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用于激光器的电感储能发生器

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摘要:研制了适用于激光器的电感储能发生器(GIES),并研究了它在高压混合气体中的放电和激光参数。研究表明,电感储能发生器可产生高压预脉冲并引起放电电流的突然增大,可在不同的混合气体中形成长时间的稳定放电,从而方便地控制和优化每一种气体混合物的预脉冲参数。在未知 IES 击穿电压和首次放电幅度下的参数时,电流尖峰会按因子 1.5~2 减少,从而产生纯激光参数。得到了氮气激光器的最大的辐射功率,输出能量和脉冲持续时间,在脉冲持续时间为 40 ns 时,紫外输出高达 50 mJ,红外输出高于 25 mJ,实现了氮分子激光跃迁的级联激射。因此 $C^3\Pi_u - B^3\Pi_g$ 带总的脉冲持续时间延长至 100 ns。在 XeCl, XeF 和 KrF 受激准分子激光器中,脉冲宽度和输出能量都得到了改善。XeF 激光器的最大效率达到了 1.6%,同时峰值输出能量达到了 0.85 J,最大脉冲持续时间超过了 200 ns。在 248 nm 波长处,效率 3.3% 的 KrF 激光器产生的 160 ns 脉冲能量高达 650 mJ,最终得到了效率为 7.7%~10% 的非链式 HF(Df)激光器。演示了基于 CO₂ 分子高峰值功率的有效运行,结果表明,激光器在 10 600 nm 处的输出能量为 6.2 J,转换效率高达 25%。

关键词:电感储能发生器;高压气体放电;激光参数

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Generator with inductive energy storage for laser application

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Abstract: Generators with Inductive Energy Storage (GIES) are developed for laser applications. Discharge and laser parameters in high-pressure gas mixtures are studied. It is shown that the IES generator produces a high-voltage pre-pulse and the sharp increase of discharge current, which allows to form a long-lived stable discharge in different gas mixtures. Therewith the pre-pulse parameters can be easily controlled and optimized for each gas mixture. Without the IES breakdown voltage and amplitude of the first discharge, the current spike decreases by a factor of 1.5–2 and results in pure laser parameters. The maximal radiation power, output energy and the laser pulse duration of a N₂ laser are obtained. The UV output is as high as 50 mJ in 40 ns pulse duration (FWHM), while that on the IR transition exceeds 25 mJ. The cascade lasing on N₂ molecule transitions is achieved. As a result, the total pulse duration on the $C^3\Pi_u - B^3\Pi_g$ band is extended up to 100 ns. The improvement of both pulse duration and output energy are achieved for XeCl, XeF and KrF excimer lasers. The maximal efficiency of XeF laser is as high as 1.6%, while peak output is 0.85 J and maximal pulse duration ex-

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ceeds 200 ns. Up to 650 mJ in a 160 ns pulse is obtained at 248 nm by the discharge KrF laser with the efficiency of 3.3%. Finally, HF(DF) non-chain lasers with ultimate efficiency of 7.7–10% are developed, and the efficient operation on CO₂ molecules with high peak power is demonstrated. The laser output at 10 600 nm is 6.2 J with the efficiency up to 25%.

Key words: Generator with Inductive Energy Storage (GIES); volume discharge in high pressure gas; laser parameter

1 Introduction

The development of efficient discharge lasers on different gas mixtures is associated with the solution of following two problems. The first problem consists of formation and sustaining of uniform volume discharge in halogen containing gas mixtures. The second one is improvement of the efficiency of a stored energy transfer from a pumping generator to the 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.

Comprehensive double discharge pumping circuits based on spark switches or saturable inductors are used for efficient energy transfer to the discharge plasma^[1-2]. In this circuits, a high-voltage pre-pulse generator with low stored energy ignites the volume discharge while a low-voltage storage deposits main part of pumping energy in the impedance matched mode. This pumping technique based on PFL allowed developing long-pulse XeCl discharge lasers with efficiency up to 4%–5%^[1]. However, application of the double discharge circuits for lasers on gas mixtures with F₂ or NF₃ (XeF, KrF, and ArF and other lasers) was limited due to the fast discharge collapse^[2-3].

Early we suggested alternative way of the pre-pulse formation using generators with IES for the pre-pulse formation^[4-7]. In this generators, the part of energy stored in a primary capacitor is transferred into the circuit inductor of the generator and then switched to the load u-

sing a special device named opening switch.

The present paper reports the operation of IES-generators with a semiconductor opening switch based on SOS-diodes on gas discharge load. Output laser parameters obtained with the generators are presented, as well.

2 IES generator design and measurement procedure

Two laser devices were used in experiments. Their circuit diagram is shown in Fig. 1. The discharge cross-sections and active lengths of lasers No. 1 and No. 2 with spark UV preionization were $S = (0.5-2) \text{ cm} \times 4 \text{ cm}$ and $l = 72 \text{ cm}$, 90 cm, respectively. The discharge gap d was 4 cm. The pumping generator consisted of a storage capacitor C_0 in 38 or 70 (No. 1) nF, 160 nF (No. 2) and a capacitor peaking C_1 in 2,45 nF (No. 1) or 3,3 nF (No. 2).

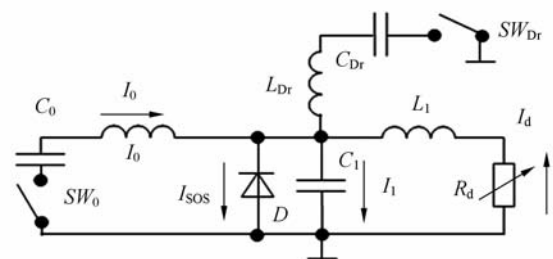


Fig. 1 Circuit diagram of the laser with IES generator. SW_0 , SW_{Dr} : spark gaps; C_0 : storage capacitor; C_1 : peaking capacitor; C_{Dr} : driving capacitor of SOS-diodes D ; L_0 , L_1 , L_{Dr} : circuit inductors, R_d : discharge resistance, I_i : currents in different circuits

Semiconductor opening switch consists of 10 SOS-diodes placed in parallel with the peaking capacitors. The maximal opening current of the SOS diode was measured to be as high as 4 kA, the response time is 10–20 ns. 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_{Dr} in 10 nF charged to the voltage U_{Dr} in 10–35 kV and triggered by the spark gap SW_{Dr} . Therewith the driving energy can be as low as 1 J.

The generator of the laser can operate as conventional LC-circuit. In this case capacitor C_{Dr} 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 , He- CO_2 - N_2 mixtures at total gas pressure up to 350 kPa.

Optical cavity was formed by totally reflecting Al mirror and dielectric mirrors with reflectivity 30%–80% at 222–10 600 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 with FEK-22 or FEK-29 vacuum photodiodes or a FSG-33-3A1 Ge-Au photoresistor. The laser spectra were recorded using a StellarNet EPP2000-C25 spectrometer or MDR-12 monochromator equipped with the above photodetectors.

In the experiments, we measured current I_d through the laser gap, I_0 current in the C_0 circuit, I_1 in C_1 capacitor, I_{SOS} in SOS-diode with Rogovsky coils and voltage U_d across the laser gap and diodes U with voltage dividers. Electrical signals were recorded with a TDS-3034 digital oscilloscope.

3 Operation of IES generator on a gas discharge load

Comparison of the operation of IES- and LC-

pumping generators in the case of N_2 laser is shown in Fig. 2. Stage of the direct pumping of SOS-diodes is not shown. The inverse current begins to pass through the opening switch from the storage capacitor C_0 after spark gap SW_0 closing. In ~ 30 ns resistance of SOS-diodes sharply increases, and current through the diodes is interrupted. During this time, the part of energy E_L is $L_0 I_{open}^2/2$, where I_{open} is the opening current, and is transferred into the circuit inductance L_0 . For the case shown in Fig. 2 $I_{open} = 20$ kA and $E_L = 5$ J. Then the IES and C_0 sharply charges the peaking capacitors up to $U_{peak} = 40$ –80 kV within 20–30 ns, and a high-voltage pre-pulse across the laser gap is formed. After the laser gap breakdown, the residual IES current I_0 is added with the discharge current of peaking capacitors I_1 providing current spike in the laser gap 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 allows to form a long-lived volume discharge in gas mixtures with halogens [5]. I_{open} is controlled by C_{Dr} and U_{Dr} . Therefore, for each gas mixture parameters U_{peak} and dI_d/dt can be easily optimized. Besides, the pre-pulse with high pumping power forms high-density discharge plasma and inversion population in gas mixtures under study within about 10 ns and provides both early onset of lasing and conditions for efficient excitation of an active medium from the storage capacitor during about 150–200 ns.

When the LC-generator is used, peaking capacitors are charged only from C_0 , and the rate of the voltage increase is slowed down. Therewith breakdown voltage and amplitude of the first discharge current spike decrease by a factor of 1.5–2 resulting in pure laser parameters.

By the end of half-period of the I_0 current, the voltage across the diodes changes its sign, and the current through the opening switch begins to pass again. This means that in the case

of mismatching between the IES generator impedance and discharge resistance at high U_0 subsequent, current oscillations will pass through the diodes. This reduces erosion of the electrode surface and improves the reliability of laser operation under excitation by the IES generators. Duration of discharge current I_d is longer than the half-period of I_0 due to discharge of inductance L_1 through diodes and the laser gap.

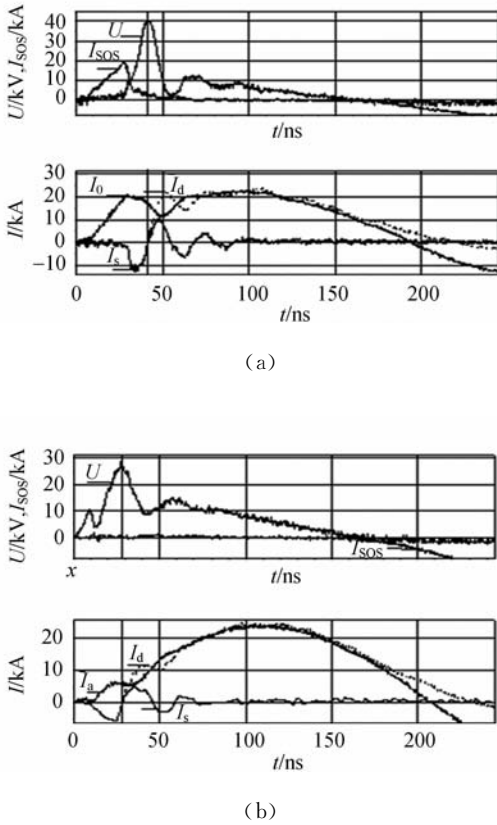


Fig. 2 Waveforms of voltage across SOS-diodes and $C_1(U)$, SOS-diode current (I_{sos}), current in the laser gap (I_d) and currents in the circuit of storage (I_0) and peaking (I_1) capacitors for the IES- (a) and LC- (b) generators pumped N_2 laser with $l=72$ cm. $p=10, 38$ kPa, $C_0=70$ nF, $U_0=30$ kV, $U_1=25$ kV

4 Experimental results and discussion

Nitrogen laser. UV lasing on first (electron

bands $B_3\Pi_g - A^3\Sigma_u^+$) and second positive system ($C^3\Pi_u - B^3\Pi_g$) of N_2 can be obtained only at high electric field strength across the laser gap $E/p > 100$ V/cm \times kPa. Therewith under transverse discharge excitation from LC-generators, the voltage across the laser gap collapses during few nanoseconds and the laser pulse duration is as usual no longer than about 10 ns. Additions of electronegative admixtures, such as NF_3 and SF_6 into N_2 can slow-down the voltage drop rate due to increase of the electron attachment coefficient and slightly expand the laser pulse duration. The maximal laser output on the UV transition 0-0 ($\lambda=337,1$ nm) was 40 mJ^[8], while that on the IR lines did not exceed 5 mJ^[9] using LC-generators.

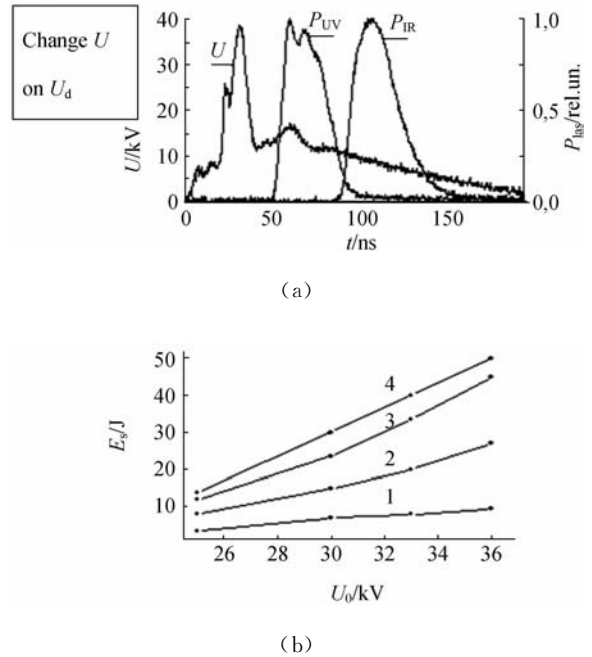


Fig. 3 Waveforms of the voltage across the laser gap U_d and UV (P_{UV}) and IR (P_{IR}) laser pulses in the $N_2 : SF_6 = 30 : 3$ mixture at $U_0 = 33$ kV (a); laser energy at 337.1 nm (1, 3, 4) and IR transitions (2) in pure N_2 at 0.8 kPa (1) and with 0.2 kPa (2) and 10.0 kPa (3) SF_6 and in the $N_2 : SF_6 = 30 : 9$ mixture (b) as function of U_0 . Laser with $l=90$ cm.

Optimization of excitation mode with the IES generator allows to improve the output ener-

gy in the UV and IR ranges and expand the laser pulse at 337.1 nm (see Fig. 3). In our experiments, maximal UV laser output was as high as 50 mJ, while that on the IR transition exceeds 25 mJ. The IR lasing occurs on three lanes at 869.5; 888.3 and 1 046.9 nm. Lasing at 337.1 nm began within 40 ns earlier the IR pulse and was about 40 ns in duration (FWHM). Therewith weak UV laser action was observed during the IR pulse. Level $B^3\Pi_g$ is lower for the UV-transition. At the same time, it is upper level for the IR-transition. This means that intense IR lasing strongly depopulates $B^3\Pi_g$ state and can maintain population inversion on the $C^3\Pi_u - B^3\Pi_g$ transition. Therewith the UV laser pulse duration on the base was as long as 100 ns.

XeF laser. Fig. 4 depicts waveforms of the voltage across the laser gap, XeF laser pulse and discharge view in different pumping modes. Slow increase of the voltage pulse and low breakdown voltage is typical for pumping by the LC-generator. As a result, the violation of discharge uniformity is observed. The IES increase both the rate of the voltage rise and breakdown voltage by a factor about 1.5. Improvement of discharge stability results in expansion of the laser pulse and higher laser output. In experimental conditions of Fig. 4, total pulse duration was 120 ns while that at half-maximum was over 50 ns with the IES. At lower concentration of Xe and NF_3 in the mixture similarly to [10], the pulse durations increase by a factor of 2 and was as long as 200 ns. Therewith maximal output at 351–353 nm was as high as 0.85 J with laser No.2. The maximal electrical efficiency η_0 (with respect to stored energy) with laser No.1 was as high as 1.6%.

KrF and XeCl lasers. The great discharge improvement and lasing duration extension were also achieved in the Ne-Xe-HCl and Ne-Kr-F₂ mixtures. Therewith total pulse duration on both XeCl^* and KrF^* molecules was 160 ns while duration at half-maximum was as long as

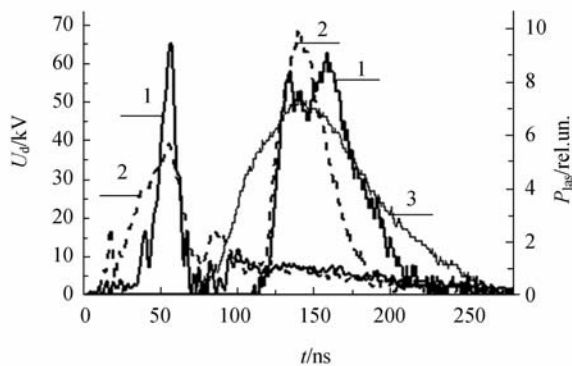


Fig. 4 Waveforms of the voltage across the laser gap U_d and laser pulses P_{las} obtained with IES- (1,3) and LC-generators (2) in the Ne : Xe : $\text{NF}_3 = 250 \text{ kPa} : 6 : 0.2 \text{ kPa}$ (1, 2) and Ne : Xe : $\text{NF}_3 = 250 \text{ kPa} : 3 : 0.1 \text{ kPa}$ (3) mixtures. Laser No. 1, $C_0 = 70 \text{ nF}$, $U_0 = 30 \text{ kV}$

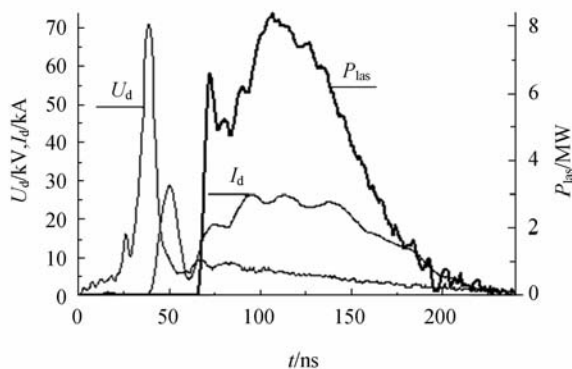


Fig. 5 Waveforms of the voltage across the laser gap U_d , discharge current I_d and laser pulse at 248 nm P_{las} obtained in the Ne : Kr : $\text{F}_2 = 300 \text{ kPa} : 60 : 0.2 \text{ kPa}$ mixture. Laser with IES No. 1, $C_0 = 70 \text{ nF}$, $U_0 = 36 \text{ kV}$.

about 100 ns (see Fig. 5). The laser energy of 1 J with intrinsic efficiency (with respect to deposited energy) up to $\eta_{\text{int}} = 4\%$ was obtained on XeCl^* molecules. Up to 650 mJ in a 160 ns pulse was obtained at 248 nm. The intrinsic efficiency of discharge KrF-laser was as high as 3.3%.

HF(DF)-lasers. Fig. 6. depicts output energy and intrinsic efficiency of HF(DF)-lasers pumped by the IES. Output up to 1.4 J with ultimate efficiency of 7%–10% were easily achieved with the IES generator^[11].

CO₂ laser. To shorten the pulse duration of

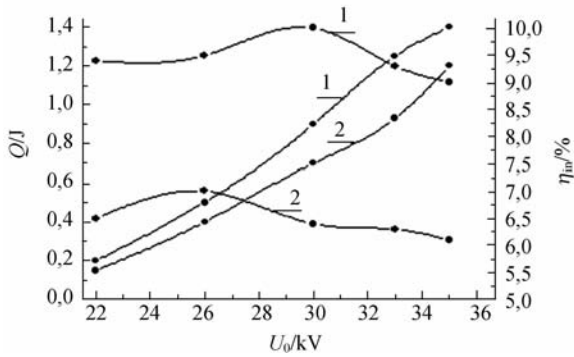


Fig. 6 Laser energy and intrinsic efficiency of HF (1) and DF (2) lasers pumped by the IES generator. Mixtures $\text{SF}_6 : \text{H}_2(\text{D}_2) = 48 : 6$.

CO_2 lasers, it is necessary to increase the working mixture pressure, to use mixtures with hydrogen, and (or) to shorten the pump pulse duration. However, an increase in the content of the molar component and (or) gas pressure when using generators with inductive energy storages makes it difficult to produce a volume discharge. This leads to a rapid development of spark channels in the discharge gap and decreases the CO_2 laser efficiency.

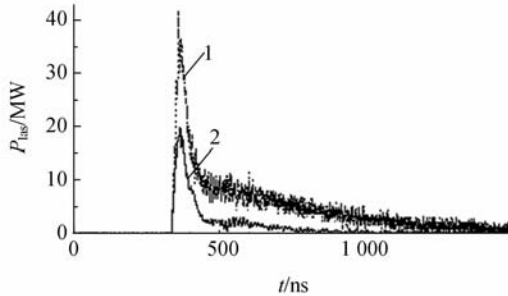


Fig. 7 Waveforms of the CO_2 laser pulses in He : $\text{CO}_2 : \text{N}_2 = 3 : 1 : 1$ at 100 kPa (1) and $\text{CO}_2 : \text{N}_2 = 5 : 1$ at 50 kPa (2) mixtures, IES generator; $U_0 = 36$ kV.

Fig. 7 depicts the laser pulses at 10 600 nm obtained with the IES generator. The IES allows to form laser pulses with a short powerful spike (up to 40 MW). Therewith, the maximum laser output was 6.2 J at the lasing efficiency with respect to the stored energy of up to 15 % and in-

trinsic efficiency up to 25%.

5 Conclusions

Pre-pulse-sustainer circuit technique on the basis of the IES generators was developed for excitation of different gas lasers. It was found that the pre-pulse with high amplitude and short rise-time along with sharp increase of discharge current significantly improve the discharge stability and life-time of volume discharge in halogen containing gas mixtures. The pre-pulse with high pumping power forms high-density discharge plasma and inversion population in gas mixtures under study within about 10 ns and provides both early one-set of lasing and conditions for efficient excitation of an active medium from the storage capacitor.

Long-pulse operation of N_2 , excimer lasers was demonstrated. Maximal at the date output and pulsed power of N_2 laser was demonstrated.

UV laser pulses on XeCl^* , XeF^* and KrF^* molecules with total duration up to 150–200 ns were easily obtained. The maximal output of the excimer laser was as high as 1 J with the intrinsic efficiency up to 4%.

Efficient laser action was easily achieved on HF(DF) and CO_2 molecules.

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● 下期预告

基于共路光线漂移补偿的直线度测量

由凤玲,冯其波,张 斌

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激光光线漂移是影响激光测量直线度误差的主要因素之一,为此提出了一种基于共路光线漂移测量与补偿的直线度误差测量方法,给出了具体的测量原理和系统构成。从产生激光光线漂移的几个因素出发,理论上分析了各种因素产生的光线漂移对直线度误差测量的影响,建立相对应的光线漂移补偿模型。补偿模拟激光器出射光线引起的光束漂移的结果为:X 方向的最大漂移量由 $28.4 \mu\text{m}$ 减少为 $5.6 \mu\text{m}$,Y 方向的最大漂移量由 $21.6 \mu\text{m}$ 减少到 $5 \mu\text{m}$;补偿由温度梯度引起的光束漂移的结果为:最大漂移量由 $65.7 \mu\text{m}$ 减少到为 $8.9 \mu\text{m}$ 。实验结果与理论分析均表明:该方法能有效减少各种因素引起的光线漂移对直线度测量结果的影响,提高了测量直线度误差的准确性。