Application of Fiber Laser Chirped Pulse Amplifiers

Application Notes

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Overview

Ultrashort pulses are a new technology with many applications from sampling to non-thermal machining and surgery. Fiber lasers provide a stable and reliable mode-locked platform for generation of these pulses. These ultrashort pulse fiber lasers are the primary expertise of Calmar Laser.

Rather than higher average power, higher energy pulses are sometimes required for applications such as non-thermal machining or surgery. However, the small optical mode diameter in a fiber limits short pulse energy throughput due to nonlinear optical mechanisms. Although fiber lasers can generate Kilowatts of average laser power, sub-picosecond pulse energies are limited to 10s of µJ in commercial systems today. The Fiber Laser Chirped Pulse Amplifier (FLCPA) is one method for increasing the energy output of a fiber to many µJ and above.

The Chirped Pulse Amplifier is a method for amplifying short pulses by time stretching in such a way that the stretched pulse can later be recompressed back into a short pulse after the fiber amplifier system. The typical method for stretching is to “chirp” the short pulse, where different optical frequencies are delayed by different amounts of time to create a much longer pulse. The chirp stretching can be accomplished with a grating pair or a fiber grating. The typical method for recompressing a chirped pulse is a grating pair in free space at the exit aperture of the laser. This grating pair is the only free-space element of the FLCPA, which typically emits a beam in free space that’s guided to the target by free-space optics that can handle the high peak energy. For more details on this process, see our white paper “Fiber Laser Chirped Pulse Amplifier”.

Although FLCPA have been demonstrated to generate 100s of µJ of optical pulse energy in scientific experiments, current commercial FLCPAs are in the 10 µJ range. With a pulse rate of 100s of KHz, overall FLCPA produce an average power of several Watts of high energy sub-picosecond pulses.

Advantages of Lasers for Material Removal

- Capable of processing in the atmosphere
- Maintenance Free
  No need to replace blades, drill bits and laser works for long time continuously.
- Not cause wastes. Wastes after process will evaporate.
- No need to use cutting fluid.
- Capable of 100 µm or less processing.
- Capable to rather easily cut, drill or process hard materials like diamonds, ceramics, SiC and so on.
- Capable of selective processing in Dry Process.

Advantages of High Energy Ultrafast Pulses for Material Removal

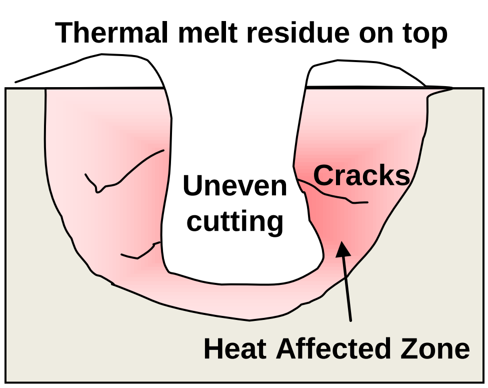
For machining and surgical applications, a pulse width under 1 picosecond works through ablation rather than heating and melting. Energy deposited by the laser upon a surface cannot thermally propagate a significant distance into the material during the time of the pulse, so thermal effects and material stress are significantly reduced. Deposition of energy in sub-picosecond times causes the surface material to become a plasma that consumes the pulse energy and dissipate in a gas phase, leaving a clear cutting edge. The uncut material remains in original form with greatly reduced stress, fractures, melts, or other unwanted thermal processes. In contrast, a laser with nanosecond or longer pulses, will leave a large "heat affected zone" around the cutting edge, as well as numerous stress fractures.

Although a 0.5 to 0.7 picosecond pulse generated by a fiber laser is longer than achievable by a solid state laser, the laser-material interaction remains dominated by ablation for sub-picosecond pulses. As such, the fiber laser CPA is an excellent candidate for such applications with equal capability. Most importantly, the stability, reliability, compactness, lifetime, and total cost of ownership of a fiber laser system is a major advantage for commercial use.

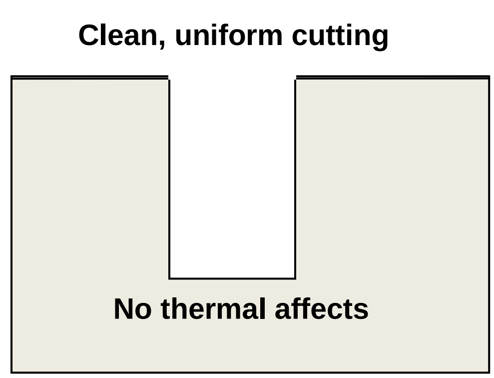
Comparison of Pulsed versus Ultrafast lasers

Parameter	Long Pulse Lasers	Ultrafast Laser
Pulse Width 'T'	T > 5 ps	T < 5 ps
Damage Mechanism	Thermal Melting	Ablation
Optical Physics	Absorption/Heating	Zener Ionization
Wavelength Requirement	Absorbed by Material	Any Material & Wavelength
Pulse Damage Threshold	$\sim T^{1/2}$	~ 1-5 J/cm^2
Stress	Thermal Shock & Cracks	None
Heat Affected Zone	thickness $\sim(DT)^{1/2}$	None
Material Removal Rate	Depth $\sim(DT)^{1/2}$	Depth ~30-50 nm/Pulse
Maximum Pulse Rate	~MHz	100 KHz – 1 MHz
Uniformity of Cut Dimension	20-50%	1%

D is the diffusion constant. T is the Pulse Width of the laser.



Long Pulse Laser
Thermal Drilling / Cutting



Ultrafast Laser
Ablation Drilling / Cutting

Material Physics of High Energy Ultrafast Pulses

As a high energy laser pulse duration reduces below a few picoseconds, the damage threshold becomes deterministic and is very sharp and reproducible (within 1%), as opposed to the 20–50% variations with the stochastic behavior of longer pulses (> 5ps). The reason for this ultrafast deterministic behavior has been ascribed to a physical process that is dependent primarily on the valance band electron density, which remains quite uniform across a given material, as well as fairly stable across many different materials.). [1] [2]

This ablation process starts with an optically induced Zener ionization followed by Zener-seeded avalanche ionization. The material removal per pulse is typically around 30 to 50 nm deep, which is the optical penetration or "skin depth" for a plasma density of $\sim 10^{23}/cm^3$, equal to the valance band electron density for many materials. Furthermore, because of the Zener initiation mechanism, the intensity threshold for damage remains nearly constant at a few J/cm^2 with pulse widths from 5 to 100 fs. [3]

The ultrashort laser pulse ablation process emits particles for up to several hundred nanoseconds after the laser pulse, observed to occur in two distinct steps. Variation of optical pulse duration in the range of 200 fs to 3.3 ps shows no significant effect on this ablation behavior. [4] In the first step, a thin layer of the surface on the order of the optical penetration depth of the laser pulse (~50 nm) is ablated by electron emission, sublimation, transition to the plasma state and gasdynamic effects. This ablation process proceeds on a nanosecond time scale or faster. [4]

The second distinct emission step originates from the remaining heat that is meanwhile diffusing into the material, so that thermal effects on longer time scales can occur. This second ablation step is assumed to result from boiling after heterogeneous or homogeneous nucleation. This second step starts after about 40 ns with emission of hot material and droplets, increases to a maximum after about 150 ns and then vanishes after a few microseconds. If the laser pulse energy is reduced towards the critical threshold, the amount of material emitted in this second step is observed to significantly decrease. [4]

The laser is typically focused onto the material with a spot diameter of approximately 10 to 20 µm. Thus a 10 µJ energy laser pulse will provide a fluence of 2-10 J/cm^2, the damage threshold of most materials. At a 10 to 20 µm spot diameter, the laser can remain focused over a depth of ~100 to 500 µm, respectively. Furthermore, the focusing lens should stand off 1 to 2 cm from the material to reduce material spray. A forming gas flow is useful to remove the effluent from obscuring the view of the laser (see below). This forming gas should be vented in a safe manner as it contains the ablated material in a gaseous form, which could be toxic or harmful if inhaled.

For a material removal of ~50 nm depth per pulse, a Calmar FLCPA operating at a pulse repetition rate of 100 KHz can drill at a depth rate up to 5 mm/sec. Often, for shallow drill depths the cut rate can be limited by movement of the laser or material between pulse trains.

For repeated drilling of deeper holes at one location, or "percussion" drilling, two physical mechanisms come into play. [5] First, the plasma emission from the ablated material can block the light of the next pulse as the repetition rate approaches 1 MHz, reducing the drill rate to as low as 10 nm/pulse. [4] Second, residual heat can build up at the drill point, which aids in the drill rate, but through a thermal rather than ablation process at the expense of a poor quality thermal hole.

[5] As such, the repetition rate of ultrafast athermal percussion drilling is limited to a few 100 KHz to 1 MHz, with the higher rates possible on higher conductivity materials like copper.

As an alternative to percussion drilling, “trepanning”, has greatly improved the quality of holes at higher repetition rates of ultrafast lasers. [5] Laser trepanning consists in moving the beam on a circular path relative to the target, differently from percussion drilling in which consecutive pulses are superimposed in the same focal volume. The scanning helps in avoiding plasma attenuation and thermal buildup effects. Similarly, linear scanning can also be beneficial for fast clean cuts.

Technical References

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[4] König, J., Nolte, S., & Tünnermann, A. (2005). Plasma evolution during metal ablation with ultrashort laser pulses. *Optics Express* , *13*, 10597-10607.

[5] Ancona, A., Röser, F., Rademaker, K., Limpert, J., Nolte, S., & Tünnermann, A. (2008). High speed laser drilling of metals using a high repetition rate, high average power ultrafast fiber CPA system. *Optics Express* , *16* (12), 8958-8968.

Applications

Calmar's FLCPA has applications in bio-medical, precision material processing, and nanostructuring

Ophthalmology

Femtosecond laser cataract procedure has recently gained significant market presence, with new tools from companies such as Alcon, LensAr, Optimedica, and Technolas PV. The Cazadero laser is ideal for this application, which consists of four major procedures:

- Laser Capsulotomy
  - This procedure cuts the outer surface of a 3D cylindrical section of the cornea to allow it to be removed. The location of the cut is usually defined by surgeon using computer aided suggestions based on advanced 3D imaging, such as Optical Computerized Tomography (OCT).
  - At a laser wavelength of 1.0 µm, the laser light can reach through the cornea to cut before opening a flap, usually starting at the back of the cornea. The femtosecond laser will only cut at the focus by creation of a bubble based on the physical processes discussed before. This beam focus is scanned in the desired 3D cut pattern for creation of the Capsulotomy .
  - Precise cuts (capsulorhexis) are required for accurate vision correction and insertion of advanced Intra-Ocular Lens (IOL) that replaces the cornea. Whereas a good surgeon can cut a 5-8 mm circle manually within a fraction of mm, a femtosecond laser can cut with a precision in the 10s of µm.
  - Errors in Effective Lens Position (ELP) are biggest source of error in IOL power.
    - 1 mm error leads to a 1.25 diopter change in result.
    - Multifocal IOLs have even tighter tolerance, with errors leading to visual aberrations like halo and coma that are difficult to tolerate.
- Lens Fragmentation
  - Places patterns of cuts on the cornea nucleus to soften harder cataracts
  - Reduces the amount of ultrasound energy from the phacoemulsification probe
  - Diminishes the risk of capsule complications and corneal endothelial injury
  - Added safety benefits from reducing the number of instruments used, intraocular movements, and manipulations of the lens
- Relaxing incisions
  - Corneal or limbal relaxing incisions (LRIs) to correct up to 3.5 diopter of astigmatism, flattening the steepest meridian of the cornea, a source of refractive error
  - An axis misalignment of just 58 results in a 17% reduction in effect
- Clear corneal incisions (CCI)
  - Self-sealing CCI is the preferred method of access into the anterior chamber to remove the cornea and implant the new IOL, used by 72% of US cataract surgeons
  - Not 100% because of obstacle of increased incidence of endophthalmitis
  - Laser-made wounds may have less features of damage and faster healing

Bio-medical applications

Because subpicosecond pulses interact with material athermally, FLCPA is a best choice for precision cutting of benign material such as human tissue. Femtosecond lasers have long been used for optical tissue diagnostics and therapeutic surgery. Today they are also used for cutting cornea in the LASIC surgery process.

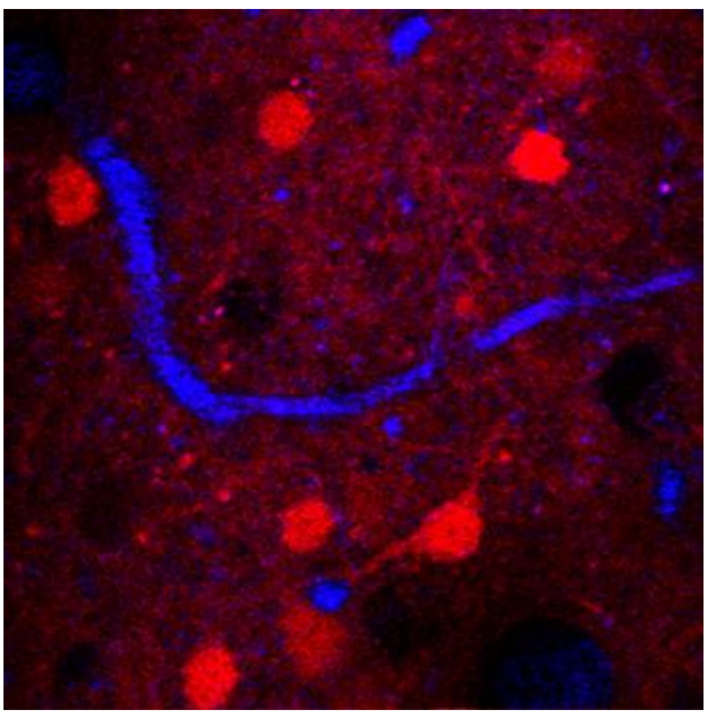
Furthermore, high energy femtosecond pulses are used to manufacture nano-scale structures for bio-medical instrumentations. Such structures have been used as microfluidic channels for molecule separation. Ultrafast lasers are also used for precision drilling of stents.

Bio-medical Imaging

The imaging uses three photon fluorescence microscopy to image vascular structures and red florescent protein-labeled neurons within a live mouse hippocampus. The combination of higher order non-linear excitation at a longer excitation wavelength allowed high resolution, three dimensional imaging at a 3X greater depth than previously achieved, by to overcome effects such as tissue scattering and absorption, which can limit the depth of high-resolution imaging in two photon microscopy.

This approach needed the high energy 1.5 µm wavelength pulses of the Cazadero in order to up convert to 1.7 µm wavelength light through nonlinear processes. This longer wavelength light allows greater depth penetration for the three photon absorption process.

The article, "*In Vivo* three-photon microscopy of subcortical structures within an intact mouse brain" was published online in Vol. 7 of Nature Photonics in January, 2013

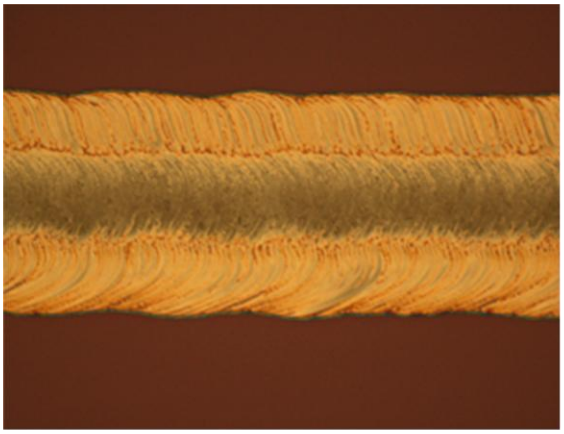


In the article "Three-photon microscopy improves biological imaging" on Cornell's web site, senior author Chris Xu states "Brain mapping could be the so-called grand challenge within the next decade. With MRI, we can see the whole brain but not with the resolution we have demonstrated. The optical resolution is about 100 to 1,000 times higher and allows us to clearly visualize individual neurons."

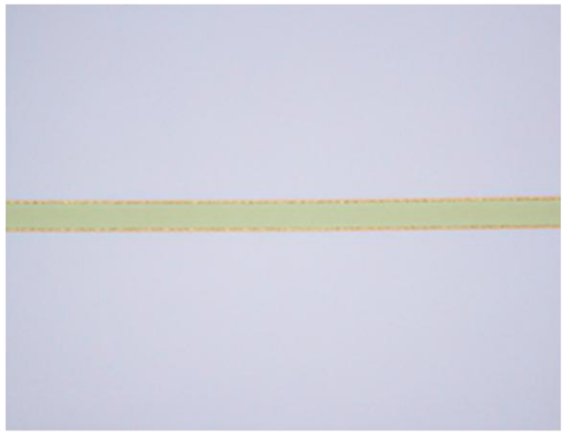
Semiconductor processing

Example processing on Sample: 50nm a-Si thin film on synthetic silica substrate

	Nano sec Laser	Ultra Fast Laser
Wavelength	1064nm	1552nm
Pulse Energy	300μJ	1μJ
Rep. rate	3kHz	100kHz
Stage Speed	50mm/sec	50mm/sec
Process width	100μm	10μm



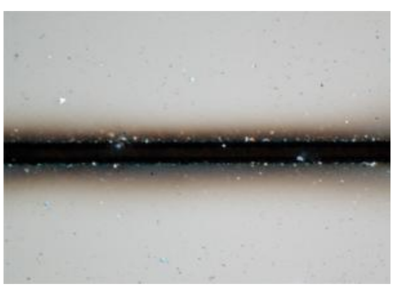
Thin film removal with nanosec laser
Process width: approx. 100 μm



Thin film removal with ultra fast laser
Process width: approx. 10 μm

Example: Sapphire is used for LED substrate

Pulse Energy	5μJ
Rep. rate	500kHz
Stage Speed	50mm/sec
Process width	4μm



Process width is approx. 10um incl. debris.

Precision material processing

High energy subpicosecond pulses interacts with material athermally a great advantage when micro-precision material processing is concerned. It is possible that femtosecond pulses can cut a smaller hole size than the wavelength, through intensity higher than ablation threshold and typical infrared femtosecond lasers can write fine structure with size under several tens of nanometers.

Example: Polyimide is a material used in flexible substrate.

Pulse Energy	5μJ
Rep. rate	500kHz
Stage speed	50mm/sec
Process Width	17μm

Nanostructuring

Compared to the well-known lithography method, femtosecond pulses are cost-effective in MEMs structuring. Femtosecond lasers provide a convenient, economical, and flexible way to fabricate three-dimensional biomedical patterns by varying the beam-scanning speed during ablation whereas clean room lithography requires a highly controlled environment and has limited capability for 3-D structuring.

Beside these listed applications a reliable high energy femtosecond source is now expanding its usages from academic research, through industry, to consumer medical markets and fiber laser can provide reliable source for various applications.

More information

For more information, the following references may be of interest.

General applications

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Bio-medical applications

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Machining of metals

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Machining of glass

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Machining of semiconductors

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Other Applications

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Packaging

Fiber lasers offer advantages in maintaining stable operation over years, low total cost of ownership, and predictable operation in a small package. See our white paper "Fiber Laser Advantages".

The FLCPA is usually preferred to be packaged into two boxes. The controller box handles the controls and electrical drives for the diode pump lasers, and monitors system performance in communication via a USB. The second optical box contains the fiber optical elements and can remain isolated on a laboratory table. The output of the CPA is in free space, so the optical box is designed for steady mounting on an optical table.

Figure 1 Typical Pulse Amplifier Package

If desired, Calmar can also package the entire FLCPA system into one closed box with USB interface for OEM integration.

Beam Performance

The following test results give an indication of the performance of Calmar's Femtosecond Fiber Lasers. Please note that the noise in the measured beam profile is caused by the sampling aliasing between the detector frequency (20 Hz) and the laser frequency (100 kHz).

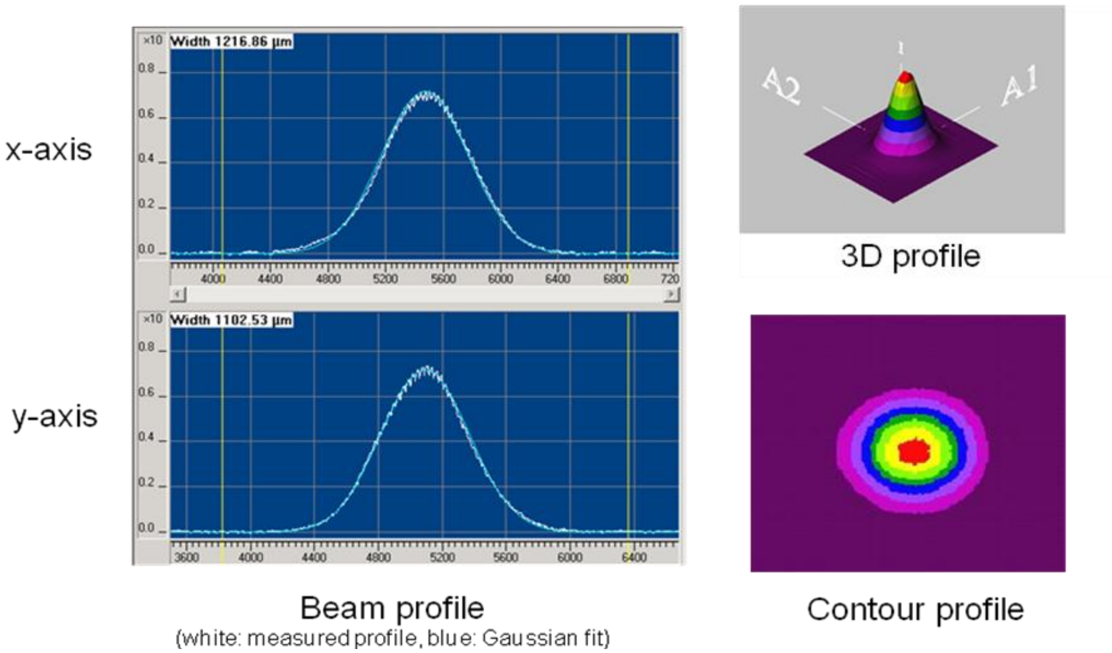

Figure 2 Beam Output Quality, $M^2 < 1.2$

Technical Specifications

Model Number	FLCPA-01C	FLCPA-01U	FLCPA-02U	FLCPA-05U
Pulse Width (ps)*	<0.5	<0.5	<0.5	<0.5
Central Wavelength (nm)	1545 ~ 1555 (selectable)	1030 ~ 1065 (selectable)		1030
Average Power (W)	1	Up to 4	Up to 4	Up to 4
Repetition Rate (KHz)	Up to 1000	Up to 4000	Up to 1350	Up to 200
Pulse Energy (µJ)	1	1	3	20
Polarization Extinction Ratio	20 dB (typical)			
Output Beam (mm)	Free space, diameter 3.0 (typical), $M^2<1.2$			
Operating Temp (°C)	15 ~ 30			
Operating Voltage (VAC)	85 ~ 264			

** A sech_2 pulse shape (convolution factor of 0.65) is used to determine the pulse width for the second harmonic autocorrelation trace. Due to our continuous improvement program, specifications are subject to change without notice.*

For more information on our Picosecond Fiber Laser series, Femtosecond Fiber Laser series, or any other Calmar products, please contact us.

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