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Use of a LiF colour centre laser for pumping an Yb : YAG active medium

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***Abstract*. An Yb : YAG laser crystal containing 20 % of Yb was pumped by a F_2^+ : LiF colour centre laser emitting in the spectral range from 0.89 to 0.95 μm. We managed to pump 10 % of a total amount of Yb ions to the $^2F_{5/2}$ metastable level of ytterbium in small volumes of the optically dense Yb : YAG laser crystal, which corresponds to the energy density stored in the crystal equal to 30 J cm^{-3}. Nanosecond pulses were generated at transitions between the Stark components of the $^2F_{5/2}$ and $^2F_{7/2}$ levels of Yb^{3+} ions at the wavelengths near 1.03 and 1.05 μm. The possibility of using Yb : YAG crystals and ceramics in high-power laser drivers in laser fusion experiments is discussed.**

Keywords: *colour centre pump laser,* Yb : YAG *laser.*

1. Introduction

One of the interesting problems in the field of solid-state lasers is the development of active media for the creation of a repetitively pulsed laser with the megajoule output energy for applications in laser fusion experiments and as a laser driver in the future thermonuclear reactor [1 – 3]. The active medium of the driver should be pumped by semiconductor diodes with the efficiency no less than 10 % [1 – 3]. The main problem of using laser glasses in the laser driver is their low heat conduction compared to crystals. The use of crystals in high-power lasers was hindered so far by the complexity of manufacturing large active elements required for amplification of short ($10^{-8} - 10^{-12}$ s) high-energy pulses. New possibilities opened up after the advent of ceramic laser media [4, 5]. The optical homogeneity of laser ceramics is as good as that of single crystals, whereas the size of ceramic elements can be substantially greater [5].

The properties of laser glasses, crystals, and ceramics were compared in papers [1 – 3, 6] from the point of view of their use in laser drivers. The Nd^{3+} and Yb^{3+}ions with laser transitions at ~ 1 μm were considered as activators of the active medium for drivers. It was shown that ytterbium-doped crystals can be used in the driver [2, 6 – 10]. Along with the known anisotropic Yb : S-FAP medium [2, 8, 9], crystals of the cubic symmetry, which may be also used in ceramic laser elements, possess a combination of parameters that makes them promising for applications in divers [4 – 6]. One of them is an Yb : YAG crystal, whose heat conduction is higher by a factor of six than that of an Yb : S-FAP crystal [8]. The Yb : YAG crystals were extensively studied in a number of laboratories [10, 11].

The building of full-scale driver modules is an expensive undertaking. At present, driver prototypes are being developed – diode-pumped glass and crystal lasers emitting 10 – 100 J at a pulse repetition rate of 10 Hz [9, 10, 12]. At the same time, active media for drivers can be also studied in model experiments with small samples in the regime of single laser shots. The media can be pumped not only by semiconductor diodes but also by some other lasers. Thus, in [11, 13, 14] the pumping into the absorption bands of Yb^{3+} near 0.9 μm was performed by Cr : LiSAF, Ti : sapphire, and Nd : YAG lasers. In this paper, we pumped optically dense Yb : YAG crystals containing 20 % of Yb ions by a LiF colour centre laser [15, 16]. We report the generation of nanosecond pulses in the Yb : YAG crystal at the wavelengths near 1.03 and 1.05 μm and discuss the possibility of using the Yb : YAG crystals and ceramics as active media in laser drivers.

2. Yb : YAG active medium

The Yb : YAG laser operates at room temperature in the quasi-three-level scheme on transitions between the Stark components of the metastable $^2F_{5/2}$ and ground $^2F_{7/2}$ levels. The main laser transition at ~ 1.03 μm occurs between the components of the $^2F_{5/2}$ and $^2F_{7/2}$ levels with energies 10327 and 612 cm^{-1} [8, 17]. Lasing is also observed at ~ 1.05 μm from the $^2F_{5/2}$ level to the 785-cm^{-1} component of the $^2F_{7/2}$ level [11, 14]. The populations of the lower levels of transitions at 1.03 and 1.05 μm at room temperature are $N_{612} \approx 0.046N_0$ and $N_{785} \approx 0.02N_0$, where N_0 is the ytterbium concentration [8]. Thermal population is responsible for absorption at ~ 1.03 μm in the Yb : YAG crystal. The saturated the absorption power density at the pump transition at ~ 0.94 μm is $I_s \approx 28$ kW cm^{-2}, $I_s \sim h\nu_p/(\sigma_p\tau)$ [8, 17]. (Here, $h\nu_p$ and σ_p are the photon energy and effective cross section of a transition in the pump band, respectively, and τ is the lifetime of excited ions.) A moderate value of the transition cross section at 1.03 μm (2.3×10^{-20} cm^2) and $\tau \approx 1$ ms favour the storage of a

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considerable energy upon pumping of the Yb : YAG crystal.

To remove the population inversion efficiently, the radiation energy density of up to 9 – 10 J cm^{-2} is required [8, 10, 17]. The optical strength of YAG crystals and ceramics for nanosecond pulses (more than 20 J cm^{-2} [8, 18, 19]) allows the use of such energy densities. At the same time, a rather high value of the nonlinear refractive index in garnet $n_2 \approx 2.7 \times 10^{-13}$ esu [6] restricts the laser radiation energy density.

An important characteristic of the Yb : YAG crystal is that it can be doped up to high concentrations (up to 60 %) without a noticeable reduction in the lifetime τ [20]. Upon 100 % doping, the lifetime τ decreases only by half [8]. We studied the Yb : YAG crystals containing 20 % of ytterbium, which were made in the form of 8 × 8-mm plates of thickness $L = 1 - 2$ mm. For $N_0 \approx 2.9 \times 10^{21}$ cm^{-3}, the optical density of 2-mm thick plate at 0.94 μm achieved four.

3. LiF colour centre pump laser

Pumping into the absorption bands of the Yb : YAG crystal was performed using an F_2^+ : LiF colour centre laser. This laser can emit in the range from 0.83 to 1.1 μm [15], covering all the absorption bands in the Yb : YAG crystal. The emission region of the colour centre laser for a specific experimental scheme depends on the selective properties of the resonator and is usually narrower than the above wavelength range. The scheme of the experiment is shown in Fig. 1. The F_2^+ : LiF crystal of size 6 × 20 × 40 mm was placed in the resonator formed by a plane mirror R_1 (with reflectivities of 100 % and 13 % at 0.9 and 0.7 μm, respectively) and a glass plane – parallel plate. The F_2^+ : LiF crystal was pumped through this plate by single 1-J, 30-ns pulses from a ruby laser. Radiation at 0.694 μm was focused into the crystal by lens L_1 with the focal distance $F_1 \approx 500$ mm. Radiation from the colour centre laser was focused by lens L_2 with $F_2 = 120$ mm on the Yb : YAG active element in the form of a plane – parallel plate. The plate was placed into the resonator with selective mirrors R$_2$ and R$_3$. The transmission coefficient of mirror R$_2$ at 0.9 μm was 87 % and its reflectivity at 1.0 μm was ~ 100 %. The transmission coefficient of R$_3$ at 1.0 μm was 10 %. This mirror reflected ~ 30 % of unabsorbed pump radiation back to the crystal. The resonator axis of the ytterbium laser was oriented along the axis of the colour centre laser.

The temporal shapes of pulses from the ruby, colour centre, and ytterbium lasers were recorded with a two-beam oscilloscope using photocells. The pulse energy was measured with calorimeters. Emission spectra were analysed with an STE-1 spectrograph in the near-IR region. The colour centre laser emitted 20 – 30-ns pulses with an energy from 100 to 150 mJ depending on the absorbed energy of the ruby laser. The shape of pulses is mainly similar to the shape of pulses from the ruby laser (Fig. 2 a). Figure 2b shows the emission spectrum of the F_2^+ : LiF laser. The emission lines of an argon spectral lamp superimposed on the spectrum were used as wavelength markers. The laser produced emission in the region from 0.89 to 0.95 μm. Therefore, the Yb : YAG crystal was mainly pumped to the short-wavelength absorption band of ytterbium. Only a part of the colour centre laser energy fall into the 0.94-μm absorption band. The 2-mm thick Yb : YAG plate absorbed more than 80 % of pump radiation.

The divergence of radiation from the F_2^+ : LiF laser was $(2 - 3) \times 10^{-3}$ rad and the diameter of the focal spot was $d_p \approx 300$ μm. The power density I_p required for bleaching the medium of length L can be estimated as

$$I_p > I_s(\alpha_p L)(\tau/t_p), \qquad (1)$$

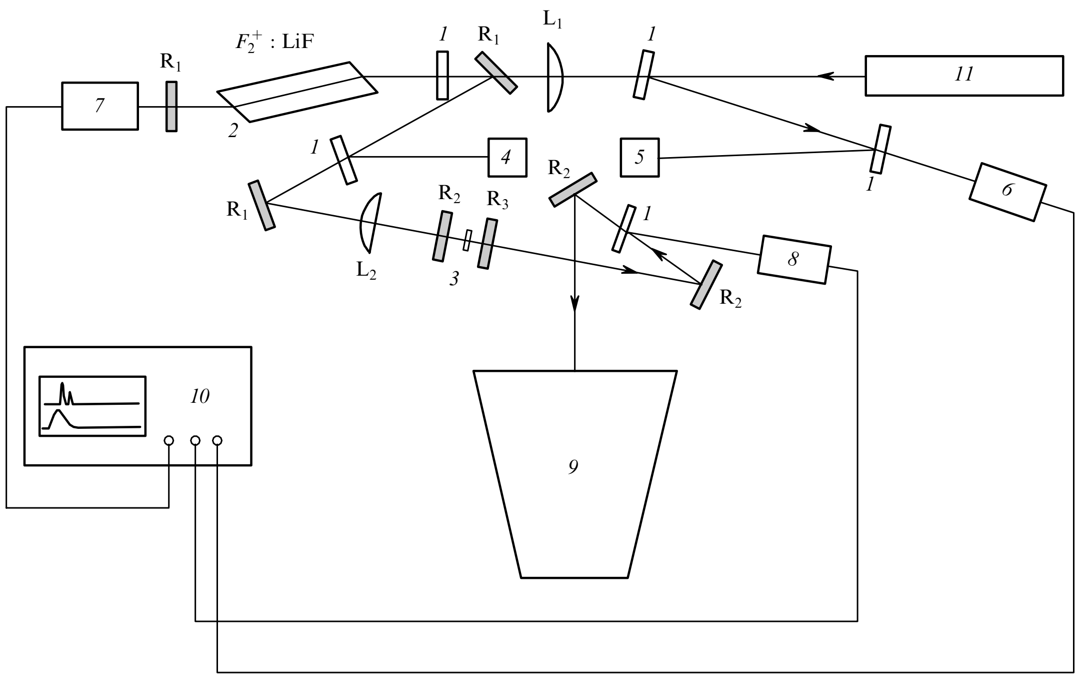

Figure 1. Scheme of the experiment: (R$_1$, R$_2$, R$_3$) selectively reflecting mirrors; (L$_1$, L$_2$) lenses; (*1*) glass plates; (*2, 3*) F_2^+ : LiF and Yb : YAG active elements; (*4, 5*) calorimeters; (*6–8*) photocells; (*9*) STE-1 spectrograph; (*10*) oscilloscope; (*11*) ruby laser.

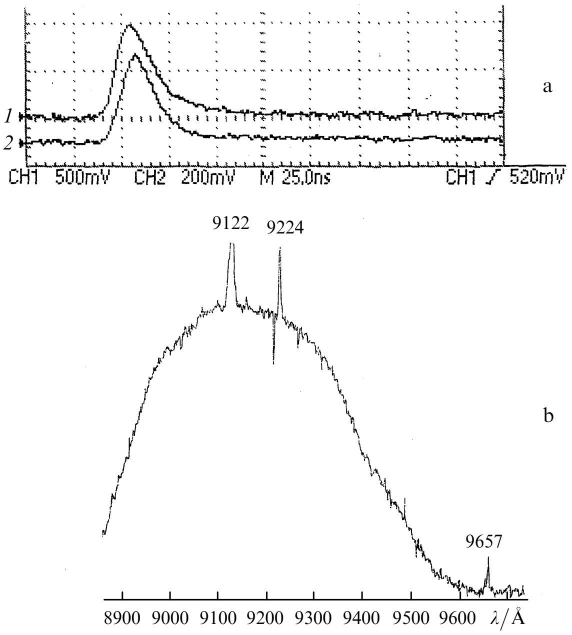

Figure 2. (a) Oscillograms of pulses from a ruby laser (*1*) and a colour centre laser (2) and (b) the densitogram of the emission spectrum of the F_2^+ : LiF laser with superimposed reference lines from an argon spectral lamp.

where $\alpha_{\rm p}$ is the absorption coefficient and $t_{\rm p}$ is the pump pulse duration [17]. By substituting the values $L = 0.2$ cm, $\alpha_{\rm p} = \sigma_{\rm p} N_0 \approx 21\ {\rm cm}^{-1}$, $I_{\rm s} = 28\ {\rm kW\ cm}^{-2}$, and $t_{\rm p} \approx 25$ ns, we obtain $I_{\rm p} \approx 4\ {\rm GW\ cm}^{-2}$. The estimate of the pump energy density $E_{\rm p}$ required for bleaching the plate with $L = 0.2$ cm gives $E_{\rm p} \geqslant 130\ {\rm J\ cm}^{-2}$. Therefore, to bleach completely the 2-mm thick Yb : YAG plate, the energy density and pump power exceeding the optical damage threshold of the material were required.

We could change the energy density on samples by moving them along the axis of the focused pump beam. Our experiments showed that the energy of the F_2^+ : LiF laser incident on samples was sufficient for their partial bleaching in the pump band. The absorption losses in plates at the 1.03-μm and 1.05-μm transitions were completely compensated upon pumping. The pump energy density in some experiments exceeded the damage threshold of the Yb : YAG crystal. As a rule, the local damage of the input (with respect to the pump) surface of the plates and adjacent volume of the material was observed.

4. Lasing of the Yb : YAG crystal pumped by the colour centre laser

We obtained lasing in 1- and 2-mm thick Yb : YAG plates both with AR coated and uncoated faces. Most of the experiments were performed with 2-mm thick plates without the AR coating. The plate was oriented parallel to the resonator mirrors, the resonator base being 20 mm. The data on the operation of the ytterbium laser presented below correspond to this case. The Yb : YAG plates were pumped by single pulses from the F_2^+ : LiF laser at room temperature.

The Yb : YAG laser operated in the regime of the so-called gain switching on the operating transition by a short pump pulse [21]. Because the relaxation time of excitation over closely spaced Stark components of the $^2F_{5/2}$ level in Yb : YAG is $\sim 10^{-12}$ s [8], particles were stored on the metastable level virtually without the delay with respect to the pump pulse.

The shape and duration of laser pulses and the emission spectrum were recorded for several positions of the Yb : YAG laser on the axis of the focused pump beam. The transverse size $d_{\rm las}$ of the lasing region was smaller than the size $d_{\rm p}$ of the pump region. This is probably explained by the inhomogeneous intensity distribution over the pump beam cross section. When the Yb : YAG laser was placed near the focus of lens L_2, the size $d_{\rm las}$ was $\sim$ 100 μm and the lasing energy achieved 0.5 mJ. In this case, the population $N_{\rm m}$ of the metastable level in the lasing channel could exceed $3 \times 10^{20}\ {\rm cm}^{-3}$ according to our estimates, corresponding to pumping of 10 % of Yb ions to this level and to the stored energy $\varepsilon > 30\ {\rm J\ cm}^{-3}$. The estimate of $N_{\rm m}$ and ε from the conditions of self-excitation of single-mode lasing on the 1.03-μm transition gives close values.

We observed tuning of the lasing region when the Yb : YAG laser was displaced along the axis of the focused pump beam. The pump energy ($\sim$ 60 mJ) was kept constant, but the energy density on the sample could change almost by an order of magnitude during the sample displacement. Figures 3 and 4 show the oscillograms of ytterbium laser pulses and pump pulses (preceding laser pulses) for different distances Δl of the plate from the focus. Away from the focus, for $\Delta l > 20$ mm, no lasing was observed. As the pump intensity was increased, beginning from $\Delta l = 15 - 20$ mm, lasing appeared at 1.05 μm (Fig. 3a); the pulse duration was approximately 50 ns and the delay time was up to 1.2 μs with respect to the pump pulse. For $\Delta l = 5 - 7$ mm, lasing was observed simultaneously at 1.03 and 1.05 μm (Fig. 3b). Finally, for $0 < \Delta l < 5$ mm, lasing occurred only at 1.03 μm (Figs 3c, 4). Near the focus, $\Delta l \approx 1$ mm, the shortest pulses were observed at the

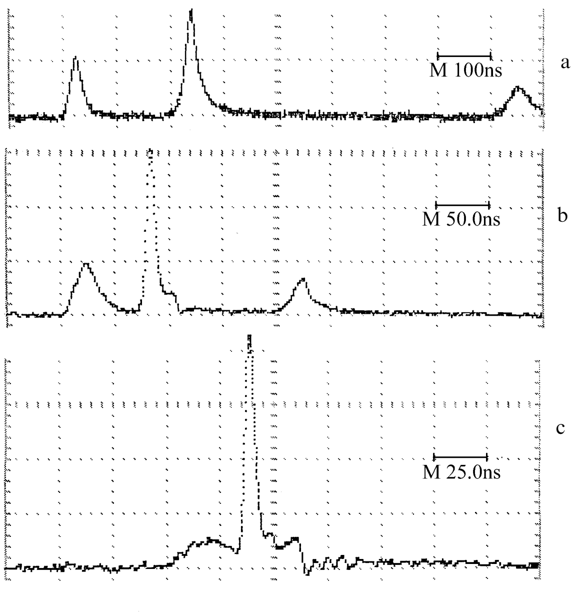

Figure 3. Oscillograms of radiation pulses from the ytterbium laser and of pump pulses at different positions Δl of the Yb : YAG crystal on the axis of the focused pump beam: (a) lasing at 1.05 μm for $\Delta l \approx 15$ mm, (b) lasing at 1.03 and 1.05 μm for $\Delta l \approx 7$ mm, and (c) lasing at 1.03 μm for $\Delta l \approx 1$ mm.

maximum or at the trailing edge of the pump pulse (Fig. 3c). The duration of these pulses (4 – 5 ns) was limited by the pass band of the detection system. In the region of $l = 2 - 4$ mm, the duration of pulses and their delay increased up to 5 – 15 ns and 150 – 500 ns, respectively (Fig. 4). Small distortions of the trailing edge of pulses caused by the mismatch of the elements of the detection system were observed (Figs 3, 4).

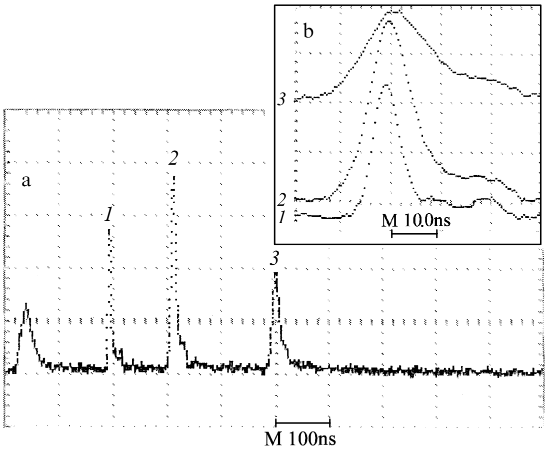

Figure 4. (a) Oscillogram of a train of pulses from the ytterbium laser at 1.03 μm and of the pump pulse for $\Delta l \approx 4$ mm (scale: 100 ns/div) and (b) oscillograms of individual pulses (*1, 2, 3*) of the train (10 ns/div).

The lasing spectrum was recorded for each pulse with an image-converter tube mounted instead of a spectrograph cassette. The spectra were photographed using an IR photographic film or from the converter screen. The lasing spectra at both transitions exhibited typically a few lines (longitudinal lasing modes). Such spectra of a free-running Yb : YAG laser caused by the selective properties of the resonator were detected in [14].

Switchings of the lasing region of the Yb : YAG laser can be explained by taking into account the values of cross sections of laser transitions at 1.03 and 1.05 μm and absorption losses in Yb : YAG at these wavelengths. The cross section of a strong transition at 1.03 μm exceeds almost by a factor of eight that of a weak transition at 1.05 μm ($\sigma_{1.05} \approx 3 \times 10^{-21}$ cm^2) [22]. But because of the difference between populations of the lower levels of these transitions with energies 612 and 785 cm^{-1}, the absorption losses at 1.05 μm are substantially lower than those at 1.03 μm. For $N_0 \approx 2.9 \times 10^{21}$ cm^{-3}, the absorption coefficients at these wavelengths at room temperature are ~ 0.17 and ~ 3 cm^{-1}, respectively. Oscillograms of laser pulses in Figs 3, 4 correspond to variations in the levels of inversion and losses at the 1.03-μm and 1.05-μm transitions during the displacement of the Yb : YAG crystal. Near the focus of the pump beam, the inversion density was maximal and absorption at the 1.03-μm transition decreased, resulting in the rapid development (for $10^{-9} - 10^{-8}$ s) of a short radiation pulse (< 5 ns) at 1.03 μm (Fig. 3c). A rapid inversion drop at a strong transition prevented lasing at a weak transition. When the pump intensity was lower ($\Delta l = 5 - 7$ mm), the inversion density decreased, the losses at 1.03 μm increased, the gain (taking losses into account) at 1.03 and 1.05 μm levelled off, and simultaneous lasing at both transitions was observed (Fig. 3b). The estimates showed that lasing at these transitions at room temperature can occur simultaneously when $N_{\rm m} \approx 0.05N_0$. When the Yb : YAG laser was placed at the distance $\Delta l > 10$ mm from the focus, the absorption losses increased and lasing at 1.03 μm was quenched. Under these conditions, only lasing at the 1.05-μm transition was observed. The competition between free-running lasing at 1.03 and 1.05 μm was observed in [14]. Note that in the 1-mm thick Yb : YAG plate we managed to obtain lasing only at 1.03 μm. No lasing at 1.05 μm was observed in this case because the gain was insufficient.

The appearance of several short 5 – 15-ns laser pulses with delay times with respect to the pump pulse up to 500 ns (Fig. 4) requires an additional explanation. Such a development of lasing is not observed in *Q*-switched neodymium lasers. The generation of these pulses in the ytterbium laser can be explained by the formation of a few lasing channels due to the inhomogeneous distribution of the pump intensity. Another reason can be the influence of the thermal relaxation of the medium on the lasing kinetics of the ytterbium laser, which operated, unlike the neodymium laser, in a quasi-three-level scheme.

Heat release in a Yb : YAG crystal pumped by focused radiation can lead to a substantial increase in the crystal temperature, resulting in the increase in the population N_{612} of the lower level of the lasing transition. In this case, the number of particles on the metastable level required for the development of lasing should be not $N_{\rm m} \approx 0.046N_0$ (as at room temperature) but greater. For example, to exceed the lasing threshold at $T = 350$ K, the population of the metastable level should be $N_{\rm m} > 0.07N_0$. The first of the observed laser pulses could partially deplete the population inversion down to the threshold value. The thermal relaxation of the crystal for the time $\tau_{\rm r} \approx 10^{-7} - 10^{-6}$ s reduced the population N_{612}, while the population $N_{\rm m}$ at $\tau_{\rm r} \ll \tau$ increased due to the particles coming from the higher-lying Stokes components. As a result, the population inversion could be restored, resulting in the generation of the next pulse. This process could repeat several times until the population of the levels of the lasing transition returned to its equilibrium value. In this way, short ($\sim 10^{-8}$ s) laser pulses could appear within a few hundreds of nanoseconds after the pump pulse termination.

5. Conclusions

We have demonstrated the pumping of an Yb : YAG crystal by a F_2^+ : LiF laser and showed that the colour centre laser can be efficiently used for investigations of ytterbium-doped media. The intensity of radiation from this laser can exceed by a few orders of magnitude that from laser diodes. Colour centre lasers can be tuned and their temporal parameters can varied [15, 16]. The short-wavelength wing of the emission spectrum of the F_2^+ : LiF laser overlaps the absorption bands of a number of neodymium-doped media and can be used to pump them.

Our experiments have shown the possibility of producing high inversion and generating short pulses in an optically dense active medium – thin heavily doped Yb : YAG crystal plates. The use of such plates and low-coherence radiation [23] should reduce nonlinear losses in high-power Yb : YAG lasers. The reduction of dimensions of the medium also improves the heat removal from active elements. The use of ceramics in high-power lasers [5, 6, 10] opens up new approaches both to the design of active elements and pump systems and to the design of the optical scheme of the amplifier and methods of formation of laser pulses. It is expected (see references in [6]) that the parameters of repetitively pulsed Yb : YAG and Nd : YAG lasers at low temperatures can be substantially improved. This gives grounds to consider also possible schemes and devices for the development of a high-power low-temperature laser operating on transitions in Yb and Nd ions.

We have obtained nanosecond pulses from the Yb : YAG laser at 1.03 and 1.05 μm. The experimental results obtained in the paper can be used for the development of the method for switching the wavelength of repetitively pulsed ytterbium lasers. The generation of nanosecond pulses at 1.05 μm can be also used as an additional (to the main 1.03-μm transition) channel for formation of working pulses for subsequent amplification in a high-power laser setup. The results presented in the paper show that it is worthwhile to further investigate the possibility of using Yb : YAG crystals in high-power laser drivers for laser fusion.

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