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Sources of high-power laser pulses at a wavelength of 1550 nm based on thyristor switch–laser designs

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Compact sources of high-power laser pulses at a wavelength of 1550–1600 nm for LIDAR applications based on laser diode–thyristor switch assemblies have been developed and investigated. The peak power of 73 W laser pulses at an operating voltage of 50 V is demonstrated. The measured amplitude of the current pulses in the compact assembly circuit was 300 A at an operating voltage of 30 V.

Keywords: Pulsed semiconductor laser, thyristor, current switch.

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Compact sources of high-power laser pulses operating within the wavelength range of 1300–1600 nm are in demand in applications involving the propagation of radiation in free space, which is attributable to eye safety concerns [1]. The issue of increasing the peak optical power of such sources is relevant to range-measuring equipment and automotive lidars, since this provides an increase in range and additional protection from external interference [2–4]. Another important requirement is the small source size, since systems for constructing three-dimensional images of the surrounding space may use up to several dozen sources of this kind [5]. Pulsed sources with an external pump current pulse generator and radiation power up to several kilowatts operating within the spectral range of 900–910 nm have been demonstrated in [6,7]. In this case, current switches based on field-effect transistors, control drivers, and other circuit elements were positioned on a separate board in close proximity to laser crystals and occupied a significantly larger space (compared to these crystals). It was shown in [8,9] that a thyristor switch–laser diode design is a possible solution to the problem of reducing the dimensions of pulsed sources. A power of 20 W at a wavelength of 1475 nm was demonstrated in [10] for a radiator with this design, but the emitter aperture width was limited to 200 μm. In the discussed cases, the peak currents achieved did not exceed 100 A, which is insufficient for pulsed sources with a high peak power. An approach to production of pulsed sources based on epitaxially integrated laser and thyristor heterostructures is also known [11,12], but was implemented in the AlGaAs/GaAs/InGaAs solid solution system and does not support operation at wavelengths of 1550–1600 nm. In the present study, we report new data on the development of compact sources of high-power laser pulses operating at wavelengths of $\sim$ 1600 nm corresponding to the spectral range that is safe to the eyes.

Experimental samples of the examined compact pulsed sources were constructed based on vertical laser diode–thyristor switch assemblies. Their schematic diagram is shown in Fig. 1. As was demonstrated earlier, efficient switching-on of a thyristor switch is ensured by a small-signal control current with an amplitude at the level of several tens of milliamperes and no strict requirements as to the shape and front of control pulses. This is the reason why the proposed designs do not require complex control circuits, eliminating the need for many typical components of transistor-based electrical circuits and ensuring that the source is compact. Another important factor contributing to their small size is the possibility of vertical integration of a thyristor switch and a laser crystal of the stripe geometry, which ensures the suppression of external parasitic coupling that reduces the operating speed and efficiency. Laser diode crystals were produced based on a semiconductor heterostructure grown by metalorganic vapor-phase epitaxy (MOS hydride epitaxy). One of the typical heterostructure designs for high-power stripe AlInGaAs/InP lasers with a lasing wavelength of 1400–1500 nm was used. The heterostructure included an ultra-narrow 130-nm-thick AlInGaAs waveguide layer with an active region based on two quantum wells, which provided emission at a wavelength of 1580 nm, located at its center. The waveguide layer was bounded by wide-band AlInAs barriers. These barriers were set due to the need to suppress leakage of carriers from the waveguide layer, since the AlInGaAs/InP heterointerface is formed by a second-order heterojunction and does not allow for the formation of an energy barrier for carriers in transition from the narrow-band AlInGaAs waveguide to wide-band emitters based on InP [13]. Laser crystals with an ultra-wide emitting

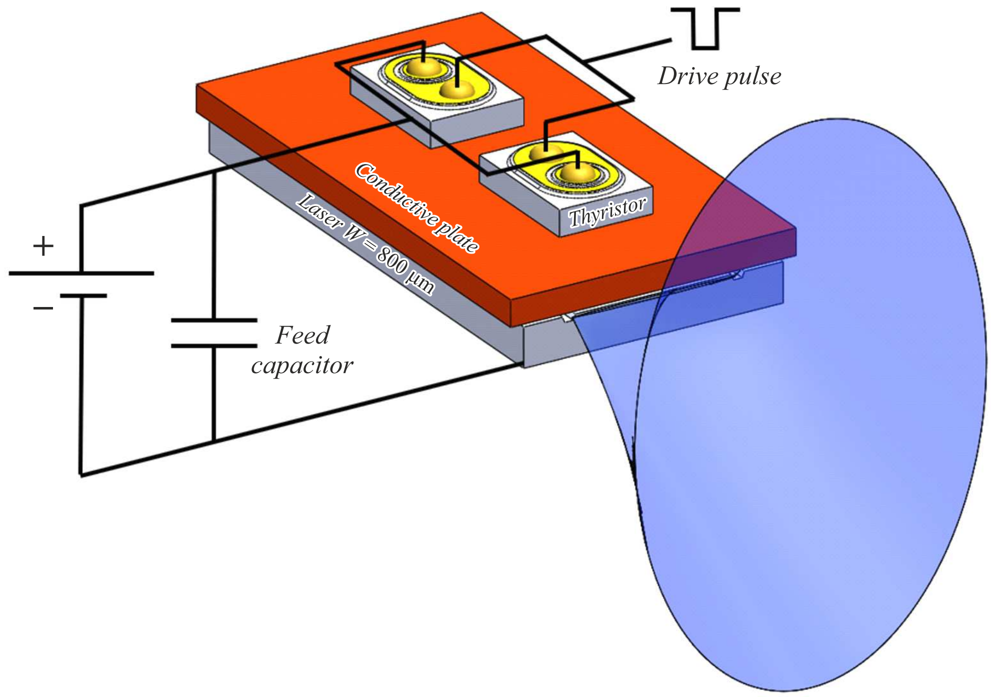

Figure 1. Design of compact pulsed sources based on vertical laser diode−thyristor switch assemblies at different operating voltages.

aperture (800 μm) and a Fabry−Pérot cavity length of 2 mm with reflective (95 %) and antireflective (4 %) coatings were manufactured from the designed heterostructure. It has already been demonstrated that this monolithic emitting aperture design provides the maximum fill factor and ensures linearity of the watt–ampere characteristic at high pump currents due to a reduction in current density [6]. Since the present study was focused on the possibility of increasing the peak power, the pulsed source was fitted with an external capacitor with a nominal value of 900 nF, which provided the required level of stored energy for generation of current pulses with an amplitude well above 100 A. Thyristor chips $500 \times 340\,\mu$m in size were used, and the anode contact diameter was 150 μm. With the emitter aperture width of 800 μm and the laser cavity length of 2 mm taken into account, two thyristor current switch chips were used to ensure more uniform pumping of the laser crystal in the emitting assembly (Fig. 1).

Experimental studies were carried out in two stages. At the first stage, laser pulses generated by compact laser diode−thyristor switch assemblies were examined. However, it is quite difficult to estimate the amplitude of current pulses excited in the circuit in this case, since the current circuit was deliberately designed in such a way as to contain only the vertical radiating assembly and a supply capacitor without any additional elements that could limit the current amplitude. Therefore, in order to evaluate the amplitude of current pulses, separate measurements for laser crystals with an ultra-wide (800 μm) emitting aperture pumped by an external current pulse generator were performed at the second stage. These measurements provided an opportunity to determine directly the peak current through the use of test resistors. Typical shapes of laser pulses produced by laser diode−thyristor switch assemblies at different operating voltages are shown in Fig. 2, *a*. A peak optical power of 73 W, which, as far as we know, is the highest value demonstrated for sources with a monolithic emitting aperture, was achieved at an operating voltage of 50 V. The corresponding value of power per unit aperture length is comparable to the results obtained by pumping high-power semiconductor 1550−1600 nm lasers with an external pulsed source [14–16]. The efficiency of the designed source is set by the efficiency of the laser and the current switch. The latter value is related to the residual voltage in the on state. The residual voltage for the studied switches was as low as 1.5 V, which is significantly lower than the measured levels (50 V [17]) for switches based on avalanche transistors. The thyristor switch was switched on by a control current pulse with an amplitude of 100 mA. The switching-on rise time determined at the level of 10−90 % was 10 ns, while the overall duration of laser pulses measured at half maximum was 95 ns. It is evident from Fig. 2, *a* that the overall duration of laser pulses and the rise time do not vary with amplitude of laser pulses, which indicates that the dynamic characteristics of the thyristor current switch are preserved within the voltage range under study. The results of examination of the radiation intensity distribution across the emitting aperture and the radiation pattern are shown in Figs. 3, *a* and *b*, respectively. The indicated distribution remained fairly uniform throughout the entire range of supply voltages. This fact demonstrates that although the pulsed current amplitudes are high and the

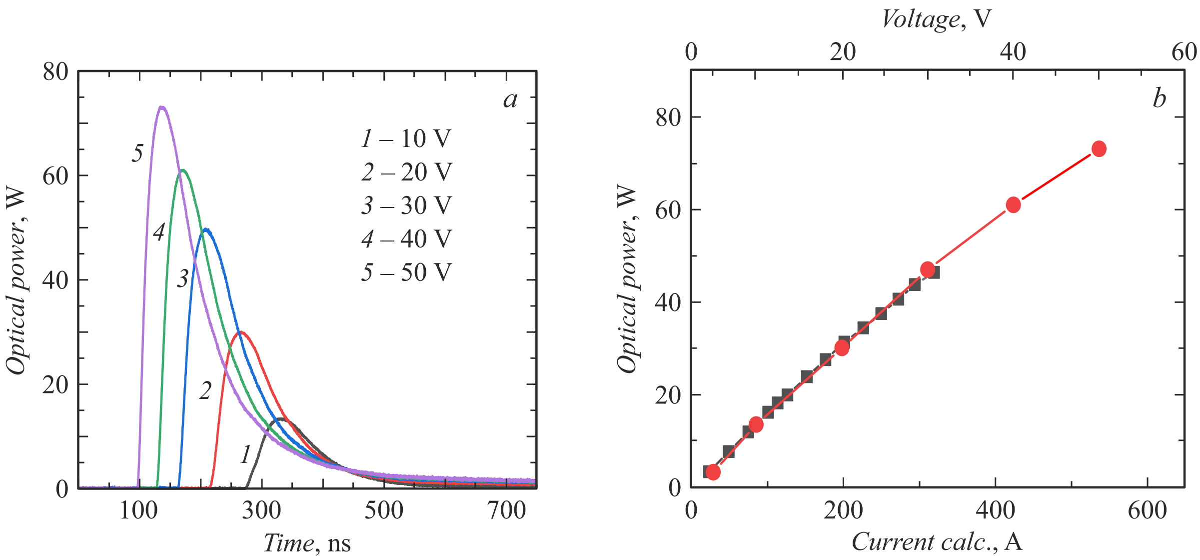

Figure 2. *a* — Dynamics of the output optical power for compact pulsed sources based on vertical laser diode–thyristor switch assemblies. *b* — Dependence of the peak power of laser pulses on the pump current amplitude for a separate laser diode crystal with an emitting aperture width of 800 μm pumped by an external source of current pulses (squares) and dependence of the peak power on the operating voltage for a compact pulsed source based on a vertical laser diode–thyristor switch assembly (circles).

emitting aperture is ultra-wide, the used vertical assembly design provides fairly uniform pumping over the entire laser emitter area. The radiation pattern did also demonstrate that the laser emitter mode structure remains stable through to maximum pump currents. The radiation divergence in the plane of heterostructure layers was 9° within the entire range of supply voltages, which also verifies the stability of the emitter mode structure. The radiation divergence in the plane perpendicular to heterostructure layers was 23° and corresponded to the fundamental transverse optical mode. Figure 3, *c* presents the lasing spectra. The central wavelength was positioned within the 1590–1600 nm range. It can be seen that the FWHM of the spectrum increases from 11 to 18 nm (with a noticeable shift to the long-wavelength region) as the peak power grows. This behavior may be attributed both to thermal heating [18] and to effects associated with non-uniform distribution of gain along the cavity axis [19] and requires further study.

To estimate the amplitude of pump current pulses in compact laser diode–thyristor switch assemblies, we examined the watt-ampere characteristics of laser diodes identical to those used in the compact assemblies and pumped by an external source based on commercial field-effect transistors (with a pulse duration of 130 ns at half maximum) that produced current pulses with an amplitude up to 300 A. The current amplitude in this external source was measured using a test resistance. Figure 2, *b* shows separately the dependence of the output optical power on the pump current for the laser diode with external pumping and the dependence of the peak power on the operating voltage for the compact vertical laser diode–thyristor switch assembly. For ease of analysis, the initial linear sections of the obtained dependences of the output optical power were combined, which allows for an indirect assessment of the amplitude of current generated in the circuit of the compact assembly. It is evident that the watt–ampere (currents up to 300 A) and watt–volt (voltages up to 30 V) characteristics match closely and are nearly linear in nature. This comparison demonstrates the generation of current pulses with an amplitude of 300 A in the circuit of the compact vertical laser diode–thyristor switch assembly at an operating voltage of 30 V. At higher operating voltages, the „peak output power–operating voltage“ dependence deviates from linearity (Fig. 2, *b*). This feature warrants further research, since it may be attributed to the specifics of operation of both the laser emitter and the current circuit of the designed assembly.

Thus, compact pulsed sources with a wavelength of 1550–1600 nm based on vertical laser diode–thyristor switch assemblies were demonstrated. The use of laser crystal designs with an ultra-wide aperture (800 μm) allowed us to maintain high emission efficiency levels and achieve a peak power of 73 W at a pulse duration of 95 ns. The demonstrated set of dimensional and power characteristics combined with eye safety assurance makes the developed sources promising for lidar applications. The estimated pump current pulse amplitude of 300 A at an operating voltage of 30 V also demonstrates the potential for further enhancement of output optical power through the use of multi-element emitters based both on hybrid vertical stacks of several individual chips and epitaxially integrated multi-junction heterostructures.

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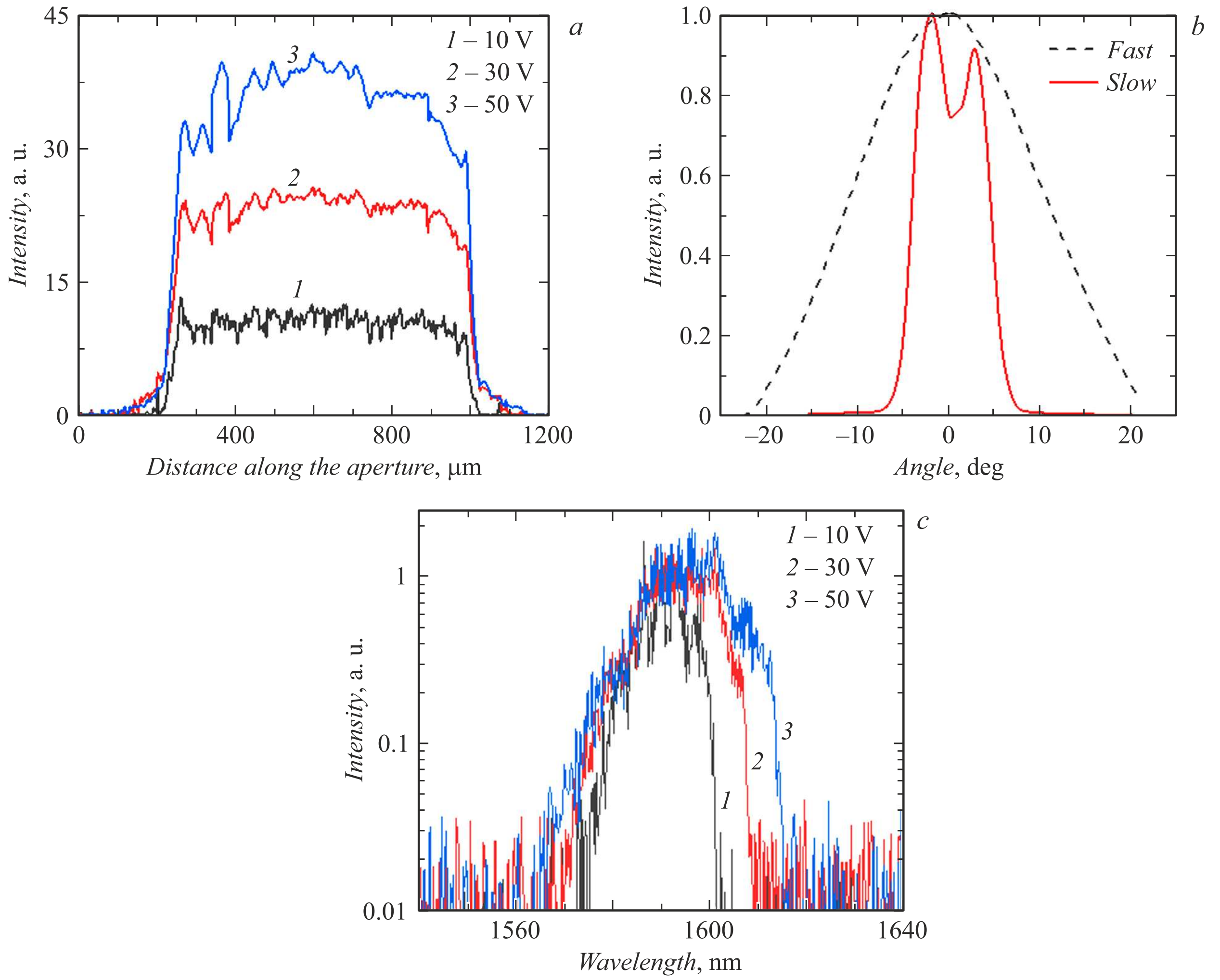

Figure 3. Distributions of radiation intensity in the near (*a*) and far (*b*) field and optical spectra (*c*) recorded at different operating voltages for compact pulsed sources based on vertical laser diode–thyristor switch assemblies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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