High Energy Picosecond Lasers: Ready for Prime Time

Industrial-grade picosecond laser systems extend micromachining applications

High-pulse energy picosecond laser systems provide industrial-level reliability combined with the performance features required for many ultrafast material processing applications. Current diode-pumped solid-state systems provide pulse energies into the 100's of microjoules at 1064 nm wavelength and pulse widths of approximately 10 picoseconds, which allows effective "cold" ablation of most materials with high efficiency. Average power of these systems is scalable up to 50 W and will further increase into the multi-100 W range, allowing for very high speed picosecond micromachining.

This article first reviews the basics of picosecond micromachining, gives a short perspective on the development of these lasers over the last few decades, then summarizes their current performance. We review some of the applications that are enabled with these lasers, before we discuss future developments in this rapidly changing field.

Basics of picosecond micromachining

Cold ablation has been a topic of research for approximately the last 20 years. All materials have an ablation threshold i.e. a point where they are directly vaporized when hit with a laser beam of sufficient peak optical intensity. For a given pulse energy, one obtains higher peak intensity as the pulsewidth gets shorter. Additionally, the threshold fluence (energy per unit area) for ablation reduces as a function of pulsewidth. This ablation threshold reaches a practical value of about 1 J/cm^2 (Joule per centimeter-squared) at 10 ps pulsewidth, typically about a factor of 2 from the minimum value observed in the sub-picosecond range.

The low ablation fluence with picosecond pulses means that less pulse energy is required to ablate the material. Additionally, the pulse is short enough that very little energy from the laser couples into the material as heat. Most of the optical pulse goes into exciting electrons which then quickly cause a small section of the material to ablate. The resulting ejected material is mostly gaseous or very fine particles, and leaves behind a very limited heat-affected zone (HAZ), typically much less than a micron. There is limited or no melted material, so that recast and burs are minimized. This type of laser-material interaction is fundamentally different than material processing with nanosecond or longer pulses, which always have some element of heating and melting involved. Hence, the application of the term "cold ablation" exists for laser microprocessing with pulsewidths in the range of 10 ps or lower.

Typical numbers for a picosecond micromachining process might be: given an ablation threshold of 1 J/cm^2 and choosing a spot diameter of 36 microns, a pulse energy of 10 µJ is required to reach the ablation threshold. With 10 W of average power, we could operate as high as 1 MHz repetition rate. Typical volume ablation rates can be in the range of 1 mm^3 per minute, and with higher average power and process optimization can reach 10 mm^3 per minute.

The final choice of the laser parameters – spot size, pulse energy, average power, repetition rate – is a complex function of the material type and the micromachining goals, and is beyond the scope of this article. In general, we can say that picosecond micromachining may ultimately be limited by the scan speeds and accuracy of currently available scan heads. For a more detailed overview of this topic, please see the presentation from Prof. Beat Neuenschwander from the Bern University of Applied Sciences [1].

FIGURE 1: **Picosecond MOPA laser system with 10 ps pulsewidths, up to 200 µJ pulse energies, repetition rate to 8 MHz, and average power exceeding 10 W.**

In the end, as for many laser machining processes, each application has to be carefully optimized, and all of these factors depend on the material chosen and the type of micromachining required.

Why not use a femtosecond system? Much of the original R&D work on cold ab-

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Dr. Kurt Weingarten earned a Bachelor degree in electrical engineering at Georgia Institute of Technology in 1983 then earned his Masters and Ph.D. in electrical engineering from Stanford University in 1988, using mode-locked lasers to electro-optically measure high-speed GaAs integrated circuits. He worked at one of the pioneering companies in diode-pumped solid-state lasers, Lightwave Electronics, from 1988 to 1993, then moved to Switzerland where he founded Time-Bandwidth Products in 1995.

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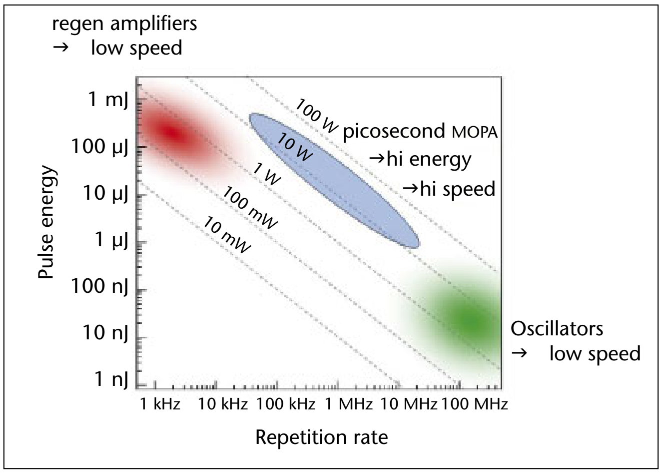

FIGURE 2: **Pulse energy versus repetition rate for the picosecond MOPA, compared to typical values for oscillators and regenerative amplifiers**

lation was performed with femtosecond regenerative amplifier systems. These systems are much more complex, relying on the technique of "chirped-pulse amplification", and are much more difficult to scale in terms of average power. Although some applications may benefit from femtosecond pulses, many cold-ablation applications work just fine with picosecond pulses.

A look back

Ultrafast lasers have long had the reputation of "unreliable" or "requires a Ph.D. to operate". During my Ph.D. research at Stanford in the mid-80's, this was true. We used a lamp-pumped, actively modelocked Nd:YAG laser that was more than two meters long, with external water cooling required, combined with a fiber-grating pulse compressor, to generate less than a Watt of picosecond pulses. We really did spend a good part of the morning making sure the laser was adjusted and stable. This allowed for convenient coffee breaks but didn't much help to move the research forward. These systems also produced pulses in the nanojoule regime, well below the pulse energy necessary for micromachining.

THE COMPANY

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Time-Bandwidth Products produces industrial and customized ultrafast laser solutions for OEM and R&D customers. Our product family covers a broad range of parameters, from wavelengths of 266 nm to 1550 nm, femtoseconds to picoseconds, repetition rates from single-shot to > 10 GHz, and average powers to 50 W. Key markets include precision micromachining, semiconductor diagnostics, life sciences, high-energy physics, and R&D.
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The advent of diode-pumping of solid-state lasers in the late 1980's led to much improvements in terms of size, cost, and robustness. In the picosecond regime, regenerative amplifiers were the early choice to scale pulse energy into the microjoule or millijoule regime, with first commercial products available in the late 1990's. This allowed researchers to investigate micromachining with picosecond pulses and demonstrate the benefits of cold ablation. While good results were obtained, there was the clear need to scale the repetition rate and also the corresponding average power in order to obtain processing speeds which were competitive with existing nanosecond Q-switched lasers.

We also learned about the inherent weaknesses of regenerative amplifier: as the amplifier forms a cavity (requiring 10's of round trips), they are sensitive to alignment, are difficult to vary key parameters such as repetition rate without changing output beam parameters, and have the tendency to damage components (due to the high average intensity resulting from the large number of cavity round trips). Additionally they require an electro-optic Pockels cell as the switch, which adds extra cost, complexity, and power consumption.

Our approach – a picosecond MOPA using bulk solid-state laser crystals

These weaknesses led Time-Bandwidth Products to develop a novel approach to the challenge of both high pulse energy and high average power. This resulted in the Duetto product family, based on the concept of master-oscillator power-amplifier (MOPA). In our case, the master oscillator consists of a proven workhorse, a simple diode-pumped Nd:Vanadate oscillator producing 10 ps pulses at 100 MHz. This oscillator uses our proprietary SESAM technology which allows for simple, robust, low-cost passive modelocking of this oscillator. The output of this laser is switched by a pulse picker into a multi-pass amplifier arrangement. One notable feature of this amplifier is the ability to configure both an effective pre-amplifier, with power gain factors in excess of 40 dB, and to configure it as a power amplifier to further boost pulse energy or more importantly average power.

Another key feature of the MOPA approach is the ability to instantaneously (i.e. from one pulse to the next) change the repetition rate without significantly effecting key beam parameters (i.e. spatial mode quality, mode size, and pointing). As long as the repetition rate is faster than the recovery time of the amplifier (i.e. 50 kHz), changing the repetition rate results in a change of the pulse energy but negligible change of the average output power.

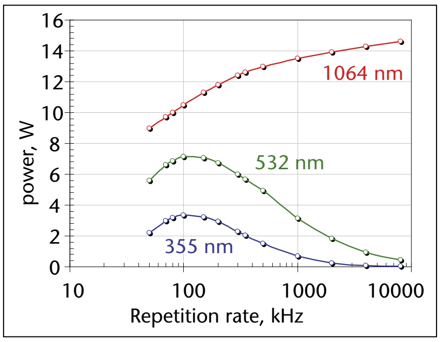


FIGURE 3: **Output power versus repetition rate for 1064 nm, and for frequency conversion to either green (532 nm) or UV (355 nm) for picosecond MOPA system**

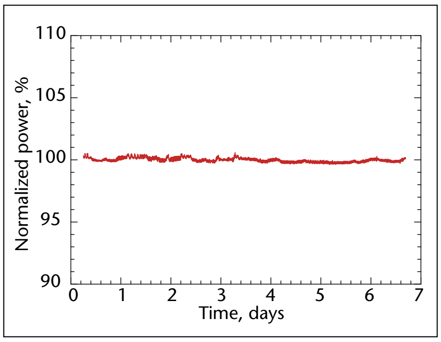


FIGURE 4: **long term stability of Duetto. Average power measurement at PRF = 100 kHz over one week showing fluctuations of 0.14 %/°C rms and 0.2%/°C peak-to-peak . Ambient temperature stability during the measurement was ± 2.5 °C.**

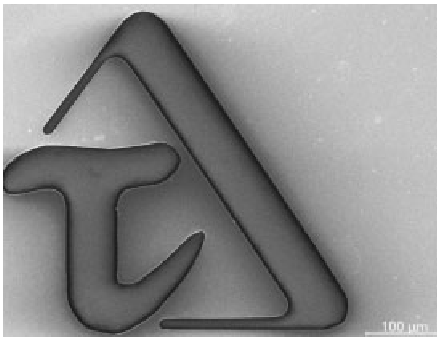


FIGURE 5: **TBP logo cut in thin steel foil.**

This has allowed us to offer a basic laser system producing 10 ps pulses with 10 W average power. This corresponds to 100 kHz repetition rate with 100 microjoules of pulse energy, or switching to 1 MHz would give 10 microjoules for example. Repetition rates can be set as high as 8 MHz currently (limited by electronics, not the MOPA). Figure 1 shows the laser head of the Duetto system, and Figure 2 shows the range of pulse energies versus repetition rates that can be covered with the Duetto.

Repetition rates below 50 kHz, i.e. to single-shot or arbitrary pulse sequences, are typically achieved with an external pulse picker to give a clean, triggerable "pulse-on-demand" (PoD). This approach avoids the difficult, but often neglected "first-pulse problem" which can be found in MOPAs, regenerative amplifiers, and also Q-switched systems. Due to energy storage in the gain material, if the laser is not operated for some time period, the energy builds up, and is released in an oversize "first pulse". This can have consequences ranging from inconvenient to disastrous, depending on the application.

Due to its high peak power (in the megawatt range) the Duetto can be efficiently converted to shorter wavelengths, allowing typically 70 % conversion to the green (532 nm) and 30 % conversion to the UV (355 nm) as shown in Figure 3.

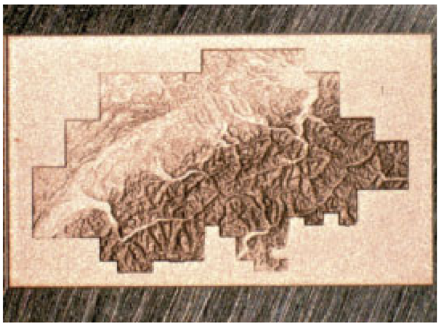


FIGURE 6: **Micro-structured copper plate (circa 9 mm wide) using topographical data from the Swiss Federal Office of Topography swisstopo (www.swisstopo.ch) used with permission geodata© swisstopo. Photo and sample preparation courtesy of Prof. B. Neuenschwander, Bern University of Applied Sciences.**

Modular booster amplifiers allow for further scaling of the average power, with 50 W systems currently shipping. We expect further progress in the scaling of the average power as the markets develop.

The end result is a simple, turn-key solution for picosecond micromachining. The Duetto is built in a sealed, hands-off housing which can be taken out of the shipping box and installed in 1–2 hours. Power-up and turn-on is accomplished in minutes. Long-term stability is excellent, as shown in Figure 4.

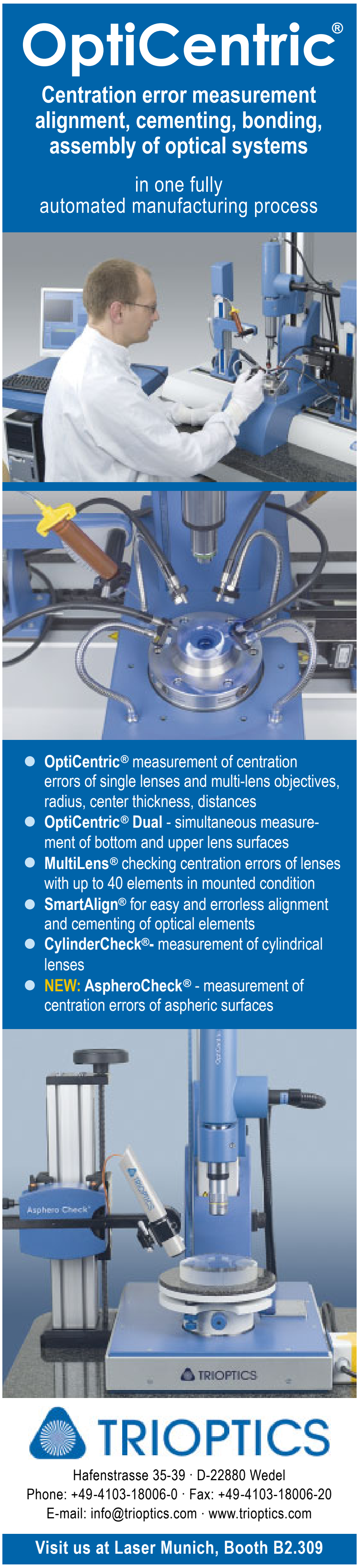
What about high energy fiber lasers?

Fiber lasers have been the talk of the town for the last few years. However when it comes to high pulse energy, particularly with picosecond pulses, they struggle, since they are typically limited in terms of maximum peak power due to nonlinearity in the fiber and optical damage. Current commercial fiber systems produce pulse energies in the few microjoule range, which is often below the energy needed to achieve the ablation threshold. Moreover, there can be trade-offs even here, such as significant spectral broadening of the output, leading to degraded performance and limited frequency conversion efficiency. Photodarkening of the fiber, particularly in high energy amplifiers, is still an ongoing issue. Laboratory results are still improving, although the complexity of such fiber systems can then be said to exceed the more straightforward bulk solid-state laser approach. In all cases, care must be taken with the opto-mechanical-thermal design – much of the "simplicity" of fiber lasers starts to disappear at these kind of power levels, and the differences (including the cost advantages) between bulk solid-state lasers and sophisticated large-mode-area or photonic-crystal fiber begins to very much blur.

It is worth noting that all of the currently available commercial products producing high energy picosecond pulses for micromachining rely on bulk solid-state laser elements for the pulse amplification.

Applications

Let's review the key features of picosecond micromachining. Each pulse removes only a small quantity of material, and does so with nearly negligible heat-affected zone. Burs, microcracking, and recast can be vir-



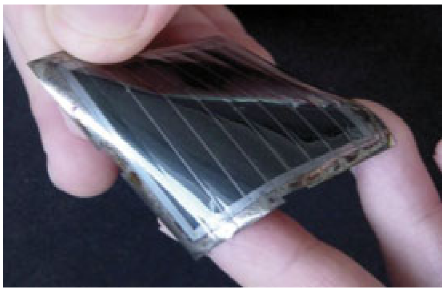


FIGURE 7: **Thin-film CIGS flexible solar cell selectively scribed with Duetto laser**

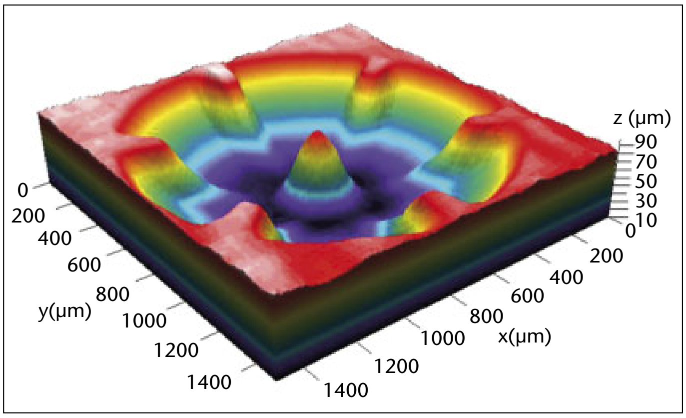


FIGURE 8: **Sophisticated micromachined structures are possible in transparent and hard material, such as sapphire as shown here. The profile is measured with a laser scanning microscope.**

tually eliminated. The spot size can be reduced into the micron range with sufficient care. In addition to the basic wavelength of 1064 nm, green and UV wavelengths are available, allowing for improved spot size or possibly better laser-material coupling. The pulse repetition rate can be increased into the megahertz regime, potentially enabling very fast scanning speed.

Applications include a broad range of micro-structuring, scribing, or hole drilling in many varieties of materials. Here we list some of the key applications, and provide more details for a few selections below.

Metals

- cutting / structuring (particularly thin-films or foils)
- precision holes (sub-100 µm, large aspect ratios)
- surface features / tribology (improved friction properties)

Semiconductor / Photovoltaics

- hole / via drilling
- ablative processes / micro-structures
- singulation / scribing

Dielectrics

- structuring, particularly "difficult" materials such as ceramics
- selective ablation
- glass scribing, welding

R&D applications

- material research, picosecond spectroscopy
- OPO/OPG pumping
- photocathode excitation (particle accelerators)

Figure 5 shows a simple example of cutting of thin metal. The steel foil (approximately 50 micron thick) can be cut with very high precision and with very sharp edges showing no recast or burs, allowing the structuring very fine, small metal pieces. Additionally, precision, shaped holes can be drilled into metals, particularly hard metals, for applications in areas such as spinnerets, injection nozzles, and turbines. Figure 6 shows a "fun" example of a micro-structured piece of copper, width of approximately 9 mm, using topographical data of Switzerland with 100 levels in the vertical.

Cold ablation is particularly interesting for applications requiring processing of "mixed" materials e.g. combinations of the metals, semiconductors, plastics, and dielectrics. Examples include semiconductors using low-k coated dielectrics, or thin-film technologies such as CIGS, CdTe, etc. used to make flexible solar cells. Figure 7 shows a CIGS solar cell fabricated on a flexible substrate. Each of the isolation scribe processes P1/P2/P3 must be achieved with no substantial heat affected zone, no damage to neighboring material, and no damage of underlying layers. This is achievable with proper selection of the process wavelength with picosecond laser ablation.

Transparent materials, even very hard ones, can be effectively micro-structured. Figure 8 shows a complex shape structured out of sapphire. Other materials such as ceramic, which are sensitive to heat-triggered cracking due to their brittleness, can also be effectively micro-structured with picosecond lasers.

Future outlook

Picosecond micromachining is still a new and not fully explored area. As laser engineers, we continue to see, somewhat to our surprise, that the work required to develop processes using these lasers can be very intensive. This is due both to the basic nature of micromachining (complex) and also due to new effects being discovered in the world of picosecond micromachining. Nonetheless we continue to find many applications where results are achieved that are "difficult to impossible" to achieve with other laser types.

In the end, for a proven process, the bottom line comes down to either cost, quality, or a combination of the two. Cost is associated with both the cost of the laser system, and the process speed. Picosecond lasers are still relatively new to the market, and tend to be high-priced. This is partially due to the extreme performance features i.e. very clean TEM_{00} beams with $M^2 < 1.3$, and also partially due to their relatively low volumes of sales. We expect the price per Watt to continue to decline, and there is certainly much room for cost reduction as the unit volumes increase. While fiber laser technology may play a role in the next 5–10 years, the low pulse energy and photodarkening are still issues that must be addressed.

System integration also plays a key role in the process speed, quality, and cost. We have already seen that high average power picosecond systems can be limited not in terms of their average power but in terms of the speeds / accuracy of available scan heads, which places an upper limit on process speed. This may be an area for new development opportunity in the future.

For applications requiring sub-picosecond pulses, we also expect to see solutions emerge in the next few years comparable to the picosecond MOPA approach i.e. most likely diode-pumped MOPA's with novel gain and dispersion elements, to allow scaling of the pulse width into the sub-picosecond regime with flexible repetition rates and pulse energies. These systems may be particularly interesting for applications requiring stronger multi-photon effects or an absolute minimum for the required fluence to reach the ablation threshold.

Literature

[1] http://www.swisslaser.net/libraries.files/HighThroughputStructuring.pdf