

## Compact sources of short (1 ns) laser pulses based on heterothyristor current switches

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Compact pulsed laser sources based on a heterothyristor current switch—laser diode assembly have been developed and investigated. These sources emit at a wavelength of 940 nm. It is shown that the use of heterothyristor current switches with an extended base makes it possible to increase the operating voltage up to 100 V without sacrificing the speed of transient processes. As a result, the possibility of generating laser pulses 1 ns in duration and peak power of 50 W has been demonstrated.

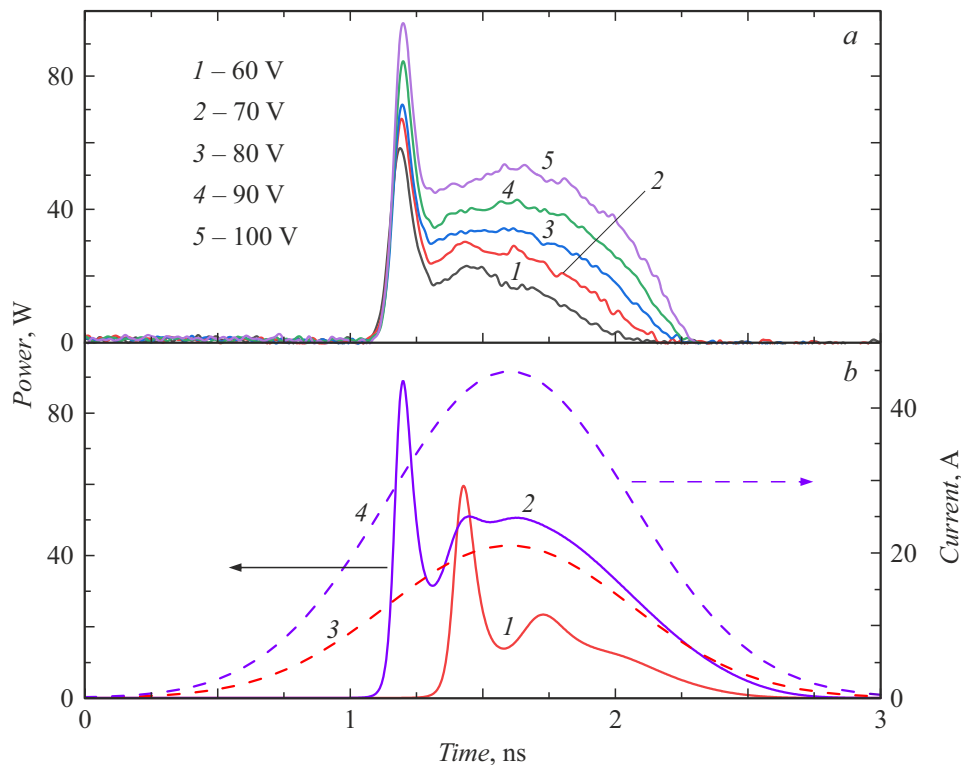
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Sources of laser pulses with nanosecond duration are being actively developed because of a wide range of their applicability: free-space information transmission, range measurement, material processing. However, practical application is associated with a number of requirements, among which are accessibility, compactness, and high peak optical power. While crystals of semiconductor lasers meet these requirements, external electrical systems are still in the stage of active development. At the same time, as concerns powerful laser pulses with durations in the nanosecond range, the electrical and optical parts cannot be considered separately, i.e., the approaches under development should account for their mutual influence. First of all, this means the necessity of searching for solutions ensuring creation of integrated designs that include a high-speed current switch and laser diode crystal. What is important is to ensure the possibility to reduce the duration of laser pulses since this may expand their application areas. By now there have already been demonstrated approaches enabling creation of such sources of pulses of nanosecond durations and peak powers of tens of Watts, whose operating spectral range is 900–1060 nm. In [1], pulsed sources were realized based on laser diodes with the 905 nm wavelength and external circuit formed by GaN field-effect transistors. Note that, depending on the field-effect transistor design, the achievable minimal current pulse durations are 1.96 ns at operating voltages of up to 100 V, current amplitude of 63 A, and form factor of  $1.5 \times 1.5$  mm. It has been also shown that a further increase in the current amplitude may be achieved in the framework of developed solutions by increasing the form factor and operating voltage of the GaN field-effect transistor; however, such variations are accompanied also by pulse broadening.

In addition, let us point to the approaches in which high-speed avalanche S-diodes [2] and bipolar transistors [3] demonstrating current pulses of 17 A/1.2 ns (amplitude/duration) and 40 A/1.1 ns, respectively, are used as high-current switches. Another approach is based on using as high-current switches low-voltage heterothyristors. Paper [4] demonstrates the laser pulse sources based on the low-voltage heterothyristor—laser diode assembly with pulse duration of 2.25 ns and peak power of 45.6 W; if the laser efficiency is 1 W/A, this may be provided by generating in the circuit current pulses with amplitude and duration of about 46 A and 2.3 ns, respectively.

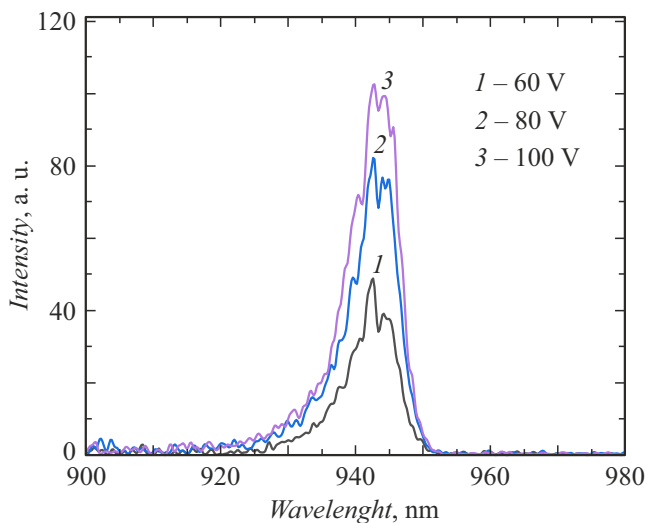
Thus, for a number of approaches being developed, the problem of reducing the laser pulse duration to 1 ns without losing the level of achievable peak powers remains important. In this study, we investigated laser pulse sources created based on the laser diode—thyristor switch assemblies and demonstrating the possibility of reducing duration of current pulse and, hence, laser pulses to 1 ns with simultaneously increasing the achievable peak power. The most widely used circuits for generating short current pulses are those involving a capacitive energy storage device in the form of a capacitor. In this case, the current pulse amplitude and duration will be related to the operating voltage and capacitor value. In a general case, reduction of the current pulse duration in such circuits may be provided at the selected operating voltage by reducing the capacitor value; however, this leads, among others, to a decrease in the current amplitude. Therefore, it is necessary to solve the problem of increasing the rate of transient processes in the circuit. In such circuits, the transient process rates are limited by two factors: (i) parasitic elements of the current



**Figure 1.** *a* — experimentally measured dynamics of the pulse source lasing with the aperture of  $400\mu\text{m}$  at different supply voltages; *b* — optical pulses obtained by using numerical simulation of the lasing dynamics (1, 2) (left axis), and calculated current pulses (3, 4) (right axis) corresponding to operating voltage of 60 (1, 3) and 100 V (2, 4).

circuit; (ii) operation speed of the high-current switch. Experimental studies have shown that negative impact comes from both the active and reactive parasitic elements of the current circuit. The influence of additional ohmic resistance is clearly demonstrated in [5] and manifests itself in an increase in the current pulse duration and decrease in amplitude; this shows the importance in developing current switch designs with low additional resistance. In addition, it is critically important to reduce the parasitic inductance of the current circuit. The search for optimal designs allows reduction of parasitic inductance, but not to zero. For this reason, the task of reducing the current pulse duration without reducing the peak current comes down to simultaneously increasing the operating voltage and reducing the capacitor value. The maximum operating voltage of the thyristor current switch is limited by the maximum blocking voltage at which the thyristor arbitrarily switches to the ON state. The maximum blocking voltage may be increased by expanding the region of the reverse-biased  $p-n$  junction. The performed simulation enabled selection of this region design that is optimal in terms of dynamic characteristics and manufacturing procedure. The main solution is to use a composite  $p$ -base of the thyristor's  $n-p-n$  transistor part. The composite  $p$ -base comprises a heavily doped  $p$  layer which „locks“ the electric field of the reverse-biased  $p-n$  junction and prevents the punch-through effect, as well as a lightly doped  $p$  layer of increased thickness which provides a

field with the peak strength below the breakdown threshold. As a result, heterostructures of semiconductor lasers and thyristors were fabricated using the method of metal-organic vapor-phase epitaxy (MOS-hydride epitaxy). The thyristor heterostructure included the following layers for the  $n-p-n$  transistor part: heavily doped  $n$ -emitter based on  $n\text{-Al}_{0.1}\text{Ga}_{0.9}\text{As}$  ( $n = 10^{18}\text{ cm}^{-3}$ ), composite  $p$ -base based on heavily-doped  $p\text{-GaAs}$  ( $p = 10^{18}\text{ cm}^{-3}$ ) and lightly doped  $p\text{-GaAs}$  ( $p = 10^{15}\text{ cm}^{-3}$ ), heavily doped  $n$ -collector  $n\text{-GaAs}$  ( $n = 10^{18}\text{ cm}^{-3}$ ). For the  $p-n-p$  transistor part, the  $p$  emitter was made based on  $p\text{-GaAs}$  ( $p = 10^{18}\text{ cm}^{-3}$ ). Thicknesses of layers of the composite  $p$ -base were  $0.1\mu\text{m}$  for the heavily doped part and  $8\mu\text{m}$  for the lightly doped part. Then, on the epitaxial-layer side of the planar heterostructure there were formed an anode contact  $200\mu\text{m}$  dia and control-section contact surrounding the anode electrode. The cathode contact was formed on the substrate side. The laser heterostructure had an asymmetric design with the active region based on the InGaAs quantum well. To fabricate laser diode crystals, on the layer side there was created a strip contact forming an emitting aperture  $400\mu\text{m}$  wide, and also a continuous contact on the substrate side. Pulsed laser radiation sources were fabricated in the form of a vertical assembly comprising a semiconductor laser crystal  $2\text{ mm}$  long on which a thyristor switch crystal was mounted. After that, the vertical assembly was soldered onto a copper base, and an electrical circuit was assembled,



**Figure 2.** Lasing spectra for the pulsed source with emitting aperture 400  $\mu\text{m}$  wide at different supply voltages.

which involved a capacitive storage device and contact electrodes for switching with the external power source and generator of control current pulses.

The lasing dynamics was examined using the technique described in [6]. In the course of pilot experiments, we selected the optimal capacitor value (300 pF) providing the optical pulse duration of 1 ns at the maximum peak power. Illustration to the lasing dynamics is given in Fig. 1, *a*. The technique used to measure laser pulses [6] does not imply estimation of the lasing turn-on delay; therefore, leading edges of laser pulses in Fig. 1, *a* are combined artificially. Experiments have shown that there is no lasing at operating voltages below 55 V. However, the thyristor switch turns on efficiently at operating voltages below 55 V, but the number of injected charge carriers is insufficient to meet the lasing threshold conditions. Also clearly visible is a feature of the lasing turn-on dynamics, which manifests itself as a narrow intense peak. In our opinion, this feature is explained by the fact that at the first stage lasing turns on under the mechanism of gain modulation described in [7]. This feature also indirectly confirms the high switch-on speed of pump current. The maximum relaxation peak amplitude reaches 96 W at the full width at half maximum (FWHM) duration of 90 ps. The main part of the laser pulse has a regular bell shape. At the maximum operating voltage, the peak power amounts to 52 W, while the FWHM pulse duration is 1 ns. A decrease in the operating voltage is accompanied by a decrease in the laser pulse amplitude and duration. The decrease in the laser pulse duration even at a constant duration of the pump current pulse is explained by the following factors. To achieve the lasing threshold, the active region should be filled with a certain number of charge carriers. A decrease in the pump current pulse amplitude results in a decrease in the rate of filling the active region with charge carriers. Thus, it takes longer to achieve the

required threshold concentration, which increases the delay in lasing turn-on and, hence, reduces its duration.

To estimate the peak current, lasing dynamics was numerically simulated via a one-dimensional model. Within this simulation, the pump-current pulse shape (duration and amplitude) was optimized so as to ensure the best agreement between the calculations and experiment at the operating voltage of 100 V. The simulation results are shown in Fig. 1 *b*. One can see a satisfactory agreement between the calculated and measured shapes and amplitudes of laser pulses. This allows a conclusion that the calculated laser-pulse FWHM amplitudes and durations are close to the experimental ones and reach 45 A and 1 ns, respectively, at the maximum operating voltage of 100 V. Fig. 1, *b* shows evidently that a decrease in the pump-current pulse amplitude at constant duration leads to both an increase in the lasing turn-on delay and reduction in laser pulse duration.

Fig. 2 demonstrates the lasing spectra. The spectrum shape is typical of high-power multimode semiconductor lasers; the FWHM width is 8 nm. Despite the short duration of pulses whose largest part is spent on transient processes of lasing turning on and off, the spectrum shapes change insignificantly.

Note in conclusion that the developed pulsed sources exhibit the possibility of efficiently reducing the laser pulse duration to 1 ns and increasing the peak power to 52 W at the operating wavelength of 945 nm. The demonstrated possibility was realized by using heterothyristor switches with extended *p*-base, which provide an increase in operating voltages up to 100 V without loss of transient process rates. Evaluation of the shape of current pulse generated in the current switch–laser diode circuit has shown that the achievable duration is 1 ns, while the amplitude is 45 A.

## Conflict of interests

The authors declare that they have no conflict of interests.

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