Pumping pulsed gas lasers by longitudinal discharge from a generator with inductive energy storage and a semiconductor opening switch

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Received January 20, 2000

We present the results of our experimental study of pumping nitrogen (λ = 337.1 nm) and CO_2 (λ = 10.6 μm) lasers by a longitudinal discharge. The discharge was generated by a generator with an inductive energy storage and a semiconductor opening switch. The power and temporal output characteristics of the lasers are presented. The oscillograms and dependences have been obtained that characterize different modes of laser operation. A model for calculating voltage and current in the discharge circuit as well as energy deposition and losses in the opening switch is described. The calculated results are in close agreement with the experimental data.

In our previous papers[1–8] it was shown that the inductive energy storage can be successfully used for pumping pulsed dense-gas lasers. Generators with the inductive energy storage allow one to readily change pump modes to provide optimal conditions for exciting different lasers.[4,8] Creation of specialized semiconductor opening switches (SOS diodes)[9,10] significantly extended the capabilities of generators with the inductive energy storage. However, detailed data characterizing various pumping modes of pulsed gas lasers from the inductive energy storage are absent in the literature, especially on the pump by a longitudinal discharge.

In this connection we have studied the operation of the pump generator with the inductive energy storage and a semiconductor opening switch. The pulsed gas laser excited by a longitudinal discharge was used as a gas-discharge load.

Experiment

To study the peculiarities of pumping the nitrogen (λ = 337.1 nm) and CO_2 (λ = 10.6 μm) lasers by a longitudinal discharge from a generator with the inductive energy storage and a semiconductor opening switch, the experimental setup was designed, whose circuitry is shown in Fig. 1. We used a TGI–10000/25 thyratron (T), C_0 = 5.5 nF, L_0 = 16 μHn, U_0 = 25–32 kV (usually 31 kV), inductance L_1 = 1–5 μHn (usually 3 μHn), and the opening switch D. The storage capacitor C_1 = 4.4 nF was charged from a primary thyratron generator up to the voltage U_1 ~ 30 kV for about 600 ns. The maximum charge current was ~ 350 A.

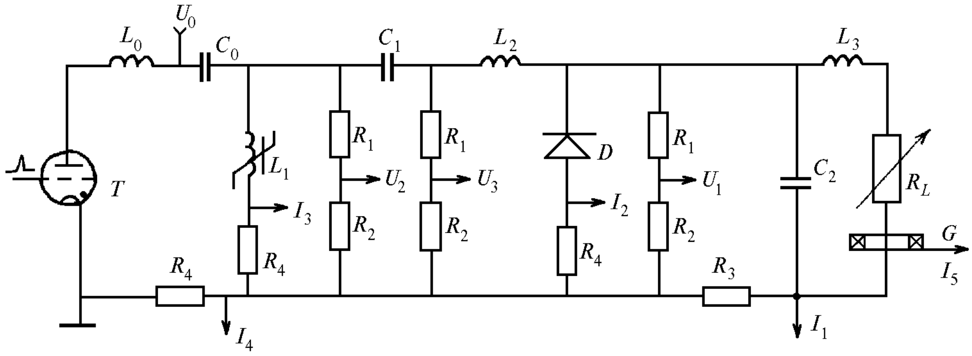

Fig. 1. Principal circuitry of the experimental setup with a semiconductor opening switch.

0235-6880/00/03 220-07 $02.00

Specialized silicon diodes of the SOS–100–2 or SOS–150–2 type[9] with the maximum reverse voltage of 100 or 150 kV, respectively, and the maximum cut-off current amplitude of 2 kA were used as the opening switch. A magnetic switch L_1 was recharged being under the voltage equal to the voltage applied to the capacitor C_1. It was made as a nonlinear choke with the core of 6 cm in diameter and 2.6 cm in cross section made from 50NP permalloy strip of 0.01 mm thickness. The number of windings was equal to six. As C_1 was completely charged, the core was saturated, the inductance L_1 decreased down to $L_{1s} \ll L_1$, and the capacitor C_1 became to discharge into the circuit C_1–L_2–D–L_1 and, by this moment, the current was already flowing through the diode in the reverse direction. The time of current rise in this circuit was about 150 ns, then the diode resistance increased drastically.

Due to the fast drop of the current in the circuit (its inductance $L_\Sigma = L_{1s} + L_c + L_2 \approx 5$ μHn, where L_c is the constructive inductance of the circuit taking into account interaction of magnetic fields of separate inductances), a high-voltage pulse arose at the load R_L and the diode D. The energy stored in the inductance L_Σ charged the peaking capacitor C_2 up to the voltage of 40–80 kV for 20–70 ns, depending on C_2. At the voltage across the gas-discharge tube of 50–80 kV, the breakdown in the working gas occurred. The inductance of leads in the L_3 circuit was usually made as low as possible. In some experiments, the laser tube was replaced by a TVO resistor connected in series with a spark gap of a micrometer size. This allowed the current and voltage to be measured at a constant load resistance. In the laser, the gas-discharge tube was a glass tube whose length (20 and 40 cm) and inner diameter (2.2, 3.4, 6.8, and 9.5 mm) were different in different experiments. The tube was filled with nitrogen or the mixture CO_2–N_2–He and connected in parallel with a diode having minimal inductance.

The inner cavity was set at the tube ends. It consisted of a plane aluminum-coated mirror and a plane-parallel quartz plate, or a flat copper mirror and a germanium plate with a multilayer coating having 80% reflectance at λ = 10.6 μm. The voltage and current in the setup were measured with an ohmic divider R_1–R_2 and shunts R_3 and R_4, as well as Rogovskii loop G, signals from which came to a 6–LOR oscilloscope. In some experiments the leads to the load from the peaking capacitor and diode were made in parallel, and the current through them was measured with separate shunts. The shape and power of a laser pulse were measured with a FEK–22 SPU or FSG–22–3A2 photodiode, and the mean output power, in the repetitively pulsed mode, was measured with an IMO–2N calorimeter.

Pump features

In the experiments with the inductive energy storage various types of loads were used. Figure 2*a* shows the oscillograms of the generator current at a constant load. The load resistance was changed only when connecting TVO resistors of different nominal values. At the constant load resistor, its resistance was high at the initial moment before the breakdown of the spark gap. After the breakdown, the load became, for several nanoseconds, equal to the resistance of the resistor. It is an important circumstance that the current cut-off rate in the diode is different at different load current. From Fig. 2*b* it is seen that at the low-resistance load (short circuit mode) the current cut-off rate is the highest, and as the load resistance increases up to 193 Ω, the time of current cut-off increases and the rate dI/dt decreases.

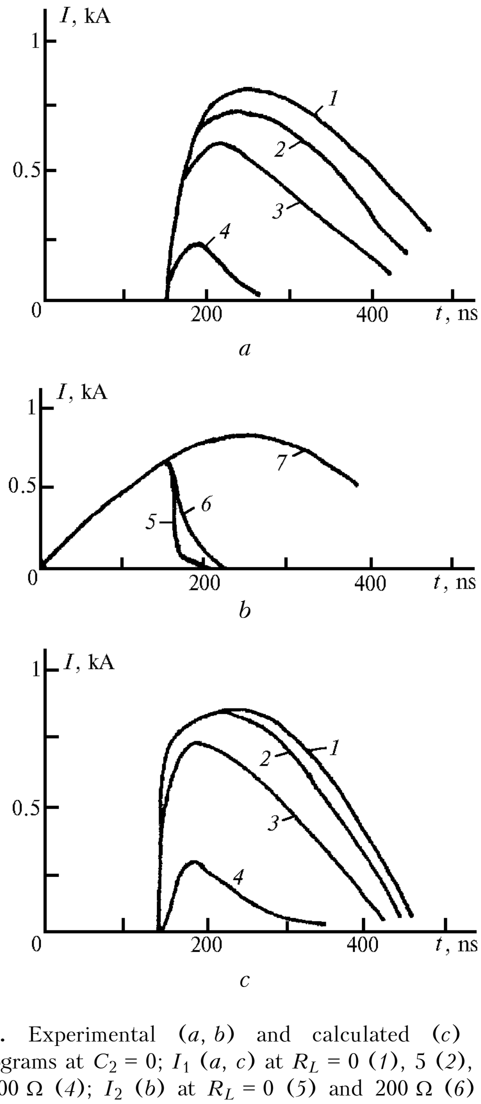

Fig. 2. Experimental (*a*, *b*) and calculated (*c*) current oscillograms at $C_2 = 0$; I_1 (*a*, *c*) at $R_L = 0$ (*1*), 5 (*2*), 20 (*3*), and 200 Ω (*4*); I_2 (*b*) at $R_L = 0$ (*5*) and 200 Ω (*6*) and at short-circuit switch (*7*).

Note that in this circuit low current continued to flow through the load for several hundreds nanoseconds after the main pulse. It is explained by the fact that in the actual circuit the magnetic switch L_1 opened somewhat earlier than needed, and some part of the energy remained in the capacitor C_0. This energy provided its recharge through the circuit L_0–T–L_1. Once the current through L_1 stopped, the capacitor C_1 began to receive charge from C_0 through the load resistor R_L. All these processes are clearly seen in Figs. 3 and 4, which illustrate operation of the actual circuit with two different values of C_1 capacitance. For the ranges of pressure and gas-discharge tube length used in our experiments, the resistance of gas-discharge tubes filled with nitrogen was tens ohms, and that of tubes filled with the mixture CO_2–N_2–He was hundreds ohms. This caused the choice of the loads, at which the oscillograms shown in Figs. 3 and 4 were recorded. Figure 3 shows the oscillograms of the current through the load I_5 (curve *1*) and opening switch I_2 (*2*), short-circuit current (*3*), current through the magnetic choke I_3 (*4*), and capacitor C_0 I_4 (*5*), as well as the oscillograms of voltage U_1 (*6*), U_3 (*7*), and U_2 (*8*). These oscillograms were recorded at the constant load of 58 Ω and at almost equal capacitance of the C_0 and C_1 capacitors. These conditions are optimal for this circuit from the viewpoint of energy transfer from C_0 to the inductance. The breakdown of the spark gap occurred almost immediately after the current cut-off in the opening switch and the voltage across the load increased (that is, the load of 58 Ω was connected to the inductive energy storage very fast before reaching the maximum voltage). So, the maximum voltage across the load was less than 40 kV. The current flowing for several hundreds nanoseconds after termination of the main pulse was caused by the discharge of the capacitor C_0 (oscillogram *3* in Fig. 3).

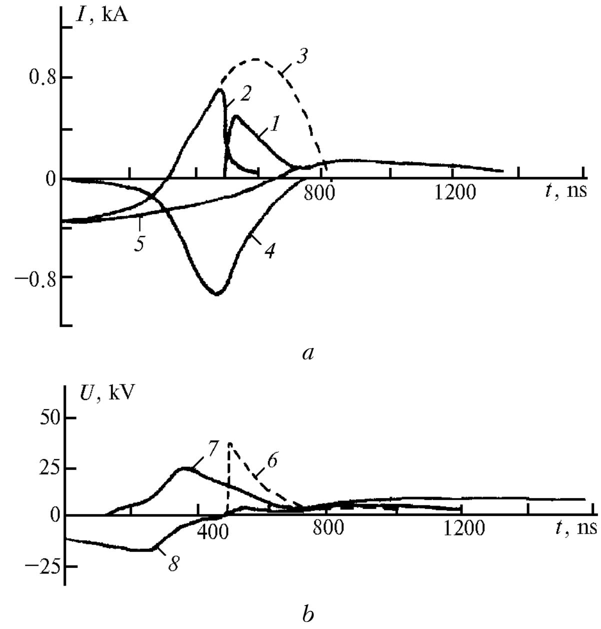

Fig. 3. Oscillograms of current and voltage at the setup operation with the load $R_L = 58$ Ω ($C_1 = 4.4$ nF, $C_2 = 0$): I_1 (*1*), I_2 (*2*), I_2 at the short-circuit opening switch (*3*), I_3 (*4*), I_4 (*5*), U_1 (*6*), U_3 (*7*), and U_2 (*8*).

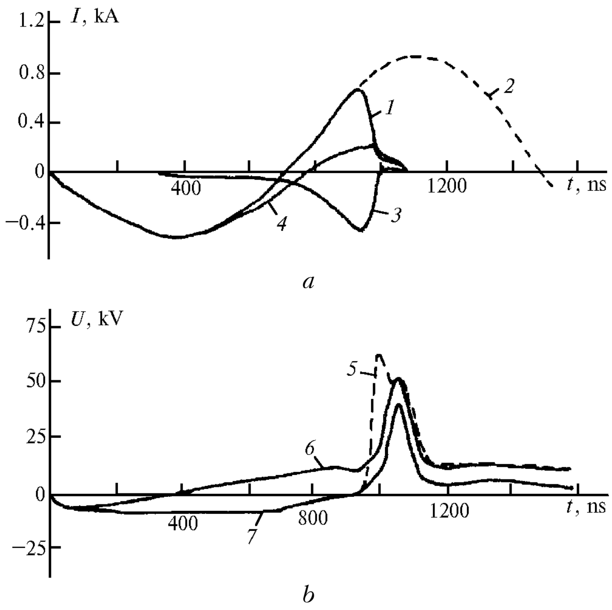

Fig. 4. Oscillograms of current and voltage at idle operation of the setup ($C_1 = 16.5$ nF, $C_2 = 0$): I_2 (*1*), I_2 at the short-circuit opening switch (*2*), I_3 (*3*), I_4 (*4*), U_1 (*5*), U_3 (*6*), and U_2 (*7*).

Figure 4 shows the current and voltage oscillograms at idle operation of the setup: current I_2 through the diode D (curve *1*), at the short circuit of the diode (*2*), current through the magnetic choke I_3 (*3*) and capacitor C_0 I_4 (*4*), as well as voltages U_1 (*5*), U_3 (*6*), and U_2 (*7*). The current and voltage dynamics is clearly seen from the moment of the thyratron T initiation. In this case the C_1 capacitance was specially increased (up to 16.5 nF), what allowed, when pumping a CO_2 laser, the discharge to be formed using the energy stored in the inductance while the main pump took place using the energy remaining in the capacitor C_1. This operating mode is characterized by longer pulses of current and voltage across the load and two peaks in the voltage pulse. The second peak in the voltage pulse is likely to be caused by an increase in the inductance of the magnetic switch for the capacitor C_1 to discharge at an increase of the resistance of the opening switch.

It should be noted that the nitrogen laser is a laser on self-limited transitions, and lasing in them occurs practically within the leading edge of the current pulse. Figure 5 shows oscillograms of the voltage pulses at the gas-discharge tube filled with nitrogen and the current through it with the peaking capacitor C_2 connected in parallel with the discharge tube. Inclusion of the peaking capacitor results in an increase of the current flowing through the discharge tube, but the value of the maximum voltage across the tube decreases in this case. At relatively low values of the C_2 capacitance and short tubes, the current growth rate and the pump power in some operating modes can even increase as compared with pumping from only the inductive energy storage. Therefore, to achieve the maximum pump power, both the inductive energy storage and the capacitive one charged from the inductive energy storage can be used in particular discharge tubes. As the tube length (inductance L_3) increases significantly, the highest pump power can be achieved with the use of the inductive energy storage.

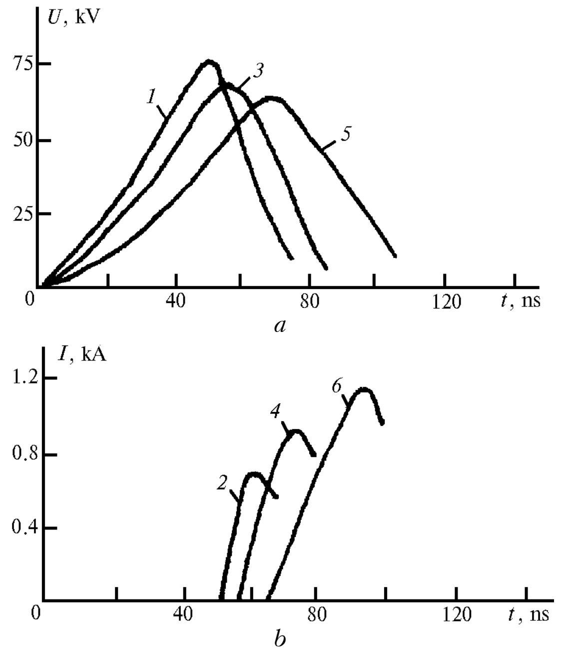

Fig. 5. Oscillograms of voltage across a gas-discharge tube (*1*, *3* – *5*) and the discharge current (*2*, *4*, *6*). Discharge in nitrogen, p = 30 Torr, C_2 = 94 (*1*, *2*), 170 (*3*, *4*), and 330 pF (*5*, *6*).

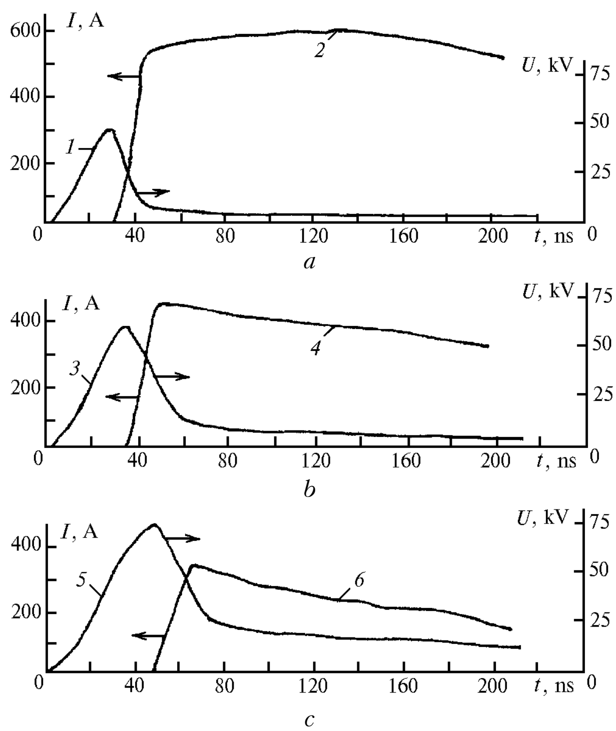

Fig. 6. Oscillograms of the discharge current (*1*, *3* – *5*) and voltage across a gas-discharge tube (*2*, *4*, *6*). Discharge in nitrogen, C_2 = 0, p = 6 (*a*), 15 (*b*), and 30 Torr (*c*).

Figure 6 shows the characteristic oscillograms of the discharge current and voltage in the case that the inductive energy storage loaded by the gas-discharge at different nitrogen pressure in the tube. It is seen that as the pressure increases, the breakdown voltage of the gas-discharge tube and the discharge resistance increase too, whereas the discharge current decreases and the drop of voltage applied to plasma slows down. The highest current growth rate is achieved at low pressure, at which the load resistance is lower.

To realize the conditions optimal for lasing in CO_2, the C_1 capacitance was increased up to 16.5 nF. This led to the increase in the C_1 charge voltage up to about 14.5 kV and increased the energy loss at charging the capacitor C_1 from the C_0 capacitor. However, in this mode the major part of energy is deposited into the working mixture at a relatively low voltage across the gas-discharge plasma, and the pump pulse duration exceeds 1 μs (see Fig. 4). As was noted above, the features of this system are the appearance of the second voltage peak caused by the increasing inductance of the discharge magnetic switch of the capacitor C_0 and formation of longer voltage and current pulses.

Model for calculations

To simulate the operation of the generator with the inductive energy storage into the load, the computer program was developed for calculation by the equivalent simplified scheme of the generator. The equivalent scheme consisted of the RLC oscillation circuit with $L = L_\Sigma$ and $C = C_1$ and two resistors connected in parallel whose resistance varies in time. One resistor (R_D) corresponded to a semiconductor opening switch, and another (R_L) corresponded to the gas-discharge load, and their resistances at different time were described by the equations similar to those used in Ref. 11:

$$R_D = \begin{cases} 0.5; & 0 \le t \le t_1 \\ \mathrm{d}R/\mathrm{d}t \cdot (t - t_1) + 0.5; & t > t_1 \end{cases}, \quad (1)$$

$$R_L = \begin{cases} 10^6; & 0 \le t \le t_2 \\ 60 + 10^6/\exp(\alpha \times (t - t_1)); & t > t_2 \end{cases}, \quad (2)$$

where t_1 is the time of the current cut-off start and t_2 is the moment of the gas-discharge gap breakdown.

The values of the coefficients $\mathrm{d}R/\mathrm{d}t \approx 6{\cdot}10^9$ Ω/s and $\alpha \approx 9{\cdot}10^8$ s^{-1} were fitted by comparing the experimental and calculated data. Presentation of the SOS diode impedance in the current cut-off phase as a resistance linearly varying in time allows close description of experimental oscillograms (Fig. 2*c*). However, it certainly cannot replace specially developed models. This model allowed us to calculate the loss in the semiconductor opening switch and energy deposition into the load, as well as to analyze qualitatively the generator operation, while its parameters are being changed (e.g., at decreasing time of the direct pumping of the SOS diode). Besides, it allowed us to exclude the influence of the adjacent circuits, which are present in the actual setup, on the shape of the experimental oscillograms.

Lasing in nitrogen

In Refs. 1–4, 6, and 8 the longitudinal discharge was used to obtain lasing in nitrogen in the case of pumping by the generator with the inductive energy storage. It was shown that the use of the inductive energy storage allows pumping by unipolar pulses with a steep leading edge and efficient energy transfer into the load. In the case of pumping from the inductive energy storage, the influence of inductance of the discharge circuit L_3 drops down and the range of the working pressure, at which lasing occurs, extends. The peaking capacitors connected in parallel with the discharge tube decrease the energy loss in the opening switch and can increase the laser output energy. We obtained the pulse power of 40 kW and the mean output power of 12 mW in the repetitively pulsed operating mode (pulse repetition rate of 100 Hz) of the laser pumped by the generator with the inductive energy storage.

The maximum radiation intensity in the case of the nitrogen laser pumped by the generator with the inductive energy storage was achieved at L_Σ = = 4–5 mHn for the analyzed parameters of the circuit (C_1 = 4.4 nF, $U_1 \approx 30$ kV). The range of the analyzed diameters and lengths of laser tubes was significantly expanded in this paper. Figure 7 shows the dependence of the output energy per pulse and the mean output energy density on the nitrogen pressure in the tubes of different diameter. All the tubes were 20 cm long. The highest output energy of 0.4 mJ was obtained for the nitrogen laser at p = 15 Torr and C_2 = 170 pF, whereas at p = 30 Torr and C_2 = 94 pF it was 0.3 mJ. This is connected with the fact that the rate of capacitor charging and the duration of the leading edge of the current are different, and the difference between the discharge voltage increases with increasing pressure – the capacitor with lower capacitance is charged up to higher voltage and provides more steep leading edge of the current (see Fig. 5). The contribution of the inductive energy storage current to the total discharge current becomes significant in this case: for p = 30 Torr and C_2 = 94 pF it was 36% of the total current. The further decrease of the C_2 capacitance resulted in the decrease of the output energy, since the voltage across C_2 did not achieve its maximum (practically equal to the breakdown voltage at C_2 = 0), and the discharge current decreased.

Figure 8 shows the dependence of the pulse output energy on the nitrogen pressure at different capacitance of the peaking capacitor. The maximum output energy was obtained with the peaking capacitor of 170 pF and the tube 6.8 mm in diameter. It was 0.55 mJ. The maximum energy density was obtained in the tube of the least diameter (2.2 mm) and was 4.5 mJ/cm^2. As the tube length was doubled, the optimal nitrogen pressure was almost halved, that is, the value of U_0/pd remained constant (U_0 is the breakdown voltage of the gas-discharge tube, p is the gas pressure, and d is the interelectrode separation). The pulse output energy in the long tube increased by 45%. In the case of pumping from the inductive energy storage without the peaking capacitor, the maximum output energy for this tube was lower (Fig. 8, curve *4*). However, as the pressure increased, this difference started to decrease, then the output energy became the same in both the cases. At the maximum pressure, lasing in nitrogen was observed only in the case of pumping from the inductive energy storage without peaking capacitor. Note that SOS diodes allow kiloamper current to be switched into a load for several nanoseconds, but to realize this capability one should decrease the time of back pumping of the SOS diode (decreasing L_Σ in the first turn) and increase the charge voltage of the capacitor C_1. In this case one would expect a significant increase in the output energy and higher efficiency when pumping from the inductive energy storage as compared to pumping from the peaking capacitor. The high efficiency of pumping from the inductive energy storage can be likely realized in long discharge tubes (about 1 m) and in capillary tubes as well, in which the inductance of the circuit with the peaking capacitor increases significantly.

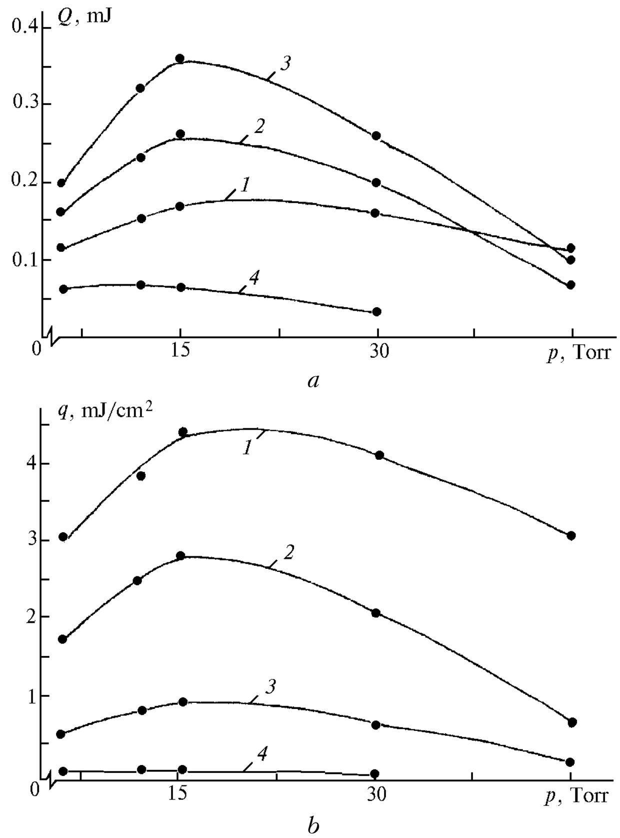

Fig. 7. Output energy (*a*) and output energy density (*b*) of nitrogen laser vs. nitrogen pressure in discharge tubes of different diameter d = 2.2 (*1*), 3.4 (*2*), 6.8 (*3*), and 9.5 mm (*4*) (tube length of 200 mm, C_2 = 330 pF).

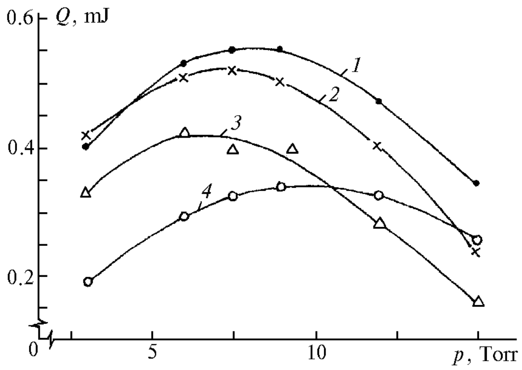

Fig. 8. Output energy of nitrogen laser vs. nitrogen pressure at 400 mm long discharge tube: d = 6.8 mm, C_2 = 170 (*1*), 330 pF (*2*), 0 (*4*) and d = 9.5 mm, C_2 = 330 pF (*3*).

Lasing in CO_2

The longitudinal discharge was not earlier used to obtain lasing in CO_2 with pumping from a generator with the inductive energy storage. In Refs. 7 and 8 it was shown that powerful and highly efficient lasing can be obtained in the case of pumping by the longitudinal discharge from the generator with the inductive energy storage. In this section we present the first results obtained for longitudinal pumping. We did not state the goal of complete optimization of the parameters of the pump generator for obtaining maximum lasing efficiency. As compared to the nitrogen laser, the pump pulse length should be increased, and the specific pump power should be decreased. Correspondingly, the highest output energy and pump efficiency were obtained at least-diameter and longest tubes.

To decrease the pump power and to increase the pump pulse length, we used the circuit with particular transfer of energy into the inductance and discharge sustaining at the expense of the energy stored in the capacitor C_1. Figure 9 shows the dependence of the output energy on the pressure of the working mixture for generators with peaking capacitor and without it. Since the role of the peaking capacitor reduces to the increase of the current in the first 100 ns, its use in the pump circuit of the CO_2 laser did not increase the output power and, what's more, resulted in the 10% decrease of the output energy per pulse. It is likely caused by the fact that the main part of energy stored in the peaking capacitor was deposited into the discharge at too high value of the parameter U/pd (U is the voltage across the tube). As the C_1 capacitance dropped down from 16.5 to 4.4 nF, the output power decreased by about 30%. The decrease of the diameter of the gas-discharge tube from 9.5 to 6.8 mm also led to the significant decrease of the output energy (Fig. 9). The highest output power per pulse was 11 mJ. Figure 10 shows the oscillogram of the laser pulse (curve *3*) along with the oscillograms of the voltage across the gap and the discharge current. It is seen that lasing occurs at almost constant voltage across the discharge gap, as the conductivity of the plasma generated in the first 200 ns decreases. As was noted above, the second peak in the current pulse is caused by the additional increase of the voltage across the gap as the inductance of the magnetic switch grows.

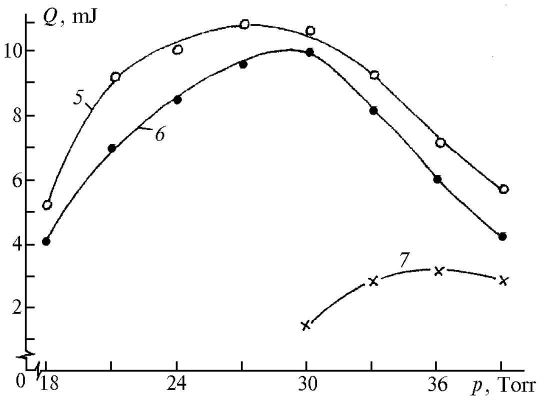

Fig. 9. Output energy of CO_2 laser vs. pressure of the working mixture CO_2:N_2:He =1:3:3; the tube is 400 mm long: d = 9.5 mm, C_1 = 16.5 nF, C_2 = 0 (*1*); d = 9.5 mm, C_1 = 16.5 nF, C_2 = 170 pF (*2*); d = 6.8 mm, C_1 = 4.4 nF, C_2 = 0 (*3*).

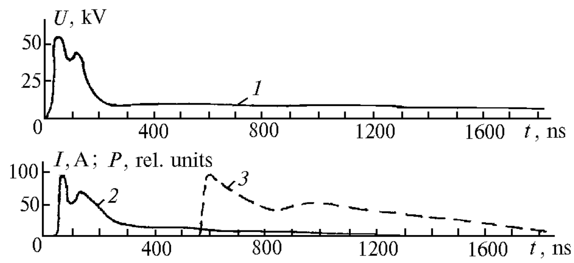

Fig. 10. Oscillograms of voltage across gas-discharge gap (*1*), discharge current (*2*), and CO_2 laser pulse (*3*) (CO_2:N_2:He =1:3:3, C_1 = 16.5 nF, tube length is 400 mm, d = 9.5 mm, p = 27 Torr).

Conclusion

The generators with inductive energy storage allow pumping by unipolar pulses with a steep leading edge and effective energy transfer into the load. Pumping from the inductive energy storage decreases the influence of the inductance of the discharge circuit and expands the range of the working pressure at which lasing occurs, whereas the peaking capacitors connected in parallel with the discharge gap decrease the energy loss in the semiconductor opening switch and can increase the laser output energy.

For the nitrogen laser we obtained the output energy of 0.55 mJ and the output energy density of 4.5 mJ/cm^2. For the CO_2 laser the mode of pumping by a longitudinal discharge from the generator with the inductive energy storage was implemented for the first time.

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