

Continuous-wave operation at 2.1 μm of a diode-laser-pumped, Tm-sensitized Ho:Y₃Al₅O₁₂ laser at 300 K

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Room-temperature operation of a continuous-wave Tm-sensitized Ho:YAG laser at 2.0974 μm has been achieved under diode-laser pumping at 781.5 nm. Observed thresholds are as low as 4.4 mW, with a slope efficiency of 19% with 0.5% output coupling.

The 2.1- μm 5I_7 - 5I_8 laser transition in Ho³⁺ is attractive because of its long upper laser level lifetime, of the order of 5 msec, and its eye-safe wavelength. However, this laser typically is cooled to liquid-N₂ temperatures to achieve continuous-wave (cw) or high-repetition-rate operation because its lower laser level is in the ground-state manifold, a few hundred inverse centimeters above the ground state, and therefore is populated at room temperature. Despite the three-level nature of this transition, we initiated a study of diode-laser pumping because the long upper laser level lifetime may permit larger energy storage than Nd:YAG for the same continuous pump power and because of the interest in eye-safe wavelengths for coherent radar and medical applications.

We recently reported the first cw, diode-laser-pumped operation on this transition at room temperature¹ by codoping a Ho:YAG crystal with Tm³⁺. Here, the Tm³⁺ ion is pumped by a diode laser followed by energy transfer to populate the Ho 5I_7 upper laser level. Cw operation at room temperature was previously achieved in Ho³⁺-doped garnets codoped with Cr³⁺ and Tm³⁺ by pumping with a Kr⁺ laser into the Cr³⁺ absorption bands.^{2,3} Energy is transferred to Tm³⁺ and then to the Ho³⁺ 5I_7 upper laser level. Pulsed room-temperature operation also is possible under flash-lamp pumping⁴⁻⁶ by codoping⁷ the crystal with other ions such as Er³⁺, Tm³⁺, and Cr³⁺ to absorb a larger fraction of the pump power and achieve higher pumping densities.

In this Letter we report in more detail on 300-K operation in Ho:YAG codoped with Cr³⁺ and Tm³⁺. Diode-laser pumping at 77 K was demonstrated in Ho:YAG.⁸ Diode-laser-pumped operation of the 946-nm transition in Nd:YAG with a similar three-level nature at 300 K was reported recently, indicating that population in the lower laser level is not a fundamental difficulty.⁹ Our work is the first reported demonstration of the use of codoping for lowering the threshold and obtaining room-temperature operation of a three-level laser system under diode-laser pumping.

The work also points to the possibility of overcoming the large quantum defect by an energy-transfer process.

Figure 1 shows the energy-level diagram and pumping scheme. The Tm³⁺ 3F_4 manifold is pumped by the AlGaAs diode laser. This is followed by either radiative and nonradiative relaxation to the 3H_4 state or a cross-relaxation process between adjacent ions, Tm(3F_4 - 3H_4)-Tm(3H_6 - 3H_4), which converts one 3F_4 excited state into two 3H_4 states. For high enough Tm³⁺ doping densities this cross-relaxation process can be efficient and lead to an overall pump quantum efficiency of nearly 2. There is fast spatial energy migration among the Tm³⁺ ions, subsequent energy transfer to the Ho 5I_7 energy level, and finally laser action on the Ho 5I_7 - 5I_8 transition.² In diode-laser pumping Cr³⁺ plays no active role, but it is convenient to have Cr³⁺ in the crystal to allow for pumping into the 4T_2 Cr³⁺ absorption band by a higher-power source such as a Rhodamine 6G (R6G) dye laser or a Kr⁺ laser. The laser scheme for pumping with one of these sources is similar to that for diode pumping except for an additional Cr³⁺ to Tm³⁺ energy-transfer step.²

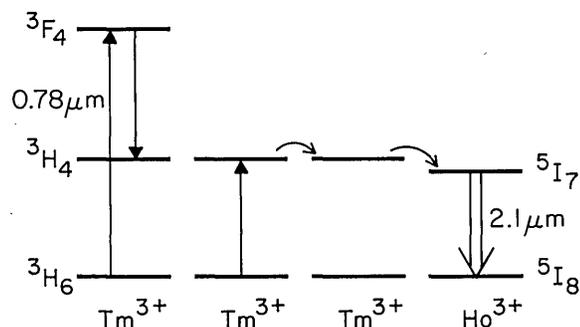


Fig. 1. Energy-level scheme illustrating pumping the 3F_4 Tm manifold, Tm-Tm cross relaxation, Tm-Tm energy migration, Tm-Ho energy transfer, and finally laser action on the Ho 5I_7 - 5I_8 transition.

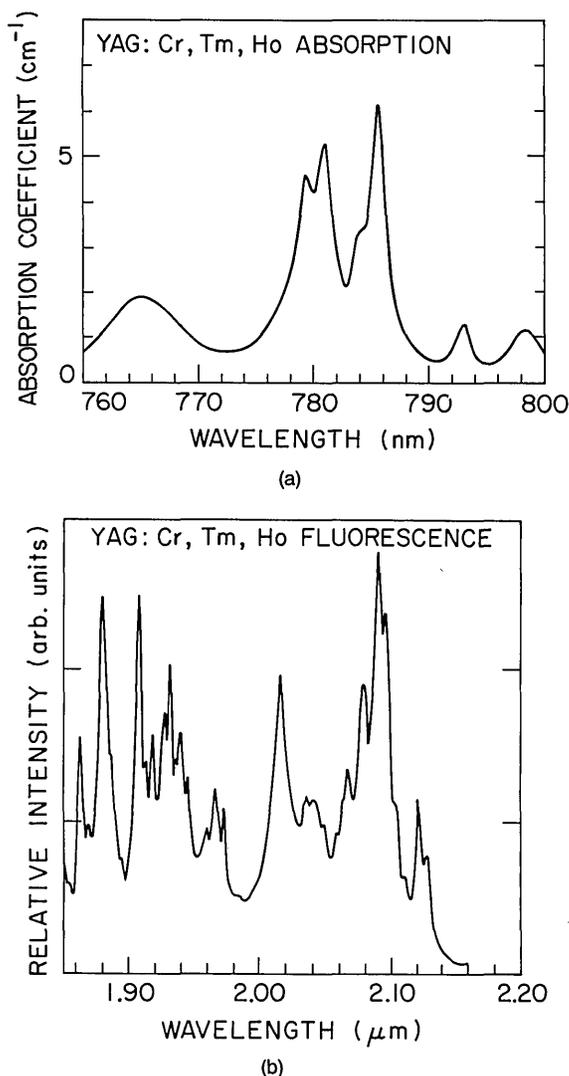


Fig. 2. (a) Absorption spectrum of Tm^{3+} in YAG in the near infrared. (b) Emission spectrum of Ho ion in YAG.

The laser crystals used in this experiment were grown by a standard Czochralski technique. The nominal doping levels are $2.5 \times 10^{20} \text{ cm}^{-3} \text{ Cr}^{3+}$, $8 \times 10^{20} \text{ cm}^{-3} \text{ Tm}^{3+}$, and $5 \times 10^{19} \text{ cm}^{-3} \text{ Ho}^{3+}$. The low Ho^{3+} concentration keeps the reabsorption loss at 300 K due to population in the lower laser level to only 0.07 cm^{-1} . This lower laser level is at $\sim 462 \text{ cm}^{-1}$ above the ground state for the $2.0974\text{-}\mu\text{m}$ transition.¹⁰ The $\text{Ho}^{5}I_7$ lifetime was measured to be 3 msec, which is much longer than the $240\text{-}\mu\text{sec}$ Nd:YAG lifetime, showing that high-energy storage is possible in this material. However, a measurement in another YAG sample with similar Tm^{3+} and Ho^{3+} doping levels with no Cr^{3+} yielded a lifetime of 8.5 msec. The reason for the difference in lifetime between the crystals is unclear, but one possibility may be additional impurities in the Cr-doped sample.

The $\text{Tm}^{3}H_6\text{-}^3F_4$ absorption and $\text{Ho}^{5}I_7\text{-}^5I_8$ emission spectra are shown in Fig. 2. This absorption lies in a wavelength region where diode lasers and diode-laser arrays are currently available. Based on the concentration of Tm^{3+} , the effective absorption cross sections

at 781.5 and 785.5 nm are near $7 \times 10^{-21} \text{ cm}^2$. The absorption line centered at 780 nm is particularly attractive for diode pumping because of its linewidth of 4 nm full width at half-maximum, which is large compared with 1 nm for the strongest absorption line in Nd:YAG. A fluorescence spectrum near $2 \mu\text{m}$ was measured previously and is shown here for reference.³ The multiple-peaked spectrum suggests that it may be possible to tune the laser over a reasonable wavelength range.¹¹ The fluorescence extends into the $1.9\text{-}\mu\text{m}$ H_2O absorption band, which is important for medical applications.

A schematic of the experimental apparatus is shown in Fig. 3. A cw R6G dye laser operating near 590 nm and a single-stripe AlGaAs diode-laser output are combined at a dichroic beam splitter. The diode laser is temperature controlled to tune its output wavelength to the peak absorption at 781.5 nm. The beams pass through a 4-cm focal-length lens and are focused into the cavity. The dye-laser pump beam was focused to a spot $\sim 20 \mu\text{m}$ in radius and the diode laser to an elliptical spot $\sim 10 \times 14 \mu\text{m}$ in radius. The laser cavity mirrors are a 2.5-cm radius-of-curvature high reflector at $2.1 \mu\text{m}$ and a 5-cm radius-of-curvature 99.5% reflector. These are spaced so the cavity is nearly concentric with the sample at the cavity mode waist. The sample was cut and polished at 1.14 mm thick and antireflection coated at $2.1 \mu\text{m}$. For this sample thickness 53% of the incident pump light at 590 nm is absorbed; at 781.5 nm, 48% is absorbed. Any residual pump light was blocked by a filter and the output monitored using a PbS detector.

Figure 4 shows the output under both diode-laser pumping and R6G dye-laser pumping. The diode-laser results are for true cw operation; the R6G-laser results are for quasi-cw operation with $\sim 10\text{-msec}$ pump pulses and 30% duty cycle, although true cw operation was possible. The absorbed power thresholds are 4.4 and 6.2 mW for diode-laser and dye-laser pumping, respectively. This power for diode-laser pumping corresponds to an average threshold pump power density of 18 kW/cm^3 . A fit to the highest three data points for diode pumping yields a slope efficiency of 19%. Under dye-laser pumping, we were able to obtain up to 7.2-mW output for 62-mW absorbed power with a slope efficiency of 13% for operation well above threshold.

One would expect the diode-laser pump results to be

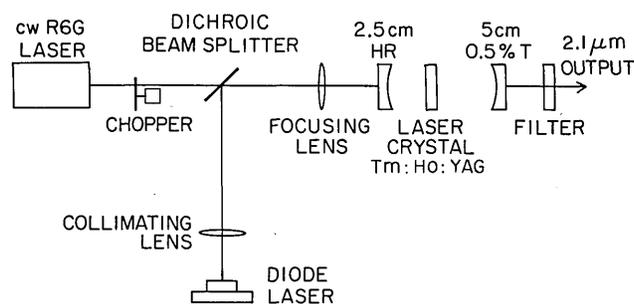


Fig. 3. Schematic of the experimental apparatus for dye- and diode-laser pumping of Tm:Ho:YAG.

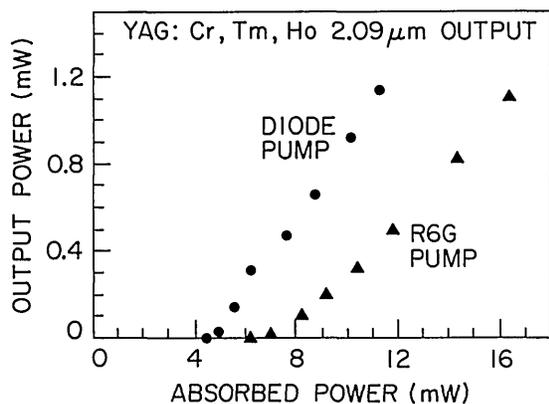


Fig. 4. Output power near 2.1 μm as a function of the absorbed pump power for both the diode laser and the R6G laser. Slope efficiency for diode-laser pumping is 19% for a 0.5% transmittance output coupler.

better than those obtained under R6G laser pumping because of the lower pump photon energy (i.e., lower quantum defect) and the need for one less energy-transfer step. The photon energy is 1.3 times higher for the R6G laser, and the Cr-Tm energy-transfer efficiency is estimated to be 0.8–0.9,⁵ so the R6G laser slope efficiency should be ~ 0.65 times that for diode pumping on the basis of absorbed pump power. Our data are in good agreement with these expectations.

It should be possible to obtain lower thresholds and higher slope efficiencies. As previously noted, an almost three-times-longer upper-state lifetime has been measured for a sample without Cr^{3+} doping. Such an increase in lifetime could lower threshold by a factor of nearly 3. Higher slope efficiencies should be achievable by increasing the value of output coupling from the relatively low value used in this work. For example, if the Tm-Tm cross relaxation is high enough for the pump quantum efficiency to be 2, the upper limit on diode-laser-pumped slope efficiency is 74%, compared with 76% for Nd:YAG. Thus this transfer laser system offers the potential for diode-laser pumping without the penalty of low efficiency due to a large quantum defect. We are performing spectroscopic measurements to model the system and see whether the Tm^{3+} and Ho^{3+} dopant concentrations can be optimized. Currently, there are no adequate models to derive such quantities as the population inversion density at threshold. Some of the important issues that remain to be understood include net Tm-Ho transfer efficiency, efficiency of Tm-Tm cross relaxation, and energy-transfer upconversion processes.

However, these initial results show that this laser is quite attractive for diode-laser pumping at room temperature.

In summary, we have demonstrated the first reported cw, room-temperature, diode-laser-pumped Tm:Ho:YAG energy transfer laser with output at 2.1 μm , which may have important applications in medicine and coherent laser radar.¹² This work shows promise for use of energy transfer as a means of utilizing existing diode lasers for excitation and as a method of obtaining room-temperature operation for three-level laser systems.

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