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Pulsed generation in a combined-diode-pumped Nd^{3+} : $Ca_3Ga_2Ge_3O_{12}$ laser with a small jitter of the pulse repetition rate

M.I. Belovolov, A.F. Shatalov

***Abstract*.** **Pulsed generation in a solid-state Nd^{3+} : $Ca_3Ga_2Ge_3O_{12}$ (Nd : CGGG) laser (SSL) with passive *Q*-switching by the Cr^{4+} : YAG crystal is studied. To reduce the pulse repetition rate jitter of the SSL generation, the current through a pump diode was combined from a constant component and short pulse. It is shown that if the sum of the constant and pulsed components of the optical pump power exceeds the threshold pump power by less than twice ($1 < x_p < 2$), the pulse repetition rate jitter of the SSL generation has the local minimum, which is obtained when the constant component of the pump power relative to the threshold power is $2 - x_p$. The natural lifetime τ of the upper level of the laser element (LE) in the SSL cavity is proposed to be measured by the delay of the SSL pulse with respect to the leading edge of the pump pulse. It is shown that the lifetime measured in this way is shorter than the time τ measured by the standard method in which the LE resides outside the SSL. At the laser pulse repetition rate of 192 Hz, the pulse energy of 3.5 μJ and duration of 11 ns, the relative jitter of the laser pulse period was ~0.06 %, which is by more than two orders of magnitude lower than that under a constant current through the pump diode.**

Keywords: *solid-state laser, diode pumping, passive Q-switching, jitter of pulses.*

1. Introduction

Neodymium-doped crystals of $Ca_3Ga_2Ge_3O_{12}$: Nd^{3+} (CGGG : Nd) calcium – gallium – germanium garnet are a promising material for producing compact pulsed solid-state diode-pumped lasers (SSLs) because they are close to Nd : YAG laser crystals [1 – 4] in the lasing efficiency outperforming the latter due to the four-fold wider absorption band [4] (which simplifies their matching with the radiation of the pump diode) and due to a few times greater energy and peak power of generated pulses [5, 6]. An important parameter of pulsed SSLs is the jitter T of the pulse repetition interval, which determines the stability of the pulse repetition rate $f = 1/T$. The jitter in a passively *Q*-switched diode-pumped SSLs increases with decreasing the pulse repetition rate f as $1/f^{\gamma}$ ($\gamma = 1.3 - 1.4$) and is approximately 10 % at $f \sim 10$ kHz [7, 8]. The jitter of a pulsed Nd : YAG SSL is reduced by employing combined pumping of the laser crystal either by two pump diodes [9] or, which is simpler, by a single pump diode [10, 11], in which the combined pumping of the SSL occurs due to the controlled variation in the current through the pump diode.

In this work, we study theoretically and experimentally the possibilities to reduce the jitter of a pulsed passively *Q*-switched Nd : CGGG SSL pumped by a single diode with the current combined from a constant component and a short-duration pulse.

M.I. Belovolov, A.F. Shatalov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia;
e-mail: bmi@fo.gpi.ru, shatalov@fo.gpi.ru, afshatalov@yahoo.co.uk

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2. Theory

The dynamics of the inversion population density n in a laser element (LE) and of the photon density ϕ inside the laser cavity is described by the Eqns [12]

$$\frac{d\phi}{dt} = \left[2\sigma n d - 2\sigma_s n_s d_s - 2\sigma_{es} n_{es} d_s - \ln\left(\frac{1}{R}\right) - L\right]\frac{\phi}{t_r}, \quad (1)$$

$$\frac{dn}{dt} = N_p - \frac{n}{\tau} - \gamma\sigma c\phi n, \quad (2)$$

where n_s and σ_s are the population density and the absorption cross section of the lower level (for Cr^{4+} : YAG it is $^3A_2$) for the saturable absorber (SA), respectively; n_{es} and σ_{es} are the population density and the absorption cross section for the SA excited level ($^3T_2$); σ is the effective cross section of induced transitions in the LE; d is the LE thickness; d_s is the SA thickness; R is the reflectance of cavity mirrors; L are the passive losses per cavity round trip (excluding SA losses); γ is the inversion degeneration coefficient in the LE; N_p is the pump rate; τ is the natural lifetime for the upper level in the LE; $t_r = 2l'/c$ is the round-trip time of light in the cavity; c is the speed of light; l' is the optical length of the laser cavity.

Prior to generation, we have $d\phi/dt = 0$ and the $^3T_1$ absorption level of the SA is actually empty, hence, by neglecting the term with σ_{es} we find from Eqn (1) the threshold density of the inversion population in the LE

$$n_i = \frac{2\sigma_s n_{si} d_s + \ln(1/R) + L}{2\sigma d}, \quad (3)$$

which is equal to the inversion population density in the LE at the instant of the lasing onset (here, n_{si} is the population density for the lower SA level at the instant of the lasing onset). Then, the solution for Eqn (2) in the absence of lasing ($\phi = 0$) can be written in the form

$$n(t) = N_p\tau - (N_p\tau - n_{0f})\exp(-t/\tau), \tag{4}$$

where n_{0f} is the initial density of the inversion population in the LE.

Figure 1 shows the time dependences of the optical pump power and inversion population density in the LE. Expression (4) entails the expression:

$$T_0 = \tau \ln \frac{x_p - x_0}{x_p - 1} \tag{5}$$

for the delay of the lasing onset relative to the leading edge of the pump pulse, where $x_p = N_p\tau/n_i$; $x_0 = n_{0f}/n_i$.

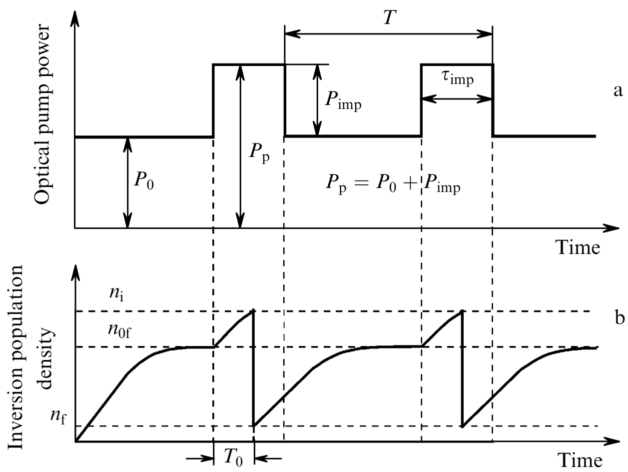

Figure 1. (a) Optical pump power P_n and (b) inversion population density n for the LE as functions of time; P_0 and P_{imp} are the constant and pulsed components of the optical pump power $P_p = P_0 + P_{imp}$, T and $f = T^{-1}$ are the pump pulse period and repetition rate, τ_{imp} is the pulse duration, T_0 is the delay of laser generation onset with respect to the leading edge of the pump pulse, n_f is the final inversion population density in the LE.

Depending on the laser operation regime, the parameter n_{0f} may be equal to zero, n_f, or the product $N_{0p}\tau$, where N_{0p} is the pump rate corresponding to the power P_0. The pump rate N_p corresponds to the power P_p. The final inversion population density n_f in the LE depends on the laser operation regime and LE characteristics and may be zero or nonzero. At $P_{imp} = 0$ ($P_p = P_0$) and $N_p\tau > n_i$ the laser operates in the self-oscillating regime with a pulse repetition interval $T = T_0$, the density n_{0f} being equal to n_f.

It follows from Eqn (5) that the jitter j of the laser pulse repetition interval T is defined by fluctuations $j_1 = \delta n_{p\tau}$, $j_2 = \delta n_{0f}$ and $j_3 = \delta n_i$ of the parameters $n_{p\tau} = N_p\tau$, n_{0f} and n_i:

$$j = \left[\left(\frac{\partial T_0}{\partial n_{p\tau}}\right)^2 j_1^2 + \left(\frac{\partial T_0}{\partial n_{0f}}\right)^2 j_2^2 + \left(\frac{\partial T_0}{\partial n_i}\right)^2 j_3^2\right]^{1/2} =$$

$$= \frac{\tau}{n_i}[y_1^2 j_1^2 + y_2^2 j_2^2 + y_3^2 j_3^2]^{1/2}, \tag{6}$$

where

$$y_1 = \frac{1 - x_0}{(x_p - x_0)(x_p - 1)}; \quad y_2 = \frac{1}{x_p - x_0};$$

$$y_3 = \frac{1}{x_p - 1}; \quad x_p > 1; \quad 0 \leqslant x_0 < 1. \tag{7}$$

As follows from Eqn (3), fluctuations j_3 of the parameter n_i may be revealed via fluctuations of the parameters R and L under temperature and mechanical actions on the laser. Since the latter are mainly low-frequency factors, their influence can be sufficiently reduced by means of damping and temperature stabilisation as well as by reducing the coefficient y_3 (by increasing x_p). In most cases, the jitter j is caused by fluctuations of the pump diode power [13]. In these cases, at $P_0 \neq 0$, $j_1 = i_2 = j_d$ the value of the jitter j in (6) is determined by the coefficient

$$y = (y_1^2 + y_2^2)^{1/2} = \frac{[x_p^2 + x_0^2 - 2(x_p + x_0) + 2]^{1/2}}{(x_p - x_0)(x_p - 1)}. \tag{8}$$

The coefficient $y(x_p, x_0)$ at $x_0 = x_{0\,min} = 2 - x_p$ has a local minimum equal to $y(x_p, x_{0min}) = y_{min} = [\sqrt{2}(x_p - 1)]^{-1}$.

Figure 2 shows the dependences of the coefficient y on x_0, on x_p, on x_p, x_0 and of the parameter $x_{0\,min}$ on x_p. The analysis of the obtained results shows that at $P_0 \neq 0$ and $1 < x_p < 2$ (P_p is less than twice above the threshold value) by choosing P_0 ($x_0 = x_{0\,min} = 2 - x_p$) at a given x_p one can obtain the minimal jitter that will be determined by the coefficient y_{min}. A further decrease in the jitter can only be obtained by increasing x_p (a greater increase in the power P_p).

The laser operation regime where n_{0f} is equal to n_f or zero is of interest. In this case, fluctuations of the pump diode power are revealed in the jitter j only via the coefficient y_1. Figure 3 presents y_1 as a function of x_p and x_0. In this case, one can always reduce the jitter j by an order or two by appropriately choosing $x_p(P_p)$ at given $x_0(P_0)$ or by choosing x_0 at given x_p.

The optical energy E_{imp} of the SSL generation initiated by a pulse with the duration t_{imp} (see Fig. 1) can be presented in the form

$$E_{imp} = P_{imp}T_0 = (P_p - P_0)T_0 = kn_i\tau y_{imp}(x_p, x_0), \tag{9}$$

where$P_0 = kn_{0f}$; $P_p = kn_{p\tau}$; and k is the proportionality coefficient;

$$y_{imp}(x_p, x_0) = (x_p - x_0)\ln\frac{x_p - x_0}{x_p - 1}. \tag{10}$$

Figure 4 shows the dependences of the coefficients y_{imp} on x_p and x_0. It follows from the results obtained that when x_p is increased, the coefficient y_{imp} is reduced and tends to its limiting value $y_{imp} = 1 - x_0$, which corresponds to the difference in energies acquired in the laser cavity at inversion population densities n_i and n_{0f}, respectively. At $x_p \geqslant 2$ and $0 \leqslant x_0 \leqslant 0.95$, the coefficient y_{imp} and the energy E_{imp} of the SSL initiation exceed their limiting values by no more than 40 %.

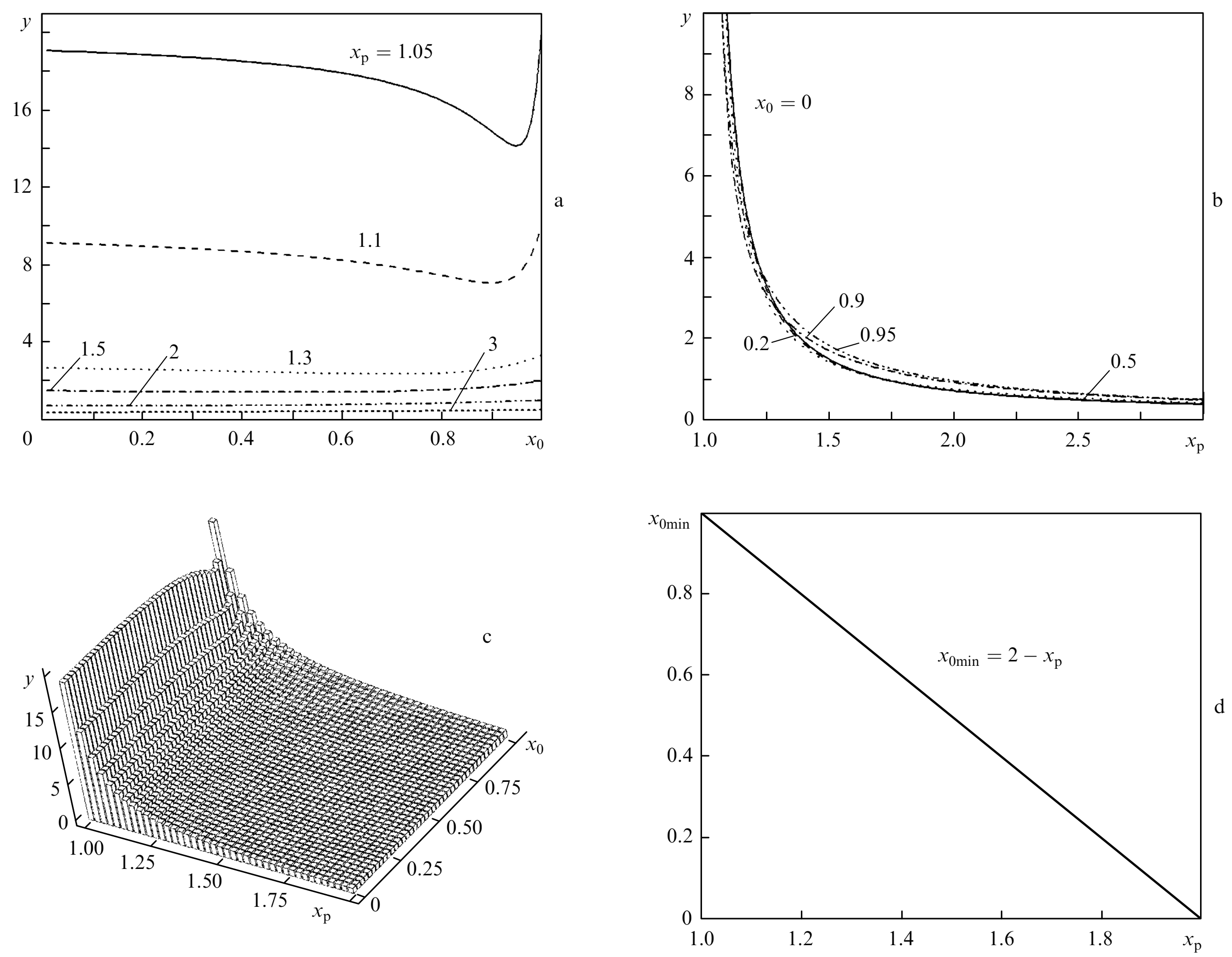

Figure 2. Dependences of the coefficient y on x_0 (a); x_p (b); x_p and x_0 (c) in the ranges $0 \leqslant x_0 < 1$, $1 \leqslant x_p \leqslant 2$ as well as the parameter $x_{0\,min}$ as a function of x_p (d).

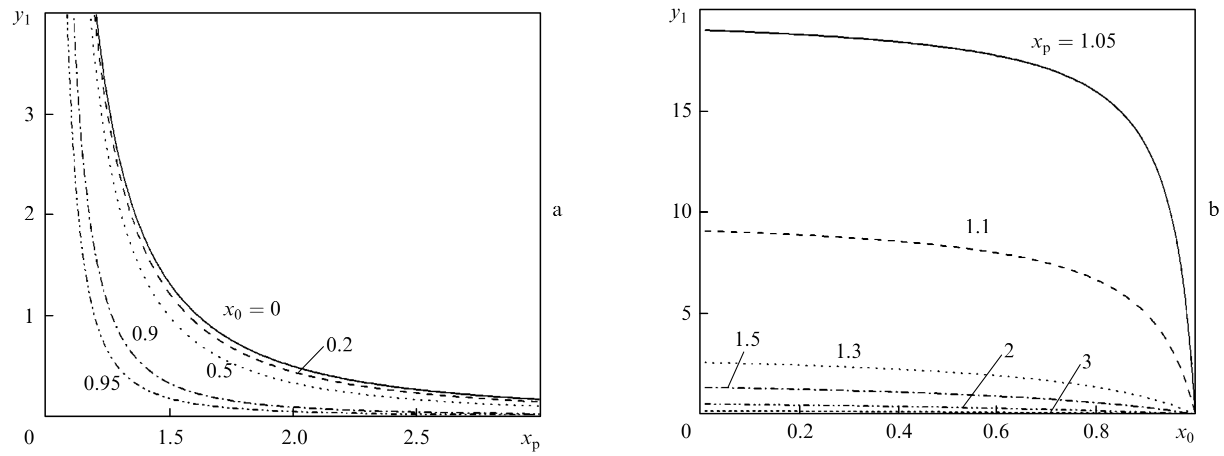

Figure 3. Coefficient y_1 as a function of x_p (a) and x_0 (b).

Taking into account the behavior of the coefficient y_{imp} at large x_p and using Eqn (9) one can show that the optical pump parameters P_0, P_{imp}, and t_{imp} in the case of pulsed SSL generation should necessarily meet the constraint

$$P_{imp}\tau_{imp} > \tau(P_{th} - P_0), \qquad (11)$$

where P_{th} is the threshold optical pump power to which the inversion population density n_i ($P_{th} = kn_i$) corresponds. Constraint (11) actually simplifies obtaining the pulsed generation regime in a passively Q-switched intracavity SSL.

3. Experiment

The scheme of the setup for studying the jitter of radiation pulses from a Nd : CGGG laser at a combined current through the pump diode is shown in Fig. 5. Current source

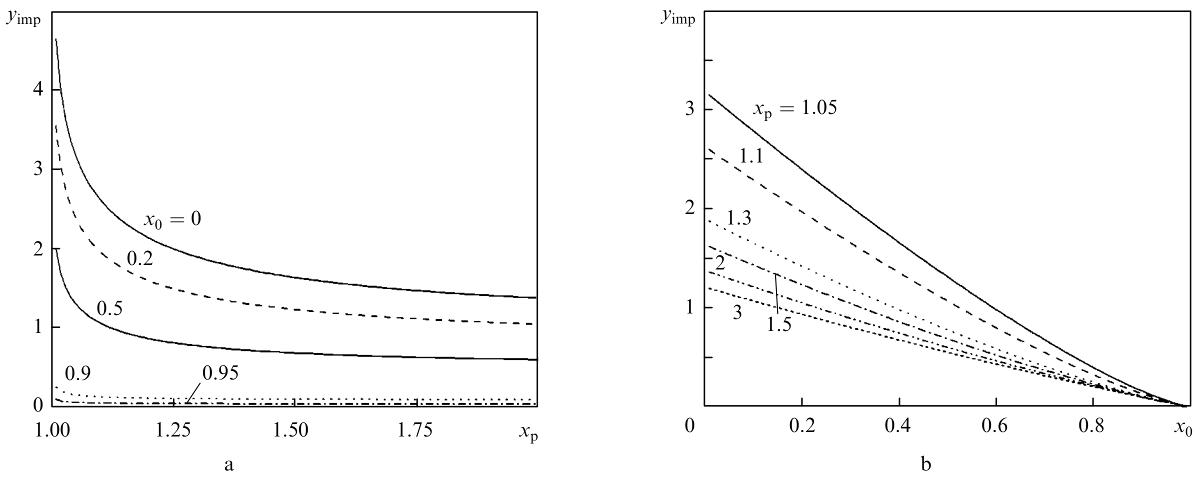

Figure 4. Coefficient y_{imp} as a function of x_p (a) and x_0 (b).

(*1*) modulates the output radiation power (with the wavelength $\lambda_p = 805$ nm) of laser diode (*2*) with fiber outlet (*3*) (NA = 0.22, $d_c = 100$ μm). The full width at half maximum (FWHM) of the pump radiation spectrum is 2 nm. Microlens (*4*) focuses the pump radiation to a spot 90 μm in diameter on laser element (*5*). The LE is fixed on a copper heatsink with a heat-conducting paste. Its front side (black in Fig. 5), which is actually a mirror, and spherical mirror (*7*) (with the transmission coefficient of 0.01 and radius of 5 cm) form a laser cavity. Saturable absorber (*6*) (1-mm-thick Cr^{4+} : YAG crystal with the antireflection coating at 1.06 μm and the transmission coefficient of 0.9 at low intensities of incident radiation) is placed into the cavity. The concentration of Nd^{3+} ions in the Nd : CGGG crystal is 2.0×10^{20} cm^{-3}. The thickness of LE is 1.5 mm so that 80 % of pump radiation is absorbed per single pass. The shape and temporal parameters of laser pulses are measured with low-noise broadband photodetector (*8*) and Tektronix TDS 5104 oscilloscope (*9*). Coherent FieldMaster FM power meter (*10*) with a LM10 measuring head is used to measure the power.

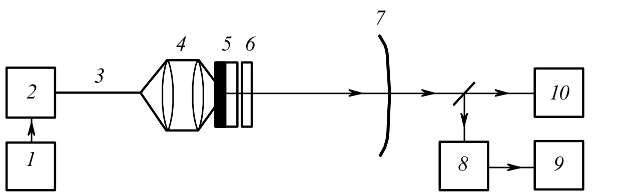

Figure 5. Experimental setup for studying laser pulse jitter in the Nd : CGGG laser under the combined current through the pump diode.

Figure 6 shows the dependences of the pump diode power P_d on the pump current I in addition to oscillograms of the current pulses and pump power. The threshold current through the pump diode was 0.32 A.

The constant I_0 and pulsed I_{imp} components (effective values) of the current through the pump diode were determined less the threshold current. The slope of light – current characteristic for the diode was 0.96 W A^{-1}. Because the parameters I_0 and I_{imp} are proportional to P_0 and P_{imp} as well as $P_{th} \propto I_{th}$, in view of (11) we obtain

$$I_{imp}\tau_{imp} > \tau(I_{th} - I_0). \quad (12)$$

Figure 7 shows the jitter of the laser pulse repetition rate for different pump currents. In the case of self-oscillating laser operation [7, 8] (see Fig. 7c) the pulsed component of

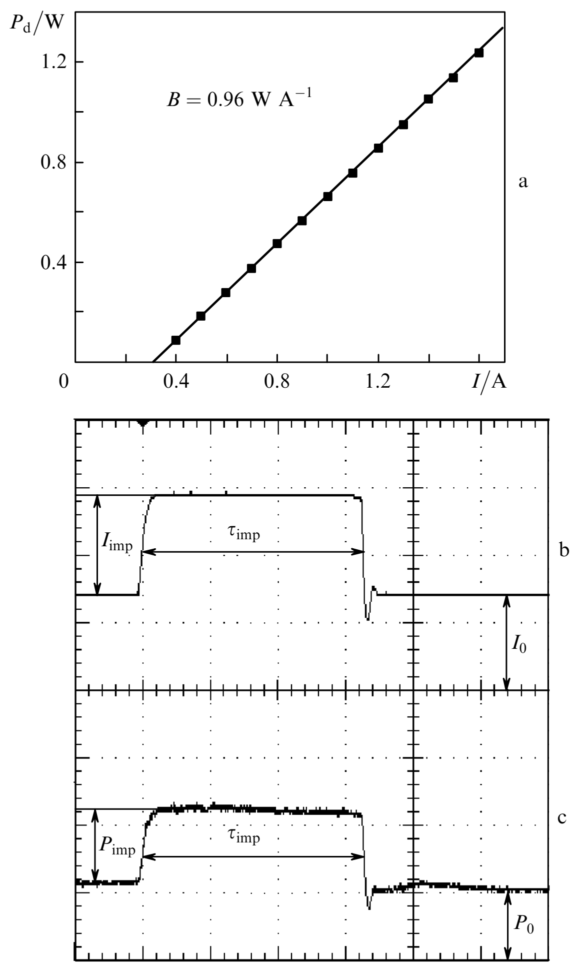

Figure 6. Light – current characteristic of the pump diode (a) and current oscillograms (b) and optical pump power (c); $I_0 = 0.49$ A, $I_{imp} = 0.43$ A; $\tau_{imp} = 130$ μs, $P_0 = 0.47$ W, $P_{imp} = 0.41$ W.

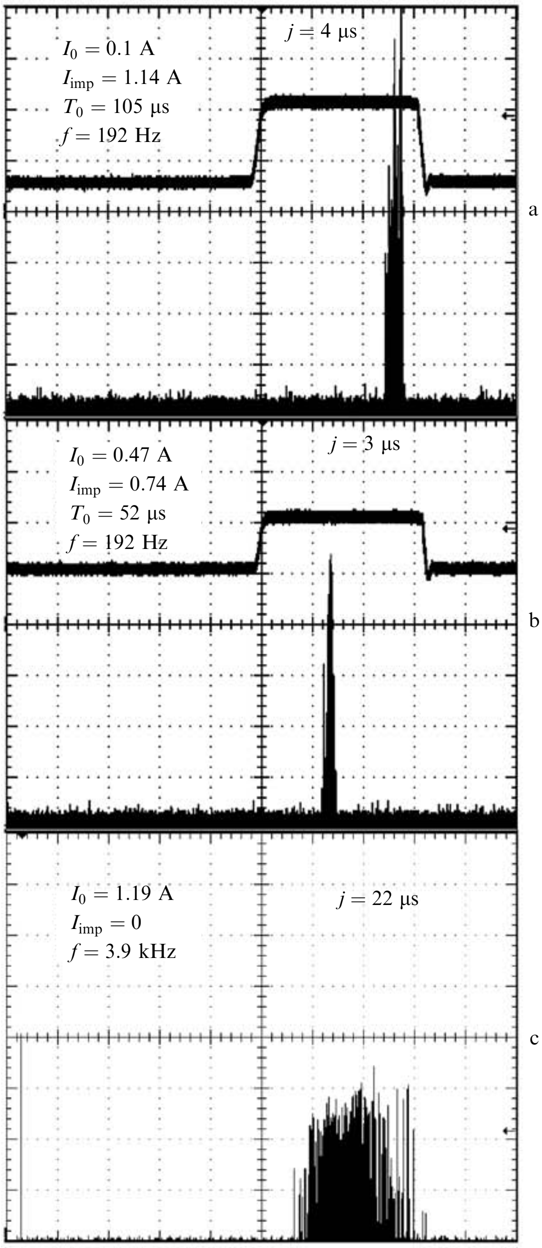

Figure 7. Jitter of the laser pulse repetition rates under various parameters of the pump diode current. The horizontal scale is 50 μs div.$^{-1}$.

the pump current is $I_{imp} = 0$, the pulse repetition rate is $f = 3.9$ kHz, and the jitter is $j = 22$ μs. Similarly to [8], the jitter j was measured as a quarter of the spread interval for generated pulses observed on a screen of the oscilloscope. The jitter was reduced from 22 to 3 μs (by more then 7 times) by appropriately choosing the current parameters. The relative value of the jitter in this case was reduced from 8.6 % to 0.06 %, i.e. by a factor of 143. Note that if the pump current is constant and no special measures are taken, the decrease in the pulse repetition rate f results in an increased jitter $j \sim 1/f^{\gamma} (\gamma = 1.3 - 1.4)$ [8].

Experimental and theoretical dependences of the jitter on the parameter x_0 ($x_p = 1.56$) are shown in Fig. 8. The theoretical curve (corresponds to the y parameter multiplied by $\tau j_d/n_i = 2.8$ μs) and experimental points show the minimal jitter near $x_0 = 2 - x_p = 0.44$.

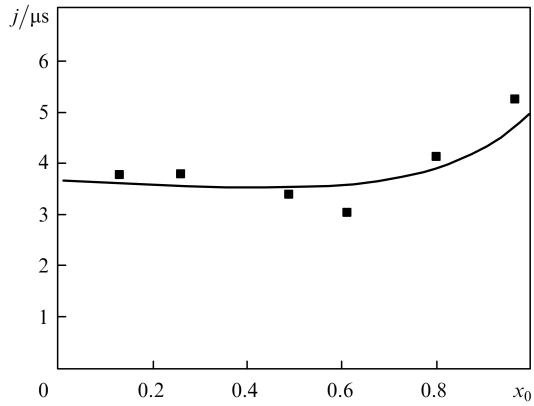

Figure 8. Experimental (dots) and theoretical (curve) dependences of the jitter on the parameter x_0 ($x_p = 1.56$).

Figure 9 shows the dependence of the time delay T_0 on $\ln[(x_p - x_0)/(x_p - 1)]$. The slope of the straight line approximating the experimental points is equal to the natural lifetime τ of the LE upper laser level in the SSL cavity. One can see from Fig. 9 that $\tau = 114$ μs; it is shorter than the same lifetime ($\tau = 230$ μs [8]) measured by a standard method with the LE residing outside the cavity. The shorter time τ for the LE inside the cavity is explained by greater spontaneous emission which results in a reduced natural lifetime of the LE upper laser level [14]. Hence, when pumping the SSL [see Eqns (4), (5), (9), (11), (12)] one should take into account the natural lifetime τ of the upper laser level for the LE residing inside the cavity, which can be measured by the delay T_0 of the SSL pulse with respect to the leading edge of the pump pulse.

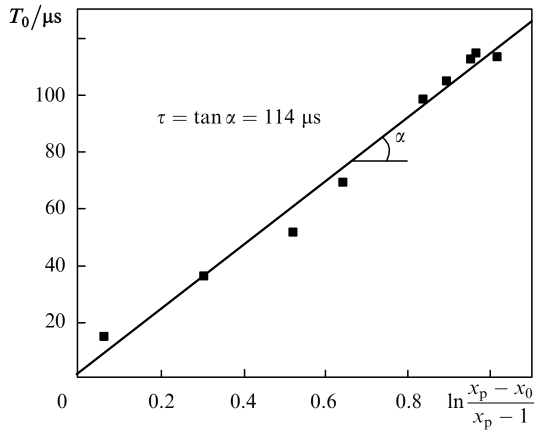

Figure 9. Delay T_0 of the laser generation pulse with respect to the pump pulse leading edge as a function of $\ln[(x_p - x_0)(x_p - 1)^{-1}]$.

For the lowest experimental point in Fig. 9 ($T_0 = 15$ μs) the optical energy E_{imp} initiating the SSL generation is 6.3 μJ, which exceeds the limiting value (3.0 μJ) by a factor of 2.1. The ratio of the energy $E_{las} = 3.5$ μJ of pulse generated by the SSL to the energy E_{imp} in this case is 0.56 and the ratio of the peak power of laser pulses to the pump pulse power P_{imp} is 8×10^2.

4. Conclusions

The possibilities to reduce the pulse repetition rate jitter of the Nd : CGGG SSL with a Cr^{4+} : YAG saturable absorber inside the cavity have been theoretically and experimentally studied for the case of the pump current combined from the constant I_0 and pulsed I_{imp} (with the duration τ_{imp}) components.

It has been shown that the laser jitter has a local minimum at $I_0 = 2I_{th} - I_p$ if the effective current $I_p = I_0 + I_{imp}$ is less than twice the threshold current I_{th}. The necessary requirement to the parameters I_0, I_{imp}, and t_{imp} of the pump current is formulated for the case of the pulsed SSL generation: $I_{imp}\tau_{imp} > \tau(I_{th} - I_0)$.

It has been shown that at $0 \leqslant I_0 \leqslant 0.95I_{th}$ and $I_p \geqslant 2I_{th}$ the optical energy E_{imp} corresponding to initiation of the SSL generation by the pulse τ_{imp} exceeds its limiting value $E_0 = (P_{th} - P_0)\tau$ by more than 40 %. For the energy $E_{imp} = 2.1E_0$, the ratio of the peak power of laser pulses to the pump pulse power is 8×10^2.

By appropriately choosing the parameters I_0, I_{imp}, and τ_{imp} at the laser pulse repetition rate of 192 Hz, the pulse energy of 3.5 μJ and the duration of 11 ns, the relative jitter of ~ 0.06 % has been obtained which is more than two orders of magnitude less than the corresponding jitter under the constant diode pumping.

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References

1. Belovolov M.I., Dianov E.M., Timoschechkin M.I., Morozov N.P., Prokhorov A.M., Timoschechkin K.M. *Proc. CLEO/Europa'96* (Hamburg, Germany, 1996) paper CThI60, p. 281.
2. Jaque D., Caldino U., Romero J.J., Garcia Sole J. *J. Appl. Phys.*, **86**, 6627 (1999).
3. Jaque D., Romero J.J., Garcia Sole J. *J. Appl. Phys.*, **92**, 3436 (2002).
4. Belovolov M.I., Derzhavin S.I., Mashkovskii D.A., Sal'nikov K.S., Sysoev N.N., Timoshechkin M.I., Shatalov A.F. *Kvantovaya Elektron.*, **37**, 753 (2007) [*Quantum Electron.*, **37**, 753 (2007)].
5. Montes M., Heras C., Jaque D. *Opt. Mater.,* **28**, 408 (2006).
6. Belovolov M.I., Derzhavin S.I., Shatalov A.F. *Kvantovaya Elektron.*, **38**, 923 (2008) [*Quantum Electron.*, **38**, 923 (2008)].
7. Nodop D., Limpert J., Hohmuth R., Richter W., Guina M., Tunnermann A. *Opt. Lett.*, **32**, 2115 (2007).
8. Belovolov M.I., Shatalov A.F. *Kvantovaya Elektron.*, **38**, 933 (2008) [*Quantum Electron.*, **38**, 933 (2008)].
9. Khurgin J.B., Jin F., Solyar G., Wang C.C., Trivedi S. *Appl. Opt.*, **41**, 1095 (2002).
10. Lai N.D., Brunel M., Bretenaker F., Floch A.L. *Appl. Phys. Lett.*, **79**, 1073 (2001).
11. Yan P., Tian X., Gong M., Xie T. *Opt. Eng.*, **44**, 14201 (2005).
12. Degnan J.J. *IEEE J. Quantum Electron.*, **31**, 1890 (1995).
13. Afzal R.S., Yu A.W., Zayhowski J.J., Fan T.Y. *Opt. Lett.*, **22**, 1314 (1997).
14. Zverev G.M., Golyaev Yu.D. *Lazery na kristallakh i ikh primenenie* (Crystal Lasers and Their Applications) (Moscow: Radio i Svyaz', 1986).