TECHNICAL NOTE

# Laser-diode end-pumped $Tm^{3+}$:YAG eye-safe laser

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The lasing characteristics of a laser-diode end-pumped Tm:YAG laser were investigated. We obtained a laser output power of 124 mW, a slope efficiency of 36%, and a threshold power of 77 mW with a 3% Tm-doped YAG crystal at room temperature. This lasing performance was improved when the crystal was cooled. The dependencies of both slope efficiency and threshold power on temperature were measured.
*Key words:* $Tm^{3+}$YAG laser, eye-safe laser, laser-diode end-pumped laser. 

## 1. Introduction

There has been much interest in the development of an eye-safe laser as a source for remote sensing.[1] In particular a laser-diode (LD) end-pumped $Tm^{3+}$:YAG laser (Tm laser) is expected to be an important candidate for such applications in the 2-μm-wavelength region, because it has been shown to be a highly efficient laser.[2,3] Moreover, it can oscillate between 1.87 and 2.16 μm,[4] which contains the strong absorption band of water vapor.[5] Therefore the Tm laser is particularly promising for both laser radar and medical applications. For these reasons we have studied the lasing performance of the Tm laser as a function of Tm concentration, pumping power from the LD, and output coupling so as to determine the optimum operating condition of this laser.

The Tm-laser results reported here are for end pumping by a cw LD. The LD (made by Sony) had a maximum output power of 1 W at a wavelength of 785 nm. A collimating lens with a 6-mm focal length, a cylindrical lens with a 400-mm focal length, and a focusing lens with a 50-mm focal length were used to focus the light emitted from the LD onto the laser crystal. The spot size of the pumping beam on the crystal was measured to be approximately 340 μm × 140 μm.

Although the crystals used in the present experiments had three different Tm concentrations (3%, 6%, and 12%). Their different lengths (4, 1.8, and 1 mm, respectively) gave them the same absorption. Each crystal was coated for antireflection at 785 nm and high reflection at 2 μm on the pumping side and antireflection at 2 μm on the other side. The temperature of the crystal could be controlled by use of a thermoelectric cooler within an accuracy of 0.1 °C. A coupling mirror with a curvature of 100 mm was placed approximately 100 mm away from the opposite surface of the crystal. The output power was measured with a PbS detector and a power meter placed behind a Si plate so as to avoid the transmitted pump at 785 nm.

## 2. Results and Discussion

### A. Dependence of Output Power on the Reflectivity of the Output Mirror

Figure 1 shows the output power as a function of the absorbed power for several reflectivities of the coupling mirror at room temperature. Approximately 60% of the incident power of the LD was absorbed by the 3% Tm:YAG rod at room temperature. The threshold value of the 3% Tm:YAG laser with a 99%-reflectivity mirror was found to be 77 mW from this figure. An output power of 120 mW was obtained for an absorbed power of 400 mW with a slope efficiency of 36%. The output power and the slope efficiency decreased for the 97%-reflectivity coupling mirror. But in the case of a reflectivity of 99.3% they were comparable to the values for the 99%-reflectivity mirror. The reduction in slope efficiency as the reflectivity drops below 99% indicates that upconversion loss becomes significant[6] at a gain of $\geq 3\%\ cm^{-1}$ in this crystal.

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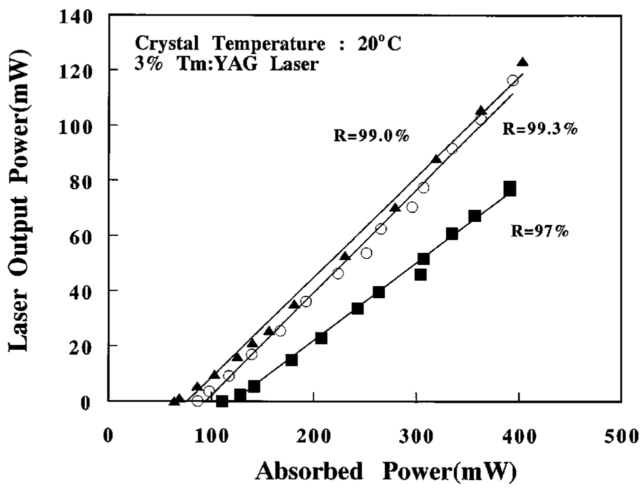


Fig. 1. Laser output power from Tm(3%):YAG laser with various output couplings at room temperature (20 °C).

### B. Dependence of Output Power on Tm-Dopant Concentration

The threshold power and the slope efficiency also depend on the Tm-dopant concentration of the laser crystal. Figure 2 presents the output power when the Tm concentrations changed in the laser crystal at room temperature. The slope efficiency decreases with the increase in Tm concentration. The slope efficiency for 12% Tm:YAG was approximately one half that for 3% Tm:YAG. The threshold power was less sensitive to change in Tm concentration and only increased slightly with increasing Tm concentration. The lower slope efficiency for higher dopant concentration can be explained in terms of the migration-limited nature of the upconversion of the upper-laser-level process at low dopant concentration.[6] The effect of upconversion loss on threshold was not as noticeable, probably because the longer length of the lower-concentration crystals made them more susceptible to the undesirable diffraction of the pump beam within the crystals. The latter effect would favor the shorter, i.e., the higher-concentration, crystals.

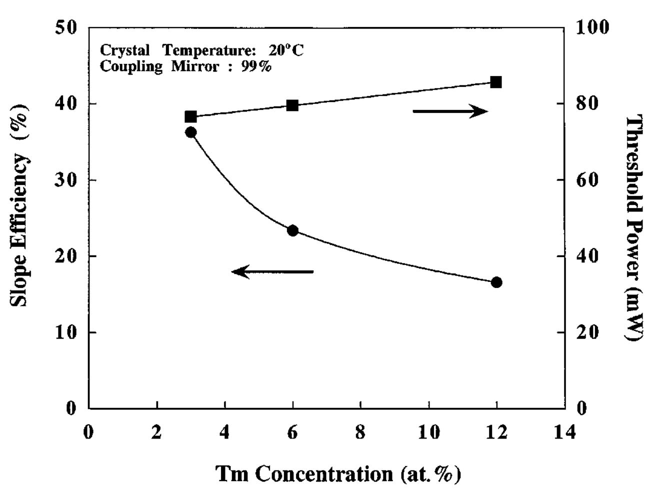


Fig. 2. Laser performance of the Tm-doped YAG laser as a function of the Tm-dopant concentration at the crystal temperature of 20 °C.

### C. Dependence of Output Power on Temperature

Because the Tm:YAG laser is a quasi-three-level laser, the threshold power and the slope efficiency are expected to depend on the crystal temperature.[7] Figure 3 presents the threshold power and the slope efficiency of the 3% Tm:YAG laser as functions of the crystal temperature. A slope efficiency of 44% and a threshold power of 46 mW were obtained at a crystal temperature of −10 °C. The slope efficiency at 40 °C was approximately 50% smaller than that at −10 °C. The threshold power, on the other hand, jumped by more than a factor of 2 for the same change in temperature. The latter effect can be easily understood on the basis of the Boltzmann distribution of the various Stark components within the lower laser manifold. Because the lower level of the laser transition corresponds to the Stark component lying 588 $cm^{-1}$ above the true ground state,[8] its population grows rapidly as the temperature is raised. This makes it more difficult to achieve inversion on the transition, thus raising the threshold dramatically. The drop in slope efficiency at higher temperature is probably due in part to the reduced ability to extract power from the outer regions of the pumped cross section, which remain below threshold even under maximum pumping.

Figure 4 presents the change in the lasing spectrum of the Tm:YAG laser as the crystal temperature is varied. The lasing wavelength extends from 2011 to 2018 nm at the crystal temperature of 20 °C. The center of the lasing spectrum shifted to a shorter wavelength when the crystal temperature was lowered. The shift in wavelength was more than 2 nm for the change in temperature from 40 °C to −10 °C. The width of the lasing spectrum also decreased with the lowering of the crystal temperature, going from 5 to 2 nm when the crystal temperature was decreased from 40 °C to −10 °C. Both the shift and the change in emission width probably have their origin in changes in the absorption and emission line profiles

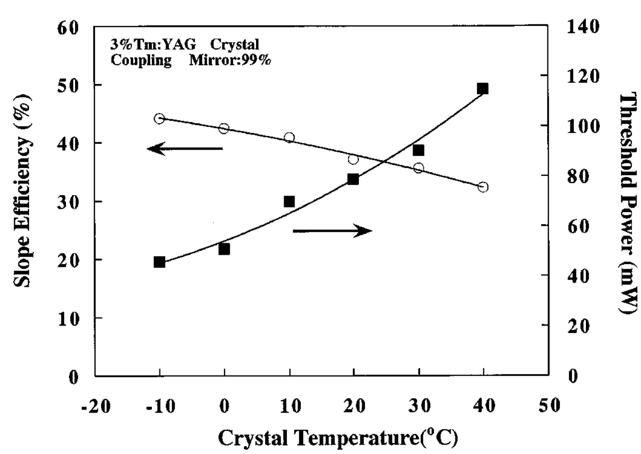


Fig. 3. Slope efficiency and threshold power of the Tm(3%):YAG laser as a function of the crystal temperature.

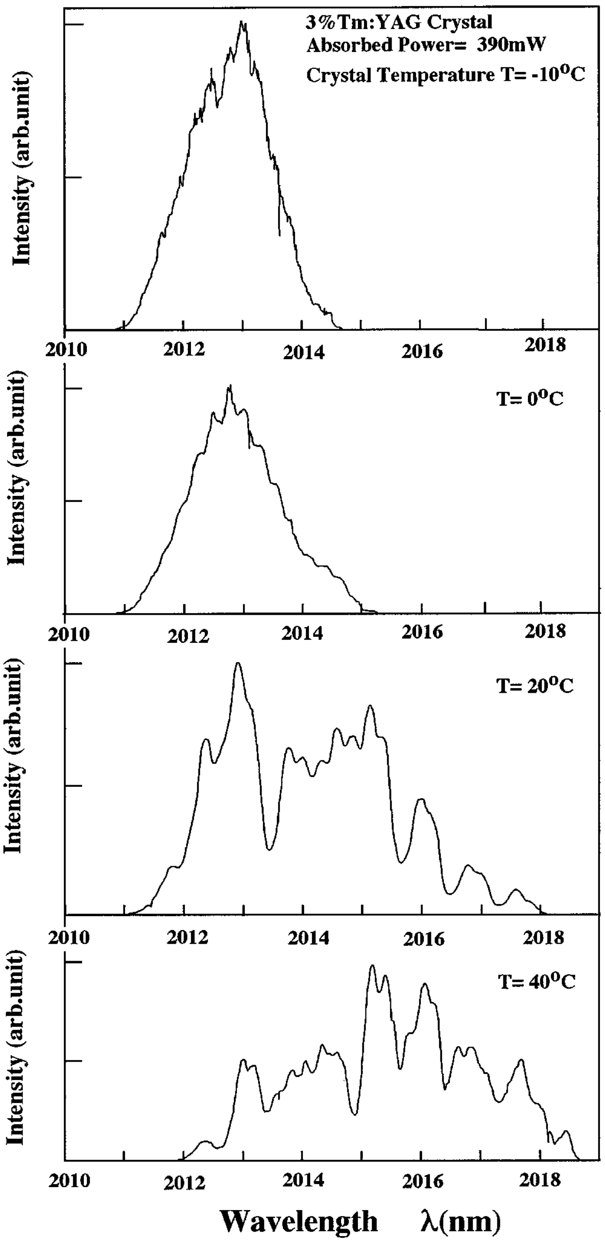


Fig. 4. Change in output spectrum of the Tm(3%):YAG laser with the crystal temperature for absorbed pump power of 390 mW.

with temperature. The dips in the emission spectra are due to intracavity absorption by water vapor lines. In addition, the lasing spectrum of the Tm laser as a function of the absorbed pump power was measured. The width of the lasing spectrum was approximately 1.5 nm for the near-threshold condition. It grew with larger amounts of absorbed pump power. A width of 4 nm was obtained at the absorbed pump power of 390 mW. This can be explained by the well-known phenomenon of spatial hole burning. As pump power is increased, gain in the wings of the gain profile in the valleys of the standing-wave laser modes also increases. When sufficient gain is realized at those wavelengths, lasing would occur.

### 3. Conclusion

The performance of a cw laser-diode (LD) end-pumped Tm:YAG laser has been extensively characterized. These results are directly applicable to the scaling of this laser to higher power levels. They will also be useful in the design of single-frequency microchip Tm:YAG lasers.

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