

High Average Power Cryogenic Lasers Will Enable New Applications

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For military applications, efficiency, size and weight, reliability, performance, and cost are the fundamental metrics used to determine effectiveness. In the commercial world, size and weight are less important than in military applications, but desirable nevertheless to decrease cost of ownership. Modern solid-state lasers with CW average powers exceeding 100 kW have now been demonstrated, but large performance gaps exist at any power level, particularly with regard to wallplug efficiency and beam-quality. Complexity is an additional issue that is often ignored: *the “best solution” laser system for a particular application is the one that offers the least system complexity while providing just the performance needed to accomplish the task at hand.* This general principle leads to the conclusion that laser systems that minimize the number of optical components, pump diodes, and support equipment, and provide the best possible beam-quality are the most desirable.

The importance of beam-quality and efficiency

If we consider cases where the effects of a laser beam are determined primarily by the intensity achieved on target, it is not difficult to show that if the laser output beam is N times diffraction-limited, then the intensity on target in the far-field is reduced by N^2 . Thus in order to achieve the desired intensity on target, one must therefore increase the average power, also by N^2 . As an example, if the laser output is 2 times diffraction-limited, the laser average power must be increased to 4 times that needed to produce a diffraction-limited spot on target. While for low average power lasers this is not very important, for high average power lasers operating at say the 25-100 kW power level, the increase in average power is very significant and costly. In effect, if one defines the laser *system* to include the laser output beam all the way to the target, the system efficiency has been reduced by N^2 .

Laser system size and weight are approximately proportional. The size of a laser system is roughly inversely proportional to the system efficiency. Modern diode-pumped fiber lasers routinely achieve a true wallplug efficiency of greater than 30 %, while diode-pumped bulk solid-state lasers are somewhat lower. The Northrop-Grumman and Textron 100 kW laser systems for example are estimated to have wallplug efficiencies of 27.5 % and 16.2 % respectively. Both lasers have been reported to operate at < 2 times diffraction-limited but require wavefront correction methods to do so.

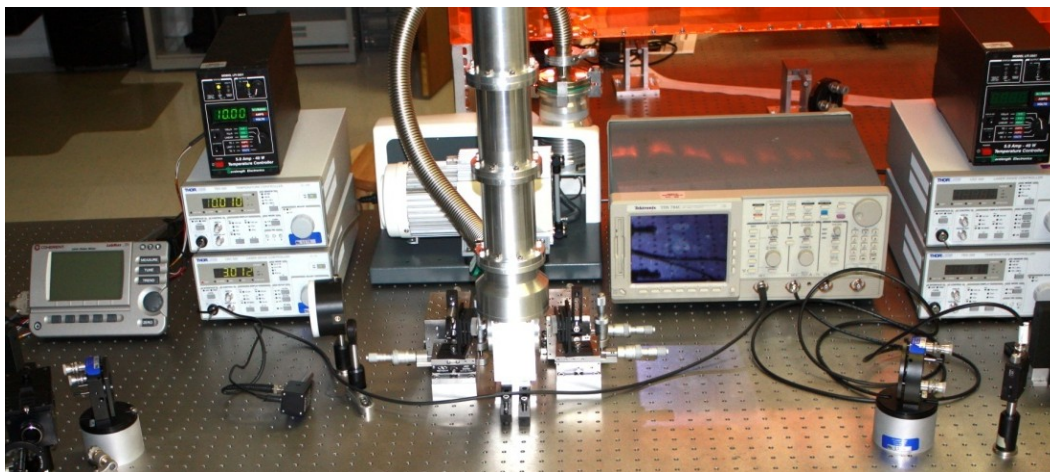
Enter cryogenic lasers

A quiet revolution in solid-state laser technology has been taking place for the past decade in which cryogenically-cooled solid-state lasers have made important strides in addressing the beam-quality and efficiency shortfalls. Why would someone want to operate a laser with liquid nitrogen (LN_2) or other cryogen cooling? For starters, cryogenic cooling of the material Yb:YAG leads to optimum thermal, thermo-optic, and laser kinetics performance, using a laser material that is simple, reasonably well-understood, and that is free from up-conversion and other efficiency robbing effects. Cryogenic lasers are not difficult to build and operate, and LN_2 is ubiquitous and inexpensive. The beam-quality obtainable from cryogenic lasers is better than room-temperature devices because of far-better laser materials properties at cryogenic temperatures, and obtainable without wavefront correction methods that only add to system

complexity. While cryogenic lasers require a source of cryogen, and may only be applicable initially to ground-based or naval platforms, the technology is so compelling that the advantages far outweigh the resulting slight increase in system complexity.

Record high efficiency demonstration

Snake Creek researchers have recently reported a high efficiency Yb:YAG cryogenic oscillator, shown in the photo, that achieved a heat-fraction-limited slope efficiency of 91.9 %, a maximum optical-optical efficiency of 86 %, and a 100 % photon slope efficiency. All efficiencies are new world records.

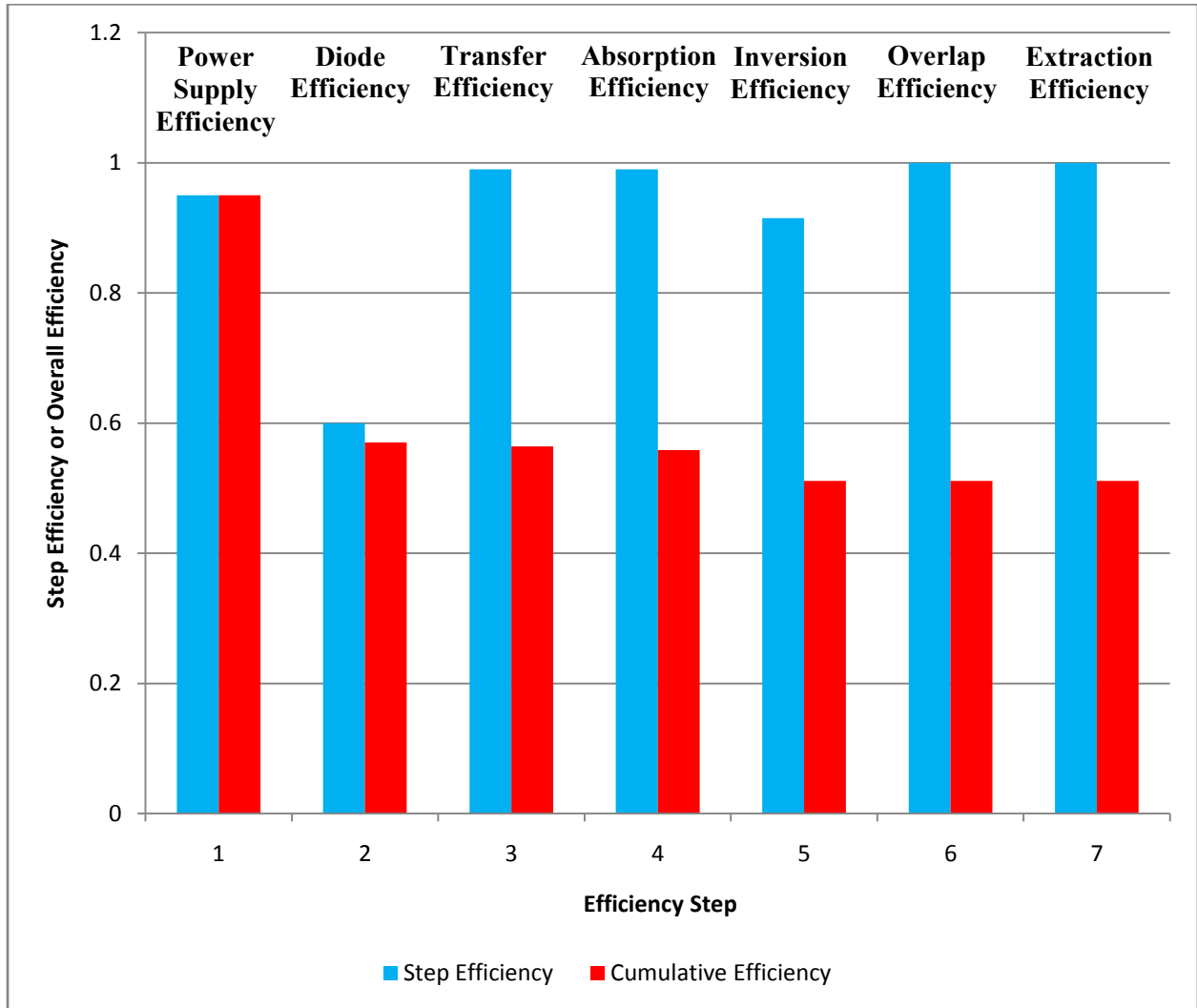


Yb:YAG cryogenic oscillator (D. C. Brown, T. Bruno, and V. Vitali, Optics Express August 2, 2010)

The laser was pumped by a CW diffraction-limited 946 nm Nd:YAG laser. A diffraction-limited output beam resulted with an M^2 of 1.0-1.1. High efficiencies were achieved by choosing a resonator that produced a high ratio of internal resonator intensity to saturation intensity, a low saturation intensity at 77 K, a near-unity overlap efficiency of the pump and resonator beams, a near unity extraction efficiency, the use of a diffraction-limited pump beam, the absence of any thermal effects, and by choosing a laser material with a low heat fraction and negligible parasitic effects. The slope efficiency of 91.9 % is the best one can achieve with Yb:YAG. Other laser materials with lower heat fractions than Yb:YAG may in the future produce even higher slope efficiencies.

This laser demonstration has provided a roadmap for producing high wallplug efficiency solid-state lasers. In the future high wallplug efficiency lasers may be achieved by replacing the 946 nm pump source with high-brightness pump diodes and by increasing the pump absorption. In the Figure below, we show the most important efficiency steps in a Yb:YAG laser, as well as the cumulative laser wallplug efficiency that can be achieved using the most realistic best values for each step. Recently, a diode efficiency of 83.5 % was demonstrated at 975 nm by employing advanced diodes operated at cryogenic rather than room temperature. If we assume that 80 % efficiency can also be demonstrated at 940 nm, then an overall system wallplug efficiency in excess of 68 % results. Using room-temperature diodes with an efficiency of 60 % still results in a wallplug efficiency > 51 %. We conclude that advanced all cryogenically-cooled solid state

lasers can be demonstrated with factors of 1.7-2.3 times the wallplug efficiency of fiber lasers operating today. We believe that this conclusion will further hasten the development of cryogenic solid-state laser technology. Clearly the implications for addressing the efficiency, size, and weight performance gaps in current laser technology are compelling, and the benefits accrue across-the-board for both military and commercial applications.

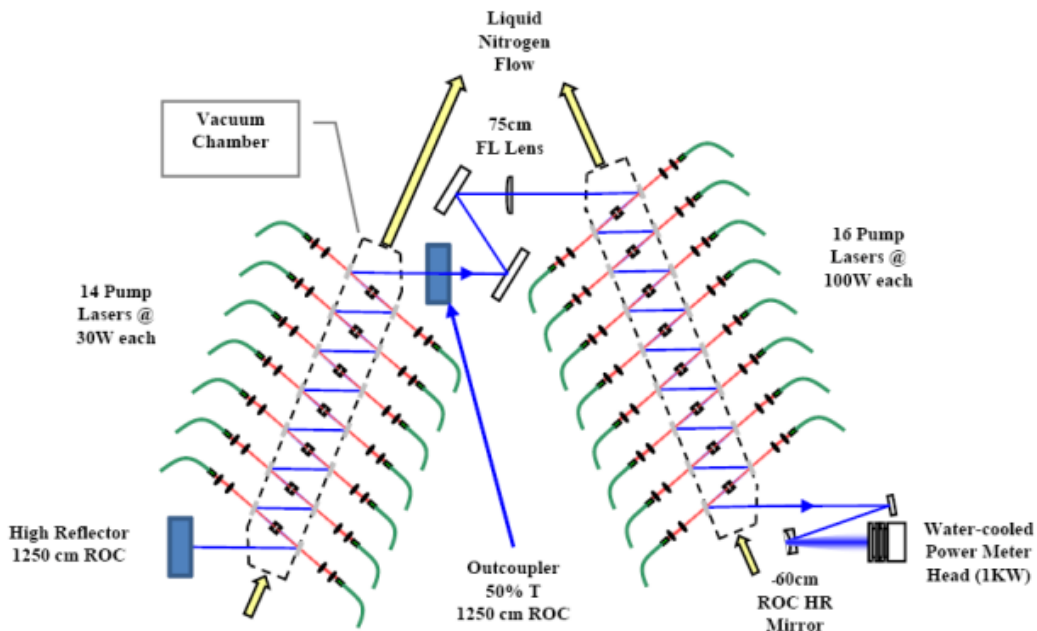


Step and Cumulative Efficiency For Cryogenic Yb:YAG Lasers

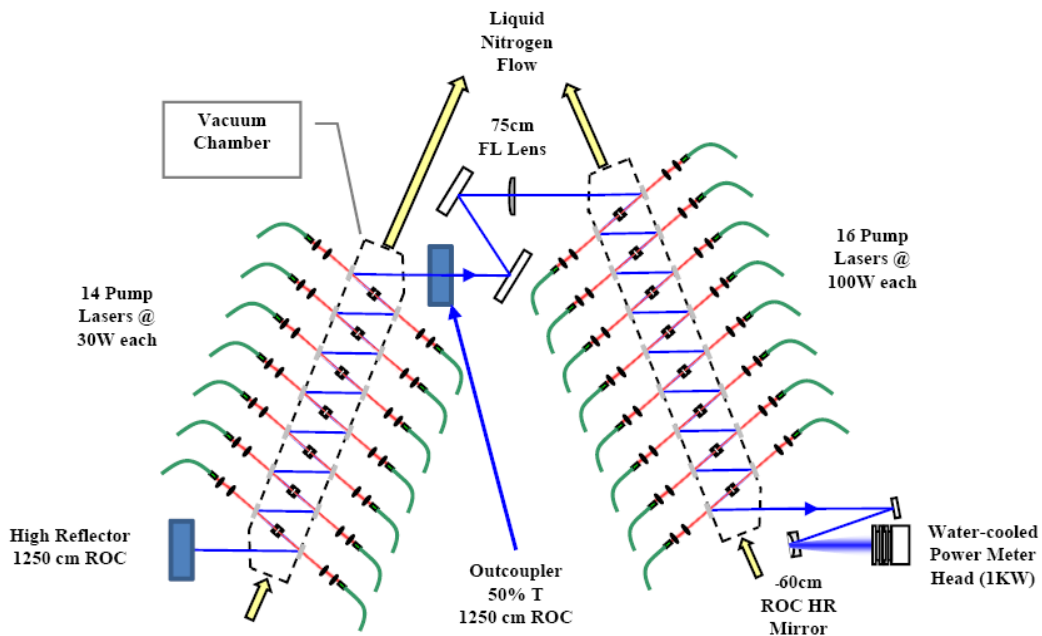
High average power CW and ultrafast results

SCL has recently produced two high average power (HAP) performance milestones for Yb:YAG cryogenic lasers, the first operating CW and the second producing a 50 MHz train of 12.4 ps pulses. In the first Figure below, a CW oscillator using seven Yb:YAG disks, each pumped with two 30 W 940 nm fiber-coupled diode sources, is used to drive a power amplifier with eight Yb:YAG disks, each pumped with two 100 W 940 nm fiber-coupled diodes. Each Yb:YAG disk is pumped through dichroic windows that are totally reflecting at the lasing wavelength of 1029 nm and highly transmissive at the pump wavelength of 940 nm. The laser beam zig-zags through

each disk, mimicking a laser slab and providing a compact design. A flowing liquid nitrogen system is used to cool all the Yb:YAG crystals.



Yb:YAG cryogenic oscillator-amplifier system producing 963 W of output average power with $M^2 < 1.3$.



Yb:YAG ultrafast cryogenic laser with 758 W of output average power with $M^2 < 1.3$

In the second Figure above, a mode-locked Yb fiber laser producing a 50 MHz train of 12.4 ps pulses is directly amplified, first in the seven disk amplifier which is double-passed, and secondly in a single-pass of the eight disk amplifier. At the maximum average power of 758 W, energy per pulse was 15.2 μ J and the peak power was greater than 1.23 MW. The performance of this HAP ultrafast laser was achieved without the use of chirped-pulse-amplification, considerably simplifying the design and reducing the complexity.

As a preliminary test of the capabilities of this HAP ultrafast system, we have in collaboration with Jefferson National Laboratory conducted a preliminary frequency-doubling experiment using an LBO crystal, producing 60 W of 515 nm (green) average power with the fundamental 1029 nm output idling at 160 W. In the near-future much higher green average power is expected.

The future of cryogenic laser technology

In the coming years we may expect to see a dramatic increase in the average power of cryogenic lasers while maintaining outstanding beam-quality, operation using many different laser materials and transitions, and ultimately very high wallplug efficiency. It is now clear that HAP CW, Q-switched, and ultrafast operation can be obtained using this technology. While the need for a cryogen is often mentioned as an obstacle to the widespread use of this technology, the overwhelming advantages offered by cryogenic lasers substantially negate this assertion. In those situations where liquid nitrogen is not readily available such as on aircraft platforms, it is likely that alternative low-temperature cooling methods may be used. One such method uses low temperature air readily available at high altitudes for example.

Cryogenic laser applications

It is clear that the major advantages offered by kilowatt-class cryogenic lasers, high wallplug efficiency and excellent beam-quality, critically important for military applications, are also applicable to micromachining applications, which are currently limited by ~50 Watt average power room-temperature-cooled ultrafast lasers. With a factor of 10 more average power in the fundamental 1029 nm, SHG (515nm), THG (343nm), or FHG (257nm) wavelengths from cryogenic lasers, an order of magnitude faster laser processing speeds are suddenly feasible for the photovoltaic, flat-panel display, semiconductor, and printed circuit board industries. The same argument is valid for the nuclear industry, which has been searching for an effective laser source to safely decontaminate surfaces from radioactive isotopes.

With Gaussian-shaped spatial beam shapes, cryogenically cooled lasers are ideal pump sources for optical parametric amplifiers, as well as photocathode illuminators for high-power free-electron lasers or other accelerator applications requiring well-timed picoseconds electron injectors. It's also conceivable that SCL's cryogenic laser technology can be employed for ion-stripping of Hydrogen beams, since its active Yb:YAG discs are side-pumped, and, thus, this laser technology is scalable to 100 kilowatt level and beyond.

SCL is currently seeking business partnerships to quickly bring to market the laser technology described here.

Acknowledgement

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