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Diode-pumped passively *Q*-switched high-repetition-rate Yb microchip laser

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***Abstract*. The system of balance equations is modified for quasi-three-level passively *Q*-switched lasers with a slow saturable absorber. Optimal parameters of a Yb^{3+} : YAG microchip laser with a passive Cr^{4+} : YAG *Q* switch are calculated at a pulse repetition rate of $\sim$ 100 kHz. The single-mode operation of the Yb : YAG – Cr : YAG laser with a pulse repetition rate above 100 kHz, the average output power 0.45 W and peak power 1.5 kW is experimentally demonstrated. In the multimode lasing regime, pulses with a peak power of 4.2 kW are obtained at an average output power of 0.8 W and a pulse repetition rate of 10 kHz.**

Keywords: *passive Q switching, quasi-three-level lasers, balance equations, Yb : YAG microchip laser, passive Cr : YAG Q switch.*

1. Introduction

Diode-pumped passively *Q*-switched solid-state lasers are widely used in scientific, medical, and idustrial systems. The advantages of such lasers are their simplicity, reliability, and low cost. The majority of papers on these laser systems are devoted to the investigation of neodymium and ytterbium lasers passively *Q*-switched with the help of Cr^{4+}-containing crystal and semiconductor saturable absorbers [1, 2].

Lasers emitting high-peak-power pulses at relatively low (up to several tens of kilohertz) pulse repetition rates attract the greatest attention; however, some practical applications, such as high-resolution ranging and flow cytometry, require higher pulse repetition rates ($\sim$ 100 kHz). Recently, a stable single-frequency passive *Q*-switching has been demonstrated in a Nd : $GdVO_4$ laser with a passive Cr : YAG *Q* switch. Pulses with a peak power up to 4 kW and a pulse repetition rate up to 80 kHz have been obtained in [3]. This paper is devoted to the development of a diode-pumped, passively *Q*-switched Yb : YAG laser emitting a train of pulses with a pulse repetition rate of $\sim$ 100 kHz and a peak power above 2 kW.

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2. Theoretical model of a quasi-three-level laser with a 'slow' saturable absorber

Laser materials doped with Yb^{3+} ions are quasi-three-level active media. The thermal population of sublevels of both upper and lower laser levels (multiplets) in these materials leads to the interaction of both laser levels with the pump and laser radiation. This should be taken into account in describing the laser operation.

The system of balance equations for a quasi-three-level laser with a passive Cr : YAG *Q* switch for the quantities averaged over the volume of the laser radiation mode can be written in the form

$$\frac{dI_g}{dt} = \frac{c\mu}{n}(k_g - k_L - k_{sa})I_g,$$

$$\frac{dN_2}{dt} = \frac{I_p}{h\nu_p}k_p - \frac{I_g}{h\nu_g}k_g - \frac{N_2}{\tau},$$

$$\frac{dN_{gs}}{dt} = -\xi\frac{I_g}{h\nu_g}\sigma_{gs}N_{gs} + \frac{N_{sa} - N_{gs}}{\tau_{sa}}, \qquad (1)$$

$$N_1 + N_2 = N,$$

$$N_{gs} + N_{es} = N_{sa}.$$

Here, I_g and I_p are the laser and pump radiation intensities; $\mu = l_a n/l_c$ is the resonator filling factor; l_a is the active element length; n is the refractive index of the active element; l_c is the optical length of the resonator; ν_p and ν_g are the pump and laser radiation frequencies; $k_g = \sigma^g_{em}N_2 - \sigma^g_{abs}N_1$ is the gain at the laser radiation frequency; τ is the lifetime of the upper laser level; σ^g_{em} and σ^g_{abs} are the cross sections for the stimulated emission and absorption at the laser frequency; $k_p = \sigma^p_{abs}N_1 - \sigma^p_{em}N_2$ is the absorption coefficient at the pump frequency; σ^p_{em} and σ^p_{abs} are the cross sections for the stimulated emission and absorption at the pump frequency; $k_L = -[\ln R_{out} + \ln(1-L)]/(2l_a)$ is the resonator loss coefficient; N is the concentration of impurity centres in the active medium; R_{out} is the reflection coefficient of the output mirror; L is the coefficient of relative inactive losses in the resonator; $k_{sa} = (\sigma_{gs}N_{gs} + \sigma_{es}N_{es})l_{sa}/l_a$ is the loss coefficient in a passive *Q* switch; σ_{gs} and σ_{es} are the ground- and excited-state absorption cross sections of a Cr : YAG passive *Q* switch; N_{gs} and N_{es} are the ground- and excited-state populations of the passive Q switch; l_{sa} is the length of the passive Q switch; N_{sa} is the concentration of Cr^{4+} ions in the passive Q switch; τ_{sa} is the excited-state lifetime of chromium ions; $\xi = A_g/A_{sa}$ is the ratio of the effective areas A_g and A_{sa} of the lasing mode in the active medium and the passive Q switch.

At the stage of the single-pulse generation, system of equations (1) is simplified by dropping the terms describing the pump rate and relaxation processes in the active element and passive Q switch. The system of truncated equations in new variables takes the form

$$\frac{d\Phi_g}{dt} = \frac{c\mu}{n}(\sigma_g N_{2g} - k_L^*)\Phi_g,$$

$$\frac{dN_{2g}}{dt} = -\Phi_g \sigma_g N_{2g}, \tag{2}$$

$$\frac{dN_{gs}}{dt} = -\xi\Phi_g\sigma_{gs}N_{gs},$$

where $\sigma_g = \sigma_{abs}^g + \sigma_{em}^g$ is the sum of the effective cross sections for laser radiation; $N_{2g} = N_2 - \beta_g N$ is the effective population of the upper multiplet for laser radiation; $\beta_g = \sigma_{abs}^g/(\sigma_{abs}^g + \sigma_{em}^g)$ is the parameter characterising the condition providing the bleaching at the laser frequency; $\Phi_g = I_g/(h\nu_g)$ is the photon flux density at the laser frequency; $k_L^* = k_L + k_{sa}$.

The system of equations (2) is analogous to the systems of equations describing the laser operation based on four-level active media in the passively Q-switching regime and a 'slow' passive Q switch, the solutions of these systems of equations being well known [4]. In our case, these solutions will be similar in form and only the meaning of some quantities will be different.

The expression for Φ_g as a function of N_{2g} has the form

$$\Phi_g(N_{2g}) = \frac{c\mu}{n}\left\{N_{2g}^i - N_{2g} - \frac{k_L l_a + \beta\ln(1/T_0)}{l_a\sigma_g}\ln\left(\frac{N_{2g}^i}{N_{2g}}\right) - \frac{(1-\beta)\ln(1/T_0)}{l_a\sigma_g\alpha}\left[1 - \left(\frac{N_{2g}}{N_{2g}^i}\right)^\alpha\right]\right\}, \tag{3}$$

where

$$\alpha = \xi\sigma_{gs}/\sigma_g;\ \beta = \sigma_{es}/\sigma_{gs};\ N_{2g}^i = (k_L l_a - \ln T_0)/(\sigma_g l_a);$$

$T_0 = \exp(-\sigma_{gs}N_{sa}l_{sa})$ is the initial transmission of the saturable absorber. The maximum Φ_g is achieved at some effective population $N_{2g} = N_{2g}^t$, which is determined from the equation

$$\frac{N_{2g}^t}{N_{2g}^i} = \frac{N_{2g}^0}{N_{2g}^i} + \left(1 - \frac{N_{2g}^0}{N_{2g}^i}\right)\left(\frac{N_{2g}^t}{N_{2g}^i}\right)^\alpha. \tag{4}$$

Here, $N_{2g}^0 = (k_L l_a - \beta\ln T_0)/(l_a\sigma_g)$. The value of $N_{2g} = N_{2g}^f$, which corresponds to the termination of the laser pulse, is found from the equation

$$1 - \frac{N_{2g}^f}{N_{2g}^i} + \frac{N_{2g}^0}{N_{2g}^i}\ln\left(\frac{N_{2g}^f}{N_{2g}^i}\right) - \frac{1}{\alpha}\left(1 - \frac{N_{2g}^0}{N_{2g}^i}\right)\left[1 - \left(\frac{N_{2g}^f}{N_{2g}^i}\right)^\alpha\right] = 0. \tag{5}$$

The output laser pulse energy is

$$E_{out} = V_g k_{act} h\nu_g \frac{1}{\sigma_g}\ln\left(\frac{N_{2g}^i}{N_{2g}^f}\right), \tag{6}$$

where V_g is the effective volume of the laser radiation mode and $k_{act} = -\ln R_{out}/(2l_a)$ are the active resonator losses. The quantity $\Phi_g(N_{2g}^t)$ is the maximum photon flux density determining the peak output power:

$$P_{out}^{peak} = V_g k_{act} h\nu_g \Phi_g(N_{2g}^t). \tag{7}$$

The laser pulse duration t_{dur} is calculated from the expression

$$t_{dur} = E_{out}/P_{out}^{peak}. \tag{8}$$

Consider now the operation of a Q-switched laser between laser pulses. We assume that the passive Q switch is completely recovered between two adjacent pulses. Pump radiation should ensure an increase in the volume-average effective population at the upper multiplet from $N_{2g} = N_{2g}^f$ to $N_{2g} = N_{2g}^i$. We assume that pump radiation propagates in the active element along the z axis from $z = 0$ at the active element input to $z = l_a$ at its output. The interaction of pump radiation with the active medium is described by the system of equations

$$\frac{n}{c}\frac{\partial\Phi_p(t,z)}{\partial t} + \frac{\partial\Phi_p(t,z)}{\partial z} = -k_p(t,z)\Phi_p(t,z), \tag{9}$$

$$k_p(t,z) = \sigma_{abs}^p N - \sigma_p N_2(t,z). \tag{10}$$

We will pass in equations (9) and (10) to quantities averaged over the active element volume and obtain a system of equations describing the laser operation between the laser pulses:

$$\frac{d\Phi_p(t)}{dt} = -\frac{c}{n}k_p(t)\Phi_p(t) - \frac{c}{nl_a}\Phi_{p0}(t)\{\exp[-k_p(t)l_a] - 1\}, \tag{11}$$

$$\frac{dk_p(t)}{dt} = -\frac{1}{\tau}\left\{k_p(t)\left[1 + \frac{\Phi_p(t)}{\Phi_{ps}}\right] - \sigma_{abs}^p N\right\}. \tag{12}$$

Here, $\Phi_{ps} = 1/(\sigma_p\tau)$ is the photon-flux saturation density at the pump frequency. Because the pump intensity at the active element input is assumed constant, we have $\Phi_{p0}(t) = \Phi_{p0} = P_{p0}/(A_p h\nu_p) = \text{const}$, where P_{p0} is the pump power at the active element input and A_p is the effective area of the pump beam. In the general case, the system of equations (11) and (12) is solved numerically. In some cases, for example at a high laser pulse repetition rate, when the initial effective population $N_{2g} = N_{2g}^i$ only slightly differs from the final population $N_{2g} = N_{2g}^f$, we can assume that $\Phi_p(t) \approx \overline{\Phi_p} = \text{const}$ and obtain from (12) the expression for the pulse repetition rate:

$$f = \left(\frac{\tau}{a}\ln\frac{ak_p^f + b}{ak_p^i + b}\right)^{-1}. \tag{13}$$

Here,

$$a = 1 + \overline{\Phi_p}/\Phi_{ps};\ b = -\sigma_{abs}^p N;\ k_p^f = (N - N_2^f)\sigma_{abs}^p - N_2^f\sigma_{em}^p;$$

$$k_{\rm p}^{\rm i} = (N - N_2^{\rm i})\sigma_{\rm abs}^{\rm p} - N_2^{\rm i}\sigma_{\rm em}^{\rm p};$$

the populations of the upper multiplet $N_2^{\rm f}$ and $N_2^{\rm i}$ correspond to the effective populations $N_{2\rm g}^{\rm f}$ and $N_{2\rm g}^{\rm i}$. In the case of a single transit of radiation through the active element, $\overline{\Phi_{\rm p}}$ is calculated from the expression

$$\overline{\Phi_{\rm p}} = \Phi_{\rm p0}[1 - \exp(-\overline{k_{\rm p}}l_{\rm a})]/(\overline{k_{\rm p}}l_{\rm a}), \qquad (14)$$

where $\overline{k_{\rm p}} \approx (k_{\rm p}^{\rm f} + k_{\rm p}^{\rm i})/2$.

Because the aim of this paper is to design a laser emitting short light pulses, we simulated a microchip laser consisting of a 0.8-mm-thick Yb : YAG active element (with the Yb concentration of 10 %) and a 0.2-mm-thick Cr : YAG passive Q switch in optical contact. Calculations were performed by using expressions (4) – (8), (13), and (14). The average output power was calculated as $P_{\rm av} = E_{\rm out}f$. The laser was longitudinally pumped by pump radiation focused in the active element into a spot $\sim$ 100 μm in diameter. The pump power at the active element input was $P_{\rm p0} = 3.4$ W. The parameters of the saturable absorber were: $\tau_{\rm sa} = 3.4$ μs, $\sigma_{\rm gs} = 4.3 \times 10^{-18}$ cm^2, $\sigma_{\rm es} = 8.9\times 10^{-19}$ cm^2. The lifetime of the Yb upper laser level, absorption and stimulated emission cross sections were borrowed from papers [5, 6]. In calculations we took into account the spectral power distribution of the laser diode radiation at 940 nm, which leads to the change in the effective cross sections for pump radiation [7]. The results of calculations are shown in Fig. 1.

One can see from the presented results that the initial transmission of the Q switch significantly affects the output parameters of the laser. To operate at a pulse repetition rate of $\sim$ 100 kHz, the transmission of the output mirror should be approximately 20 % and the initial transmission of the switch – $\sim$ 98 %. In this case, the peak power achieves more than 3 kW. The calculations show that as the initial transmission of the saturable absorber was reduced down to 96.5 %, the peak power increased up to $\sim$ 10 kW and the pulse repetition rate decreased down to $\sim$ 62 kHz.

3. Experimental results

We used in the experiments two laser resonator configurations – for multimode and single-mode lasing (at longitudinal resonator modes).

In the case of multimode lasing, the microchip laser resonator was formed by a plane highly reflecting mirror and a plane output mirror deposited on one of the faces of the Yb : YAG active element and passive Cr : YAG Q switch, respectively. Pumping was performed by a 6-W, 940-nm laser diode with a fibre pigtail. The focused pump beam had the waist diameter of about 100 μm in the active element. The Cr : YAG crystal was in optical contact with the Yb : YAG active element. All the Cr : YAG crystals were cut along the [001] axis. The thickness of the microchip laser was $\sim$ 1 mm.

Single-mode lasing was obtained by placing two Fabry – Perot etalons into the laser resonator. These etalons were formed by the Cr : YAG crystal and an air gap between the Yb : YAG and Cr : YAG crystals.

In the case of multi-mode lasing, the output emission spectrum consisted of four – five adjacent longitudinal resonator modes. For the passive Q switch with the initial transmission $T_0 = 98$ %, we obtained 8-μJ, 1.9-ns laser pulses with the peak power of 4.2 kW, repetition rate of 100 kHz, and average output power of $\sim$ 0.8 W at $\sim$ 1029.7 nm.

For a laser with the transmission $T_0 = 96.5$ %, we obtained 11.1-μJ, 1.5-ns pulses with the peak power above 7 kW and repetition rate of 65 kHz at 1029.7 nm. The

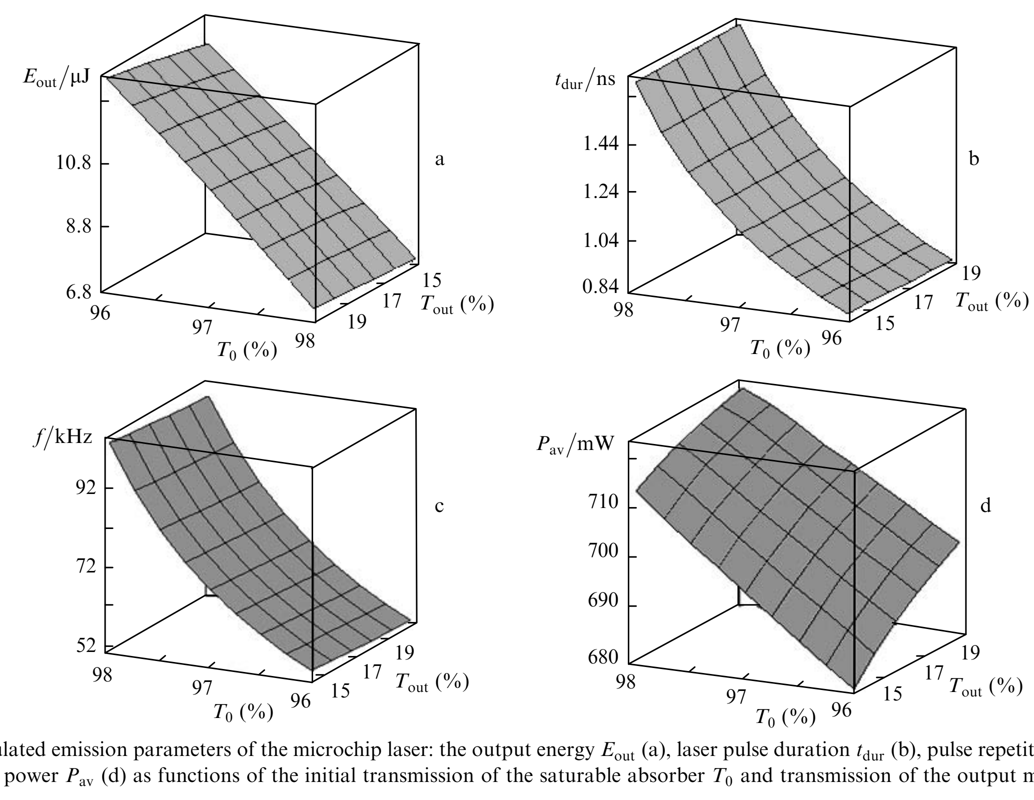

Figure 1. Calculated emission parameters of the microchip laser: the output energy $E_{\rm out}$ (a), laser pulse duration $t_{\rm dur}$ (b), pulse repetition rate f (c), and average output power $P_{\rm av}$ (d) as functions of the initial transmission of the saturable absorber T_0 and transmission of the output mirror $T_{\rm out}$.

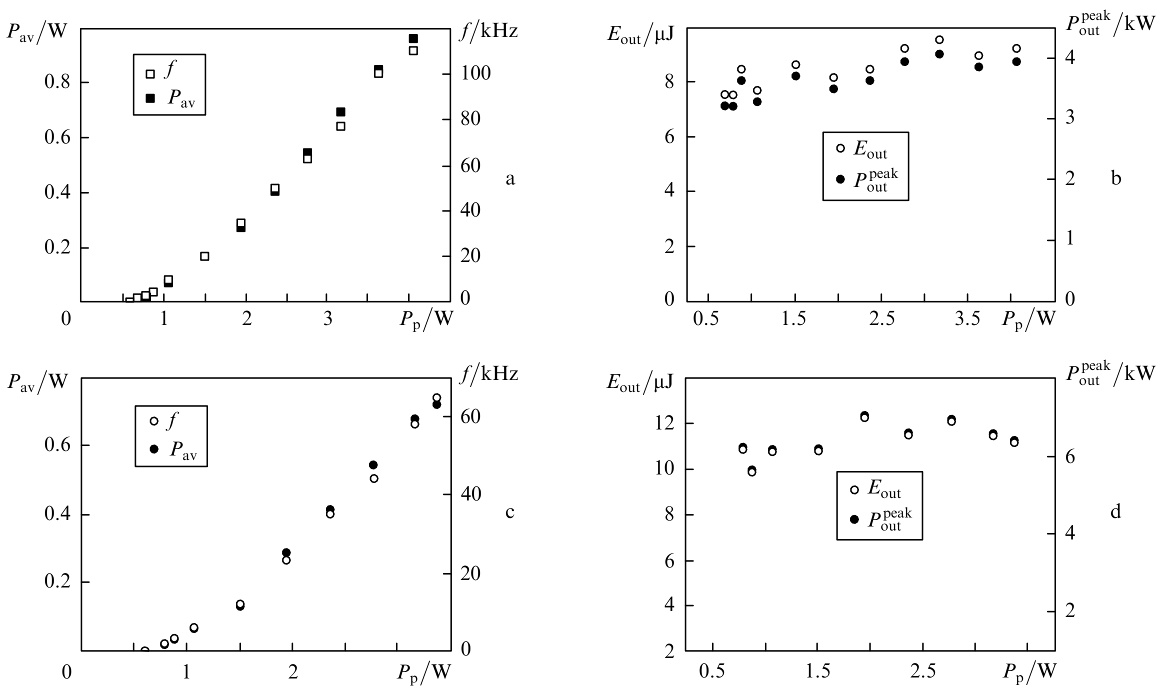

Figure 2. Output parameters of the Yb : YAG laser as functions of the pump power in the case of multimode lasing at $T_0 = 98\ \%$ (a, b) and 96.5 (c, d).

maximum average output power was ~ 0.72 W at the pulse amplitude instability of $\sim 4\ \%$, the time jitter (scatter of the time intervals between adjacent pulses) less than 2 μs and the repetition rate of 65 kHz. Figure 2 presents the dependences of the output power, pulse repetition rate, peak power, and pulse energy on the pump power. A train of pulses is shown in Fig. 3. As the pump power was further increased, we observed a significant increase in the amplitude instabilities and the pulse repetition rate.

The results obtained in the experiments well agree with the calculated data. A small discrepancy between the measured and calculated pulse durations, especially for a more optically dense Q switch, is explained by the restricted time resolution (~ 1.7 ns) of the measuring device.

In the case of single-mode lasing, at the pump power of 2.95 W and $T_0 = 96.5\ \%$ the average output power of the laser was 620 mW for the optical generation efficiency of $\sim 21\ \%$. The single-pulse energy was equal to 12.9 μJ at its duration less than 2 ns (the peak power of 6.8 kW) at a wavelength of 1029 nm. The maximum pulse repetition rate under these conditions was 50 kHz. When we used a saturable absorber with $T_0 = 98\ \%$, the average output power achieved 450 mW at a pulse energy of 4.25 μJ, pulse duration of 2.8 ns (the peak power of 1.52 kW) and the

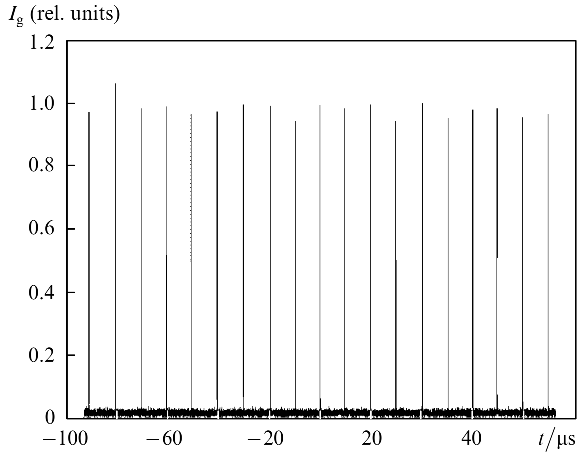

Figure 3. A train of pulses from the Yb : YAG laser in the multimode regime.

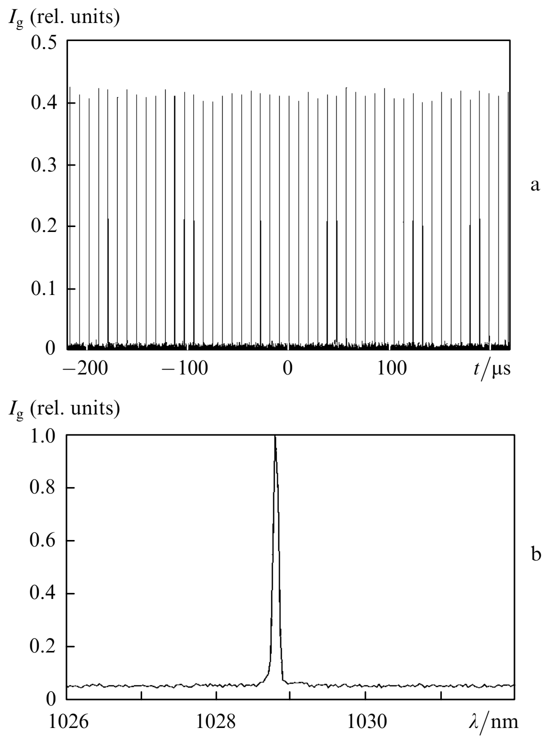

Figure 4. A train of pulses from the Yb : YAG laser in the single-mode regime (a) and the output emission spectrum of the single-mode Yb : YAG laser (b).

pulse repetition rate of 106 kHz at 1029 nm. The train of pulses and the output emission spectrum are presented in Fig. 4. The pulse amplitude instability did not exceed 2 % and the time jitter was no more than 1 μs at a pulse repetition rate of 106 kHz.

In the case of both the multimode and single-mode lasing, the Yb : YAG laser output was linearly polarised, normally to the [100] crystallographic axis of the Cr : YAG-crystal passive *Q* switch.

4. Conclusions

We have modified the system of balance equations for quasi-three-level passively *Q*-switched lasers with a 'slow' saturable absorber and have calculated optimal parameters of the microchip Yb : YAG laser with a Cr : YAG passive *Q* switch for the pulse repetition rate of~ 100 kHz. Lasing in the microchip Yb : YAG – Cr : YAG laser has been demonstrated at one longitudinal resonator mode with the pulse repetition rate higher 100 kHz, average output power of 0.45 W, and peak power of 1.5 kW. Pulses with the peak power of 4.2 kW, average output power of 0.8 W, and pulse repetition rate of 100 kHz have been obtained in the multimode generation regime.

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