Room-temperature Q-switched $Tm:BaY_2F_8$ laser pumped by CW diode laser

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Abstract: We report on the realization of CW diode-pumped $Tm:BaY_2F_8$ Q-switched laser at 1.93 µm. Active Q-switching was obtained by means of an intracavity Pockels cell. A functional characterization of the laser performance is presented with particular attention to output energy, pulse duration, pulse stability, and wavelength tunability. Pulses with time duration as short as 170 ns were demonstrated at the minimum repetition rate of 5 Hz with an energy of 3.2 mJ (corresponding to a peak power of 19 kW). A wavelength tunability range from 1905 nm to 1990 nm has been observed.

OCIS codes: (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched.

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1. Introduction

The development of novel high-efficiency solid-state laser sources in the near-infrared spectral region around the eye-safe wavelength of 2-µm is busted by the increasing number of applications in remote sensing and gas detection, high-resolution spectroscopy, and biomedicine. Indeed, in this spectral region, several atmospheric components, such as H_2O, CO_2, and NO_2, have many absorption lines that can be exploited in Dial systems; moreover, the liquid water shows strong absorption in the specific interval between 1.92 and 1.94 µm, which can be used for medical applications. For most of these applications pulsed laser sources are needed, with pulsewidth in the range from few hundreds of nanoseconds to tens of microseconds and few millijoules of pulse energy. As an example, coherent optical radar systems with 1 mJ pulse energy and 200 ns pulsewidth is able to cover an observation range of tens kilometers [1].

Both thulium-doped and thulium-holmium co-doped crystals are primarily used as laser sources at 2 µm, with specific reference to the $^3F_4 \rightarrow {}^3H_6$ Tm^{3+} and $^5I_7 \rightarrow {}^5I_8$ Ho^{3+} transitions [2-3]. The major advantages of these active media are the direct diode pumping at ~785 nm, a pump quantum efficiency close to two (for one absorbed pump photon two Tm ions are raised to the upper laser level), and a relatively long lifetime of the upper laser level, in the range of few milliseconds. Moreover, the diode-pumped solid-state laser technology offers the advantages of low mass, small size, long operating lifetime, and the absence of consumable materials, which are to be taken into account when airborne and satellite systems have to be realized.

In this paper, we report on a cw diode-pumped active Q-switched 1.93-µm laser, based on Tm-doped BaY_2F_8 (Tm:BaYF) crystal. Peak output power of 19 kW and pulse duration of 170 ns are demonstrated for pulse repetition frequency of 5 Hz. The central wavelength of the Q-switched pulses can be continuously tuned within the range from 1.9 µm to 1.99 µm, due to the large phonon broadening and the high-multiplicity of the Stark levels concerning the 4*f* electrons of Tm^{3+} ions. As compared with Tm-Ho, Tm-doped crystals show better performance thanks to the reduced up-conversion mechanisms and the longer upper laser level lifetime [4]. The BaYF crystal host presents, in addition, noticeable features providing advantages in terms of laser performance. These include low phonon energy, which makes it particularly suitable for IR transitions, longer fluorescence lifetime with improved energy storage, lower up-conversion losses, reduced thermal lensing and extremely low beam depolarization under strong pumping, being the natural birefringence larger than that induced by thermal effects [5-6]. The results obtained with Q-switched Tm:BaYF operated at room temperature show a better slope efficiency and a wider tunability range compared with those reported for other Tm-doped bulk hosts [7-9].

2. Laser resonator

Figure 1 shows the experimental configuration of the Q-switched Tm:BaYF laser. The folded resonator comprises a plane high-reflectivity (HR) input mirror, a spherical HR folding mirror (75-mm radius of curvature), and a plane output coupler with power transmissivity of 5% or 10%. A 2.2-mm thick BaYF crystal doped with Tm^{3+} ions at a concentration level of 12% at. [10] is placed at Brewster angle close to the input mirror and is longitudinally pumped by a CW AlGaAs pump diode with emission wavelength of 780 nm (Coherent, model S-79-2700C-100-H/L). The TM polarization is selected for the pump beam to minimize the Fresnel reflection losses at the input face of the active medium. The pump beam is collimated and then focused into the active crystal through the input mirror (92% transmission at 780 nm), using a pair of anti-reflection (AR) coated spherical lenses with focal lengths of 62.9 mm and 38.1 mm, respectively. To obtain higher pump absorption and a more uniform inversion profile inside the active medium, the unabsorbed pump beam transmitted through the folding mirror is back reflected into the cavity using a plane mirror and an AR-coated spherical lens (75 mm focal length).

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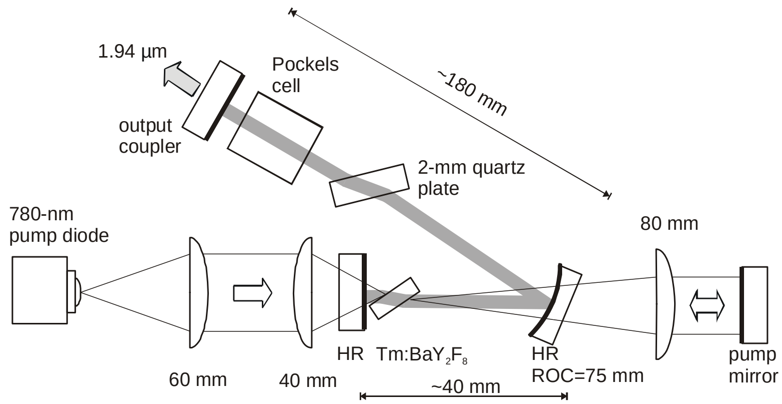

Fig. 1. Diode-pumped electrooptically Q-switched Tm:BaYF laser.

In this configuration the measured pump absorption is 85%. To tune the laser emission wavelength, a 2-mm thick quartz plate with the optical axis lying on the crystal plane, acting as a birefringent filter, is inserted at Brewster angle in the longest arm of the resonator. The birefringent filter, mounted on a precision rotator for a fine control of the angle between the crystal optical axis and the laser beam, has a free-spectral range of ~18 THz (corresponding to 240 nm at the laser wavelength). The slight astigmatism introduced by the active material and the birefringent filter is compensated by folding the cavity with an angle of ~18°. In CW regime the laser was linearly polarized along the TM direction (with the electric field parallel to the **b** crystal axis) and in single transverse mode TEM_{00} [11]. Figure 2 shows the typical output power as a function of the incident pump power for an output coupling level of 5% (open circles). The maximum output power and the optical to optical slope efficiency were found to be 620 mW and ~30%, respectively. Active Q-switching is achieved by means of an

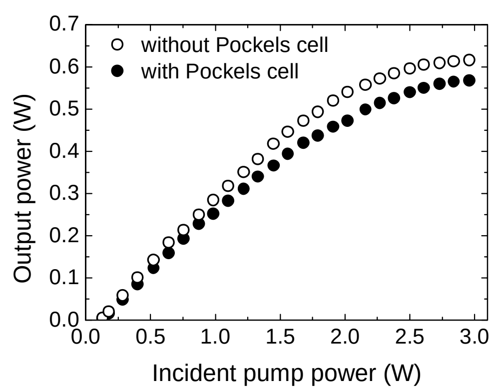

Fig. 2. CW Tm:BaYF output power versus input pump power with 5% output coupling.

intracavity Pockels cell. The Pockels cell (Linos, model LM 9 IR), based on a lithium niobate crystal, is characterized by a half-wave voltage of ~6.6 kV and is AR-coated around 2 µm (R<0.5%). The Pockels cell operates in an OFF Q-switching configuration: a high cavity quality factor is achieved when the Pockels cell is switched off, corresponding to an intracavity round trip losses of ~3%, as obtained with a Findlay and Clay analysis [12] on the CW laser performance using 3%, 5%, and 10% output couplings; whereas a low resonator quality factor is obtained when the electrooptic modulator is supplied with 3.3 kV voltage (Linos, model HVD-1000). When the Pockels cell is switched on, the linear polarization of the laser beam after a double pass through the Pockels cell is rotated by 90° and the

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intracavity round trip losses are increased due to reflection on the Brewster interfaces. In this case, the intracavity losses increased to ~45%, a sufficiently high value to prevent any laser action in this low-gain laser oscillator.

3. CW-pumped Q-switched laser characterization

Starting from the results achieved in CW laser regime, it is possible to estimate the value of the maximum pulse energy that can be extracted from the CW-pumped Q-switched Tm:BaYF laser. Assuming a single longitudinal mode laser emission, the pulse energy of a continuously pumped, repetitively Q-switched laser can be calculated from Ref. [13] as:

$$E = P_{CW}\tau\left(\frac{n_\infty - n_f}{n_\infty - n_{th}}\right)\left[1-\exp\left(-\frac{1}{f_r\tau}\right)\right] \qquad (1)$$

where P_{CW} is the continuous wave output power, τ is the upper laser level lifetime, n_∞ is the asymptotic population inversion, n_{th} is the threshold population inversion, n_f is the final population inversion, and f_r is the pulse repetition frequency. Population inversions n_∞ and n_{th} can be calculated on the basis of the pump power level, the threshold pump power, the total internal losses, the output coupling, and the laser emission cross section [13]. The final inversion, n_f, has to be numerically calculated using the following expression [13]

$$(n_\infty - n_f)[1-\exp(-1/f_r\tau)] = n_{th}\ln\left\{\frac{n_\infty}{n_f}[1-\exp(-1/f_r\tau)] + \exp(-1/f_r\tau)\right\} \qquad (2).$$

The maximum pulse energy is achieved when $f_r \ll 1/\tau$. Assuming a lifetime of 17 ms and an emission cross section of 2.5×10^{-21} cm^2 for the $^3F_4$ Tm^{3+} laser level [10], an incident pump power of 0.7 W, a threshold pump power of 0.15 W, and 5% output coupling, a theoretical pulse energy of 3.4 mJ is predicted by eq. (1) when the repetition rate is lower than 10 Hz ($n_{th}/n_\infty \cong 1/8$; $n_f/n_\infty \cong 1/1650$). During the Q-switching experiments, to avoid crystal damages due to the high intracavity fluence at 1.9 µm the incident pump power was limited to 0.7 W. Figure 3 shows the Tm:BaYF output pulse energy versus repetition frequency with 5% (open circles) and 10% (filled circles) output couplings, when the incident pump power is 0.7 W. The 5% output coupling leads to the best performance: the maximum output pulse energy and the optical to optical slope efficiency are 3.2 mJ and 4.6 mJ/W, respectively. In the same figure the best fits of Eq. (1) to the experimental data are also reported.

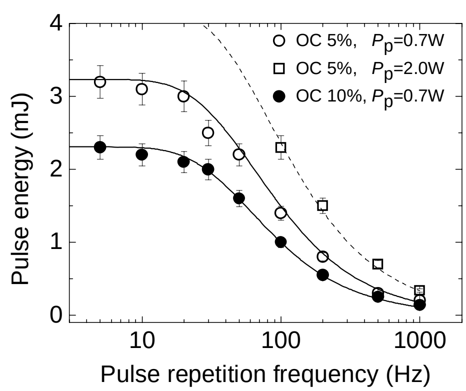

Fig. 3. Output energy versus pulse repetition frequency for an incident pump power of 0.7 W with 5% (open circles) and 10% (filled circles) output couplings. Open squares represent the pulse energy for an incident pump power of 2 W with 5% output coupling. Continuous and dashed lines represent the best fits to the experimental data.

For both the output couplings the Tm^{3+} in BaYF upper level laser lifetime retrived from the fitting curves is 16±0.5 ms, in fairly good agreement with the value measured by means of the fluorescence spectroscopy [10]. For repetition rates higher than 100 Hz the incident pump power can be safely increased up to ~2 W. In Fig. 3 the output pulse energy versus repetition frequency for an incident pump power of 2 W and 5% output coupling (open squares) and the relative best fit curve (dashed line) are also reported. At the repetition rate of 100 Hz the maximum pulse energy was limited to 2.4 mJ due to a slight reduction of the upper laser level lifetime. Indeed, due to the increased pump intensity, the lifetime retrieved by the fitting was 12±0.5 ms.

Pulse width characterization was performed by a fast InGaAs photodiode with sensitivity extended up to 2.6 µm and a 500-MHz bandwidth digital oscilloscope. The time resolution of the measurement system was of the order of 1 ns, mainly limited by the photodiode bandwidth of 350 MHz. Figure 4 shows the pulsewidth as a function of the repetition frequency for 5% (open circles) and 10% (filled circles) output couplings, with an incident pump power of 0.7 W. The minimum pulse durations of 170 ns and 220 ns are obtained for pulse repetition rates of 200 Hz (5% output coupling) and 100 Hz (10% output coupling), respectively. Figure 5 (a) shows the typical Q-switching pulse train recorded at a repetition frequency of 200 Hz. Pulse to pulse peak power stability is better than 2.5%. Energy stability of 10% was achieved over 1-h observation time, as shown in Fig. 5 (b).

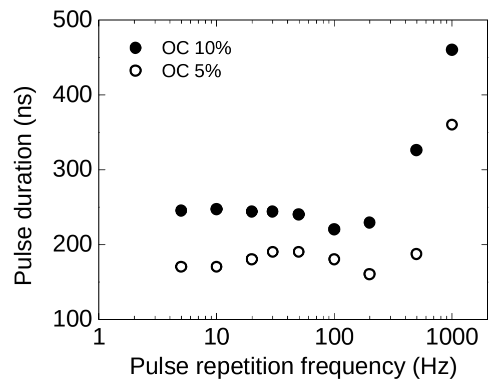

Fig. 4. Pulse duration versus pulse repetition frequency for an incident pump power of 0.7 W.

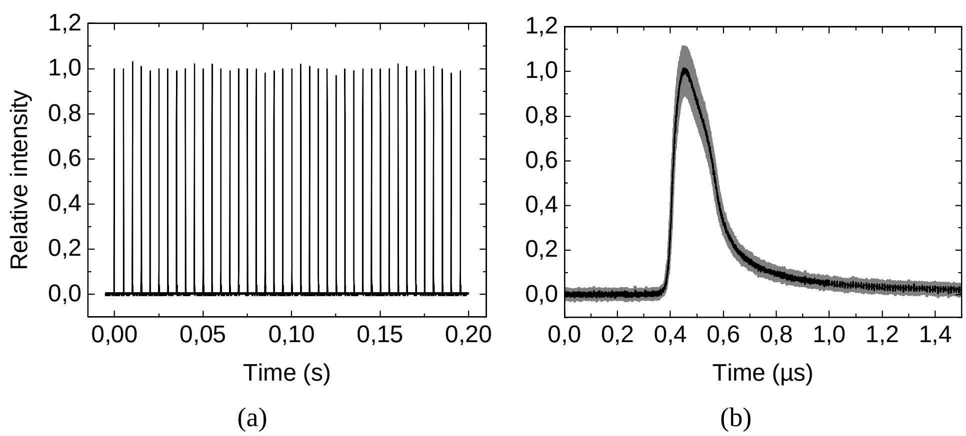

Fig. 5. (a) Pulse train of the Q-switched Tm:BaYF laser at 200 Hz repetition frequency with 5% output coupling. (b) Oscilloscope persistence trace of the pulse temporal profile for an observation time of 1 h.

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The wavelength tunability of the Q-switched pulses was also investigated. Figure 6 shows the tunability curves obtained acting on the intracavity birefringent filter, as measured with a fixed incident pump power of 0.7 W, output couplings of 5% and 10%, and pulse repetition frequencies of 200 Hz and 100 Hz, respectively. The widest tunability range of 85 nm, from 1905 to 1990 nm, was obtained with the 5% output coupling, with a maximum output energy of 0.7 mJ at 1927 nm wavelength. Increasing the output coupling the measured tuning interval is reduced to 58 nm.

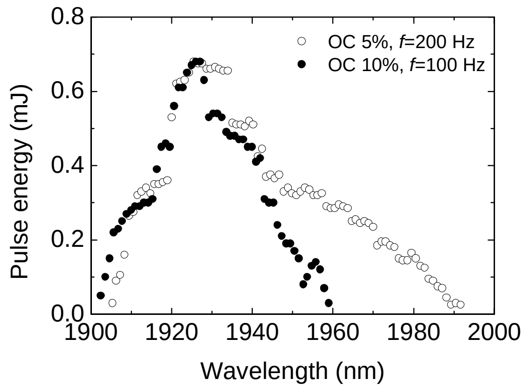

Fig. 6. Wavelength tunability for 5% and 10% output couplings with pulse repetition frequencies of 200 Hz and 100 Hz, respectively. In both configurations the incident pump power was 0.7 W.

4. Conclusion

A novel diode-pumped Q-switched Tm:BaY_2F_8 laser operating at room-temperature has been demonstrated. A maximum peak power of 19 kW was obtained for a pulse repetition frequency of 5 Hz at 0.7 W CW pump power level. A characterization of the Q-switched laser was performed in terms of pulse energy (up to 3.2 mJ), pulse duration (170 nm minimum), and pulse stability (10% over 1 h observation time). The laser can be operated in Q-switched regime within an emission wavelength ranging from 1.91 µm to 1.99 µm. The Tm:BaY_2F_8 laser can find useful applications in Lidar and Dial systems for atmospheric remote sensing.

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