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Diode-pumped erbium-ytterbium-glass laser passively Q-switched with a PbS semiconductor quantum-dot doped glass

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Abstract. Q-switched and cw operation of different diode-pumped erbium-ytterbium doped glasses at 1.5 μm has been studied in a compact microlaser setup. For Q-switching we used a novel PbS semiconductor quantum-dot doped glass which offers low saturation intensity compared with typical absorbers used and a fast time response. The cw laser delivered output powers of 35 mW with slope efficiencies of 16%. In Q-switched operation pulse energies of 1 μJ at repetition rates of 1–2 kHz and pulse durations of about 30–50 ns, depending on absorber thickness were obtained.

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The eyesafe wavelength region of the optical spectrum (1.5–1.6 μm) is favoured for applications such as telemetry and ranging [1–4]. Erbium ions in glass hosts are the material of choice if a laser directly emitting in this spectral region without use of nonlinear frequency conversion is desired. Numerous studies in this field have been carried out on actively [2, 4] as well as on passively Q-switched lasers [5, 6]. For compactness, simplicity, and robustness in everyday use the research tends towards diode-pumped passively Q-switched setups [7], avoiding maintenance neccesary for flashlamp pumping and additional electronic equipment required for active switching. Saturable absorbers currently used are erbium [8], uranium [9] and cobalt [10] ions in different crystal hosts. All absorbers are used in resonator setups of a few centimeter length, setting a limit for compactness. All of these absorbers have a relatively high saturation intensity of about 40–200 MW/cm^2. In a diode-pumped setup these intensities are normally not accessible with single-emitter laser-diode pump-sources with pump powers of 1–2 W. The use of semiconductor quantum-dot doped glass is an interesting possibility to overcome this problem. With an saturation intensity of 0.18 MW/cm^2 in PbS-doped glass [11] complete bleaching of the absorber is possible with the intensities achievable in a standard microlaser setup. Another way for Q-switching is the use of semiconductor saturable absorber mirrors [5, 7] which offer a similar saturation characteristic based on quantum wells with their one-dimensional confinement of electronic states in contrast to the three-dimensional confinement in quantum-dots. Their production process is complicated because of the sophisticated MOCVD techniques necessary for production of these devices. Semiconductor quantum-dot doped glasses on the other hand can be produced by common melting techniques well known and elaborated in glass technology and can be easily tuned in their spectral properties by changing the quantum-dot size by different growth conditions. Details about the glass composition are to be found in [12].

1 Setup

Three different glasses were used as active material, a commercial phosphate glass (Kigre QX/Er) and two glasses melted at the Otto-Schott-Institute, an ultraphosphate and a fluoride phosphate glass. The phosphate glass had a doping concentration of 1.24×10^{19} cm^{-3} Er^{3+} and 1.6×10^{21} cm^{-3} Yb^{3+} and the two other glasses had a doping concentration of 5×10^{19} cm^{-3} Er^{3+} and 8×10^{20} cm^{-3} Yb^{3+} each. Fluorescence lifetimes are 7.9 ms for the phosphate, 6.8 ms for the ultraphosphate, and 9.5 ms for the fluoride phosphate glass, respectively. Samples were cut and polished to peaces of 8×8 mm with 1.8 mm thickness.

Thin plates of 200 μm and 300 μm thickness of the PbS-doped glass, developed at Corning, acting as the saturable absorber were prepared for Q-switch experiment. An absorption of 0.1 cm^{-1} was measured at the wavelength of the first exciton peak which coincides with the laser wavelength. Completely bleaching this absorbance would result in a change of transmission of the absorber of 0.2% and respectively 0.3% which acts as a time-dependent saturable loss coefficient q_o. If bleaching occurs, light is absorbed and electrons are excited into the upper conduction band. Time response of the recovery of the bleaching is determined by intra and interband thermalization processes and was determined to be around 50–200 ps [13] near the first exciton peak.

cw as well as Q-switched experiments were carried out in a laser cavity consisting of a mirror with high reflectivity coating from 1450–1650 nm and low reflectivity from

950–990 nm, radius of curvature was 75 mm. The other mirror had a reflectivity of 99% around the laser wavelength and a radius of curvature of 150 mm. The cavity length for all experiments was about 4–5 mm, resulting in spot sizes of 175 μm and 147 μm on the mirrors with a beam waist of 88 μm.

Pump source was a 100-μm single-emitter laser diode from Polaroid 2000 − 977 − TO3 − MCL − BW giving a maximum power of 2 W at 974 nm. Pump radiation was collimated with an acromatic lens of 50 mm focal length and focused into the active medium with another acromat with 150-mm focal length along the axis of the resonator.

2 cw operation

In order to determine the laser performance of the different laser glasses cw experiments were performed without the saturable absorber inside the cavity. Uncoated glass samples were placed inside the resonator and longitudinally pumped. No active cooling was applied. Table 1 summarizes the slope efficiencies with the output powers for a given absorbed power.

The phosphate glass reached the highest output power of the laser glasses limited by thermal problems for higher pump powers. Lasing threshold was higher by a factor of two for the other two glasses which was attributed to the different doping concentrations and imperfections of the glasses such as striae and bubbles. The influence of higher OH content in the ultraphosphate glass is reflected in the lower lifetime compared with the phosphate glass, Table 1 shows the measured absorption at the 3-μm band which is proportional to the OH concentration and responsible for lifetime quenching by energy transfer from erbium ions to OH groups [14] leading to a decrease in laser efficiency. The fluoride phosphate glass lases due to the different chemical environment of the active ions around 1560 nm in contrast to the pure phosphate type glasses which lase at 1535 nm; with this the laser works at a lower value of emission cross-section which has its maximum at 1534 nm [15], resulting in a lower performance. From the cw lasing behaviour the phosphate glass shows higher potential in Q-switched use.

3 Q-switched operation

For Q-switch operation the uncoated absorber samples were inserted independently adjustable inside the resonator, close to the output coupler and about 1 mm from the laser glass. Figure 1a, shows the absorption spectra of the PbS nanocrystal doped glass. From the spectral position of the first exciton peak a average size of the nanocrystals of 3.1 nm was concluded [11, 13]. Pulse duration of the Q-switched pulses were measured with a fast photodiode (Hamamatsu G3476-03) and recorded by a digital oscilloscope (LeCroy 9362). Figure 1b, shows two typical pulse forms measured with different absorber thickness. The normalized traces were set with their maximum to the trigger point. The pulse shapes show a simmilar time dependence, with a stronger pulse shortening in the rising edge of the pulse with higher absorber thickness.

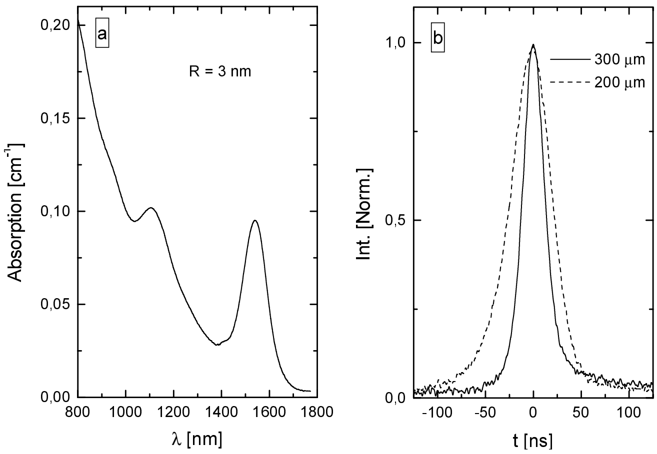

Fig. 1. a Absorption of PbS doped glass. **b** Pulse duration for different absorber thickness

A theoretical value for the pulse duration is given by [5]

$$\tau_\mathrm{p} \approx \frac{7.04l}{cq_\mathrm{o}}\,, \tag{1}$$

where l is the cavity length, c the velocity of light and q_o the unbleached value of the saturable loss coefficient. With the typical cavity length and absorber thickness of 200 μm and 300 μm pulse durations of about 52 ns and 35 ns are expected. In Figs. 2 and 3 values for pulse energy, pulse duration and pulse repetition rate are given for the phosphate and fluoride phosphate glass with 300-μm-thick saturable absorber. Both show only small deviations from constant values for pulse en-

Table 1. cw lasing performance for phosphate (P), ultraphosphate (UP) and fluoride phosphate (FP20) glasses

	Slope	P_out (mW)	P_abs (mW)	α_OH (cm^{-1})
P	15.8	34.8	320	0.45
UP	10.4	24.2	474	2.70
FP20	9.7	18.8	452	< 0.1

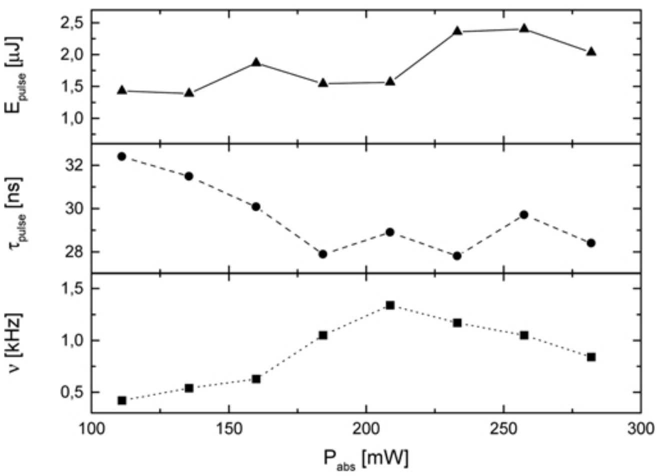

Fig. 2. Pulse energy, pulse width and repitition rate for phosphate glass with 300-μm-thick absorber

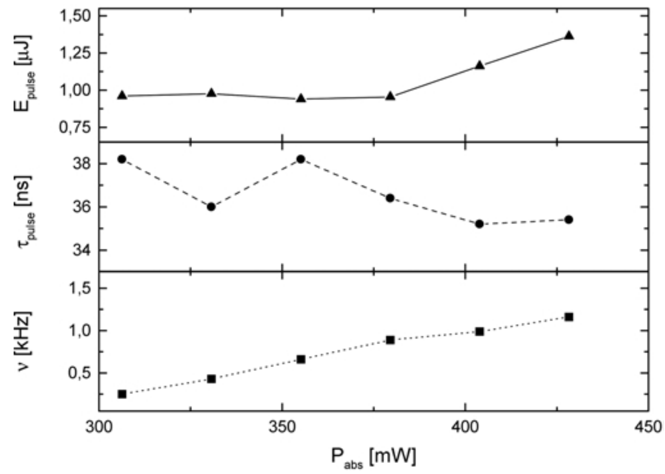

Fig. 3. Pulse energy, pulse width and repitition rate for fluoride phosphate glass with 300-µm-thick absorber

ergy and duration with a linear increase in repetiton rate as expected from theory [5].

With pulse energies around 1 µJ a output coupling of 1% and a laser mode of 100 µm a peak intensity of about 6 MW/cm^2, 33 times the saturation intensity, the absorber should be completely bleached. Nonsaturable losses are in the order of 2% [11] of q_o. Recovery time of the absorber is short compared with lanthanide ions used as saturable absorbers. With the quantum-dot doped glass the recovery time, some hundred picoseconds [13], is much shorter than the pulse duration of the laser. Consequently an edge cutting effect can take place with increasing loss inside the laser at a time when it still emits radiation. This effect reduces the tail often observed in passively Q-switched lasers but also affects the energy extraction. Future rate equation, analysis will give a detailed insight into the absorbers' influence in the pulse-forming process.

The ultraphosphate glass showed similar behaviour to that of the fluoride phosphate glass as already indicated in the cw experiment. The highest output energies were obtained with the phosphate glass and the 300-µm absorber, this glass showed thermal lensing effects prohibiting higher output powers, which may be possible with active cooling applied. Laser mode size increased with pumping power showing the effect of a thermal lens inside the laser glass. Average values for peak energy, power and pulse duration are summarized in Table 2.

From theory [5] an increase in pulse energy $E_p \propto q_o$ and a decrease in pulse duration, see (1), of both 50% is expected with increase of q_o from 0.2% to 0.3%. Repetition rate decreases because $f_{rep} \propto 1/E_p$ for a given inversion level. The experimental data show increase in pulse energy of about 40% for the different glasses and a decrease in pulse duration of the same order with the repetition rate at a given pump level being lower for the higher q_o, as expected from theory. So in ultraphosphate, with the 300-µm absorber, the repetiton rate was 1 kHz compared with 1.8 kHz for the other absorber at 400 mW absorbed pump power. Slope efficiency of quasi-cw power, over absorbed power stayed almost constant for different absorbers, about 2% for phosphate and about 1% for the other two laser glasses. Slope efficiency is much lower than in the cw laser, also the laser threshold is higher by a factor of 2.3 indicating a higher intracavity loss with the saturable absorber inserted. Saturable and nonsaturable losses introduced by the absorber are too low to cause such a deterioration of laser performance as can be shown by calculations of the laser model [16]. Losses are attributed to reflection losses from the absorber surfaces which were slightly wedged by 0.6 degrees, measured by backreflex of a He-Ne laser and could not be cancelled out by laser adjustment. With thermal steady state of the laser glass the laser operated continuously for hours.

Single-mode operation is difficult to achieve with active ions in glass hosts, because of their broad linewidth. With the use of an intracavity filter, such as the etalon effect introduced by the saturable absorber, a significant reduction in linewidth can be achieved but could not exactly be determined due to the limited resolving power of our spectrograph.

With a longer cavity of 150 mm length the pulse duration increased to over 1 µs with the onset of selfmodelocking under the Q-switched pulse train giving reason to believe that this PbS quantum-dot doped glass is also a good candidate for passive modelocking of the erbium laser in a properly chosen resonator setup. No effects of photodarkening [17] were observed throughout the experiment showing the stability of the quantum-dots in their glass host matrix.

Further reduction of pulse duration and increase of pulse energy would be possible with a saturable absorber with higher quantum-dot concentration giving a higher saturable loss coefficient q_o and a monolithic microchip setup with a shorter cavity causing furthermore lower intracavity losses giving a better slope efficiency. Further spectroscopic investigations of bleaching behaviour under different conditions of quantum-dot size and excitation intensity and wavelength will help to determine the parameter ranges accessible with this technology.

Table 2. Q-switch performance for phosphate (P), ultraphosphate (UP) and fluoride phosphate (FP20) glasses

	d_{PbS} (µm)	E_{pulse} (µJ)	τ_{pulse} (ns)	P_{peak} (W)
P	200	1.51	42.1	35.9
	300	1.82	30.3	60.2
UP	200	0.66	44.4	14.8
	300	1.09	35.2	31.3
FP	200	0.77	52.0	14.9
	300	1.06	36.6	29.1

4 Conclusion

cw and Q-switched operation of different erbium-ytterbium doped glasses have been studied in a compact setup. cw slope efficiencies of up to 15.8% were found. In the Q-switch experiment the use of a semiconductor quantum-dot doped glass as a saturable absorber in a compact diode-pumped setup was demonstrated for the first time. Pulse energies of 1.8 µJ and pulse durations of 30 ns with peak powers of 60 W were demonstrated. With the absorption edge of the absorber depending on quantum-dot size which is easy to tune by growth conditions it should be possible to Q-switch a wide range of active materials through the infrared to the visible region in compact diode pumped setups.

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