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CW and Q-switched diode-pumped laser operation of Yb^{3+}:$NaLa(MoO_4)_2$

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ABSTRACT Continuous wave (CW) and Q-switched diode-pumped laser operation of Yb^{3+}:$NaLa(MoO_4)_2$ single crystal was to our knowledge, demonstrated for the first time. A CW output power of 220 mW and slope efficiency of 46% were obtained. Q-switched laser operation was achieved with a pulse duration of 60 ns average output power of 70 mW and slope efficiency of 22%.

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1 Introduction

New Yb^{3+}-doped laser crystals are of high interest due to favorable spectroscopic parameters of Yb ion for built up efficient high power directly diode-pumped lasers, and for generation of femtosecond pulses. Laser related spectroscopy and oscillation of a number of materials doped with Yb^{3+} ions were intensively investigated (see e.g. [1–3]). Special attention is paid to host matrices with mixed cations which cause a disordered environment of ytterbium ions. This results in more broad and smooth gain bands in comparison with ordered crystals. The spectroscopic data for Yb disordered crystals with the general formula Yb:$NaR(MeO_4)_2$ (R = La, Gd; Me = W, Mo) [4, 5], indicate that ultrashort pulses with duration of less than 50 fs could be generated. So, detailed studies of spectroscopic properties and laser characteristics of these materials will give an opportunity to estimate their real potential for ultrafast lasers.

Here we present the results of spectroscopic investigations of Yb^{3+}:$NaLa(MoO_4)_2$ (Yb:NLM) crystal grown by the Czochralski technique, along with diode-pumped laser experiments in CW and Q-switched modes of operation. Preliminary spectroscopic parameters of this material were reported in [6]. It is also important to note that NLM is an efficient Raman active medium [7, 8].

2 Spectroscopic properties

Yb-doped Yb:NLM single crystal was grown by Czochralski technique from the melt. As raw materials the crystals of $NaLa(MoO_4)_2$ (95 mol %) and polycrystalline ceramics of (5 mol %) $NaYb(MoO_4)_2$ were used. The crystal was pulled along the [001] direction and a sample of about 25 mm in diameter and 40 mm in length was grown. NLM crystal has a tetragonal sheelite-like structure with space group $I4_1a$ (C^6_{4h}) [9, 10]. Na^+ and La^{3+} ions are distributed randomly between eightfold coordinated 4*a* sites. The content of ytterbium ions in the crystal was determined to be equal to 1.57 at. % by means of atomic-emission analysis. It means that the segregation coefficient for Yb^{3+} ions is about 0.3. Absorption cross-sections $\sigma^{\alpha}_{abs}(\lambda)$ for different light polarizations ($\alpha = \pi, \sigma$) were determined from absorption spectra recorded with a spectral resolution of 0.6 nm (Fig. 1). Peak absorption cross sections for π and σ polarization at 977 nm are 2.5×10^{-20} cm^2 and 1.5×10^{-20} cm^2, respectively. For σ polarization there is another peak of 1.3×10^{-20} cm^2 at 934 nm.

Emission lifetime was measured to be 285 ± 10 μs from luminescence decay curves of fine crystalline powder of Yb:NLM immersed in ethylene-glycol. Such a technique allows avoidance of radiation trapping which is very important for Yb-doped materials as quasi three-level active media [11]. Our results correlate with corresponding data reported in [6].

Detailed energy level structures of two manifolds $^2F_{7/2}$ (lower) and $^2F_{5/2}$ (upper) of Yb^{3+} ion in NLM has not estimated so far. The spectra of stimulated emission cross section

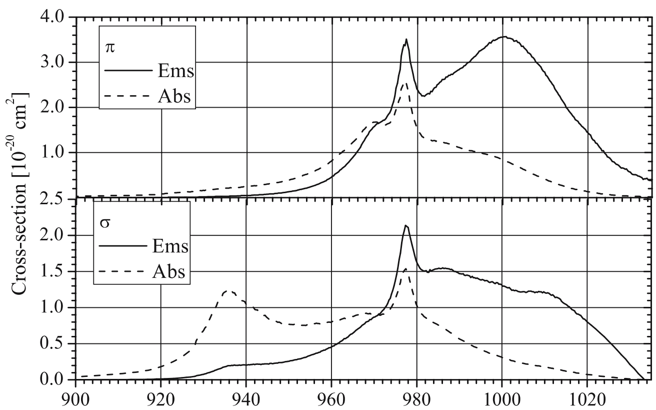

FIGURE 1 Polarized absorption and stimulated emission cross-section spectra of Yb:NLM at room temperature

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$\sigma_{em}^{\alpha}(\lambda)$ for light polarizations ($\alpha = \pi, \sigma$) were determined by means of the modified (integral) reciprocity method [12]:

$$\sigma_{em}^{\alpha}(\lambda) = \frac{3\exp(-hc/(kT\lambda))}{8\pi n^2 \tau_{rad} c \left[\sum_{\beta} \int \lambda^{-4} \sigma_{abs}^{\beta}(\lambda) \exp(-hc/(kT\lambda))\, d\lambda \right]} \sigma_{abs}^{\alpha}(\lambda)\,, \quad (1)$$

where λ is the light wavelength, the index β characterizes a light polarization state, τ_{rad} is a radiative lifetime, T is a host crystal temperature, h and k are the Plank's and Boltzman's constants, respectively, c is the light speed in a vacuum, and $n = 2$ is the refraction index of the host crystal. Emission spectra demonstrate broad band between 980 nm and 1040 nm with maximum at 1000 nm and 1010 nm for π- and σ-polarizations, respectively.

3 Laser experiments

Continuous wave laser experiments were carried out with a nearly hemispherical laser cavity. It was comprised of a 50 mm radius-of-curvature output coupler (OC) and a plane high reflector in the spectral range of 1020–1100 nm. Yb:NLM crystal was cut so that its optical axis was perpendicular to the cavity axis for possible laser operation in both π and σ polarizations. The laser element with a thickness of 2.5 mm was antireflection coated at the pump and laser wavelengths and mounted onto an aluminium heatsink kept at about 10 °C. We used a CW fiber-coupled (Ø = 100 μm, N.A. = 0.22) laser diode (LD) with an output power of 8 W at 980 nm as a pump source. The pump beam was focused into a circular spot with a diameter of 110 μm and a confocal length of about 2.5 mm inside the crystal. The diameter of the TEM_{00} transversal mode of the cavity in the active element was close to the pump beam waist (110 μm). Input–output diagrams for a Yb:NLM laser in CW mode of operation with OC transmittance (Toc) of 1% and 3.5%, are given in Fig. 2.

For both output couplers we obtained approximately the same maximum output powers of about 220 mW at absorbed pump powers of 785 mW and 775 mW, respectively. Slope efficiency reached 46% with Toc = 3.5%. The laser threshold was 147 mW of absorbed pump power for 1% OC and 225 mW for 3.5% OC. Due to the quasi three level scheme of laser operation of Yb:NLM the output wavelength was shifted from 1017 nm for 3.5% OC to 1023 nm for 1% OC. For both cases the output laser emission was π-polarized due to a higher stimulated emission cross section for this polarization ($\sigma_{em}^{\pi} = 1.7 \times 10^{-20}$ cm^2 at 1017 nm). Very recently in [4], laser performance of Yb(2.2 at. %):NLM under Ti:sapphire laser excitation at 976.6 nm was reported. A laser threshold absorbed pump power of 150 mW (Toc = 1.1%), slope efficiency of 30% (Toc = 5.4%) and tunability from 1015 to 1053 was demonstrated.

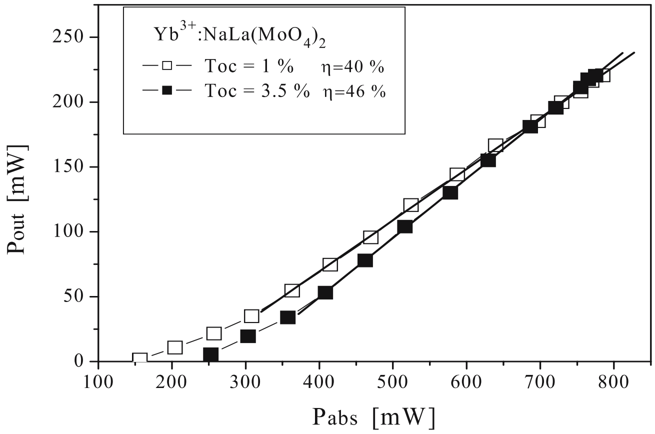

FIGURE 2 Output power versus absorbed power of cw Yb:NLM laser

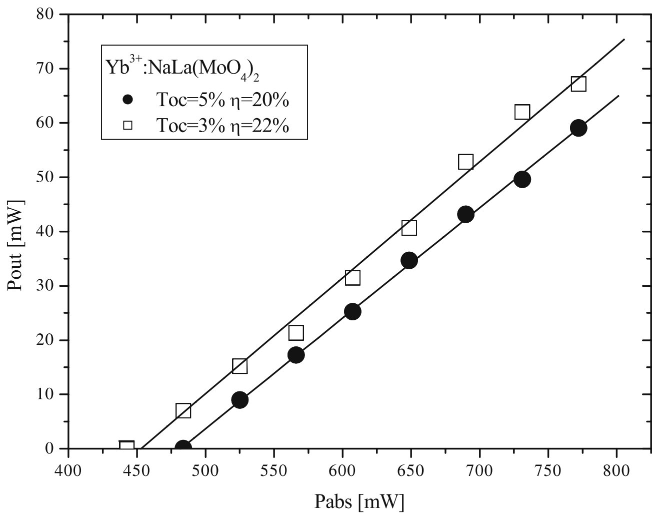

FIGURE 3 Output power versus absorbed power of Q-switched Yb:NLM laser

For Q-switched laser experiments the same cavity configuration was used. The antireflection coated Cr^{4+}:YAG crystal with a thickness of 120 μm was used as a passive shutter. The shutter has an initial transmittance of about 97% at 1020 nm and was mounted onto the opposite side of the heat sink 4 mm apart from the active element. In Q-switched mode average output power was 70 mW and 63 mW with slope efficiencies of 22% and 20% for 3.5% and 5% OCs, respectively. The Q-switched laser operated at wavelength $\lambda_p = 1010$ nm for both OCs. Input-output diagrams for the Q-switched laser are shown in Fig. 3. The shortest light pulse duration τ_p of 60 ns was obtained with a Toc of 3.5% with maximal repetition rate f of 25 kHz. The summary of the results of Q-switched laser experiments is presented in Table 1. A conversion efficiency is a ratio between the average out-

TABLE 1 The parameters of Q-switched diode-pumped Yb:NLM laser with Cr:YAG saturable absorber

Toc, %	Average output power, mW	Pulse energy, μJ	Slope efficiency, %	Conversion efficiency, %	τ_p, ns	f, kHz	λ_p, nm
3.5	70	2.8	22	40	60	25	1010
5	63	2.84	20	48	72	22.2	1010

put power in Q-switched mode and the output power in CW mode for the same OC. Though NLM crystals are efficient Raman media we did not observe frequency conversion in our experiments.

4 Conclusion

High quality Yb^{3+}:$NaLa(MoO_4)_2$ single crystal doped with 1.57 at. % of Yb^{3+} ions was grown by the Czochralski technique. Absorption and stimulated emission cross-section spectra for π and σ polarizations were determined. The gain band of smooth shape for π polarization is extended approximately over 70 nm which is very attractive for generation of light pulses of femtosecond duration. Radiative lifetime for Yb^{3+} ions was measured to be 285 μs. The CW and Q-switched laser operations of Yb^{3+}:NLM crystal under longitudinal laser diode pumping at 980 nm was demonstrated. A CW slope efficiency of 46% with maximum output power of 220 mW was achieved. In the Q-switched regime an average output power of 70 mW with a slope efficiency of 22%, repetition rate of 25 kHz, and pulse duration of 60 ns was obtained. Spectroscopic and laser properties demonstrate the high promise of the Yb^{3+}:$NaLa(MoO_4)_2$ crystals for femtosecond pulse generation.

REFERENCES

1 L.D. DeLoach, S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway, W.F. Krupke, IEEE J. Quantum Electron. **QE-29**, 1179 (1993)
2 W.F. Krupke, IEEE J. Sel. Top. Quantum Electron. **6**, 1287 (2000)
3 A. Brenier, J. Lumin. **92**, 199 (2001)
4 J. Liu, J.M. Cano-Torres, C. Cascales, F. Esteban-Betegon, M.D. Serrano, V. Volkov, C. Zaldo, M. Rico, U. Ceribner, V. Petrov, Phys. Stat. Solidi A **202**, 29 (2005)
5 M. Rico, J. Liu, U. Griebner, V. Petrov, M.D. Serrano, F. Esteban-Betegon, C. Cascales, C. Zaldo, Opt. Express **22**, 5362 (2004)
6 Y.K. Voron'ko, E.V. Zharikov, D.A. Lis, A.A. Sobol, K.A. Subbotin, S.N. Ushakov, V.E. Shukshin, Proc. SPIE **5478**, 60 (2004)
7 T.T. Basiev, A.A. Sobol, Y.K. Voronko, P.G. Zverev, Opt. Mater. **15**, 205 (2000)
8 P.G. Zverev, T.T. Basiev, A.M. Prokhorov, Opt. Mater. **11**, 335 (1999)
9 M.V. Mohosoev, V.I. Krivobok, C.M. Aleikina, N.S. Zhigulina, N.C. Kisel, Inorg. Mater. **3**, 1657 (1967)
10 S.B. Stevenson, C.A. Morrison, T.H. Allik, A.L. Rheingold, B.S. Haggerty, Phys. Rev. B **43**, 7386 (1991)
11 D.S. Sumida, T. Fan, Opt. Lett. **19**, 1343 (1994)
12 A.S. Yasukevich, V.G. Shcherbitskii, V.E. Kisel, A.V. Mandrik, N.V. Kuleshov, Appl. Spectrosc. **71**, 202 (2004)