USE OF INDUCTIVE ENERGY STORAGE GENERATORS FOR EXCITATION OF PULSED GAS LASERS

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Possibility of using inductive energy storage generators for excitation of exciplex, plasma, and self-terminating lasers is demonstrated. Lasing in He(Ne, Ar)–Xe–HCl *gas mixture at* λ = 308 nm, *in* $Ne–H_2$ *mixture at* λ = 585.3 nm, *and in nitrogen at* λ = 337.1 nm *has been obtained. Data on plasma, semiconductor, and low-pressure opening switches are presented.*

1. INTRODUCTION

As compared to capacitive storage units the inductive energy storage systems allow one to store electrical energy at one to two orders of magnitude higher density and to increase the energy loading.[1,2,3] However, their use is limited by the lack of opening switches which provide fast interruption of the current ranging from 1 kA to 1 MA at high pulse repetition rates, which can stand under the voltage one to two orders of magnitude higher than the initial voltage value and which are comparatively simple in operation. Nevertheless, many different opening switches (i.e., mechanical, semiconductor, vacuum, fusible, explosive, with a plasma gun, superconductive, thermal, based on hydromagnetic instability, diffuse discharge, plasma erosion, etc. (see Refs. 1–8)) are used at present in experimental setups, in particular, in the accelerators of electrons.[8,9] The inductive energy storage generators are promising candidates for gas laser pumping.[10,13]

In this paper, a possibility of using inductive storage generators to pump exciplex, plasma, and self-terminating lasers is demonstrated.

It should be pointed out that an inductive energy storage has been used earlier in a copper-vapor laser excited by transverse discharge for pulsed vapor production.[14] The highest specific output parameters of the copper-vapor laser have been apparently obtained in these experiments.

Some gas mixtures can serve as active media and media in controlled opening switch simultaneously. For instance, when exciting by e-beam controlled discharge, $Ar–Xe–NF_3$ mixture showed rapid recovery of its resistance after the e-beam pulse termination.[15,16] It is attributed to rapid termination off of gas ionization by e-beam and to an increase in the rate of electron attachment to NF_3 when the mean drift velocity of electrons increases up to 2 eV (see Ref. 17). The combined influence of these two factors leads to the formation of a short high power pumping pulse of 10 ns duration (Ref. 15).

Lasing in $Ar–N_2$ mixture has been reported by Arteev et al. (Ref. 18) when excited by ion beam formed in plasma opening switch; XeCl laser operation under excitation from an electron accelerator with an inductive energy storage and an opening switch has been examined in Ref. 19. It should be noted here that in the above-mentioned experiments[18,19] the energy stored in the inductive storage generator is transferred into the energy of ion or electron beam, and only the second step is the energy deposition from the beam into a gas mixture. In our experiments described in this paper, we have directly used the voltage pulses formed by an inductive storage generator to pump the gas mixture.

2. EXPERIMENTAL INSTRUMENTATION AND MEASUREMENT TECHNIQUE

Circuitry of our experimental setup is shown in Fig. 1. A capacitive storage C_0 is discharged through an inductivity L_0 and an opening switch OS. The voltage pulse formed after current interruption is applied to the electrode assembly mounted within laser chamber LC filled with a laser gas mixture.

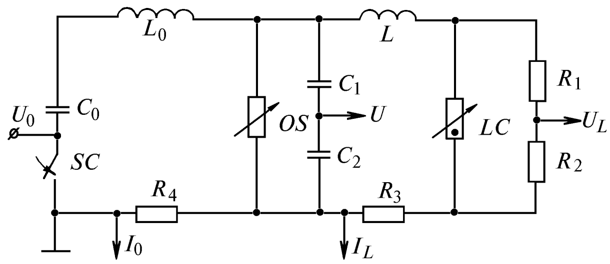

FIG. 1. Circuitry of an inductive storage generator with an opening switch: the opening switch OS, closing switch SC, the laser chamber LC, inductance of the discharge loop with the opening switch and the laser chamber L, voltage dividers C_1, C_2 and R_1, R_2, shunts R_3 and R_4.

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Metal plasma produced by an exciplex laser beam irradiating the surface of a metal target,[12,13] the device with low pressure discharge and completely controlled current, and commercially available semiconductor diodes of KC201E and SDL 0.4–800 types were used as opening switches. The device based on low-pressure discharge called crossatron has been developed at the Scientific and Production Association "Plasma" (Ryazan').

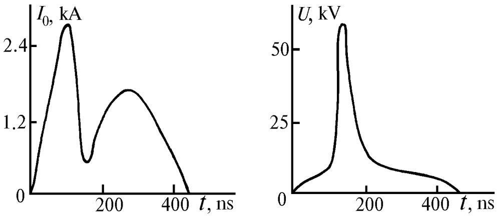

FIG. 2. Waveforms of the total current I_0 and the voltage U across the opening switch for operation without a load, U_0 = 15 kV.

Plasma opening switch has an Al electrode and a stainless steel electrode placed in a vacuum chamber 1 cm apart, the residual pressure in the chamber being $p = 3\cdot10^{-5}$ Torr. The electrode gap was first filled with laser plasma. About 10 to 15 mJ XeCl laser output was usually required to produce this plasma. The capacitor C_0 discharged through the opening switch at pulse repetition rate up to 10 Hz. The capacitor C_0 of 30 nF was used in experiments on laser excitation and L_0 was 0.35 μH.

Figure 2 presents typical waveforms of the current through plasma opening switch I_0 and of the voltage across the switch electrodes U when operating without a load. The current interruption occurred 100–200 ns after the ignition of closing switch (*SC*) (see Fig. 1) at current value from 1.5 to 3 kA depending on laser energy used for plasma formation.

The conditions for current interruption are characterized by an increase in the voltage across the opening switch up to 50–60 kV during 10–15 ns. It was 4–5 times higher than the charging voltage of the C_0 capacitor and 10–15 times higher than the initial voltage applied to the opening switch. The resistance of the opening switch increased from 2–4 Ω to several tens of ohms at a rate of 1 GΩ/s. Then for operation without a load the resistance dropped again due to the filling of the electrode gap by dense anode and cathode plasma. The rate of the current interruption depends on polarity of the voltage pulse applied to the electrode whose surface served as a target for the laser beam and reached ~10^{11} A/s.

For operation with a gas discharge load, peak voltage across the opening switch was limited by the electrical strength of the gas in laser chamber and was determined by properties of a gas mixture and total pressure. After the gas breakdown, the load resistance dropped down to the value lower than that of the opening switch during ~10 ns. In this case, up to 85% of the total current can be transferred to the load.

Crossatron is a sealed-off ceramic-metal device with a cold cathode filled by hydrogen. It operates at a gas pressure corresponding to the left-hand side of the Paschen's curve. Current interruption is achieved by applying to the grid of a blocking voltage pulse of ~1.5 kV amplitude. This device is capable to operate at pulse repetition rates up to some hundreds of hertzs. The current interruption is reached at charging voltage from 2 to 12 kV, C_0 capacitance being 12, 95, or 2000 nF, inductance of the discharge circuit ranging from 10 to 260 μH and current values ranging from 150 to 500 A. The highest overvoltage was observed at U_0 = 2 kV, C_0 = 2 μF, and L = 32 μH and reached 15 (the voltage across the crossatron increased up to 30 kV). In the case of gas discharge load, up to 90% of the total current could be transferred into the load.

Waveforms of the current through the crossatron with (*a*) and without (*b*) blocking pulse and the voltage across the inductance L_0 (*c*) are shown in Fig. 3. The highest dI/dt value during the current interruption reached ~10^9 A/s.

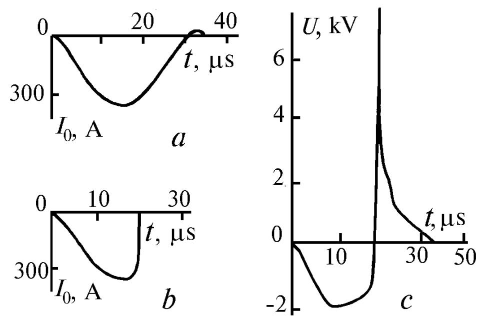

FIG. 3. Waveforms of the total current I_0 without blocking pulse (a), with current interruption (b), and the voltage across the inductance L_0 during interruption (c); C_0 = 2 μF, L_0 = 32 μH, U_0 = 2 kV.

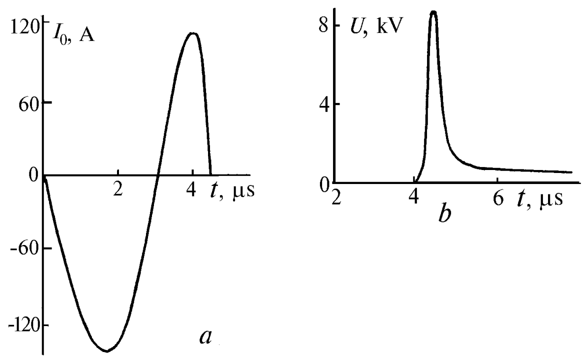

FIG. 4. Waveforms of the current I_0 through the opening switch based on KC–201E *diodes and the voltage across the opening switch U for operation without a load*, U_0 = 5 kV.

Opening switches based on commercially available diodes are very simple devices and can interrupt the reverse current after conduction of the direct one[9]. In our experiments we have used high-voltage KC–201E and SDL 0.4–800 rectifiers which could be connected both in parallel and in series.

Figure 4 presents waveforms of the current through the KC–201E diodes and the voltage across them in the no-load mode of operation. The overvoltage available with semiconductor diodes did not typically exceed 3 times, but the rate of current interruption was as high as $5\cdot10^9$ A/s with KC–201E diode and $2\cdot10^{10}$ A/s with SDL 0.4–80 diode. The main parameters which determine current pulse duration after polarity inversion and current interruption time in the case of semiconductor diodes are direct current pulse duration and the value of the current conducted by one diode. Varying these parameters one can provide both interruption at the peak value of the reverse current and the shortest cut-off time. The value of the current interrupted can be varied by varying the number of diodes connected in parallel. It should be pointed out that the peak voltage at the opening switch after interruption should be lower than the allowable inverse voltage for one diode or several diodes connected in series.

To study the gas laser performance under excitation by inductive energy storage generators, different laser chambers providing both longitudinal and transverse discharge pumping were connected in parallel to the opening switch with the lowest possible inductance. Experiments on excitation by the longitudinal discharge have been carried out using glass tubes with internal diameter of 4.5 mm and 3, 4 or 6.6 mm and active length of 19 cm and 10 cm, respectively. Examination of transverse discharge excitation was performed in a laser chamber with the active length of 20 cm, electrode spacing from 1 to 2.5 cm and discharge width of 4 mm. In this case, surface discharge served as a source of preionization. The optical cavity in all experiments was formed by an Al mirror and a flat quartz output coupler.

Time profiles of the voltage at the opening switch and the laser gap were monitored using a capacitive (C_1, C_2) and a resistive (R_1, R_2) dividers, both total current and current through the laser gap were measured using shunts R_3 and R_4. All electrical signals were displayed using an S8–14 oscilloscope. Laser pulses were monitored using a FEK–22SPU photodiode and S8–12 or S8–14 oscilloscopes. The laser output (in excess of 0.1 mJ) was measured with IMO–2N calorimeter.

3. GAS LASERS PUMPED BY INDUCTIVE ENERGY STORAGE GENERATORS

A. Nitrogen UV laser

To provide effective operation of a nitrogen laser, it is necessary to maintain the high value of E/N parameter (at constant gas temperature, E/p parameter) as long as possible. Here E is the electrical field strength, N is the gas concentration, and p is the gas pressure. The optimal E/p value for N_2 laser kinetics[20] is ≈ 120 V/cm·Torr. If a capacitive storage is employed, the E/p value decreases rapidly during ~ 5 ns since, on the one hand, resistance of the discharge plasma decreases after gas breakdown, and, on the other hand, there is a spurious inductance between the primary capacitor and the laser gap. When an inductive storage is employed, there is a possibility to decrease the rate of the voltage drop by increasing L_0 and R_L values. By varying L_0 and R_L, it is possible also to control the pumping pulse duration.

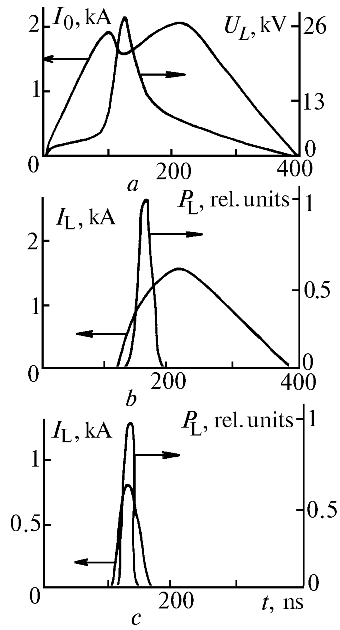

FIG. 5. Time profiles of the total current I_0, the voltage across the laser gap $U_L(a)$, the current through the laser gap I_L and output pulse $P_L(b)$ under transverse discharge pumping at a nitrogen pressure of 120 Torr *and charging voltage* U_0 = 15 kV. *Waveforms of the current through the laser gap I_L and laser pulse P_L under longitudinal discharge pumping at a nitrogen pressure of* 15 Torr *and* U_0 = 18 kV (*c*).

Figure 5 shows time profiles of the total current, voltage across the laser gap, current through the discharge plasma in laser chamber, and laser pulse in nitrogen under transverse and longitudinal excitation. It is evident from Fig. 5 that in the case of transverse discharge high E/p value is maintained during tens of nanoseconds (Fig. 5*a*). This leads to broadening of the laser pulse to ~ 50 ns. So, we have apparently observed the longest pulse duration of a nitrogen laser excited by transverse discharge.

Figure 6 presents laser energy at λ = 337.1 nm as a function of nitrogen pressure when the gas is excited by transverse discharge between electrodes separated by 23 mm. Laser energy reached 0.15 mJ per pulse and the laser efficiency relative to the energy stored in the inductance reached 0.2%. If the energy in a primary capacitor is completely transferred into the inductance (this can be achieved by optimization of the generator design), it is possible to obtain substantially higher efficiency of the nitrogen laser. Inductive energy storage improves conditions for homogeneous discharge formation as well as makes the operation possible at high gas pressures if optimal E/p value can be maintained. For instance, if the electrode separation is decreased to 10 mm, stable output is observed at a nitrogen pressure as high as 0.6 atm. When longitudinal discharge is used the pumping pulse is shorter since the resistance of the discharge plasma increases (see Fig. 5*c*). That mode of operation demonstrated unipolar current pulse of ~20 ns duration. In this case, the optimal gas pressure is 15 Torr.

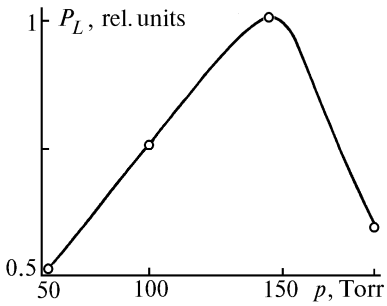

FIG. 6. Output energy as a function of nitrogen pressure under transverse discharge pumping.

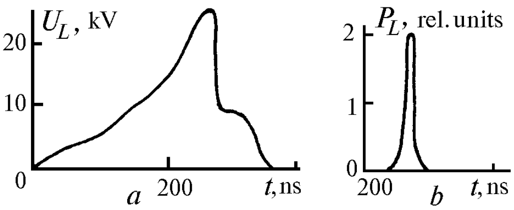

FIG. 7. Waveforms of the voltage at the inductance (a) and laser pulse in nitrogen (b) at $U_0 = 2$ kV *and* 30 Torr *nitrogen pressure. The crossatron was used as opening switch in this case.*

Figure 7 illustrates nitrogen laser performance with a crossatron as an opening switch. Nitrogen gas was pumped by longitudinal discharge. Length of the discharge tube is 10 cm and its diameter is 6.6 mm. The primary capacitor of 2 μF at a charging voltage of 2 kV with the inductance of its discharge loop of 32 μH are used. The optimal nitrogen pressure for such a generator configuration is 30 Torr. A 7-ns (FWHM) laser pulse was observed before the discharge current reached its peak value. It should be mentioned here that the task of the experiments on crossatron was to operate at a very low charging voltage. In doing so, we were forced to increase the inductance of the discharge loop resulting in broadening of the pumping pulse over its optimal value.

Figure 8 presents waveforms of the discharge current through the laser gap, voltage across the laser electrodes and output pulse at λ = 337 nm when an assembly of commercially available silicon SDL 0.4–800 diodes was employed as an opening switch. Longitudinal pumping was performed in a tube 10 cm long and 3 mm in diameter. The assembly of three SDL 0.4–800 or twenty four KC–201E diodes as opening switch provided laser action in nitrogen at gas pressure ranging from 10 to 50 Torr. The highest output power was observed at a pressure of 25 Torr. At C_0 value of 17 nF, L_0 value of 8 μH and gas pressure of 25 Torr the energy deposited into the gas within the laser pulse duration was 20 mJ. Based on this energy the laser efficiency is estimated to be 0.2%.

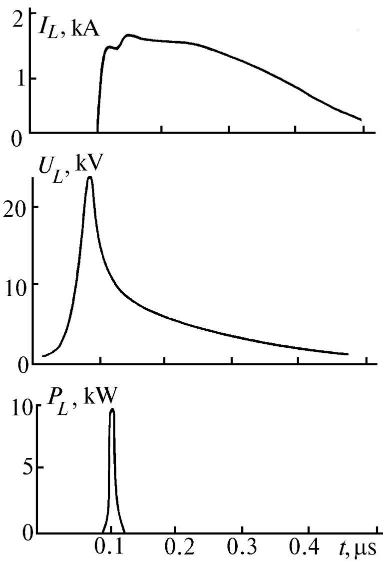

FIG. 8. Waveforms of the discharge current through the laser gap I_L (a), the voltage across the electrodes of the laser chamber U_L (b) and laser pulse in nitrogen P_L (c) at $U_0 = 20$ kV *and nitrogen pressure of* 24 Torr. *Semiconductor diodes* SDL 0.4–800 *served as opening switch.*

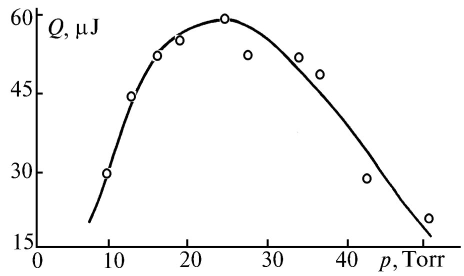

FIG. 9. Output energy as a function of nitrogen pressure at $U_0 = 20$ kV, $C_0 = 15$ nF, *pulse repetition rate of* 2 Hz. *Semiconductor opening switch was used.*

Figure 9 presents the laser output energy as a function of gas pressure at a pulse repetition rate of 2 Hz. This curve is similar to that obtained elsewhere with a capacitive storage.

B. Exciplex XeCl laser

For an optimal XeCl laser operation it is necessary, on the one hand, to provide a homogeneous discharge formation using an appropriate preionization and electrode assembly as well as sufficiently high overvoltage and, on the other hand, to match the discharge and generator impedances. Generally speaking, these conditions contradict to each other. Consequently, to develop an efficient XeCl laser, one has to use a complicated storage generators with a prepulse.[21]

Inductive storage generators make it possible to solve this problem without a prepulse technique.

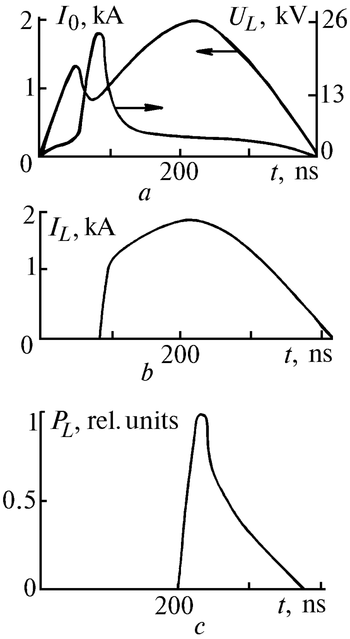

FIG. 10. Waveforms of the total current I_0, *the voltage across the electrodes of the laser chamber* U_L *(a), the current through the laser gap* I_L *(b) and laser pulse* P_L *(c). Gas mixture* Ne:Xe:HCl = 160:10:1 *at a total pressure of* 3.5 atm; U_0 = 12 kV. *Electrode separation in the laser chamber was* 1.5 cm.

Figure 10 presents waveforms of the total current, current through the load, voltage across the laser electrodes, and laser pulse at λ = 308 nm in Ne-based gas mixture. The current cut-off occurs before the total current approaches its peak value. A plasma erosion opening switch is used. In those experiments the laser gas was excited by transverse discharge. One can see that the inductive storage generator produces a short high voltage pulse which is necessary for a homogeneous discharge formation. Then energy deposition from the primary capacitor takes place. Laser pulse was delayed with respect to the beginning of the discharge current by 100 ns, its duration being about 180 ns. The time profiles of the spontaneous emission and pumping are similar. Therefore, a stable discharge was obtained even at high HCl concentration. Laser energy reached 2.5 mJ in that case.

Similar results were observed in He-based gas mixtures. As much as 85% of the total current was transferred into the load under these conditions showing relatively high resistance of the opening switch. Lasing in Ar-based mixtures was observed up to 2 atm demonstrating high discharge stability, but a fraction of the current transferred into the load in this case was lower due to higher discharge resistance.

In general, when analyzing results of the experiments with an exciplex XeCl laser, we can conclude that inductive energy storage can easily provide homogeneous discharge formation in mixtures of rare gases with halogens. Moreover, this generator serves as a prepulse one producing the initial high voltage splash whereas the major energy deposition is provided by a capacitive storage, impedances of discharge plasma R_h and capacitive storage being matched according to the equation: $(L_0/C_0)^{1/2} = R_h$. The charging voltage U_0 of the capacitive storage should be two times higher than the voltage maintained at the quasistationary stage of the discharge.[21] It should be noted also that the inductive energy storage enables one to operate easily under non-stationary pumping mode and therefore to increase the output pulse duration of exciplex lasers.[16,22]

C. Penning plasma Ne laser

Efficient operation of a plasma laser can be achieved using a hard ionizer (for instance, e-beam, ion beam, or X-rays). As a rule, these lasers operate in the afterglow when discharge excitation is employed.[23] Capacitive energy storage generators are unable to produce pumping pulses with rapid current decay. Moreover, subsequent oscillations of the discharge current reduce significantly the intrinsic laser efficiency or even disrupt lasing.

In our experiments, a Ne Penning plasma laser (λ = 585.3 nm, gas mixture Ne–H_2 at p = 0.5 atm) was pumped using an inductive energy storage with the plasma opening switch. Laser pulse duration was ~ 400 ns. As compared to the capacitive storage generator (Ref. 24), an increase in output power and total gas pressure was observed.

4. CONCLUSION

A possibility of using inductive energy storage generators to excite different gas lasers has been demonstrated. Laser action at λ = 308 nm in He(Ne, Ar):Xe:HCl gas mixture (exciplex XeCl laser), at λ = 585.3 nm in N–H_2 gas mixture (Penning plasma Ne laser) and at λ = 337.1 nm in nitrogen (self-terminating N_2 laser) was obtained. A plasma erosion opening switch, a semiconductor opening switch, and a commercially available low pressure opening switch were employed in our experiments. It was shown that the use of inductive storage generators makes it possible to vary parameters of the pumping pulse over a wide range and to provide optimal conditions for pumping of pulsed gas and plasma lasers. It should be noted also that the inductive energy storage generators can be successfully used for excitation of UV and VUV lamps,[25–27] which operate in a wider range of the pumping parameters as compared to laser devices.

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