3, left: the first pulse experiences highest amplification while the amplitude of subsequent pulses decays exponentially.

Considering the fundamental concept of the burst, this energy distribution within the burst is not ideal. To obtain maximum energy efficiency a burst with pulses of similar energy as shown in Figure 3, right would be desirable in a first approximation.

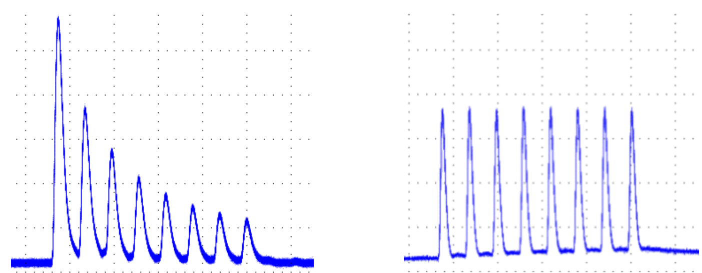


Figure 3: Left: exponentially decaying burst as produced by simple burst implementations. This burst shape is not ideal for obtaining maximum efficiency. Right: "flat" envelope function, created with FlexBurst technology; every pulse in the burst can be programmed to operate at maximum efficiency.

Lumentum FlexBurst technology
To use the burst feature of a USP laser efficiently, it is necessary to have control over the envelope shape of the burst. Lumentum invented FlexBurst technology that lets the user freely program the amplitude of every individual pulse inside the burst, to optimize the process. Since this is a powerful feature, FlexBurst is implemented in all of the Lumentum USP laser products.

Depending on the specific requirements, a burst with non-equal pulses could be beneficial. FlexBurst allows to adapt to such requirements (Figure 4).

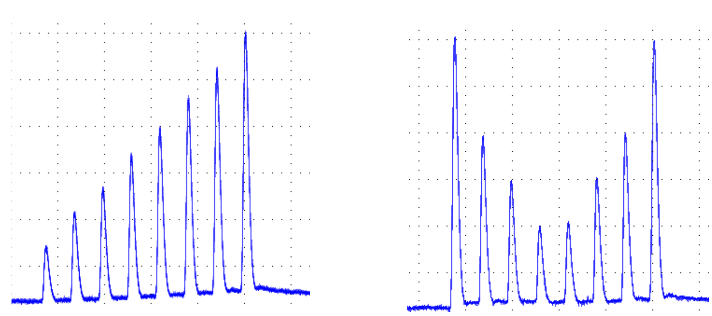


Figure 4: FlexBurst programmed to have a controlled rising slope (left) and a somewhat arbitrary shape ("V-groove", right).

Especially for very heat-sensitive materials, it is sometimes beneficial to vary the temporal spacing between pulses inside the burst to reduce heat accumulation. FlexBurst also allows for blank pulses, thereby increasing the temporal spacing to the next pulse.

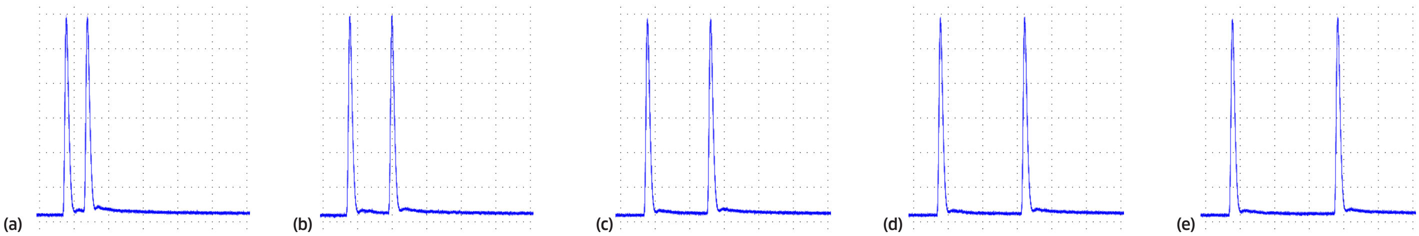


Figure 5: The temporal spacing between pulses inside the burst can be varied in steps of 12.5 ns, which is also the minimum spacing possible. This can be programmed independently for any two neighbouring pulses. The example shows only a total of two pulse with temporal spacing from 12.5 ns (a) to a total of 62.5 ns (e).

Example using burst mode

To give an example how FlexBurst can be used for power scaling while maintaining or even improving the resulting quality, we have milled cavities into stainless steel AISI 316 (Table 1).

Starting with a single-pulse process, adjusted to operate close to the optimum efficiency fluence, we obtain a good surface quality (Table 1, left column). Because the process works at low average power, the obtained total volume removal rate (VRR) is comparably low.

In a simple power scaling approach, we increased the average power by a factor of five, keeping the pulse repetition rate constant (Table 1, center column). Because of the higher average power, the obtained VRR increases, but since the fluence on the workpiece has also increased by a factor of five, the process efficiency has been reduced significantly. The energy not used for the ablation process has been transformed into heat, causing the surface to build melt droplets.

By distributing the high pulse energy of the single pulse used in the previous example, over a burst of pulses (Table 1, right column), we have obtained an even higher VRR and by optimizing the parameters, we could also improve the surface quality. Adjusting the number of pulses in the burst, the energy per pulse and the temporal spacing between pulses inside the burst gives extensive control over the heat deposition necessary to create a thin molten layer on the surface resulting in an almost polished-like surface roughness. The areas showing different shades of gray (Table 1, center column) depict the individual grains of the alloy.

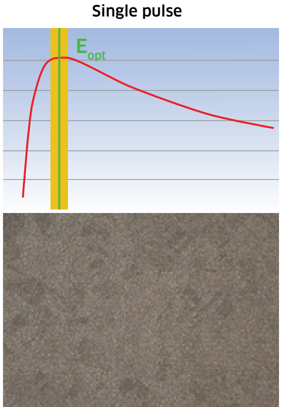
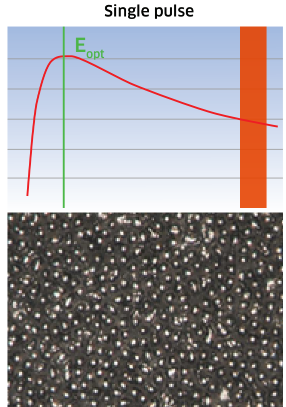
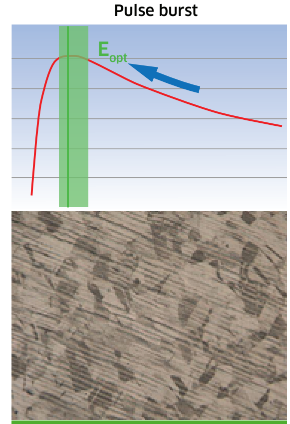
Single pulse	Single pulse	Pulse burst
		
• Low power • Low pulse energy - Good quality - Low-volume removal rate	• High power • High pulse energy - Bad quality (melting) - High volume removal rate	• High power • Low pulse energy - Excellent quality - High volume removal rate (5x of single pulse process) - Very flat surface due to controlled micromolten film

Table 1: Ablation of stainless steel AISI 316 with a single pulse at low pulse energy (left, yellow), a single pulse with high energy (center, red) and a burst of pulses (right, green). The colored bars in the top row show the respective operation point, the center row shows microscopic images of the respective processing results.

Conclusion

Pulse bursts are a powerful tool for powerscaling. In micromachining applications, they can be used to scale up the average power for a USP laser process while maintaining the obtained processing quality with respect to a low-power, single-pulse process. In order to take full advantage of pulse bursts, it is necessary to freely program not only the number of pulses within a burst, but also the amplitude of every individual pulse as well as the temporal spacing between those pulses. Lumentum FlexBurst technology delivers this freedom: up to 40 pulses can be programmed with arbitrary energy distribution. The minimum temporal spacing is 12.5 ns and can be varied individually for neighbouring pulses in steps of 12.5 ns. With this flexibility, you are equipped to get the most out of your process.

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