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High Power 2 μm diode-pumped Tm:YAG laser

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ABSTRACT

Using a scalable diode end-pumping technology developed at Lawrence Livermore National Laboratory we have demonstrated a compact Tm:YAG laser capable of generating greater than 50 W of cw 2 μm laser output power. The design and operational characteristics of this laser, which was built originally for use in assessing laser surgical techniques, will be discussed.

The 2 μm radiation produced by the 3F4−3H6 transition of Tm3+ has many practical applications because it is strongly absorbed by water and also because it is an ‘eye-safe’ wavelength. The strong absorption of 2 μm radiation by water makes this transition a very attractive candidate for performing laser surgical procedures as most tissue types are predomately composed of liquid water. The fact that 2 μm radiation is considered ‘eye-safe’ makes this transition attractive for laser range finding and remote sensing applications where other laser wavelengths could pose a safety hazard. At sufficiently high doping densities, Tm3+ exhibits a beneficial two-for-one quantum pump efficiency enabling well developed AlGaAs laser diode arrays to be used as efficient excitation sources. Many applications requiring 2 μm laser radiation such as remote sensing, laser radar, anti sensor, sensor spoofing, and OPO pumping have driven the development of diode pumped all solid state Tm3+ laser systems because of their potential for efficiency, compactness, and ruggedness. Here we focus on Tm3+:YAG and the scalable diode end-pumping technology developed at LLNL which enables higher average power operation of diode pumped Tm3+ laser systems than has previously been possible. Figure 1 shows a schematic the layout of our laser.

Figure 2 shows a scaled drawing of the actual cw Tm:YAG laser system. To date we have demonstrated cw operation of this laser to power levels of 51 W. The end-pumping technology used is the same as was previously used to demonstrate a 100 mJ Q-switched Nd:YLF laser1. A microlens conditioned stack of laser diode arrays having an overall aperture of 2.5 cm x 1 cm and consisting of 24 silicon microchannel cooled modules, each carrying a 1 cm long laser diode bar and microlens as shown in Fig. 3, has its output radiation delivered to the end of a Tm:YAG laser rod that is 2.5 mm in diameter and 5 cm long and doped with 4% Tm. The purpose of the microlenses is to collimate the fast axis radiation.
from the laser diode arrays. By expanding and collimating the fast axis radiation from individual bars, but not increasing the overall aperture area, the effective radiance of the diode arrays (where effective means the radiance referenced to the overall aperture area), can be increased without violating the conservation of radiance. Once the pump radiation is conditioned it can then be delivered to the end of the laser rod with very high efficiency by the lens duct that works by both lensing the conditioned pump light at its curved input face and then ducting the pump light down to the rod aperture by total internal reflection off its canted planar sides. The laser rod itself is held in a cooling jacket that permits water to be flowed along its length during laser operation.

To allow average power scaling of this laser it is not possible to pump at the peak of the $^3\text{H}_6-{^3}\text{H}_4$ absorption feature located at 785 nm as is conventionally done in end-pumped Tm$^{3+}$:YAG lasers. This is because in the heavily doped samples that give two-for-one pump quantum efficiencies, the resulting absorption length of the pump in the rod is too short to allow for effective thermal management in the rod. These short absorption lengths in turn lead to high intensity thermal generation near the pump input face of the laser which results in unacceptable temperature rises in the rod there, negatively impacting the systems performance. Our analysis and experimental results demonstrate that wing pumping of the Tm$^{3+}$ off the peak of the main absorption feature can still be effective at creating sufficient inversions to overcome ground state reabsorption and allow for efficient laser operation while at the same time allowing the pump to penetrate deeply enough into the sample that the resulting thermal load becomes manageable. To illustrate the importance of the wing-pumping on thermal management, the present wing-pumped system is calculated to be at 15% of fracture at the pump input end of the Tm doped portion of the laser rod when operating at an output power of 50 W cw. If the pump wavelength were at the 785 nm peak of the absorption feature rather than the 805 nm wing-pumped value, the calculated loading would be 100% of thermal fracture at this operating point.

The laser rod itself has a polished barrel finish over its entire length allowing the pump light that enters the rod at the pump input end to be efficiently ducted down the rod due to TIR confinement. The pump input end of the rod is dichroically coated to be transmissive at the pump wavelength and reflective at the 2.01 µm laser wavelength. The other end of the laser rod is AR coated at the laser wavelength and 90% reflective at the pump wavelength. This allows the pump light to be effectively double passed up and back down the laser rod. The wavelength of our pump laser diodes was 805 nm which corresponds to a 1/e pump absorption distance of 2.5 cm in the 4% doped rod used here. To date we have demonstrated optical-to-optical slope efficiencies of 24% and cw optical output powers up to 51 W as displayed in Fig. 4. In this figure the cw optical output power is plotted against total pump power measured at the diode array before the microlenses so that the quoted efficiency includes the collection efficiency of the cylindrical microlenses used to condition the diode output radiation as well as the delivery efficiency of the lens duct. In the present system the collection efficiency of the cylindrical microlenses is 0.71 and the delivery efficiency of the lens duct for the microlens conditioned pump light is 0.98 giving an overall pump delivery efficiency of 0.7.
One of the key technical developments that has enabled the level of performance we have achieved to date with the system was the use of a laser rod having undoped end-caps fusion bonded to both ends of the Tm:YAG laser rod as shown in Fig. 1. This end caps are 3 mm in length and effectively isolate the uncooled ends of the laser rod from the thermal loaded portion of the rod corresponding to the doped portion of the laser rod. We have found the use of such laser rods with undoped end-caps to be critical to the performance of the laser. As a point of comparison, using the same laser with a laser rod not having an undoped end-cap, but in other ways identical to the one with the undoped end-cap, the maximum cw output power we could obtain from the system was 6 W at which point the laser output began to roll over because of the heat generated at the pump input face. An additional benefit of the undoped end-caps is that the dichroic coatings see a nearly uniform temperature profile as they are sufficiently removed from the heat source.

In summary we have demonstrated a Tm$^{3+}$:YAG laser with an output power capability of 51 W cw. This level of performance was demonstrated on a system using a number of new developments and innovations such as: the scalable diode end-pumping technology that has been developed at LLNL, wing-pumping the Tm$^{3+}$ off to the side of its main absorption feature at 785 nm to give a manageable thermal load, and the inclusion of laser rods incorporating undoped end-caps fusion bonded to the doped portion of the laser rod to isolate the thermally loaded portion of the laser rod from its uncooled ends.

We gratefully acknowledge the expert technical assistance provided by Helmuth and Oliver Meissner at Onyx Optics in Dublin, CA who fabricated the laser rods with the undoped diffusion bonded end-caps that were used in our system and Ralph Hutchinson of Scientific Materials in Bozeman, MT for the Tm:YAG and undoped YAG that was used in fabricating these laser rods. We also gratefully acknowledge many useful conversations with Steve Payne, Bill Krupke, and Rich Solarz all of Lawrence Livermore National Laboratory.
Fig. 1. Schematic layout 2 μm Tm:YAG laser using LLNL’s scalable diode end-pumping technology.

Fig. 2. Exploded diagram showing the layout of the Tm³⁺:YAG laser.

Fig. 3. Cross-sectional view of LLNL silicon microchannel cooler diode package with cylindrical microlens attached.

Fig. 4. Measured cw performance of 50 W cw Tm³⁺:YAG laser. The model prediction uses one adjustable parameter, the 1-way cavity transmission excluding reabsorption losses and output coupler losses which was set at 0.98.

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Fig. 2

- Output Coupler
- Rod Assembly
- Duct Assembly
- Diode Array
- Water Connector
- Electrical Connector

Dimensions:
- 3.063”
- 9.750”
Wing-pumped cw Tm:YAG DPSSL

![Graph showing the relationship between 2 micron cw laser output (W) and 805 nm cw pump input measured before microlenses (W)].

- Experimental data
- Model prediction

Slope efficiency = 0.24 W/W

Fig. 4