Long-Pulse Excimer and Nitrogen Lasers Pumped by Generator with Inductive Energy Storage[1]

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Abstract – Laser and discharge parameters in mixtures of rare gases with halogens driven by a pre-pulse-sustainer circuit technique are studied. Inductive energy storage with semiconductor opening switch was used for the high-voltage pre-pulse formation. It was shown that the pre-pulse with a high amplitude and short rise-time along with sharp increase of discharge current and uniform UV- and x-ray preionization allow to form long-lived stable discharge in halogen containing gas mixtures. Improve of both pulse duration and output energy was achieved for XeCl-, XeF- and KrF excimer lasers. Maximal laser output was as high as 1 J at intrinsic efficiency up to 4%. Increases of radiation power and laser pulse duration were obtained in N_2-NF_3 (SF_6) and He-F_2 (NF_3) gas mixtures, as well.

1. Introduction

The development of efficient discharge lasers on different gas mixtures is associated with solution of the following two problems. First problem consists in formation and sustaining of uniform volume discharge in halogen containing gas mixtures. Second one is improvement of the efficiency of a stored energy transfer from a pumping generator to this volume discharge plasma. Volume discharge is formed using different preionization sources (UV radiation, x-rays, electron beam and so on) and over-voltage applied to a laser gap. This pumping technique allows to expand pulse duration of XeCl-laser up to ~200 ns[1]. Non-steady-state excitation mode which involves specific build-up and decay rates of the discharge current had been suggested to improve discharge stability and laser pulses on XeCl and XeF molecules up to 1000 and 400 ns, respectively, were obtained[2, 3].

Comprehensive double discharge pumping circuits based on spark switches[4] or saturable inductors[5] providing complete energy transfer to the discharge plasma are necessary for development of efficient discharge gas laser. In this circuit a high-voltage pre-pulse generator with low stored energy ignites volume discharge while a low-voltage storage deposits main part of pumping energy in the impedance matched mode. This pumping technique with the use of a pulse forming line allowed developing XeCl discharge lasers with efficiency up to 4-5% with long pulse duration. On the other hand, it is difficult task to expand the output pulse duration of lasers on gas mixtures containing fluorine donor (XeF, KrF, and ArF and other lasers) due to fast discharge collapse[5, 6].

Alternative way of the pre-pulse formation is the use of inductive energy storage. In this pumping technique part of energy stored in a primary capacitor is transferred into circuit inductor of the pumping generator and than using special device named opening switch to the load. Historically, laser application of inductive energy storage (IES) was studied using exploding wires[7] or plasma erosion opening switches[8]. These experiments have very well demonstrated the effectiveness of IES in pulsed laser pumping. However, the practical use of IES was limited due to the complicated controlling system, low repetition rate, or low interrupted current.

Experiments on laser excitation by IES were continued after development of industrial SOS-diodes and pulsed generator based on this type of opening switch[9]. Efficient laser action on HF, CO_2 and N_2 molecules was obtained using IES generator with SOS-diodes[10]. Than sufficient improvement of discharge stability and expansion of radiation pulse duration were achieved in XeCl-, XeF- and KrF-lasers pumped by IES generators[11, 12].

In the present paper we report experimental results on pumping of discharge excimer and nitrogen lasers and visible laser on atomic transition of fluorine by a generator with IES and semiconductor opening switch.

2. Laser design and measurement procedure

The laser used in our experiment was similar to that described in[11]. The laser electrodes were located in a cylindrical chamber separated from the pump generator by a plastic insulator. The laser active volume was $V = (0{,}8\text{-}2) \times 4 \times 72\ \text{cm}^3 = 230\text{-}570\ \text{cm}^3$ for a discharge gap between electrodes d = 4 cm. The discharge width depends on the mixture composition, its pressure and charging voltage of the primary capacitor. The pre-ionization was accomplished by the radiation of 72 spark gaps evenly distributed on either side of the cathode. In our experiments, we found for the first time that the spark gaps emit strong X-radiation.

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The pumping generator consisted of storage C_0=38 or 70 nF and peaking C_1=2,45 nF capacitors. Semiconductor opening switch consists of 10 SOS-diodes placed in parallel with the peaking capacitors. Maximal opening current of the SOS diode is as high as 2 kA, the response time is 10-20 ns, and the pulse repetition rate amounts to 1 kHz with oil cooling. To run the diodes as current interrupters, a current of 100 - 500 A was passed through each diode in the forward direction during 500 ns from a driving capacitor C_D = 10 or 36 nF charged to a voltage U_1=10-30 kV. The generator can operate as conventional LC-circuit. In this case capacitor C_D is not charged.

Discharge and laser parameters were studied in gas mixtures of Ne, Xe, Kr with HCl, F_2, NF_3, N_2 with NF_3 or SF_6 and He with F_2 (NF_3) at total gas pressure up to 3,5 atm.

Optical cavity was formed by totally reflecting Al mirror and mirror with dielectric coatings with the reflectivity of 30% or 80% at λ = 248-337 nm or uncoated quartz plate.

The laser output energy was measured using an OPHIR calorimeter with FL-250A or PE-50BB sensors. The laser pulse waveforms were measured in the far zone with a FEK-22 SPU vacuum photodiode. The laser spectra were recorded using a StellarNet EPP2000 - C25 spectrometer with resolution of 0,75 nm.

In the experiments, we measured current through the laser gap I_d, discharge current of primary capacitor I_0, SOS-diode current I_D with Rogovsky loops and voltage across the laser gap U_d and diodes U_{SOS} with voltage divider. Electrical signals were recorded with a TDS – 224 digital oscilloscopes.

3. Experimental result and discussion

3.1. Nitrogen laser

UV lasing on second positive system (electron bands $C^3\Pi_u - B^3\Pi_g$) of nitrogen molecule can be obtained only at high electric field strength across the laser gap E/p >100 V/cm×Torr. Therewith the laser output on the most intensive transition 0-0 (λ=337,1 nm) and 0-1 (λ=357,7 nm) can be as high as several tens of mJ. However, under transverse discharge excitation from Blumlein or capacitor-transfer circuits the voltage across the laser gap collapses during few nanoseconds and the laser pulse duration is as usual no longer than ~5 ns[13]. Additions of electronegative admixtures, such as NF_3 and SF_6 into nitrogen can slow-down the voltage drop rate due to increase of the electron attachment coefficient and slightly expand the laser pulse duration[14]. Early we obtained double laser pulses at λ=357,7 nm the N_2-SF_6 mixture pumped by inductive generator[15]. Optimization of that excitation mode allows to improve the output energy and expand the laser pulse at λ=337,1 nm.

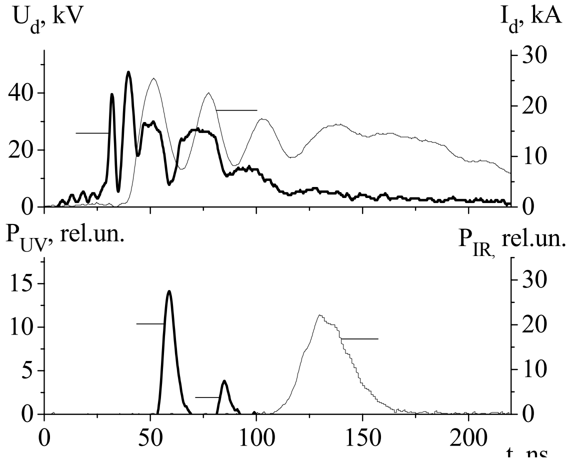

Fig.1. Waveforms of voltage across the laser gap U_d, discharge current I_d and laser pulses at λ=337,1 nm (P_{UV}) and λ~1040 nm (P_{IR}) obtained in the N_2:NF_3=75:3 Topp mixture pumped by the IES. C_0 =70 nF, U_0=33 kV.

Fig.1 depicts waveforms of the voltage across the laser gap, discharge current and laser pulses at λ=337,1 nm and λ~1040 nm obtained in optimal mixture of N_2 with NF_3 pumped by the IES. The IES in the instant of current interruption, produces across the laser gap there appeared a high voltage pre-pulse with amplitude up to 75 kV. Than IES simultaneously with peaking capacitors provided fast increase of discharge current and formed short powerful pumping pulse. Joint action such factors as high breakdown voltage and sharp increase of the discharge current improve discharge uniformity and allow to obtain long-lived volume discharge in gas mixtures with halogens [3, 16, 17].

UV laser pulse consisting from two peaks was obtained. The time interval between the laser peaks was ~20 ns, while total pulse duration was as long as 45 ns. The laser energy was as high as 25 mJ. The laser spectrum includes lines at λ=337,1 nm, λ=357,7 nm and λ=316 nm. Therewith ~98% energy was emitted at λ=337,1 nm. Besides the UV lines, laser action at λ ~ 1040 nm during 60 ns was observed after termination of the UV pulse. The laser energy on IR transition in mixtures of nitrogen with NF_3 was below 1 mJ. In mixtures with SF_6 similarly to[15] second laser peak at λ=337,1 nm was observed only at concentration of SF_6 more than 50%. In this conditions pause between the laser peaks disappears and continuous lasing was observed during 50 ns. The laser output (up to 30 mJ) was distributed between lines at λ=337,1 nm (~80% of energy), λ=357,7 nm (~5%) and λ~1040 nm (~15%). Therewith laser pulse at λ~1040 nm began after termination of the UV lasing. In mixtures with F_2 only single laser pulse was observed.

Very interesting result was obtained in N_2-NF_3 (SF_6) mixtures at low gas pressure. Amplitude and duration of the second peak sharply increased at mixture pressure. As a result, rectangular laser pulses at λ=337,1 nm with total duration of 50 ns were obtained. The laser output in this excitation mode was 5-7 mJ.

3.2. Atomic fluorine laser.

Laser action on atomic transitions of fluorine was obtained for the first time in a longitudinal discharge in mixtures of CF_4, C_2F_6, or SF_6 with helium[18]. Since than pulsed and CW lasing on red lines of FI in the spectral range from 640 to 775 nm was reported in only few papers. Therefore study of FI laser has considerable interest[19, 20].

In our experiments, we try to obtain laser action at 157 nm on fluorine molecules. The laser threshold was not achieved because of low excitation power. However, uniform volume discharge of long duration and lasing on FI transition was obtained in mixtures of 2-3 Torr F_2 or NF_3 with He at total pressures up to 2 atm.

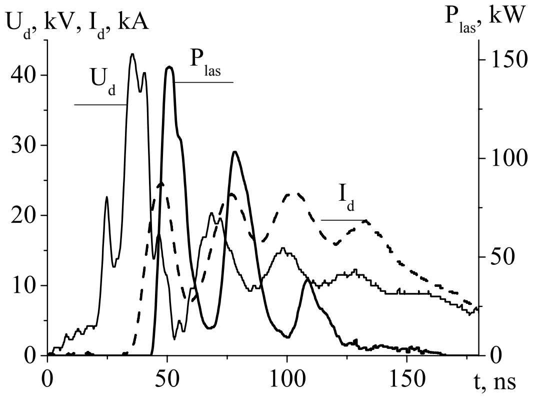

Fig.2. Waveforms of the voltage across the laser gap U_d, discharge current I_d and integral laser pulse on FI transitions P_{las} obtained in the He:F_2=1 atm:2,2 Topp mixture pumped by the IES. C_0=70 nF, U_0=36 kV

Fig.2 depicts typical waveforms of voltage across the laser gap, discharge current and integral laser pulse on red fluorine lines in optimal gas mixture. As in the case of N_2-laser the radiation pulse follows discharge current peaks and lasts during more than 100 ns. Usually severe arcing is observed within is observed within several tens of ns in mixtures of fluorine with helium under transverse discharge excitation, and therefore the lasing lasts only 10-20 ns[19, 21]. The same discharge behavior was observed in our experiments under excitation from conventional LC-circuit. The use of the inductive generator allows igniting stable volume discharge with duration about 200 ns. As a result, the laser pulse duration increases by several times. Peak laser power (150 kW) was doubled as compared to the data from available literature[21]. Maximal output on the FI lines in fluorine containing mixtures was about 4 mJ. Pulse duration and lasing energy in mixtures with NF_3 decreases by a containing mixtures was about 4 mJ.

The laser output was distributed over 5 doublet and quartet lines. Maximal radiation intensity in all mixture under study was observed at λ=731,1 nm, transition $3p^2S^0{}_{1/2}$-$3s^2P_{3/2}$. Up to 70% and 85% energy was emitted on this line in He-NF_3 and He-F_2 mixtures, respectively.

In near future we are going to reduce the laser active volume and return to experiment on lasing at 157 nm.

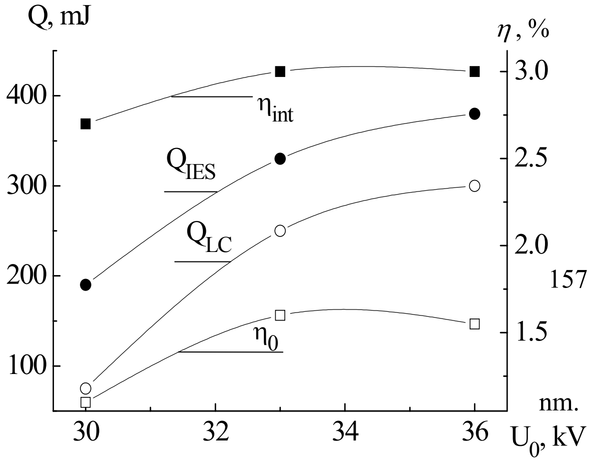

Fig.3. Output of XeF-laser (Q_{SOS}), intrinsic (η_{int}) and electrical (η_0) efficiency of XeF-laser pumped by the IES and laser energy (Q_{LC}) obtained with the LC circuit as functions of charging voltage of C_0=38 nF. Mixture of the Ne:Xe:NF_3 =2,5 atm:6:1.5 Torr composition is used.

3.3. Excimer lasers

Fig.3 depicts XeF laser output and efficiency obtained with the IES and LC-generators. In the gas mixture with 1,5 Torr NF_3 pumped by the IES with C_0 = 70 nF the laser energy increases with Ne pressure and at p=3,5 atm was as high as 0,5 J which corresponds to specific energy of 1,8 J/l and the electrical efficiency (with respect to the stored energy) of 1,1%. However, the laser pulse was slightly shorter than excitation pulse because of development of micro-arcs (filaments)[5, 6, 16]. Decrease of excitation pulse duration to 150 ns with C_0=38 nF significantly improve XeF-laser efficiency. Therewith the laser pulse duration did not change. Maximal electrical efficiency in this case was 1,6%. The output up to 0,36 J was easily achieved with intrinsic laser efficiency (with respect to deposited energy) of 3%. Similar intrinsic efficiency was obtained under e-beam excitation of Ne-Xe-NF_3 mixtures when the problem of discharge non-uniformity is absent [22, 23]. With the LC-generator the laser output was lower by a factor of 1,5-2.

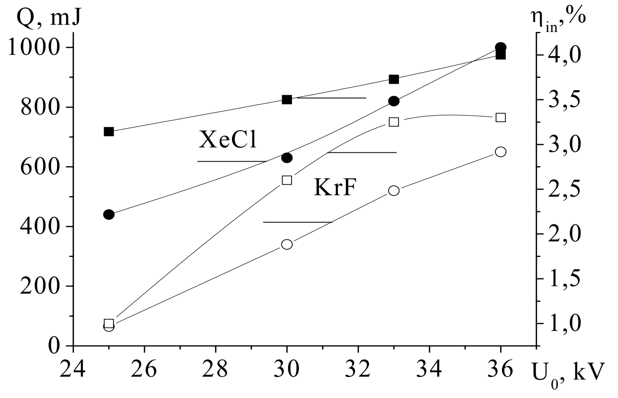

Fig.4. Output laser energy and intrinsic efficiency of XeCl-laser (solid simbols) and KrF-laser (empty simbols) pumped by the IES as functions of charging voltage of C_0=70 nF. Mixtures Ne:Xe:HCl=3,5 atm:24:3 Torr and Ne:Kr:F_2=3 atm:60:1,5 Torr are used.

Fig.4 depicts output and efficiency of XeCl- and KrF-laser pumped by the IES. Laser energy of 1 J with the efficiency up to η_{int}=4% was obtained on XeCl molecules. Up to 650 mJ in a 160 ns pulse was obtained at λ=258 nm. Intrinsic efficiency of discharge KrF-laser was as high as 3,3%. Long-pulse lasing was obtained in Ne-Ar-F_2 mixtures pumped by the IES, as well. However, the ArF-laser output was only few mJ because of insufficient pumping power.

4. Conclusion

Pre-pulse-sustainer circuit technique on the base of inductive energy storage and semiconductor opening switch was developed for excitation of different gas lasers. The pre-pulse with high amplitude and short rise-time along with sharp increase of discharge current and uniform UV- and x-ray preionization significantly improve discharge stability and life-time of volume discharge in halogen containing gas mixtures. The pre-pulse with pumping power of ~1MW/cm^3 forms high-density discharge plasma and inversion population in gas mixtures under study within ~10 ns and provides both early one-set of lasing and conditions for efficient excitation of an active medium from the primary capacitor. Long-pulse operation of N_2-, excimer lasers and laser on atomic transition of fluorine was demonstrated. Lasing duration at λ=337,1 nm up to 50 ns was achieved in mixtures of nitrogen with NF_3 and SF_6. Output energy and radiation power of FI-laser was doubled with the IES generator. UV-laser pulses on XeCl*, XeF*, KrF* and ArF* molecules with duration up to 150-200 ns was easily obtained. Maximal output of the excimer lasers was as high as 1 J with the intrinsic efficiency up to 4%.

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