Efficient Q-switched Tm:YAG ceramic slab laser pumped by a 792 nm fiber laser

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\textbf{Abstract}

High-efficient continuous wave (cw) and actively Q-switched Tm:YAG ceramic lasers were described successfully. Pumping with fiber coupled laser diode at 792 nm, the maximum cw output power of 5.21 W with improved beam quality was obtained with a slope efficiency of 46.1\%. The shortest pulse width of 107 ns was achieved with the pulse repetition frequency (PRF) of 0.5 kHz, resulting in a largest pulse energy of 1.44 mJ and a highest peak power of 13.42 kW.

\section{1. Introduction}

Compared with single crystals, laser ceramics permit higher doping concentration with more uniform distribution, while optical properties are preserved. Moreover, they can easily and economically be fabricated with large volume due to the lower processing temperature and the shorter processing time \cite{1–8}. Recently, thulium-doped polycrystalline ceramics around 2 \( \mu \)m, has been considered as a promising laser material to build up high-efficiency and high-average-power diode-pumped all-solid-state lasers \cite{9–14}. In our previous report, the benefits of ceramics in developing high efficient 2 \( \mu \)m lasers were proved \cite{9}. Firstly, the scattering losses in the ceramic at 2 \( \mu \)m wavelength are much smaller than that at 1 \( \mu \)m wavelength, owing to the inverse proportional of the scattering loss to the four orders of the laser wavelength. In the other hand, UV light coming from the up-conversion process in 2 \( \mu \)m solid-state lasers will be scattered by the grain boundaries, that also supposed to be beneficial to resulting in high efficiency of 2 \( \mu \)m ceramic lasers. Another potentially positive influence factor to the laser efficiency is the slightly higher doping concentration around grain boundaries in the ceramics than that in the center of grain \cite{15}, which leads to high quantum efficiency due to the “1-for-2” energy transform process of Tm\textsuperscript{3+} -ions and compensates its disadvantage of small emitting cross-section of 2 \( \mu \)m laser. Meanwhile, we demonstrated the maximum cw output power of 17.2 W around 2016 nm with a slope efficiency of 36.5\% for Tm:YAG ceramic with Tm\textsuperscript{3+} -ion doping concentration of 6 at\%. A maximum cw output power of 7.3 W at 2015 nm was achieved for 4 at\% Tm:YAG ceramic pumped by an Er:YAG laser at 1617 nm, corresponding to a slope efficiency of 62.3\% \cite{10}. With the same doping concentration Tm:YAG ceramic pumped by a high power 786 nm LD, the slope efficiency as high as 65\% was realized \cite{11}.

Up to the present, all the results mentioned above were mainly focused on the high efficiency of its cw laser characteristics. Relatively fewer reports on the pulsed operation were carried out, expect that a shortest width of 69 ns was achieved with the pulse repetition frequency of 500 Hz by our group for the first time \cite{9}. However, in the Ref. \cite{9} we exploited a fast-axis collimated laser diode array (LDA) with a dimension \( ~1.5 \text{ mm} \times 0.5 \text{ mm} \) in the laser medium. As we known, the fast-axis collimated laser diode can be well matched with the slab laser medium to generate high power laser, while the larger dimension in its width position can also lead to the oscillation of high-order mode, resulting in the poorer beam quality. That will limit its many further applications, such as the source of optical parametric oscillators to obtain mid-infraRed laser.

In this letter, the cw and Q-switched laser characteristics of Tm:YAG ceramic end-pumped by a fiber coupled diode laser were investigated. The maximum cw output power of 5.21 W with improved beam quality was achieved at the absorbed pump power of 12.7 \( W \), corresponding to the slope efficiency of 46.1\%. For pulsed operation, we obtained the shortest pulse width of 107 ns with the pulse repetition frequency (PRF) of 0.5 kHz at the absorbed pump power of 12.7 \( W \). The largest single pulse energy...
and the highest peak power were calculated to be 1.44 mJ and 13.42 kW, respectively.

2. Experimental setup

Fig. 1 shows the experimental setup of the Tm:YAG ceramic slab laser. A fiber coupled diode laser emitting at 792 nm was used as the pump source. The fiber core is 200 μm in diameter with a numerical aperture of 0.22. A compact plane-parallel resonator consisted of mirrors M1 and M2 were used for the Tm:YAG ceramic slab laser. The rear flat mirror M1 was AR-coated at 792 nm and HR-coated at 2000 nm. The output coupler M2 has different transmissions of 2%, 5% and 7% at 2000 nm, respectively. The Tm:YAG ceramic with doping concentration of 6 at% has the dimension of $1 \times 5 \times 6$ mm$^3$, AR-coated at 792 nm and 2000 nm on both end faces. To efficiently remove the waste heat, the ceramic slab was sealed with indium foil solder to the micro-channel copper heat sinks with the water temperature of 12 °C, which were cooled by high-pressure water flux in our experiments. And the Q-switched operation was carried out by inserting an AO Q-switcher (Gooch & Housego, QS027-4M-AP1) into the resonator with the cavity length increasing to 80 mm.

3. Experimental results and discussions

The results of the cw output power of Tm:YAG ceramic slab with different output couplers ($T = 2\%, 5\% \text{ and } 7\%$) as a function of the absorbed pump power are shown in Fig. 2a. When the transmission of the output coupler was 5%, we obtained the highest output power of 5.21 W under the maximum absorbed pump power of 12.7 W with the threshold pump power of 1.4 W, resulting in an optical conversion efficiency of 41% and slope efficiency of about 46.1%. The laser spectrum of the Tm:YAG ceramic in such condition is illustrated in Fig. 2b. It is shown that the central laser wavelength of the Tm:YAG ceramic is 2019.5 nm, with a full width at half-maximum (FWHM) of about 3 nm. And the $M^2$ factor was measured to be about 1.6. The improved beam quality than our previous work in the Ref. [9] is mainly attributed to better mode-matching, owing to smaller diameter of the pump fiber core. When the coupler was replaced by the transmissions with 2% and 7%, the highest cw laser output power of 4.14 W and 4.59 W under the absorbed pump power of 12.7 W was obtained respectively, with the slope efficiency of 36.1% and 41.7%. And the corresponding threshold pump power was 1.2 W and 1.7 W, respectively. No saturation phenomenon appeared in our experiment, which indicates that higher laser output can be obtained with the pump power increasing.

For the Q-switched operation, the laser output characteristics at different PRF with the transmission of 5% are illustrated in Fig. 3, and the cw result is also described under the same experimental condition in this figure. Due to the larger loss of the longer cavity, the maximum cw output power reduced to 2.83 W at the absorbed pump power of 12.7 W, with the threshold pump power of 1.2 W and the cavity length of 80 mm, corresponding to a slope efficiency of 37.8%. When the PRF increased from 0.5 kHz to 10 kHz, the maximum average output power rised from 0.72 W to 2.16 W at the absorbed pump power of 12.7 W. It can be also seen that the output characteristics of the cw laser and the Q-switched laser have similar tendency, and the higher PRF leads to higher average output power and lower threshold pump power in the same condition.
Fig. 4 shows the pulse width versus the absorbed pump power with the transmission of 5%. It can be seen that the pulse width becomes shorter gradually with the increasing of absorbed pump power, while the PRF is changed from 5 kHz to 0.5 kHz. When the absorbed pump power is 12.7 W, the shortest pulse width of 107 ns was achieved operating at the PRF of 0.5 kHz, and the corresponding peak power were calculated to be 1.44 mJ and 13.42 kW, respectively. Fig. 5 describes the dependence of the peak power and the pulse width upon the PRFs at the absorbed pump power of 12.7 W. The pulse width increases with adding the pulse repetition frequency under the same absorbed pump power, while the peak power has inverse behavior. It can be also seen that the pulse width decreases from 390 ns to 109 ns but the peak power increases from 0.6 kW to 13.1 kW, corresponding to the PRF reducing from 10 kHz to 0.5 kHz. Fig. 6 depicts a typical pulse profile with the pulse width of 107 ns at the absorbed pump power of 12.7 W with the transmission of 5%, which indicates the excellent characteristics of the Tm:YAG ceramic for the AO Q-switched operation.

4. Conclusion

In summary, we have successfully developed a high efficient cw and AO Q-switched transparent Tm:YAG ceramic slab laser in this paper. The pulsed characteristics of the Tm:YAG ceramic end-pumped by a fiber coupled diode laser was investigated for the first time. The maximum cw output power of 5.21 W was achieved at the absorbed pump power of 12.7 W, resulting in an optical conversion efficiency of 41% and a slope efficiency of 46.1%. The shortest pulse width of 107 ns was achieved at the PRF of 0.5 kHz, resulting in the largest single pulse energy of 1.44 mJ and the highest peak power of 13.42 kW, respectively. The results and characteristics demonstrate that transparent Tm:YAG ceramic is a prospective laser material for 2 μm Q-switched operation.

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