Co^{2+}:ZnSe Saturable Absorber Q-switch for the 1.54 μm Er^{3+}:Yb^{3+}:Glass Laser

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Abstract

A potentially superior eye-safe laser Q-switch material has been demonstrated. Pulses of 77 ns and 2.6 mJ were obtained in a non-focused Er:glass resonator.

Key words

Transition metal doped materials, Infrared and far-infrared lasers, Optical properties of materials, Fluorescence.

Introduction

We have demonstrated a new application for the important class of materials: transition-metal-ion-doped II-VI semiconductors as saturable absorber Q-switches.

Those semiconductors are very attractive because of their optical properties and their utility in laser devices. Co:ZnSe is a zinc-chalcogenide belonging to this class of materials. It is grown by modified vertical Bridgman process, crystallizing in a sphalerite or zinc-blend structure. Its lattice can be cubic or hexagonal with Co substituting Zn^{2+}, in tetrahedral sites.[1-3] The tetrahedral sites are noncentrosymmetric and the even-parity components of the crystal field are weak, resulting in mid-infrared transitions.[4]

For Co^{2+}:ZnSe, the d-d transitions are electric-dipole forbidden according to Laporte selection rules and as a consequence, cobalt radiative lifetime is quite long.[1]

Co^{2+} has the electronic structure [Ar-core]$3d^7$. Its outermost 3d-shell interacts strongly with lattice phonons, resulting in broad absorption bands. The first energy levels for a $3d^7$ configuration in tetrahedral symmetry are ${}^4A_2({}^4F)$ or ground-state and the excited states ${}^4T_1({}^4F)$, ${}^4T_2({}^4F)$, absorbing from 1,200 to 2,000 nm and ${}^4T_1({}^4P)$, absorbing from 680 to 800 nm. We are particularly interested in the broad absorption feature peaking at 1.6 μm, covering the eye-safe range, from 1.5 to 1.8 μm.[3,5,6]

Co^{2+} in YSGG and in YAG were previously demonstrated by our group to function as saturable absorber Q-switches for the Er:glass laser.[5] However, the Co^{2+}:garnet Q-switches required the use of an intracavity focusing lens.

It is advantageous to develop an efficient saturable absorber Q-switch with improved performance and reduced vulnerability to component damage, which does not require any intracavity focusing lens. The results reported in this paper indicate that Co^{2+}:ZnSe may be the saturable absorber Q-switch of choice for the Er:glass laser.

In the Co:garnet crystals, the Co^{2+} excited-state lifetime is very short (less than 1 ns).[6] For a fast relaxing Q-switch, one must consider the saturation intensity, which is proportional to $(\sigma\tau)^{-1}$ where σ is the absorption cross-section, and τ is the lifetime of the relaxation. Therefore, even materials which possess relatively high cross-section values can have high saturation intensities due to a short lifetime. The saturation intensities for Co in garnets is on the order of 100 MW/cm^2.[5]

Co^{2+}:ZnSe possesses a much longer excited-state lifetime (~290 μs), and a cross-section of ≈ 7 x 10^{-19} cm^2 at 1.53 μm.[1] Thus, this material acts as slowly relaxing absorber, so that its high cross-section (about an order of magnitude higher[7] than U:CaF_2) can be fully utilized. These considerations indicate that Co:ZnSe as a passive Q-switch material may perform even better than the U^{4+}-doped difluoride crystals.[7,8]

OSA TOPS Vol. 10 Advanced Solid State Lasers, 1997
Clifford R. Pollock and Walter R. Bosenberg (ed.)

Experimental Results

Q-switch

A Q-switch sample was fabricated from a nominal 0.001% Co^{2+}:ZnSe boule fragment obtained from the Eagle-Picher Co.[9] We are interested in the Co^{2+} absorption band peaking at around 1.54 μm, which is shown in Fig. 1. A sample thickness of 1.53 mm provided an internal loss of about 6%. Utilizing the cross-section data of reference 3, we estimate that the Co concentration in our sample was 9×10^{17} cm^{-3}.

The experimental arrangement is shown in Fig. 2. The laser consisted of a flashlamp pumped Er:glass laser rod (3 x 50 mm), Kigre Er:Yb:phosphate glass, QE-7S, with an overall cavity length of 19 cm. The reflectivities of mirrors M_1 and M_2 were 100% , 50 cm radius of curvature, and 95%, flat respectively.

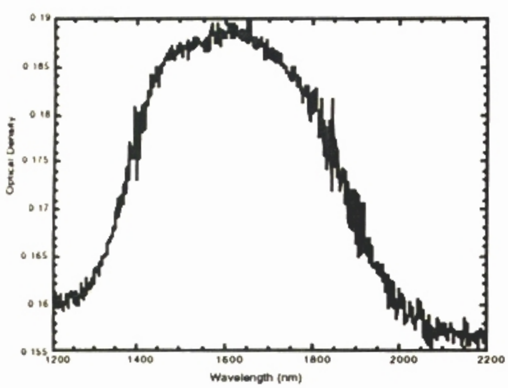

Figure 1. (0.001%)Co^{2+}:ZnSe, 1.53 mm thick crystal, absorption spectrum at 1.54 μm.

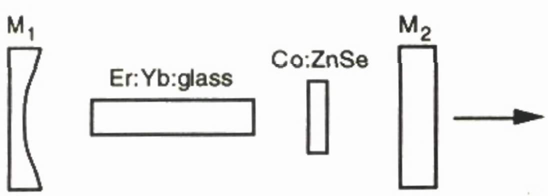

Figure 2. Experimental resonator cavity.

A typical output pulse is shown in Fig. 3. The full-width-half-maximum (FWHM) for the pulse is about 100 ns. The tail in the pulse is an artifact of the Judson InGaAs photodiode used in the experiment. In a shorter laser resonator (14.5 cm long), with a flat outcoupler of R = 85%, we observed pulses of about 2.6 mJ and 77 ns.

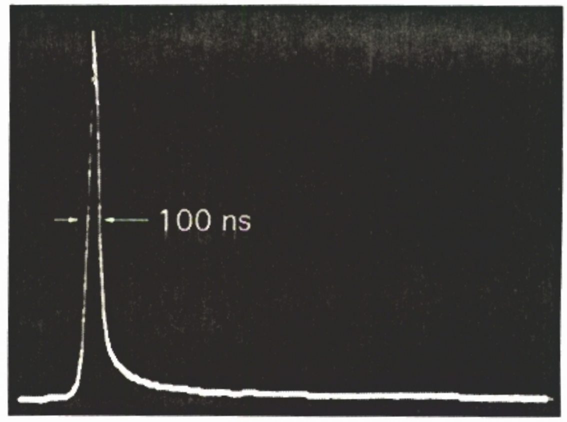

Figure 3. Q-switched pulse. Tail on pulse is an artifact of the detector used.

Bleaching

The bleaching experiment was performed using a 1.4 mm thick, (0.1%)Co^{2+}:ZnSe crystal and a Q-switched Er:glass laser (28 cm long laser resonator) at 1.53 μm. The output energy was 10.1 mJ and the pulsewidth 60 ns. The laser beam was then focused over the sample with a +12.5 cm lens. The spot size at the sample was about 0.096 mm diameter.

We analyzed the bleaching results using a modified Avizonis-Grotbeck equation,[10] which includes excited state absorption (ESA):

$$\frac{dE}{dz} = -h\nu N_0 \left\{ \left(1 - \frac{\sigma_2}{\sigma_1}\right) x \left[1 - \exp\left(-\frac{\sigma_1 E}{h\nu}\right)\right] + \frac{\sigma_2 E}{h\nu} \right\} - \alpha E \qquad (1)$$

where, E is the 1.53 μm fluence and N_0 is the Co^{2+} concentration. σ_1 and σ_2 are the ground-state and ESA cross sections, and α corresponds to all the nonsaturable losses. Equation (1) was solved numerically, and the parameters σ_1 and σ_2 were adjusted to match the theory with the experimental data. We assumed $\alpha = 0$.

The plot in Fig. 4 represents the curve fitting with a contrast 40:1 (i.e., σ_1/σ_2). Hence, according to our preliminary measurements the effects of ESA are negligible. The value adjusted for σ_1 was 6.19×10^{-19} cm^2 and the saturation fluence was 210 mJ/cm^2. σ_2 was on the order of 1.55×10^{-20} cm^2.

Since the Q-switched pulse used to bleach the sample (60 ns) is much shorter than the relaxation lifetime (290 μs) of the absorber (i.e., slowly-relaxing regime), it is appropriate to discuss the saturation in terms of energy/cm^2, or fluence. However, as a comparison to the 100 MW/cm^2 saturation intensity for the fast-relaxing Co:garnets, it is useful to note that the intensity corresponding to saturation fluence of Co:ZnSe is only 3.5 MW/cm^2, in the bleaching experiment described above.

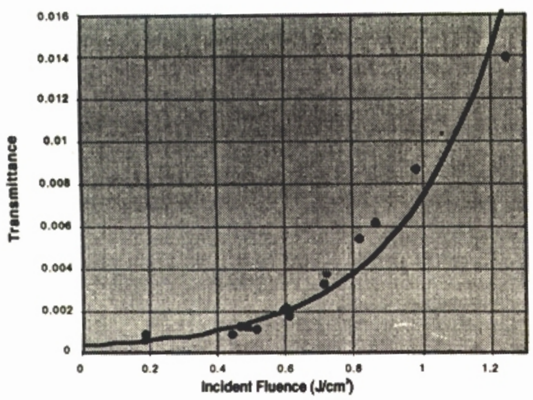

Figure 4: Transmittance as function of the incident fluence for a 1.4 mm thick (0.1%)Co^{2+}:ZnSe crystal. The solid line represents the Avizonis-Grotbeck model.

Theoretical Modeling

The rate equations for a slowly relaxing saturable absorber Q-switch with a three-level laser are given by:[11]

$$\frac{d\phi}{dt} = \left(K_g N_g - K_a N_a - \gamma_c\right)\phi \qquad (2)$$

$$\frac{dN_g}{dt} = -\gamma K_g N_g \phi \qquad (3)$$

$$\frac{dN_a}{dt} = -K_a N_a \phi \qquad (4)$$

where ϕ is the number of photons traveling in the cavity, γ_c is the photon-decay rate excluding the saturable loss, and N_g and N_a are the gain and the absorber media population differences. $\gamma = 1 + g_2/g_1$, where g_2 and g_1 are the upper and lower laser levels degeneracies for the laser media, respectively. We assumed $g_1 = g_2$, or $\gamma = 2$, for the Er:glass laser. The coupling coefficients K_i are given by $K_i = \sigma_i/t_1A_i$, where $\sigma_{g,a}$ are the gain and the absorber media cross sections and t_1 is the one-way photon-cavity transit time.

Using the resonator and Q-switch parameters from the experiment (19 cm resonator, R = 95%) and solving numerically the saturable absorber Q-switch rate equations (2) through (4), pulses of 3.7 mJ and 58 ns are predicted. Losses due to the uncoated Co:ZnSe surfaces were included, and it was assumed that the entire 6% internal loss was saturable. The loss associated with the uncoated surfaces of the Q-switch can be substantial, and it is expected that AR-coatings, as well as an increase in the saturable losses (thicker Q-switch) will significantly shorten the pulsewidth and increase the output energy.

Conclusion

We have demonstrated a new passive Q-switch material for eyesafe lasers, particularly the Er:glass laser, which preliminary results indicate to be superior to the present state-of-the-art ($U:CaF_2$) saturable absorber Q-switches.

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