Kilowatt Class High-Power CW Yb:YAG Cryogenic Laser

D.C. Brown, J.M. Singley, E. Yager, K. Kowalewski, J. Guelzow, and J. W. Kuper

Snake Creek Lasers, LLC, Hallstead, PA
18822

ABSTRACT

We discuss progress towards a kilowatt class CW Yb:YAG cryogenic laser. Cryogenically-cooled crystalline solid-state lasers, and Yb:YAG lasers in particular, are attractive sources of scalable CW output power with very high wallplug efficiency and excellent beam-quality that is independent of the output power. Results are presented for a high power Yb:YAG oscillator that has produced over 550 W of output power with good slope and optical-optical efficiencies while maintaining single transverse mode output. We also describe a new oscillator-amplifier cryogenic Yb:YAG system nearing completion, that will build on the work presented here and result in CW power output of > 1 kW while maintaining near-diffraction-limited beam quality.

The oscillator described here consists of a distributed array of seven highly-doped thin Yb:YAG-sapphire disks in a folded multiple-Z resonator. Individual disks are pumped from opposite sides using 100 W fiber-coupled 940 nm pump diodes. The laser system produces a near-diffraction-limited TEM_{00} output beam with the aid of an active conduction-cooling design. In addition, the device can be scaled to very high average power in an oscillator-amplifier configuration, by increasing the number and diameter of the thin disks, and by increasing the power of the pump diodes with only minor modifications to the current design. We will present experimental results including output power, threshold power, and slope and optical-optical efficiencies.

INTRODUCTION

It has been previously shown that Yb:YAG lasers can produce ultrahigh-average-power at room temperature [1] but with limitations regarding beam quality due to nonlinear thermal distortions [2,3]. Cryogenic cooling of the lasing medium allows the laser designer the freedom to scale-up Yb:YAG lasers without the need for compensating optics applied to the laser system. The benefits of cooling Yb:YAG lasers from 300 ^{o}K to 77 ^{o}K results in a large decrease of the thermooptic coefficient (dn/dT), a significant increase in the thermal conductivity (k), and a decrease in the thermal expansion coefficient (α) [4]. However, the absorption bandwidth near 941 nm narrows from about 17 nm at room temperature to 13 nm at cryogenic temperatures [4]. This fact is manageable due to the typical FWHM bandwidths of ~ 3-4 nm for commercially available pump diode sources. A good review of recent progress that summarizes the advantages of cryogenic cooling may be found in [5].

Previous demonstrations of cryogenically-cooled Yb:YAG lasers have been published in recent years yielding high-average-power with near diffraction-limited beam quality [6,7,8]. Two approaches have been used: end-pumped rods [6,7] and single thin disk [8] configurations of the lasing medium. Both approaches have used passive conduction cooling for the Yb:YAG crystal by way of a static LN_2 dewar. A passive cryogenic cooling system ultimately has scalability limitations whereas an active cooling system allows scalability far beyond that achievable with a passive dewar. The goal of this project is to extend the performance reported at this conference last year [9] to over 500 W, and ultimately to > 1 kW. A cryogenically-cooled Yb:YAG laser with a practical, robust, and highly scalable resonator that was capable of > 1 kW CW output and near diffraction-limited beam quality in a compact package was used. With scalability being the primary driving force we elected to use a multiple thin-disk approach that employed active conduction cooling for the Yb:YAG crystals along with a folded Z-resonator to minimize size.

LASER DESIGN

Design considerations for this project included ease of scalability, high-average-power per-unit-volume, and a rugged package. This oscillator is highly scalable due to its unique folded resonator and multiple thin disk layout as shown in Figure 1. It is also extremely compact measuring just 50 cm wide x 65 cm long for the resonator portion of the laser. A major goal was to not just demonstrate an advanced cryogenic laser but also to provide a solution that was robust and close to a finished product. The gain medium consists of a 2 mm thick x 1 cm diameter 25-at-%-doped Yb:YAG disk sandwiched between two 1 mm thick x 1 cm diameter c-cut pieces of Sapphire. This is the first time to our knowledge that anyone has used Yb:YAG sandwiched between c-cut sapphire in a high-power CW Yb:YAG cryogenic laser in order to avoid birefringence. The Yb:YAG/Sapphire crystal assemblies are bonded together and mounted into a copper sub-mount that provides face-cooling of the crystal assembly. The laser resonator incorporates seven of these crystal assemblies, each in their own copper sub-mount that is then mated to a copper baseplate.

The copper baseplate is part of an active conduction cooling system that has LN_2 flowing through it via double-evacuated hoses which are connected to an LN_2 reservoir and re-circulating pump. This open cycle cooling approach vents gas to the atmosphere after the cryogen passes through the copper baseplate, removing heat from the crystals. An active conduction cooling system allows for ease of scaling unlike a passive conduction approach such as a static dewar due to the size of the cryogenic reservoir and the ability to minimize the thermal resistance due to the LN_2-copper boundary layer. Due to this advantage very long run times on the order of approximately 4 hours continuous use can be realized from a single 180 liter LN_2 tank. The laser can be run continuously for longer times by simply increasing the LN_2 reservoir. The cryogenic cooling system implemented in this laser cools the crystals to a temperature of around 85 to 100 ^{o}K without boiling of the LN_2. The cryogen usage has been improved by carefully eliminating heat leaks in the cooling system.

The crystal assemblies, copper sub-mounts, and copper baseplate are all enclosed by an evacuated aluminum pump chamber that also incorporates fourteen dichroic mirrors and two AR-coated (@1029 nm) windows. The resonator mode is formed by the curved high and partial reflectors and zig-zags back and forth between the dichroic mirrors with a multiple-Z pattern (shown as a dashed line in Figure 1). The high reflectivity coatings on the dichroic mirrors are the key to the practicality of this pump chamber design. The inside coating is a high reflector at 1029 nm (R = 99.9977 %) and both sides are AR coated for 940 nm (T = 98.973 %). Both coatings were optimized for the pump and resonator beam incidence angles. The calculated round-trip loss due to the windows, mirrors, non-AR coated sapphire, and the index mismatch between the YAG and Sapphire interfaces accumulate to be about 3.0 %. The losses estimated by the Findlay-Clay method amount to ~ 6 %. These losses are manageable due to the high gain nature of Yb:YAG at cryogenic temperatures which has a greater than 4 times larger emission cross section relative to room temperature [10].

Each of the seven crystals is pumped by two opposing but slightly off-axis 100 W 940nm fiber-coupled diodes. The opposing pump diodes are positioned slightly off-axis to avoid exposure of opposite diodes from any unabsorbed pump diode radiation. Pumping seven crystals allows us the opportunity to distribute the pump power and the heat load in the Yb:YAG which further increases the scalability of this resonator design. An imaging lens pair with a magnification of 10X is used to deliver the pump diode radiation from the end of the 3 m long, 200 μm core, 0.22 NA fibers to the center of each Yb:YAG crystal. This produced an ~ 1.98 mm excitation diameter ($1/e^2$) that is well matched to the average TEM_{00} mode diameter in the resonator of ~ 1.99 mm. The pump diodes are water-cooled and temperature-tuned via needle valves that control the amount of water flowing through the individual coldplates that the pump diodes are mounted on. Needle valves allow precise control over the center wavelength of each pump diode so they can be tuned to the peak absorption region of Yb:YAG [4] which optimizes near 939-941 nm and depends on the diode center wavelength and bandwidth.

The high reflector and the partial reflector are both located exterior to the pump chamber, which is evacuated to avoid condensation, and have a radius of curvature of 12.5 m. The high reflector was coated for a maximum reflectivity at 1029 nm of 99.8724 % and the outcoupler was coated for a partial reflectivity at 1029 nm of 54.8 %. The folded multiple-Z resonator allows for a cavity length of 1.75 m in a compact 65 cm long pump chamber. A photograph of the laser while operating can be seen below in Figure 2.

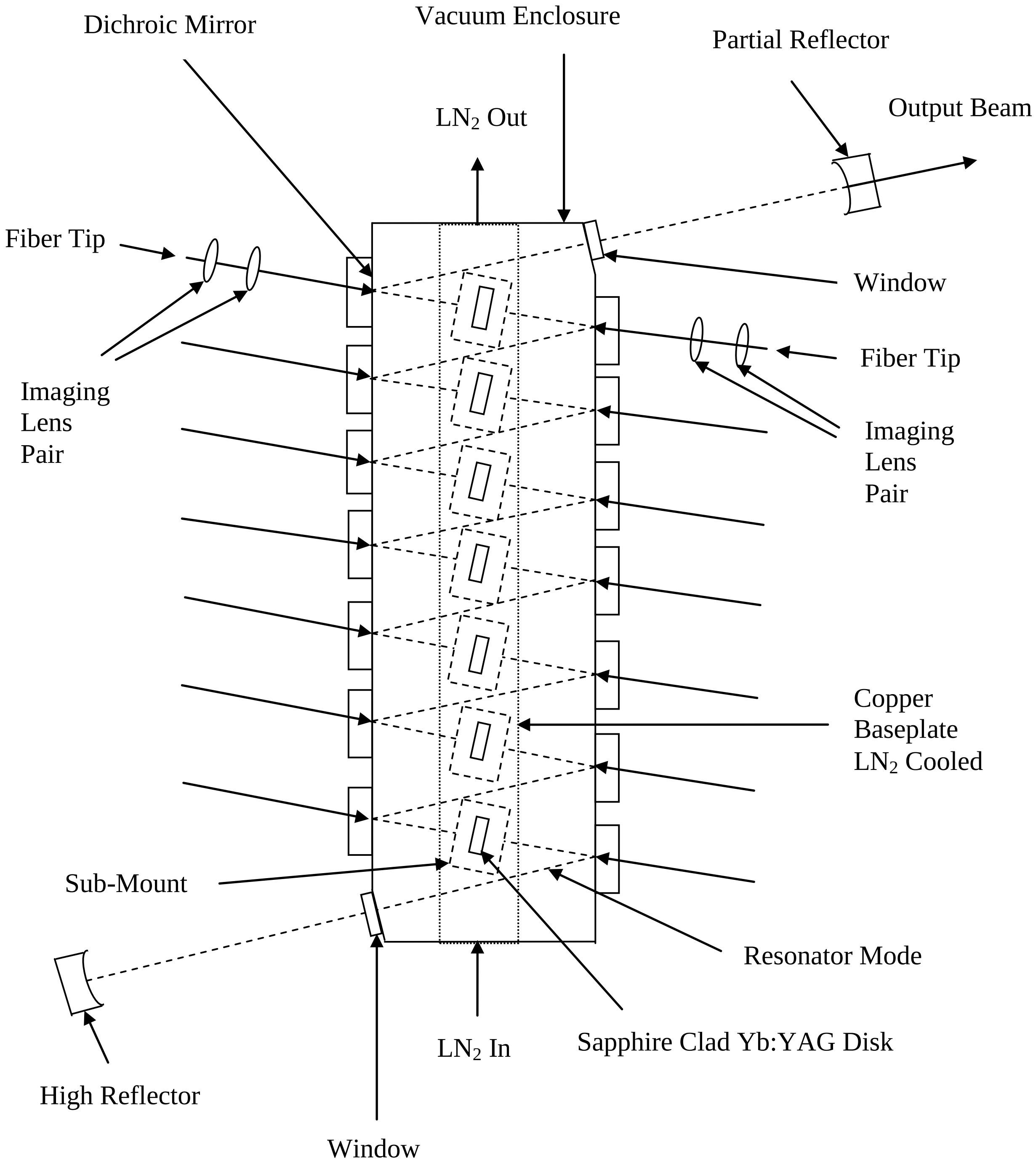

Figure 1: Schematic Diagram of the CW Diode pumped Yb:YAG Cryogenic Laser.

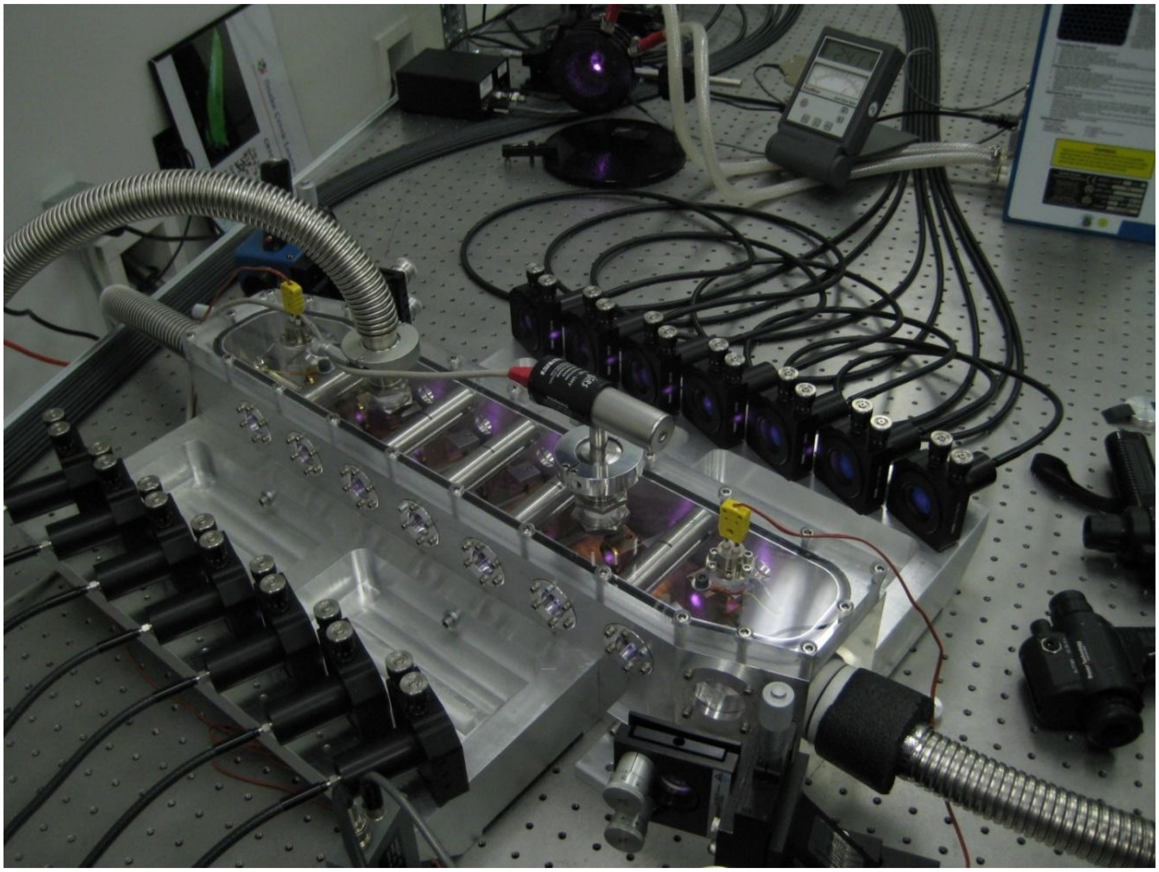

Figure 2: Photograph of the Pump Chamber including the Fiber-Coupled Pump Diode Arrangement and Cryogenically-Cooled Actively Flowing Yb:YAG Pump Chamber.

EXPERIMENTAL RESULTS

This laser provides a high quality beam that has a very symmetric beam profile with a TEM_{oo} Gaussian spatial mode (See Figure 3). In Figure 4, we show preliminary data obtained from the configuration shown in Figure 1; the efficiency has not yet been optimized for the maximum overlap of the pump beams in the crystals with the resonator mode or the outcoupler reflectivity. We have observed > 550 W of output power with slope and optical-to-optical efficiencies of 59 % and 53 % respectively, and with an outcoupler reflectivity of 54.8 %. A threshold of approximately 49 W was measured. At the last data point at approximately 1030 W of absorbed pump power, a drop in power is noted. This occurred because of the internal resonator beam intercepting a plastic washer in one of the crystal holder assemblies, which coated the surface of the crystal with an absorbing film and reducing the output power. In the near future this same experiment will be run with a new pump chamber that eliminates this problem and we expect the power output to increase even further. Because of this problem the M^2 value was not measured for this experimental campaign, but based on our observations of the output beam and comparing it to previous lower power runs, we are confident it is very good.

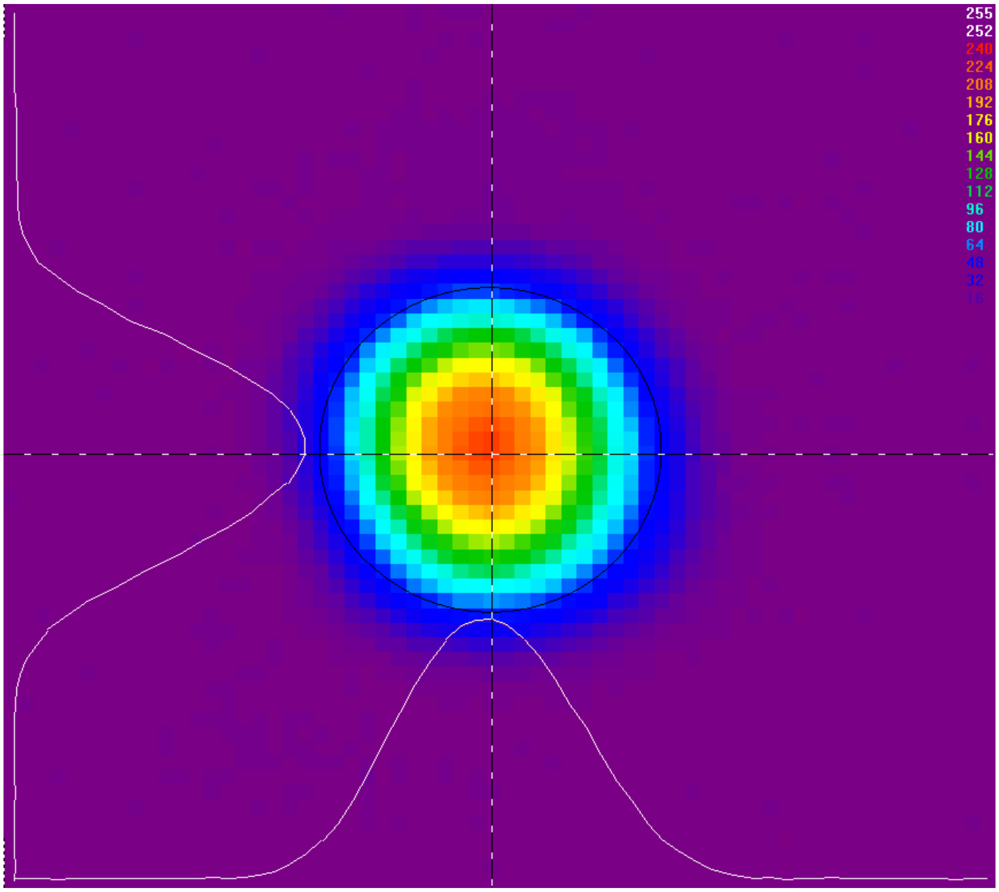

Figure 3: Far-field beam profile of the 1029 nm Yb:YAG laser operating at 250 W average power.

As in our earlier experiments [9], measurements determined the amount of absorbed pump power by the Yb:YAG crystals, which was found to average > 99 %. This result is in good agreement with the theoretical value of > 99 % [4] of the incident pump power being absorbed by the lasing medium. The absorbed power data was then used in the calculation regarding the optical-optical and slope efficiencies of the laser. Up until the final data point the data are quite linear, indicating that in agreement with our calculations no thermal effects are operative.

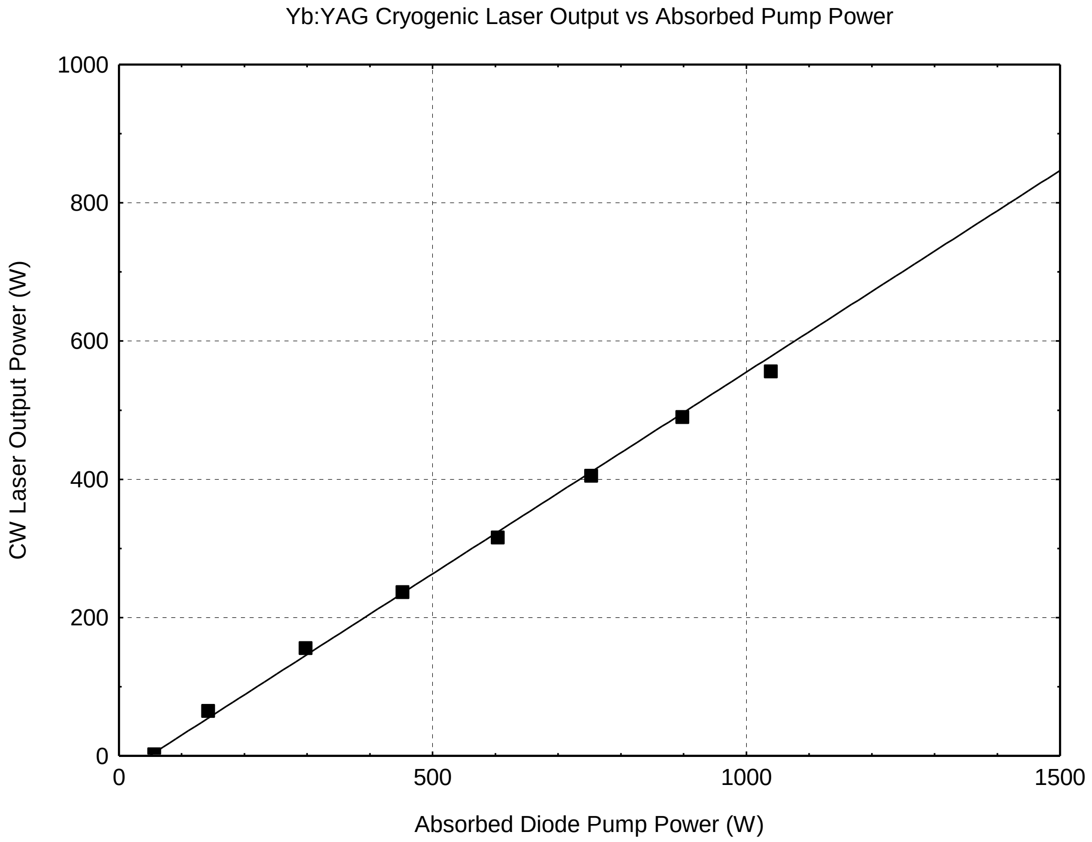

Figure 4: Output Power of the Yb:YAG Cryogenic Laser as a Function of Absorbed 940 nm Pump Power.

CONCLUSION

Our unique approach to providing a highly scalable and efficient Yb:YAG cryogenically cooled laser while retaining a practical and robust design has yielded a CW output power of > 550 W with a slope efficiency of 59 % and an optical-to-optical efficiency of 53 %. The output beam is a high quality near-diffraction-limited spatial mode.

The design of this laser can easily be scaled-up in output power by simply replacing the diode pump sources with higher output sources which are currently commercially available. Off-the-shelf 100 W 940nm fiber-coupled pump diodes were used that are efficiently coupled directly into the same type of 200µm core fibers used previously with this laser and 35 W diode sources [9]. This change increased the net total pump power to approximately 1.4 kW and should ultimately yield an output power in the 800 to 900 W range. Even higher power pump diodes are available (~350 W each) that would require only slight modifications to our current pump chamber configuration. These modifications would include changing the 200 µm core fibers to 400 µm core fibers, providing higher capacity chillers to cool the higher output pump diodes, and implementing more aggressive cryogenic cooling for the crystal assemblies.

Incorporating pump diodes of this size would easily push this laser’s output into the kW range while retaining the same resonator construction.

Once the tolerable thermal aberration limit for individual crystals has been reached (defined as that distortion needed to give an unacceptable degradation in M^2), another pump chamber of the same design can be incorporated into the system to be used as a single-pass amplifier. If carefully designed, multiple single-pass amplifiers can be added to the system to further increase the output power of this laser design in still compact structures. Single-pass CW extraction is quite efficient because of the low saturation intensity of Yb:YAG at cryogenic temperatures [5,9]. The system we are currently building uses this approach as shown in Figure 5. An oscillator with seven Yb:YAG disks and 35 W per diode is used to extract a single-pass amplifier with eight identical disks and 100 W diode sources. An optical isolator is used to eliminate feedback into the oscillator and a beam expander is used to adjust the size of the mode in the amplifier and to image the oscillator beam into the center of the amplifier.

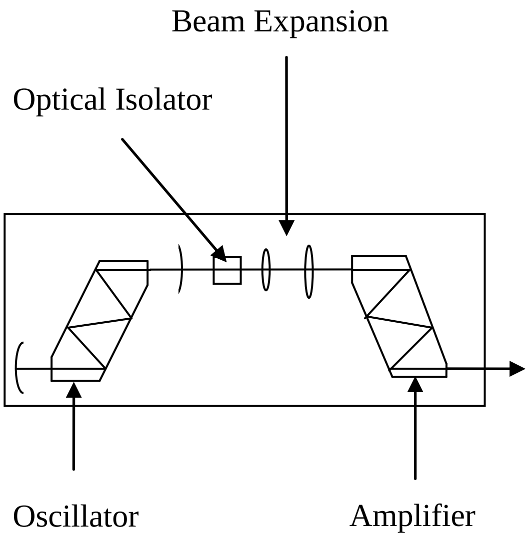

Figure 5: Oscillator-Amplifier Cryogenic Yb:YAG Laser System With > 1 kW Output Power

ACKNOWLEDGMENT

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