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Market Trifurcation in Ultrafast Laser Applications

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Abstract

Micromachining with ultrafast lasers is continuing to gain importance for industry. Pulse lengths from femto- to picosecond at wavelengths, in infrared, green and UV are used. New industrially designed, lower cost and highly reliable femtosecond lasers have stimulated the debate which pulse length is optimal for specific materials and applications. We will review sweet spot applications, markets and provide guidance as to where femto- or picosecond lasers are best applied. One applications segment is demanding low power around 10W @ 10ps, compact footprint and are extremely sensitive to the laser price. A second segment of applications is power hungry and only becomes economically viable at power levels above 100W. A burgeoning market for applications requiring fs-laser pulses can be observed. We describe these three market sub segments by showcasing applications from the automotive, consumer electronics and machine tool domains.

Keywords: Ultrafast; Femtosecond; Picosecond; micromachining

1. Introduction

The market for laser micromachining applications is growing rapidly driven by demand to produce fine detailed parts with very high precision, without heat affected zone and minimal material re-deposition.

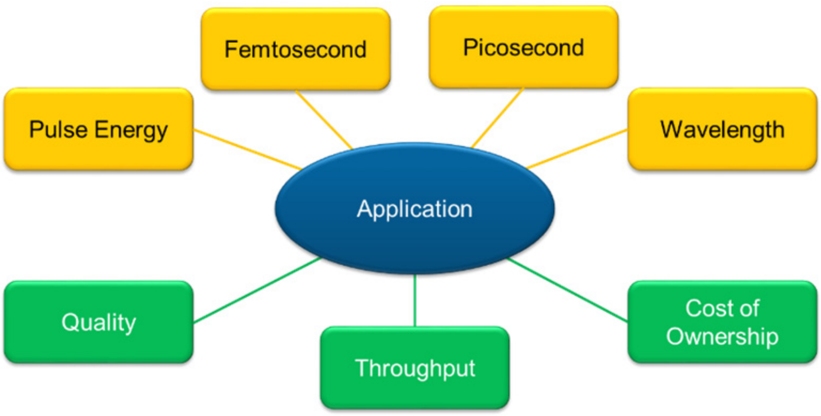

Fig. 1. Trade-off between laser process parameter choice (top, yellow) and application performance indicators (bottom, green) in ultrafast laser micromachining applications.

Applications can be found across many different markets ranging from consumer electronics, flat panel display, semiconductor, medical device to automotive industry. Each of the industries have their special requirements in terms of highest precision manufacturing and lowest heat affected zone versus throughput and cost of operation. Depending on the specifics of their application customers have to make a decision which of the

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available technologies to use in their process: They will have to choose the proper pulse length e.g. pico- vs. femtosecond, the right laser wavelength – IR, green or UV, and the optimal pulse energy and average power required to meet the desired quality, throughput and cost of ownership. (Figure 1) In many cases customers have to run extensive application tests to define the laser source with optimum parameters. The scope of this paper is to guide customers making their initial decision which laser type fs vs. ps laser by describing 3 technology segments, where most of the ultrafast lasers are used. In the next step it describes the state of the art and the latest developments in ultrafast laser technology.

2. Application Sweet Spots Femto- vs. Picosecond lasers

With the development of industrial fs lasers there is more debate which pulse length is ideal for given applications. In some applications it is quite obvious which laser to choose. An ideal application for ps lasers are low cost precision marking or LED dicing (Figure 2a). Although the manufacturing throughput, yield of LEDs on a wafer and higher LED efficiency are increased, there is high price pressure. Low cost ps lasers with a few W in laser power output do not require chirped pulse amplification and therefore the initial investment is unbeaten. This is why they low cost & low power ps lasers are the first of 3 main technology segments for ultrafast lasers.

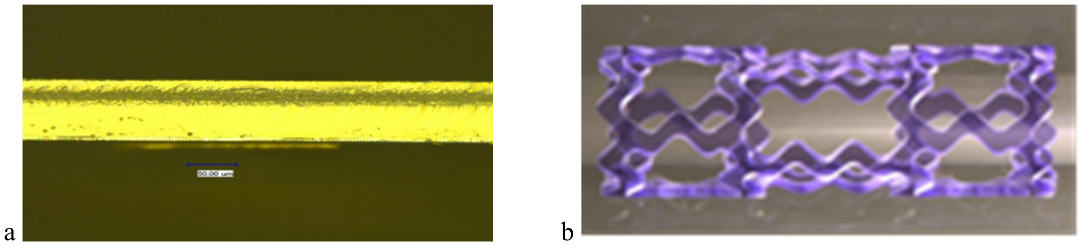

Fig. 2. (a) Cross section of a ps-laser diced LED. The scribe line is nicely visible. (b): PLLA stent cut with 400fs laser–no post processing required

When cutting materials that are very sensitive to heat and thermal effects, such as polymer bio-absorbable stents (PLLA), use of a femtosecond laser is required. Only these very short laser pulses can generate a cut which would leave no heat effect on the material. This is particularly important when post processing of the resulting stent structure is not desired or even impossible (Figure 2b).

How does the pulse length of an ultrafast laser influence the processing result outside of these special applications or materials? In an experimental setup the ablation efficiency of a Monaco fs-laser and a HyperRapid ps- laser was compared when processing different materials. Both lasers were operated in IR with a pulse repetition rate of 250 kHz and a pulse overlap of 60%. The laser beam was steered with a galvanometric scanner. A rectangular structure of 2.5×0.3 mm^2 was ablated by using 400fs, 800fs, 1,5ps, 5ps, 10ps and 19ps pulse durations. The spot size was set to 19µm +/- 0.1µm, output power of the laser was 0.2W - 2W. In the experimental setup the ablation rate [mm^3/W·min] was determined when using various average pulse fluences [J/cm2].

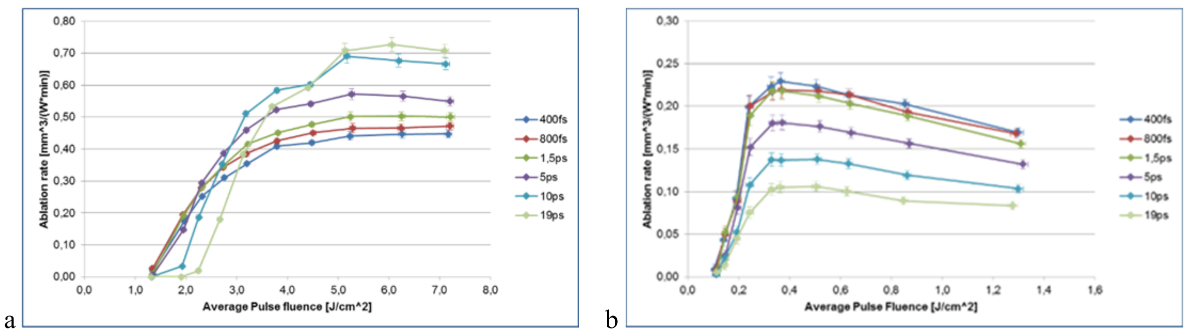

Fig. 3. (a) Ultrafast laser ablation rate on Al_2O_3; (b) Ultrafast laser ablation rate on steel.

The tests demonstrated different material behaviors for metals and brittle materials, which are shown in Figure 3. These graphs display the ablation rate efficiency in mm^3/W·min when operating at different average pulse fluence in J/cm^2. It can be observed that there is an optimum ablation efficiency at a certain average pulse fluence. When operating at lower or higher fluence the efficiency decreases. Figure 3a displays the results when processing Al_2O_3. The ablation rate efficiency is increasing with increasing average fluence. At 6J/cm2 seems to be a maximum; picosecond lasers achieve ablation rate efficiencies in the order of 0,7 mm^3/W·min, femtosecond lasers only achieve 0,4 $mm^3/W \cdot min$. It seems that the roll over effect to decreasing ablation efficiencies is just starting. We observe a similar behavior with other brittle materials.

Figure 3b shows the results when processing steel. The ablation rate efficiency reaches its maximum at an average fluence of 0,27 J/cm^2. If more or less fluence is applied, the ablation rate efficiency declines. When applying single pulses the average ablation rate is higher with femtosecond lasers compared with picosecond lasers. With femtosecond lasers an ablation rate of 0,23 $mm^3/W \cdot min$ can be achieved compared with 0,13 $mm^3/W \cdot min$ of a 10ps laser.

Comparing the ablation rate efficiency of Al_2O_3 and steel it is obvious that the average fluence levels to reach the maximum ablation efficiency is higher with Al_2O_3. This is an indicator that high pulse energies are beneficial when processing Al_2O_3. Due to high heat conductivity, there is no melt or plasma formation at high pulse energies. The efficiency curves for steel are steep, the maximum efficiency window is rather small compared with Al_2O_3.

Tests in Coherent application labs have shown that burst mode operation optimizes fluence of pico- and femtosecond lasers when processing metals. When operating at high average powers, burst mode therefore allows operating closer to optimum fluence, as picosecond lasers operating in a burst mode split the single pulse fluence up within several lower fluence pulses. If the individual pulses within the burst have optimal pulse fluence for maximum ablation efficiency burst mode can ablate more material than a single pulse achieving the same ablation quality. Higher ablation rates can be achieved when applying more power – with the caveat of reduced surface quality.

Figure 4 shows a conclusion and explains the 3 technology segments where ultrafast laser technology is used. 1.) High Power Picosecond lasers are ideally suited for processing brittle materials, like glass, ceramics and sapphire. 2.) Low power picosecond lasers are used for low cost marking, surface texturing and scribing applications. 3.) Femtosecond lasers are used when sensitive polymers with low heat conductivity have to be processed. They are also required, if steel has to be processed achieving the best processing quality. However if surface quality can be compromised the use of a picosecond laser offers higher processing speeds.

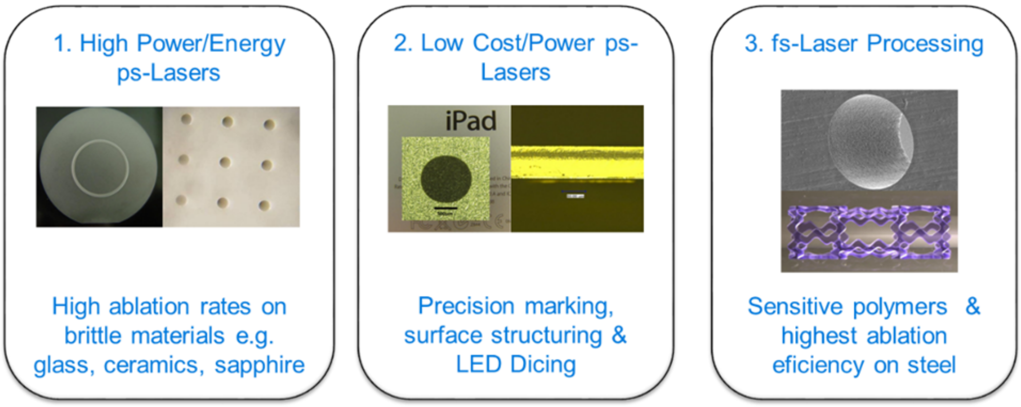

Fig. 4. Appropriate pulse length and energy.

3. Trends in Ultrafast Lasers

The introduction of the Coherent HyperRapid platform in 2007 marked the first time a ps laser could be use in a production environment. With the introduction of a truly industrial ps laser concept by a multitude of established laser vendors, the investment levels for these lasers have become more attractive, as cost per watt of average power is a very important figure of merit. Also the physical size is increasingly important for this class of lasers, because footprint of laser tools need to become smaller and smaller. Both these financial drivers, and the use of HyperRapid in true 24/7 production environments also require design for reliability.

The recently introduced HyperRapid NX platform will be the next generation platform that provides a suitable answer to these three drivers. The laser architecture now uses more modern components like a fiber-laser based seed laser that allows for more compact integration and much higher ease of maintenance. Implementation of advanced electronics allow for electronics integration inside the laser head, omitting the need for a large sized control box. The fact that all electronics are inside the laser head, also means the vulnerable connections between the power supply and the laser head is now much more reliable. The HyperRapid NX is also adding integrated harmonics to the equation. The UV and Green versions of the platform are both dedicated to this wavelength, and the conversion optics are internal to the laser head. A modular optics design allows for a field replacement of just the harmonics conversion optics in the field. Hermetically sealing all optical modules allows this to be an activity that can be done outside the controlled environment of a production clean room.

4. Summary

This paper has discussed which applications are ideally suited for lasers with femto- or picosecond pulse durations. 23 technology segments can be defined. 1.) Low cost & low power picosecond lasers serve applications, which are price sensitive. 2.) High power and high pulse energy picosecond lasers are ideally suited for processing brittle materials. 3.) Femtosecond lasers are used when processing sensitive polymer materials and steel if customers are seeking for the best processing quality. Trends in Ultrafast lasers were discussed in particular the desire to reduce footprint and cost but increase reliability and ease of use in industrial manufacturing. The HyperRapid NX is a premier example for this where smallest footprint are combined with 100+W and low cost of ownership.