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GENERATION OF SMOOTH MICROSECOND PULSES IN AN YTTERBIUM-DOPED GLASS FIBER LASER

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An active acousto-optic Q-factor modulation in a double-clad ytterbium-doped glass fiber laser has been experimentally implemented and investigated. A repetitive generation of smooth long (2-μs) pulses is attained. The parameters of the laser-pulse train generated are estimated. Based on numerical modeling, the main mechanisms responsible for the laser operation studied are explained.

INTRODUCTION

Double-clad ytterbium-doped glass fiber lasers are of great practical interest as pumping sources for Raman lasers and amplifiers [1–5]. In this work, we have studied an active Q-factor modulation in an ytterbium-doped glass fiber laser. Fiber lasers differ from cavity lasers by a substantially longer resonator length which reaches a few tens of meters. This is responsible for the long decay time of the field in the resonator and for some specific features of the lasing dynamics. The long resonator length of fiber lasers makes them capable of repetitive-pulse operation with a relatively long pulse duration. We note that to attain a regular train of pulses of microsecond duration in ordinary lasers requires application of special negative feedback systems or complex resonator Q-factor modulation algorithms. In the present work, we have implemented a repetitive Q-switched mode in a double-clad ytterbium-doped glass fiber laser.

EXPERIMENTAL

The experimental setup shown in Fig. 1 is similar to that used in [4], except that the exit end of the fiber laser in our experiment terminated in the gradient-index lens *4*. This allowed us to materially

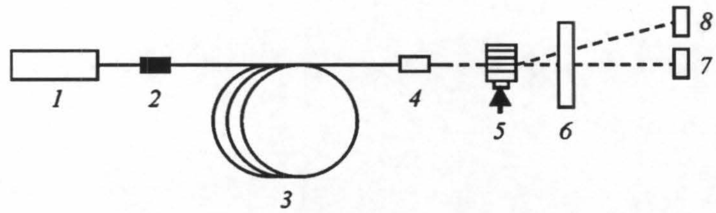

Fig. 1

Optical scheme of the experimental setup: (*1*) semiconductor pumping laser ($\lambda = 978$ nm) with output fiber; (*2*) Bragg angle diffraction grating; (*3*) double-clad ytterbium-doped glass fiber (30 m); (*4*) gradient-index lens; (*5*) acousto-optic modulator (Q-switch); (*6*) external mirror; (*7*) photoreceiver; (*8*) photoreceiver.

reduce the radiation divergence and to exclude the collimating lens from the optical system of the Q-factor modulator. Measurements showed that the radiation divergence amounted to 0.003 rad, which was much less than the aperture of the light-guide glass fiber equal to 0.17 rad.

The acousto-optic Q-switch *5* used was a quartz plate to which a 50-MHz signal was applied in a repetitive-pulse mode with controlled pulse repetition frequency (from 15 to 50 kHz) and relative pulse duration. 80% of the radiation intensity incident on the Q-switch was deflected into the first diffraction order. The Q-switch on and off time was 0.1 μs.

The radiation that had passed through the acousto-optic Q-switch partially reflected from an additional external mirror *6* with a reflection coefficient $R = 40\%$. The distance from the external mirror to the gradient-index lens *4* was equal to 85 mm. With the mirror properly adjusted, the radiation got back into the fiber. The external mirror thus served as an additional element of the laser resonator.

RESULTS

The watt-ampere characteristic of the laser, measured under continuous-wave operating conditions, with the gradient-index lens used but without the external mirror, is presented in Fig. 2. The maximal power of the laser operated in the continuous-wave mode $P_{\text{cont}} = 0.18$ W.

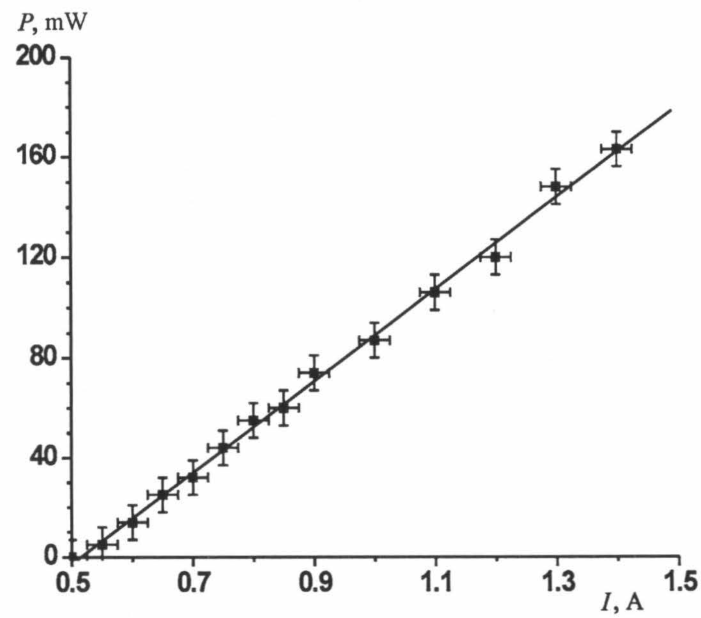

Fig. 2

Watt-ampere characteristic of the ytterbium-doped glass fiber laser at the gradient-index lens output.

Figure 3*c* presents a typical $P_{\text{pulse}}(t)$ oscillogram of pulses generated in the repetitive Q-switched mode, obtained with a Model ACK-3151 dual-beam digital-storage virtual oscilloscope. The measurements showed that the laser-pulse duration at the $P_{\max}/2$ level in the Q-switched mode amounted to 2 μs. It also follows from Fig. 3*c* that the pulse substantially lagged (for some 10 μs) behind the switch-off instant of the acousto-optic modulator.

Varied in the experiment was not only the operating frequency of the Q-switch, but also the relative duration of the pulses applied to it. It turned out that the pulse-delay time τ_{del} strongly depended on the Q-switch off time. The pertinent plot is presented in Fig. 4. It can be seen from this plot that the pulse-delay time varied in the range 10.5–17.5 μs.

Finally, Fig. 5 presents the experimentally measured frequency dependence of the ratio $P_{\text{pulse}}/P_{\text{cont}}$ (where P_{pulse} is the maximal pulse power in the Q-switched mode under continuous pumping conditions

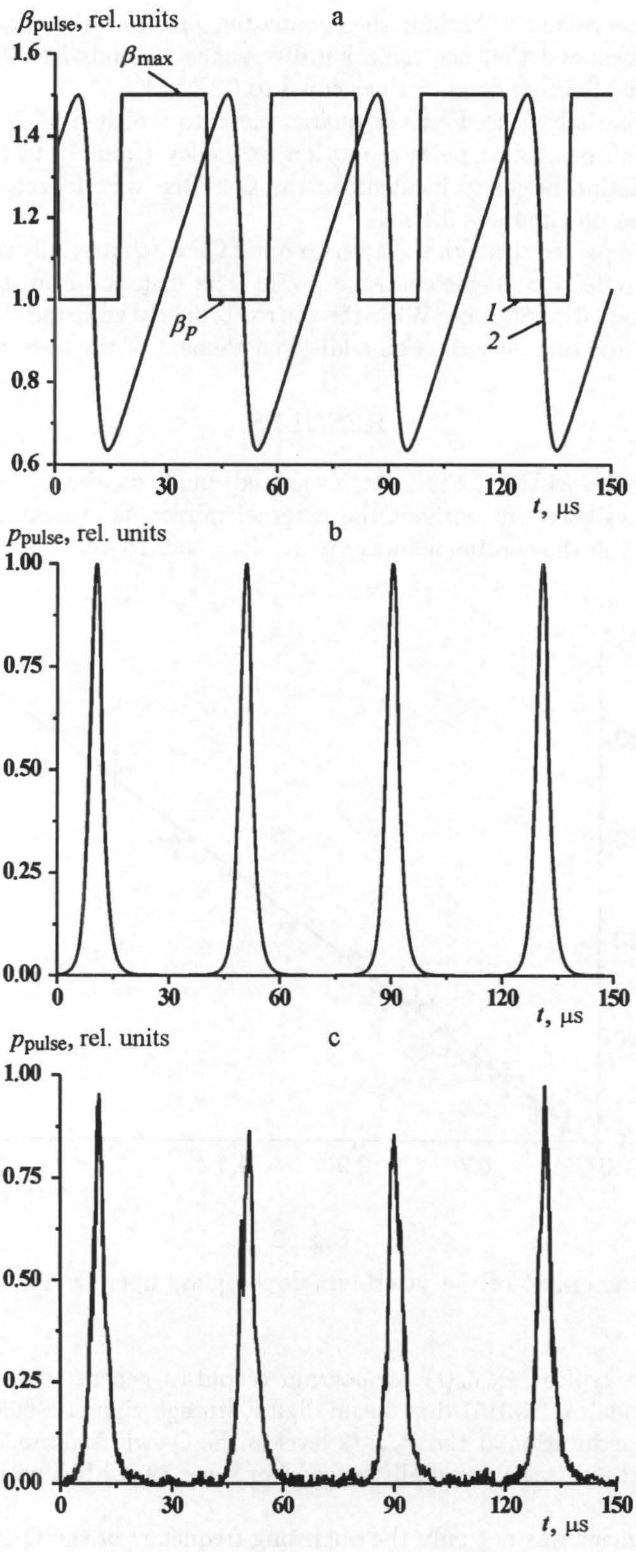

Fig. 3

(a) Time dependences of lasing threshold (curve *1*) and gain (curve *2*); (b) theoretical laser-pulse oscillogram; and (c) experimental laser-pulse oscillogram. Q-switch operating cycle period $T = 40.4$ μs, Q-switch off time $\tau = 16.8$ μs, semiconductor pump laser current $I = 0.74$ A.

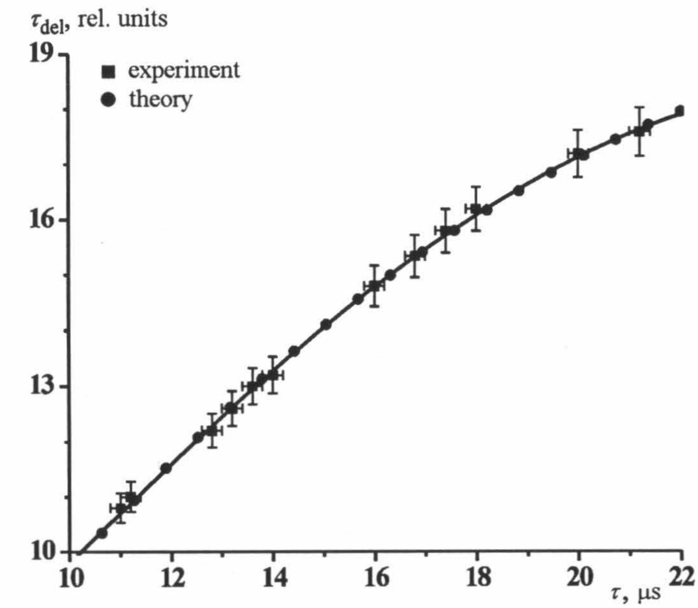

Fig. 4

Pulse-delay time τ_{del} as a function of the Q-switch off time τ.

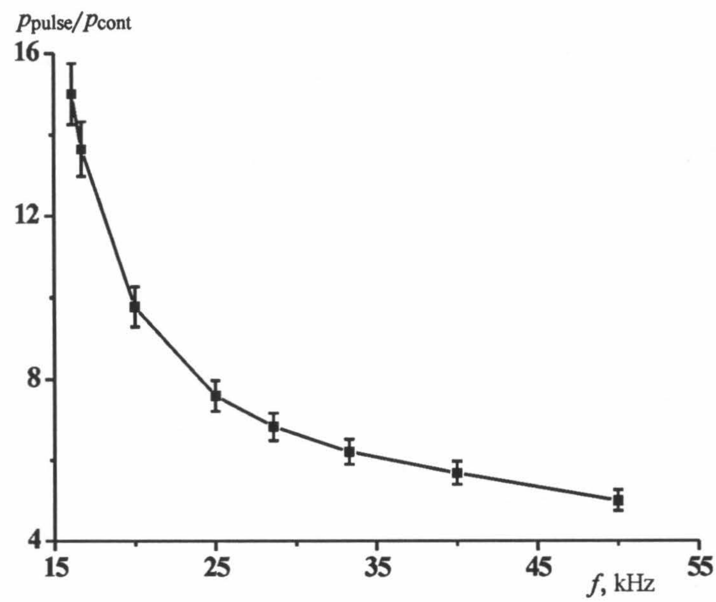

Fig. 5

P_{pulse}/P_{cont} as a function of the modulation frequency. The pump current was adjusted so as to attain maximal pulse power.

and P_{cont} is the laser power in the continuous-wave mode in the absence of the external mirror under the same pumping conditions). It follows from Fig. 5 that in the frequency range from 15 to 50 kHz the peak pulse power, which we estimated at 0.5 W, could be 5–15 times as high as the power output of the original laser in the continuous-wave mode.

DISCUSSION OF THE RESULTS

The results obtained were analyzed on the basis of the known kinetic equations for the four-level laser, with due regard given for the specific features of the experimental setup [6]

$$\frac{d\beta}{dt} = [x\beta_p - \beta]\frac{1}{\tau} - \Phi\beta\frac{c\sigma}{V}, \tag{1}$$

$$\frac{d\Phi}{dt} = \left\{\left[e^{2l\beta}e^{-2\alpha L}R(t) - 1\right]\Phi + \xi\right\}\frac{c}{2nL}. \tag{2}$$

Here β is the gain averaged over the length of the active sample; $x = W/W_p$ is the ratio between the pumping rate and the threshold pumping rate; $\beta_p = 9\times10^{-2}$ m^{-1} is the threshold gain; $\sigma = 0.25\times10^{-24}$ m^2 is the cross section of the stimulated transition between the laser levels [6]; $\tau = 10^{-3}$ s is the relaxation time of the upper laser level [7]; Φ is the number of photons averaged over the length of the resonator; $\xi = 1$ is the term characterizing the spontaneous emission of radiation; $e^{-2\alpha L} = 0.86$ is the double-pass radiation loss of the fiber laser; $V = \frac{\pi r_0^2}{2}L = 3\times10^{-10}$ m^3 is the effective resonator mode volume; $L = (30+2)$ m is the resonator length (30 m is the length of the ytterbium-doped glass fiber and 2 m is the length of the technological fiber segment); $l = 10$ m is the length of the active fiber segment; and $R(t)$ is the reflection coefficient of the composite output reflector constituted by several reflective surfaces, namely, the output face of the gradient-index lens and the external mirror, with the acousto-optic Q-switch between them. In the general case, the reflection coefficient $R(t)$ varies with time, because of the variation of the transmission coefficient of the Q-switch, as $R(t) = \left(\sqrt{R_1} + \sqrt{R_2}\,T(t)\right)^2$, where R_1 is the coefficient of reflection from the end face of the gradient-index lens, R_2 is the reflection coefficient governed by the external mirror and the parameters of the acousto-optic Q-switch, and $T(t)$ is the Q-switch state function. This function was approximated by the following expression:

$$T(t) = \begin{cases} T_2 + \frac{1}{2}\left\{1 + \sin\frac{\pi(t - mT - 0.5\tau_1)}{\tau_1}\right\}(T_1 - T_2), & mT \le t < mT + \tau_1, \\ T_1, & mT + \tau_1 \le t < mT + \tau, \\ T_1 + \frac{1}{2}\left\{1 + \sin\frac{\pi(t - (mT + \tau) - 0.5\tau_2)}{\tau_2}\right\}(T_2 - T_1), & mT + \tau \le t < mT + \tau + \tau_2, \\ T_2, & mT + \tau + \tau_2 \le t < (m+1)T, \end{cases} \tag{3}$$

where T is the Q-switching period, τ_1 and τ_2 are the leading and trailing edges of the Q-switch pulse, respectively, $T_1 = 1$ — the Q-switch is off, $T_2 = 0.2$ — the Q-switch is on.

The ratio between the threshold laser gain values with the acousto-optic Q-switch on and off was calculated on the basis of the relations

$$\left(\sqrt{R_1} + \sqrt{R_2 T}\right)^2 e^{-2\alpha L}e^{2\beta_p l} = 1, \tag{4}$$

$$\left(\sqrt{R_1} + \sqrt{R_2 T_2}\right)^2 e^{-2\alpha L}e^{2\beta_{\max} l} = 1, \tag{5}$$

to be $\beta_{\max}/\beta_p \cong 1.5$.

Equality (4) refers to the case where the Q-switch is off and (5) to that where the Q-switch is on.

The threshold laser gain levels are illustrated in Fig. 3*a* (curve *1*). The unit of measurement is taken to be the threshold gain of the laser with the external mirror (Q-switch is off). When the Q-switch is on (the resonator Q-factor is low, the threshold gain ratio $\beta_{\max}/\beta_p \cong 1.5$), the semiconductor laser radiation pumps the fiber laser. In that case, the inverted population, hence the gain, of the fiber laser rise as illustrated by curve *2* in Fig. 3*a*.

Let us estimate the pulse duration τ_{pulse} at the $P_{\max}/2$ level in the Q-switched mode. Assuming that the terms in equation (1) that are responsible for pumping and spontaneous emission of radiation vary but little during the pulse, so that they can be disregarded [8], we get

$$\tau_{\text{pulse}} = \tau_c\frac{(\beta_{\max}/\beta_p)\eta_E}{(\beta_{\max}/\beta_p) - \ln(\beta_{\max}/\beta_p) - 1}, \tag{6}$$

where $\tau_c = 0.18$ μs is the photon lifetime in the resonator and $\eta_E = 0.6$ is the inversion utilization factor.

Hence the pulse duration $\tau_{\text{pulse}} = 1.6\ \mu$s, which differs by 20% from the experimentally measured value of 2 μs.

As for the estimation of the pulse delay relative to the acousto-optic modulator switch-off instant, our analysis showed that the approximations made in equation (1) led to excessively large errors. For this reason, equations (1) and (2) were numerically solved, with due regard for expression (3), without using the approximations made in deriving expression (6), for several parameters of the pulse train being generated. We computed the time variation of the laser gain, the pulse delay relative to the acousto-optic modulator switch-off instant, and the pulse duration. The last two parameters were compared with the experimentally measured data. In all cases, a good agreement (with an accuracy no worse than 5%) was observed between the experimental and theoretical results. As an illustration, Fig. 3 presents the time dependences of the laser gain (Fig. 3*a*, curve *2*) and laser pulse (Fig. 3*b*).

Figure 4 presents the delay of the pulse maximum relative to the acousto-optic modulator switch-off instant as a function of the modulator off time τ. It follows from the figure that the experimental and theoretical data points fit the delay curve well enough. Comparison between Figs. 3 and 4 shows that as τ is increased, the excess of pumping above the threshold at the acousto-optic modulator switch-off instant decreases, which leads to the increase of the pulse delay. In numerical modeling, we also achieved a good (accurate to within 5%) agreement between the theoretical and experimental pulse delay values (Fig. 3*b* and *c*).

Finally, the character of the dependence presented in Fig. 5 is explained by the fact that the pulse power remained unchanged, no matter what the Q-switching frequency, for it was governed by the ratio between the threshold gain values with the Q-switch on and off. At the same time, as the Q-switching frequency was increased (period decreased), progressively greater pump current was required to attain the maximal pulse power, which was tantamount to increasing the laser power in the continuous-wave mode and reducing the $P_{\text{pulse}}/P_{\text{cont}}$ ratio.

CONCLUSIONS

Thus, in this work we have experimentally implemented a repetitive Q-switched mode in a double-clad ytterbium-doped glass fiber laser continuously pumped by a semiconductor laser.

Laser pulses with a duration of 2 μs were obtained in the frequency range 15–50 kHz at a peak power from 5 to 15 times higher than the laser power in the continuous-wave mode.

The use of a gradient-index lens allowed us to substantially simplify the experimental setup, namely, to exclude the collimating optical elements and precision three-coordinate adjusting device.

We have found that the short-pulse approximation frequently used to describe lasing in the Q-switched mode is inapplicable in the case of relatively long, microsecond pulses characteristic of fiber lasers.

Our estimates of the parameters of the laser-pulse trains generated and numerical modeling results allowed us to explain the main mechanisms responsible for the laser operation studied.

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