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Compact high-power sources of nanosecond laser pulses (940 nm) based on „semiconductor laser–thyristor switch“ vertical stacks

© S.O. Slipchenko [1], A.A. Podoskin [1], I.V. Shushkanov [1], A.E. Rizaev [1], M.I. Kondratov [1], N.A. Rudova [1], V.A. Strelets [1], N.V. Shuvalova [1], A.E. Grishin [1], T.A. Bagaev [2], M.A. Ladugin [2], A.A. Marmalyuk [2], N.A. Pikhtin [1]

[1] Ioffe Institute, St. Petersburg, Russia
[2] „Polyus“ Research Institute of M.F. Stelmakh Joint Stock Company, Moscow, Russia
E-mail: SergHPL@mail.ioffe.ru

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High-power ns-duration laser pulse sources based on vertical stacks of „semiconductor laser–thyristor switches“ emitting at the wavelength of 940 nm have been developed and studied. The possibility to increase the peak power to 45.6 W and reduce pulsewidth to 2.25 ns by using a 400 μm-wide monolithic emitting aperture design has been demonstrated. For the developed sources, the lasing turn-on non-uniformity along the emitting aperture has been reduced to 50–80 ps.

Keywords: current switch, semiconductor laser, thyristor, vertical stack.

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Compact sources of short laser pulses are in demand for a number of practical applications. Nowadays, such sources are actively used to create automotive lidars that provide three-dimensional images of the surrounding space. This allows formulating requirements for their emission characteristics. Using silicon to create photodetectors, it is possible to make the recording unit more affordable than InGaAs-based detectors; this determines the optical source's operating spectral range as $\sim 850{-}950$ nm. Other important characteristics are the laser pulse duration and peak power. Optical pulse duration determines the system resolution. However, efficient receivers for recording low-power subnanosecond optical signals have a small receiving area, which restricts the possibility of detecting low-power optical signals. In this case, optical pulses a few nanoseconds in duration are a compromise solution. At the same time, to increase the range and signal–noise level, it is necessary to increase the laser pulse peak power. Papers [1,2] have demonstrated for emitters designed as stacks of current switches and chips based on a heterostructure with three laser parts and two tunnel $p{-}n$-junctions optical pulses 1.5 and 1.92 ns in duration. The total output optical power reached 135 and 184 W, respectively; relevant values calculated per a single-laser heterostructure were 45 and 61 W. However, the current switches used to generate the pump current pulses needed high power-supply voltage of up to 300 V. In [3], the pulse duration was reduced to 1.1 ns, while optical power from a single laser section exceeded 30 W at the total emitter power of 92 W. The power-supply voltage was reduced but still was as significant as 110 V. Paper [4] demonstrated that the use of GaAs/AlGaAs thyristor current switches in a vertical stack with a laser emitter allowed obtaining from the single laser part laser pulses 3 ns long with the total peak power of 33 W. The power-supply voltage was 55 V, which demonstrates the perspectiveness of using such current switches to create pulsed radiation sources. However, there still remains an unresolved issue of optimizing the design of the semiconductor laser's emitting aperture ensuring the maximum power for the selected current switch design. It has been shown that, in the case of nanosecond laser pulses, the emitting aperture design strongly affects the lasing dynamics because of arising of the effect of turn-on nonuniformity [4–6]. For instance, when an emitting aperture with optically uncoupled waveguides is formed, there arise both the turn-on nonuniformity reaching 160 ps [4] and intensity nonuniformity between the aperture elements [4,5]. If monolithic ultra-wide (e. g. 800 μm) emitting apertures are used, the turn-on nonuniformity only increases [6]. Thus, the presented study was aimed at creating compact sources of high-power nanosecond laser pulses at 940 nm based on the „semiconductor laser–thyristor switch“ vertical stacks and also to investigate the influence of the semiconductor laser's monolithic emitting aperture width on the power and dynamic characteristics in creating the pulse source.

Schematic representation of the experimental source of laser pulses is given in the inset to Fig. 1, *d*. The pulse source has a form of a vertical stack consisting of a thyristor switch and semiconductor laser. The thyristor switches were constructed based on a semiconductor heterostructure grown by vapor-phase epitaxy from metal-organic compounds (MOCVD) on an n-GaAs substrate and consisting of the following layers: n-$Al_{0.1}Ga_{0.9}As$ (0.1 μm, $n = 10^{18}\,cm^{-3}$), p-GaAs (0.1 μm, $p = 10^{18}\,cm^{-3}$), p-GaAs (4 μm, $p = 10^{15}\,cm^{-3}$), n-GaAs (1 μm, $n = 10^{18}\,cm^{-3}$), p-GaAs (0.5 μm, $p = 10^{18}\,cm^{-3}$). The thyristor design

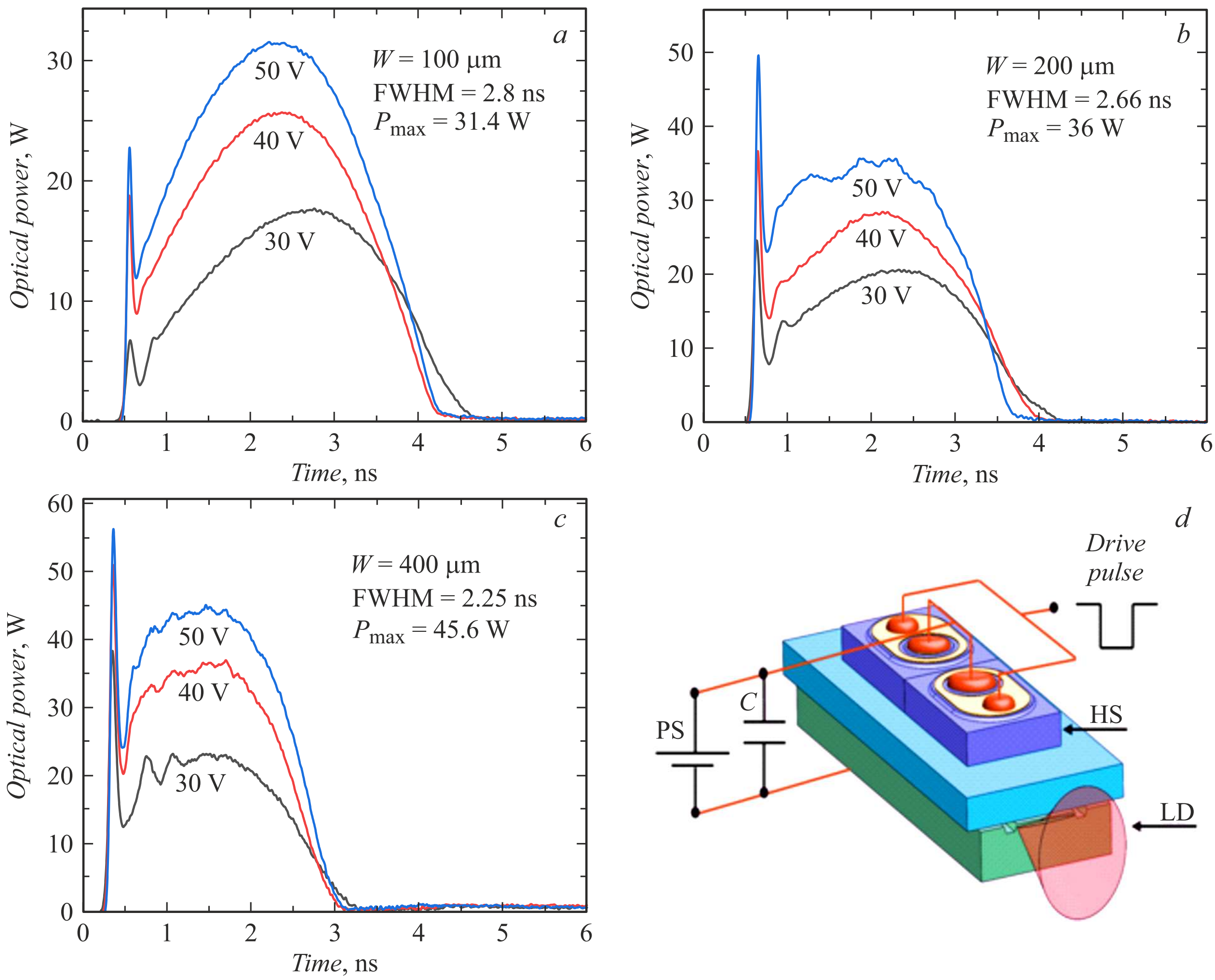

Figure 1. Laser pulses at different operating voltages generated by vertical stacks with the laser-part emitting aperture widths of 100 (*a*), 200 (*b*) and 400 μm (*c*). Panel *d* represents schematically the experimental laser pulse source comprising a laser diode chip (LD) on which a heterothyristor-based current switch, storage capacitor (*C*), power supply (PS) and source of control pulses are mounted.

included an anode contact formed on the top *p*-GaAs layer, control electrode formed on the *n*-GaAs layer, and cathode contact formed on the substrate. The laser heterostructure was grown by MOCVD on the *n*-GaAs substrate and included the following layers: *n*-emitter based on $Al_{0.25}Ga_{0.75}As$, *p*-emitter based on $Al_{0.35}Ga_{0.65}As$, 2 μm thick waveguide based on $Al_{0.2}Ga_{0.8}As$, and InGaAs quantum well located at 0.8 μm from the *p*-emitter. The semiconductor laser's emitting aperture was formed by mesa recesses; in the experimental crystals, the emitting aperture width was 100, 200 and 400 μm. The cavity length was 2 mm for all the crystals. Next, current circuit „semiconductor laser–thyristor switch–capacitor“ was formed by using vertical stacks. The capacitor rating was 1.5 nF, which, as shown below, ensures nanosecond-long optical pulses. Controllable thyristor switch turn-on was performed by using current pulses 200 mA in amplitude. Lasing dynamics was studied at different external-capacitor charging voltages (operating voltages) which provide different amplitudes of the semiconductor laser's pump current pulses generated in the circuit constructed. Fig. 1 demonstrates laser pulses at different operating voltages generated by the developed vertical stacks (in developing, the same optical pulse onset was chosen for each series of samples). At the optical pulse leading edge there was observed a characteristic transient process looking as a short high-power pulse followed by damped oscillations. This transient process is a typical manifestation of the lasing dynamics as a response to drastic variations in the pump current and active-region charge carrier concentration [7]. Dynamic characteristics of the process depend on the rate of pumping conditions variation and parameters of the specific laser cavity. In addition, it is evident that the emitting aperture width significantly affects the lasing dynamics. Variations in the observed optical pulse durations with increasing power-supply voltage are explained by the following factors: 1) variations in the discharge rate of the power-supply capacitor (which is caused, among others, by variations in the thyristor current switch

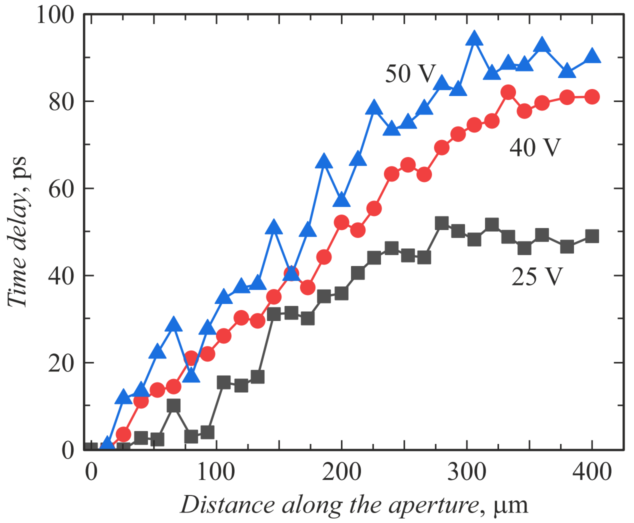

Figure 2. Distributions of the lasing turn-on delay along the emitting aperture measured at different operating voltages for a pulse source with the emitting aperture 400 μm wide.

operation dynamics with varying power-supply voltage); 2) variations in the current pulse amplitude and, hence, in duration of that part of the pulse where instantaneous pump current values exceed the lasing threshold; 3) dependence of dynamics of the lasing turn-on and its delay with respect to the pump current front on the front steepness that also changes with changing power-supply voltage. Thus, a rather complex character of variations in the optical pulse duration gets formed as the power-supply voltage increases. Samples of lasers with the aperture width of 100 μm exhibit the lowest peak power and longest optical pulse duration, which are 31.4 W and 2.8 ns, respectively. Widening of the emitting aperture results in reduction in the optical pulse duration and increase in its peak power: 2.66 ns and 36 W for 200 μm, 2.25 ns and 45.6 W for 400 μm. Reduction in the pulse duration and increase in the peak power may be associated with such factors as resistance, diffusion capacitance, and specific features of lasing turn-on in the gain modulation mode. Here we can analyze those factors only qualitatively; quantitative assessment of each factor's contribution will require both additional numerical simulation and experiments, which is beyond the scope of this short paper. Increase in the current circuit resistance with decreasing emitting aperture width leads to both an increase in the current pulse duration and decrease in the peak current due to an increase in the capacitor discharge time. This is caused by an increase in the *RC* constant characterizing the circuit dynamics. The structure's diffusion capacitance is associated with accumulation of excess charge carriers in the waveguide [8,9]. Hence, as the pump current density increases, the current component responsible for charging the diffusion capacitance increases; this leads to a decrease in the active-region peak pump current for a structure with a narrower emitting aperture. While the cavity length remains constant, widening of the emitting aperture leads to a decrease in the pump current density. As a result, accumulation of the active-region charge carrier concentration takes more time for the lasers being pumped with a lower current density. Hence, the lasing turn-on delay is longer for lasers with a wider emitting aperture, which leads to a decrease in the laser pulse duration.

Another important factor characterizing the lasing turn-on dynamics is the turn-on delay along the emitting aperture. Fig. 2 presents the distributions of lasing turn-on delay along the emitting aperture, which were measured at different operating voltages. One can see that lasing begins from one edge of the emitting aperture. The opposite edge comes into action with delays equal to 50, 90 and 80 ps for operating voltages of 25, 40 and 50 V, respectively. The obtained values are considerably lower than nonuniformity for the emitting apertures 800 μm wide [6], which reached 300 ps.

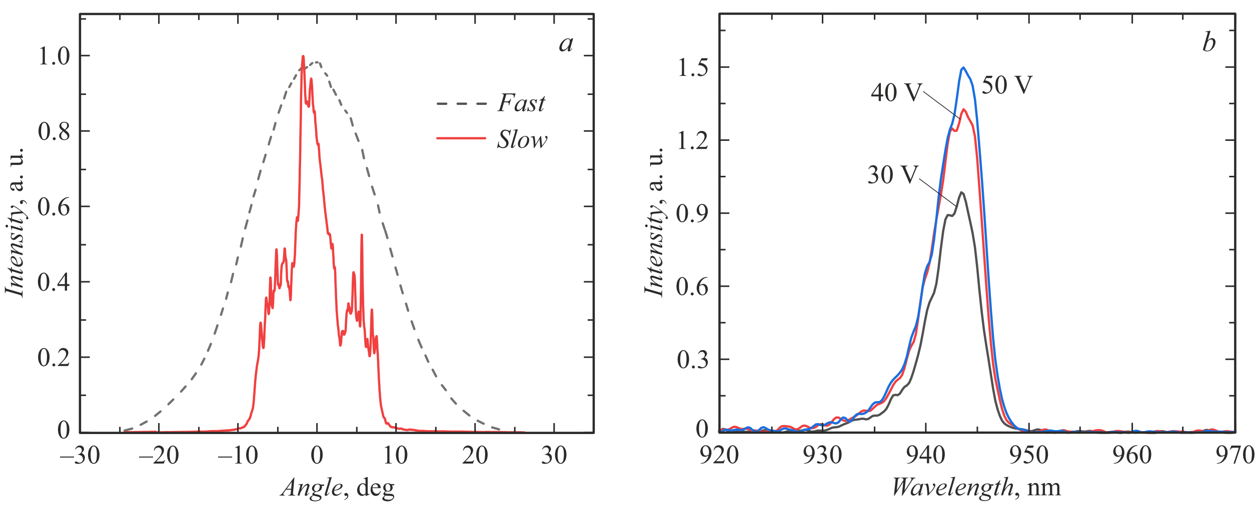

Figure 3. Typical intensity distributions of the perpendicular (along the fast axis) and parallel (along the slow axis) far fields (*a*) and lasing spectra for pulse sources with the emitting aperture 400 μm wide (*b*).

Fig. 3 demonstrates typical distributions of the perpendicular and parallel far fields, as well as lasing spectra for pulse sources with the emitting aperture $400\,\mu$m in width. The measurements show that the fields and spectral characteristics retain their shapes in the operating voltage (pump current) range under consideration.

Note in conclusion that the emitting aperture width is critically important for creating sources of high-power nanosecond laser pulses. By increasing the aperture width, it is possible to improve all the main emission and power characteristics, i.e. to reduce the laser pulse duration and increase the peak optical power. In addition, just the use of monolithic structures allows increasing the turn-on uniformity in terms of both the intensity and turn-on delay time. By optimizing the emitting aperture design, we managed to significantly increase the peak power (from 33 W demonstrated in [4] to 45.6 W in this paper).

Conflict of interests

The authors declare that they have no conflict of interests.

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