Quantum Electronics **40** (6) 475 – 478 (2010)

PACS numbers: 42.55.Rz; 42.55.Xi; 42.60.Gd; 42.60.Pk
DOI: 10.1070/QE2010v040n06ABEH014308

Cw and *Q*-switched Nd : NaLa(MoO_4)$_2$ laser noncritical to the temperature drift of the diode pump laser wavelength

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***Abstract*. Lasing in Nd : NaLa(MoO_4)$_2$ crystals is obtained without stabilisation of the diode pump wavelength. A dependence of the cw laser output power (at a wavelength of 1059 nm) on the pump diode temperature is found within a range of 10 – 45 °C. It is shown that the variations in the diode temperature within this region change the lasing efficiency no more than by 30 %. In the passive *Q*-switching regime, the experiments were performed under both pulsed and cw pumping. Upon pulsed pumping, the laser energy was 16 μJ at the output pulse duration of 11 ns. The laser wavelength was 1059 nm, as well as in the case of cw operation. Upon cw pumping with a power of 1.5 W, laser pulses were obtained with an energy of 15 μJ.**

Keywords: *Nd : NaLa(MoO_4)$_2$ crystals, cw or pulsed lasing, wavelength temperature drift.*

1. Introduction

Significant advances made recently in production of diode lasers and laser arrays operating in the region of $\lambda = 819$ nm resulted in the creation of solid-state compact lasers based on Nd-doped crystals (YAG, YAP, YLF, etc.). These lasers are compact, have a simple design, and are highly efficient due to a good overlap of the spectrum of laser diodes (LDs) with the absorption band of Nd^{3+} ions. However, the narrow linewidth of Nd^{3+} absorption in these crystals in combination with a strong temperature dependence of the LD emission spectra requires accurate thermal stabilisation of the pump source (which can be achieved using, for example, Peltier elements, which considerably increases the size, design complexity, and energy consumption of laser systems) and complicates the use of these lasers under difficult climatic conditions (when the environment temperature varies over a wide range).

The possible ways to overcome these problems are related either to simultaneous use of several LDs whose wavelengths are shifted from each other by 1.5 – 2 nm or to the use of active crystals with a wide absorption band, which are not so sensitive to the temperature drift of the pump wavelength. One of these crystals is Nd^{3+} : NaLa(MoO_4)$_2$ (Nd : NLM).

The first papers on the spectroscopic and lasing characteristics of Nd : NLM crystals under lamp pumping appeared in 1960s [1 – 3]. However, due to the comparatively low thermomechanical parameters (thermal conductivity 2.3 W $m^{-1}K^{-1}$, Mohs hardness ~ 4 [2]), they have found no wide application in flashlamp-pumped lasers. The use of diode pumping considerably reduces the thermal load on the active element, as well as requirements to its thermomechanical characteristics. Our first laser experiments on Nd : NLM crystals with a Nd^{3+} concentration of 3.8 at % performed using longitudinal diode pumping at different wavelengths are described in [4]. Further studies of the optical, spectral, and luminescent properties of Nd : NLM crystals in order to optimise the neodymium concentration and the active element configuration, as well as laser experiments in different regimes, are of practical importance.

2. Structure of the crystal and its optical, spectral, and luminescent properties

The Nd : NLM crystal has a scheelite ($CaWO_4$)-type structure (crystal lattice parameters $a = 5.344$ Å, $c = 11.730$ Å; space group $C_{4h}^6 - I4_1\bar{a}$; density 4.8 g cm^{-3}; congruently melts at a temperature of 1140 °C [5]). The molybdenum ions in this crystal lie in the centre of oxygen tetrahedra. The Na^+ and La^{3+} cations lie between the tetrahedra along the fourth-order crystallographic axis and are almost strictly statistically distributed over the crystallographic sites [6]. Thus, the Nd^{3+} ions substituting the La^{3+} ions are affected by an infinitely large set of crystal fields with an infinitely small difference between each other. Therefore, the absorption and luminescence lines of Nd^{3+} ions in these crystals demonstrate pronounced inhomogeneous broadening.

To perform spectroscopic investigations, determine the optical constants, and fulfil lasing experiments, we have grown Nd : NLM crystals with neodymium concentrations

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Received 11 March 2010
Kvantovaya Elektronika **40** (6) 475 – 478 (2010)
Translated by M.N. Basieva

$C_{Nd} = 0.2$, 2, and 3.8 at % by the Czochralski method. The crystals were grown on a Kristall-2 setup from an iridium crucible in the N_2 atmosphere with O_2 concentration of 1 % at a pulling rate of 0.7 mm h^{-1} (at the nominal stage). The single-crystal seed was cut perpendicular to the fourth-order axis. The concentration of Nd^{3+} in the grown crystals was determined by X-ray microprobe analysis to be almost the same as in the charge, i.e., the distribution coefficient in this case is almost exactly equal to unity.

Figure 1 presents the absorption spectra of a Nd : NLM crystal with the concentration $C_{Nd} = 0.2$ at %, which are measured at $T = 300$ K for the π and σ polarisations. The spectra correspond to the transition from the Stark sublevels of the ground $^4I_{9/2}$ state of Nd^{3+} ions to the levels of the $^4F_{5/2}$ and $^2H_{9/2}$ states.

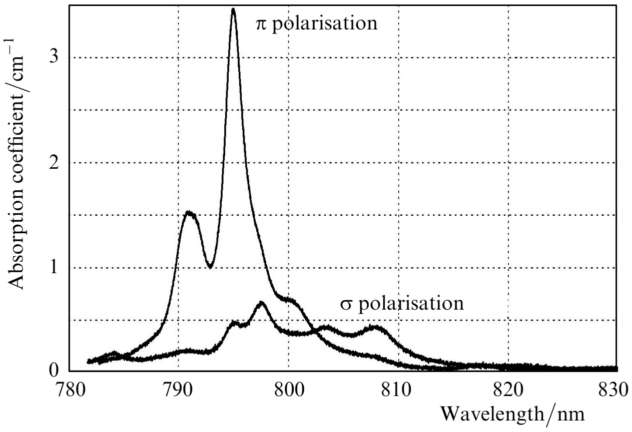

Figure 1. Absorption spectra of a Nd : NLM crystal ($C_{Nd} = 0.2$ at %) in the region of pump LD wavelengths for two orthogonal polarisations.

Figure 2 presents the dependence of the integral (effective) absorption coefficient of the Nd : NLM crystal ($C_{Nd} = 0.2$ at %) at the diode pump wavelength on the LD temperature. The measurements were performed for unpolarised pumping. One can see that the absorption coefficients above 5 cm^{-1} (the 5-mm-long active element absorbs more than 80 % of the incident radiation) are achieved at the LD temperatures from 11 °C to 40 °C. This means that the LD temperature can vary by ±15 °C and more without dramatic changes in the pumping efficiency.

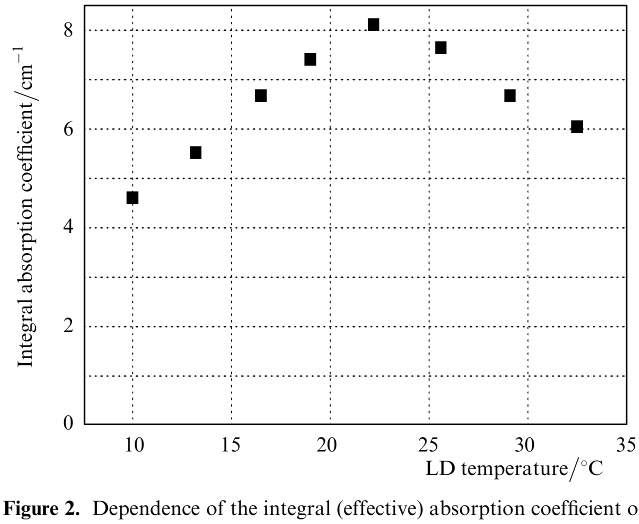

Figure 2. Dependence of the integral (effective) absorption coefficient of a Nd : NLM crystal ($C_{Nd} = 0.2$ at %) at the wavelength of an 1.5-W AlGaAs LD on the LD temperature.

Under the same conditions, the active element with a neodymium concentration of 3.8 at % absorbs more than 50 % of pump radiation in a layer 1 mm thick. At the same time, at a lower concentration of dopant, the pump radiation is absorbed more uniformly over the active element length, which considerably decreases the thermal load on the crystal.

To determine the lifetime of the upper laser level $^4F_{3/2}$ of Nd^{3+} ions and evaluate the effect of luminescence concentration quenching, we studied the decay kinetics of luminescence from this level in the crystals. The luminescence decay curves for the crystals with the dopant concentrations 2 and 3.8 at % are given in Fig. 3. According to our measurements, the lifetime of the $^4F_{3/2}$ level of Nd^{3+} is 220 μs for $C_{Nd} = 2$ at % and 130 μs for $C_{Nd} = 3.8$ at %, i.e., as the neodymium concentration increases by 1.9 times, the lifetime of the upper laser level decreases by more than 90 μs (by 41 %). At the higher concentration, the decay kinetics noticeably differs from single exponential. All these facts testify to the occurrence of concentration quenching in Nd : NLM crystals with $C_{Nd} = 3.8$ at %, which considerably decreases the quantum yield of luminescence from the $^4F_{3/2}$ level. In [7], it was observed that an increase in the neodymium concentration from 1 % to 4 % decreases the fluorescence quantum yield of Nd : NLM crystals by two times. In addition, all other conditions being the same, the decrease in the upper laser level lifetime limits the population inversion, which increases the lasing threshold and decreases the pulse energy in the case of the passive *Q*-switching regime.

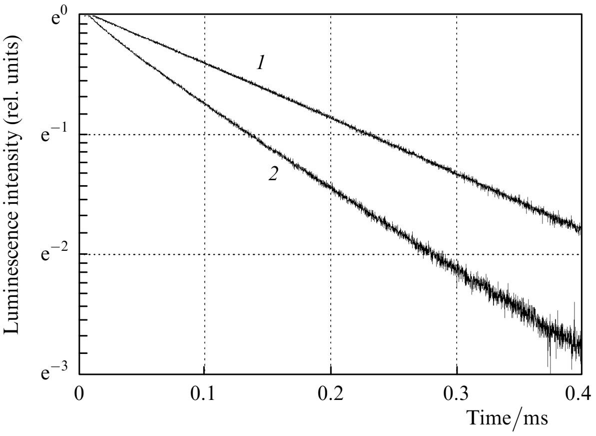

Figure 3. Decay kinetics of the luminescence from the $^4F_{3/2}$ level in Nd : NLM single crystals with neodymium concentrations of 2 (*1*) and 3.8 at % (*2*) at a temperature of 300 K.

Thus, based on our investigations, we can conclude that the crystal with the neodymium concentration 2 at % is more promising for operation under longitudinal diode pumping.

Despite the fact that the Nd : NLM crystal has been studied for a long time, the literature contains very few data on its optical characteristics.

To determine the refractive index dispersion in the Nd : NLM crystal ($C_{Nd} = 0.2$ at %), we cut from it a prism with an angle of 25° between the polished faces. The optical axis of the crystal was perpendicular to the prism base. The ordinary (n_o) and extraordinary (n_e) refractive indices of the crystal were measured at wavelengths of the mercury lamp spectrum using this prism and a GS-5 goniometer. The dispersion dependences $n_o(\lambda)$ and $n_e(\lambda)$ are shown in Fig. 4. The investigations show that the dispersion in the visible spectral region has a normal character and can be described by the approximate Sellmeier relation

$$n^2(\lambda) = 1 + \frac{S\lambda^2}{\lambda^2 - \lambda_0^2}. \qquad (1)$$

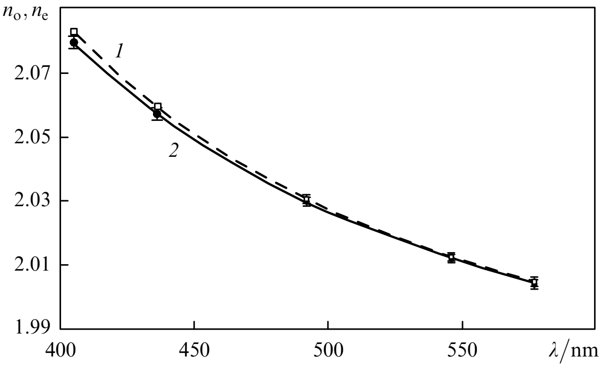

Figure 4. Dispersion of the n_o (*1*) and n_e (*2*) refractive indices in Nd:NLM single crystals in the visible region.

The dependences obtained according to formula (1) in the coordinates $1/\lambda^2, 1/(n^2 - 1)$ allowed us to determine the constants $A = 1/S$ and $B = \lambda_0^2/S$ for the ordinary ($A = 0.36, B = -9.88 \times 10^{-3}$ nm^2) and extraordinary ($A = 0.36$, $B = -9.56 \times 10^{-3}$ nm^2) waves. Using these constants and assuming that the Sellmeier approximation is also valid for longer wavelengths, we calculated the refractive indices for the lasing wavelength 1059 nm to be $n_o = 1.958$ and $n_e = 1.959$.

3. Results of laser experiments

3.1 Cw regime

For laser experiments, we used crystals $3 \times 3 \times 5$ mm in size, whose faces were AR coated for wavelengths of 808 and 1064 nm. The crystals were pumped by an AlGaAs LD with an output power of 1.5 W operating in the cw regime and in the pulsed regime with a pulse repetition rate of 500 Hz. The pump radiation was delivered into the active element through a flat highly reflecting cavity mirror and was focused into a spot ~ 300 μm in diameter inside the active crystal at a distance of ~ 1 mm from the input face. The output mirror was spherical (radius of curvature 120 mm), which ensured the cavity stability. We studied the laser characteristics as a function of the LD temperature. For this purpose, we placed the diode on the Peltier element and controlled its temperature using a thermistor. Changing the current flowing through the Peltier element, we changed the LD temperature from 10 to 45 °C. Figure 5 shows the dependence of the laser output power in the case of the output mirror transmittance of 5 % on the temperature of the pump LD operating in the cw regime. One can see that the change in the LD temperature within the given range changes the lasing efficiency no more than by 30 %.

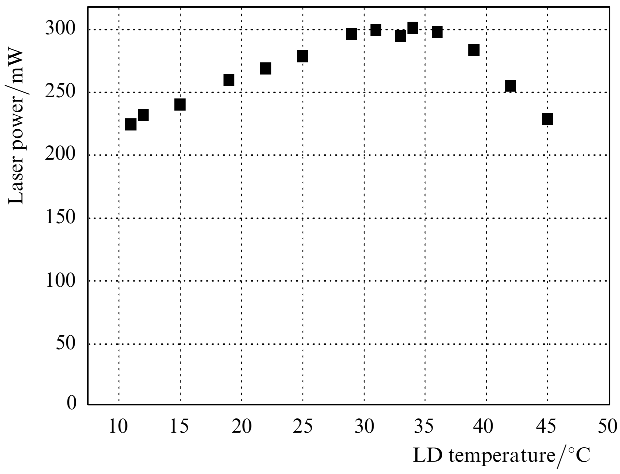

Figure 5. Output power of a cw laser based on a Nd:NLM crystal ($C_{\mathrm{Nd}} = 0.2$ at %) at a wavelength of 1059 nm versus the pump diode temperature.

In the absence of selecting elements in the cavity, lasing occurs at a wavelength of 1059 nm. Forming the orthogonal polarisation of radiation in the cavity (by introducing in it polarising elements), we obtained lasing at a wavelength of 1065 nm.

3.2 Passive Q-switching regime

In this work, we also experimentally studied passively Q-switched operation of a Nd:NLM crystal with the neodymium concentration 2 at %. We used a Cr^{4+}:YAG saturable absorber Q-switch with the initial transmission of 92 %. The reflectance of the output mirror was 94.4 %. The experiments were performed using two (cw and pulsed) pumping regimes.

We used pulsed pumping with a pulse repetition rate of 500 Hz, while the pump pulse duration (180 μs) was chosen so that a single laser pulse was emitted at the end of the pump pulse. We obtained a laser pulse with an energy of

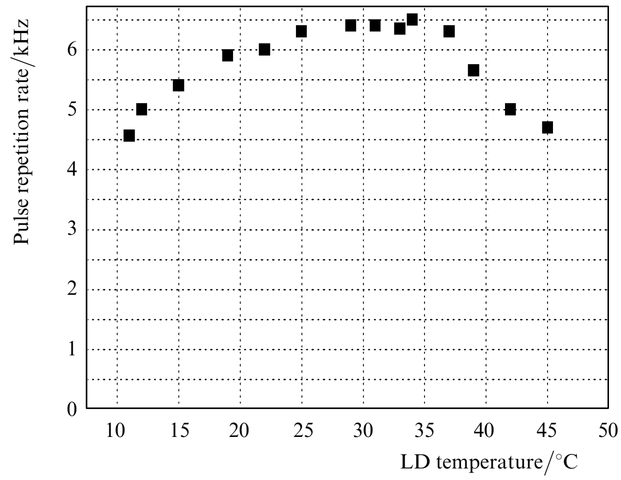

Figure 6. Pulse repetition rate of a passively Q-switched Nd:NLM laser ($C_{\mathrm{Nd}} = 2$ at.%) with a Cr^{4+}:YAG Q switch as a function of the pump diode temperature (at a wavelength of 1059 nm).

16 μJ and a duration of 11 ns in a cavity 30 mm long. Lasing occurred at a wavelength of 1059 nm, as well as in the case of cw lasing.

In the case of cw pumping with a power of 1.5 W, we obtained laser pulses with an energy of 11 μJ. The dependence of the laser pulse repetition rate on the pump LD temperature is shown in Fig. 6. It is seen that the difference in the pulse repetition rate within the considered temperature range is rather small, of about 36 %.

4. Conclusions

The results obtained in this work allow us to conclude that the disordered scheelite-like $Nd:NaLa(MoO_4)_2$ crystal is rather promising for application in diode-pumped solid-state lasers operating under conditions when it is difficult to precisely stabilise the LD wavelength. In particular, this crystal can be applied in devices used under field conditions, when, on the one hand, there are significant climatic temperature variations and, on the other hand, the energy consumption is a key parameter due to the off-line supply.

References

1. Morozov A.A., Tolstoi M.N., Feofilov P.P., Shapovalov V.N. *Opt. Spektrosk.*, **22** (3), 414 (1967).
2. Zverev G.M., Kolodnyi G.Ya. *Zh. Eksp. Teor. Fiz.*, **52** (2), 337 (1967).
3. Kaminskii A.A., Kolodnyi G.Ya., Sergeeva N.I. *Zh. Prikl. Spektrosk.*, **9** (5), 884 (1968).
4. Zharikov E.V., Lis D.A., Onishchenko A.M., Romanyuk V.A., Subbotin K.A., Ushakov S.N., Shestakov A.B. *Kvantovaya Elektron.*, **36** (1), 39 (2006) [*Quantum Electron.*, **36** (1), 39 (2006)].
5. Mokhosoev M.V., Getman E.I. *Zh. Neorg. Khim.*, **14** (9), 2351 (1969).
6. Kuz'micheva G.M., Lis D.A., Subbotin K.A., Rybakov V.B., Zharikov E.V. *J. Cryst. Growth*, **275**, e1835 (2005).
7. Zverev G.M., Kolodnyi G.Ya. *Zh. Eksp. Teor. Fiz.*, **52** (2), 337 (1967).