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Diode-Pumped Cryogenic Yb^{3+}:YLF Laser of 100-W Output Power with High Beam Quality*

Luis E. Zapata, Daniel E. Miller, Daniel J. Ripin, and Tso Yee Fan

MIT Lincoln Laboratory, 244 Wood St., Lexington, MA, USA 02420

ABSTRACT

A cryogenically cooled Yb:YLF laser with 224-W output power at 995 nm, linearly polarized along the c-axis, has been demonstrated, and laser oscillation has also been obtained polarized along the a-axis. The beam quality had an $M^2 \sim 1.1$ at 60-W output and $M^2 \sim 2.6$ at 180-W output for c-axis polarization. This level of average power is approximately two orders of magnitude higher than demonstrated previously in cryogenic Yb:YLF. A cryogenic Yb:YLF mode-locked oscillator is under development, which will be used to as the input to a Yb:YLF amplifier to generate a short pulses at high average power.

Keywords: Yb lasers, ultrashort pulse lasers, cryogenic lasers

1. INTRODUCTION

Cryogenic cooling of Yb:YAG lasers to liquid nitrogen temperature has enabled high-average-power operation (to multi-kW power) with excellent beam quality in simple laser geometries.[1-6] Operation at cryogenic temperature has the fundamental advantages relative to room-temperature operation of much better thermo-optic properties and dramatically reduced thermal population of the lower laser level that have led to the excellent performance. However, in short-pulse operation the gain bandwidth in cryogenic Yb:YAG limits the pulsewidth to a few ps.[7] Cryogenic Yb:YLF offers similar improvements in fundamental properties with larger gain bandwidth than YAG, which has enabled sub-ps pulse generation.[8-10] However, demonstrations of cryogenic Yb:YLF have been limited to Watt-class average power. Here, we report on scaling of Yb:YLF to the >100-W average power level with good beam quality, limited only by the pump power, which leads the way to high-average-power, sub-ps laser systems. Here we report on a large advance in average-power performance and work to develop a mode-locked oscillator on a path to high-average-power femtosecond laser systems.

2. PROPERTIES OF YB:YLF

The thermo-optic and spectroscopic properties of Yb:YLF at cryogenic temperature are attractive for high-average-power short-pulse operation. The thermo-optic properties improvements in YLF at cryogenic temperature relative to room temperature are large.[11] The thermal conductivity increases, the magnitude of dn/dT decreases, and the coefficient of thermal expansion decreases, all of which are favorable for average-power scaling. Some of this data are shown in Fig. 1. The thermal conductivity in undoped YLF is 24 W/mK at 100 K compared with 5.3 W/mK at 300 K along the a-axis and 34 W/mK at 100 K compared with 7.2 W/mK at 300 K along the c-axis. At 100 K, dn_o/dT is -0.5 ppm/K and dn_e/dT is -1.8 ppm/K compared with -4.6 ppm/K and -6.6 ppm/K respectively at 300 K. The coefficient of thermal expansion is 2.4 ppm/K along the a-axis and 3.2 ppm/K along the c-axis at 100 K compared with 14 ppm/K and 10 ppm/K respectively at 300 K. YLF is also attractive as a host material because it is uniaxial, which means that stress-induced birefringence is negligible compared to its natural birefringence.

The spectroscopic properties of cryogenic Yb:YLF have been reported previously,[1,9] and they attractive for high-power short-pulse lasers. Figure 2 shows the absorption cross section for the two polarizations at 80 K. The 960-nm absorption feature is attractive for pumping because of its strength and the relatively low quantum defect heating, although it is relatively narrow at 3-nm full-width half maximum (FWHM). The polarized cryogenic gain spectrum is shown in Fig. 3, with a high-gain line at 995 nm and a lower gain, but broader, pedestal extending out to a peak at 1020 nm. The relatively broad gain bandwidth for the E||a polarization is particularly attractive for fs-laser operation.
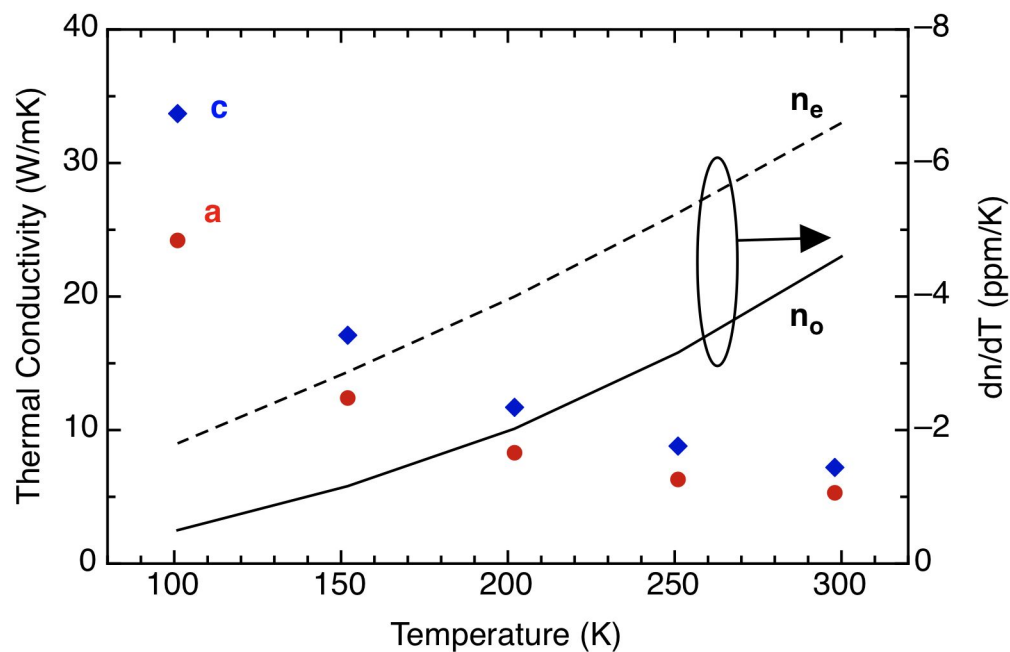
YLF properties

Figure 1. Thermal conductivity (individual data points) and dn/dT of YLF as a function of temperature. Data from ref. 11.
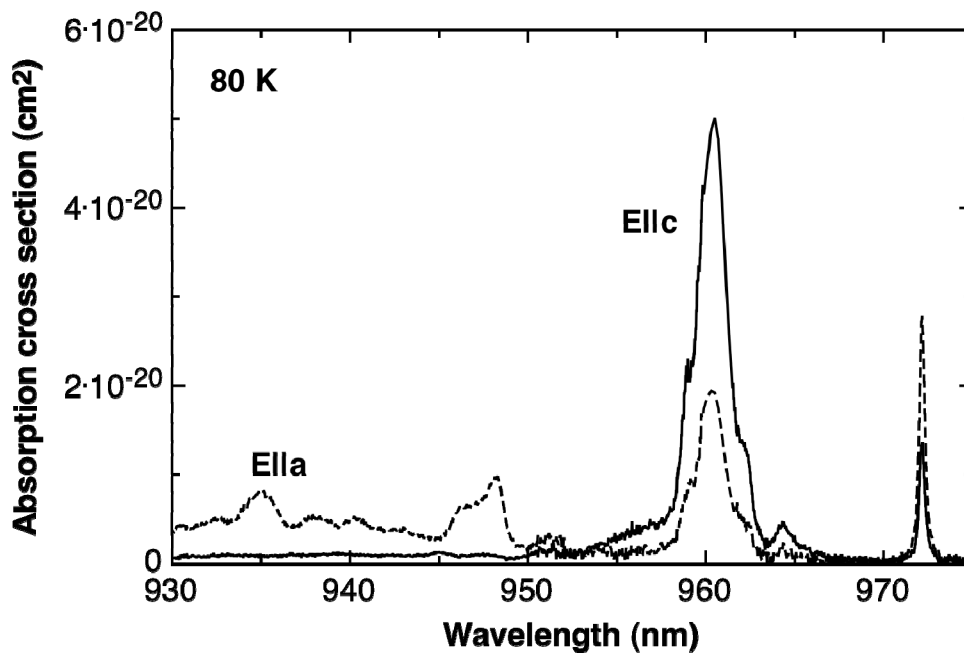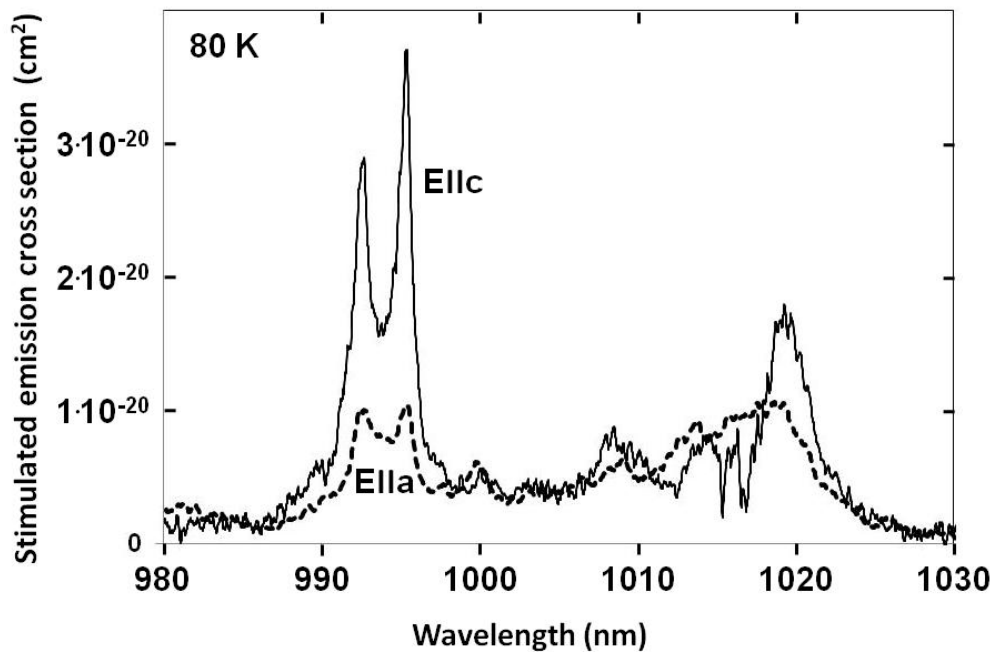

Figure 2. Polarized absorption spectrum of Yb:YLF.

Figure 3. Polarized stimulated emission cross section of Yb;YLF.

3. LASER EXPERIMENTS

We are working toward high-average power femtosecond sources and are currently demonstrating two aspects separately: short-pulse operation from a low-power oscillator and power scalability of cryogenic Yb:YLF using a cw power oscillator. These two aspects will then be combined to demonstrate a high-power short-pulse system using a master-oscillator power-amplifier (MOPA) architecture.

3.1 High-power cw oscillator

An end-pumped geometry was used as shown in Fig. 4. The laser gain element was composed of an AR coated 1%-doped Yb:YLF crystal 10 mm in length with an undoped end-cap. The c-axis of the YLF was oriented normal to the axis of the resonator.
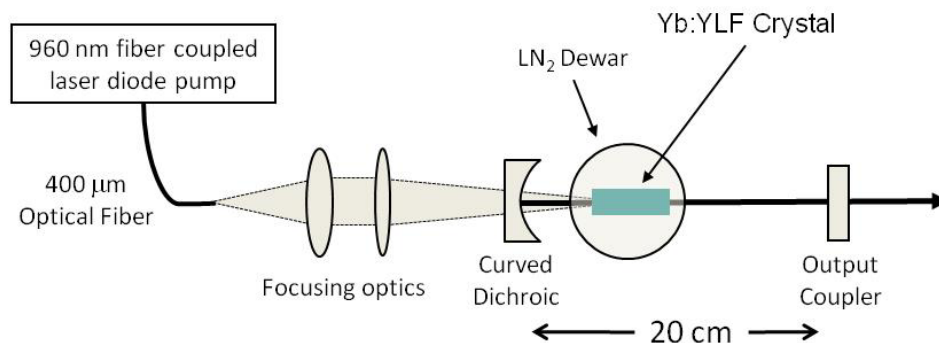

Figure 4. Schematic of cw laser oscillator demonstration.

The laser gain element was pumped by a fiber-coupled (400-μm core diameter, 0.22-NA fiber) diode array, which had a spectrum centered at 960 nm with 2.2 nm FWHM. The pump beam was imaged to a spot in the Yb:YLF approximately

1.2 mm in diameter. The pump beam transmitted through the cavity back-mirror, which had dichroic coating of 98% transmittance at 960 nm and 97.5% reflectivity at 995 nm. The back-mirror was placed 5 cm from the gain element and had a concave radius of 40 cm. The output coupler was flat and had 44% reflectivity.   The cavity length was approximately 20 cm.

With this laser, we obtained a maximum of 224-W laser output power at 995 nm polarized along the c-axis as shown in Fig. 5. The slope efficiency relative to the absorbed power was 68% and 57% relative to the incident pump power. There is no departure from linearity in the output power up to the maximum input power available, and the output power was limited only by the diode pump power of 396 W of 960-nm radiation incident on the gain element. This laser transition terminates at the third Stark level of the lower $^2F_{7/2}$ electronic manifold at 218 cm^{-1} (ref. 13) and exhibits the largest Stark emission cross section in Yb^{3+}:YLF.   At cryogenic temperatures the lower laser level has a favorable occupation factor (2.6% at 100 K) making the π-polarized transition at 995 nm the strongest free running line in cryogenic Yb:YLF lasers in low Q resonators. With a higher reflectivity output coupler, laser oscillation has been observed on the π-polarized transition at 1019 nm and σ-polarized transition at 1017 nm with the addition of a Brewster plate in the resonator.
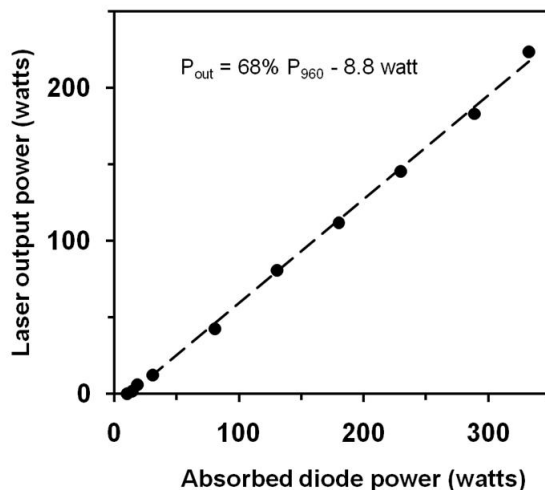

Figure 5. Laser output power at 995 nm pumping at 960 nm.

Cryogenic operation enables laser operation with very low quantum defect.[14] Pumping at 960 nm in Yb:YLF is preferred because it exhibits the strongest absorption and low quantum defect (3.6% for 960 nm pumping, 995 nm lasing). The diode pump had diode bars with a FWHM that varied from 1.5 nm FWHM at low powers to 2.6 nm FWHM at 396 W of output power. The narrow spectral profile of the absorption (3.0 nm FWHM) is a challenge for temperature tuning of the pump wavelength, but the development of grating-stabilized, high-power diode arrays[15,16] should ease this difficulty.

A high-reflector with curvature of 40 cm produced a nearly perfect Gaussian beam with a measured M^2 ~ 1.1 as the laser produced 60-W output. With the same resonator configuration, the M^2 value was seen to increase up to M^2 ~ 2.6 at 180-W output. This reduction in beam quality can be explained by excitation of higher order modes as the thermally induced negative lens in the YLF gain medium influenced the resonator at higher pump powers. The measured data supports our theoretical estimates for the absorption, laser output and thermo-optic effects; absorption data shows that during lasing, 71% and 84% of the pump power was absorbed in the gain medium while pumping with pure E||a and with both polarizations respectively. These numbers are consistent with our calculations including the 960-nm pump and Yb:YLF absorption spectra.   An aperture-averaged ground-level depletion of 7% was used in our 2-level, Boltzman-occupied laser energetics model in order to fit our calculations to the laser output data of Fig. 5. Assuming only quantum defect heating, the temperature rise across the pumped region is estimated to be 5 K. A simple calculation following the formulae in Koechner[17] showed that a temperature rise between 5 and 10 K within the confines of a 10-mm-long rod-like region in YLF with 1.2 mm diameter would result in about −1 to −2 diopter lens due to the effect of dn$_e$/dT. However, a

good estimate for thermal lens associated with stress-optic effects cannot be made because the stress-optic tensor elements for YLF have not been reported. Assuming only thermal lensing caused by dn_e/dT, this "loaded cavity" optical power when added to the resonator's ABCD formalism shows decreasing stability and mode-selection properties explaining at least qualitatively the reduction in beam quality.

3.2 Femtosecond oscillator

A passively mode locked Yb:YLF laser at room temperature has been previously demonstrated using saturable absorber to provide loss modulation.[19] In our work, we have instead chosen a master oscillator design based on Kerr-lens mode locking (KLM). Pulses with high peak intensity experience a lensing effect due to the nonlinear index of refraction, which CW light does not. The cavity is designed such that this changes the laser mode, improving the pump overlap (soft aperture) or reducing loss at an aperture (hard aperture).

The KLM mechanism is extremely fast, and can saturate fully. This avoids the tendency to passively Q-switch which can be a challenging obstacle in lasers mode locked by semiconductor saturable absorbing mirrors (SESAM). Solid-state lasers, which have long lifetimes and small emission cross sections, are particularly susceptible to this instability.

KLM has the added advantage that the gain and mode locking mechanism are independent. We use SF57 glass, which has a nonlinear index of refraction 30 times that of YLF, to obtain Kerr lensing. This relaxes a number of constraints on the cavity design. A much larger focus can be used in the gain, which reduces the effects of thermal distortions. The additional working distance is also more accommodating to a cryogenic dewar. Experiments have begun on this laser.

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