High-Pulse Energy Q-switched Tm^{3+}:YAG Laser for Nonlinear Frequency Conversion to the Mid-IR

Georg Stöppler, Christelle Kieleck, Marc Eichhorn

Institut Franco-Allemand de Recherches de Saint-Louis,
5 rue du Général Cassagnou, 68301 Saint-Louis Cedex, France

ABSTRACT

For some medical fields in laser surgery and as a pump source for nonlinear materials to generate mid-IR radiation, e.g. for countermeasure applications, it is very useful to have a solid-state laser with high pulse energy at 2 μm. The rare earth ion Thulium offers a cross relaxation and can thus be directly diode pumped with common laser diodes around 800 nm for an efficient pumping. However, it was not considered for high pulse energy operation due to the high saturation fluence of around 62 J/cm^2 at 2 μm. A limiting factor has always been the damage threshold of the optical elements inside the cavity. One of the reasons is the strong thermal lens of YAG, which affects a change of the beam radius inside the resonator and additionally degrades the beam quality with increasing pump power. Using a new pump geometry of the Tm^{3+}:YAG laser system, it is now possible to reach pulse energies > 13 mJ at a diffraction limited beam quality of $M^2 < 1.1$. The Q-switched Tm^{3+}:YAG laser system uses an AOM operating at 100 Hz and will be described in detail. Due to the high pulse energy and very good beam quality, this laser is very interesting for nonlinear parametric frequency conversion.

Keywords: Thulium, Tm:YAG, Q-switch

1. INTRODUCTION

Since several years laser sources emitting around 2 μm have gained strong interest for a lot of applications in medical, commercial and military fields and as a pump source for nonlinear materials. One of the main reasons of the fast development in these areas are the relatively cheap diode lasers for direct solid-state laser pumping with hundreds of Watts to kW for wavelengths from 780 nm to 805 nm. Tm^{3+}:YAG can be directly diode-pumped with common diode lasers in this 800 nm band and emits efficiently around 2 μm due to its well-known cross-relaxation process at doping levels around 2 % - 4 %. In pulsed operation, however, the high saturation fluence of Tm^{3+}:YAG ($\sim$ 62 J/cm^2) will make it difficult to achieve a high pulse energy with Q-switching at a good extraction efficiency.[1] Furthermore, Tm^{3+}:YAG has an upper laser level fluorescence lifetime of around 10 ms - 12 ms. Thus pulsed pumping has to be considered to allow high-efficient operation at repetition rates below 500 Hz. These two special features have to be taken into account for high-energy Q-switching. In addition, YAG shows a positive thermal lens which has to be taken into account for optimum cavity design and best beam-quality.

1.1 History and challenges of the diode-pumped 2 μm Tm^{3+}:YAG laser

A lot of publications show direct pumping of Tm^{3+}:YAG around its strongest absorption peak at 785 nm (Fig. 1) which is well suited for low pump power. The doping concentration of Tm^{3+}:YAG should be in the range of 2 % - 4%. A lower doping concentration results in lower cross-relaxation efficiency and at a higher concentration strong upconversion losses will be present. Pumping at this pump wavelength allows only short rod lengths but offers a well confined volume for pumping with diode lasers. Thus, it is possible to pump along the rod with a collimated beam from the diode laser. However, at high pump power the temperature inside the rod increases significant due to the small volume and the relatively large diameter of the rod, i.e. the long heat transport distance from the active regime to the cooled barrel surface. The quasi-three-level material Tm^{3+}:YAG shows a

Further author information: (Send correspondence to Georg Stöppler)
E-mail: Georg.Stoeppler@isl.eu, Telephone: +33 (0)3 89 69 51 69

Technologies for Optical Countermeasures VII, edited by David H. Titterton, Mark A. Richardson,
Proc. of SPIE Vol. 7836, 783609 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.864435

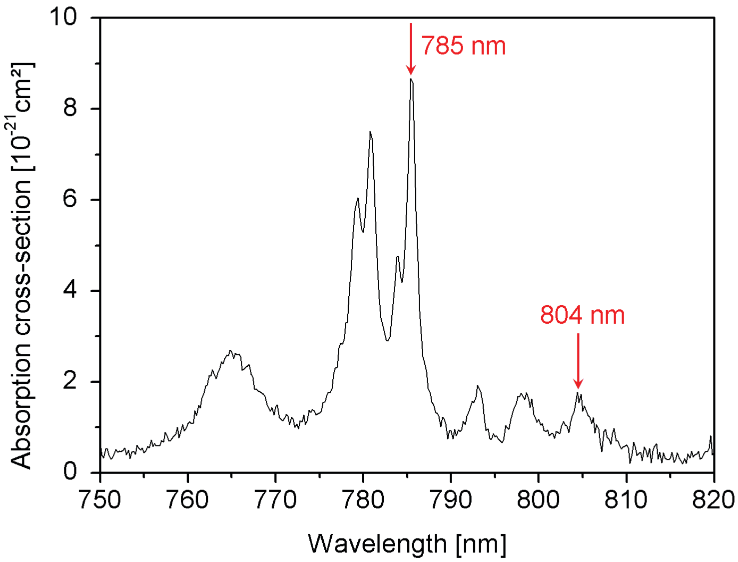

Figure 1. Absorption cross section of TM:YAG with 2% doping concentration

strong reabsorption with increasing temperature. Thus, the laser threshold will increase and the slope efficiency will reduce for fundamental mode (gaussian) operation. Another disadvantage at high pump powers and the resulting high temperatures will be the localized, highly aberrated thermal lens of the host material YAG which will limit the laser performance for high output power. To decrease thermal lensing, longer rods in the range of several cm and a lower absorption cross section are needed. The first published experiments directly pumping into a lower absorption cross section in the $^3H_4$ manifold at 804 nm (Fig. 1) were performed in 1997 with an output power of 115 W cw at $M^2 \sim 14$ - 23 by Honea et al.[2] Pumping at 804 nm gives a low absorption and thus allows the use of longer rods. By increasing the length of the rod the heat distribution dilutes over a larger volume. The only problem of the long rods is then the efficient pumping with a diode laser. The beam quality of diodes cannot provide collimated pump beams allover this length. In this case the pump beam is focussed inside the rod and the diverging pump radiation has to be conducted inside the rod by total internal reflection (TIR). By focussing and maintaining the pump beam into the rod in this way, a high pump intensity is achieved and results in a high inversion. Due to the larger volume the cooling is enhanced and the temperature and the reabsorption in the rod stays low which increases the slope efficiency. The lower temperature gives a distributed, less aberrated thermal lens which allows good compensation in well designed cavities.

The first pulsed Tm^{3+}:YAG laser system was realizated in 1990 by Kane et al.[3] with acousto-optic Q-switching. The laser rod was pumped from both sides at 785 nm where one side of the rod was HR coated and acted as an end mirror. The system emitted a pulse energy of 1.5 mJ at 150 Hz with a FWHM of 1.2 μs. In 2002 Goldring et al.[4] reached 2.4 mJ at 20 Hz and with a pulse-width of 57 ns with an electro-optic Q-switch.

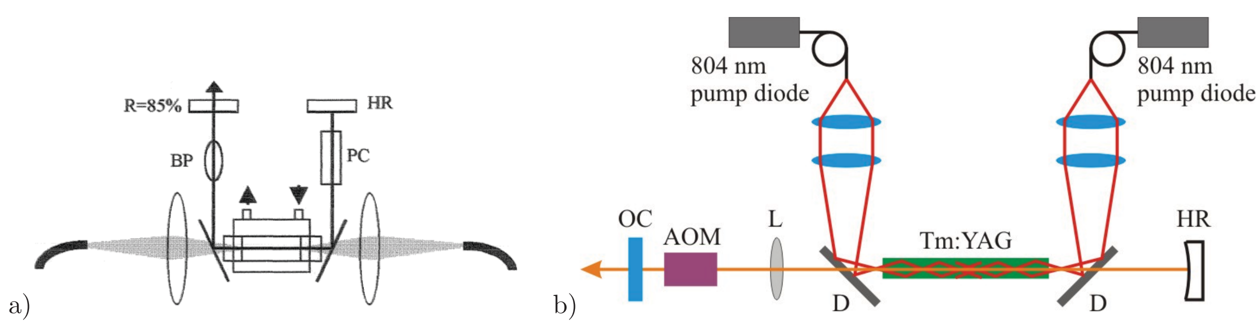

Figure 2. Resonator of a) Goldring et al.[4] and b) Eichhorn et al.[5]

The pump light was focussed through beam combiner plates which were close to the rod ends, see Fig. 2a. Thus, due to thermal lensing, the mode radius on the plates was quite small and limited the pulse energy due to optical damage. As the coating had to be HR for 2 μm, the coating thickness is important and shows lower damage threshold. As for a 2 μm HR and 800 nm AR coating the coating is quite thick and complex, switching the two reflectivities, which can be seen in Fig. 2b, results in a thinner coating. Thus the content of water or defects in the coating layers is reduced. In 2009 the latest published pulse energy from a Tm^{3+}:YAG system using this inverse coating design was 5.6 mJ at 100 Hz and a pulse-width of 200 ns by Eichhorn et al.[5] with an AO Q-switch, see Fig. 2b. The pulse energy at that time was again limited by the damage threshold of the beam-combiner plates. The pulse intensities on the beam-combiner plates are too high if they are close to the rod ends. Thus, in this setup, the distance to the rod end needs to be increased. Another important fact refers to the thickness of the coating in the setup. In this paper, we report the new world record for cross-relaxation diode-pumped diffraction-limited Q-switched Tm^{3+}:YAG operation of 13.6 mJ.

2. EXPERIMENTAL RESULTS AND DISCUSSION

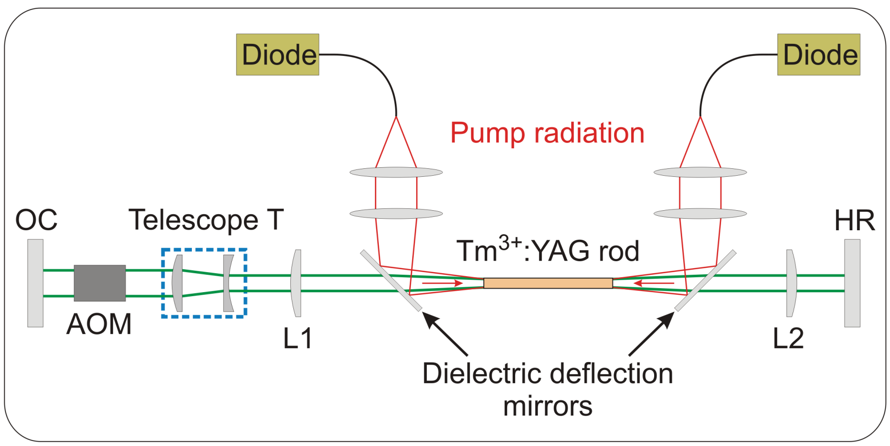

Figure 3. The resonator setup with an integrated telescope

With further development of the laser setup of Eichhorn et al.[5] an increasing distance between the beam-combiner plates and the rod ends could be achieved in order to avoid high pulse peak intensities on the combiner plates. In Fig. 3 the resonator setup can be seen which allows to create a large beam radius on all critical components and to increase the output coupler (OC) transmission to up to 50 %. The laser consists of a barrel-polished Tm^{3+}:YAG rod with a diameter of 3 mm and a length of 90 mm with a Tm^{3+} doping of 2 %. In Fig. 3 the rod is pumped by two fiber coupled pump diodes from each end providing each a cw power of 120 W at 804 nm out of a 400 μm diameter NA = 0.22 fiber. The diodes are driven in quasi-cw at 40 % duty cycle at 100 Hz to minimize the thermal load and to enhance extraction efficiency. The rod is water cooled at 20°C. The fiber emission is imaged into the crystal with a 2.5 magnification onto a 1 mm diameter spot, sligthly located inside the Tm^{3+}:YAG rod in order to obtain maximum output power. To compensate the strong thermal lens, the lenses L1 and L2 are used to create a stable cavity for different output coupler transmissions.

In this way, a thermal lens with low aberration is created, which results in a good beam quality. The diagram in Fig. 4 shows the outcoupled laser power for three different pump spot sizes with different OC reflectivities. For all displayed curves in Fig. 4 the beam quality was kept as good as possible over the hole pump region. With increasing pump spot size, the laser power drops dramatically and the OC reflectivity has to be increased which is not recommended to extract high pulse energy. More than 10 W of cw output power with an OC of 80 % reflectivity is achieved in free-running operation as shown in Fig. 5. The pump spot of 1 mm allows laser operation with an ouput coupling of 50 % at internal losses of < 3 % as determined by a Caird's analysis.[6] The coupling between intra-cavity power inversion and thermal load causes a decreasing mode radius for increasing outcoupling.

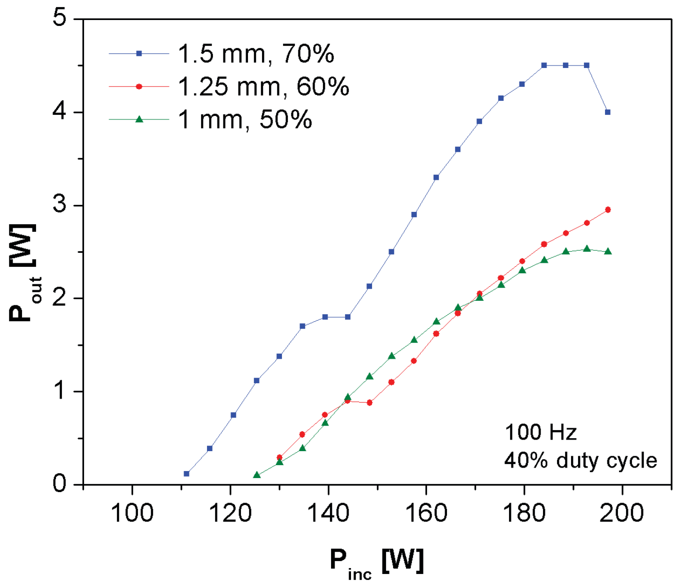

Figure 4. Three different pump spot sizes with different outcoupling.

However, the higher outcoupling overcompensates this effect and results in a lower intra-cavity intensity to reduce optical damage probability. In Q-switched operation, a plane-plane AOM with an AR-coating for 2 µm is inserted into the cavity. For high pulse energy it is necessary to limit the intra-cavity power by high outcoupling. Fig. 5 shows the laser performance for three different ouput coupler reflectivities and for some points at 70 % OC reflectivity the measured M^2. At this value of 70 % OC reflectivity an increase in pump power causes a transition of the cavity parameters through the origin of the stability diagram. This results in the power drop around 150 W incident peak pump power. In pulsed operation, this transition has to be avoided as it causes small spot sizes of the cavity mode on the rod ends. At high pump power the beam diameter approaches the pump spot size and the resulting soft aperture limits the output power. It is important to mention that fundamental-mode operation with diffraction-limited beam quality could be obtained at every operating point and for all OC reflectivities.

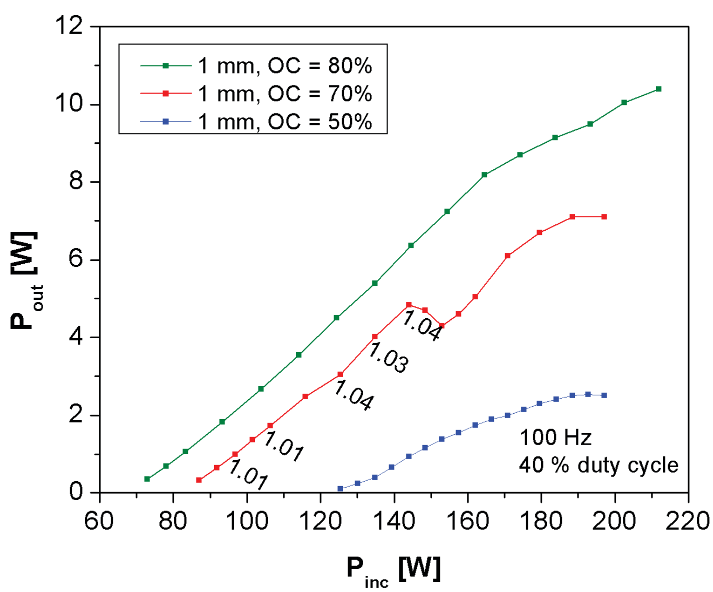

Figure 5. Laser power for different output coupler reflectivities.

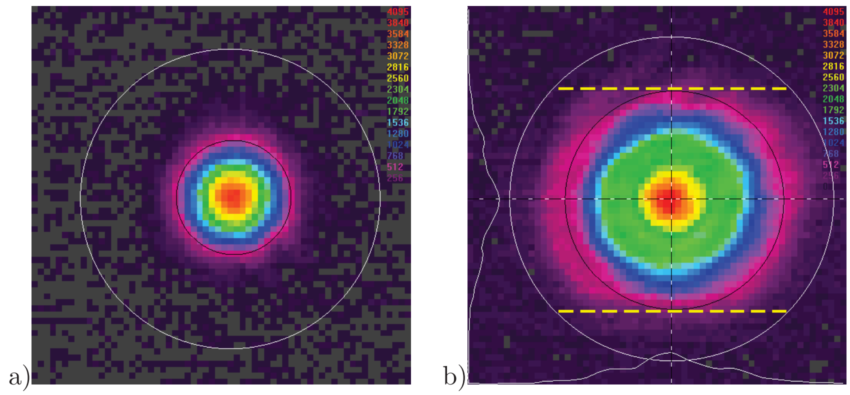

Figure 6. Beam intensity profile a) without a telescope and b) with a telescope inside the cavity.

To obtain a continuously variable output pulse energy at constant operation point with respect to the stability diagram, i.e. at constant thermal lens, the laser was driven at constant duty cycle and average pump power with variable repetition rate, as shown in Fig. 7. Up to 13.6 mJ at 100 Hz and a pulse width of $\sim$ 400 ns is obtained using resonator configuration A (with telescope T at 144 W peak pump power). The beam intensity profile is shown in Fig. 6b. As can be seen, the beam is affected by the limiting aperture of the transverse dimensions of the AOM. Using resonator B (without telescope, same resonator length as A), a pulse energy of 13.2 mJ at 130 Hz with a FWHM of $\sim$ 300 ns, $M^2 = 1.09$ is reached, before rod end face damage occurs. With the measured data of the resonator cavity we have calculated a damage threshold of 16 J/cm^2 for our rod. The next steps will be increasing the pulse energy by using a Brewster-cut rod to scale up the extractable pulse energy of the Tm^{3+}:YAG laser system.

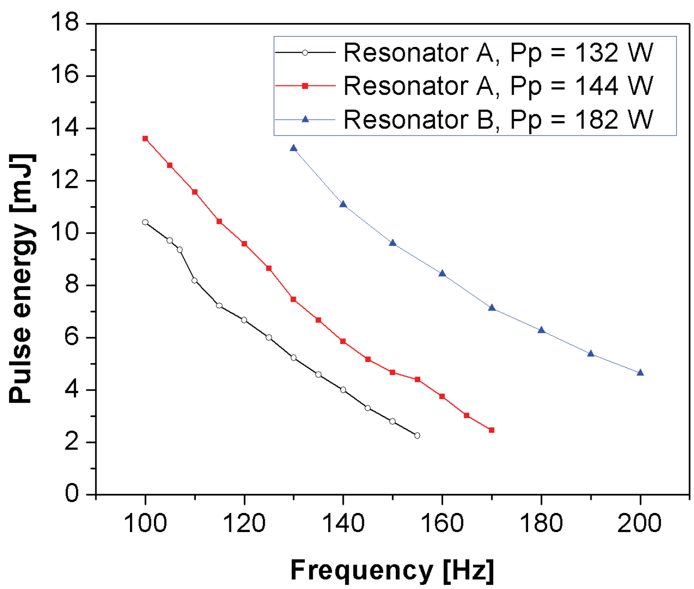

Figure 7. Pulse energy for different repetition rates and three different resonator configurations.

ACKNOWLEDGMENTS

We want to thank our technician Marc Christen for the fast and very good work for different opto-mechanical parts which were used for the experiments.

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2011 under grant agreement n° 224042.

REFERENCES

[1] Eichhorn, M., "Quasi-three-level solid-state lasers in the near and mid infrared based on trivalent rare earth ions," *Applied Physics B* **93**, 269–316 (Nov 2008).

[2] Honea, E., Beach, R., Sutton, S., Speth, J., Mitchell, S., Skidmore, J., Emanuel, M., and Payne, S., "115-W Tm:YAG Diode-Pumped Solid-State Laser," *IEEE Journal of Quantum Electronics* **33**, 1592–1600 (Sep 1997).

[3] Kane, T., Kubo, T., and Wallace, R., "Diode-Pumped, Injection-seeded, Q-Switched Tm:YAG Laser," *Lasers and Electro-Optics Society Annual Meeting* , 514–516 (Nov 1990).

[4] Goldring, S., Lebiush, E., and Lavi, R., "RTP Q-Switched 2-Micron Tm:YAG Laser," *Solid State Lasers XI* **4630**(1), 13–16 (2002).

[5] Eichhorn, M., Kieleck, C., and Hirth, A., "Q-Switched Tm^{3+}:YAG Rod Laser with Crystalline Fiber Geometry," *Conference on Lasers and Electro-Optics* , CWH2 (2009).

[6] Caird, J., Payne, S., Staber, P., Ramponi, A., Chase, L., and Krupke, W., "Quantum Electronic Properties of the $Na_3Ga_2Li_3F_{12}$:Cr^{3+} Laser," *IEEE Journal of Quantum Electronics* **24**, 1077–1099 (Jun 1988).