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# 41 kHz repetition rate passively Q-switched Ho:YAP laser with Cr:ZnS as a saturable absorber

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ABSTRACT

We report a continuous wave Tm:YAP laser resonantly pumped Ho:YAP laser in CW mode and passive Q-switched mode. Multilayer Cr:ZnS is used as the saturable absorber for the Q-switched operation. The maximum continuous wave output power of 6.36 W at 2118.67 nm was obtained, corresponding to a slope efficiency of 25.2% and the overall optical-to-optical conversion efficiency of 19.8%. The maximum pulse repetition frequency reached 41.25 kHz and the minimum pulse width of 382 ns was obtained at average output power of 5.24 W. Meanwhile, the output beam spatial profile was close to fundamental $TEM_{00}$ mode and the beam quality factor $M^2$ was 1.4.



## 1. Introduction

Q-switched lasers with wavelength around 2 μm have important applications, including laser lidar, remote sensing [1], rangefinders, wind shear detection and medical applications. Moreover, Q-switched lasers in the 2 μm region also can be used as a pump source for non-linear crystals or for Cr:ZnSe lasers and optical parametric oscillators for obtaining 3 to 12 μm lasers [2,3]. Previously, Q-switched solid state lasers were mostly realized by the active Q-switched scheme [4,5]. The structure of acousto-optic and electro-optic modulators were complex and the additional electrical consumption makes the active Q-switched scheme costly and inconvenient. In contrast, passively Q-switched (PQS) lasers with saturable absorbers are usually accompanied with significant advantages such as inherent compactness, simplicity, reliability and low cost of the system design. Recently, more and more attentions have drawn in the PQS $Tm^{3+}$ doped or $Tm^{3+}$, $Ho^{3+}$ doped lasers with the Cr:ZnS and saturable absorbers [6]. The Cr:ZnS saturable absorbers have high absorption cross section ($5.2 \times 10^{19}$ $cm^2$) [7] and low saturable intensity which can reduce the risk of damage in Q-switched operation. However, compared with the $Tm^{3+}$ doped, $Ho^{3+}$ doped crystals are relatively more superior because $Ho^{3+}$ doped crystals have larger stimulated emission cross section and longer lifetime [8], which decreases laser threshold and increases laser efficiency [9]. Therefore, the $Ho^{3+}$ doped PQS lasers around 2 μm is an attractive research area.

With the development of high power 1.9 μm laser, Ho lasers based on YLF, YAG, and $GdVO_4$ [10–13] host material resonantly pumped by 1.9 μm Tm doped laser have been extensively investigated. For rare-earth ions doped host materials, YAP is chosen as a promising efficient singly doped laser material [14]. YAP crystals exhibit optically anisotropic properties and the laser emission is linearly polarized [9]. It is a naturally birefringence crystal, and hence it is less sensitive to a thermally induced birefringence, compared with the common laser crystal YAG. The absorption band of Ho:YAP is broad and emission cross-section is smaller than that of Ho:YAG and Ho:YLF, which can directly produce pulses of the proper duration without excessively long resonator or elaborate cavity-loss control schemes. These significant properties of the Ho:YAP crystal shows that it is a potential gain medium. Mond et al. reported a diode-pumped passively Q-switched Tm:YAG laser using Cr:ZnSe as a saturable absorber, and achieved a maximum average output power of 1.57 W [15].

In this paper, we reported a high power continuous wave (CW) Ho:YAP laser and a passively Q-switched Ho:YAP laser with Cr:ZnS as a saturable absorber. To our knowledge, this is the first time that Cr:ZnS is used in PQS Ho:YAP laser. The maximum CW output power of 6.36 W at 2118.67 nm was obtained when the pump

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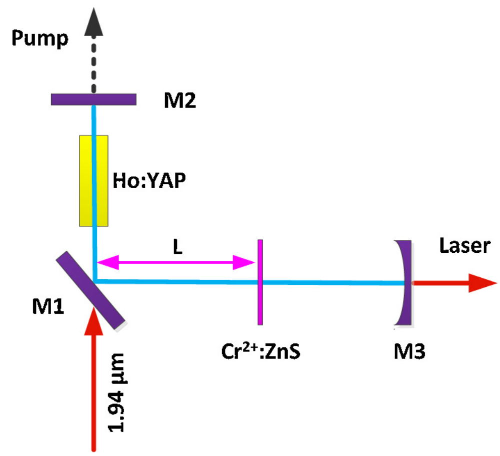


**Fig. 1.** Experimental setup of the PQS Ho:YAP laser.

power was 32.1 W, corresponding to a slope efficiency of 25.2% and the overall optical-to-optical conversion efficiency of 19.8%. Using a Cr:ZnS as a saturable absorber, passively Q-switched Ho:YAP laser was demonstrated. The maximum pulse repetition frequency of 41.25 kHz was obtained at average output power of 5.24 W, corresponding to a minimum pulse width of 382 ns. To the best of our knowledge, 41.25 kHz was the maximum pulse repetition frequency for the passive Q-switched Ho:YAP laser with Cr:ZnS as the saturable absorber at present. Meanwhile, the beam quality factor $M^2$ was 1.4, and the output beam was close to fundamental $TEM_{00}$.

## 2. Experimental setup details

The PQS Ho:YAP laser setup is shown in Fig. 1. The distances between M1 and M2, and between M2 and M3 are 95 and 100 mm, respectively. The Ho:YAP crystal is placed in the resonator 3 mm away from the plane mirror M1. The physical length of resonant cavity is 195 mm. The pump source was a 1.94 μm Tm:YAP laser with a maximum output power of 32.1 W. The pump beam was shaped and focused by two lens with the total transmission of 92% at 1.94 μm, and the radius of the pump in the center of the Ho:YAP crystal was approximately 200 μm. The dimension of Ho:YAP crystal was 3 × 5 × 50 $mm^3$ with a $Ho^{3+}$ doped concentration of 0.3 at.%. Both end faces of the Ho:YAP crystal were coated with antireflection coating at 1.94 μm ($R$ < 0.5%) and 2.1 μm ($R$ < 0.3%). Ho:YAP crystal was wrapped in indium foil and mounted in a copper heat sink. Temperature of the heat sink was held at 290 K by a TEC cooler. The 45° plane mirror M1 and the plane mirror M2 were both coated with high reflectivity at 2.1 μm and high transmission at 1.94 μm. The output coupler was a concave mirror with a curvature radius of 300 mm, coated with a transmission of 30% at 2.1 μm. A Cr:ZnS saturable absorber was inserted between the M1 and M3 with a dimension of 9 mm × 9 mm in cross section and 2.2 mm in thickness, and the distance between the Cr:ZnS and M1 was represented by $L$. Cr:ZnS crystal was coated with antirefection coating at 2.1 μm and the initial transmission was 95%. Cr:ZnS mounted in a copper heat sink and cooled by water. The L-shaped configuration of the resonator could prevent the pumping light from affecting the Cr:ZnS saturable absorber.

## 3. Experiment results and discussion

The CW output power of Ho:YAP laser as a function of the total incident pump power was shown in Fig. 2. The maximum output power was 6.36 W at the pump power of 32.1 W and the laser threshold was 7.99 W. No power saturation was observed in the CW mode. The slope efficiency was 25.2% and the overall optical-to-optical conversion efficiency was 19.8%. The output power increased almost linearly with the increase of incident pump power.

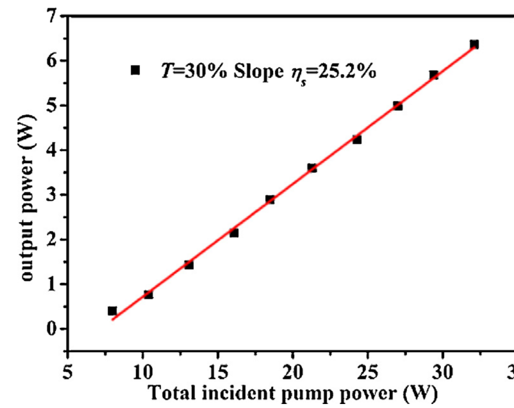


**Fig. 2.** Output power of the CW mode versus the total incident pump power.

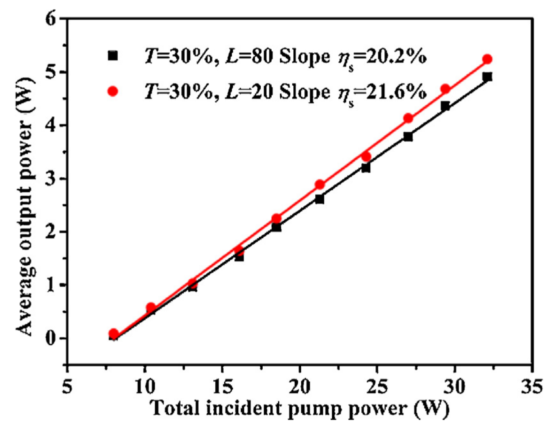


**Fig. 3.** Average output power of the PQS mode versus the total incident pump power.

Fig. 3 shows the measured average output power of the Ho:YAP laser with a Cr:ZnS saturable absorber inserted inside the cavity at different $L$. When the $L$ was 20 mm, the average output power increased from 0.09 W to 5.24 W with the pump power increased from 7.99 W to 32.1 W, corresponding to a optical-to-optical conversion efficiency of 16.3% and a slope efficiency of 21.6%. When the length of $L$ was 80 mm, a maximum average output power of 4.91 W was achieved at the incident pump power of 32.1 W, corresponding to a slope efficiency of 20.2% and a optical-to-optical conversion efficiency of 15.3%.

The pulse width versus the pump power at the different $L$ was shown in Fig. 4. As shown in Fig. 4, the pulse width decreased rapidly with the increase of the incident pump power at a lower incident pump power and the decreasing of pulse width was relatively slow at higher incident pump power. Meanwhile, it can be seen that the pulse width was narrower with a shorter length of $L$. It can be seen from Fig. 4 that the pulse width at $L$ = 20 mm decreased from 1264 ns to 382 ns as the pump power increased from 10.4 W to 32.1 W. When the length of $L$ was 80 mm, a maximum pulse width of 1585 ns and a minimum pulse width of 504 ns were achieved.

The pulse repetition frequency versus the incident pump power is shown in Fig. 5. It can be seen that the pulse repetition frequency was almost linearity with the increase of the incident pump power. Meanwhile, the pulse repetition frequency was higher with a shorter length of $L$. When the length of $L$ was 20 mm, the pulse repetition frequency increased from 16.71 kHz to 41.25 kHz as the pump power increases from 10.4 W to 31.2 W. When the length