A NEW AGE OF HIGH ENERGY LASERS

Advantages of All Diode-Pumped Laser Systems

CEO
CUTTING EDGE OPTRONICS
A Northrop Grumman Company

Introduction

Cutting Edge Optronics Headquarters

OVER THE PAST DECADE, Cutting Edge Optronics (CEO), a wholly owned subsidiary of Northrop Grumman, has designed and built several high energy diode-pumped solid state (DPSS) laser systems for a variety of scientific, industrial and military applications. In business since 1992, CEO is a vertically-integrated manufacturer of standard and custom unmounted laser diode bars, packaged laser diode arrays, DPSS laser modules, laser system controllers and complete DPSS laser systems. All design and manufacturing activities are performed at CEO's 36,000 ft^2 facility located in St. Charles, Missouri. This includes semiconductor wafer processing of the laser diode bars that are constituents in almost all of CEO's products, as well as the electronics used to drive them. Because the entire design and manufacturing processes of building and testing high energy DPSS laser systems are conducted under one roof, CEO employs a great deal of control over the end product, enabling the highest performance, reliability and lifetime.

This paper provides a general overview of CEO's high energy laser design approach and system architecture, and then dives deeper into the technical details of example high energy DPSS laser systems installed around the world. Output pulse energies range from 0.5 J to 10 J, with average output powers of 20 W to 200 W, repetition rates from 5 Hz to 50 Hz, and output wavelengths in both green and infrared.

A list of several high energy laser systems manufactured by CEO is contained in **Table 1**.

Table 1. Example High Energy Laser Systems

Model Number	Pulse Energy (J)	Pulse Width (ns)	Pulse Temporal Profile	Repetition Rate (Hz)	Average Power (W)	Output Wavelength (nm)
CPL-020-QSG	2	<10	Gaussian	10	20	532
CPL-040-QSF	4	~20	Gaussian	10	40	527
GS-025-QTG	0.5	<10	Gaussian	50	25	532
CPL-025-QSF	5	1-5*	Square	5	25	527
CPL-010-QSF	1	~5	Square	10	10	527
CPL-070-QSF	7	~4	Square	10	70	527
CPL-210-QSH	10	>20	Gaussian	20	200	1053

* Variable

Advantages of DPSS over LPSS

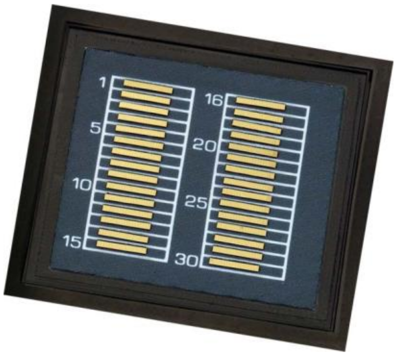
FLASH LAMP-PUMPED HIGH ENERGY LASERS (LPSS) were the original system architectures used for pumping Titanium:Sapphire (Ti:S) lasers, optical parametric amplifiers (OPA), and optical parametric chirped-pulse amplifiers (OPCPA), as well as for most direct materials processing industrial applications requiring high pulse energies and high average powers. Due to severe limitations of this technology, including inefficient pumping leading to excessive heat generation, short lamp lifetimes, continuous optical alignment drift due to lamp degradation, large power supplies requiring extremely high voltages, and low beam quality leading to reduced harmonic generation efficiencies (to name just a few), most of these applications have benefitted from switching to more advanced DPSS laser systems.

DPSS lasers offer several advantages over LPSS systems including, but not limited to:

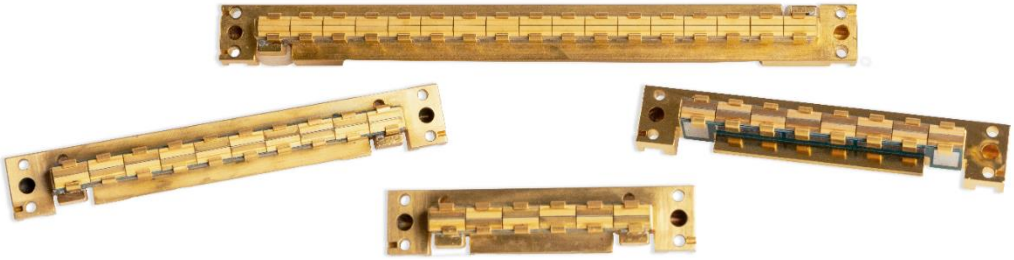
- **Overall system performance**
- **Superior beam profile**
- **Higher conversion efficiencies**
- **Rock-solid stability**
- **Higher reliability/robustness/longevity**
- **Lower maintenance/higher uptime**
- **Lower system complexity**

Each of these advantages will be discussed throughout this paper in more detailed sections on system architecture technologies and components.

At the heart of every DPSS laser system are the pump laser diodes. Significant improvements in high power laser diode technology and manufacturing processes have increased their peak power, lifetime and reliability to the point where DPSS lasers use fewer, higher power bars that produce stable pumping over 10s of billions of shots (>10^9) before noticeable degradation that might require a slight change in operating parameters. Even with this very low, slow degradation, DPSS laser system performance remains stable over days, weeks, months, and even years of operation depending on utilization. Individual diode bar failures are nearly non-existent. Typical laser system warm-up times are less than 30 minutes, with mean-time-to-realignment (MTTR) on the order of months (and often years.) As a result, CEO's robust DPSS laser systems are nearly service- and maintenance-free, mainly requiring only routine coolant refreshes and filter replacements.



Diode Bars

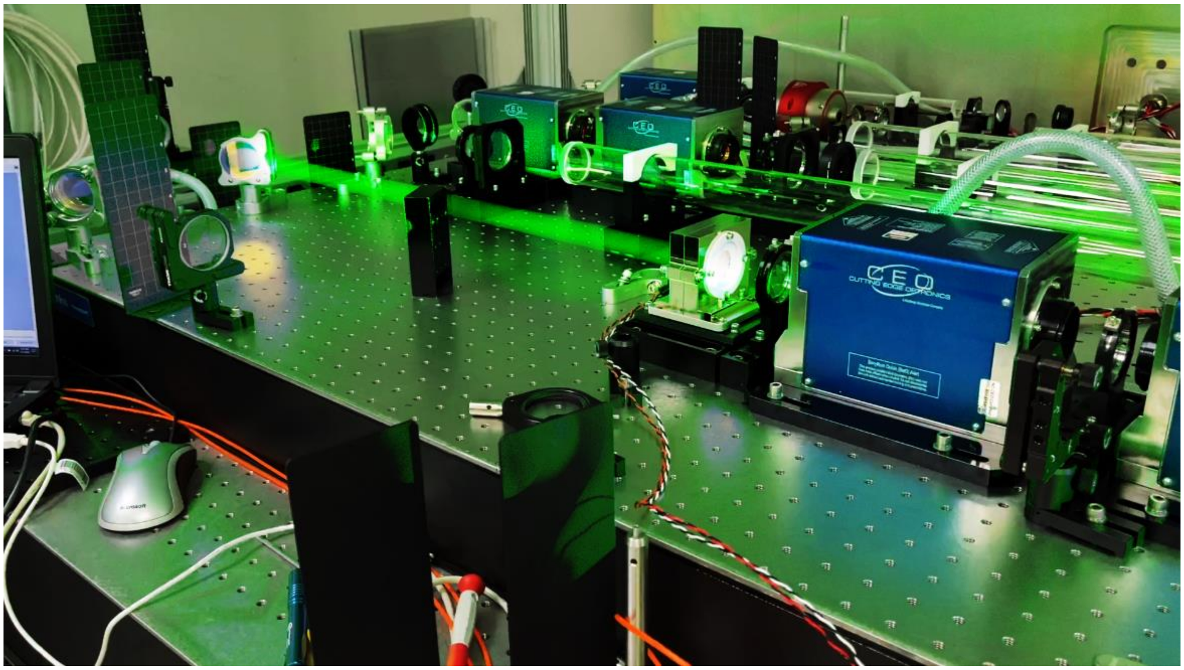


Rugged Laser Diode Arrays for High Energy Lasers

High Energy DPSS Laser System Architecture

A HIGH-LEVEL, GENERAL OVERVIEW of CEO's high energy DPSS laser system architecture is described in this section. Detailed descriptions of individual components and technologies used for specific laser performance specifications are presented in later sections. CEO uses several design approaches for how the 'first photon' is generated in the front end of the laser, based on the end user's application and requirements; high-energy oscillators (in the 10s of mJs), pre-amplifiers, and/or regenerative amplifiers are employed where appropriate for efficient amplification resulting in specific pulse widths, beam profiles, and pulse energies. The subsequent amplifier stages are similar in all of CEO's high energy laser systems.

A beam shaper (apodizer) is used to spatially-select the center portion of the oscillator beam, which is then relay-imaged through a series of DPSS amplifier modules to produce a highly stable, flat-topped output beam. This high energy infrared (IR) output beam is used for applications such as materials processing and 3D printing; however, the IR output is most often relay-imaged at the center of a single-harmonic generating crystal (SHG) to produce a green output wavelength (532 nm or 527 nm.)



A High Energy DPSS Laser Build in Progress

In-situ diagnostic capabilities such as cameras and monitors for beam profile, pulse energy and temporal profile are included in the laser system when required. An electronics rack contains all of the laser diode drivers, power supplies, component and system controllers, timing units and control electronics required for each laser system. The system is controlled with a Graphical User Interface (GUI) designed to enable intuitive laser start-up and operation, along with integrated laser 'health and safety' features that monitor the laser's health and prevents the input of any operational parameters that might harm the laser and/or reduce its reliability and lifetime.

MOPA

CEO'S STANDARD DPSS HIGH ENERGY LASERS utilize a master oscillator power amplifier (MOPA) system architecture. This configuration is typically used when pulse widths are >10ns and/or the beam quality requirement is straightforward. It is also more cost-effective when compared to the other options presented below. The master oscillator uses a stable resonator design well-suited for TEM_{00} operation. DPSS laser modules are used both in the cavity itself and in one or more pre-amplifiers after the output of the oscillator. The specific laser modules (*i.e.* rod sizes, laser diode pump power) and their operational parameters are chosen based on the overall requirements of the laser system, and typically include one or more 2-3 mm rod-sized modules in the oscillator cavity. The high gain in the pre-amplifier(s) are susceptible to amplified spontaneous emission (ASE), which limits the maximum gain. A block diagram of a typical MOPA laser system is shown in **Figure 1** below.

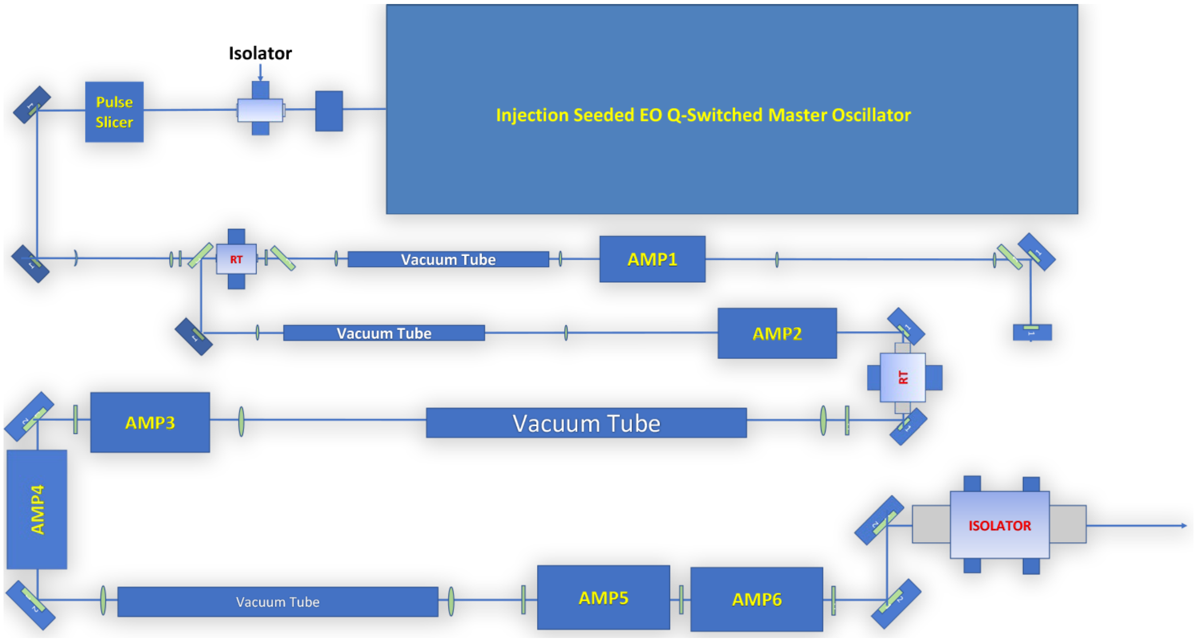
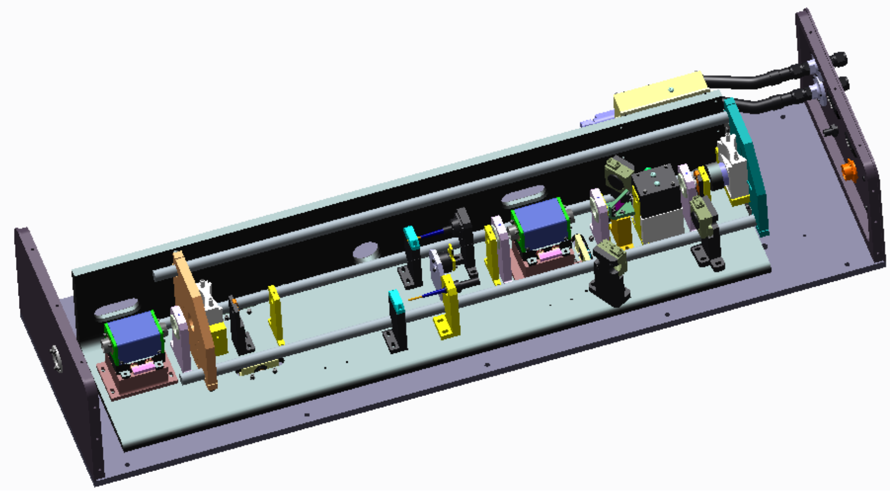


Figure 1. Diagram of Typical High Energy Laser with MOPA Configuration

Injection-Seeded Master Oscillator

WHEN REQUIRED, THE CAVITY IS INJECTION-SEEDED with a CW single wavelength fiber laser to generate single longitudinal mode output enabling smooth, Gaussian temporal profiles and short delay times for low jitter (<1ns). In injection-seeded lasers which utilize Nd:YLF as the gain medium, C-cut crystals are typically employed in the master oscillator to avoid gain spatial hole burning effects, and the light in the Nd:YLF rod is circularly polarized.



Example Injection-Seeded EO-QS TEM$_{00}$ Mode Oscillator with Preamplifier

The temporal profiles of the output laser pulse from a typical oscillator are shown in **Figures 2** and **3**. Injection seeding enables the laser to have a smooth temporal profile and short delay time. Jitter with respect to an external trigger is typically <1ns, and long term (>24 hrs) pulse energy stability of the oscillator is <0.25% RMS.

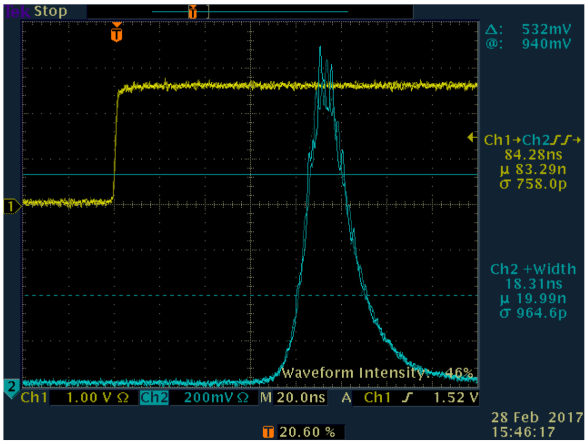


Figure 2. Temporal Profile without Injection Seeding

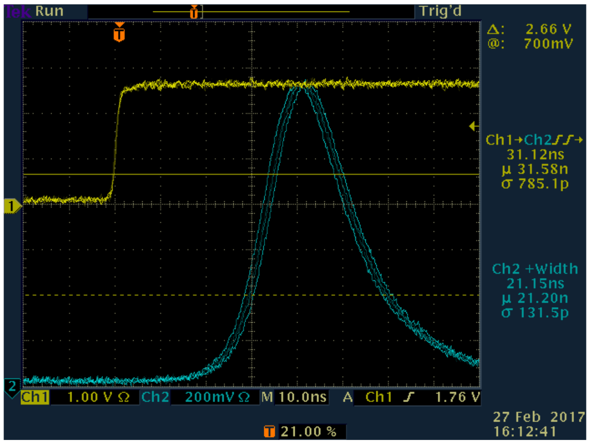


Figure 3. Temporal Profile with Injection Seeding

FFE + AWG + Regenerative Amplifier

IF VARIABLE PULSE WIDTHS, improved beam quality, and/or higher conversion efficiencies are required, an alternative laser configuration is employed; one that uses a single wavelength, CW fiber laser front end (FFE) along with an arbitrary waveform generator (AWG) for temporal pulse shaping. Using an AWG also enables the jitter to be reduced to ~25ps. A regenerative amplifier is added after the FFE + AWG to increase the pulse energy before launching into the power amplifiers. One advantage of using a regenerative amplifier is that ASE is not an issue, which enables excellent beam quality and thus higher conversion efficiency. However, longer pulse widths (>10ns) are not feasible with regenerative amplifiers, thus high energy oscillators or pre-amplifiers are used as alternatives. In some applications, a ring amplifier is used in place of a traditional power amplifier chain. A description of the AWG technology and its performance advantages are included later in this paper, along with details of these high energy laser components.

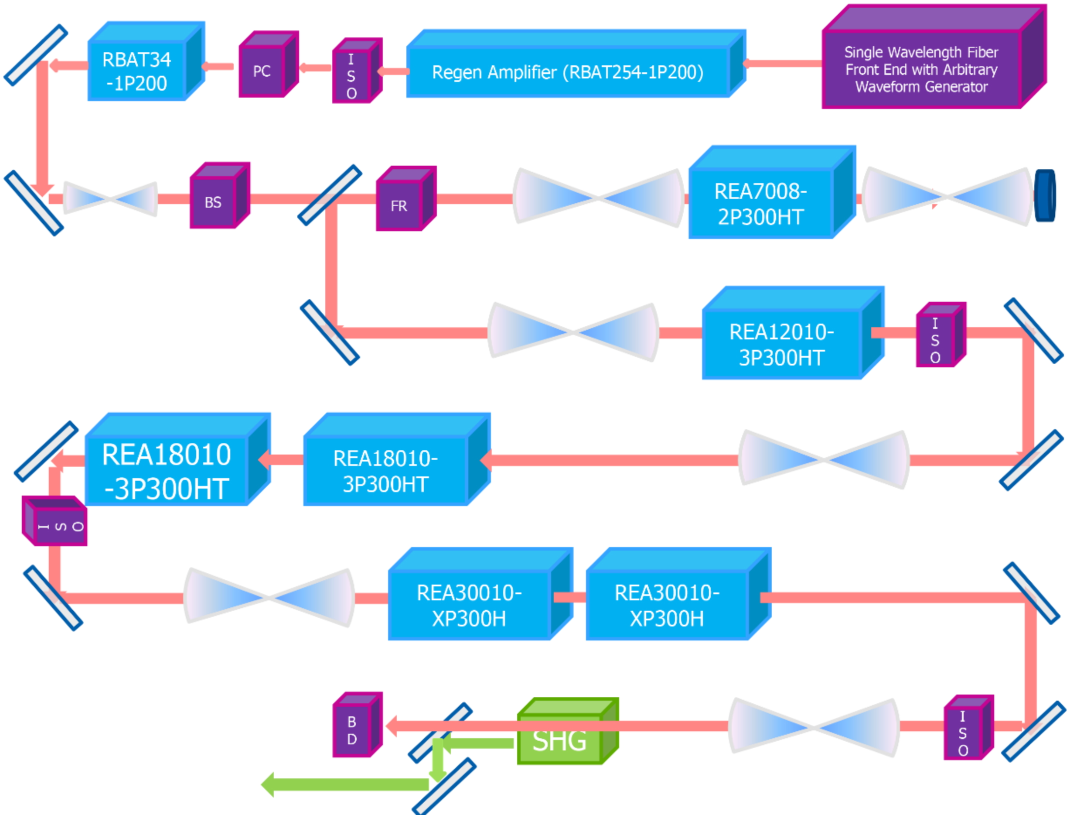
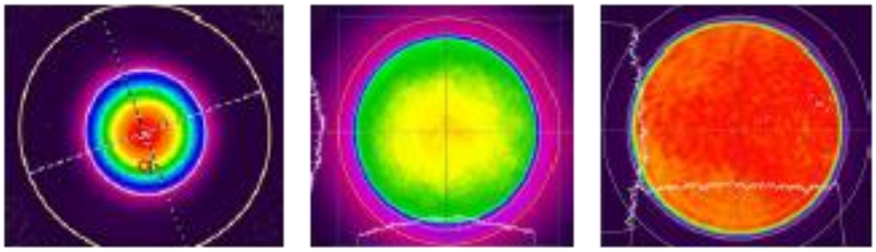


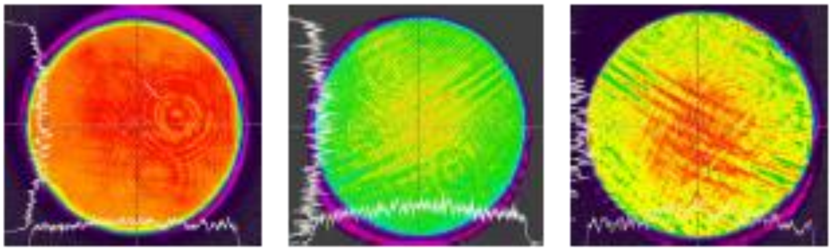
Figure 4. Example High Energy Laser Design with FFE + AWE + Regenerative Amplifier

Beam Shaping / Beam Profile

A BEAM SHAPER, TYPICALLY CONSISTING OF AN APODIZER, is used to spatially-select the center portion of the Gaussian beam and generate a flat top beam profile. This smooth flat top beam is relay-imaged to the center of each power amplifier module. The beam is expanded appropriately to fill the rod to the correct diameter in each amplifier to produce optimal beam uniformity and gain while preventing diffraction effects. Beam uniformity is additionally optimized through careful attention to the laser diode pump architecture in each amplifier module along with temperature tuning the pump diode wavelengths.



Oscillator AMP1 Input AMP2 Input



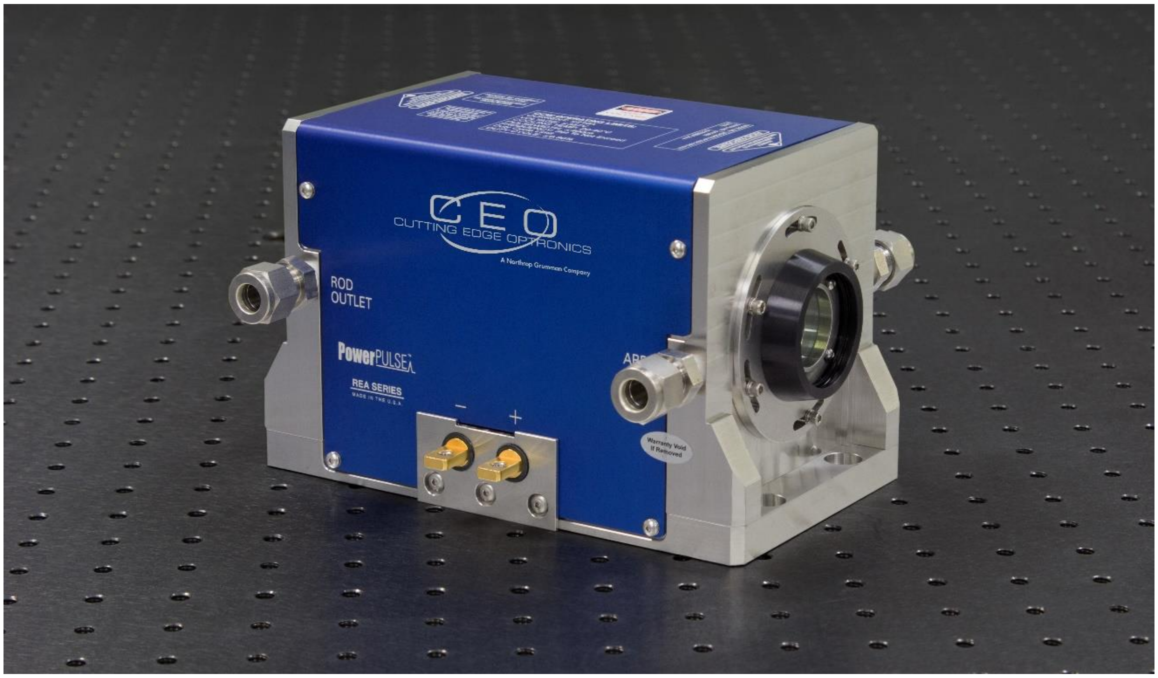
AMP3 Input AMP5 Input Output 527nm

Beam Profiles at Various Points in a High Energy 527nm Laser

If the absolute best possible beam quality is required (e.g. M2<2 and/or <15% RMS modulation over 80% of the beam) in the output of a high energy laser system, further optimization is possible by paying close attention to laser system alignment, the use of low wavefront distortion mechanical mounts, and (in the case of Nd:YLF) magnetorheological finishing (MRF) of the laser rod surfaces. The latter significantly improves transmitted wavefront error (TWE) and results in superior beam quality.

DPSS Laser Amplifier Modules

LARGE LASER AMPLIFIER MODULES enable high pulse energy output. Nd:YAG and Nd:YLF are excellent laser crystals for high energy DPSS lasers due to their robustness, availability and optimal pump and output wavelengths. Each gain medium has its advantages and disadvantages. While Nd:YAG is more robust and homogeneous, and its high stimulated emission cross section results in low stored-energy density adequate for high frequency operation, its poor performance under high thermal load (thermal lensing and thermally induced stress birefringence) limits its achievable maximum average output power.



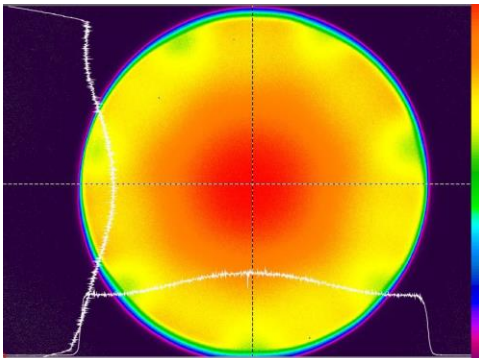
25.4mm Diameter Nd:YAG Amplifier Module

Nd:YLF's high saturation fluence (low-gain cross section) allows high laser fluence while minimizing pulse distortion. It has a relatively weak thermal astigmatism as well. However, its poor transmitted wavefront quality and low thermal fracture limit are disadvantages that must be addressed. In the design of large diameter high energy Nd:YLF amplifiers, CEO employs the use of MRF on the laser crystals in order to minimize TWE. Large TWE can negatively impact beam quality and subsequent SHG conversion efficiency (as well as efficiencies in Ti:S, OPA and OPCPA pumping.) MRF enables higher energy pulses, higher repetition rates, and thus, higher average power. Pairs of modules with increasingly larger A-cut rods are used further downstream to amplify the light, with the crystal axes in each pair arranged orthogonally to minimize thermal birefringence distortions.

CEO's DPSS amplifier module design is a culmination of decades of experience designing and manufacturing tens of thousands of gain modules for industrial, scientific, and military/aerospace applications. Available rod diameters range from 2mm to 30mm with pump laser diode bar counts between 9 and >500 in a single high energy laser amplifier module.

DPSS Laser Modules

The most important performance requirement of a high energy laser amplifier is gain uniformity, which impacts everything from the maximum pulse energy (gain) to beam quality (beam profile, beam uniformity, conversion efficiency), and stability (pointing, pulse energy, long term). Each of CEO's amplifier modules is designed with the ultimate laser performance and end application in mind. The peak power and total number of pump laser diode bars, their position around the laser rod, their center wavelength distribution under the module's operating conditions and the margin for reliable operation over the lifetime of the laser are all factors taken into account when designing an amplifier module. Great care is taken in the module design to ensure that crystal fracture limits are not exceeded. Because CEO manufactures the pump laser diodes in-house, complete control over the module's design and manufacture is maintained in the same location where the entire laser system is built.



Fluorescence Profile of a 22mm Diameter Nd:YLF Module

The uniformity of the laser output flat-top beam is determined by the gain uniformity and stored energy of the power amplifier chain and the output fluence profile of the laser beam.

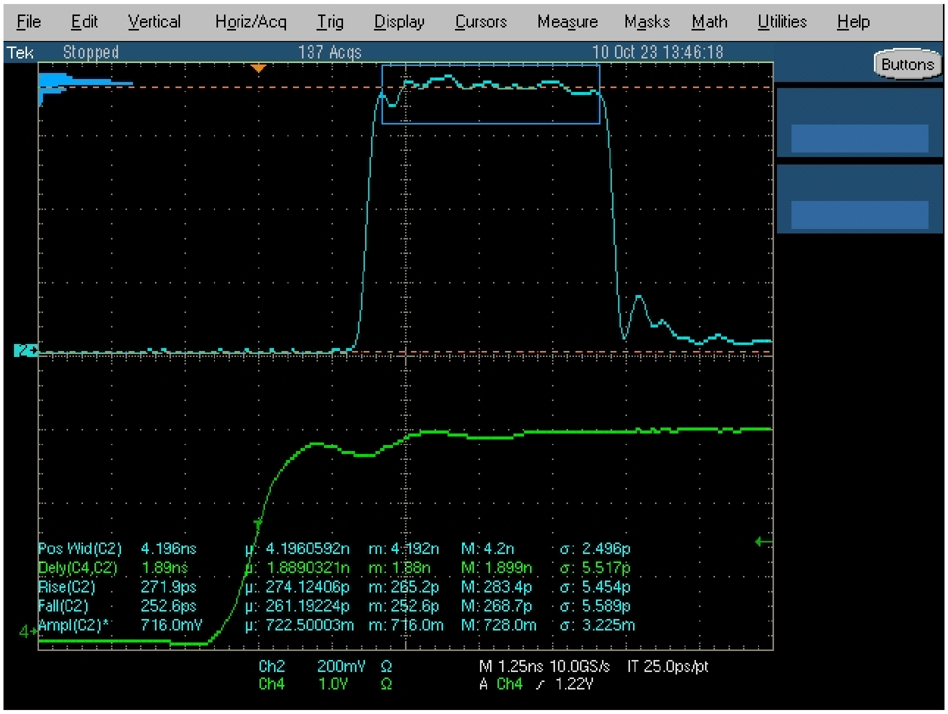
Second Harmonic Generation

WITH THIS UNRIVALLED UNIFORMITY across the beam profile, very high conversion efficiencies in second harmonic generation (SHG), as well as in Ti:S. OPO, OPA, and OPCPA pumping, can be achieved. The beam exiting the power amplifier chain is reduced and relay-imaged at the middle of the SHG crystal (LBO, KTP or other type depending on the system requirements) to ensure good SHG conversion efficiency. The crystal is housed in a temperature-controlled mount, with the temperature tuned for optimal phase matching. The excellent flat-top beam profile with good beam quality, a square temporal pulse profile and a highly linearly polarized beam combine to achieve SHG conversions of 70%-80% at high (> 11J) IR input pulse energies. An SHG conversion of 80% was attained in the CPL-070-QSF, a 7J, 10Hz, 527nm laser described below.

Temporal Pulse Shaping

IT IS OFTEN A REQUIREMENT of a high energy laser system to have a square (or other) shaped temporal pulse with very specific modulation as well as tailored rise and fall times. An additional or stand-alone requirement for very low jitter with respect to the input trigger signal is often specified. Both of these requirements can be achieved with careful use of an arbitrary waveform generator (AWG) in combination with the fiber seed laser and low-jitter timing units.

In the power amplifiers of high energy lasers, the front portion of a laser pulse ‘sees’ more gain than the back portion of the pulse, resulting in temporal pulse profile distortion. To obtain a flat-top (square), or any other temporally shaped pulse at the laser output, the temporal shape of the input pulse must be pre-compensated for the distortion through amplification. This distortion is related to the saturation energy fluence, which is determined by the gain medium. With the saturation energy fluence of Nd:YLF being roughly double that of Nd:YAG, Nd:YLF is a preferred gain medium in most high energy lasers. The higher output energy fluence is preferred for high extraction efficiency, however this results in high temporal distortion. Peak power density must also be considered, and trade-offs are studied during the design phase. With properly tailored temporal pulse shaping of the input pulse, the desired output pulse shape can be achieved, along with very low jitter. The timing synchronization between the pump laser diode currents for the amplifier modules and the seeder injection pulses is critical. Temporal pulse profile monitors provide good references to ensure optimal performance. The square temporal pulse of a 9J, 1053nm laser is shown in **Figure 5**.



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Pos Wid(C2)   4.196ns    µ: 4.1960592n   m: 4.192n   M: 4.2n      σ: 2.496p
Dely(C4,C2)   1.89ns     µ: 1.8890321n   m: 1.88n    M: 1.899n    σ: 5.517p
Rise(C2)      271.9ps    µ: 274.12406p   m: 265.2p   M: 283.4p    σ: 5.454p
Fall(C2)      252.6ps    µ: 261.19224p   m: 252.6p   M: 268.7p    σ: 5.589p
Ampl(C2)*     716.0mV    µ: 722.50003m   m: 716.0m   M: 728.0m    σ: 3.225m

              Ch2   200mV  Ω          M 1.25ns 10.0GS/s   IT 25.0ps/pt
              Ch4   1.0V   Ω          A  Ch4  ⟋  1.22V
```

Figure 5. Square Temporal Profile of a 9 J, 1053 nm Laser Pulse

Pulse Energy Stability

A 100% DIODE-PUMPED LASER SYSTEM offers unparalleled pulse energy stability and beam pointing stability. This is because of the rock-solid performance of the pump laser diodes over 10’s of billions of shots before any noticeable degradation might require a slight change in operating parameters. Even with this very low, slow degradation, DPSS laser system performance remains stable over days, months, and even years of operation depending on utilization and repetition rate.

Short term pulse energy stability, defined as a time duration of 20 seconds, is readily specified as < 4% peak-to-valley and < 1% RMS.

Long term energy stability (≥ 1 hr) is typically < 1% RMS. **Figure 6** shows the long term stability of a 7J, 4ns, 527nm laser over 10 hours, at 0.45% RMS.

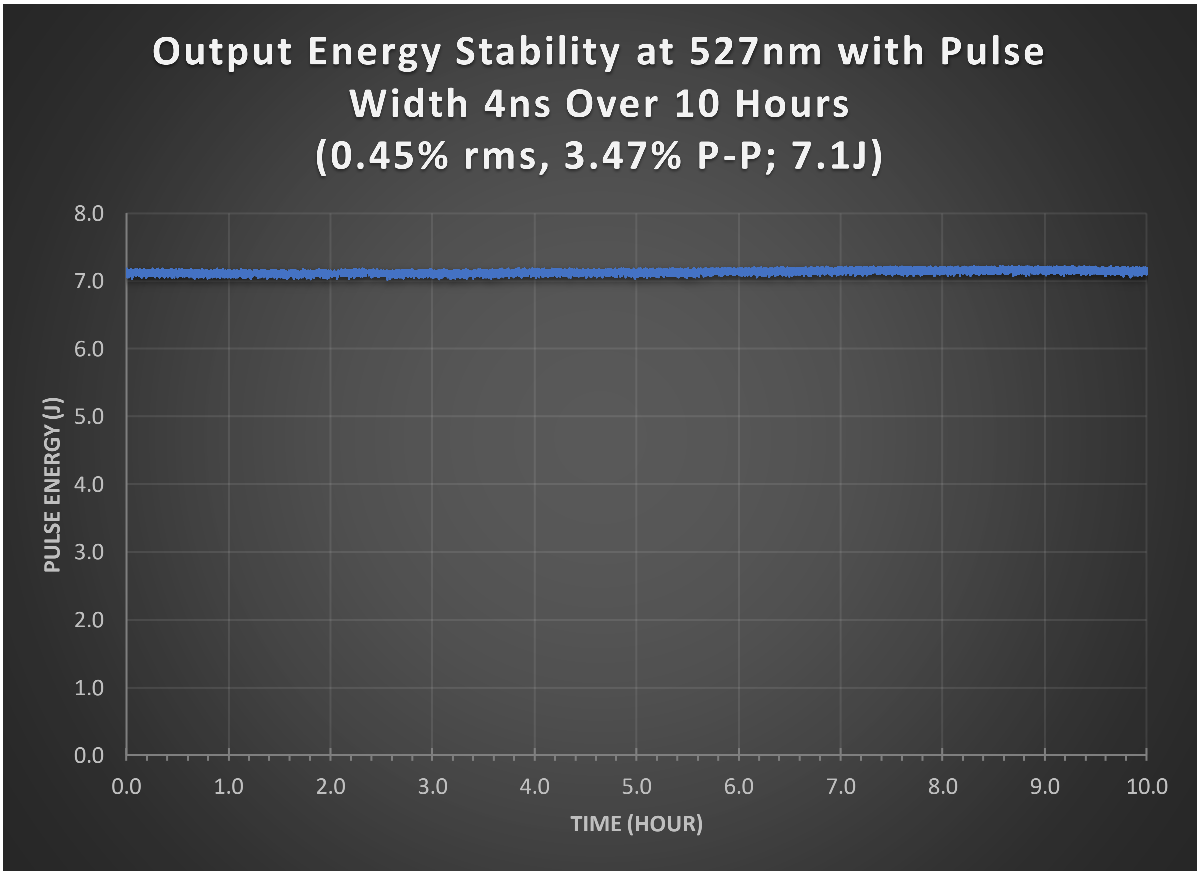


Figure 6. Output Energy Stability at 527nm with Pulse Width 4ns Over 10 Hours

Beam pointing stability of 25 µrad (rms) is typical over 30 minutes, and beam modulation can be less than 13% rms over the beam size containing 90% of the pulse energy at the image plane.

The warm-up time is less than 30 minutes, with mean-time-to-realignment (MTTR) on the order of months (and often years.)

Drive Electronics

eDrive Laser Diode Drivers

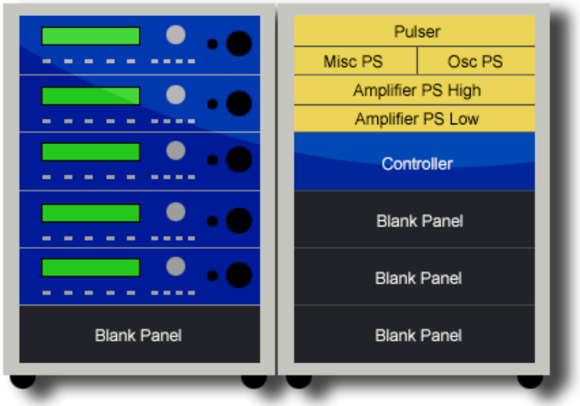
CEO DESIGNS AND MANUFACTURES LASER DIODE DRIVERS that manage all critical DPSS laser parameters including diode drive current and Q-switching. CEO's eDrives are coupled with DC power supplies that provide current and voltage to each laser module within the system. Current and duty cycle limits, shutter control, safety interlocks, Q-switch and thermal electric cooler drivers, external triggering and timing synchronization outputs are all incorporated into the eDrives, and utilize digital remote control through a customized Graphical User Interface (GUI).

Some high energy DPSS laser systems contain multiple large (18-30 mm dia) amplifiers with a significant number of pump laser diode bars requiring many diode drivers. These systems benefit from CEO's DC2P dual-channel driver, which reduces overall system complexity and cuts the required electronics rack space in half. Each of the two channels in a single, 2U DC2P driver delivers up to 300A current pulses and supports loads of up to 365V (~165 laser diode bars.)

This simplifies overall laser system architecture, with communication that utilizes the Telnet protocol over TCP, with built-in safety features to protect the laser if communication is lost. AC input power and Ethernet network connection is shared between the channels in a single unit, with each channel independently controlled and triggered for fine-tuning of each module's performance and timing within the laser system.

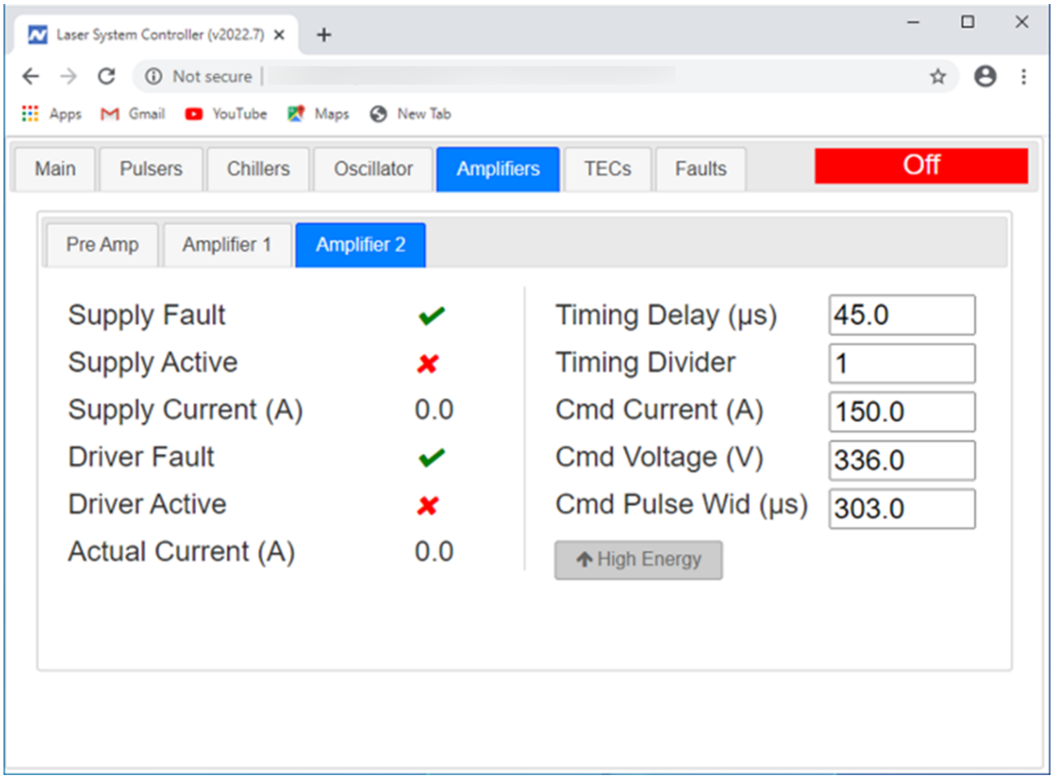
DC2P Dual-Channel Driver

System Control



Typical Control Electronics Rack

THE ELECTRONICS SUBSYSTEM consists of a turn-key equipment rack populated with eDrives, power supplies, a system controller, and a timing unit. The timing unit provides synchronized timing sequences for the individual pumping currents (via the eDrives), and receives its trigger input from the facility timing system. The system controller houses the SHG controllers, power control, interlock and emergency stop systems, shutter control system, and the control computer. The control computer provides all laser system management functions through an intuitive GUI that utilizes a tabbed design to group controls and indicators by function. The GUI is accessed by a laptop computer or other device. An example GUI screen is shown in **Figure 7** below.



Supply Fault ✓
Supply Active ✗
Supply Current (A) 0.0
Driver Fault ✓
Driver Active ✗
Actual Current (A) 0.0

Timing Delay (µs) 45.0
Timing Divider 1
Cmd Current (A) 150.0
Cmd Voltage (V) 336.0
Cmd Pulse Wid (µs) 303.0

Figure 7. Example Web-Based High Energy Laser Control Screen

Thermal control and heat removal from the laser is accomplished through temperature-controlled coolant supplied from a closed-loop, recirculating chiller system. The coolant can either be distilled water with an additive (e.g. Optishield), or a specific mixture of ethylene glycol/distilled water/Optishield.

Diagnostics and Remote Service/Support

SEVERAL DIAGNOSTIC CAPABILITIES are contained in the laser system to monitor performance and health. Additional diagnostics can be included per the end user's requirements, or room for them left available for installation post-delivery by the end user. These include, but are not limited to a variety of cameras, energy meters and temporal profile monitors, which can all be communicated with through the GUI and controlled by the laser system controller.

The laser system can be accessed through the control computer, either locally onsite or remotely over the internet. This enables diagnostics monitoring and laser system parameter changes remotely by operators or CEO's technical resources, with permission and access given by the end user. In the unlikely event that service and/or support are required, this capability often precludes the need for on-site support, and the laser system can be returned to full performance in real time.

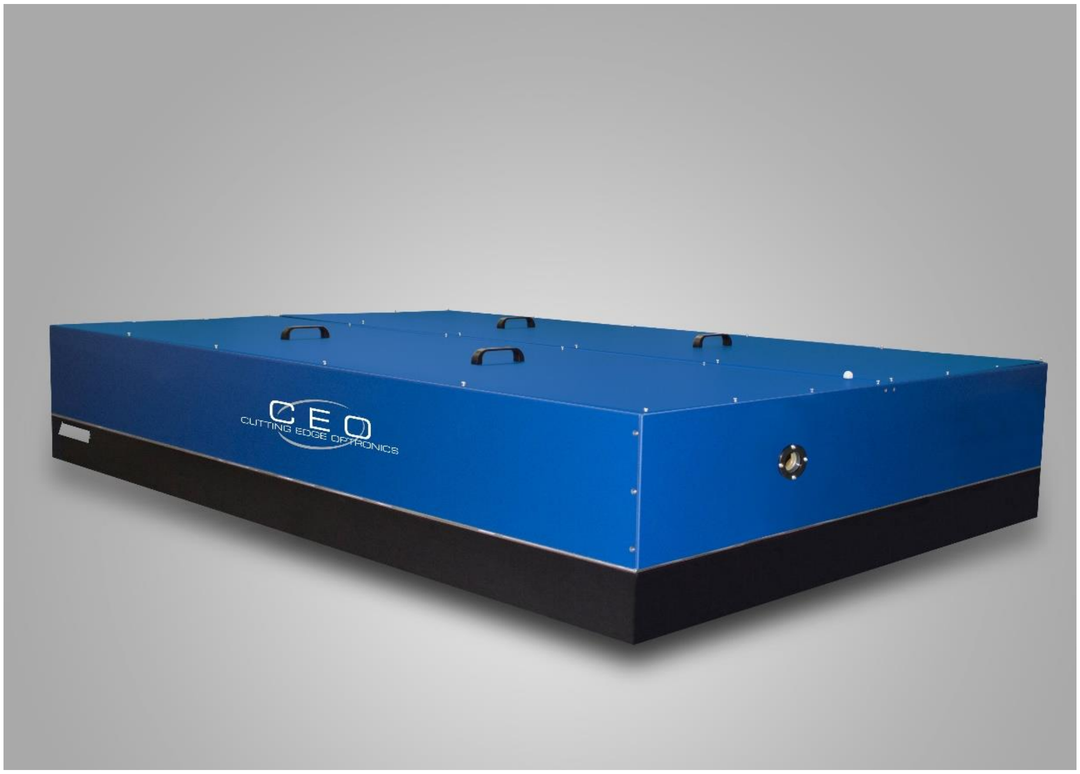
Dr. Faming Xu (Left) and Joe Redding Put the Finishing Touches on a 5J 527nm Laser Prior to Shipment.

High Energy Laser Systems Manufactured by CEO

CEO HAS DESIGNED AND DELIVERED SEVERAL high pulse energy laser systems (HELS) which are currently in use around the world for a variety of scientific and industrial applications. Example laser systems are described in detail below.

CPL-020-QSG

ONE OF THE FIRST HELS THAT CEO DELIVERED IS A 2J, 10HZ, 532NM pump laser for Lawrence Livermore National Laboratory (LLNL). It is used in their High-repetition-rate Advanced Petawatt Laser System (HAPLS) as a pump laser for their Ti:Sapphire CPA. LLNL incorporated this pump laser into the HAPLS in California before shipping the entire system to the European Union's Extreme Light Infrastructure (ELI) Beamlines high-intensity laser science facility outside of Prague, Czechia. The CPL-020-QSG was fully commissioned in the HAPLS at ELI Beamlines in 2018 and has been operational ever since with very little realignment necessary between shipments from CEO to LLNL to Czechia, or thereafter.



CPL-020-QSG: 2J, 10Hz, 532nm

Additional information about this pump laser, HAPLS, and ELI Beamlines can be found in these links:

https://cuttingedgeoptronics.com/2015/02/05/ceo-laser-installs-joule-class-laser-llnl/

https://www.eli-beams.eu/facility/lasers/laser-3-hapls-1-pw-30-j-10-hz/

CPL-210-QSH

This laser is a 10J, 20Hz, 1053nm commercial system for laser shock peening applications. CEO has supplied several of these lasers over the past decade to LSP Technologies Inc for use in the laser peening industry. These lasers are in use on three different continents around the world and typically produce ~11J when shipped from CEO. There is significant margin in the design and operation of the laser such that this pulse energy can be maintained for years with little required but simple routine maintenance.

Additional information about the installation of the first of these lasers can be found at this link: **https://cuttingedgeoptronics.com/2015/05/01/ceo-installs-10-joule-laser-at-lsp-technologies/**

Figure 8 below is a picture of a 10J peening laser prior to shipment. The laser is built on a 4’ x 6’ optical table which is inserted into a customer-supplied enclosure. The entire system is designed to be used in a manufacturing environment.

Figure 8. CPL-210-QSH: 10J, 20Hz, 1053nm

The datasheet for this laser system can be found here:

https://cuttingedgeoptronics.com/dpss-lasers/qs-10000-qmi-pulsed-laser-system/

GS-025-QTG

CEO SUPPLIED A 0.5J, 50HZ, 532NM laser system to an international university in Asia. This laser is used for Ti:S CPA pumping. The scientists using this system have published several papers on their investigations with the lasers system utilizing this pump laser.

GS-025-QTG Laser

A similar, higher average power laser system was delivered to a US university for use as a Ti:S CPA pump laser. The **CPL-040-QSF** produced 40W, 4J, 10Hz, 532nm.

CPL-025-QSF

THIS 5J, 5HZ, 527NM LASER SYSTEM WAS MANUFACTURED BY CEO with a variable, 1-5ns, square-shaped temporal pulse. It was delivered to the University of Rochester's Laser Laboratory for Energetics (LLE) for use in their FLUX CLARA (Crystal Large-Aperture Ring Amplifier) laser. CEO's pump laser integrates a seed laser provided by LLE and employs LLE's CLARA architecture in the power amplifier.

CPL-025-QSF Ready for Shipment

Additional information can be found at this link:

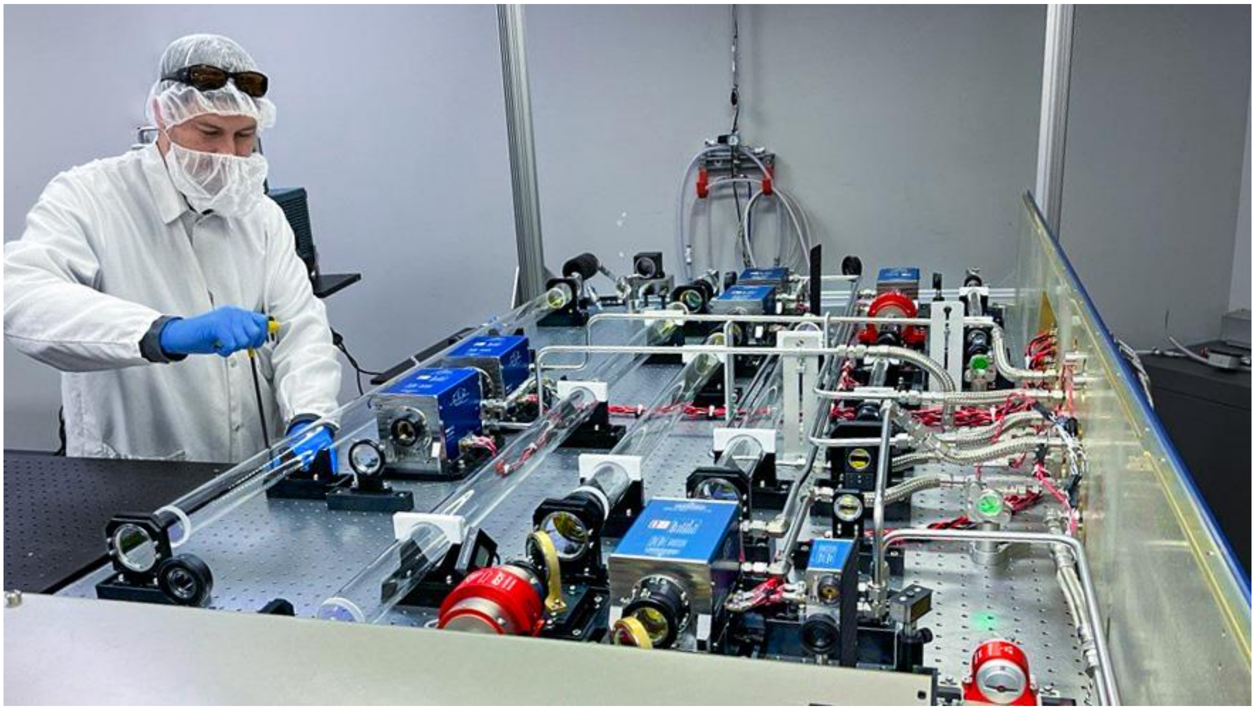
https://www.lle.rochester.edu/the-fourth-generation-laser-for-ultra-broadband-experiments-flux/

CPL-070-QSF

CEO IS CURRENTLY BUILDING A 7J, 10HZ, 527NM LASER SYSTEM for use as an OPCPA pump laser for a petawatt system produced by the United Kingdom's (UK) Central Laser Facility's (CLF) Rutherford Appleton Laboratory (RAL). The RAL petawatt laser will be used in the UK's new Extreme Photonics Applications Center (EPAC). This all diode-pumped, 7J / 70W laser is the highest green pulse energy and average power laser produced by CEO to date. It incorporates almost every high energy laser technology that CEO has developed thus far; including:

- **25.4mm Nd:YLF amplifier module**
- **MRF of Nd:YLF laser rods**
- **Pulse-shaping with FFE + AWG**
- **Superior beam quality**
- **80% SHG conversion**
- **Advanced system diagnostics**
- **Sophisticated control software and GUI**

This laser system will be delivered to RAL in early 2024.



Dustin Garrett Adjusts the Alignment of the CPL-070-QSF

Information about EPAC can be found in this link:
https://www.clf.stfc.ac.uk/Pages/EPAC-introduction-page.aspx

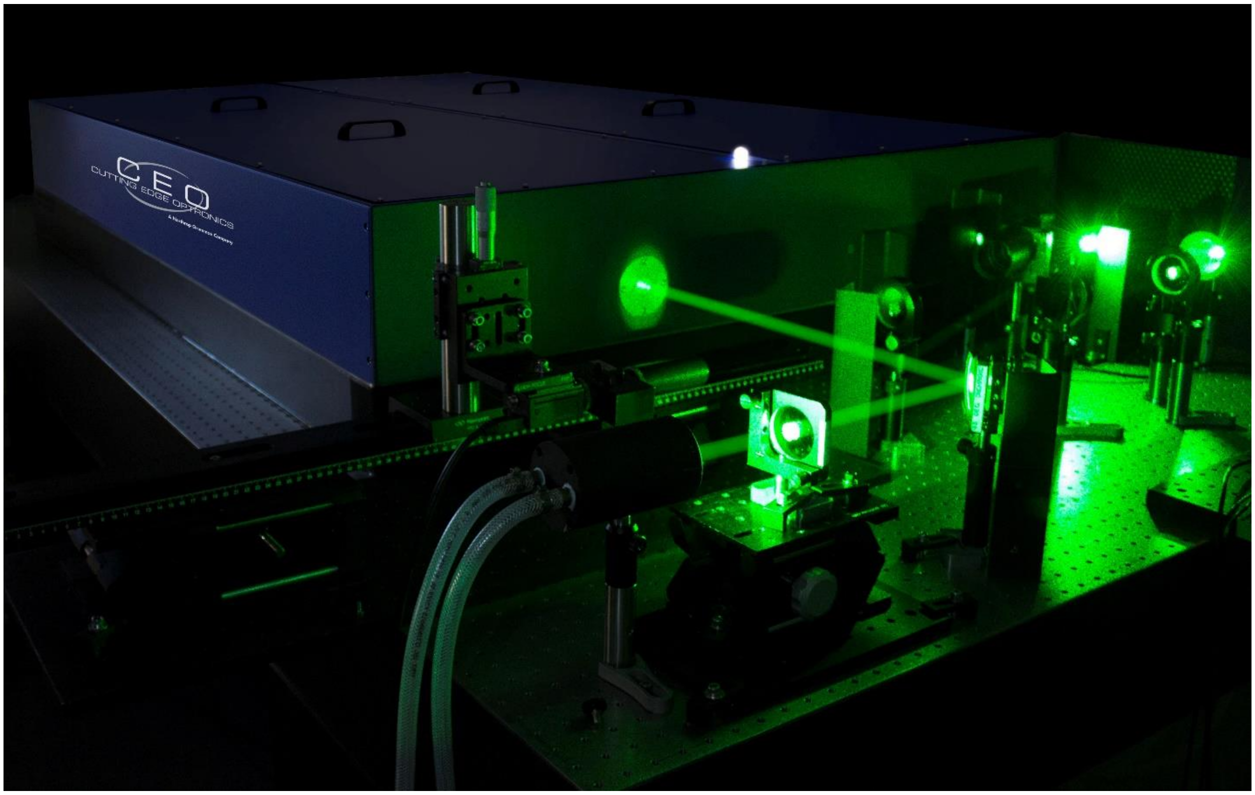
Conclusions

CUTTING EDGE OPTRONICS HIGH ENERGY LASER SYSTEMS are installed and operating in commercial and scientific facilities worldwide in applications varying from metals manufacturing to OPCPA pumping and high-density plasma physics research. These lasers are 100% diode-pumped and incorporate pump laser diodes, DPSS oscillator and amplifier modules, drive electronics, system controllers and GUIs developed and manufactured at CEO's St. Charles, MO facility. CEO is uniquely positioned to offer both the optimal laser design architecture and the manufacturing flexibility to produce the most critical components in-house to support a variety of laser system outputs and performance parameters.

Each of CEO's laser system designs and performance has advanced from the experience gained from the laser that preceded it. What began as a 2J, 532nm (20W) Ti:S pump laser with a Gaussian temporal profile has expanded to a 7J, 527nm (70W) OPCPA pump laser with a square-shaped temporal pulse and 80% SHG conversion efficiency.

Several different 'front end' options for how the first photons are produced, shaped and amplified through the rest of the optical system are described above. System output energies range from 0.5J to 10J, with average output powers of 20W to 200W, repetition rates from 5 Hz to 50 Hz, and output wavelengths in both green and infrared.

CEO's diode-pumped solid-state high energy laser systems enable extremely stable, reliable and long-lived performance over the lifetime of the application.



LLNL 2J 10Hz 532nm Pump Laser in Action