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Stable *Q*-switched mode-locking of an in-band pumped Ho : Y_2O_3 ceramic laser at 2117 nm

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Abstract. **We have demonstrated stable *Q*-switched mode-locked operation of an in-band pumped Ho : Y_2O_3 ceramic laser at 2117 nm by using an InGaAs/GaAs-based saturable absorber. An average output power of 330 mW is reached for 2.7 W of absorbed pump power with stable mode-locked pulses having a 98.9-MHz repetition rate and 100 % modulation depth embedded inside *Q*-switched envelopes of ~1.7-μs duration. The duration of the mode-locked pulses is estimated to be less than 1.5 ns.**

Keywords: *Q-switched mode-locking, mid-IR range, laser ceramic, Ho : Y_2O_3; pulsed laser.*

1. Introduction

Pulsed solid-state lasers operating in the 2.1-μm spectral region are of particular interests in some applications, including spanning time-resolved spectroscopy, LIDAR, and laser medicine, as well as for generation of mid-IR supercontinuum and frequency combs [1–6]. Conventionally, in-band pumping of singly Ho-doped materials, such as Ho : YAG, Ho : YAP, Ho : YLF, etc. [7–12], have been proved to be effective for obtaining a high-power, continuous-wave (cw) laser and high-energy pulsed laser at 2.1 μm due to their inherent high quantum efficiency, large gain cross section and relatively simple thermal management [13].

Holmium-doped yttria (Ho : Y_2O_3) ceramic, as one of the polycrystalline cubic sesquioxides, possesses unique advantages of high thermal conductivity [~11.1 W $(m\ K)^{-1}$ for 0.7 at.% Ho : Y_2O_3 ceramic at room temperature], low maximum phonon energy (~597 cm^{-1}), and high mechanical strength [14–16], making it a promising active element of a high power laser at ~2.1 μm. In-band pumped by a high power Tm fibre laser at 1931 nm, the power scaling of Ho : Y_2O_3 ceramic laser was recently reported, generating over 113 W of output power with an overall slope efficiency of 55.6% [17]. Of particular note is that the strong crystal field of the Y_2O_3 host leads to a relatively large splitting of Stark manifolds and hence a long wavelength emission peak with relatively broad emission bandwidth [18, 19], which makes Ho : Y_2O_3 ideally suited for generating ultrashort pulses around 2.1 μm. However, mode-locked operation of a Ho-doped sesquioxide laser at ~2.1 μm has not been demonstrated yet.

Passive mode-locking using a semiconductor saturable absorber (SESA) is a widely used method for generating ultrashort pulses owing to SESA simplicity, reliability, and robust functionality. To date, several studies have been conducted in solid-state mode-locked lasers at ~2.1 μm by employing SESAs as a mode locker. Wavelength-tunable continuous-wave mode-locking (CWML) of a Ho : YAG ceramic laser was demonstrated by using a GaSb-based near-surface SESA with the shortest pulse duration of 2.1 ps at 2064 nm [20]. Employing an InGaAs/GaAs-based SESA, *Q*-switched mode-locked (QML) operation of a diode-pumped Tm, Ho : YVO_4 laser was reported [21].

In this paper we describe stable *Q*-switched mode-locked operation of a Ho : Y_2O_3 ceramic laser emitting at 2117 nm by adopting a commercially available InGaAs/GaAs-based SESA. In-band pumped by a self-built high-brightness Tm fibre laser at 1931 nm, over 330 mW of an average output power was achieved with stable mode-locked pulses having a repetition rate of 98.9 MHz. The mode-locked pulses were fully modulated and embedded in the *Q*-switched envelops with a duration of several microseconds. To our knowledge, this is the first demonstration of *Q*-switched mode-locked operation of a Ho-doped sesquioxide laser. The experimental results showed that the Ho : Y_2O_3 ceramic is a promising gain medium for stable *Q*-switched mode-locked lasers and possesses great potential for designing cw mode-locked lasers at ~2.1 μm.

2. Experimental setup

Figure 1 shows schematically the design of the *Q*-switched mode-locked Ho : Y_2O_3 ceramic laser. A self-built high-brightness Tm-fibre laser was used as the pump light, which

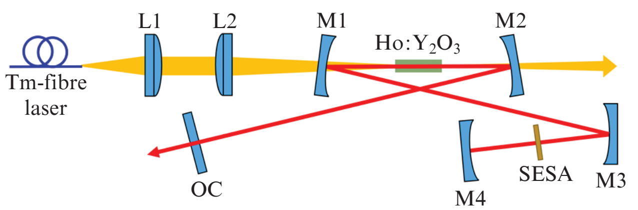

Figure 1. Schematic of a *Q*-switched mode-locked Ho : Y_2O_3 ceramic laser: (L1, L2) lenses of a telescope system; (M1–M4) dichroic folding mirrors; (OC) output coupler.

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could generate more than 5 W of output power at 1931 nm with diffraction-limited beam quality. The output from Tm-fiber laser was collimated and then focused by lenses (L1 and L2 in Fig. 1) of a 1:7 telescope system onto the Ho:Y_2O_3 ceramic with a beam radius of ~35 μm.

An X-shape folded resonator consisting of five mirrors was employed for the *Q*-switched mode-locked operation. The dichroic folding mirrors (M1, M2, M3 and M4 in Fig. 1) were all high-reflection ($R > 99.8\%$) coated at 2040–2250 nm and antireflection ($T > 99.8\%$) coated at 1880–1950 nm, with radii of curvature of 100 mm, 100 mm, 100 mm, and 50 mm, respectively. A plane-wedged mirror with transmission of 2% at 2000–2300 nm was used as the output coupler (OC in Fig. 1). The Ho:Y_2O_3 ceramic used in our experiments was made in-house by employing the 'vacuum sintering plus hot isostatic pressin'g (HIPing) technique, which was described in detail in Ref. [16]. The Ho:Y_2O_3 ceramic with 0.5 at.% doping has a cuboid dimension of 1.4 × 3 mm in cross section and 20 mm in length, with both end surfaces antireflection coated at 1880–2150 nm. It was mounted in a 20 °C-water-cooled copper heat sink and positioned in the centre of the confocal cavity formed by M1 and M2. A commercially available InGaAs/GaAs-based saturable absorber (BATOP GmbH, SA-2000-1-10ps) was inserted into the cavity, which was antireflection coated at 1900–2100 nm with a saturation fluence of 300 J cm^{-2}, a modulation depth of 0.6% and a relaxation time constant of 10 ps. It was glued on a copper heat sink for passive heat dissipation and placed at the second intracavity beam waist formed by M3 and M4. The lengths of the two cavity arms were almost the same. Total length of the cavity was nearly 1.52 m, corresponding to an intermode beat frequency of ~99 MHz. To minimise the astigmatism, the folding angles of mirrors were less than 7°. The TEM_{00} beam waist radii on the Ho:Y_2O_3 ceramic and SESA were calculated to be ~36 and ~40 μm, respectively.

3. Results and discussion

Lasing performance of the Ho:Y_2O_3 ceramic in the cw regime was evaluated first without insertion of the SESA. The threshold for cw laser oscillation was reached for an absorbed pump power of ~0.8 W, and the laser produced 0.77 W of output power for 2.7 W of absorbed pump power, which is shown in the red circles of Fig. 2. The corresponding optical slope efficiency with respect to the absorbed pump power was 46%.

After inserting the SESA into the cavity, the laser initially exhibited unstable *Q*-switched mode-locking when the absorbed pump power was between 1 W and 1.3 W. After careful alignment of the cavity, stable *Q*-switched mode-locked operation was demonstrated when the absorbed pump power rose to above 1.3 W. The QML laser produced over 330 mW of average output power at maximum absorbed pump power of 2.7 W (see the blue squares of Fig. 2), corresponding to an average slope efficiency of 21%. The conversion efficiency from continuous wave operation to *Q*-switched mode-locking was 41.3%.

Temporal characteristics of the *Q*-switched mode-locked Ho:Y_2O_3 ceramic laser were monitored by a 1-GHz bandwidth oscilloscope (Keysight, DSO-S 104A) with a high speed InGaAs detector (Newport, 818-BB-51, 28 ps rise time). The dependence of the *Q*-switched envelope duration and repetition rate on the absorbed pump power is depicted in Fig. 3. The repetition rate of *Q*-switched pulse envelopes can be tuned from 19.4 to 43.9 kHz by increasing the absorbed pump power from 1.3 to 2.7 W, with the duration of *Q*-switched envelops decreasing. At the maximum absorbed pump power of 2.7 W, the *Q*-switched envelope had a shortest FWHM duration of 1.7 μs with a repetition rate of 43.9 kHz.

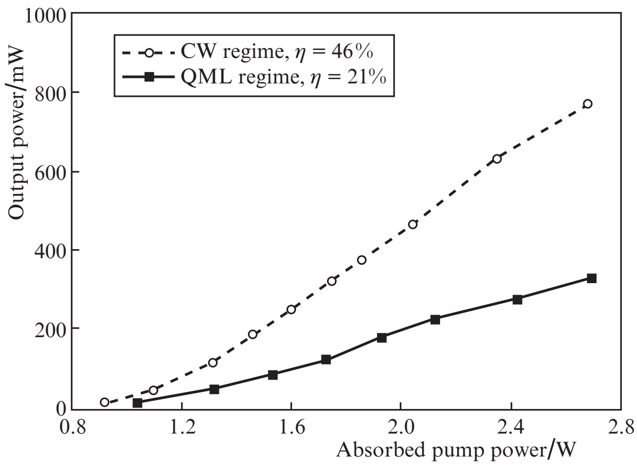

Figure 2. Output power vs. absorbed pump power in (○) cw and (■) QML regimes.

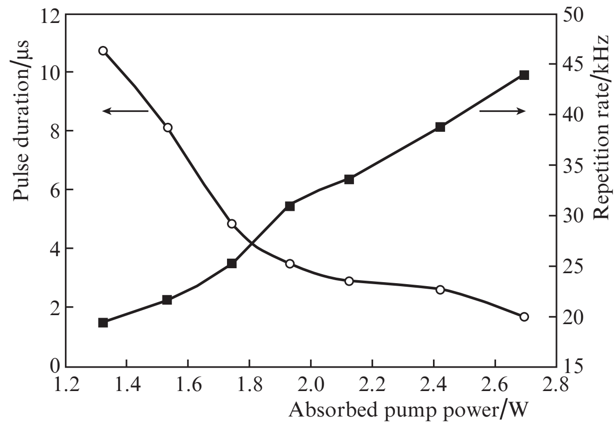

Figure 3. (○) Pulse duration and (■) repetition rate of a *Q*-switched pulse envelope vs. absorbed pump power.

A typical *Q*-switched pulse train, a single pulse envelope and a mode-locked pulse train within the envelope are shown in Fig. 4. Stable *Q*-switched pulses were obtained with the pulse-to-pulse amplitude fluctuation of less than 5% (see Fig. 4a). As shown in Fig. 4b, the mode-locked pulses were fully modulated and embedded in a *Q*-switched envelope with a 1.7 μs duration. The expanded oscilloscope trace of mode-locked pulses within the envelope is shown in Fig. 4c, in which the mode-locked pulses have a period of ~10.1 ns. The corresponding pulse repetition rate is ~99 MHz, matching well with the cavity round-trip time. The duration of the mode-locked pulses was determined to be less than 1.5 ns.

Stability of the *Q*-switched mode-locked operation was characterised by measuring the radio frequency (RF) spectrum with a 3 GHz electronics spectrum analyser (Agilent, N9320B), as shown in Fig. 5. The fundamental beat frequency was located at 98.9 MHz with a signal-to-noise ratio of above 40 dB, revealing stable *Q*-switched mode-locked operation of the Ho:Y_2O_3 ceramic laser. The lasing emission spectrum in the QML regime was detected by an optical spectrum analyser (YOKOGAWA, AQ6375) with a spectral resolution of

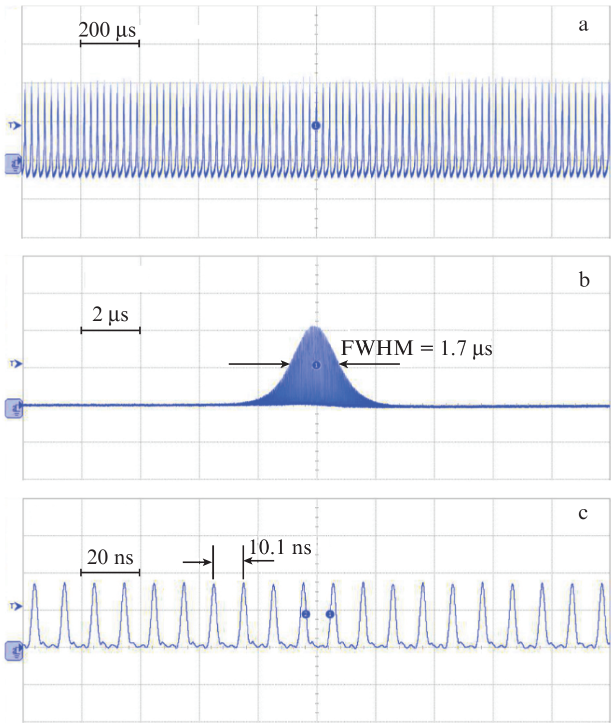

Figure 4. Oscillogram of (a) a Q-switched pulse train, (b) QML pulse envelope, and (c) expanded mode-locked pulse train.

0.02 nm, as illustrated in Fig. 6. The laser wavelength was centred at 2117.8 nm with a spectral linewidth of 0.16 nm (FWHM).

According to the criterion of minimum intracavity pulse energy for achieving stable continuous wave mode-locking described in Ref. [22], the following inequality should be fulfilled:

$$E_{\rm p} > E_{\rm pc} = \sqrt{F_{\rm sat\,L} F_{\rm sat\,A} A_{\rm sat\,L} A_{\rm sat\,A}\, \Delta R}\,,$$

where $E_{\rm pc}$ is the intracavity pulse energy; $F_{\rm sat\,L}$, $F_{\rm sat\,A}$, $A_{\rm sat\,L}$, $A_{\rm sat\,A}$ represent the saturation fluence of the gain medium and the absorber, laser mode area inside the gain medium and the absorber, respectively; and ΔR is the modulation depth of the saturable absorber. In order to obtain continuous wave mode-locking against Q-switching, the gain saturation effect should be sufficiently strong to prevent the exponential rise of the pulse energy resulting from the stronger bleaching of the absorber, indicating that a further decrease in the laser mode area on the ceramic and SESA and using SESA with reduced modulation depth are effective methods to suppress Q-switched mode-locking. Continuous wave mode-locking with improved laser performance should be achievable by employing a shorter $Ho:Y_2O_3$ceramic, an optimised GaSb-based SESA with appropriate bandgap-control, and a modified resonator design in the future.

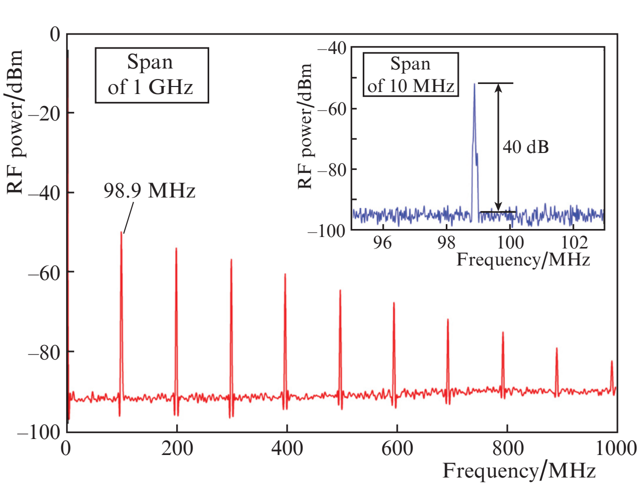

Figure 5. Radio frequency spectra of the Q-switched mode-locked $Ho:Y_2O_3$ ceramic laser at a resolution bandwidth of 1 kHz. The inset shows the fundamental beat frequency. The resolution bandwidth is 1 kHz.

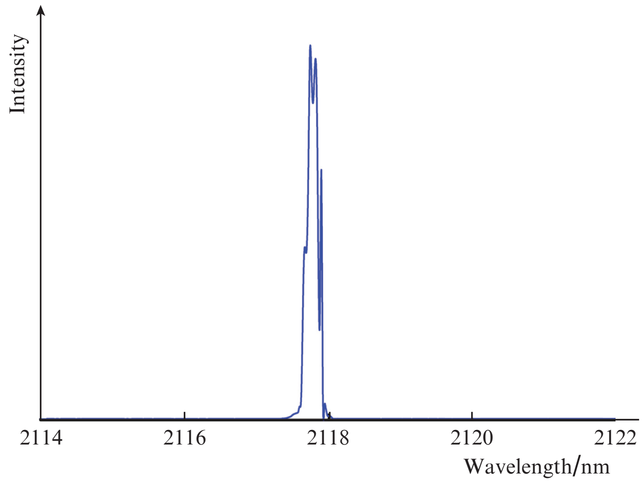

Figure 6. Laser emission spectrum in the QML regime.

4. Conclusions

We have experimentally demonstrated stable Q-switched mode-locked operation of a $Ho:Y_2O_3$ ceramic laser at 2117 nm by using a commercially available InGaAs/GaAs-based SESA. An average output power of more than 330 mW was yielded at an absorbed pump power of 2.7 W, corresponding to an overall slope efficiency of 21 %. The Q-switched envelope had a shortest FWHM duration of 1.7 µs embedded with fully modulated mode-locked pulses. The duration of the mode-locked pulses was determined to be less than 1.5 ns with a repetition rate of 98.9 MHz. We believe that this stable 2.1-µm Q-switched mode-locked laser could be a reliable pump source for $ZnGeP_2$ optical parametric oscillators or amplifiers to generate laser radiation in the 3–5-µm mid-infrared region. With further optimisation of the resonator design and by use of a shorter laser ceramic and customised SESA, it should be possible to achieve continuous wave mode-locking of a $Ho:Y_2O_3$ ceramic laser with picosecond pulses at the output.

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References

1. Scholle K., Lamrini S., Koopmann P., Fuhrberg P., in *Frontiers in Guided Wave Optics Optoelectronics*. Ed. by Bishnu Pal (InTech, 2010) p. 471.

2. Ebrahim-Zadeh M., Vodopyanov K. *J. Opt. Soc. Am. B*, **33** (11), MIC1 (2016).
3. Lee C., Mohr C., Bethge J., Suzuki S., Fermann M.E., Hartl I., Schibli T.R. *Opt. Lett*., **37** (15), 3084 (2012).
4. Taczak T.M., Killinger D.K. *Appl. Opt*., **37** (36), 8460 (1998).
5. Mandon J., Guelachvili G., Picqué N. *Nat. Photonics*, **3** (2), 99 (2009).
6. Swiderski J., Michalska M., Maze G. *Opt. Express*, **21** (7), 7851 (2013).
7. Yao W., Li E., Shen Y., Ren C., Zhao Y., Tang D., Shen D. *Laser Phys. Lett*., **16** (11), 115001 (2019).
8. Shen Y., Yao B., Duan X., Zhu G., Wang W., Ju Y., Wang Y. *Opt. Lett*., **37** (17), 3558 (2012).
9. Shen Y., Yao W., Li E., Shao Z., Wang F., Shen D. *Appl. Phys. Express*, **13** (5), 052006 (2020).
10. Dergachev A., Moulton P.F., Drake T.E., in *Advanced Solid-State Photonics (TOPS)*. Ed. by C. Denman, I. Sorokina (Optical Society of America, 2005) Vol. 98, paper 608.
11. Tang J., Li E., Wang F., Yao W., Shen D. *IEEE Photonics J*., **12** (2), 1501107 (2020).
12. Guo L., Zhao S., Li T., Qiao W., Wang Y. *Opt. & Laser Technol*., **126**, 106015 (2020).
13. Li E., Tang J., Shen Y., Wang F., Wang J., Tang D., Shen D. *IEEE Photonics Technol. Lett*., **32** (8), 492 (2020).
14. Kränkel C. *IEEE J. Sel. Top. Quantum Electron*., **21** (1), 250 (2014).
15. Word-Daniels A., Newburgh A., Michael A., Merkle L., Dubinskii M. *Proc. SPIE*, **7686**, 76860F (2010).
16. Wang J., Zhao Y., Yin D., Liu P., Ma J., Wang Y., Shen D., Dong Z., Kong L., Tang D. *J. Europ. Ceramic Soc*., **38** (4), 1986 (2017).
17. Wang F., Tang J., Li E., Shen C., Wang J., Tang D., Shen D. *Opt. Lett*., **44** (24), 5933 (2019).
18. Koopmann P., Lamrini S., Scholle K., Schäfer M., Fuhrberg P., Huber G. *Opt. Express*, **21** (3), 3926 (2013).
19. Newburgh G.A., Word-Daniels A., Michael A., Merkle L.D., Ikesue A., Dubinskii M. *Opt. Express*, **19** (4), 3604 (2011).
20. Wang Y., Lan R., Mateos X., Li J., Hu C., Li C., Suomalainen S., Härkönen A., Guina M., Petrov V., Griebner U. *Opt. Express*, **24** (6), 180032 (2016).
21. Li G., Yao B., Meng P., Wang W., Ju Y., Wang Y. *Laser Phys*., **8** (1), 42 (2011).
22. Hönninger C., Paschotta R., Morier-Genoud F., Moser M., Keller U. *J. Opt. Soc. Am. B*, **16** (1), 46 (1999).