Performance of continuous wave and acousto-optically Q-switched Tm, Ho: YAP laser pumped by diode laser

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Abstract. A two-end-pumped a-cut Tm(0.5%),Ho(0.5%):YAP laser output at 2119nm is reported under cryogenic temperature. The maximum output power reached to 7.76W with the incident pump power of 24.2W in CW mode. With the acousto-optically Q-switch, an average power of 7.3W can be obtained, when the pulse repetition frequency was 7.5 kHz. The corresponding optical-to-optical conversion efficiency was 30.2% and the slope efficiency was 31.4%. Then, the laser output characteristics in the repetition frequency of 7.5 kHz and 10kHz were researched. The output power, the optical-to-optical conversion efficiency and slope efficiency were increased with the increase of the repetition frequency. In the same repetition frequency, the pulse duration was decreasing with the growth of the incident pump power.

1. Introduction
The 2-μm laser is an useful light source. In view of its advancement such as the eye-safety wavelength regions, atmospheric transmission window and including strong absorption line of water and weak absorption line of atmosphere, the 2-μm laser possesses tremendous potential to apply in wide range of fields, for instance atmospheric remote sensing, gas detection, medical applications and so on. In addition, high-power 2-μm laser are important pump sources of optical parametrical oscillators and solid-state laser in the mid-infrared region [1-5]. Therefore, the research of 2-μm laser is hot issue and attracts many researchers’ attention.

Tm and Ho usually are the main ions to obtain 2-μm laser. But the absorption of Ho ion is weak. The absorption can be enhanced by doping Tm ion. This will result that the emission cross section of Tm and Ho co-doped media is larger than Ho single-doped media [6,7]. Tm and Ho co-doped media will meet the requirement of generation high peak power laser. In addition, the host material of doped ions is equally important for generation 2-μm laser. In the experiment, The YAP (LiYF₄) was used as the host material. The YAP is an anisotropic crystal. Compared with the similar mechanical properties of YAG (Y₃Al₅O₁₂), the natural birefringence of YAP is advantageous in the capability to provide clean linearly polarized beams with virtually no depolarization loss [8-11]. The crystal is produced by the Czochralski method.

At present, there are many studies about Tm,Ho:YAP lasers. In 2008, continuous wave (CW) and acousto-optical (AO) Q-switch operation of Tm(5%),Ho(0.3%):YAP laser at 2.13 μm wavelength were reported. In CW mode, a maximum conversion efficiency of 31.3% and a maximum slope efficiency of 30.2% were obtained. In AO Q-switch mode, an average power of 3.4W can be obtained, when the pulse repetition frequency was 10kHz. The corresponding optical-to-optical conversion efficiency was 30.2% and the slope efficiency was 31.4%.
efficiency of 35.2% were acquired. In Q-switch mode, the energy per pulse of 2.3 mJ in 64 ns was achieved at 1.5 kHz\textsuperscript{[12]}. In 2011, a high power and efficiency of c-cut Tm,Ho:YAlO\textsubscript{3} (YAP) laser was reported. In CW operation, output power of 9.30W was obtained, corresponding to a slope efficiency of 42.5%. In Q-switch mode, the output average power of 9 W was achieved at the pulse repetition frequency (PRF) of 10 kHz with a 130 ns pulse width \textsuperscript{[13]}.

In the same year, Chen et al. obtained a single frequency Tm,Ho:YAP laser of up to 31 mW with Fabry-Perot etalons in the cavity at 2130.8 nm. The conversion efficiency of 1.0% and slope efficiency 6.3% were attained. The full width at half maximum (FWHM) approximately reached to 65 pm\textsuperscript{[14]}. In 2014, Bromberger et al. reported a study about single-wavelength and multi-wavelength operations of a-and-b-oriented Tm,Ho:YAP. The maximum output powers of 890 mW at 2119 nm for a-oriented Tm,Ho:YAP crystal and 946 mW at 2103 nm for b-oriented Tm,Ho:YAP crystal was obtained\textsuperscript{[15]}.

In this paper, we reported the Tm,Ho:YAP laser in CW mode and Q-switch mode. The wavelength of two modes is 2119nm. In CW mode, the maximum of output power was 7.76W with the incident pump power of 24.2W, corresponding to an optical-to-optical conversion efficiency of 32.1% and the slope efficiency of 33.4%. In Q-switch mode at 7.5 kHz, the maximum output power of 7.3W was obtained when the incident pump power was 24.2W, corresponding to an optical-to-optical conversion efficiency of 30.2% and the slope efficiency of 31.4%. The duration of pulse was decreasing with the growth of incident pump power.

2. Experimental setup

The experimental diagram of Tm,Ho:YAP laser pumped by two laser diode from two-end is shown in fig. 1. The size of Tm,Ho:YAP crystal in the experiment was 4mm×4mm(in section)×10mm(in length), the two end surfaces of it were antireflection-coated. The reflectivity of 795nm and 2119nm was less than 0.5% and 0.3% respectively. The Tm and Ho doping concentrations were all 0.5%. The Tm,Ho:YAP crystal was wrapped in indium foil. The whole crystal was fixed in a copper heat-sink. In order to make the crystal work in a low temperature environment, the heat-sink was placed in a Dewar bottle. The temperature of crystal can be maintained in 77K by the liquid nitrogen in Dewar bottle.

2.1. Schematic diagram of the experimental setup

The two pump sources are 60-W laser diode, which core-diameter pigtail fiber is 400\textmu m. The pump lasers pumped the crystal from the two end of Tm,Ho:YAP. The pump laser beam was refocused by a pair of coupling lenses with the focus of 25mm and 50mm. The beam diameter was nearly 800\textmu m in the laser crystal. The resonant cavity was made by a 45° dichroic mirror, the output coupler and a plano-concave lens. The depleted pump source transmitted through a 45° dichroic mirror which was coated by R > 99.5% at 2119nm and T ~ 95% at 795nm. A flat mirror was used as the output coupler with a transmissivity of 30% at 2119nm. The other end of the resonant cavity was a plano-concave lens with a curvature radius of 300mm and coated by R > 99.5% at 2119nm and T ~ 95% at 795nm. The acousto-optically Q-switch was equipped between a 45° dichroic mirror and the output coupler. The physical length of the resonant cavity was about 210mm.
3. Experimental Result and Discussion
The CW and Q-switch laser data can be obtained by using the above experimental setup. The detailed data is shown in the fig. 2. In CW mode, the highest output power was 7.76W when the incident pump power was 24.2W, corresponding to an optical-to-optical conversion efficiency of 32.1%. A slope efficiency of 33.4% was yielded by linear fit of the experimental data with corresponding to the incident pump power.

![Figure 2](image.png)

*Figure 2. Output power of Tm,Ho:YAP laser versus incident pump power at CW and Q-switch*

In Q-switch mode, the repetition rate was 7.5 kHz. The maximum output power obtained was 7.3W with the incident pump power of 24.2W, corresponding to an optical-to-optical conversion efficiency of 30.2%. A slope efficiency of 31.4% was yielded by linear fit of the experimental data with respect to the incident pump power. The output wavelength of Tm,Ho:YAP laser was measured with a monochrometer of Bristol 721. The wavelength of output laser was 2119nm either in CW mode or in Q-switch mode. Compared with the above data in fig. 2, the output power of CW mode is obviously larger than the Q-switch mode in the conditions of the same incident pump power. So the efficiency of CW mode is relatively higher than the Q-switch mode whatever it is CW mode or Q-switch mode.

![Figure 3](image.png)

*Figure 3. Output power versus incident pump power at 7.5 kHz and 10 kHz*
Then, an experiment was done under the repetition rate of 10 kHz. The change of output power with the incident pump power is shown in fig. 3. The fig. 3 contains two lines in order to research the influence of the repetition rate. The red points are the experiment data of the repetition rate of 10 kHz. The maximum output power obtained was 7.54W with the incident pump power of 24.2W, corresponding to an optical-to-optical conversion efficiency of 31.2%. As the data points are higher than the data points of the repetition rate of 7.5 kHz, the slope efficiency is large. The slope efficiency of 33.2% was yielded by linear fit of the experimental data with respect to the incident pump power.

Compared with the above data in fig. 3, the output power of 10 kHz is obviously larger than the 7.5 kHz in the conditions of the same incident pump power. So the efficiency of 10 kHz is relatively higher than 7.5 kHz. The output power is increasing with the growth of the repetition rate. But the output power is lower than the CW mode.

Fig. 4 shows the duration of the Q-switch Tm,Ho:YAP laser operation with different incident pump power in the repetition rate of 7.5 kHz. The pulse width measurements were performed with the use of temperature controlled InAsSb Amplified Detector (PDA10PT-EC) and Digital Phosphor Oscilloscope (DPO 4104). The duration of pulse is decreasing with the growth of incident pump power. The change is rapid at low power and tends to be gentle at high power. The maximum duration was 257ns when the incident pump power was 2W. The minimum duration was 66.85ns when the incident pump power was 24.2W.

![Figure 4. Pulse duration versus incident pump power for the Tm,Ho:YAP laser](image)

4. Conclusion

In summary, A two-end-pumped a-cut Tm(0.5%),Ho(0.5%):YAP laser is demonstrated. The maximum output power reached to 7.76W with the incident pump power of 24.2W in CW mode. The optical-to-optical conversion efficiency and the slope efficiency respectively were 32.1% and 33.4%. In Q-switch mode with the acousto-optically Q-switch, the pulse repetition frequency was 7.5 kHz. The maximum output power of 7.3W was attained when the incident pump power was 24.2W with the optical-to-optical conversion efficiency of 30.2% and the slope efficiency of 31.4%. No matter what kind of mode, the wavelength of output laser was all 2119nm.

In addition, the experiment was conducted under changing the pulse frequency. The pulse repetition frequency reached to 10 kHz, the output power was increasing compared with the pulse repetition frequency of 7.5kHz. In the end, the experiment with respect to pulse duration was researched. The pulse duration was depressed with the increase of the incident pump power.
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