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A fiber pumped Er:YAG laser passively *Q*-switched by Co:ZnS and Cr:ZnSe crystals

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Abstract
Passive *Q*-switching of an Er-fiber–Er:YAG hybrid laser was realized by Co:ZnS and Cr:ZnSe saturable absorbers enabling operation on the 1645 nm and 1617 nm lasing transitions respectively. Single- and multi-mode regimes of operation were analyzed experimentally and theoretically.

Keywords: lasers, erbium, passive *Q*-switching, single frequency, jitter

(Some figures may appear in colour only in the online journal)

1. Introduction

Er:YAG lasers operating in the 1.6 μm eyesafe spectral range ($^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition) are widely used in a variety of medical, scientific, and defense related applications. Direct resonant pumping into the $^4I_{13/2}$ manifold by commercially available 1.532 μm Er-fiber lasers results in a small quantum defect of ~7% and more than 80% efficiency of lasing [1–4]. Passively *Q*-switched lasers are attractive due to their ability to provide low cost, compact, robust, and simple devices, and enable easy control of the cavity's transverse and longitudinal modes [5]. Chromium and cobalt doped II–VI chalcogenide crystals have been successfully utilized as passive saturable absorbers for erbium lasers operating at the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition due to the absence of excited state absorption, and the high cross-section of saturation $\sim 10^{-18}$ cm^2 [6–12]. However, Co:ZnSe/ZnS passive *Q*-switchers have been utilized only in flash lamp pumped systems. In our paper we study the characteristics of a fiber pumped Er:YAG laser passively *Q*-switched by Co:ZnS and Cr:ZnSe crystals under CW excitation. The jitter of the repetition rate in passively *Q*-switched lasers is an important parameter for applications of these lasers. In this paper, the repetition rate jitter of a passively *Q*-switched Er:YAG laser for single and multi-longitudinal mode regimes of oscillation and the temporal criterion for single frequency operation of CW pumped passively *Q*-switched lasers are studied.

2. Experimental results and discussion

The basic laser cavity configuration used in this experiment is depicted in figure 1. The 1.1 mm pump beam from an ELR-20-1532.6-LP fiber laser (IPG Photonics Corp.) is focused into an Er:YAG laser rod (0.25 at.% Er:YAG, 5 mm × 50 mm) through a dichroic flat 45° folding mirror (DM) (HR@1600–1700 nm, AR@1532 nm) by a 300 mm AR-coated focusing lens (FL). The laser scheme is based on a semi-concentric cavity design with a 250 mm back mirror and 80% output coupler (OC). Cr:ZnSe and Co:ZnS crystals with initial transmission of 85–95% at 1645 nm and 1617 nm, respectively, serve as saturable absorbers and are placed at the Brewster angle 50 mm away from the dichroic mirror.

Figure 2 shows the transmission spectra of the Co:ZnS and Cr:ZnSe crystals measured at normal incidence and normalized to the Fresnel reflectivity.

In a laser with resonance pumping, the oscillation wavelength depends on the effective emission gain cross-section spectrum (σ_g) which can be calculated as a difference of emission (σ_{em}) and absorption (σ_{ab}) cross sections multiplied by the fraction of population at upper and ground multiplets [13, 14]. Figure 2 also depicts the effective Er:YAG gain cross-section spectrum for relative inversion in the gain medium $n_2 = 0.5$ ($\sigma_g = 0.5(\sigma_{em} - \sigma_{ab})$) to compare the Er:YAG emission spectrum with the absorption bands of the saturable absorbers.

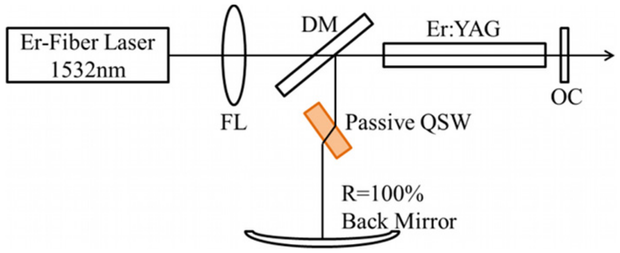

Figure 1. Experimental setup.

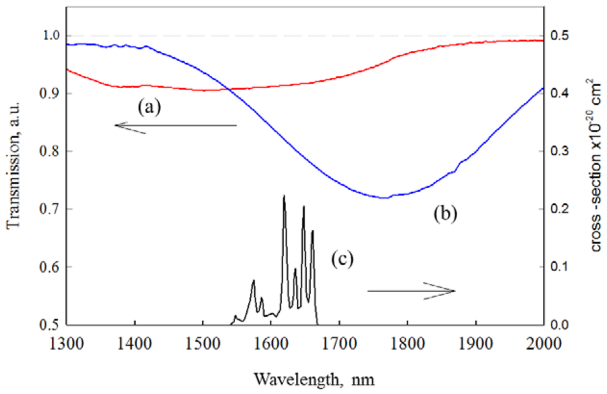

Figure 2. Transmission spectra of Co:ZnS (a) and Cr:ZnSe (b) crystals; Er:YAG effective emission gain cross-section (c) for relative inversion $n_2 = 0.5$ in the gain medium.

There are several differences which should be taken into account for Co:ZnS and Cr:ZnSe passive saturable absorbers. Er:YAG oscillation wavelengths are usually 1645 or 1617 nm, which correspond to Er:YAG emission gain maxima at different inversions. As one can see from figure 2, the maximum of Co:ZnS absorption is shorter than the Er:YAG oscillation wavelengths, while the maximum of Cr:ZnSe absorption is peaked at 1770 nm. As a result, lasing at 1617 nm has larger absorption in comparison with 1645 nm in Co:ZnS, while it is an opposite situation for Cr:ZnSe crystal. Another difference between these crystals is in relaxation life time. The upper level

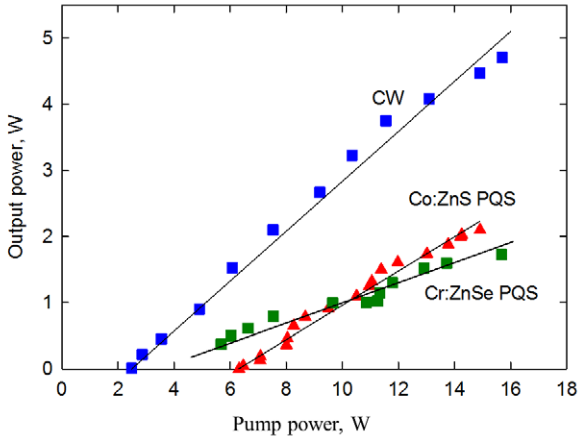

Figure 3. Output power of the CW and Co:ZnS and Cr:ZnSe passively Q-switched Er:YAG laser versus absorbed input power.

life time of Cr:ZnSe crystal is $\tau \approx 6\ \mu$s, while the relaxation time of Co:ZnS is $\tau \approx 200\ \mu$s at room temperature (RT).

Figure 3 features the output–input characteristics of a passively Q-switched Er:YAG laser utilizing a Co:ZnS passive Q-switch (PQS) with 92% initial transmission. The lasing wavelength was 1645 nm. The obtained output power reached a level of 2.1 W at 16 W incident pump with 24% slope and 14% real optical efficiencies. For comparison, the CW oscillation of the Er:YAG laser with 38% slope efficiency was measured in the same cavity without the Co:ZnS crystal. The conversion efficiency of operation in the passively Q-switched regime with respect to CW operation was as high as 63%.

Figure 4(a) represents a train of Q-switched Er:YAG pulses obtained for an input power of 7.4 W. At this pump power, the passively Q-switched Er:YAG laser operates at a repetition rate of 1.25 kHz and features an output pulse energy of ~0.1 mJ. From figure 4(b) one can see that the laser demonstrates a relatively long Q-switched pulse with a pulse duration of $\tau = 0.95\ \mu$s at FWHM. The pulse duration slightly increased to 1.2 μs at higher pump power.

The output energy of the passively Q-switched Er:YAG laser versus input power is depicted in figure 5(a). Near the laser threshold, the average output energy per oscillation

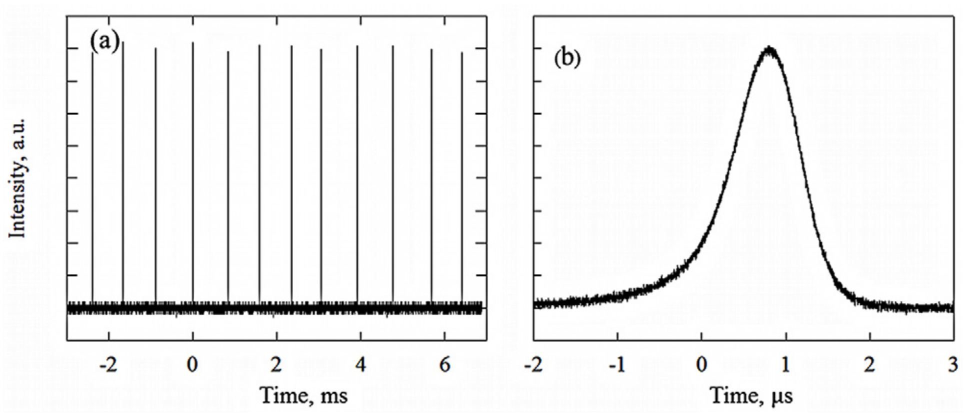

Figure 4. (a) Train of output pulses of the Co:ZnS passively Q-switched Er:YAG laser at a pump power of 7.4 W. (b) Temporal profile of a single output pulse.

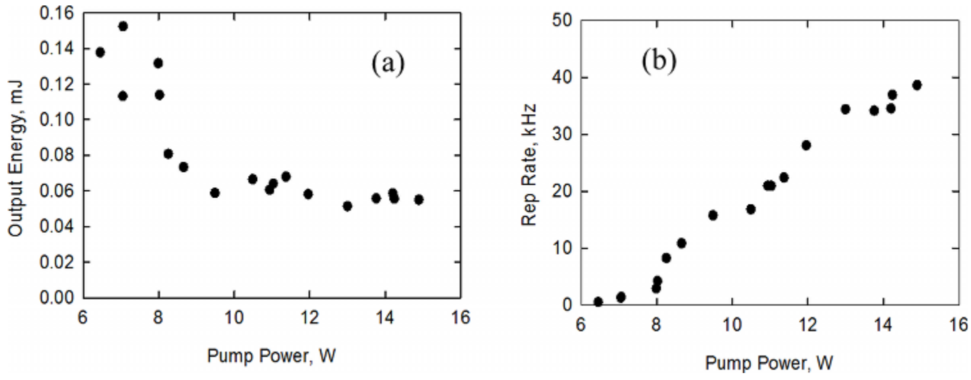

Figure 5. Output energy (a) and repetition rate (b) of the Er:YAG laser with Co:ZnS saturable absorber.

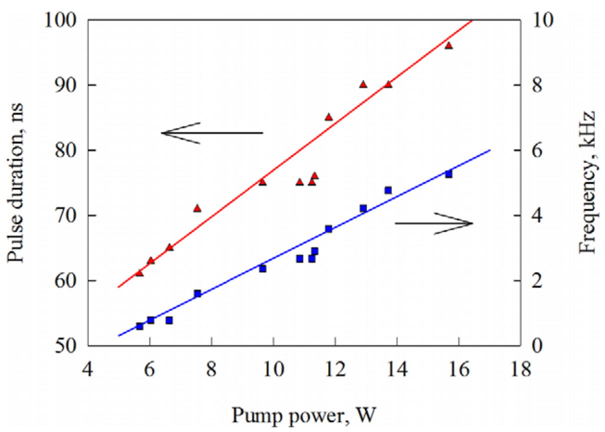

Figure 6. Pulse duration and repetition rate of the Cr:ZnSe passively *Q*-switched Er:YAG laser.

pulse was approximately 0.16–0.1 mJ. For pump power above 9 W, the averaged oscillation energy was ∼0.06 mJ and was accompanied by improved stability with further increase of the pumping power. Figure 5(b) shows the repetition rate of the passively *Q*-switched Er:YAG laser versus incident pump power.

The maximum estimated repetition rate was 38 kHz. This high repetition rate and long pulse duration demonstrate that under CW excitation, the Co:ZnS saturable absorber, due to its long relaxation life time, operates rather as a stabilizer of Er:YAG relaxation oscillation dynamics than as a 'classical passive *Q*-switch'.

For comparison, we measured the output characteristics of the Er:YAG laser in the same experimental conditions with the use of a Cr:ZnSe saturable absorber with initial transmission of 92.5% at 1645 nm. The output–input characteristics of this laser are depicted in figure 3. In spite of the fact that at maximum pump power the laser demonstrated approximately the same (∼2 W) output power, the slope efficiency was smaller (14% versus 24%) than in the Er:YAG cavity passively *Q*-switched with Co:ZnS. The output pulse duration and repetition rate versus Er-fiber pump power are plotted in figure 6.

As the pump power grows, the *Q*-switched laser repetition rate changes from approximately 0.4 to 5.2 kHz and the pulse

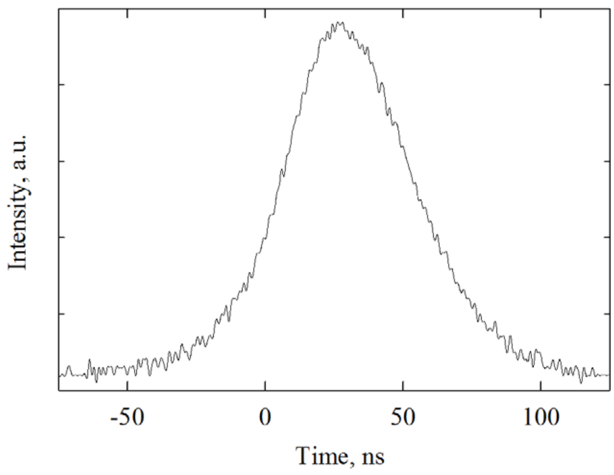

Figure 7. Temporal profile of the Cr:ZnSe passively *Q*-switched Er:YAG laser.

energy decreases from 0.8 to 0.35 mJ. The minimum pulse width was ∼60 ns at the lowest repetition rate (see figure 6) and 96 ns at 5.2 kHz (at 15.7 W of pump power). The pulse duration was an order of magnitude shorter than it was with the Co:ZnS passive *Q*-switch. From figure 7 one can see that the laser operates in a single-longitudinal mode regime without any evidence of mode beating. However, it was found that an increase of the cavity length from $L_{cav} = 148$ to 278 mm results in increasing the pulse duration to 80 ns, accompanied by a strong longitudinal mode beating and more pronounced repetition rate jitter.

The repetition rate jitter was measured using an FSEA spectrum analyzer. In our experiments we measured the relative frequency distribution of the signal from the fast detector near the repetition rate frequency for two laser cavity lengths. We tested our systems at 420 Hz pulse repetition rate, since the maximum Er:YAG pulse energy was exhibited at this rate. It is noteworthy that a dynamic distributed feedback in the gain element could be developed in a single frequency regime of oscillation. The relaxation life time of the developed distributed feedback structure depends on the upper level life time in the gain element and pump intensity. At high repetition rates, the influence of the distributed feedback from the previous pulse could result in additional frequency jitter.

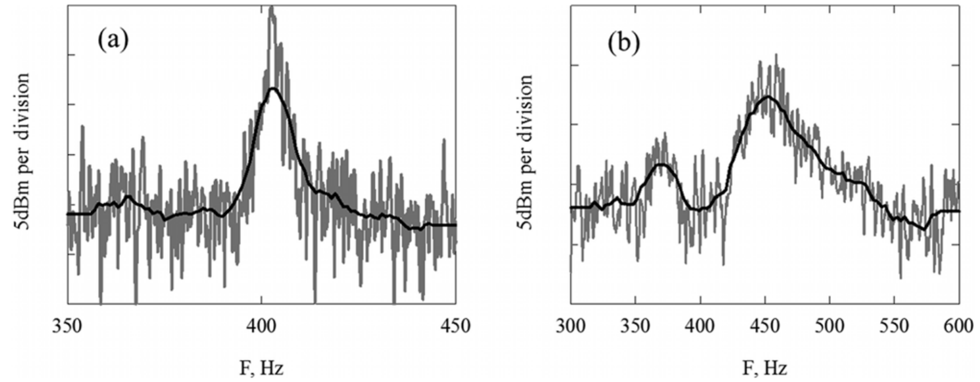

Figure 8. Pulse repetition rate jitter: (a) short cavity, $L_{cav} = 148$ mm; (b) long cavity, $L_{cav} = 278$ mm.

In our experiments short and long cavity lasers operated at the same level of relative pump power $r = 1.145$ (ratio of the pump power to the threshold power). The frequency distributions of the repetition rate are depicted in figure 8. As one can see, there is a strong instability in the pulse repetition rate for a long cavity (see figure 8(b)) due to multimode operation and mode competition ($\Delta F_{r.r.} > 170$ Hz at -10 dB level). However, the pulse repetition rate in a short cavity (figure 8(a)) exhibits a much smaller ($\Delta F_{r.r.} < 10$ Hz at -10 dB level) jitter.

The influence of the cavity length on the single frequency regime of operation can be explained using a simplified model. As was demonstrated in [5], a passive *Q*-switch enables longitudinal mode selection due to an increased pulse rise-time. The rise-time (t_{sn}) describes the pulse evolution from the laser threshold to the intracavity flux at which the saturable absorber starts to bleach. It could result in a single frequency regime of operation even without additional intracavity dispersive elements [5]. Later, the criterion for a single frequency regime of operation was suggested in [15] stating that the difference in the build-up time between two adjacent longitudinal modes should be comparable with or greater than the laser pulse duration. According to the above model, the build-up time difference, Δt_s, between the n_{th} and m_{th} modes estimated from equation (1*a*) (see equation 7 in [15]) is

$$\Delta t_s = t_{sn} \frac{(\sigma_n - \sigma_m)}{\sigma_n} \left[\frac{N_{th(n)}}{\Delta N} \right], \tag{1a}$$

where $\sigma_{n(m)}$ are the emission cross sections at the wavelength of the $n(m)$ modes, $N_{th(n)}$ is the threshold population inversion, and ΔN is the increment of the population inversion during the build-up time (in [15] the authors used the parameter $\varepsilon = \Delta N / N_{th}$). The suggested criterion was tested using a pulsed Nd:YAG laser with a LiF:F_2^- saturable absorber by estimating the build-up time t_{sn}.

A dynamic picture of the population inversion and oscillation of the Er:YAG laser studied in this work for CW pumping is depicted in figure 9. For CW excitation equation (1*a*) could be rewritten as

$$\Delta t_s = \frac{(\sigma_n - \sigma_m)}{\sigma_n} \left[\frac{N_{th(n)}}{(\mathrm{d}N/\mathrm{d}t)} \right], \tag{1b}$$

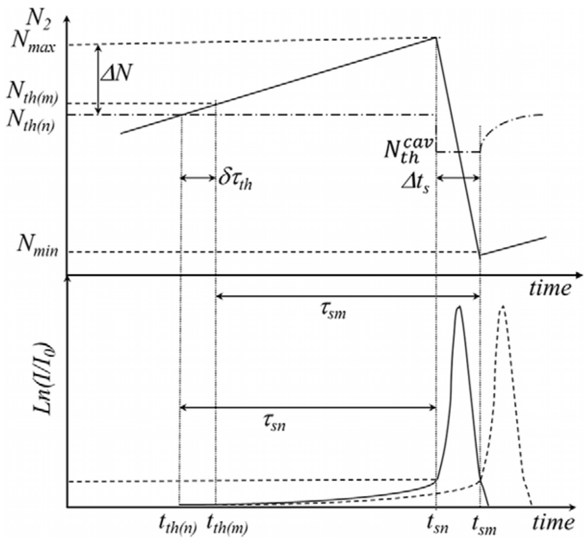

Figure 9. A dynamic picture of the population inversion (top) and laser oscillation (bottom). N_{max} is the population inversion at the onset of saturable absorber bleaching; N_{min} is the residue of the inversion after *Q*-switch pulse extraction; $\delta\tau_{th}$ is the time delay for adjacent longitudinal modes to achieve the threshold value of inversion. N_{th}^{cav} is the cavity threshold with a saturated passive *Q*-switch. The dash-dotted line represents the dynamics of the threshold inversion in the cavity.

where $\mathrm{d}N/\mathrm{d}t$ is the population inversion derivative at the laser threshold, which, in turn, could be estimated from the repetition rate (f) as

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{(N_{th(n)} - N_{min})}{T_{period}} = (N_{th(n)} - N_{min}) f = N_{th(n)} (1 - x) f, \tag{2}$$

where N_{min} is the minimum population inversion after *Q*-switch pulse oscillation, and the ratio $x = N_{min}/N_{th(n)}$. Finally, the build-up time difference could be written as

$$\Delta t_s = \frac{(\sigma_n - \sigma_m)}{\sigma_n} \frac{1}{(1 - x) f}. \tag{3}$$

The minimal population inversion after the energy extraction by a *Q*-switch pulse depends on the initial inversion ratio

$r_{QS} = N_{th(n)}/N_{th}^{cav}$ [16]. This value characterizes by how much the inversion in the gain element exceeds the threshold inversion due to the cavity losses after bleaching of the passive Q-switch. The dependence could be expressed as in [16]:

$$1 - x - \frac{1}{r_{QS}} \ln\left(\frac{1}{x}\right) = 0. \quad (4)$$

The oscillation build-up time is shorter than the pump duration; therefore in equation (4) we can consider that $N_{max} \approx N_{th(n)}$. Finally, r_{QS} could be found from the ratio of initial cavity losses with an unsaturated passive Q-switch to cavity losses with a saturated passive Q-switch as

$$r_{QS} = \frac{N_{th(n)}}{N_{th}^{cav}} = \frac{-\ln(R_{out}T_0^2)}{-\ln(R_{out})} = 1 + \frac{\ln(T_0^2)}{\ln(R_{out})}, \quad (5)$$

where T_0 is the initial transmission of the passive Q-switch and R_{out} is the output coupler reflectivity. In our experiments, from equation (5) we estimated $r_{QS} = 1.7$ using $T_0 = 0.925$ and $R_{out} = 0.8$. From equation (4), one can calculate that the minimum (N_{min}) population inversion is expected to be 30% from the initial inversion ($N_{th(n)}$).

It can be shown that for two adjacent cavity modes separated by $\delta\nu = 1/2L_{cav}$ (where L_{cav} is the cavity length), the $(\sigma_n - \sigma_m)/\sigma_n$ ratio can be estimated as $(\Delta\nu L_{cav})^{-2}$, where $\Delta\nu$ is the FWHM of the gain profile approximated by a Lorentzian function [15]. In our experiments we estimated $\Delta\nu \approx 12\ \text{cm}^{-1}$ from photoluminescence measurements. Using the above parameters we calculated a build-up time for the short cavity ($L_{cav} = 148$ mm) equal to $\Delta t_s = 135$ ns, which is longer than the measured pulse duration of ~60 ns. On the other hand, the difference in the build-up time in the long cavity ($L_{cav} = 278$ mm) is equal to $\Delta t_s = 34$ ns, which is smaller than the measured pulse duration of ~80 ns in this cavity. This result is supported by the experimental measurements where mode beating and increase of frequency jitter were observed in the long cavity.

3. Conclusions

Passive Q-switching of an Er-fiber-pumped Er:YAG fiber-bulk hybrid laser was realized with the use of Co:ZnS and Cr:ZnSe saturable absorbers enabling operation at 1645 nm or 1617 nm respectively. Conditions of passive Q-switched Er:YAG laser operation on the 1645 and 1617 nm lasing transitions were established. Single- and multi-longitudinal mode regimes of operation were analyzed experimentally and theoretically for different lengths of the cavity which did not contain additional mode selection elements. Theoretically and experimentally a single frequency regime of operation was realized for cavities and pump rates enabling a difference in build-up time between two adjacent longitudinal modes greater than the pulse duration. For the same levels of output power the jitter in the pulse repetition rate was decreased by a factor of 17, reaching 2.5% of the operating frequency.

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