Hybrid stacks of thyristor switch - semiconductor laser based on AlInGaAsP/InP heterostructures for high-power pulsed laser sources (1400–1500 nm)

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Designs of hybrid laser sources based on thyristor current switches and laser diodes have been developed and investigated. The heterostructures of the thyristor current switches and laser diodes were created using MOCVD technology in the AlInGaAsP/InP solid solution systems. For the developed sources, a peak power of 20 W was demonstrated at a pulse duration of 65 ns and an operating voltage of 15 V. The minimum turn-on delay of the laser generation relative to the start of the control current pulse was 10ns at a pulse amplitude of 280 mA.

Keywords: Thyristor, current switch, pulsed semiconductor laser.

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1. Introduction

Currently, there is a strong demand for pulsed laser radiation sources in the spectral range of 1400–1600 nm for solving rangefinder problems, development of lidars (Light Detection and Ranging) for unmanned vehicles [1,2]. This is explained by two factors: (1) the solar background radiation is noticeably lower in the specified spectral range, (2) this spectral range is considered safe for the eyes [1,3]. In addition, various medical applications are actively developed. Pulsed semiconductor lasers are the most accessible for solving such problems, which is due to their small dimensions, high efficiency, compared with fiber lasers, where an additional optical pumping cascade is required, and the possibility of creating multi-element assemblies that increase peak power. Pulsed sources based on transistor switches are usually used to generate pulsed radiation from semiconductor lasers. Pulsed sources in the spectral range of 1400–1500 nm based on such solutions with a peak power of ~ 20 W with pulse durations of tens of nanosecond were demonstrated [4–8]. Further development of such sources may be associated with the development of new types of current switches, as well as the integration of the functions of the current key and the laser structure in one crystal. Attempts have been made to theoretically [9] and experimentally [10] study thyristor-type current switches based on InP/InGaAsP heterostructures. The possibilities of creating current switches that ensure nanosecond transient times, the ability to operate at low blocking voltages and control currents were demonstrated [10]. However, the characteristics of these switches have not been studied to date in conditions when semiconductor lasers operating in the spectral range of 1400–1500 nm are used as a load. A comparative analysis of the experimental radiative characteristics of pulsed semiconductor lasers, as well as hybrid thyristor key-laser diode assemblies based on Al-In-Ga-As-P/InP heterostructures is performed in this paper. The use of Al-In-Ga-As-P/InP heterostructures will allow us moving on to the creation of fully integrated designs of such laser radiation sources in the future.

2. Experimental samples

To create experimental samples of laser diodes and thyristor switches, heterostructures Al-In-Ga-As-P/InP, grown by metal organic chemical vapor deposition (MOCVD) were used. The laser heterostructure included wide-band emitters of *n*- and *p*-types of conductivity based on epitaxial layers of InP. Potential AlInAs barriers were formed at the boundary of the emitters and waveguide to suppress leakage of charge carriers from the waveguide into wide-band emitters. The waveguide layer was formed on the basis of an AlInGaAs epitaxial layer with a thickness of 0.5 μm. Two AlInGaAs quantum wells with a thickness of 6 nm each were located in the center of the waveguide layer. The composition of quantum wells was chosen to ensure the luminescence from the spectral range of 1400–1600 nm. Stripe lasers with a Fabry-Perot resonator and a radiating aperture width of 100 μm were manufactured from the grown heterostructure. Two types of samples were prepared for experimental studies of radiation characteristics. The first type of samples — laser crystals with a resonator length of

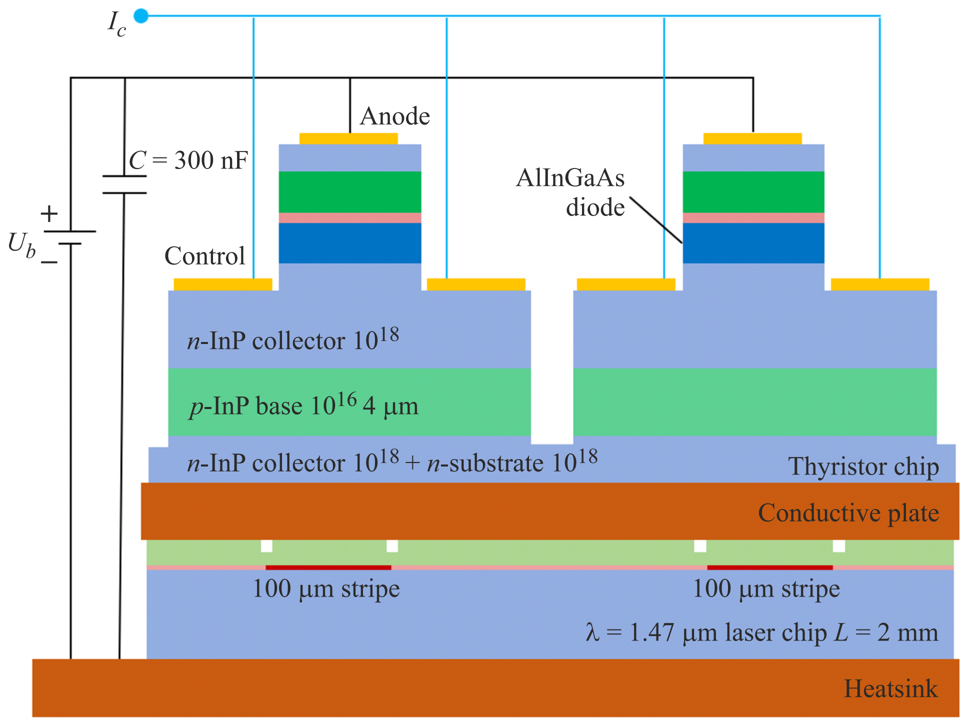

Figure 1. Scheme of a sample of a hybrid assembly of a thyristor key and a laser crystal on a common heat sink (a view from the radiating end of the laser crystal is shown, the thyristor chip is rotated for ease of display). C — supply capacity, U_b — supply voltage, I_c — control current, L — length of the laser crystal resonator. (The color version of the drawing is presented in the electronic version of the article).

1500–3000 μm were used to study the optical properties of the heterostructure and test the radiative characteristics of individual semiconductor laser crystals. Each crystal was soldered for this purpose with a stripe down onto a copper heat sink.

Samples of the second type were also developed to study the radiative characteristics— „thyristor key–laser diode hybrid assemblies" (Figure 1). The heterostructure of the thyristor key can be represented as a series-connected $n-p-n$ of transistor part and $n-p$ of LED part. The transistor part was implemented based on InP layers. The layers of n-InP at the same time were doped with silicon up to 10^{18} cm^{-3}, and the layer of p-InP base was doped with zinc up to 10^{16} cm^{-3} and had a thickness of 4 μm. The LED part included wide-band emitters n-InP and p-InP doped by silicon and zinc to 10^{18} cm^{-3}, respectively, between which a 0.4 μm thick AlInGaAs waveguide ($E_g = 1.24$ eV) was located. Three-electrode structures were made from the developed heterostructure to create thyristor key crystals. The anode contact was formed to the layer of the p-InP-emitter of the transistor part, the cathode contact was formed to the n-InP-substrate, which was an extension of n-InP-emitter of the transistor part, and the control contact was formed to the layer of n-InP-collector of the transistor part. The anode contact had a stripe geometry with a width of 200 μm, and its length was determined by the length of the manufactured crystal of the thyristor key. The control contacts were located on both sides along the anode contact. Hybrid assemblies were made on the basis of the proposed thyristor switches and laser crystals. The basic design of the hybrid assembly (Figure 1) is similar to that described in Ref. [11]. The laser diode crystal in the developed hybrid assemblies had a radiating aperture based on two regions with a width of 100 μm each, separated by a non-pumped passive region with a width of 300 μm. The length of the laser diode resonator was 2000 μm in the conducted experimental studies. The crystal of the thyristor key included two subelements, which were monolithically located on a common substrate of n-InP and were separated by a mesaditch. Each sub-element had its own anode electrode and control contacts, while the cathode for the sub-elements was common. The laser diode crystal in the developed hybrid assembly was mounted on a copper heat sink with n-contact down. Next, a thyristor key crystal was mounted on the p-contact of the laser diode. A capacitor C with a rating of 300 nF which had a common contact with the cathode and anode contacts was connected in parallel with the hybrid assembly for experimental studies of the radiative characteristics.

3. Results of experimental studies

The optical properties of the laser heterostructure were characterized in the first part of the work. The watt-

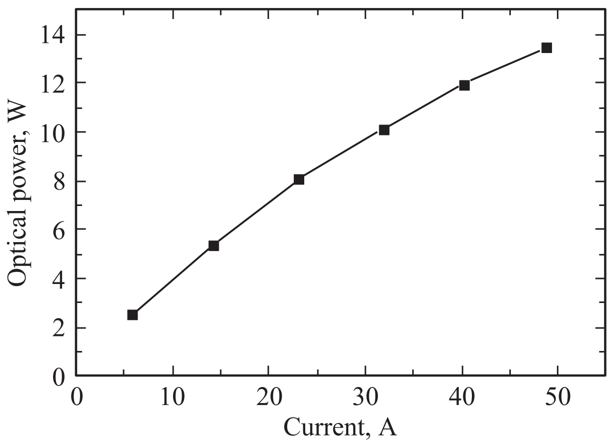

Figure 2. The dependence of peak optical power on peak current when pumped by pulses with a duration of 100 ns and a frequency of 1 kHz for a single semiconductor laser with a resonator length of $2\,\mu$m and a radiating aperture width of $100\,\mu$m. The temperature of the heat sink is 25°C.

ampere characteristics of semiconductor lasers with different resonator lengths were measured for this purpose in a continuous mode at a heat sink constant temperature of 25°C. The experimental values of the external differential quantum efficiency obtained made it possible to determine the internal optical losses and the internal quantum yield, which amounted to $2.9\,\mathrm{cm}^{-1}$ and 96%, respectively. The internal optical losses and internal quantum yield was evaluated in accordance with the methodology described in Ref. [12]. The increased value of internal optical losses of $2.9\,\mathrm{cm}^{-1}$ is associated with the use of a narrow waveguide design, which, on the one hand, ensures a high optical limitation factor in the active region and allows for high modal gain, which is important for creating lasers with a short resonator, but on the other it limits the external differential quantum efficiency of stimulated radiation when using long resonators. In the future, it is planned to optimize the design of the laser heterostructure for solving the problem of increasing the external differential quantum efficiency of stimulated radiation and peak optical power. An external pump source developed in our laboratory was used to study the pulse characteristics. Figure 2 shows typical dependences of the peak optical power on the peak pumping current for a laser diode crystal with a resonator length of $2000\,\mu$m and a radiating aperture width of $100\,\mu$m.

It can be seen that the deviation from linearity manifests itself already starting with the currents of > 15 A. The reason for this behavior is associated with an increase of internal optical losses due to the accumulation of charge carriers in the waveguide region and a decrease of the internal quantum yield, which may be attributable to parasitic nonradiative and spontaneous recombination in various layers of the heterostructure. These factors can be significantly enhanced due to the effects of spatial burning of charge carriers along the resonator. The analysis of such effects requires the use of two-dimensional models, as, for example, in Ref. [13].

The second part of the work was devoted to the study of electro-optical characteristics of thyristor key-laser diode hybrid assemblies (hereinafter referred to as the hybrid assembly). The principle of switching on of hybrid assemblies can be described in the following steps. At the first stage, the capacitor is charged from an external voltage source to the required stationary value of the operating voltage. The operating voltage range U_b was 5–15 V in this study. A current pulse was applied to the control electrodes at the second stage to set the thyristor in the switched on state. The third stage is associated with the transition of the thyristor key to the switched-on state with low resistance, which is accompanied by discharge of the storage capacitor. At the end of the third stage, the thyristor switch goes into a closed state when the storage capacitor is discharged to a state that does not allow maintaining a current greater than the holding current. The first part of the experimental studies was related to measurements of the characteristics of the on-delays of the hybrid assembly. Figure 3 shows the characteristic on-delay times of the laser generation relative to the beginning of the control current pulse, obtained for different amplitudes of the control current pulse at the selected operating voltage value. The minimum on-delay reaches 10 ns and is provided at a control current amplitude of 280 mA and an operating voltage of 15 V.

It is worth noting that the on-delay times of < 100 ns are ensured with control currents from 30 to 100 mA, which demonstrates the effectiveness of switching on with a low-signal control. However, if the switching delay is not critical, then effective switching is also possible with current pulses with an amplitude of up to 6 mA, while the delay increases

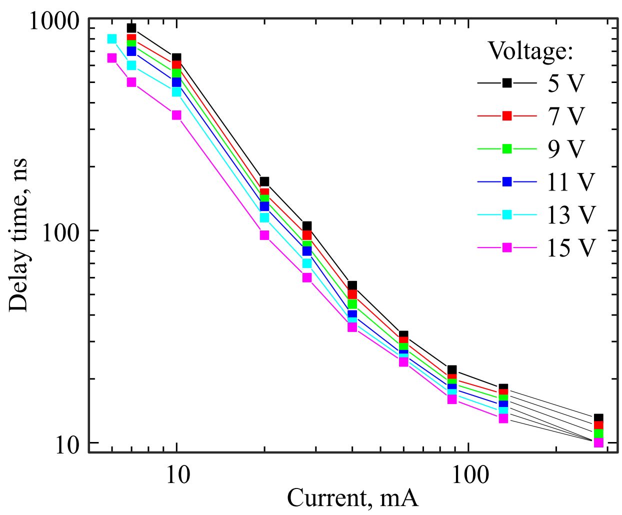

Figure 3. The dependence of the on-delay times on the amplitude of the control current pulse for operating voltages in the range of 5–15 V of a hybrid assembly based on a thyristor key and a laser diode. The temperature of the heat sink is 25°C.

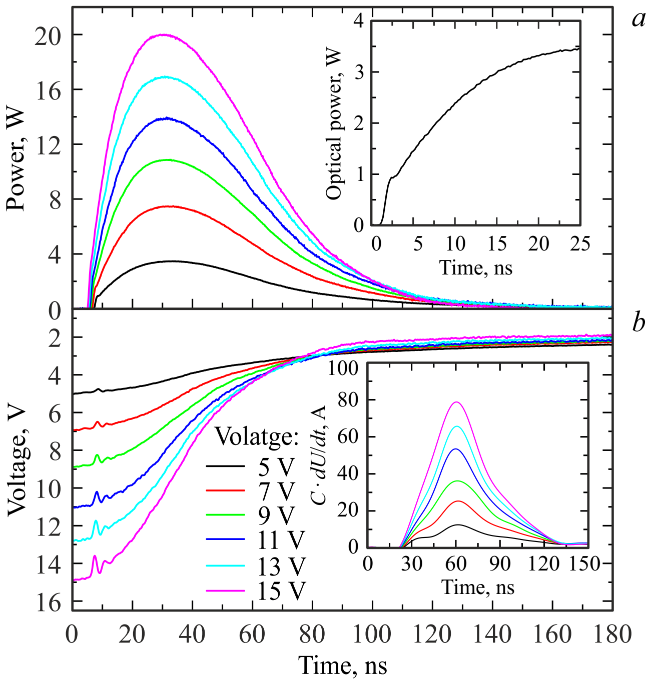

Figure 4. The dynamics (*a*) of the output optical power and (*b*) voltage on the storage capacitor during its discharge for various supply voltages obtained for a hybrid assembly based on a thyristor switch and a laser diode. Heat sink temperature is 25°C. The insert *a* shows the front part of the laser pulse for an operating voltage of 5 V, the insert *b* shows the calculated current pulses.

to ~ 650 ns. It can be seen that a decrease of the operating voltage results in a shift of the entire dependence to the region of higher delay times. No noticeable distortions in the nature of the resulting dependencies are observed when the operating voltage changes. This may indicate that the switching on is ensured by a single set of mechanisms. It is important to note that a change of the operating voltage significantly affects the on-delay time in the region of the minimum amplitudes of the control current pulses. Thus, a decrease of the operating voltage from 15 to 5 V with a control current pulse amplitude of 10 mA results in an increase of the switching delay from 345 to 645 ns, and the on-delay increases from 10 to 13 ns for a control current amplitude of 280 mA.

Further, studies were conducted on the temporal dynamics of the electro-optical characteristics of hybrid assemblies. The laser pulses emitted by the hybrid assembly crystal are shown in Figure 4, *a*, and the voltage dependences on the storage capacitor during its discharge through the switched-on thyristor current switch are shown in Figure 4, *b*. The voltage dynamics was measured using a probe and an oscilloscope with frequency bands of 200 MHz and 1 GHz, respectively.

The experimental dependences shown in Figure 4, *b* were differentiated for analyzing the voltage dynamics. The analysis was carried out within the framework of a differential equation describing the relationship between current and voltage in case of a capacitor discharge [14]:

$$I = C \cdot dU/dt,$$

where I — current through the capacitor (A), U — voltage across the capacitor (V), C — capacitance of the capacitor (F). This value can be used in the constant capacitance approximation and in case of an insignificant contribution of inductance to estimate the current dynamics in the circuit of a hybrid assembly [15]. The simplification of the insignificance of the contribution from the inductance of the circuit can be justified by the absence of negative voltage oscillations [15]. The analysis makes it possible to state the estimated value of the maximum current amplitude of 80 A for the developed circuit of the hybrid assembly (see the insert in Figure 4, *b*). A close to linear dependence of the estimated current amplitude on the operating voltage is observed at the same time. It can be seen from Figure 4, *a* that the peak optical power achieved for the operating voltage of 15 V was 20 W, and the duration of the laser pulse was at the level of half of the peak intensity — 65 ns. It is important to note that the demonstrated peak optical power of 20 W for the hybrid assembly was comparable to the peak optical power demonstrated by a separate laser crystal pumped by an external pulsed source (Figure 2, a laser crystal with a radiating aperture width of 100 μm). This suggests that the assembly design and functions of the current switch do not introduce noticeable losses and ensure efficient current pumping and laser generation. Reducing the operating voltage to 5 V results both in a decrease of peak optical power to 3.5 W and to a pulse duration of up to 55 ns. The insert to Figure 4, *a* shows the front part of the pulse for an operating voltage of 5 V for explaining the features of the dynamics of laser generation. It can be seen that the leading edge of the pulse has a faster section compared to the rear one. However, a test bench based on a photodetector with an InGaAs active region was used during these experiments, which has a frequency band of 200 MHz, which allows describing the dynamics of the main part of the optical pulse correctly, and prevents from resolving the achieved rates of transients at the time of switching on. It is planned to solve this problem in the future when studying shorter pulses, when the switching front is important by using a previously developed technique for measuring the subnanosecond dynamics of laser generation of high-power semiconductor lasers with a wide radiating aperture [16]. The results obtained indicate that the leading edge of the laser pulse does not fully reflect the shape of the leading edge of the current pulse generated in the circuit of the hybrid assembly. However, the trailing edges have a significantly higher degree of overlap.

Figures 5 and 6 show the measured spectra of laser generation and the distribution of radiation intensity at the end of the laser part of the developed hybrid assembly. The measurements were performed for the temperature of the heat sink of 25°C. For the entire operating voltage range, the maximum of the radiation spectrum is in the range

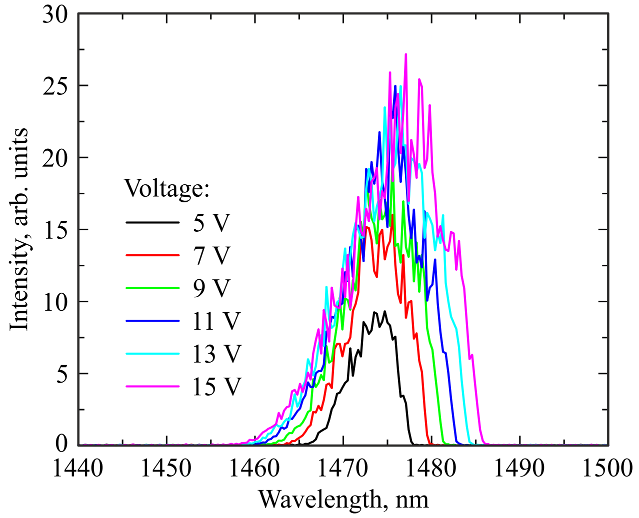

Figure 5. Hybrid assembly laser generation spectra for various operating supply voltages. The temperature of the heat sink is 25°C.

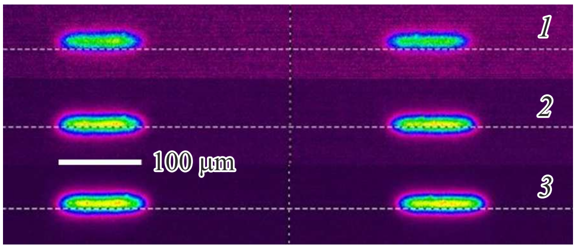

Figure 6. Radiation intensity distributions at the output end of the laser part of the hybrid assembly for various supply voltages, V: *1* — 5, *2* — 11, *3* — 15. The temperature of the heat sink is 25°C.

1475–1478 nm, while the half-peak width reaches 12 nm with a radiated peak optical power of 20 W.

The intensity distribution at the output end of the laser part of the hybrid assembly was obtained using an optical system that provides an enlarged image of the output mirror on the surface of the CCD camera matrix. It can be seen that the radiation in the near field for all operating voltages is evenly distributed in each separate part of the radiating aperture. There is also no obvious asymmetry between the parts of the radiating aperture. It follows from this that the proposed hybrid assembly design ensures uniform pumping of the laser diode crystal even with a composite aperture with a total overall width of 500 μm. Therefore, it is possible to increase the peak optical power in the future by expanding the radiating region without loss of the pumping quality and uniformity.

4. Conclusion

The conducted studies demonstrated the possibility of usage of thyristor key-laser diode hybrid assemblies for creation of radiation sources with a pulse duration of < 100 ns. It is important to note here the experimental demonstration of the fact of effective operation of a thyristor current switch based on the Al-In-Ga-As-P/InP heterostructure in a circuit with a load in the form of a semiconductor laser emitting at a wavelength of ~ 1475 nm. This suggests the possibility of creation of a monolithic epitaxial structure with a laser thyristor design in a system of solid solutions of Al-In-Ga-As-P/InP, which will combine the functions of both a thyristor current switch and a laser radiation source. The achieved values of the peak optical power of laser pulses in the developed hybrid assemblies were 20 W with a duration of 65 ns and a total width of the radiating aperture of 200 μm, which is comparable to the optical radiation power of discrete high-power stripe laser diodes at a wavelength of 1.47 μm [4–8]. At the same time, the control currents used from 6 to 280 mA allowed for on-delays from 900 to 10 ns in the range of operating supply voltages from 5 to 15 V. This confirms the high efficiency of both the laser diode and the thyristor current switch. The results obtained demonstrate a high potential for the development of sources with both higher peak optical power due to the expansion of the radiating aperture and with a shorter pulse duration.

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Conflict of interest

The authors declare that they have no conflict of interest.

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