Passive Q-Switching of a Tm^{3+} :YLF Laser at 2.3 μm with a Cr^{2+} :ZnSe Saturable Absorber

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Abstract: We describe, for the first time to our knowledge, passive Q-switching of a 2.3- μm Tm^{3+} :YLF laser. By using a Cr^{2+} :ZnSe saturable absorber, pulses with 1.2-1.4 μs duration and 0.3-2.1 kHz repetition frequency were generated.

OCIS codes: (140.3580) Lasers, solid-state; (140.5680) Rare earth and transition metal solid-state lasers; (140.3538) Lasers, pulsed; (140.3540) Lasers, Q-switched; (140.3600) Lasers, tunable; (140.3070) Infrared and far-infrared lasers.

1. Introduction

Pulsed, Tm^{3+} -pumped Ho^{3+} [1] or $\text{Tm}^{3+}/\text{Ho}^{3+}$ co-doped [2] lasers operating near 2 μm have been widely used for the pumping of ZGP optical parametric oscillators (OPOs) to reach longer wavelengths in the mid infrared (mid-IR). However, this approach involving either two different gain media or a gain medium doped with two different ions results in a complex pumping architecture. An alternative approach would involve the use of a pump laser which could operate above 2.1 μm (where the loss of ZGP is minimal) and which could be realized with a single-ion-doped gain medium. For example, a pulsed Cr^{2+} :ZnSe laser tunable in the 2.1-2.9 μm range was previously employed to demonstrate pumping of a broadly tunable ZGP OPO [3]. Among rare-earth ions that emit above 2.05 μm , an attractive possibility involves the 2.3- μm transition of the Tm^{3+} ion. Efficient laser operation of this mid-IR transition was previously reported by direct optical pumping near 800 nm, especially when crystals with low phonon energy are used and when ion concentrations are kept below 2% to minimize concentration dependent non-radiative quenching effects [4]. To date, continuous-wave [5], flash-lamp pumped [6], and gain-switched [7] operations of several Tm^{3+} -doped gain media have been demonstrated at 2.3 μm . For 2.3- μm lasing, Tm^{3+} :YLF is particularly attractive since the phonon energy of the YLF host (560 cm^{-1}) is smaller than those of oxide hosts [8, 9].

Pulsed operation of 2.3- μm Tm^{3+} lasers can also be obtained by employing the technique of passive Q-switching, where a saturable absorber (SA) is placed inside the cavity to generate a pulse train whose repetition frequency and pulse duration are determined by the parameters of the saturable absorber and resonator. Divalent Cr or Fe doped II-VI media such as Cr^{2+} :ZnSe, Cr^{2+} :ZnS, Cr^{2+} :CdSe, Fe^{2+} :ZnS, and Fe^{2+} :ZnSe have ultrabroad absorption bands which extend to 2.3 μm and hence can potentially be used as saturable absorbers at this wavelength [10-12]. Our present study focused on the passive Q-switching applications of Cr^{2+} :ZnSe, whose saturation characteristics were previously investigated between 1.5 μm and 2.8 μm [13-15].

In this work, we report, for the first time to our knowledge, passive Q-switching of a 2.3- μm Tm^{3+} :YLF laser by using a Cr^{2+} :ZnSe saturable absorber. In the experiments, a tunable Ti^{3+} :sapphire laser was used to pump a Tm^{3+} :YLF crystal located inside an x-cavity. After performing a detailed characterization of the continuous-wave operation of the Tm^{3+} :YLF laser, a Cr^{2+} :ZnSe saturable absorber was included in the cavity to initiate passive Q-switching. At all pump power levels above lasing threshold, passively Q-switched operation of the Tm^{3+} :YLF laser could be obtained at 2309 nm with pulse durations and repetition frequencies in the ranges of 1.2-1.4 μs and 0.3-2.1 kHz, respectively.

2. Experimental Setup and Results

Figure 1(a) shows a schematic of the Tm^{3+} :YLF laser, end pumped with a tunable, continuous-wave (cw) Ti^{3+} :sapphire laser. The home-built Ti^{3+} :sapphire laser, consisting of two curved high reflectors (M1-M2, R=70mm), a flat end high reflector (M3) and a 15% output coupler (M4) could produce tunable output in the 700-840 nm wavelength range. Two intra-cavity SF10 prisms (P1-P2) were used to provide tuning and reduce the linewidth to 0.09 nm. At the maximum green power of 5W, the Ti^{3+} :sapphire pump laser provided as high as 958 mW of output power at 780 nm. The Ti^{3+} :sapphire output beam was then focused with a convex lens (L2, f=75mm) into a Brewster-cut, 9-mm-long Tm^{3+} :YLF crystal which had a Tm^{3+} concentration of 1.5 at.%. The gain medium was mounted in a Cu holder and kept at 21°C with circulating water. Before the Q-switching experiments, an astigmatically-compensated x-cavity was first set up with two curved high reflectors (M7-M8, R=100mm), a flat end high reflector (M10), and a 1% output coupler (M13) to investigate the cw power performance of the Tm^{3+} :YLF laser. To determine the optimum pumping wavelength, the output power of the Tm^{3+} :YLF laser was first measured

as a function of the pump wavelength in the 760-810 nm range. As can be seen from Fig. 1(b), the optimum pumping wavelength was determined to be 780 nm, in good agreement with previous results [16]. In these measurements, the Ti^{3+} :sapphire output power remained nearly constant around 950 mW. At the pump wavelength of 780 nm, where the pump absorption was 78%, the variation of the Tm^{3+} :YLF output power near 2.3 μm was measured as a function of the incident power by using the 1% and 3% output couplers. As can be seen from Fig. 1(c), as high as 120 mW of output was obtained near 2.3 μm with 958 mW of pump power when the output coupler had 1% transmission. The corresponding slope efficiencies were 13% and 8% for the 1% and 3% output couplers, respectively. By using the lasing threshold data of the free-running Tm^{3+} :YLF laser, recorded with three different output couplers, the round-trip loss of the empty resonator was estimated to be 0.3%.

Figure 1: (a) Schematic of the 2.3- μm Tm^{3+} :YLF laser, passively Q-switched with a Cr^{2+} :ZnSe saturable absorber. (b) Measured excitation spectrum of the Tm^{3+} :YLF laser and the corresponding variation of the Ti^{3+} :sapphire output power (P_{out}) as a function of the Ti^{3+} :sapphire wavelength. (c) Measured variation of the cw output power of the free-running Tm^{3+} :YLF laser near 2.3 μm with 1% and 3% output couplers as a function of the incident power at 780 nm.

To increase the incident fluence on the Cr^{2+} :ZnSe saturable absorber, an additional beam waist was formed in the cavity by replacing the highly reflecting end mirror (M10) with two curved mirrors (M11-M12, $R=75\text{mm}$). Before Q-switching experiments (without Cr^{2+} :ZnSe in the cavity), in order to utilize the unused pump power, an additional retro-reflecting concave mirror (M9, $R=100\text{mm}$) was placed after M8 for double pumping. Double pumping increased the output power from 102 mW to 150 mW at the pump power of 880 mW. Figure 2(a) shows the measured output power variation of the Tm^{3+} :YLF laser as a function of the Ti^{3+} :sapphire pump power for the cases of single and double pumping, where power slope efficiencies of 14% and 19% were obtained, respectively. The corresponding threshold pump powers were measured to be 114 mW and 100 mW when the output coupler transmission was 1%.

Figure 2: Output power variation of the (a) cw and (b) passively Q-switched Tm^{3+} :YLF laser as a function of the pump power for the cases of single and double pumping. (c) Measured output spectrum of the passively Q-switched Tm^{3+} :YLF laser.

In Q-switching experiments, a polycrystalline Cr^{2+} :ZnSe saturable absorber (SA), with a length of 2.6 mm was placed at Brewster incidence near the focus location between mirrors M10 and M11 [Fig.1(a)]. The SA further had a measured single-pass unsaturated loss of 3.6% at 2309 nm, corresponding to a small signal round-trip loss of 7.2% within the Tm^{3+} :YLF laser cavity. At the pump power of 890 mW, the output power decreased from 150 mW (102 mW) to 27 mW (11 mW) for double- (single-) pumped Tm^{3+} :YLF laser, after the insertion of Cr^{2+} :ZnSe SA. Figure 2(b) further shows the measured output power variation of the Tm^{3+} :YLF laser containing the Cr^{2+} :ZnSe SA. After the inclusion of the Cr^{2+} :ZnSe SA, repetitive Q-switching could be achieved at all pump powers above threshold. For this case, single- and double-pumped operation of the passively Q-switched laser could be obtained with

threshold pump powers of 380 mW and 300 mW, respectively. Moreover, as can be seen from Fig. 2(c), the center wavelength of the Q-switched Tm^{3+} :YLF laser was at 2309 nm.

Figure 3: Measured dependence of the (a) pulse width and (b) repetition rate on the incident pump power for the Tm^{3+} :YLF laser, passively Q-switched with a Cr^{2+} :ZnSe saturable absorber. (c) Measured temporal profile of the generated pulses from the passively Q-switched Tm^{3+} :YLF laser.

The graphs displayed in Fig. 3(a) and Fig. 3(b) show the measured dependence of the pulse width and repetition rate of the passively Q-switched Tm^{3+} :YLF laser on the incident pump power. In particular, as can be seen from Fig. 3(a), the output pulse duration (FWHM) remained in the range of 1.2-1.4 μs. In addition, measured repetition rates varied from 300 Hz (360 Hz) to 2.1 kHz (1.5 kHz) for double (single) pumping [Fig. 3(b)]. Figure 3(c) further shows the measured temporal profile of the pulses obtained from the double-pumped, passively Q-switched Tm^{3+} :YLF laser at the maximum pump power of 890 mW. The output pulse energy was 13 μJ (7 μJ) for the case of double (single) pumping at the maximum pump power of 890 mW. In the case of double pumping, the corresponding maximum peak power was 10W during passive Q-switching.

In conclusion, we described, for the first time to our knowledge, passively Q-switched operation of a 2.3-μm Tm^{3+} :YLF laser by using a Cr^{2+} :ZnSe saturable absorber. At all pump power levels above lasing threshold, repetitive Q-switching of the Tm^{3+} :YLF laser could be achieved at 2309 nm with pulse durations in the range of 1.2-1.4 μs.

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3. References

- [1] P. A. Budni, M. L. Lemons, J. R. Mosto, and E. P. Chicklis, "High-Power/High-Brightness Diode-Pumped 1.9 μm Thulium and Resonantly Pumped 2.1-μm Holmium Lasers," *IEEE J. Sel. Top. Quant.* **6**, 629-635, (2000).
- [2] R. K. Feaver, R. D. Peterson, and P. E. Powers, "Longwave-IR optical parametric oscillator in orientation-patterned GaAs pumped by a 2 μm $\text{Tm}:\text{Ho}$:YLF laser," *Opt. Express* **21**, 16104-16110, (2013).
- [3] W. S. Pelouch, G. J. Wagner, T. J. Carrig, and W. J. Scharpf, "Mid-wave ZGP OPOs pumped by a Cr : ZnSe laser," *OSA Trends Opt. Photo.* **50**, 670-674, (2001).
- [4] V. Sudesh and J. A. Piper, "Spectroscopy, Modeling, and Laser Operation of Thulium Crystals at 2.3 μm," *IEEE J. Quantum Electron.* **QE-36**, 879-884, (2000).
- [5] J. F. Pinto, L. Esterowitz, and G. H. Rosenblatt, " Tm^{3+} :YLF Laser Continuously Tunable between 2.20 and 2.46 μm," *Opt. Lett.* **19**, 883-885, (1994).
- [6] J. A. Caird, L. G. DeShazer, and J. Nella, "Characteristics of Room-Temperature 2.3-μm Laser Emission from Tm^{3+} in YAG and YAlO_3 ," *IEEE J. Quantum Electron.* **QE-11**, 874-881, (1975).
- [7] L. Esterowitz, R. Allen, and I. Aggarwal, "Pulsed laser emission at 2.3 μm in a Thulium-doped fluorozirconate fibre," *Electron. Lett.* **24**, 1104, (1988).
- [8] J. F. Pinto and L. Esterowitz, " Tm^{3+} :YLF laser continuously tunable between 2.20 and 2.46 μm," *Opt. Lett.* **19**, 883-885, (1994).
- [9] I. Elder and M. Payne, "Lasing in diode-pumped Tm: YAP, Tm, Ho: YAP and Tm, Ho: YLF," *Opt. Commun.* **145**, 329-339, (1998).
- [10] S. Mirov, V. Fedorov, I. Moskalev, D. Martyshkin, and C. Kim, "Progress in Cr^{2+} and Fe^{2+} doped mid-IR laser materials," *Laser Photonics Rev.* **4**, 21-41, (2010).
- [11] H. Cankaya, U. Demirbas, A. K. Erdamar, and A. Sennaroglu, "Absorption saturation analysis of Cr^{2+} : ZnSe and Fe^{2+} : ZnSe," *J. Opt. Soc. Am. B* **25**, 794-800, (2008).
- [12] N. Myoung, V. V. Fedorov, S. B. Mirov, and L. E. Wenger, "Temperature and concentration quenching of mid-IR photoluminescence in iron doped ZnSe and ZnS laser crystals," *J. Lumin.* **132**, 600-606, (2012).
- [13] A. V. Podlipensky, V. G. Shcherbitsky, N. V. Kuleshov, V. P. Mikhailov, V. I. Levchenko, and V. N. Yakimovich, " Cr^{2+} : ZnSe and Co^{2+} : ZnSe saturable-absorber Q switches for 1.54-μm Er : glass lasers," *Opt. Lett.* **24**, 960-962, (1999).
- [14] A. Martinez, "Spectroscopic characterization of Iron-doped II-VI compounds for laser applications," PhD Dissertation: University of Alabama, 2015, pp. 70-81.
- [15] B. Q. Yao, J. H. Yuan, J. Li, T. Y. Dai, X. M. Duan, Y. J. Shen, Z. Cui, and Y. B. Pan, "High-power Cr^{2+} :ZnS saturable absorber passively Q-switched Ho:YAG ceramic laser and its application to pumping of a mid-IR OPO," *Opt. Lett.* **40**, 348-351, (2015).
- [16] V. Sudesh and K. Asai, "Spectroscopic and diode-pumped-laser properties of Tm, Ho : YLF; Tm, Ho : LuLF; and Tm, Ho : LuAG crystals: a comparative study," *J. Opt. Soc. Am. B* **20**, 1829-1837, (2003).