Conf-9404162--13

UCRL-JC-118148
PREPRINT

High Average Power Diode Pumped Solid State Lasers for CALIOPE

B. Comaskey
J. Halpin
B. Moran

This paper was prepared for submittal to the
Proceedings of the 1994 CALIOPE ITR Conference
Livermore, California
April 26-28, 1994

July 1994

Lawrence Livermore National Laboratory

HIGH AVERAGE POWER DIODE PUMPED SOLID STATE LASERS FOR CALIOPE

B. Comaskey, J. Halpin, and B. Moran
Lawrence Livermore National Laboratory, P.O. Box 808, L-495, Livermore, CA 94551

Abstract. Diode pumping of solid state media offers the opportunity for very low maintenance, high efficiency, and compact laser systems. For remote sensing, such lasers may be used to pump tunable non-linear sources, or if tunable themselves, act directly or through harmonic crystals as the probe.

The needs of long range remote sensing missions require laser performance in the several watts to kilowatts range. At these power performance levels, more advanced thermal management technologies are required for the diode pumps. The solid state laser design must now address a variety of issues arising from the thermal loads, including fracture limits, induced lensing and aberrations, induced birefringence, and laser cavity optical component performance degradation with average power loading.

In order to highlight the design trade-offs involved in addressing the above issues, a variety of existing average power laser systems are briefly described. Included are two systems based on Spectra Diode Laboratory's water impingement cooled diode packages: a two times diffraction limited, 200 watt average power, 200 Hz multi-rod laser/amplifier by Fibertek, and TRW's 100 watt, 100 Hz, phase conjugated amplifier. We also present two laser systems built at Lawrence Livermore National Laboratory (LLNL) based on our more aggressive diode bar cooling package, which uses microchannel cooler technology capable of 100% duty factor operation.

We then present the design of LLNL's first generation OPO pump laser for remote sensing. This system is specified to run at 100 Hz, 20 nsec pulses each with 300 mJ, less than two times diffraction limited, and with a stable single longitudinal mode. The performance of the first testbed version will be presented. We conclude with directions our group is pursuing to advance average power lasers. This includes average power electro-optics, low heat load lasing media, and heat capacity lasers.

Introduction

Laser based remote sensing in the field puts severe constraints on the laser probe source. A moving or at least transportable system must be mechanically robust and ultra stable. Spectroscopic requirements demand tunability and narrow frequency bandwidth operation which in turn magnify the mechanical stability requirements and frequently reduce the wall plug efficiency of the laser (more cavity losses, reduced laser mode/gain media overlap, spatial hole burning effects, etc.). Such a system must be very low maintenance, capable of compact packaging and exhibit the highest possible electrical to optical efficiencies to allow the laser platform to dwell at its observation positions. The operation and control of such a system must ultimately be made turnkey for any serious application to a remote sensing scenario. What makes this application particularly more challenging than most presently fielded laser systems are the power performance requirements. In order to obtain useful standoff distances and high statistical averaging for minimum observation dwell time, the laser system will have to operate at average power levels ranging from tens of watts up to kilowatt levels. At these power levels thermally induced effects in the laser complicate all the above issues.

Diode lasers are by far the most efficient, compact, rugged, and easy to operate laser systems. However, suitably powerful and efficient yet narrow line and tunable diode lasers are not available or foreseen in the reasonable future. The next most compact and rugged technology is the solid state crystal laser. In combination with harmonic, mixing, and OPO crystals, UV through mid-IR is obtainable today. Such lasers can be pumped by flashlamps, cw arc lamps, diode lasers, and other laser systems. To optimize efficiency, ruggedness, and minimize deleterious thermal effects and maintenance requirements, laser diode pumping must be chosen. A large variety of diode pumped solid state lasers are available today; however, the high average power regime is only now developing. In this paper we will briefly discuss this developing field of solid state lasers and leave for a following paper[1] a discussion of the non-linear crystal technology that it will be coupled to in the remote sensing application.

The High Average Power Lasing Regime

In this paper we define a high average power laser as a laser system whose design and operational characteristics are driven by the thermally induced effects resulting from its operation. This concern for the consequences and control of the thermal heat load is the continuing theme throughout this paper. This regime presents an entirely separate set of problems in addition to the usual laser dynamical and cavity concerns. In this regime, optimum laser cavity or media choices can be very different from low repetition rate cases. Both the solid state laser and its laser diode pumps will be operating within this regime.

High Average Power Laser Diodes

Diode pumping of solid state media has clear advantages over lamps with respect to rugged packaging, weight reduction, and operational life (10,000 hours versus 100–600 hours). These advantages are similar to the advantages that the transistor brought to the vacuum tube electronics world. In high average power solid state lasers more advantages accrue to diode pumping because of system and crystal thermal load issues. Xenon flash lamps actually have higher electrical to optical efficiencies than laser diodes (70% versus 35–50%). However, while nearly 100% of the diode emission can be absorbed in the laser crystal, only a small fraction of the lamp blackbody spectrum is utilized. Hence, system efficiencies are much higher under diode pumping resulting in smaller power supplies and cooling systems. Another very critical thermal aspect is the difference in the nature of the absorbed pump light. As seen in Figure 1 for the case of Nd:YAG pumping, the mean energy defect for Xenon lamp absorbed photons and even those of the weaker cw spectral line krypton lamp source are considerably larger than that which can be obtained by pumping a properly selected single absorption feature via laser diodes. This further system efficiency advantage for diode pumping represents a significant reduction in the induced heating in the solid state laser gain media.

At average power operation of the solid state laser's pump laser diodes, thermal management of their waste heat is critical in order to maintain diode junction temperatures. Elevated junction temperatures reduce device efficiency and shorten component life. Without temperature stability, matching the spectral output of the diodes to the absorption features (a few nanometers in Nd:YAG) would be unlikely given the junctions spectral-thermal sensitivities (0.3 nm/C).

Table 1 lists the present status for available high average power laser diode pump technology, and Figure 2 illustrates the hardware. The laser diode array system is based on the efficient heat conduction of BeO. This material is slotted to a density of up to 30 cuts per centimeter and diode bars are soldered in each slot. The BeO mount may then be mounted to a convenient heat sink. Stable pulsed performance of order 100 Hz is obtained with this system. The SDL product is the most commercialized product. It is also relies on high bulk heat conduction, in this case copper, and incorporates a simple copper to water impingement cooler. The basic unit of construction is a 1 cm diode bar carrier which is permanently assembled at the factory into stacks. This technology stacks up to 10 bars per centimeter and operates routinely up to 3% duty factor and total stack peak powers of 5 kW. Special high repetition rate systems (up to perhaps 20% duty factor) with densities up to 5 bars per centimeter are now a special order item. LLNL has the most aggressively cooled (0.035 C/(watt-mm^2)) diode bar cooling package technology. After four years of production the lab is delivering a fifth generation microchannel water cooled silicon/glass composite package. The 2 cm by 2 cm diode bar package is stackable to a pitch of 10 bars per centimeter. Stacks as large as 120 packages have been built producing peak powers of 12 kW. Pulsed duty factors of 34% were used in a kilowatt solid state laser demonstration. Recently diode and package performance has been extended to 100 watts (average) per centimeter of diode bar[2] (Figure 3). The bottom of the top silicon package section is etched with microchannels. These are typically 150 microns deep on 25 to 50 micron centers with the channels 1 mm long. The channel passages are etched along 1.8 cm of one edge of the top section. Diode bars mount directly over this microchannel zone with the P side down (the heat source). Though silicon has inferior thermal conductivity to copper and BeO, the semiconductor processing technology used in producing the microchannels is very mature resulting in precise, repeatable, and stable devices. The thinness of the top silicon sheet and the efficiency of microchannel cooling more than compensates for the thermal conductivity deficit. The stacks are assembled using thin conductive rubber gaskets. If a package fails, the stack may be broken apart and rebuilt with a replacement package. The Fraunhofer group at Aachen has recently described their developments in microchannel cooled laser diode bar packaging.[3] Their technology is based on five piece copper construction resulting in 1 cm wide packages stackable to 5 bars per centimeter with best performance to date of 71 watts per centimeter. Their technology is first generation so that microchannel aspect reproducibility and stability are yet to be established.

Laser Diode Array Inc.	BeO 20/cm arrays Cylindrical microlenses Good to ~ 100 Hz
SDL	Impingement cooled packages Developing doublet microlenses 3% duty factor with low density versions to 20%
LLNL	Microchannel cooled packages–fifth generation Micro-aspheric lenses Up to 100 watt/cm
Fraunhofer Institut Für Lasertechnik	Developing microchannel cooled packages on Cu Up to 71 watt/cm

Table 1. Average power diode package sources.

Heat Load Issues in Solid State Lasers

The absorption of a pump photon in the laser gain media results in heat production within the crystal. If the crystal boundary is in contact with a thermal reservoir (water cooling for example) or even if the pump light distribution through the crystal is not uniform, heat flow within the crystal will occur.

Thus, there must be temperature gradients set up within the crystal. Through the temperature sensitive part of the crystal's index of refraction, the optical quality of the gain media is affected. In our lab very large optical tilts have been observed in the kilowatt slab laser. In uniformly pumped rods a purely lensing effect results and the corresponding effect in a slab is cylinder focus. With non uniform pumping distributions and slab mounting effects, more complex optical distortions evolve in the gain media. These effects are laser operation point sensitive. The non-uniform temperature distribution inside the crystal also results in mechanical stresses due to the crystal's thermal expansion coefficients. These mechanical stresses result optically in induced birefringence which contributes polarization dependent terms to the above optical effects. In polarized laser cavities this also represents a major cavity loss mechanism. The thermal mechanical stresses also set a upper operational limit on laser power performance due to fracture. Systems are generally built to operate below 1/4 of the calculated fracture limit.

A variety of designs and technologies are presently applied to address these heat load driven problems. The most common geometry for a solid state laser gain media is the rod. To minimize optical distortion, one arranges the pump sources and collector optics radially about the rod to maximize the uniformity throughout the rod. The optical focusing is simply factored into the cavity design for fixed operating point operation. Much research effort has been dedicated to studying the slab geometry. Here the gain media offers two large optical pumping surfaces (the length/height aspects) which can also be water cooled. The heat flow in the crystal is oriented normal to the pump faces, hence the thermal optical effects reflect this symmetry also. To first order, a cylinder focus is induced across the thickness of the slab while no effect is seen along the height of the slab. Upon zigzagging the laser mode path through the slab using the pump faces as TIR surfaces, all parts of the wavefront sample all parts of the index distribution thus averaging away the thermal optical effects. The progress of slab laser has been hindered by the higher fabrication and material costs as well as lower than expected optical performance. Residual optical distortions are found to be the result of slab distortions resulting from the thermal transition along the length of the crystal from the pumped region of the slab to the unpumped ends. In the last few years SBS based phase conjugate techniques have been successfully applied to laser amplifier configurations. Preservation of near diffraction limited beams have been demonstrated. Work is ongoing at LLNL and TRW to achieve high repetition rate and power in diode pumped amplifier chains corrected with phase conjugate mirrors.

The problem of induced birefringence may be avoided by using already strongly birefringent materials such as YLF. Here the induced component to the birefringence is overwhelmed by the inherent birefringence resulting in negligible operational variation in the birefringence state of the crystal. This approach rules out a variety of desirable laser media including YAG and limits laser and amplifier architectures. For example polarization based double passing of amplifiers would not work with YLF since different polarizations see different emission wavelengths in this media. The oriented thermally induced stress in slabs result in birefringence conditions that reflect a rectilinear symmetry and thus are compatible with a variety of polarized cavity designs. Rods exhibit radial birefringence symmetry which is very incompatible with polarized designs. Polarization compensation of rods and other heat loaded optical components may be achieved by rotating by 90 degrees the fast and slow polarization components resulting from passage through the stressed media and then passing the beam through the same or identical element. This will retard the advanced component and advance the previous retarded component. The extent to which this technique works depends directly on how well the rotated passage repeats the first pass.

The total heat flow from a rod to reach the fraction limit depends on the material strength parameters and the rod length only. For a slab it is proportional to the material strength parameters and to the parameter:

$$\frac{(\text{height} \cdot \text{length})}{\text{thickness}}$$

For the same material and length a slab will have superior fracture limits for a height to thickness aspect greater than 2. To obtain more average power in fracture limited designs one may change the material choice if possible or use longer gain media. For slabs one may opt instead to choose a higher aspect design.

Existing Laser Examples

Table 2 lists a range of demonstrated laser systems. A recent development in commercial diode pumped solid state lasers is the Continuum HPO 300 master oscillator. This laser is available in a TEM_{00}, SLM version. This Nd:YAG laser is claimed to put out 3 mJ at 300 Hz with 18 nsec Q-switched pulses. This laser obtains SLM operation by self seeding. The cavity spectral transmission is narrowed by combinations of etalons and the Q-switch standoff is adjusted such that the laser is just at threshold near the end of the diode pump pulse. Only the highest gain (lowest order) mode lases, which seeds with perfect mode matching the cavity just prior to Q-switching. To date four months have gone by waiting for a factory demonstration of this SLM version. The delay has been due to unavailability and or operational problems with this version.

Commercial production	≤ 1 watt
Fibertek	200 watts Multi-rod MOPA ~ 2 x DL No longitudinal mode control
TRW	100 watts @ 100 Hz SLM, TEM_{00} Rod-slab MOPA Phase conjugated
LLNL	Kilowatt operation for 1.5 years 250 watts Q-switched 100 watts green A range of compact systems up to 24 watts green

Table 2. Average power diode pumped solid state laser sources.

The Fibertek corporation makes SDL laser diode pumped rod laser systems for military applications.[4] In Figure 4 we see their basic layout. The oscillator and all amplifier stages are built with two rods and a 90 degree rotator in between to compensate for YAG's thermally induced birefringence. The amplifiers are double passed using polarization based architectures. The rods are pumped by five radially arranged diode stacks to approach uniformly pumping the rods. A multi-amplifier stage system has operated up to 200 watts with 2 X DL beam quality but no spectral control on the laser.

TRW has demonstrated TEM_{00}, 100 watt at 100 Hz operation of an externally seeded SLM master oscillator amplified by an SBS based phase conjugate corrected multi-pass slab amplifier (Figure 5).[5] Near diffraction limited operation is reported. It is believed that power upgrades have been limited to date due to slab fracture resulting from very non-uniform pumping of the slab.

At LLNL kilowatt operation of a long pulse (150 microsecond), 2.25 kHz slab laser has been demonstrated.[6] The laser is diagrammed in Figure 6. Much of the optical distortions from slab end effects have been eliminated by designing a compact square cut slab rather than the traditional extended Brewster tipped ends. This constitutes a design tradeoff of reduced energy storage for better optical quality. In amplifier mode phase conjugation demonstrations of the fully heat loaded (1/3 fracture) slab have been demonstrated though the master oscillator used was itself capable of only low repetition rates.[7]

LLNL has also delivered a mil. spec. compact 24 watt in the green diode pumped laser system (Figure 7).[8] This single rod laser is based on the birefringent laser crystal Nd:YOS. Doubling is via KTP. The average power operation of this system required the development of special shortened aspect Q-switch crystals to reduce induced birefringence in that component. The 110 mm long rod is radially pumped by 4 diode stacks and 4 condensing cylinder lenses. The complete system including refrigeration occupies 0.3 m^3 and weighs 29 kg (of this the refrigerator is 16 kg).

The CALIOPE OPO Pump Laser

The LLNL diode pumped laser group has developed and tested the first generation 100% solid state OPO pump source for its CALIOPE demonstrations. Figure 8 diagrams this laser as well as the next generation upgrade. The system is based on a double etalon self seeded Nd:YAG 3 mJ 100 Hz, TEM_{00} master oscillator. Based on existing hardware it is presently end pumped but will be fielded in October with a dual rod side pumped system capable of higher pulse energies and repetition rates. The later design will also permit the permanent installation of a system alignment laser and the option of externally seeding the laser. The cavity length of the present laser can be adjusted to produce between 10 and 30 nsec wide Q-switched pulses. The master oscillator output is double passed via polarization rotation (which also compensates for rod depolarization) through 110 mm, 6.35 mm diameter Nd:YAG rod amplifier. A phase conjugate replacement return mirror is being completed as a back up choice if the present 2 times diffraction limited amplifier beam quality requires upgrading. The system has operated for 30 minute periods (after one hour warm ups) with spectral line stabilities of under 200 MHz (Figure 9). Pointing stability has been measured to be under 19 microradians. System operation up to 300 mJ per pulse has been achieved (Figure 10). When the scenario concepts are fixed the laser layout will be transitioned from the fieldable lab table hardware to the far more stable unit frame construction.

Diode Pumped Solid State Laser Direction at LLNL

Livermore is proposing very high power diode pumped laser systems. Considerable modeling of megawatt class diode pumped heat capacity based glass disk systems are underway. In heat capacity operation, the laser media is not cooled and there is no variation in the pump illumination of the disk across the view of the solid state lasers view. Hence, this system may operate up to its Boltzmann population determined limit at power levels well beyond traditionally cooled laser fracture limits and without optical distortion.

With the recent success in adapting AlGaInP diode material (620 to 690 nm lasing) to our diode packaging technology, the direct diode pumping of Cr^{3+} systems is possible at high average power (Figure 11). Today Alexandrite is the most natural mate to our high average power diode technology. Alexandrite lases between 720 nm and 810 nm. It has a thermal focus strength equal to YAG's but has a thermal fracture limit five times higher than YAG.

Diode pumped laser media with extremely small energy defects between pump and lasing photons such as Yb:YAG are under study. The absorption and fluorescence spectrum for Yb:YAG is shown in Figure 12. Such systems would greatly reduce heat loading in the laser media and simplify system design. Yb:YAG's small cross section does pose its own design difficulties. Alternate longer wavelength band pumping of Nd systems suggests a potentially useful compromise between reduced energy defect and good lasing cross section.

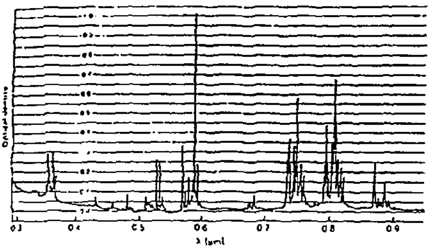
Finally development and demonstrations of thermally compensated electro-optics is actively being pursued with 250 watt Q-switching being demonstrated to date.

Acknowledgment

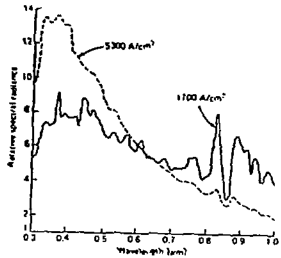
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

References

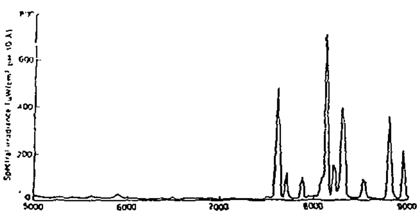
1. S. P. Velsko *et al.*, "Solid State Frequency Conversion Technology for Remote Sensing," this vol.
2. R. J. Beach *et al.*, "Improved Performance of High Average Power Semiconductor Arrays for Application in Diode Pumped Solid State Lasers," presented at SPIE OE/LASE 1994, Laser Diode Technology and Applications Conference, Jan. 1994.
3. V. Krause *et al.*, "Microchannel Coolers for High Power Laser Diodes in Copper Technology," presented at SPIE OE/LASE 1994, Laser Diode Technology and Applications Conference, Jan. 1994.
4. Ralph Burnham *et al.*, "High Average Power Diode Pumped Solid-State Lasers," Proc. SPIE **1865**, pp. 28-34, 1993.
5. R. J. St. Pierre, "One Joule Per Pulse, 100-W Diode-Pumped, Near-Diffraction-Limited, Phase-Conjugate Nd:YAG Master Oscillator Power Amplifier," Proc. SPIE **1865**, pp. 2-8, 1993.
6. B. J. Comaskey, "One Kilowatt Average-Power Diode-Pumped Nd:YAG Folded Zigzag Slab Laser," Proc. SPIE **1865**, pp. 9-16, 1993.
7. B. Comaskey *et al.*, "A One Kilowatt Average Power Diode Pumped Nd:YAG folded Zigzag Slab Laser," UCRL-JC-113200, Lawrence Livermore National Laboratory, 1994 (submitted to Applied Optics).
8. B. Comaskey, *et al.* "24 Watts Average Power 0.537 μm from an Externally Frequency Doubled Q-Switched Diode Pumped Nd:YOS Laser Oscillator," UCRL-JC-115128, Lawrence Livermore National Laboratory, 1993 (accepted for publication in Applied Optics).



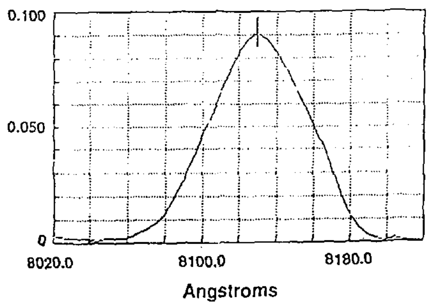
a) The absorption spectrum of Nd:YAG at 300 K.



b) The emission spectrum of a xenon flashtube (EG&G Model FX-47A) operated at high current densities.

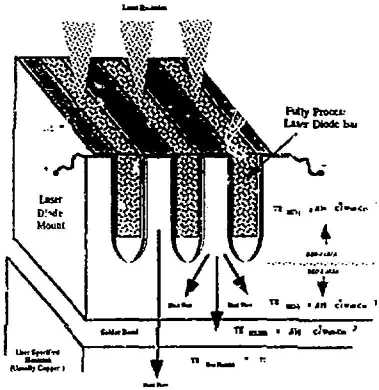


c) The emission spectrum of a cw krypton arc lamp.

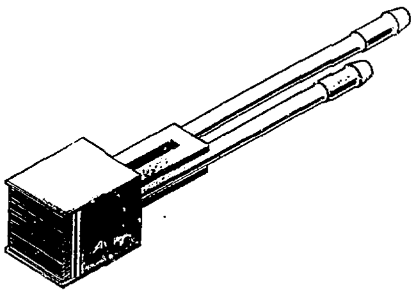


d) The emission spectrum of an early LLNL 1 kW diode pump module (78 packages – no package wavelength selection attempted).

Figure 1.

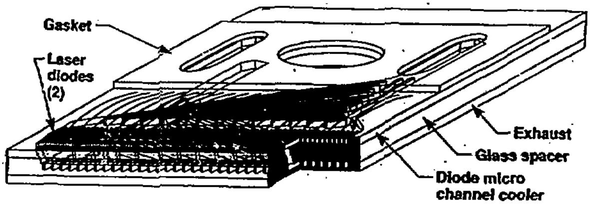


a) Laser diode array's BeO diode mount.

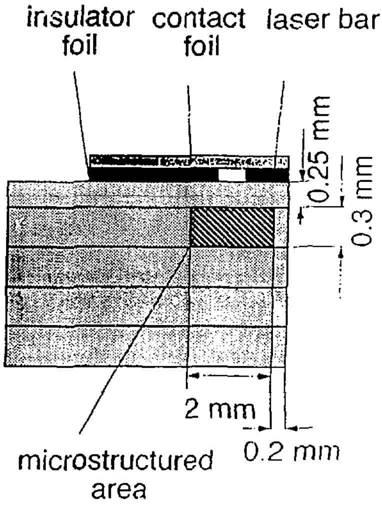


b) SDL's impingement cooled diode stock

Figure 2.



c) LLNL's stackable microchannel cooled diode package.



d) The Fraunhofer-Institut at Aachen's copper based microchannel cooled package.

Figure 2. (cont'd)

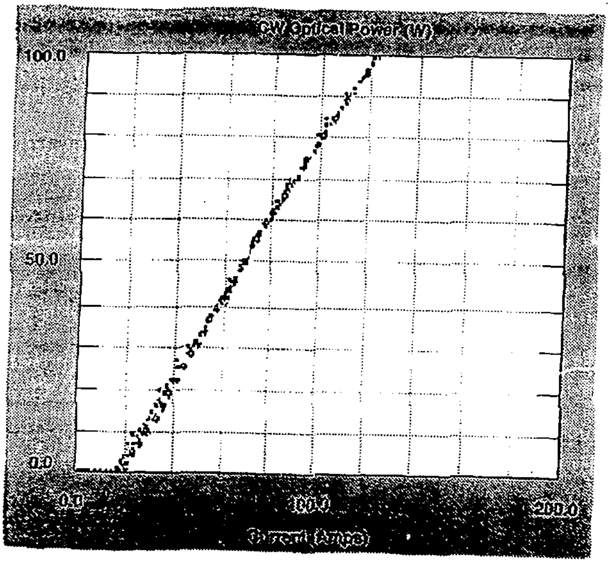
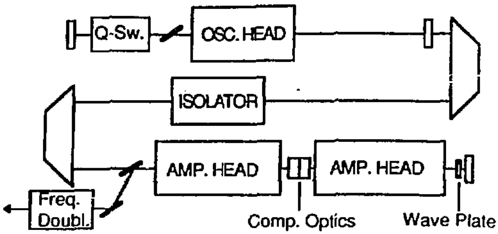
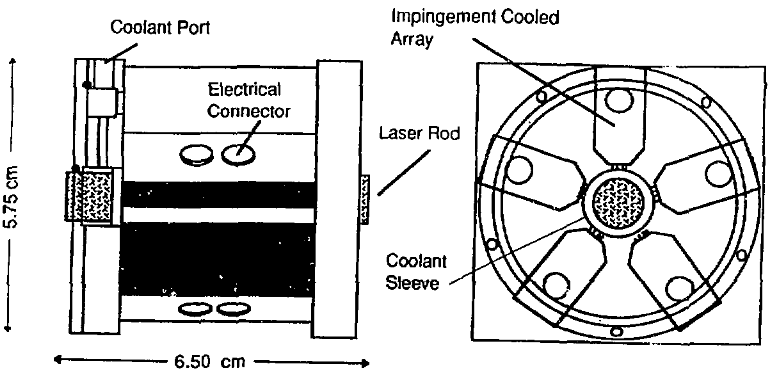


Figure 3. Recent LLNL cw power performance data for a microchannel cooled 1 cm diode bar laser.

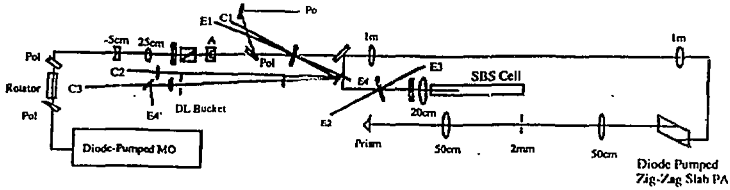


a) Schematic diagram of a diode pumped oscillator-amplifier system.

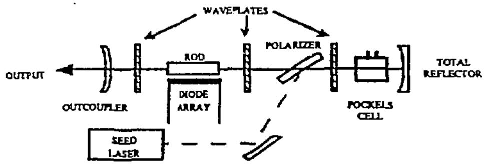


b) Design of the high-duty cycle diode pump module.

Figure 4. The Fibertek diode pumped MOPA.



a) Detailed optical layout of the diode pumped phase conjugated MOPA.



b) Schematic layout of the diode pumped master oscillator.
Figure 5. The layout of TRW's phase conjugated MOPA.

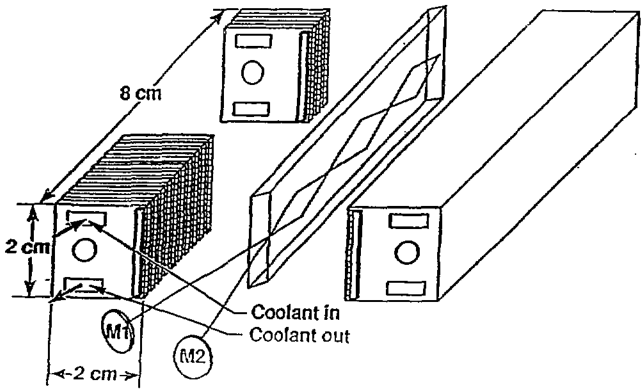


Figure 6. The layout of LLNL's kilowatt average power diode pumped square tipped folded zigzag slab laser.

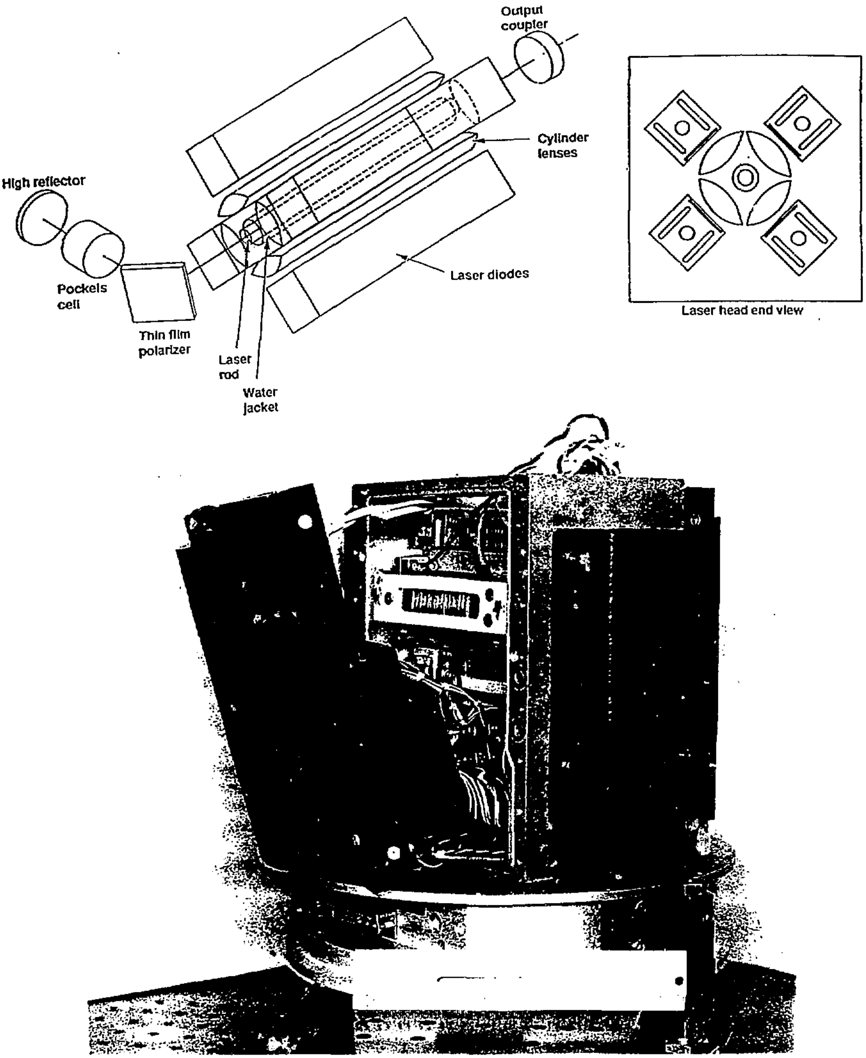
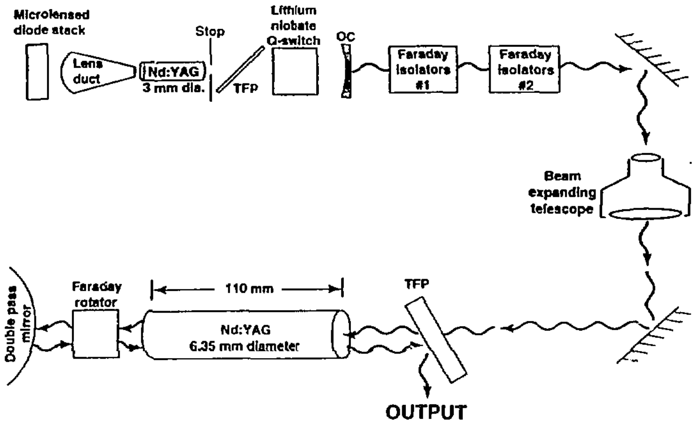
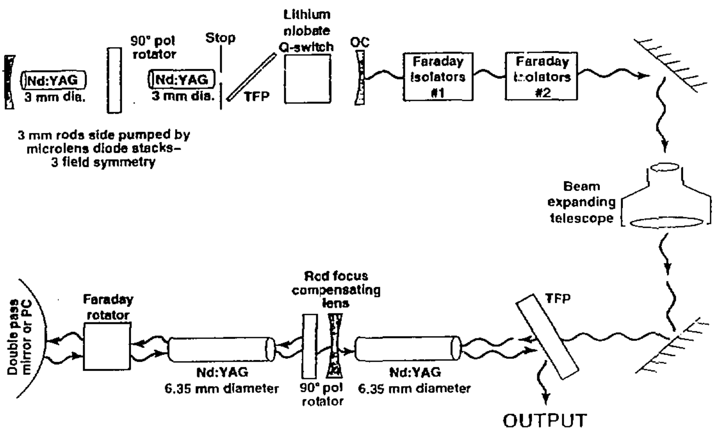


Figure 7. The layout and illustration of LLNL's MIL SPEC 24 watt green laser.



a) Generation 1 CALIOPE pump laser.



b) Generation 2 CALIOPE pump laser.

Figure 8. Diagrams of the first two generations of LLNL's CALIOPE laser for OPO pumping.

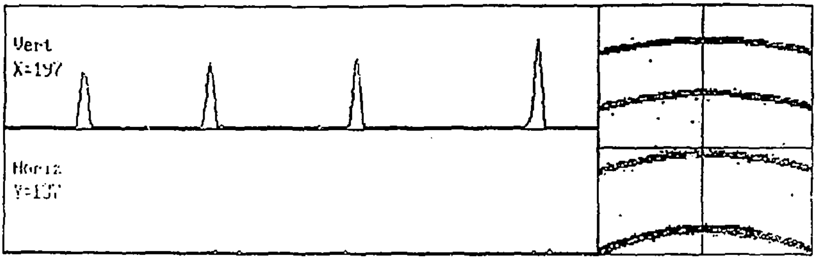


Figure 9. The output of the CALIOPE laser system viewed through a 4 GHz FSR etalon. One hour warm-up results in a laser passive stability of ~30 minutes. The line width is instrumentally limited.

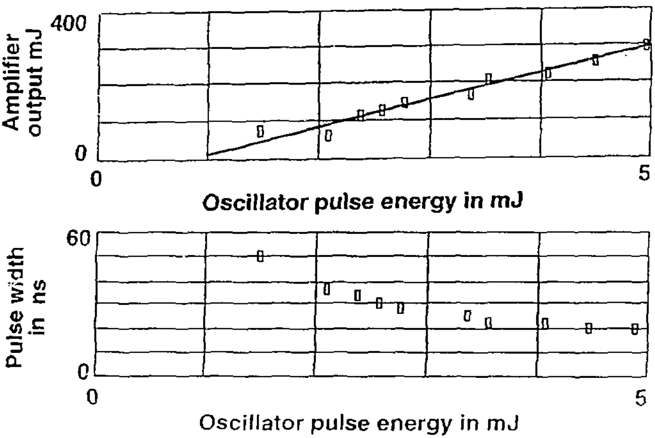
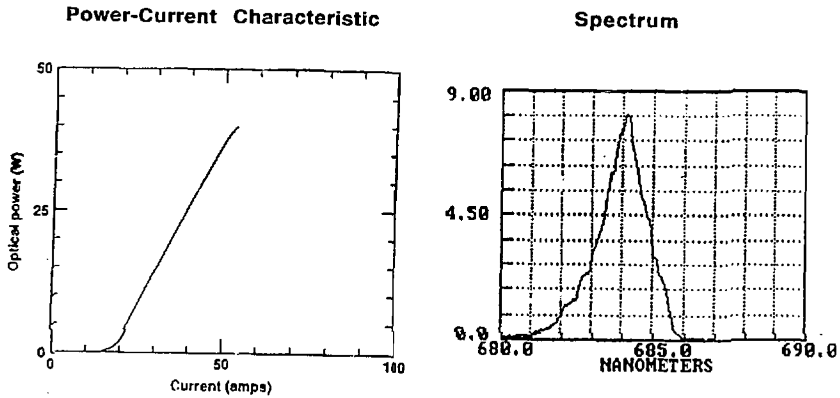
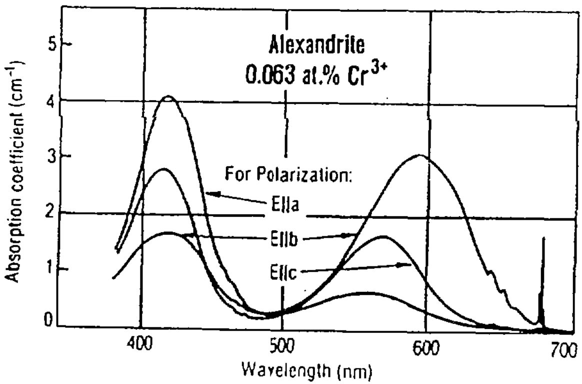


Figure 10. The pulse energy and pulse width performance of the CALIOPE pump laser for a fixed cavity length.



a) The cw performance characterization of 1 cm of AlGaInP laser diode material mounted on LLNL's microchannel cooler.



b) The Cr^{3+} absorption band of Alexandrite showing the excellent overlap with AlGaInP's 620 to 690 operating range.

Figure 11.

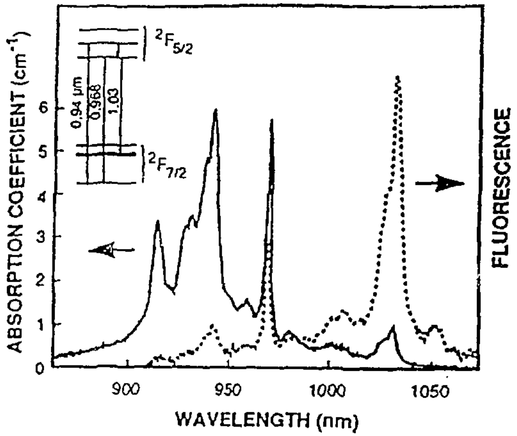


Figure 12. The absorption and fluorescence spectrum of Yb:YAG. Clearly this system exhibits a very small energy defect between pump and laser emission photons.