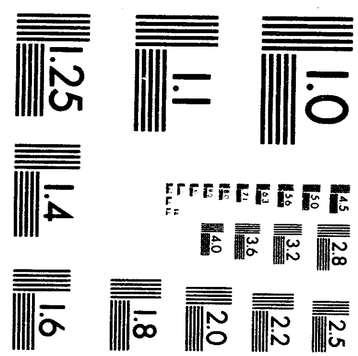
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Conf-940226--6

UCRL-JC-115513
PREPRINT

900-mW Average Power and Tunability From a Diode-Pumped 2.94-μm Er:YAG Oscillator

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This paper was prepared for submittal to the
Advanced Solid-State Lasers 9th Topical Meeting
Salt Lake City, Utah
February 7-10, 1994

January, 1994

Lawrence Livermore National Laboratory

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ABSTRACT

A diode-side-pumped Er:YAG laser generates > 500 mW at 2.94 μm, and tunes over a 6 nm range. Non-tunable versions generate > 700 mW with 8% optical efficiency, and > 900 mW with 5% optical efficiency. State dynamics and achieving higher average power are described.

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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SUMMARY

In this paper, we report on a diode-side-pumped Er:YAG laser that generates over 500 mW of average power at 2.94 μm, and tunes over a 6 nm range centered about the 2.94-μm transition. Prior to the development of the laser, diode-pumped Er:YAG lasers have been end-pumped monolithic devices that deliver ~ 200 mW of output at 2.94 μm.[1] Much of the difficulty in obtaining higher average power from Er:YAG stems from the unfavorable lifetimes of the upper and lower laser levels,[2] the complex state dynamics,[3] and a low stimulated emission cross section ($\sigma \approx 3 \times 10^{-20}$ cm^2).[4] One of the most important dynamical processes in Er:YAG is cross relaxation between neighboring Er^{3+} ions in the $^4I_{13/2}$ level.[2,5] By recycling much of the $^4I_{13/2}$ population (lower laser level) into $^4I_{11/2}$ (upper laser level), the cross relaxation overcomes the unfavorable lifetimes of the two levels, allowing the population inversion to be sustained. It is this cross relaxation along with thermalization of the two laser levels that allows cw oscillation on the 2.94 μm line to take place. The laser that we describe here is a quasi-cw device as our approach to obtaining higher average power and limited tunability relies on side pumping with a quasi-cw InGaAs laser diode array. In this way, a higher gain-length product is generated, which is necessary for extending the tuning range of the laser, and for overcoming the higher losses associated with a discreet-element resonator.

The Er:YAG oscillator, shown in Figure 1, is an angled resonator, in which the circulating 3-μm beam undergoes total internal reflection (TIR) off of a polished side face of the Er:YAG crystal. A similar TIR resonator has been used before in a recently developed, diode-side-pumped $Nd:YVO_4$ laser.[6] The advantage of the TIR resonator is that it is a side-pumping geometry that allows the gain to be well coupled into the resonating modes. This, in turn, leads to higher optical efficiencies comparable to those of end-pumped lasers. Since the cross relaxation rate increases with Er^{3+} concentration,[2] a further efficiency enhancing measure is to use more heavily doped Er:YAG material. Due to availability, the most heavily doped crystal used in our laser is 50% Er:YAG. The crystal has nominal dimensions of 2 mm x 2 mm x 14 mm. The end faces are oriented at Brewsters angle, and the TIR glancing angle is fixed at 8°. Apart from these features, the laser cavity is a 4-cm long plano-concave resonator with a flat 98.0% reflective output coupler (CaF_2 substrate), and a 5-cm radius-of-curvature high reflector. The tuning element is a 0.3 mm uncoated YAG etalon, where YAG is chosen because of its high transmission at 3 μm and its availability. The laser tunes as the etalon is tilted. A quasi-cw, 4-bar InGaAs laser diode array, emitting at 965 nm, pumps the oscillator through the side face of the crystal. Each diode bar in the array has a length of 1 cm, and a peak power of 70 Watts. The bars are bonded to separate microchannel cooling packages,[7] which upon stacking to form the array, result in a diode bar spacing of 1 mm. Three cylindrical lens elements couple the diode emission in the Er:YAG crystal. The first is a cylindrical microlens fastened directly to each diode bar package.[8] The microlens captures the fast axis of the diode bar, reducing the full angle divergence from 60° to 10 mrad. The remaining two elements are macroscopic cylindrical lenses with focal lengths of 25 mm and 6 mm. The 25 mm lens focuses the slow axis from each diode bar, while the 6 mm lens collapses the four near-collimated fast-axis outputs from the array to a single stripe at the crystal. The size of the stripe is 200 μm x 5 mm, resulting in a pump irradiance of 20 kW/cm^2.

Typically , the laser is operated at a repetition rate of 100 Hz and a pulse duration of 400 μs. Under these conditions, the laser, without the etalon, produces 710 mWatt at 2.94 μm. The optical-to-optical and the slope efficiencies are 8% and 13%, respectively. With the cavity mirrors removed, the gain-length product, $g_0 l$, is measured to be 0.05 ± 0.02 at the end of the 400-μs pump pulse. On the basis of measured threshold pump powers using 98%R and 99%R output couplers, we estimate the internal loss of the resonator to be 2 ± 1% per round trip. Even though the dominant emission line is at 2.94 μm, emission occurs at 2.83 μm and 2.70 μm as well. In keeping with notation found in the literature,[9] the 2.70, 2.83 and 2.94 μm transitions correspond to the 1→1, 6→7, and 2→7 Stark transitions of the $^4I_{11/2}$ - $^4I_{13/2}$ system, respectively. Here, the numbers label the Stark levels in the respective ^4I_J manifolds, 1 being the lowest level in a particular manifold. Figure 2 shows the temporal dependencies of the three emission lines when the laser is pumped for 700 μs. The three lines emit sequentially in the order 2.70 μm, 2.83 μm and 2.94 μm, with the first two lines quenching within 40 μs of the diode pulse leading edge. Such time dependent emission at several wavelengths has been observed before in lamp-pumped Er:YAG lasers.[9] The trend is always toward the red with increasing time. This is primarily because the levels involved with the red shifted lines are those with the most favorable Boltzmann factors for sustaining a population inversion.

The 2.94 μm emission line is 8 nm wide (FWHM), and thus affords limited tunability. The line center is at 2.936 μm. Figure 3 gives tuning curves for two 0.3 mm etalons. This etalon thickness is chosen to give a free spectral range comparable to the width of the transition. Consequently, the laser tunes without the complication of an etalon mode hop. The difference between the tuning curves is due to the thickness error (δl ~ 0.5 μm) in the etalons. Thus, while a single etalon gives a nominal tuning range of 4-5 nm, the pair of etalons allow complete coverage of the 2.933 - 2.939 μm range. Over this range, the output power varies from 30 mW to 580 mW, the output power being dependent on the frequency shift from gain peak and on the etalon tilt angle. In Figure 4, we show the dependence of the 2.94-μm power on the etalon tilt angle when etalon 2 is in the cavity. Since the laser output always has a 2.83-μm component, the 2.83-μm power dependence is shown as well. As the laser is tuned farther off the gain peak at 2.936 μm, laser emission at 2.83 μm becomes dominant. This is likely a result of hindered depletion of the sixth Stark level in the $^4I_{11/2}$ manifold as the 2.94 μm emission is suppressed.

Thermal lensing in the YAG rod, by causing the resonator to become unstable, limits the duty factor of the laser to 4%. With our plano-concave cavity, the resonator becomes unstable when the focal length of the thermal lens is less than the distance between the concave high reflector and the thermal lens (center of the crystal).[10] The focal length at which the resonator becomes unstable is 25 mm. Given that heat is removed on the three non-optical side faces of the crystal, the thermal load corresponding to this focal length is 8 Watts. The duty factor is easily increased by moving the high reflector closer to the crystal. With the distance from the high reflector to the thermal lens at 18 mm, the duty factor is 6%. As an alternate method for enhancing the duty factor, the Er:YAG crystal is replaced with an AR-coated 50% Er:YAG crystal with dimensions of 1 mm x 1mm x 15 mm, and a TIR angle of 4°. With this crystal, the laser operates at a duty factor of 11%, the limitation being the diode driver, not thermal lensing. When the pulse duration is 400 μs, the laser produces 920 mW at 2.94

μm with an optical efficiency of 5% (no etalon). The reduced optical efficiency is likely due to loss on the AR-coatings, such that with Brewster faces, output levels well in excess of 1 Watt should be achievable.

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Figure Captions

1. Diode-pumped Er:YAG laser. The laser is side pumped with a 4-bar InGaAs diode array.

2. Temporal dependence of the 2.70 µm, 2.83 µm and 2.94 µm emission lines from the Er:YAG laser.

3. Tuning of the Er:YAG laser by tilting a 0.3 mm YAG intracavity etalon. The two curves correspond to two different etalons.

4. Output power dependence on etalon tilt angle. Laser emission occurs at 2.94 µm and 2.83 µm.

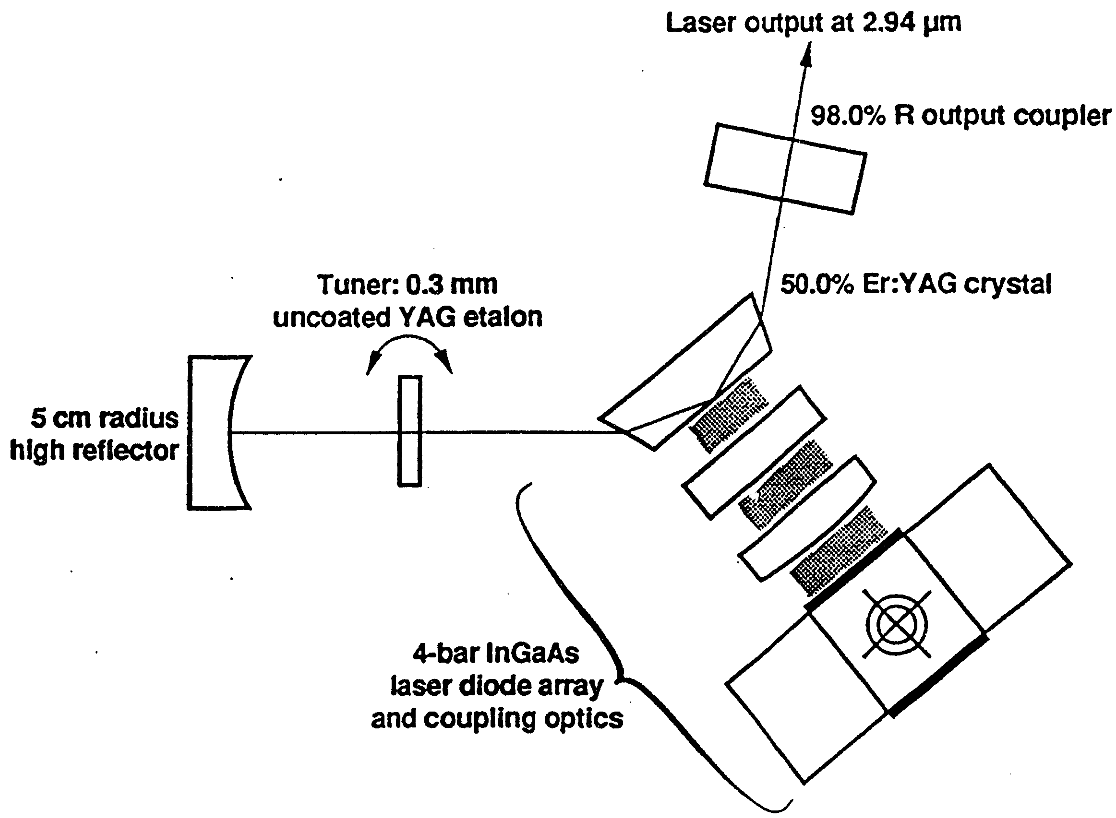

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Fig 1

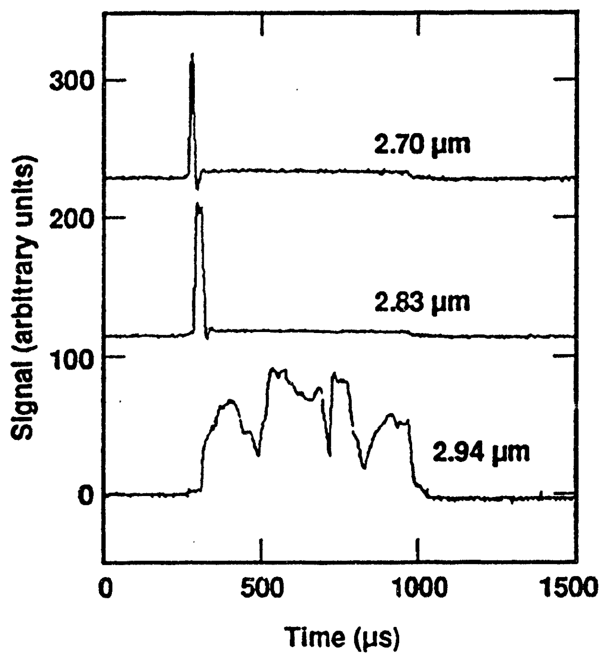

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Fig. 2

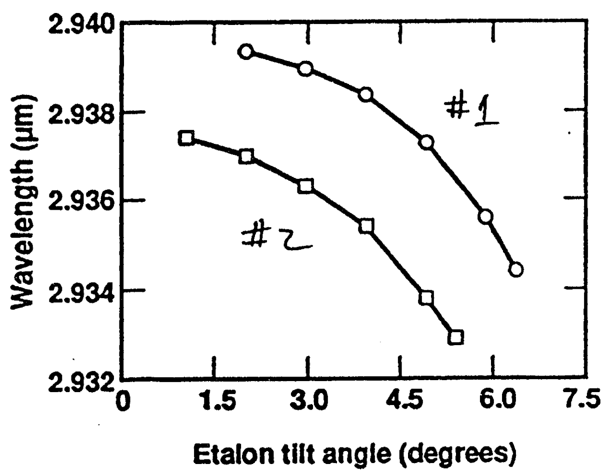

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Fig. 3

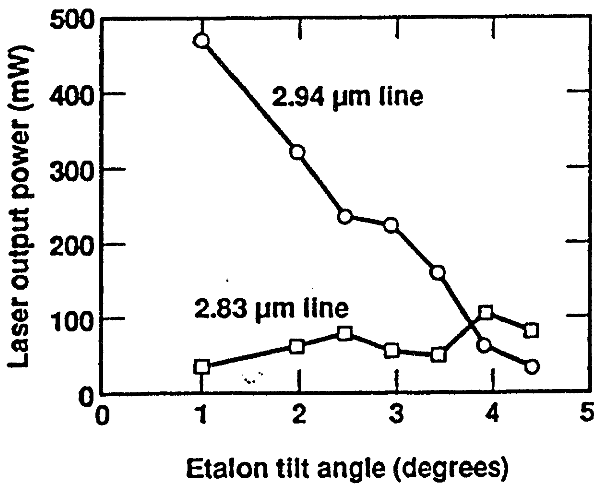

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Fig. 4

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