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Sources of high-power sub-nanosecond laser pulses based on thyristor switch—laser diode structures for the 1500 nm spectral range

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Sources of sub-nanosecond laser pulses based on compact vertical assemblies thyristor switch—laser diode have been developed and studied. Compact vertical assemblies emitting in the spectral range of 1500 nm have been implemented using the AlInGaAs/InP heterostructures. The possibility of generating single laser pulses with peak power of 1.4 W, width of 75 ps and repetition rate of up to 500 kHz has been demonstrated.

Keywords: pulse semiconductor laser, thyristor, current switch.

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High-power laser pulse sources emitting in the wavelength range of 1300—1600 nm are in demand in the field of information technology, e.g. for constructing communication lines in free space, in various areas of medicine related to diagnostics and therapy, and also in creating high-power laser systems employing fiber lasers as master oscillators. The possibility of realizing the mode of sub-nanosecond laser pulse generation allows for a significant improvement of such characteristics as spatial and temporal resolution and speed. At present, a great number of studies is devoted to approaches to the sub-nanosecond pulse generation by using GaAs/AlGaAs-heterostructure-based semiconductor lasers emitting in the spectral range of 850—900 nm [1–3]. It was shown that classical laser heterostructures optimized for operation in the continuous generation mode are also able to emit pulses with high peak powers [4]. Transition to the spectral range of 1300—1600 nm needs a change in the used material system. In addition, theoretical and experimental studies [5–7] have shown that in such structures additional losses occur regardless of the design, which significantly limits the peak power in the nanosecond pulse generation mode. This fact shows that it is necessary to conduct separate studies aimed at assessing the possibility of operating the AlInGaAs/InP laser heterostructures in the mode of sub-nanosecond laser pulse generation. In the case of high-power multimode lasers, when amplitudes of pump current pulses are to be at the ampere level, an approach based on the gain switching mode is used to solve this task [8]; this mode implies that, due to a delay in accumulation of the threshold photon concentration in the cavity, charge carriers may be accumulated to above the lasing stationary threshold and then be released like an avalanche over a short period of time, which is accompanied by emission of a single laser pulse. Here the laser pulse duration is significantly shorter than that of the pump current pulse, which allows using generators of nanosecond current pulses. Currently, field-effect transistors are widely used to generate current pulses [9], however, impossibility of integrating such transistors with a semiconductor laser crystal and necessity to use additional control circuits impose some restrictions on the creation of compact integrated sources. These problems may be solved by using thyristor-type current switches. Previously, the possibility of applying thyristor-type current switches based on GaAs/AlGaAs heterostructures was demonstrated for creating sources of sub-nanosecond laser pulses in the spectral range of 900 nm [4]. However, for the spectral range of 1300—1600 nm only devices of the hybrid-integration design may be created based on such current switches. Therefore, analysis of the possibility of creating sources of high-power sub-nanosecond laser pulses based on the vertical assembly of InP-thyristor switch with AlInGaAs/InP laser diode will in future allow turning to creation of a monolithically integrated structure realizable based on a heterostructure that combines the functions of both the current switch and laser diode. Thus, this paper considers the latest results in the field of creating compact sources of sub-nanosecond laser pulses at the wavelength of about 1500 nm, which are designed based on compact vertical assemblies InP-thyristor switch—AlInGaAs/InP-laser diode.

The design of the developed laser pulse source shown in the inset to Fig. 1 includes a thyristor switch crystal mounted via a conducting carrier on the *p*-contact of the semiconductor laser crystal. In experiments, a thyristor switch based on the AlInGaAs/InP heterostructure was used. Contrary to the case of GaAs thyristor switches, the $n-p-n$-transistor region had a homostructure based on InP epitaxial layers: *n*-InP emitter (thickness of 0.2 μm, doping

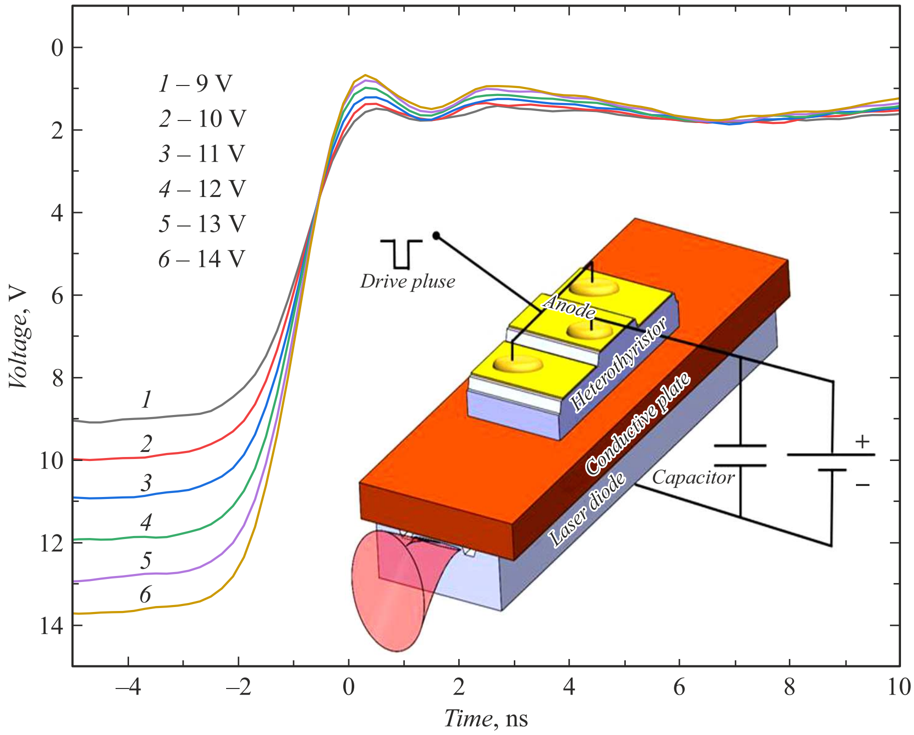

Figure 1. Time dependence of the capacitor voltage in the circuit of the thyristor switch—laser diode assembly based on the AlInGaAs/InP heterostructures. The inset presents a schematic diagram of the thyristor switch—laser diode assembly.

of $n = 10^{18}\,\mathrm{cm}^{-3}$), p-InP base (thickness $4\,\mu$m, doping of $n = 10^{16}\,\mathrm{cm}^{-3}$) and n-InP collector (thickness of $0.2\,\mu$m, doping of $n = 10^{18}\,\mathrm{cm}^{-3}$). On top of the InP transistor part there was located an InP/AlInGaAs heterodiode comprising narrow-band n-AlInGaAs ($E_g = 1.25$ eV) $0.4\,\mu$m thick and heavily doped p-InP emitter serving as a contact layer. The thyristor switch had a three-electrode design with a control electrode formed towards the n-InP collector. The thyristor switch design implied a strip-geometry anode contact $200\,\mu$m wide and $500\,\mu$m long. The control electrodes also had the strip geometry and were arranged along the anode contact long side. For the experiments, dimensions of the thyristor switch crystal were chosen to be $800 \times 500\,\mu$m. Studying static characteristics has shown that the maximum blocking voltage reached 20 V; therefore, in experiments the range of operating voltages was limited to 14 V. The laser diode was fabricated based on the AlInGaAs/InP heterostructure optimized for the continuous-wave lasing operation; the heterostructure comprised AlInAs barrier layers, a 200 nm thick AlInGaAs waveguide layer, and active region based on a single 7 nm thick AlInGaAs quantum well located in the center. The continuous-mode investigations have shown that the developed heterostructure posseses internal optical losses of $2\,\mathrm{cm}^{-1}$ and internal quantum yield of 90 %. For the experimental studies, laser crystals with the cavity 2 mm long and emitting aperture $100\,\mu$m wide were selected. Analysis of the laser diodes I-V characteristics in the continuous generation mode at room temperature exhibited the threshold current of 400 mA and linear-section optical power of 1.5 W at the current of 3 A. To realize the gain switching mode, a circuit comprising vertical assembly thyristor switch—laser diode and storage capacitor of 224 pF was constructed. For the thyristor switch power-supply and controlled switching-on, an external DC voltage source and generator of current pulses 250 mA in amplitude were used. To reveal dynamic characteristics of the thyristor serving as a high-speed switch, a probe with the frequency band of 500 MHz was used. The obtained dependencies provide a qualitative idea of the capacitor discharge time and pulse duration, but do not allow quantitative assessment of the parameters of the generated current pulses. In the future it is planned to overcome this problem by using higher-frequency probes and also by involving numerical simulation methods for interpreting experimental results.

Experimental investigation of the lasing dynamics were performed using the previously developed technique for measuring lasing dynamics with spatial resolution [4,10]. This technique is required for studying high-power multimode semiconductor lasers since it is impossible to collect radiation from the entire emitting aperture on the fast photodetector photosensitive surface because of its small size. The loss of radiation from a part of the emitting aperture can cause distortion of the integral shape of the laser pulse, which is associated with delays in turning-on various emitting aperture parts in high-power multimode laser diodes. Integral shape of the laser pulse was measured with fast photodetector NewFocus 1444-50 (20 GHz) and sampling oscilloscope Agilent 86117A (50 GHz). To calculate the

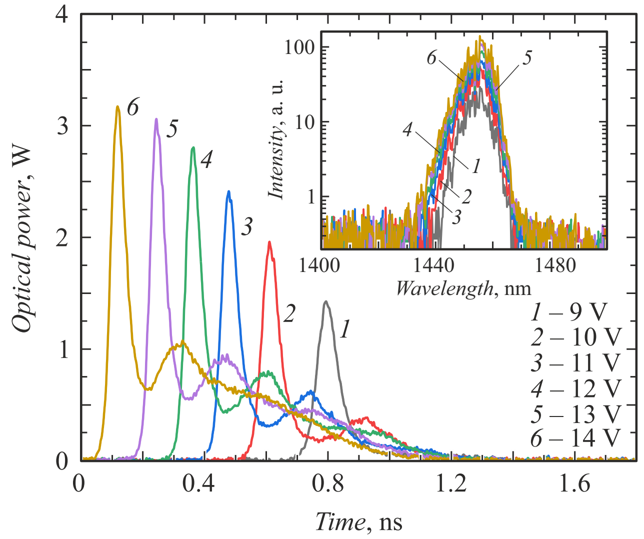

Figure 2. Laser pulses obtained at different operating voltages in the thyristor switch–laser diode assembly based on the AlInGaAs/InP heterostructures. The inset presents lasing spectra at different operating voltages. The colored figure is given in the electronic version of the article.

peak power, the average power was measured with meter Ophir 3A-P-FS-12 calibrated for the operating spectral range.

Fig. 1 shows the tracks of voltage dynamics on the storage capacitor. Evidently, the discharge rate at the level of 10–90 % is 700 ps, which may be regarded as an estimate of duration of the current pulse generated in the circuit. One can see that the thyristor switch turning-on speed increases slightly with increasing operating voltage, which may be associated with an increase in the contribution of impact ionization [11]. The observed dynamics of the thyristor switch turn-on shows that the pump current pulse duration also changes only slightly in the operating voltage ranges under study.

The shapes of integral laser pulses at operating voltages of 9–14 V are shown in Fig. 2. When blocking voltages are below 9 V, lasing is not observed. One can see that an increase in the blocking voltage is accompanied by both an increase in the peak power of the first short laser peak and increase in duration of the laser pulse slower part. For instance, peak power at the maximum voltage reaches 3.2 W, while the first peak duration is 58 ps at half maximum; total duration of the laser pulse slow part amounts up to 600 ps. A decrease in the blocking voltage results in a decrease in the pump current pulse amplitude, which is accompanied by both a decrease in peak power and reduction in duration of the pulse slow part. As a result, for the blocking voltage of 9 V there was demonstrated a pulse consisting of only the fast part with the peak power of 1.4 W and duration of 75 ps. In general, it is clear that an increase in the pump current amplitude without a considerable increase in its duration is accompanied, on the one hand, by an increase in the peak power and duration of the laser pulse slow part and, on the other hand, by a decrease in the pulse fast part duration. Studies of lasing spectra have shown that, regardless of the laser pulse shape, the spectrum maximum corresponds to the wavelength of 1456 nm, while its shape changes insignificantly (inset to Fig. 2).

Of practical importance is operation at high frequencies. Fig. 3 demonstrates the shapes of laser pulses obtained in the single short peak mode at different repetition rates, and also the capacitor charging track at the frequency of 500 kHz. It is evident that the frequency variation in the range of 160–500 kHz does not significantly affect the created assembly's operation, i. e. no significant variations are observed in duration and peak power of the generated pulses. The frequency maximum of 500 kHz was limited by the thyristor switch transition to the on-state. As noted in [12], this may be associated with that the capacitor charging current reaches the value of holding current, which prevents the thyristor turn-off after the storage capacitor gets completely discharged. This problem may be solved by optimizing the thyristor heterostructure design so as to provide an increase in holding current without losing other characteristics, e. g. due to using the *n–p–n*-transistor's composite base region including a heavily doped layer [12].

Note in conclusion that, by using the developed thyristor switch–laser diode assemblies based entirely on the AlInGaAs/InP heterostructures, it is possible to create sources of high-power sub-nanosecond laser pulses providing the peak optical power of 1.4 W in the mode of generating a single short pulse 75 ps wide. Further development towards increasing the peak power and repetition rate may be performed by optimizing the width of the laser part emitting aperture, as well as by optimizing the thyristor part design. In addition, the fact that only the AlInGaAs/InP-based heterostructures are used allows

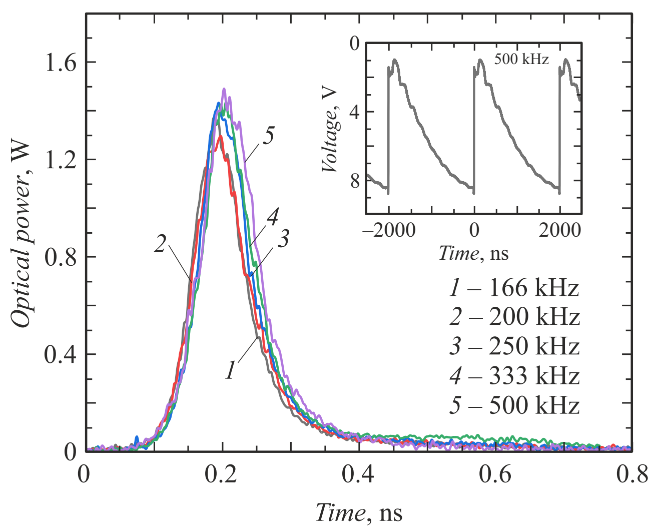

Figure 3. Laser pulses obtained at the operating voltage of 9 V for different repetition rates. The inset presents the storage capacitor charging track at the frequency of 500 kHz.

speaking about the possibility of creating in future fully integrated structures combining functions of the current switch and laser source.

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Conflict of interests

The authors declare that they have no conflict of interests.

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