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# The effect of the cavity length on the output optical power of semiconductor laser-thyristors based on AlGaAs/GaAs/InGaAs heterostructures

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The effect of laser-thyristor cavity length on the characteristics of the generated laser pulses has been studied. Results show that for pulse durations of approximately $\sim 20-30$ ns, achieved with a nominal discharge capacitor of 22 nF, increasing the cavity length from 480 to 980 $\mu$m enables a rise in maximum peak power from 16.6 W to 25.4 W. A further extension of the cavity length to 1950 $\mu$m causes an insignificant decrease in the maximum peak power to 23.7 W due to lower external differential efficiency of the samples at the initial linear region of the light-current curve. However, this extension provides a reduction of optical pulse duration compared to samples of other lengths over the entire supply voltage range.

**Keywords:** laser-thyristor, semiconductor laser, current switch, pulse laser.

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## 1. Introduction

Currently, pulsed laser radiation sources with an operating wavelength of 890–910 nm have a wide range of applications, including the fields of laser rangefinder [1], diagnostics [2,3] and medicine [4]. In this regard, the task of development of easy-to-implement systems for generating high-power laser pulses with a duration from units to hundreds of nanoseconds remains urgent. One of the approaches to creating energy-efficient and compact radiators is to combine a laser emitter and a current switch in one semiconductor heterostructure to provide current pumping. An example of the implementation of this approach is a laser thyristor (hereinafter — LT) consisting of a laser diode and a phototransistor. In detail, the principle and some features of the operation of LT similar to those studied here are described in Ref. [5,6]. In a typical electrical circuit, the LT is powered by a constant voltage source supplied to the anode and cathode of the device and charging a capacitor connected in parallel to the LT. The LT is switched to the open state after small-amplitude current pulses (usually units or tens of milliamps) are applied to the control sections. The capacitor discharged through an open LT is used for pumping the laser part, the choice of the rating of the capacitor is determined by the required pulse duration.

Modern strip lasers for operation in the spectral range of 890–910 nm can have a variety of resonator lengths depending on the type of emitter. Thus, the length of resonators with integrated Bragg gratings can reach 4 mm [1,7] or even 6 mm [8], which is primarily attributable to the need to illuminate a sufficiently long section of the grating itself (1 mm) with powerful spontaneous radiation, which it is possible only by increasing the length of the gain section. High-power lasers based on multi-junction heterostructures without Bragg grating sections are presented, as a rule, in variants with shorter resonator lengths, however, there is no unified approach in this area. The results of effective operation of lasers with several tunnel-coupled emitting regions with a resonator length of 750 $\mu$m and a strip width of 200 $\mu$m were demonstrated in Ref. [9,10]. At the same time, the authors emphasize the importance of obtaining low resistance of samples for their effective operation. Lasers of a similar design are studied in Ref. [11], however, the length of their resonator is already 3 mm, and the width of the strip varies from 3 to 100 $\mu$m. Thus, the optimal resonator length should be selected in each individual case taking into account the specific features of the device. Thyristor lasers are also devices based on multi-junction heterostructures, while the issue of the choice of the optimal resonator length for the most efficient operation of this type of emitter has not been studied until now, which is important from a practical point of view. In this regard, the impact of the resonator length on such LT characteristics as the output optical power and the duration of the optical pulse was studied in this paper.

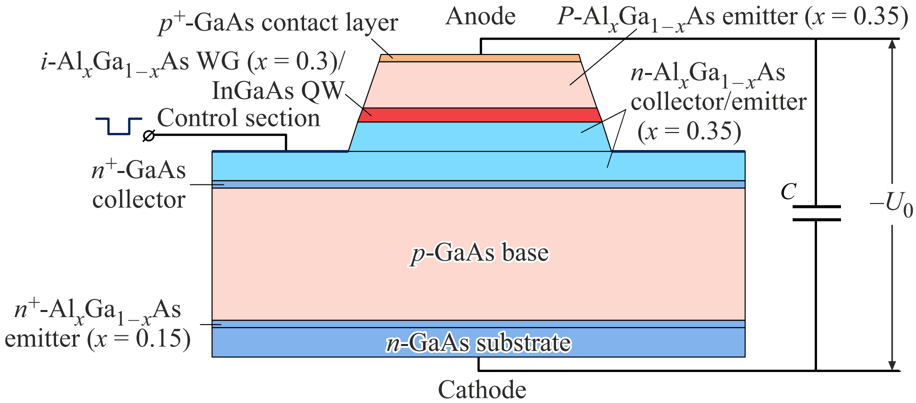


**Figure 1.** Schematic representation of a laser thyristor with an electrical wiring diagram. (A color version of the figure is provided in the online version of the paper).

## 2. Experimental samples and measurement scheme

The experimental samples were made from a heterostructure grown by the method of MOS-hydride epitaxy on a $n$-GaAs substrate. The phototransistor part consisted of $n^+$-Al$_x$Ga$_{1-x}$As ($x = 0.15$) emitter, 4.4 $\mu$m thick weakly doped $p$-GaAs base and $n^+$-GaAs/$n$-Al$_{0.35}$Ga$_{0.65}$As composite collector. The expansion of the thickness of the base region compared with similar devices considered in Ref. [5,6] made it possible to increase the maximum blocking voltage to 27 V, which should, firstly, increase the speed of the device owing to more effective shock ionization, and secondly, allow charging a parallel-connected LT capacitor to higher voltages, obtaining a higher peak current.

The laser part included Al$_{0.35}$Ga$_{0.65}$As $n$- and $p$-emitters ($n$-Al$_{0.35}$Ga$_{0.65}$As layer is simultaneously part of the composite collector of the phototransistor part), 0.4 mm thick $i$-Al$_{0.3}$Ga$_{0.7}$As waveguide and the active region — a quantum well with $i$-GaAs/InGaAs/$i$-GaAs spacers. The design of the laser part was developed for emission in $\sim$ 905 nm spectral range. Semiconductor strip lasers with a similar design repeatedly demonstrated their effectiveness previously [12–14].

The finished laser thyristors had a strip width of the laser part of 200 $\mu$m (coincides with the width of the anode contact), two control sections located to the left and right of the strip, a resonator length of 480, 980 or 1950 $\mu$m (the length of the resonator coincides with the length of the laser thyristor). No antireflective and reflective coatings were applied on the resonator face. A laser thyristor with an electrical wiring diagram is schematically shown on Figure 1. C capacitors of suitable rating of 22 nF were selected for generation of 20–30 ns laser pulses. A control current of the same amplitude of 10.4 mA and the same pulse repetition frequency of 203 Hz were used for all the studied laser thyristors. All measurements were performed at room temperature.

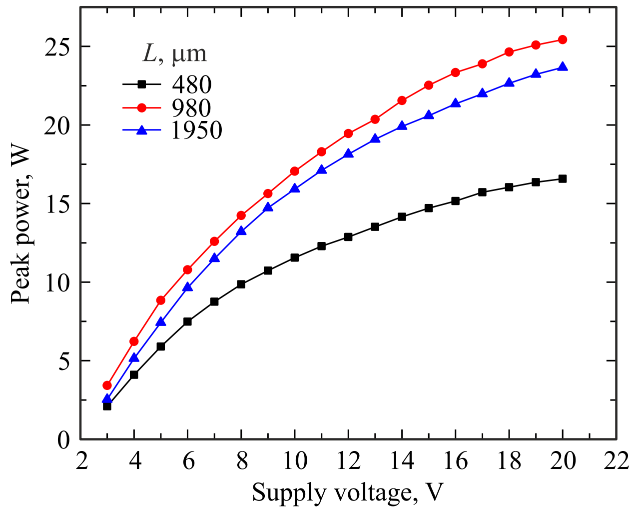


**Figure 2.** Dependence of the peak power of laser thyristors of different lengths on the supply voltage.

## 3. Measurement results

The dynamics of the optical output power and capacitor discharge in the supply voltage range from 3 to 20 V of laser thyristors with different resonator lengths (480, 980 and 1950 $\mu$m) was measured during the experiment. The following parameters were estimated based on the results of these measurements: the level of peak power of laser thyristors, the duration of optical and electrical pulses. As mentioned above, LT can block up to 27 V, so the operating voltage range could technically be extended. However, it was found during the measurements that there are signs of saturation of the output optical power level already at a voltage of 20 V, so a further increase of the supply voltage was not advisable.

Figure 2 shows the dependence of the peak power of laser thyristors of different lengths on the supply voltage. It can be seen that the following pattern persists over the

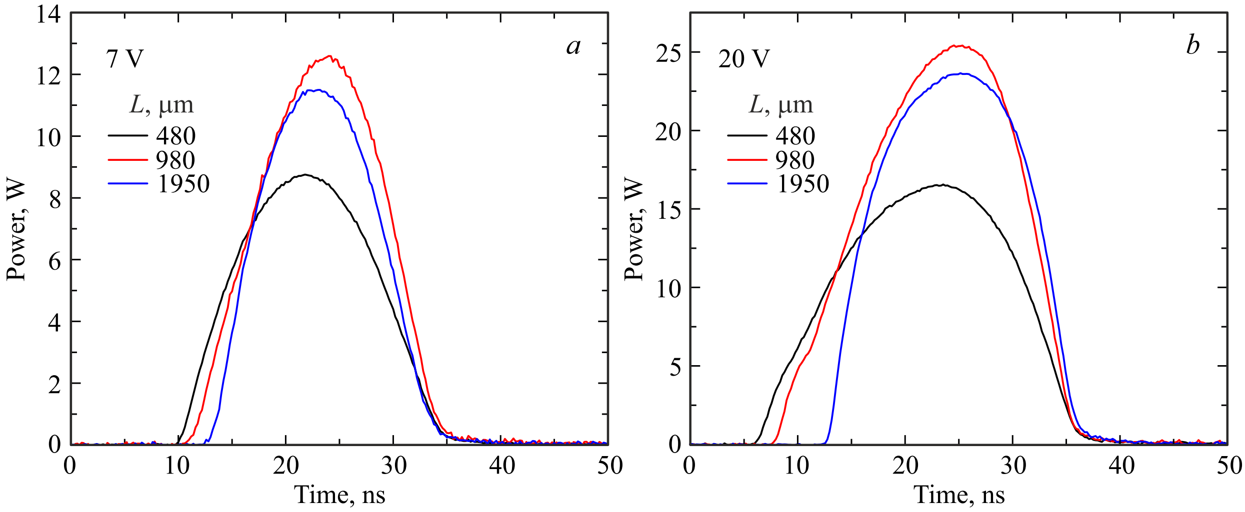


**Figure 3.** The dynamics of optical output power of 480, 980 and 1950 $\mu$m long laser thyristors at supply voltages of 7 V (*a*) and 20 V (*b*). (A color version of the figure is provided in the online version of the paper).

entire supply voltage range: the maximum power level is achieved when laser thyristors with a resonator length of 980 $\mu$m are used, the minimum level is demonstrated by laser thyristors with a resonator length of 480 $\mu$m, laser thyristors with a resonator length of 1950 $\mu$m occupy an intermediate position.

As an example, Figure 3 shows a set of optical pulses at a low supply voltage of 7 V (Figure 3, *a*) and a high supply voltage of 20 V (Figure 3, *b*). The peak power levels of the samples reach 12.5 W (7 V) and 24.8 W (20 V) with a resonator length of 980 $\mu$m, 8.7 W (7 V) and 16.6 W (20 V) with a resonator length of 480 $\mu$m, 11.5 W (7 V) and 23.7 W (20 V) at a resonator length of 1950 $\mu$m. It can be seen that at a low supply voltage of 7 V, the optical pulses of all laser thyristors have a similar bell-shaped shape and are practically symmetrical relative to the coordinate of their peak, the difference between the leading edge time and the fall time $\Delta$ does not exceed 10% of the pulse duration. Here and further, we will talk about values at the level of 10% of the amplitude when discussing the duration of the optical pulse. The symmetry of the optical pulse is lost with an increase of the supply voltage, while the most perfect pulse shape is preserved by laser thyristors with a length of 1950 $\mu$m, $\Delta$ does not exceed 7% of the pulse duration in the supply voltage range of 7–20 V. For comparison, it can be noted that similar values can be significantly higher for other laser thyristors — up to 15% (17 V) for laser thyristors with a length of 480 $\mu$m and up to 25% (17 V) for laser thyristors with a length of 980 $\mu$m.

Figure 4, *a* shows the dependence of the duration of the optical pulse on the supply voltage. The shortest pulse in the entire supply voltage range is demonstrated by laser thyristors with a resonator length of 1950 $\mu$m, while its duration smoothly increases with an increase of the supply voltage from 18.4 ns (3 V) to 22.4 ns (20 V). The duration of the optical pulse of 480 $\mu$m long laser thyristors increases from 20.6 ns (3 V) to 28.5 ns (20 V). The dependence of the duration of the optical pulse on the supply voltage of laser thyristors with a length of 980 $\mu$m is more complex — the duration increases from 18.8 ns (3 V) to 27.3 ns (14 V), and then gradually decreases to 26.4 ns (20 V).

Let's consider the dependence of the energy in the optical pulse on the energy stored in the capacitor (Figure 4, *b*). It is clearly seen that the energy dependence in the optical pulse of laser thyristors with a length of 980 $\mu$m is noticeably higher than for the other two types of laser thyristors, but it breaks when the supply voltage exceeds 14 V (indicated by a vertical dotted line), which is associated with a decrease of the pulse duration (Figure 4) and is uncharacteristic for laser thyristors of other lengths.

The following conclusions can be drawn from the data in Figures 2–4. Laser thyristors with a resonator length of 480 $\mu$m with a nominal discharge capacitor of 22 nm have the worst performance in terms of output optical power and the longest optical pulse duration among all considered laser thyristors. The decrease of peak power compared to the most powerful laser thyristors with a length of 980 $\mu$m varies from 22.7 to 36% depending on the supply voltage. The increase of the duration of the optical pulse relative to laser thyristors with a length of 1950 $\mu$m ranges from 9.3 to 42.1%. Thus, the length of the laser thyristors of 480 $\mu$m cannot be considered as optimal in any of these aspects.

As for the resonator lengths of 980 and 1950 $\mu$m, choosing the most optimal of them seems to be a slightly more difficult task. On the one hand, laser thyristors with a length of 980 $\mu$m demonstrated better level of optical output power over the entire supply voltage range. On the other hand, laser thyristors with a length of 1950 $\mu$m demonstrated significantly shorter optical pulse duration. Thus, the choice of one or another resonator length will depend on the specific tasks — achieving the maximum level of optical output power or obtaining the minimum possible duration

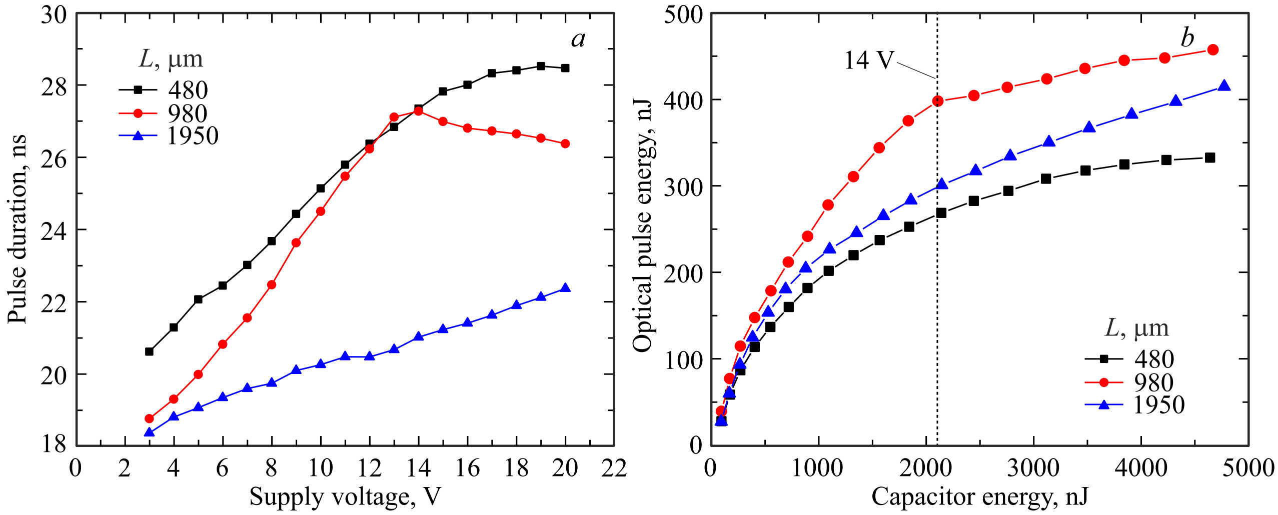


**Figure 4.** Dependence of the duration of the optical pulse on the supply voltage for laser thyristors of different lengths (*a*); dependence of the energy in the optical pulse on the energy stored in the capacitor (*b*).

of the optical pulse. This situation is shown in more detail in Figure 5. The first dependence demonstrates the difference of the peak power level, the second shows the difference of the duration of the optical pulse of 980 and 1950 $\mu$m long laser thyristors, the comparison in both cases is made relative to a laser thyristor with a length of 1950 $\mu$m. It can be seen that the increase of the peak power of laser thyristors with a length of 980 $\mu$m relative to laser thyristors with a length of 1950 $\mu$m becomes less significant as the supply voltage increases, that is from 35% (3 V) to 7.5% (20 V). It is possible to distinguish the voltage range of 10–18 V where the peak power difference fits into the range 7–8.8%, while laser thyristors with a length of 980 $\mu$m demonstrate an increase of the duration of the optical pulse by more than 20% (maximum by 31.1% at 13 V). It can be said that it is in this voltage range the use of laser thyristors with a length of 1950 $\mu$m is most appropriate from the point of view of reduction of the duration of the optical pulse without significant reduction of the level of optical output power.

So, the measurements made it possible to establish that the laser thyristors with resonator lengths of 980 and 1950 $\mu$m are the most preferable when the discharge capacitor has a rating of 22 nF. The former demonstrate the maximum peak power level, while the latter have a shorter optical pulse duration over the entire supply voltage range. The reasons for the behavior of laser thyristors with different resonator lengths discussed in this section will be discussed further.

## 4. Results and discussion

### 4.1. Study of voltage dynamics on capacitor

As it was shown earlier, both the duration of the optical pulse and its amplitude depend on the resonator length of

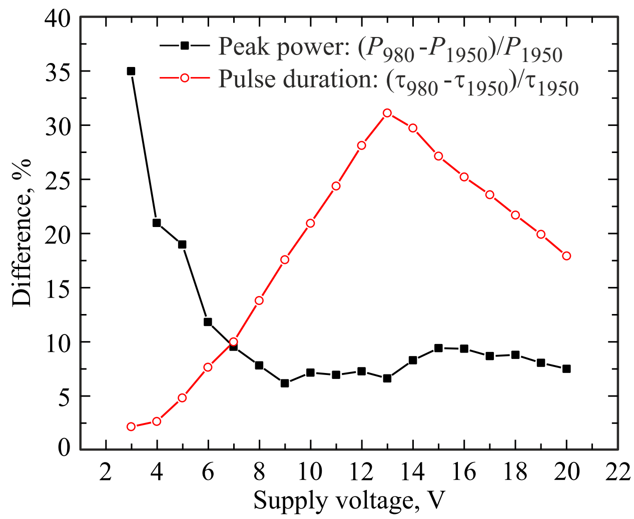


**Figure 5.** Supply voltage dependences of exceeding the peak power level $P$ and the duration of the optical pulse $\tau$ of 980 $\mu$m long laser thyristors vs. 1950 $\mu$m long laser thyristors.

the laser thyristors. There are no obvious signs of the effects of laser generation disruption in the dynamics of the output optical power (Figure3), therefore, we assume that the duration and amplitude of the laser pulse directly depend on the duration and amplitude of the current through the LT. Thus, the laser thyristors with the shortest optical pulse duration should also have the shortest electrical pulse. Figure 6 shows the dynamics of voltage on capacitor with a rating of 22 nF for laser thyristors with lengths of 480, 980 and 1950 $\mu$m and supply voltages of 7 V (*a*) and 20 V (*b*).

The standard method for estimating the amplitude of the LT current in the absence of load resistance is based on the ability to correctly differentiate the voltage dynamics on the capacitor and multiply the result by its rating [5].

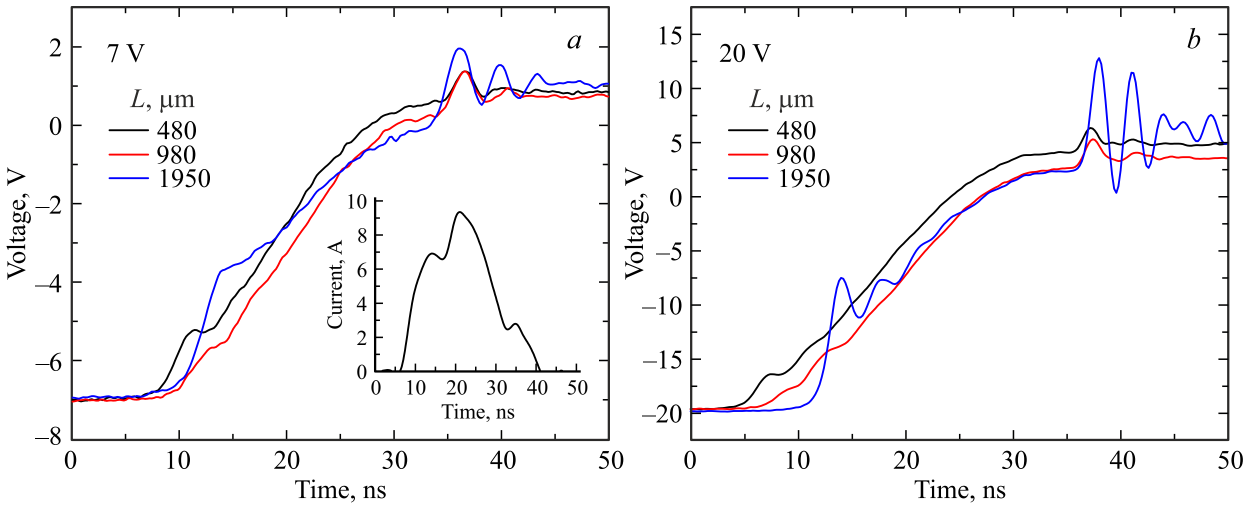


**Figure 6.** The dynamics of voltage on a capacitor with a rating of 22 nF for laser thyristors with lengths of 480, 980 and 1950 $\mu$m and supply voltages of 7 V (*a*) and 20 V (*b*). The calculated current dynamics for laser thyristors with a length of 490 $\mu$m at a supply voltage of 7 V is shown in the insert *a*.

Unfortunately, it was difficult to estimate the current amplitude in this case using the described method for laser thyristors with lengths of 980 and 1950 $\mu$m because of the complex dynamics of the voltage on the capacitor. The differentiation of voltage dynamics gave the following result in the case of a short laser thyristor with a length of 480 $\mu$m with low supply voltages: the calculated current amplitude was 9.3 A at 7 V (see insert in Figure 6, *a*). The calculated values of the current amplitude turned out to be significantly underestimated both for laser thyristors with a length of 980 $\mu$m and for laser thyristors with a length of 1950 $\mu$m and resulted in the overestimated values of the slope of the watt-ampere characteristic (WAC).

Despite the fact that the differentiation of the voltage dynamics on the capacitor provides inaccurate numerical values of the current amplitude in this experiment, some conclusions can be drawn about the very nature of the dependence of the peak current of the LT on the supply voltage based on the available measurement results. Firstly, this dependence is predominantly nonlinear in nature with a small linear section from 3 to 7 V. Secondly, the duration of electrical pulses of laser thyristors with lengths of 980 and 1950 $\mu$m is almost identical in the same supply voltage range of 3–7 V, the difference does not exceed 1 ns, which may indicate a comparable amplitude of the current flowing through the LT in the conditions of identical supply voltages and the capacitor rating. With an increase of the supply voltage, the duration of the electrical pulse of 980 $\mu$m long laser thyristors increases from 27.4 ns (8 V) to 30.3 ns (14,V), then decreases to 28.4 ns (20 V), while the pulse duration of 1950 $\mu$m long laser thyristors systematically decreases from 26.1 ns (8 V) to 24 ns (20 V). Thus, a shorter duration of the electric pulse of 1950 $\mu$m long laser thyristors in the supply voltage range of 8–20 V may indicate a greater amplitude of the current flowing through the LT. Laser thyristors with a length of 480 $\mu$m have a longer duration of an electric pulse compared to laser thyristors with a length of 1950 $\mu$m over the entire range of supply voltages and, accordingly, a lower current amplitude.

The observed dynamics of capacitor discharge is slightly different from the expected dynamics. It could be assumed that a multiple change of the LT area (in this case due to a change of the length of the resonator) in case of a compact mounting of elements would result in a comparable change of the resistance of the discharge circuit. In reality, the behavior of the discharge contour turned out to be less predictable, therefore, preliminary modeling of its dynamics was performed taking into account the parameters known to us.

The maximum contribution to the resistance of the circuit is made directly by the LT crystal, the parasitic inductance of the circuit elements has the maximum contribution to the inductance of the circuit, and the capacitance of the capacitor of 22 nF has the maximum contribution to the capacitance, since it significantly exceeds the values of the barrier (tens of pF) and diffusion (within 1 nF) capacitances of *p*-*n*-transitions for the used laser thyristor heterostructure.

It is possible to give some estimates of the observed differences in the dynamics of capacitor discharge. Both the inductance ($\leq$ 1 nH) and the resistance (may exceed 1.5 ohms) have maximum values in a circuit with a laser thyristor length of 480 $\mu$m. Therefore, we see, on the one hand, the maximum reverse polarity voltage on the capacitor because of the high inductance, and on the other hand, the fluctuations at the end of the discharge pulse associated with the transition of the LT to the closed state have a minimum amplitude and quickly attenuate due to the high resistance of the circuit.

The circuit with a laser thyristor length of 1950 $\mu$m has both a minimum inductance ($\sim$ 0.1 nH) and a significantly lower resistance compared to other laser thyristors. However, apparently, the available circuit parameters are still not ideal for the 1950 $\mu$m laser thyristor, since they do not make it possible to realize the existing advantage in resistance and pump a significantly higher current through the crystal. Circuits with 980 and 1950 $\mu$m laser thyristors have similar inductance values, therefore, the reverse polarity voltage on the capacitor is the same in them at large amplitudes of the flowing current (in particular, at a supply voltage of 20 V). The continued optimization of the electrical circuit, including a more detailed analysis of transients and the control of the parasitic parameters, is the aim of our further work.

### 4.2. Measurement of laser generation spectra

In addition to the amplitude of the current flowing through the laser thyristor, the dependence of the output optical power on the supply voltage (Figure 2) may be affected by increased internal optical losses. The estimation of their influence began with the measurement of the laser generation spectra of all laser thyristors for identifying possible features. A characteristic view of the spectra of laser thyristors of different lengths is shown in Figure 7, the measurement results at supply voltages 7, 15 and 20 V are shown as an example.

It can be seen that the position of the central line of the spectrum significantly depends on the length of the resonator, while the difference between the corresponding values of laser thyristors with lengths of 480 and 1950 $\mu$m is $\sim$ 30 nm. Such behavior of laser generation spectra based on AlGaAs/GaAs/InGaAs heterostructures without wavelength-selective elements is typical as such. The dependence of the position of the laser generation line on the length of the resonator was directly shown in Ref. [15]. The presence of factors negatively affecting the output optical power level could be indicated to a greater extent by a noticeable deformation of the spectrum of laser thyristors of the same length with an increase of the pumping current. Here and further, data will be provided for the level of 10% of the normalized amplitude of the spectra. Laser thyristors with lengths of 480 and 1950 $\mu$m in our case show a typical expansion of the generation spectra for semiconductor lasers as the supply voltage and, accordingly, the current amplitude increase. This expansion is weakest in long 1950 $\mu$m laser thyristors as the change in the width of the spectrum from 3 to 20 V is only 2 nm, the maximum width of the spectrum is 6.1 nm, while the spectrum expands by 4.2 nm in 480 $\mu$m laser thyristors, the maximum width is 10.3 nm. The difference of the width of the spectra can be explained by the fact that the current density is higher in 480 $\mu$m laser thyristor with the same supply voltage. The shift of the right edge of the spectrum to the long-wavelength region relative to its initial position does not exceed 2.2 nm for 1950 $\mu$m laser thyristor and 2.7 nm for 480 $\mu$m laser thyristor, no significant shift of the central wavelength of the spectrum is observed in any direction. Comparing the

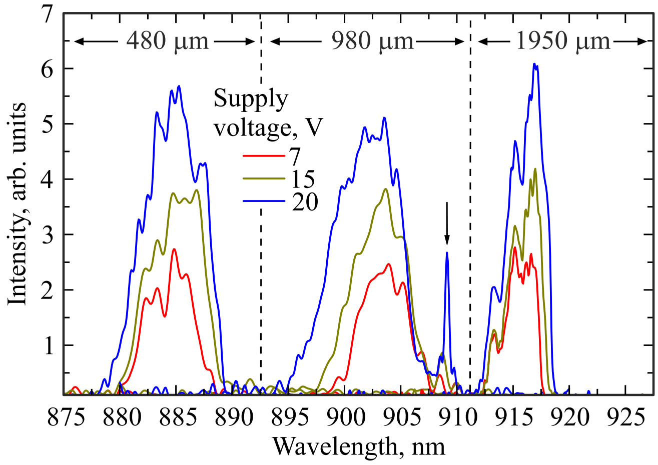


**Figure 7.** Laser generation spectra of laser thyristors with lengths of 480, 980 and 1950 $\mu$m for supply voltages of 7, 15 and 20 V.

results obtained using published data of other emitters with a similar design of a single laser part [13,14], it is possible to state that the active region of the laser part of the laser thyristor is not additionally heating compared with the active regions of laser chips for at least two of the three studied resonator lengths — 480 and 1950 $\mu$m. Thus, the nature of the internal optical losses in these laser thyristors does not allow for making any critical changes of the generation spectra.

A situation with 980 $\mu$m laser thyristors is different. As can be seen from Figure 7, the spectrum has a main part with a width of up to 11.8 nm and additional lines to the right of the main ones (shown by a vertical arrow). At the same time, the total width of the spectrum, taking into account additional lines, can reach 14.5 nm, which significantly exceeds similar values for laser thyristors of other lengths. Since this type of generation spectrum has not been previously recorded [13,14], its features can be associated not only with the design of the laser part, but with the operation of the laser thyristor as a whole. It cannot be excluded that the processes resulting in a deterioration of the spectral characteristics of 980 $\mu$m laser thyristors also limit the level of the maximum achievable optical output power of laser thyristors.

### 4.3. Evaluation of external differential efficiency

So, laser thyristors with a length of 1950 $\mu$m have the narrowest laser generation spectra with the weakest expansion with an increase of supply voltage, which may be attributable to the higher Q-factor of the resonator compared with laser thyristors of shorter length. Internal optical losses in 1950 $\mu$m laser thyristors do not significantly change the appearance of the laser generation spectra. It seems obvious that a semiconductor laser with a longer resonator length will experience a negative effect of internal optical losses on the optical power output level to a greater extent than a laser with a shorter resonator length. However, the scale of this impact will be determined primarily by the magnitude of internal optical losses themselves.

The position of the control sections to the left and right of the laser thyristor laser strip does not allow for effective direct pumping of the laser part with a high amplitude current because of the resulting heterogeneity of its flow [16]. Therefore, experimental data obtained by measuring of the WAC of semiconductor lasers made of specially grown supporting laser heterostructure were used for estimation of the magnitude of internal optical losses. The design of the supporting heterostructure completely replicated the design of the laser part of the laser thyristor heterostructure, the width of the laser strip, as in laser thyristor, was $200\,\mu$m, no antireflective and reflective coatings were applied on the crystal faces. Samples with lengths of 490, 970 and $1480\,\mu$m were selected for characterization. WAC was measured in its initial section, when the output optical power increases linearly as the pumping current increases. Further calculations were performed using the formulas (1)–(3) [17,18]:

$$1/\eta_D = (1/\eta_i) \cdot \left(1 + \frac{2 \cdot L \cdot \alpha_i}{\ln(1/(R_f \cdot R_b))}\right), \quad (1)$$

$$\eta = \eta_D \cdot 1.24/\lambda, \quad (2)$$

$$P_{\text{out}} = \eta \cdot (I - I_{\text{th}}), \quad (3)$$

where $R_f = R_b = 0.3$ — reflection coefficients of the front and back faces of the resonator, respectively, $\eta_i$ — internal quantum output, $\eta_D$ — external differential quantum efficiency, $\alpha_i$ — internal optical losses, $L$ — resonator length, $\eta$ — external differential efficiency, $P_{\text{out}}$ — optical output power, $I_{\text{th}}$ — threshold current, $\lambda$ — radiation wavelength.

The values of the internal quantum yield $\eta_i$ and internal optical losses $\alpha_i$ of the supporting heterostructure from the ratios (1)–(3) were estimated using the method described in [18]. Table 1 presents the results of measurements of the threshold current $I_{\text{th}}$ of laser thyristors with lengths of 490, 970 and $1480\,\mu$m, as well as an estimate of the values of the internal quantum yield $\eta_i$ and internal optical losses $\alpha_i$ of the supporting heterostructure.

The data obtained during the study of the supporting heterostructure helped to understand what the characteristics of the laser part of the laser thyristors could be. The measurement of the WAC of the supporting heterostructure with different resonator lengths allowed obtaining the dependence of the threshold current on the length of the resonator, approximating it with the 2nd order polynomial and determining the estimated values of the threshold current $I_{\text{th}}$ for laser thyristors with lengths of 480, 980 and $1950\,\mu$m in accordance with the lengths of the laser thyristor samples. The threshold current values calculated using approximation for samples with lengths of 480, 980 and $1950\,\mu$m are listed in Table 2. In addition, the values of $\eta_i$, $\alpha_i$ and the real data of the measured laser generation spectra were used to calculate the external differential quantum efficiency $\eta_D$ and external differential efficiency $\eta$ in accordance with the formulas (1) and (2), these values are also listed in Table 2.

**Table 1.** Threshold current $I_{\text{th}}$, internal quantum efficiency $\eta_i$ and internal optical losses $\alpha_i$ of supporting heterostructure samples

| $L$, $\mu$m | $\eta_i$ | $\alpha_i$, cm | $I_{\text{th}}$, A |
|---|---|---|---|
| 490 | | | 0.57 |
| 970 | 0.92 | 2.22 | 0.65 |
| 1480 | | | 0.75 |

**Table 2.** Threshold current $I_{\text{th}}$, external differential quantum efficiency $\eta_D$ and external differential efficiency $\eta$ of the LT laser part

| $L$, $\mu$m | $I_{\text{th}}$, A | $\eta_D$ | $\eta$, W/A |
|---|---|---|---|
| 480 | 0.57 | 0.85 | 1.18 |
| 980 | 0.65 | 0.78 | 1.07 |
| 1950 | 0.87 | 0.68 | 0.93 |

It can be seen that the external differential efficiency $\eta$ decreases with the increase of the resonator length from 480 to $1950\,\mu$m by 0.25 W/A with the internal optical loss level $\alpha_i = 2.22\,\text{cm}^{-1}$ and internal quantum yield $\eta_i = 0.92$. It is possible to determine the peak current values that would correspond to the actually measured values of peak optical power (see Figure 2) having data on the external differential efficiency of the samples at the initial linear section of the WAC, using the formula (3). The peculiar feature is that the linear dependence of peak power on voltage is maintained in the supply voltage range of 3–5 V, while the linear dependence of peak current on voltage, as previously indicated, is maintained in the range of 3–7 V. Therefore, the formula (3) can be directly used for recalculation only in the smaller of the ranges of 3–5 V, and then the linear dependence of the peak current can be approximated to determine the peak current values up to 7 V. The peak current stops to increase linearly at higher supply voltages, so it is impossible to continue the approximation.

Figure 8, *a* shows the WAC of experimental laser thyristors in which the peak power values are taken directly from the experiment (see Figure 2), and the peak current values are calculated from the ratio (3) for the voltage range of 3–5 V and approximated to 7 V. Figure 8, *b* shows the WAC of the samples of the supporting heterostructure for illustration. The efficiency of the emitters decreases with the increase of the resonator length in both cases. However, while the output optical power level is controlled by directly changing the amplitude of the pumping current in the case of conventional strip lasers, which the samples based on a supporting heterostructure were, then the directly controlled parameter in case of laser thyristor is not the amplitude of the current, but the supply voltage. One should not

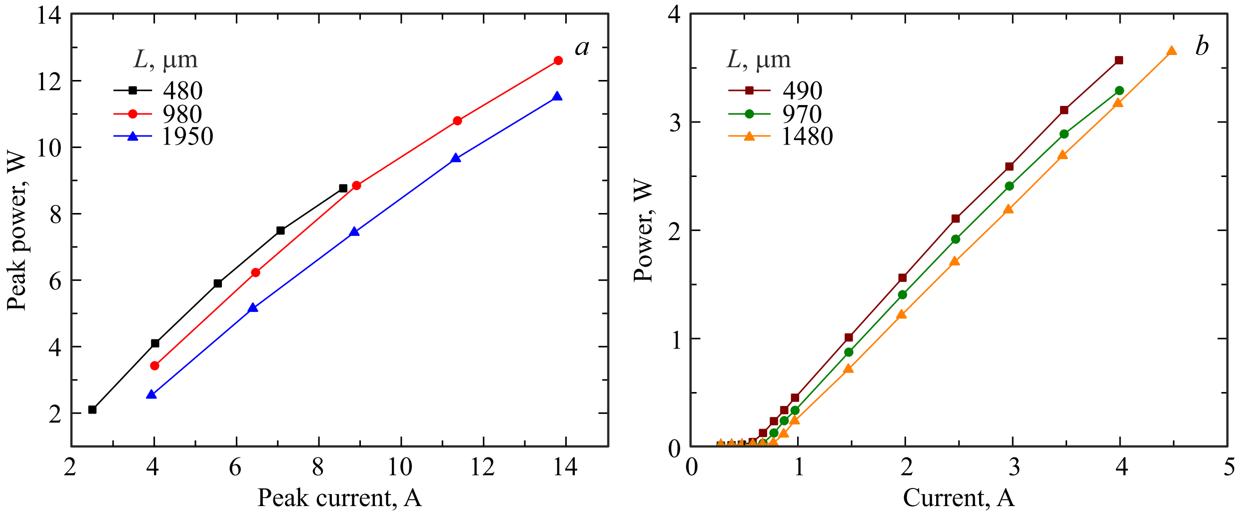


**Figure 8.** WAC of 480, 980 and 1950 $\mu$m laser thyristors in the supply voltage range of 3–7 V (*a*) and WAC of the supporting heterostructure samples with lengths of 490, 970 and 1480 $\mu$m (*b*).

rely solely on the WAC data when analyzing the overall efficiency of laser thyristors, since the dependence of the amplitude of the laser thyristor current on the supply voltage is nonlinear, it is necessary to take into account the efficiency of the laser thyristor discharge circuit as a current switch in general.

Laser thyristors with a length of 480 $\mu$m demonstrate the lowest current amplitude compared with longer laser thyristors formally having the maximum external differential efficiency at the initial linear section of the WAC. An increased sequential resistance compared to long laser thyristors may be the probable cause of this phenomenon, as mentioned earlier. Another disadvantage of short laser thyristors is a decrease of the slope of the WAC already at a current amplitude of 7.1 A (6 V), which indicates a decrease of external differential efficiency. According to Figure 2, short laser thyristors have the lowest optical output power, so there is no reason to believe that the situation will improve with a further increase in the supply voltage and, accordingly, the amplitude of the current flowing through the laser thyristor. Thus, laser thyristors with a length of 480 $\mu$m have a lower optical output power compared with longer samples with the same supply voltages, on the one hand, due to greater series resistance and, accordingly, a lower current amplitude, and on the other hand, due to a decrease of the external differential efficiency already at the current amplitude of 7.1 A (6 V).

Laser thyristors with lengths of 980 and 1950 microns have similar current amplitude values in the supply voltage range of 3–7 V (which coincides with the earlier conclusion based on the comparison of the durations of an electric pulse), while showing less obvious signs of the WAC rollover and a decrease of the external differential efficiency compared to laser thyristor with the length of 480 $\mu$m. It can be seen from the data in Figure 2 that the rate of increase of the output optical power of both types of laser thyristors significantly decreases as the supply voltage increases further, therefore, the decrease of external differential efficiency will become more noticeable for them. Taking into account all of the above, it is possible to conclude that initially lower external differential efficiency is the main reason for the decrease of optical output power in laser thyristors with a length of 1950 $\mu$m compared to laser thyristors with a length of 980 $\mu$m with a comparable current amplitude. This disadvantage can potentially be compensated by the ability to pump long samples with a higher amplitude current at a fixed supply voltage, since they have the lowest resistance. This requires conducting work for optimizing the parameters of the discharge circuit, which will be the subject of further study.

## 5. Conclusion

The dynamics of the optical output power, voltage dynamics on a capacitor connected in parallel with laser thyristor with a rating of 22 nF and laser generation spectra were measured in the course of operation for laser thyristors with different resonator lengths (480, 980 and 1950 $\mu$m). All laser thyristor were studied at room temperature under the same conditions: control current — 10.4 mA, pulse repetition rate — 203 Hz.

The highest level of optical output power in the entire supply voltage range was demonstrated by samples with a length of 980 $\mu$m. The peak power value was 25.4 W for a maximum supply voltage of 20 V. The presence of additional spectral lines in the right part of the laser generation spectra may indicate processes that limit the level of optical output power.

The lowest optical power output was shown by samples with a length of 480 $\mu$m. The first reason for this is the lower amplitude of the current flowing through the laser thyristor compared to other samples, which may be attributable to the higher series resistance of the sample due to the smaller area pumped by the current. The second reason is a decrease of the value of the external differential efficiency from its initial value of 1.18 W/A when the supply voltage exceeds 6 V, which corresponds to a current amplitude of only 7.1 A.

Samples with a length of 1950 $\mu$m had a lower level of optical output power compared to samples with a length of 980 $\mu$m because of the initially lower value of the external differential efficiency (in the linear section of 0.93 W/A versus 1.07 W/A for laser thyristors with a length of 980 $\mu$m). On the positive side these laser thyristors characterize the minimum width of the generation spectrum and the duration of the optical pulse (from 18.4 ns at 3 V to 22.4 ns at 20 V). The laser thyristors with a length of 1950 $\mu$m showed a significant reduction of pulse duration in the supply voltage range of 10–18 V compared with more powerful laser thyristors with a length of 980 $\mu$m ($> 20\%$, a maximum of 31.1% at 13 V), being inferior to the latter in the level of optical output power of only 7–8.8%.

Thus, it is possible to make a conclusion about low efficiency of laser thyristors with a length of 480 $\mu$m in case of operation in pulse generation modes with a duration of 20–30 ns. Laser thyristors with lengths of 980 and 1950 $\mu$m can be used in these operating modes, while preference for one or another resonator length will be given in accordance with the requirements of either achieving the maximum level of optical output power (980 $\mu$m) or the minimum optical pulse duration (1950 $\mu$m).

The analysis of the WAC in the initial section showed that the efficiency of the laser part of the laser thyristor depends on the length of the resonator in the same way as the efficiency of strip lasers based on the supporting heterostructure. However, the key difference between laser thyristor and a conventional semiconductor laser is the nonlinear dependence of the current in the laser thyristor circuit on the supply voltage, therefore, the question of the efficiency of the discharge circuit as a whole is added to the question of the efficiency of the laser part itself. The subject of further study will be the optimization of the discharge circuit parameters for obtaining higher peak current values and, accordingly, optical output power with the same supply voltages.

### Conflict of interest

The authors declare that they have no conflict of interest.

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