CONF-950101--9

UCRL-JC-118194
PREPRINT

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This paper was prepared for submittal to the
Advanced Solid State Lasers 10th Topical Meeting
Memphis, TN
January 30 - February 2, 1995

March 17, 1995

Lawrence Livermore National Laboratory

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Abstract

The performance of the first diode-pumped Yb^{3+}-doped $Sr_5(PO_4)_3F$ (Yb:S-FAP) laser is discussed. We found the pumping dynamics and extraction cross-sections of Yb:S-FAP crystals to be similar to those previously inferred by purely spectroscopic techniques. The saturation fluence for pumping was measured to be 2.2 J/cm^2 using three different methods based on either the spatial, temporal, or energy transmission properties of a Yb:S-FAP rod. The small signal gain implies an emission cross section of $6.0x10^{-20}$ cm^2 that falls within error bars of the previously reported value of $7.3x10^{-20}$ cm^2, obtained from spectroscopic techniques. Up to 1.7 J/cm^3 of stored energy density was achieved in a 6x6x44 mm Yb:S-FAP amplifier rod. An InGaAs diode array has been fabricated that has suitable specifications for pumping a 3x3x30 mm Yb:S-FAP rod. In a free running configuration diode-pumped slope efficiencies up to 43% were observed with output energies up to ~0.5 J per 1 ms pulse. When the rod was mounted in a copper block for cooling, 13 W of average power was produced with power supply limited operation at 70 Hz and 500 μs pulses.

I. Introduction

Yb^{3+} based lasers have received substantial attention over the past several years. For example, Fan and coworkers[1] have demonstrated efficient laser action in Yb:YAG, while DeLoach et. al.[2] have developed lasers based on Yb-doped fluoroapatite, as well as several of its crystalline derivatives. In addition, Hanna and coworkers[3] have investigated Yb-doped fiber lasers. Yb-based materials, which typically lase around 1 μm, are aided by the simple electronic structure of Yb^{3+} in that it has only two accessible electronic states, eliminating the detrimental impact of upconversion or excited state absorption. In addition, the inherently small quantum defect of ~10-15% has led to relatively large intrinsic laser slope efficiencies.[1-3] One detriment intrinsic to Yb^{3+} based lasers is that they operate as quasi 3-level systems since the terminal level can be thermally populated at room temperature. Although, if the pump source is sufficiently intense to effectively bleach the ground state, the laser will operate more like a 4-level system. Laser diodes are the obvious choice as a high irradiance pump source since the ~900-1000 nm pump region for Yb-doped crystals and glasses overlaps with commonly available diode structures. The emission lifetimes of Yb-doped materials also tend to be significantly longer (> 1 ms) than Nd^{3+} doped into the same media, offering practical advantages in lowering the cost and increasing the effectiveness of diode laser pump sources. The above considerations suggest that diode-pumped solid-state Yb-lasers may provide significant advantages over Nd-lasers for certain applications such as pulsed kJ class slab-laser systems.

We believe that Yb:S-FAP is also particularly well adapted for low to medium average power laser applications that are sensitive to overall efficiencies. Yb:S-FAP has a relatively low pump saturation intensity of 2.0 kW/cm^2 which is well suited to readily achievable diode array irradiances. In contrast, Yb:YAG has a pump saturation intensity of 28 kW/cm^2, which is more difficult to exceed, although Yb:YAG does offer significantly better thermal properties that are more desirable for high average power applications.

II. Yb:S-FAP crystal growth

We have developed a method for producing high quality S-FAP crystalline boules, up to 1" diameter by 7" long, with Yb^{3+} concentrations of $1.2x10^{19}$ cm^{-3} based on Czochralski growth techniques. This required specifications for Yb:S-FAP such as emission centered at 900.4 nm (at 12^{o}C) when running with a 1 ms pulse length at 10 Hz and 2.8 kW peak emission power. Figure 4 presents the diode emission spectra described above overlaid with the transmission spectra of a 30 mm double passed Yb:S-FAP rod fabricated from the boule described above. Clearly most of the diode emission is absorbed into the gain medium in the absence of ground state bleaching and with the bleached pumping conditions utilized in the oscillator described below; ~75% absorption was achieved.

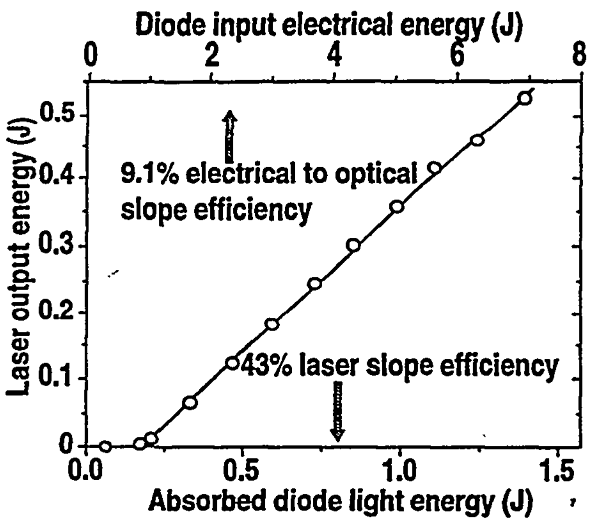

Figure 5. Diode-pumped Yb:S-FAP free-running laser output energy as a function of both absorbed diode light and input diode electrical energy. Laser slope efficiencies of 43% and overall electrical efficiencies of 9.1% were achieved.

V. Diode pumped oscillator performance

A free-running Yb:S-FAP oscillator was constructed and diode-pumped through an external lensing duct[5] delivery system which concentrated the diode light intensity. The pumped end of the Yb:S-FAP rod had a short pass coating while the other end of the crystal was had a long-pass coating such that most of the pump light was retro-reflected down the rod for a second pass. Initial results were obtained with five different output coupler reflectivities ranging from 68% to 97%, all with a 75 cm concave radius of curvature. The 76% reflective output coupler was found to produce the highest output energies of 0.55 J with a 1 ms pump pulse length. Since only radiative air cooling was present in the above test, the laser was run at 1 Hz to prevent fracture, although work at higher repetition rate is discussed later in this. Figure 5 presents the output energy from the oscillator constructed with the R=76% output coupler as a function of diode energy incident on the Yb:S-FAP rod. The diode input electrical energy is also plotted on the top axis. The slope of the oscillator output energy as a function of absorbed pump energy (laser slope efficiency) was measured to be 43% while the overall electrical slope efficiency was observed to be 9.1%.

From the slope efficiency data obtained with a variety of output couplers, a Findley-Clay analysis was performed. Cavity losses can be estimated by plotting the logarithm of the output coupler reflectivity versus

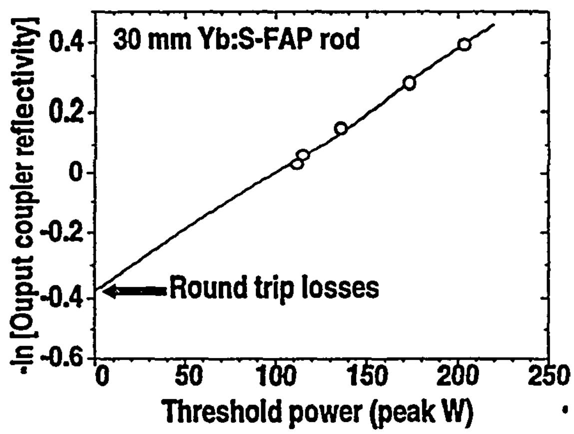

Figure 6. Logarithm of output coupler reflectivity versus threshold power of a diode-pumped free-running oscillator cavity. The intercept provides a measure of the total cavity losses.

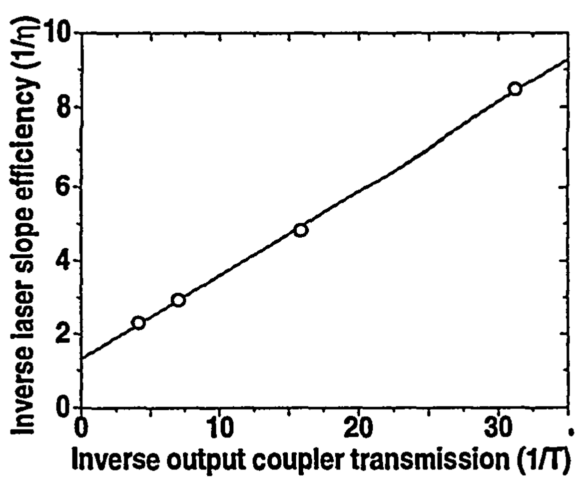

Figure 7. Diode-pumped Yb:S-FAP inverse laser slope efficiency versus inverse output coupler transmission for a diode-pumped free-running oscillator cavity. The Y-intercept and slope provide a measure of the intrinsic laser slope efficiency and the cavity losses, respectively.

the lasing threshold as shown in Figure 6. The output coupler reflectivity R, laser threshold P_{th} are related via the expression

$$-\ln(R) = aP_{th} - (L_{ext} + L_{int}) \qquad (2)$$

where L_{ext} and L_{int} are the extrinsic (e.g. impurity absorption) and intrinsic (quasi-four-level) losses respectively. Using Eq. 2, the data in Fig. 5 imply tot round trip loss (RTL) of 37.7%. By subtracting the measured coating RTL of 6.1% and the quasi-4-level RTL of 3.2%/cm leads to L_{ext}=2.1%/cm extrinsic losses. This is comparable to the measured absorption and scatter loss of 1.1%/cm, although there appears to be ~1%/cm loss unaccounted for. Perhaps this is due to fill factor considerations in the cavity.

An alternative method for obtaining similar cavity loss information is to plot the inverse slope efficiency η versus the inverse output coupling T as shown in Fig. 7. These parameters are related by

$$1/\eta = 1/\eta_o + L_{ext}/(T\eta_o) \qquad (3)$$

where η_o is the intrinsic laser slope efficiency (for zero cavity losses). The inverse intercept yields η_o=76% which is close to the ideal expected value of 86% (=900nm/1047nm) defined by the quantum defect. The slope times η_o leads to extrinsic cavity losses of 2.8%/cm after the known coating losses of 6.1% are subtracted. This extrinsic loss is similar to that obtained from the Findley-Clay analysis (2.1%/cm) described above. Consequently, we believe that future improvements in laser performance are possible with better rod coatings and less absorptive crystals at the laser emission wavelength.

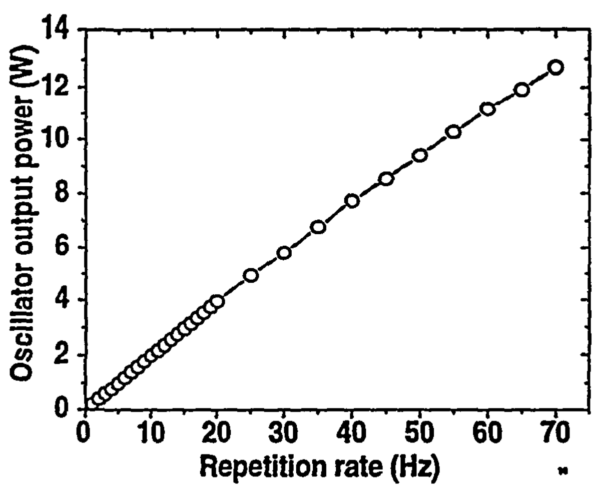

Figure 8. Diode-pumped copper block heat sinked Yb:S-FAP rod-oscillator operating at up to 70 Hz. A 500 μs pulse with 120A of drive current were utilized.

A diode-pumped free-running oscillator was also constructed with the addition of active cooling. This was accomplished by encasing a rectangular 3x3x30 mm Yb:S-FAP rod that was thermally contacted to a copper block that was water cooled to 10 °C. By operating the diode array with a 120A 500 μs pulse at 70 Hz, up to 13 W of average power was produced as shown in Fig. 8. The maximum repetition rate was power supply limited and no rods were observed to fracture under these conditions even after prolonged operation. An oscillator running under similar conditions but at 10 Hz was observed to have 0.3% rms pulse to pulse stability over one hour of operation and the long term amplitude drift was found to be less than 2% over a 14 hour period.

VI. Summary

In summary, a diode-pumped Yb:S-FAP laser has been successfully demonstrated for the first time and favorable efficiencies were observed with up to 0.5 J of output in 1 ms from a 3x3x30 mm rod. This was obtained with a 2.8 kW InGaAs laser diode array operating at up to 4% duty cycle. Yb:S-FAP laser slope efficiencies up to 43% were observed and intrinsic laser efficiencies (no losses) were inferred to be 76%. The overall electrical to optical slope efficiencies were observed to be 9% for this first demonstration. Up to 13 W of average power were also obtained with the addition of active cooling to the rod. The basic spectroscopic properties previously reported were found to properly described the physics of the laser media under operating laser conditions.

VII. Acknowledgments

We would like to thank L. DeLoach and K. Schaffers for sharing their technical expertise on the spectroscopic and crystal growth properties of Yb:S-FAP. We are also indebted to J. Tassano for constructing many of the laboratory facilities and to C. Orth for sharing his Yb:S-FAP amplifier system designs and calculations with us.

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This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.