

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Rz; 42.60.Gd; 42.70.Mp
DOI: 10.1070/QE2005v035n07ABEH008954

Passive *Q* switches for a diode-pumped erbium glass laser

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***Abstract*. A diode-pumped, passively *Q*-switched 1.54-μm erbium glass laser is studied. Zinc selenide (ZnSe) crystals doped with Co^{2+} and Cr^{2+} ions and magnesium – aluminium spinel ($MgAl_2O_4$) crystals doped with Co^{2+} ions were used as saturable absorbers in *Q* switches. It is shown that, depending on the type of a saturable absorber, the pump power, and the resonator design, the laser pulse energy can vary from 0.2 to 13 μJ, the pulse duration from 16 to 980 ns, and the pulse repetition rate from 0.1 to 30 kHz.**

Keywords: *Cr : ZnSe, Co : ZnSe, Co :* $MgAl_2O_4$ *single crystals, Q-switching, passive Q switch.*

1. Introduction

Wide applications of lasers emitting in the spectral range from 1.4 to 1.6 μm are explained by the fact that radiation in this spectral range is eye-safe, is weakly absorbed in the atmosphere, and dispersion and absorption in a silica fibre in this wavelength range are low. For this reason lasers emitting in the 1.5-μm region are widely used in ophthalmology, fibreoptic communication systems, optical location and telemetry. These applications require, as a rule, short pulses with high peak powers. One of the simple and reliable methods for generating such pulses is passive *Q*-switching.

At present passive *Q*-switching in cw diode-pumped Er-glass lasers is performed by using different saturable absorbers, for example, a semiconductor saturable-absorption mirror (SESAM) [1] and Co^{2+}-doped $LaMgAl_{11}O_{19}$ [2] and $MgAl_2O_4$ [3] crystals. In these systems, 1 – 15-μJ laser pulses of duration 1.2 – 10 ns were generated. Zinc selenide (ZnSe) crystals doped with Co^{2+} [4, 5] or Cr^{2+} [5] ions are promising saturable absorbers for a flashlamp-pumped Er-glass laser. The advantages of passive *Q* switches based on Co^{2+} or Cr^{2+}-doped crystals are the comparatively high ground-state absorption cross sections ($\sim 10^{-19}$ cm^2) and negligible excited-state absorption losses. In this paper, we study for the first time the Co : ZnSe and Cr : ZnSe crystals used as passive *Q* switches for a cw diode-pumped Er-glass laser and compare them with Co : $MgAl_2O_4$ *Q* switches under the same experimental conditions.

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Received 31 March 2005; revision received 17 May 2005
Kvantovaya Elektronika **35** (7) 611 – 614 (2005)
Translated by M.N. Sapozhnikov

2. Experimental

Zinc selenide crystals doped with chromium and cobalt were grown by the diffusion doping technique [7], while Co : $MgAl_2O_4$ crystals were grown by the Czochralski method.

The absorption spectra of the Co : ZnSe, Cr : ZnSe, and Co : $MgAl_2O_4$ crystals in the 1.5-μm region are presented in Fig. 1. The absorption bands belong to the Cr^{2+} (the $^5T_2 \rightarrow {}^5E$ transition) and Co^{2+} [the $^4A_2 \rightarrow {}^4T_1(^4F)$ transition] ions with the tetrahedral coordination [6, 8]. These crystals have approximately equal absorption cross sections $(3-5)\times 10^{-19}$ cm^2 at 1.54 μm but different excited-state lifetimes at room temperature: 290 and 5.4 μs for Co : ZnSe and Cr : ZnSe, respectively, and 350 ns for Co : $MgAl_2O_4$ [5, 6, 8, 9].

The crystals used as passive *Q* switches were studied on the experimental setup shown in Fig. 2. The laser resonator of length from 48 to 6 mm consisted of the input flat mirror

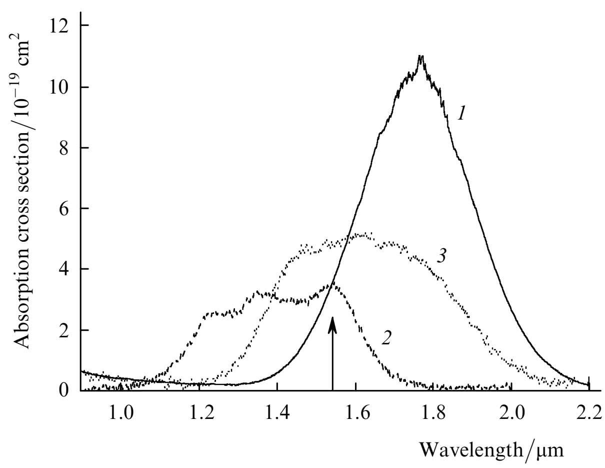

Figure 1. Ground-state absorption cross sections for the Cr : ZnSe (*1*), Co : $MgAl_2O_4$ (*2*), and Cr : ZnSe (*3*) crystals in the 1.5-μm spectral region. The arrow shows the wavelength of the erbium laser.

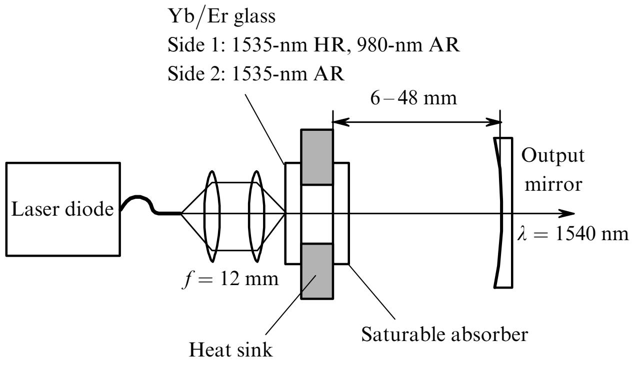

Figure 2. Scheme of the experimental setup for studying Q-switching of the Er-glass laser.

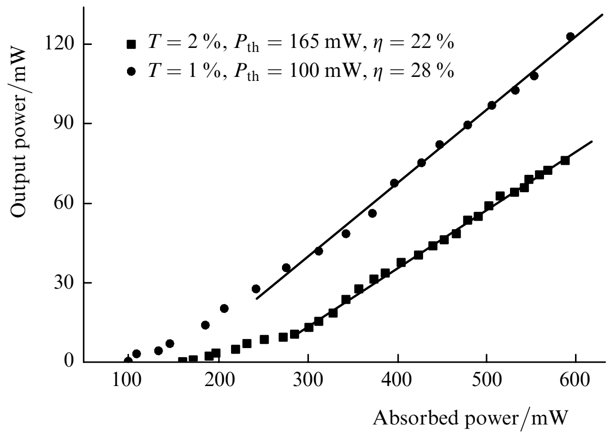

Figure 3. Output power of the cw erbium laser.

with the 100 % reflection at the laser wavelength 1540 nm and high (more than 95 %) transmission at the pump wavelength 981 nm and of the concave output mirror with the radius of curvature 50 mm and the 1 % or 2 % transmission at the laser wavelength. The Yb^{3+}/Er^{3+}-doped phosphate glass active element of thickness 2 mm was mounted on an aluminium heat sink cooled with running water. The laser was pumped by a 0.85-W, 981-nm InGaAs laser diode with a fibre pigtail (the fibre had a diameter of 150 μm and a numerical aperture of 0.12; the radiation quality parameter was $M^2 = 30$). The radiation from the laser diode was collimated and focused to the active element by a system consisting of two lenses with a focal distance of 12 mm. The pump beam waist diameter was ~ 170 μm with a confocal length of 2.3 mm. The best overlap of the resonator modes with the pump beam was achieved for the resonator length 48 mm, the diameter of the TEM_{00} resonator mode in the active element being ~ 160 μm.

Passive Q-switching was studied in polished Cr : ZnSe, Co : ZnSe, and Co : $MgAl_2O_4$ crystal samples without AR coatings, transmitting 98 %, 98 %, and 99 % of radiation at a wavelength of 1535 nm, respectively. The saturable absorbers were placed at a distance of 2 mm from the active element. The parameter of the intracavity radiation focusing (the ratio of the cross sections of the resonator mode on the active element and a bleached medium) was 0.92.

The output radiation power was measured with an Ophir power meter equipped with a 3A-P-CAL head. The temporal parameters of laser radiation were analysed with a Ge photodiode with the time constant smaller than 1 ns and a Tektronix TDS3052B digital oscilloscope with a pass band of 500 MHz.

3. Experimental results

The output power of the erbium laser in the cw mode (without passive Q switches) is presented in Fig. 3. Its maximum output power for the slope lasing efficiency with respect to the absorbed pump power $\eta = 28\,\%$ was 120 mW and was obtained in the resonator of length 48 mm with the output mirror with the transmission $T = 1\,\%$. For $T = 2\,\%$, the output power was 75 mW and the slope efficiency was ~ 22 %.

The best parameters of the laser in the Q-switching regime were obtained with the output mirror with transmission $T = 2\,\%$. The maximum 68-mW average output power (Fig. 4) for the 280-ns pulse duration, 7-μJ pulse energy, and ~ 600 mW of the absorbed pump power was achieved by using the Cr : ZnSe crystal. As the absorbed pump power increased from 110 to 600 mW, the pulse repetition rate changed from 100 Hz to 10 kHz and the pulse duration changed from 400 to 280 ns (Fig. 5). The 50-mW average output power for 150-ns, 13-μJ pulses and ~ 600 mW of the absorbed pump power was achieved for the Co : $MgAl_2O_4$ crystal.

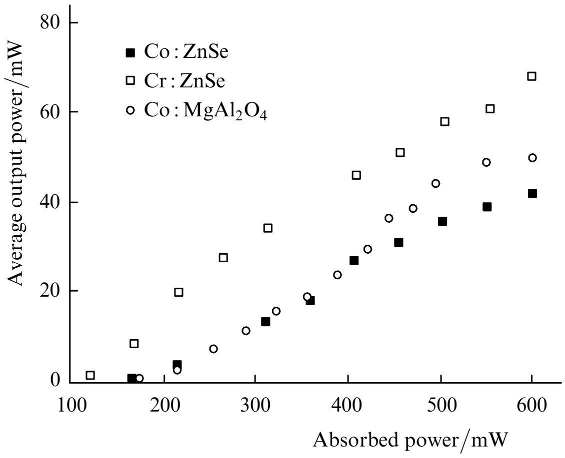

Figure 4. Averaged output power of the passively Q-switched erbium laser with Cr : ZnSe, Co : ZnSe, and Co : $MgAl_2O_4$ Q switches as a function of the absorbed power.

For the erbium laser with the Co : ZnSe Q switch, the average output power was 42 mW (Fig. 4), the pulse duration varied from 140 to 980 ns (Fig. 5), and the pulse repetition rate changed from 140 Hz to 30 kHz when the pump power was increased from the threshold to its maximum value.

Figure 6 shows the oscillograms of pulses from the erbium laser with a passive Co : ZnSe Q switch. Upon pumping near the threshold, an intense nanosecond pulse was observed, followed by up to ten low-intensity pulses. As the pump power was increased, a train of submicrosecond pulses with the same amplitude and a high repetition rate appeared. This is explained by a comparatively long relaxation time of Co^{2+} ions in ZnSe (about 290 μs)

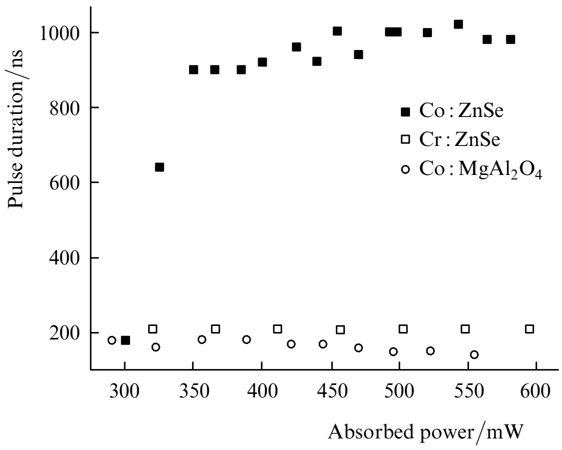

Figure 5. Pulse duration of the passively Q-switched erbium laser with Cr : ZnSe, Co : ZnSe, and Co : $MgAl_2O_4$ Q switches as a function of the absorbed energy.

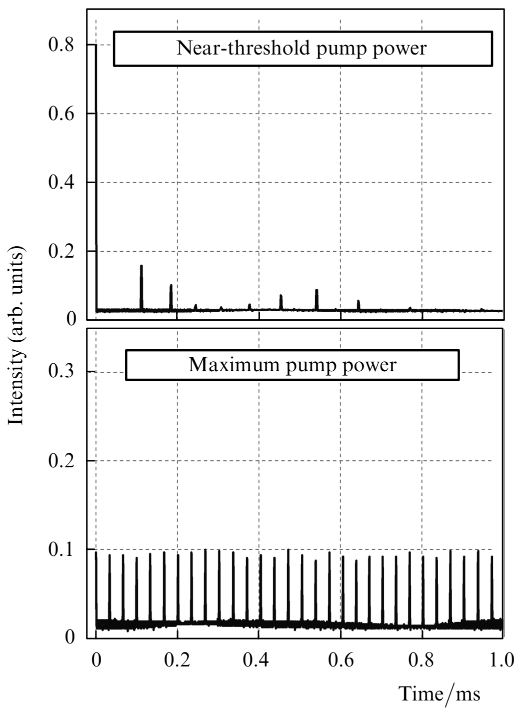

Figure 6. Oscillogram of pulses from the passively Q-switched erbium laser with the Co : ZnSe Q switch.

resulting in a decrease of saturable losses in the Q switch (modulation depth of the Q switch) at high pulse repetition rates (above 3.5 kHz), when the time interval between pulses is shorter than the relaxation time of the saturable absorber.

The Q-switching efficiency (the ratio of the average output power in the Q-switching regime to the cw output power) with the Cr : ZnSe, Co : $MgAl_2O_4$, and Co : ZnSe Q switches was 90 %, 65 %, and 57 %, respectively.

To reduce the laser pulse duration, we studied passive Q-switching in a short 6-mm resonator. The best output parameters for this resonator were obtained with the output mirror with transmission 1 %. The output cw power of the laser decreased down to 50 mW. This is explained by the decrease in the pump efficiency due to an incomplete overlap of the pump beam (of diameter 170 μm) and the resonator mode (of diameter 200 μm). The maximum average output power of 36 mW for 5.5-μJ, 16-ns pulses and 600 mW of absorbed pump power was achieved with the Co : $MgAl_2O_4$ Q switch. The pulse repetition rate was 6.5 kHz. For the same pump power and 4.7-μJ, 60-ns pulses, the average output power achieved with the Cr : ZnSe Q switch was 20 mW. The pulse repetition rate in this case was 4.3 kHz.

The average output power of the erbium laser with the Co : ZnSe Q switch was 15 mW. The pulse duration depended on the pump power, as in the case of the 48-mm resonator. When the absorbed pump power increased from100 to 600 mW, the pulse repetition rate changed from 2 to 16.5 kHz and their duration changed from 60 to 400 ns.

The results of the study of Q-switching of the erbium laser by using saturable absorbers based on the Cr : ZnSe, Co : ZnSe, and Co : $MgAl_2O_4$ crystals are presented in Table 1.

Laser pulses generated in our experiments with Co : $MgAl_2O_4$ crystals are somewhat longer (and have a lower peak power) than 9-μJ, 2.3 – 8-ns pulses with the peak power from 0.2 to 2 kW obtained in [3], however, they have a greater energy. This is caused by the different design of the resonators: in [3], a microlaser with the 1-mm resonator was investigated.

One can see from Table 1 that the most promising passive Q switches for an Er-glass laser among the crystals investigated in the paper are the Co : $MgAl_2O_4$ and Cr : ZnSe crystals. The greatest peak pulse powers were obtained in the laser with a short resonator.

4. Conclusions

We have studied passive Q-switching of a cw diode-pumped Er-glass laser by using saturable absorbers based on the Co : $MgAl_2O_4$, Cr : ZnSe, and Co : ZnSe crystals. Depending on the Q-switch type, pump power, and the resonator design, the laser pulse energy was 0.2 – 13 μJ, the pulse duration was 16 – 980 ns, and the pulse repetition rate was 0.1 – 30 kHz. A comparatively large bleaching relaxation time (290 μs) of the Co : ZnSe Q switch results in an increase in the pulse repetition rate, a decrease in the pulse energy, and an increase in the pulse duration. A consi-

Table 1.

Q-switch type	Resonator length/mm	Pulse duration/ns	Pulse energy/μJ	Pulse repetition rate/kHz	Output power/mW	Peak power/W
Cr : ZnSe		280	7	9.7	68	25
Co : ZnSe	48	170 – 980	1.4 – 9	30	42	1.4 – 52
Co : $MgAl_2O_4$		150	13	3.9	50	86
Cr : ZnSe		60	4.7	4.3	20	78
Co : ZnSe	6	60 – 400	0.2 – 1	16.5	15	0.5 – 17
Co : $MgAl_2O_4$		20	5.5	6.5	36	275

derable decrease in the average output power of the erbium laser with passive Co : ZnSe and Cr : ZnSe *Q* switches when a short resonator is used is explained by a greater sensitivity of the erbium glass laser (quasi-three-level lasing scheme) to the losses appearing due to an incomplete overlap of the pump beam (of diameter 170 μm) and the resonator mode (of diameter 200 μm). A higher losses introduced by these crystals compared to the Co : $MgAl_2O_4$ crystal are caused by a lower initial transmission (98 %) and a higher refractive index of the crystal matrix ($n_{ZnSe} = 2.44$), which increases the losses caused by Fresnel reflection from crystal faces (without AR coatings). The most promising passive *Q* switches for a cw diode-pumped Er-glass laser among the crystals investigated in the paper are the Co : $MgAl_2O_4$ and Cr : ZnSe crystals.

Acknowledgements. This work was supported by the joint project of the Belarus Foundation for Basic Research (Grant No. F04R-145) and the Russian Foundation for Basic Research (Grant No. 04-02-81015 Bel 2004A).

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