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Lasing dynamics of diode-pumped Yb–Er laser with a passive *Q* switch exposed to high-power external light

E.O. Batura, Yu.K. Bobretsova, M.V. Bogdanovich, D.A. Veselov,
A.V. Grigor'ev, V.N. Dudikov, A.M. Kot, N.A. Pikhtin,
A.G. Ryabtsev, G.I. Ryabtsev, S.O. Slipchenko, P.V. Shpak

Abstract. **The temporal dynamics of diode-side-pumped Yb–Er laser, with a passive $Co^{2+}:MgAl_2O_4$ *Q* switch illuminated by a light beam (total fluence of 0.15–0.16 J cm^{-2}) from a semiconductor pulsed module, is investigated. It is shown that, using this external illumination, one can change the lasing onset delay and the time jitter ΔT_{gi}. The dependence of ΔT_{gi} on the interval between the instant of switching the illumination module on and the lasing peak position t_i has a minimum at $|t_i| \approx 10$ μs. The decrease in ΔT_{gi} with a change in $|t_i|$ from 90 to 10 μs indicates that instant of lasing peak occurrence for the Yb–Er laser is partially controlled by the pulse from the highly stable semiconductor module. If $|t_i| < 10$ μs, the enhanced luminescence fluence in the cavity of Yb–Er laser exceeds 0.16 J cm^{-2}; the light beam from the module does not affect much the lasing process in the ytterbium–erbium laser; and, as a consequence, the time jitter recovers the initial value.**

Keywords: *solid-state laser, diode pumping, semiconductor laser module, passive Q switching, pulse jitter.*

1. Introduction

Pulsed diode-pumped erbium lasers, which emit in the conditionally eye-safe spectral range of 1.53–1.54 μm, are promising radiation sources for range finding and spectroscopy devices [1–5]. Among emitters of this type, compact transversely pumped Yb–Er : glass lasers have become popular [2, 4, 6]. To minimise device sizes, the laser *Q*-switching regime is generally set using bleachable passive *Q* switches [1, 2, 4], for example, those based on $LiGa_5O_8$, $LaMgAl_{11}O_{19}$, or $MgAl_2O_4$ crystals [7].

One of the drawbacks typical of solid-state passively *Q*-switched lasers is the significant temporal instability of lasing pulse onset (time jitter) [8], which is caused by variations in the intensity and spatial and/or spectral pump parameters, effect of spontaneous noise on the active medium, and intermodal coupling processes. As was shown in [9–12], the laser time jitter can be significantly reduced using modulation of pump power by rectangular pulses, application of two synchronised laser channels, and external illumination of passive *Q* switch. The published results of the research in this field concern solid-state Nd : YAG or ruby lasers with passive *Q* switches based on Cr^{4+} : YAG, F_2^- : LiF crystals or on dye solutions.

The purpose of this work was to investigate the temporal dynamics of diode-side-pumped Yb–Er laser with a passive *Q* switch exposed to a focused high-power external light beam. A $Co^{2+}:MgAl_2O_4$ crystal, which is widely applied in modern portable erbium lasers, played the role of the passive *Q* switch. The light beam was generated by a pulsed module based on semiconductor lasers with an ultranarrow waveguide, integrated with the pump current board.

2. Experimental setup and measurement technique

A schematic diagram of the setup for studying the temporal dynamics of a diode-side-pumped Yb–Er laser with illuminated passive *Q* switch is presented in Fig. 1. The active element (AE) was transversely pumped by a set of laser diode bars (LDBs) DPM-70-940 (Research and Production Enterprise Inject Ltd, Saratov). The LDBs were excited by (4–5)-ms current pulses at a pulse repetition rate of 2 Hz. The AE of rectangular cross section (1.5 × 2.0 × 35 mm) was made of (Yb–Er) : phosphate glass of LGS-DE grade (Fryazino Branch of the Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Science, Fryazino, Moscow region). The ytterbium and erbium ion concentrations were, respectively, 1.8×10^{21} and 3.0×10^{19} cm^{-3}. The laser cavity was formed by plane mirrors (*2* and *3*). The modulated *Q*-factor regime was provided by bleaching the $Co^{2+}:MgAl_2O_4$ *Q* switch having an initial transmittance of 75%. At room temperature the operating value of pulse energy at the Yb–Er laser output was 10 mJ, the wavelength was 1.54 μm, and the pulse width was 16 ns. The external illumination of $Co^{2+}:MgAl_2O_4$ *Q* switch was performed using a pulsed module (*15*) based on laser diodes with an ultranarrow waveguide [13]. Its 900-ns pulses with an energy of 13 μJ were focused by an optical system (*16*) on the surface of passive *Q* switch in the form of a round spot (less than 100 μm in diameter) in the vicinity of laser mode centre with a diameter of ~700 μm. The

E.O. Batura, M.V. Bogdanovich, A.V. Grigor'ev, V.N. Dudikov, A.M. Kot, A.G. Ryabtsev, G.I. Ryabtsev, P.V. Shpak Stepanov Institute of Physics, National Academy of Sciences of Belarus, prosp. Nezavisimosti 68, 220072 Minsk, Belarus;
Yu.K. Bobretsova, D.A. Veselov, N.A. Pikhtin, S.O. Slipchenko Ioffe Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, 194021 St. Petersburg, Russia; e-mail: bobre-yulya@yandex.ru

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spot diameter was measured at a level of 0.5 of the maximum intensity using a high-resolution camera; the measurement error did not exceed 10 %. The pulsed module radiation wavelength was varied within 1.54 – 1.57 μm, depending on the LDB module temperature and the excitation level. This wavelength range falls in the wide maximum of the absorption band of $Co^{2+}:MgAl_2O_4$ crystal, determined by the optical transition $^4A_2 \rightarrow {}^4T_1(^4F)$ (Fig. 2).

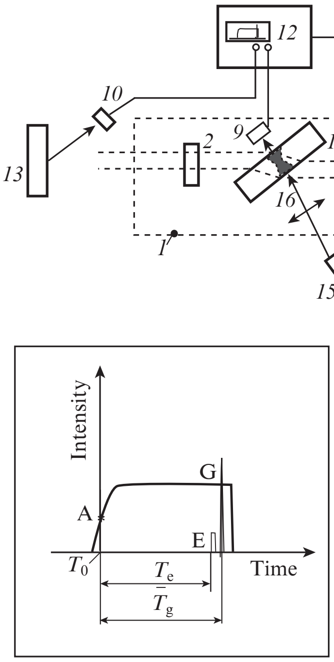

Figure 1. Optical scheme of the setup for studying the temporal dynamics of diode-side-pumped Yb – Er laser under conditions of passive-Q-switch illumination: (*1*) laser housing; (*2*) flat semitransparent output mirror; (*3*) flat highly reflecting mirror; (*4*) LDB pump unit; (*5*) LDBs; (*6*) phosphate Yb : Er : glass AE; (*7*) LDB unit radiation (940 – 950 nm); (*8*, *9*, *10*) high-speed photodiodes; (*11*) clock generator; (*12*) digital multichannel oscilloscope; (*13*) laser pulse energy meter; (*14*) passive Q switch ($Co^{2+}:MgAl_2O_4$ crystal); (*15*) pulsed illumination module; and (*16*) focusing optics. The inset shows the shape of the pump unit emission pulse (940 – 950 nm), recorded by photodiode *8*; the letters G and E denote the pulses from the Yb – Er laser (1534 nm) and illumination module, respectively; A is the reference point for time intervals.

The temporal dynamics of Yb – Er laser with an illuminated passive Q switch was investigated in the following way. The AE was excited by pump pulses (Fig. 1, inset) with simultaneous triggering (using photodiode *8*) of a clock generator (*11*) at the instant T_0. Since the instant of bleaching of a passive Q switch (*14*) with subsequent lasing development is not set by any auxiliary elements, the reference point T_0 of time intervals was taken to be (using a specialised program) point A on the linear portion of the pump-pulse leading edge (see inset in Fig. 1). Stabilisation of the Yb – Er laser temperature and electrical parameters of a pump unit (*4*) provided high pulse shape reproducibility and reduced the error in setting the point A to ± 50 ns.

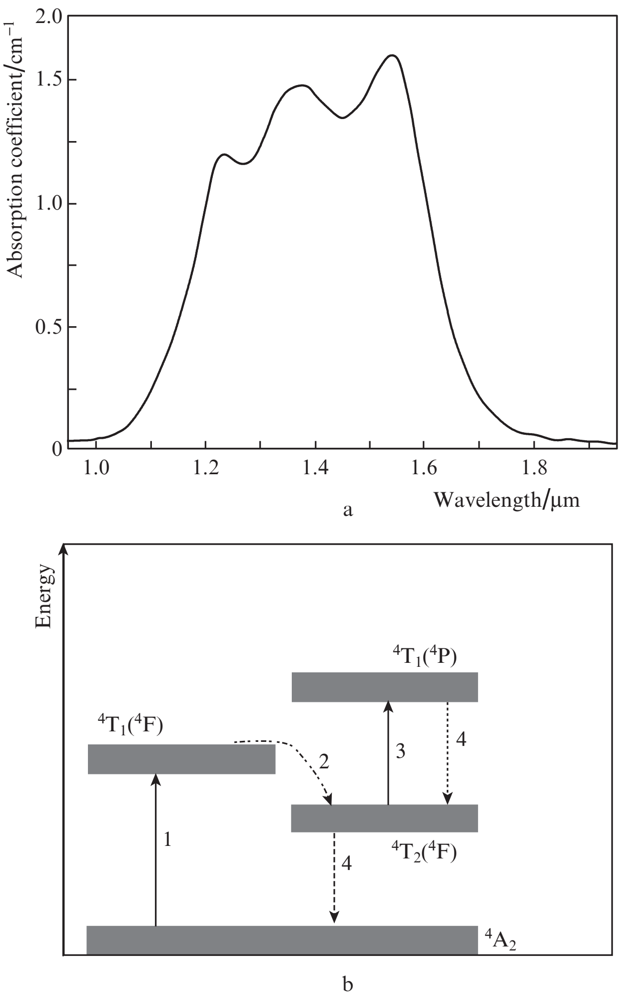

Figure 2. (a) Absorption spectrum and (b) energy-level diagram of the passive Q switch based on a $Co^{2+}:MgAl_2O_4$ crystal in the near-IR spectral range [7, 14 – 17].

Sync pulses from the generator (*11*) were used for triggering a multichannel oscilloscope (*12*) and a pulsed illumination module (*15*); the illumination module triggering was programmably delayed by time T_{ei} with respect to the AE excitation onset T_0. The laser pulse instant was determined by the intense peak of radiation (denoted by letter G in the inset in Fig. 1) scattered from the surface of an energy meter (*13*) towards photodiode *10*.

In the initial stage of experiments, the mean time $\bar{T}_{g0}$ of lasing peak occurrence was measured for a series of several tens of thousands of Yb – Er laser pulses. The time jitter ΔT_{g0} of the Yb – Er laser for the series was determined as the rms deviation of the instant of lasing peak occurrence from the $\bar{T}_{g0}$ value (Fig. 3, point P). After a time $T_{ei} < \bar{T}_{g0}$ the pulsed illumination module was switched on, and the mean time $\bar{T}_{gi}$ and time jitter ΔT_{gi} were also recorded for the chosen experimental configuration. The T_{ei} values were chosen so as to make the absolute value of the difference $t_i = T_{ei} - \bar{T}_{g0}$, which determines the time interval between the instant of illumination module switching on and the instant $\bar{T}_{g0}$ of lasing peak occurrence, lie within 9 – 90 μs.

The dependence of the difference in the mean times of lasing onset without illumination and with external pulsed illumination of the passive Q switch, $T_{dif} = \bar{T}_{g0} - \bar{T}_{gi}$, on the variable t_i is shown in Fig. 3, along with the time jitter ΔT_{gi} of the Yb – Er laser as a function of variable t_i under conditions of the passive Q switch external illumination.

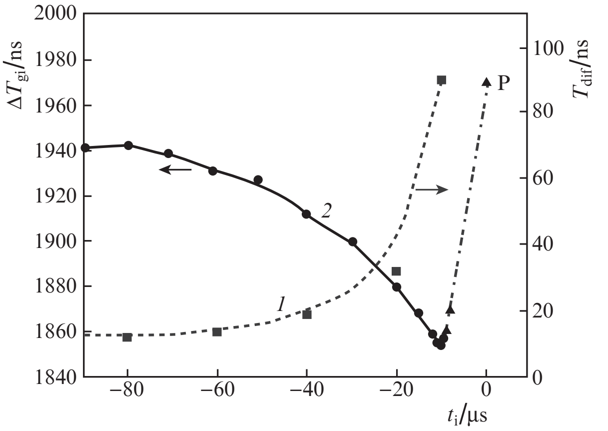

Figure 3. Dependences of the (*1*) time interval T_{dif} between the mean values $\bar{T}_{g0}$ and $\bar{T}_{gi}$ and (*2*) the time jitter ΔT_{gi} on the parameter t_i; point P indicates the initial value of time jitter.

3. Results and discussion

The semiconductor pulsed module [13] used by us emits in the wavelength range of 1.54–1.57 μm, which falls entirely in the wide IR absorption band of $Co^{2+}:MgAl_2O_4$ crystal. The absorption channel in this spectral range is set mainly by the parameters of the transition of Co^{2+} ion from the ground (lower) state $^4A_2$ to the upper wide level $^4T_1(^4F)$ with subsequent fast transition to the $^4T_2(^4F)$ level [7]. The ratio of the absorption cross sections for the $^4A_2 \rightarrow {}^4T_1(^4F)$ и $^4T_2(^4F) \rightarrow {}^4T_1(^4P)$ transitions at a wavelength of 1.54 μm is 0.03. The lifetimes for the $^4T_1(^4F)$ and $^4T_2(^4F)$ levels are 15 and 350 ns, respectively.

Approximately, with the absorption from the excited state $^4T_2(^4F)$ disregarded, the bleaching of the passive *Q* switch of erbium laser can be presented within the approach taking into consideration the ground (lower) level $^4A_2$ and the upper wide level as a combination of $^4T_1(^4F)$ and $^4T_2(^4F)$ levels. According to the calculated and experimental data of [7, 18], the absorption coefficient of this 'quasi-two-level' system, reduced to the initial value, decreases by 15%–20% even at total energy fluences $S = 0.15$–0.20 J cm^{-2}.

Since the *S* value for the pulsed illumination module is about 0.15–0.16 J cm^{-2}, we can suggest that the optical losses of erbium laser decrease to some extent as a result of the $Co^{2+}:MgAl_2O_4$ *Q* switch illumination. For this reason the lasing peak arises at the instant $\bar{T}_{gi} < \bar{T}_{g0}$. While the $|t_i|$ shifts to zero, the role of the optical transitions related to the *Q* switch bleaching by the pulsed module light in the development of Yb–Er laser generation becomes more and more important. Curve *1* in Fig. 3 rapidly rises when the t_i modulus approaches 20–30 μs. According to the results of numerical calculations of the Yb–Er laser characteristics, performed for the model taking into account the spatial cavity properties, the gain becomes comparable in order of magnitude with the optical losses at $|t_i| < 20$ μs, and an enhanced luminescence flux is formed. This leads to dominance of passive *Q* switch bleaching during lasing.

As follows from the joint analysis of curves *1* and *2* in Fig. 3, the pulsed module illumination affects not only the lasing onset delay time (the T_{dif} value increases while t_i approaches zero) but also the time jitter ΔT_{gi}. The dependence of ΔT_{gi} on t_i has a pronounced minimum at $|t_i| \approx 10$ μs. The decrease in the time jitter with a change in t_i from 90 to 10 μs is due to the fact that the lasing onset instant for the Yb–Er laser in this range of t_i values is partially controlled by the pulse emitted by the highly stable semiconductor module.

The time jitter of the pulsed illumination module did not exceed 10 ns; therefore, the relatively large time jitter of the Yb–Er laser in the minimum of the dependence $\Delta T_{gi}(t_i)$, equal to 1854 ns, is most likely due to the active-medium excitation instability. When $|t_i| < 10$ μs, the intensity of enhanced luminescence flux in the cavity of Yb–Er laser sharply increases, reaching (according to the numerical calculation data) 15–20 J cm^{-2} at $|t_i| < 0.5$ μs. Under these conditions, the pulsed module illumination does not affect much the lasing of the Yb–Er laser, and the time jitter recovers the initial value (point P in Fig. 3).

Note that, for light fluences above 0.15 J cm^{-2} but shorter (e.g., 100-ns) pulses, the *Q* switch illumination did not affect the Yb–Er laser characteristics in the entire range of t_i values from 9 to 90 μs. A possible reason is that the laser pulse development time (3–5 μs) exceeds significantly the illumination time in this case.

4. Conclusions

The temporal dynamics of a diode-side-pumped Yb–Er laser was investigated under conditions of exposure of a passive *Q* switch to a focused light beam from a high-power external illumination module. A $Co^{2+}:MgAl_2O_4$ crystal was used as a passive *Q* switch. It was found that the *Q* switch illumination by a pulsed module with an integral energy fluence of 0.15–0.16 J cm^{-2} affects the lasing onset delay time for the Yb–Er laser and its time jitter ΔT_{gi}, whose dependence on the time interval between the instants of module switch-on and lasing peak has a minimum at $|t_i| \approx 10$ μs. The decrease in the time jitter with a change in $|t_i|$ from 90 to 10 μs is due to the fact that the lasing peak instant for the Yb–Er laser in this range of t_i values is partially controlled by the pulse emitted by the highly stable semiconductor module. The relatively large value of the Yb–Er laser time jitter (1854 ns), observed in the minimum of the dependence $\Delta T_{gi}(t_i)$, is explained by the instability of active-medium excitation processes. When $|t_i| <$ 10 μs, the enhanced-luminescence energy fluence in the (Yb–Er)-laser cavity increases to 15–20 J cm^{-2}, the pulsed module illumination does not affect much the lasing process in the Yb–Er laser, and the time jitter recovers the initial value: 1970 ns.

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