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On ultimate pulse repetition rates of a XeF laser

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Abstract. The characteristics of a repetitively pulsed XeF laser in which the velocity of the gas flowing through the discharge gap was ~ 55 m s^{-1} were studied experimentally. The maximum power ~ 60 W was realised in the case of the gas mixture $F_2 : Xe : Ne = 3.2 : 16 : 2750$ mbar and the pulse repetition rate ~ 4.5 kHz. When the energy supply to the discharge was lowered, the maximum pulse repetition rate ~ 5.5 kHz was achieved.

1. Introduction

The first electric-discharge XeF laser was created in 1976 [1]. As compared to other excimer lasers, the XeF laser produces radiation at the longest wavelengths in the UV region, namely, between 351.0 and 351.3, and 353.1 and 353.4 nm [1, 2]. There is a certain scientific and technical interest in achieving high pulse repetition rates in excimer electric-discharge lasers, in particular, XeF lasers.

For example, several research groups try to attain high repetition rates in KrF lasers because these lasers are efficiently used in UV lithography. A number of authors [3 – 5] recently reported the creation of KrF lasers with pulse repetition rates of ~ 2 kHz. In our latest paper [6], we studied the factors affecting the ultimate pulse repetition rate ~ 5 kHz of a KrF laser.

The purpose of this work is to study the possibilities of attaining the ultimate pulse repetition rate in an electric-discharge XeF laser. This is necessary to estimate the potential of these lasers for laboratory experiments and technology.

2. Experiment

In the XeF laser under study, we used a compact gas-dynamic system of gas circulation, earlier described in Ref. [7], in which the electrode system, the diametrical fan, and the heat exchanger were all placed in an aluminium tube of length 760 mm and an internal diameter of 380 mm. The gas flow velocity could be smoothly varied from zero to 55 m s^{-1} by changing the rotation speed of the diametrical fan. The volume discharge between the profiled electrodes had the dimensions $L \times H \times B = 550 \times 14 \times 2.8$ mm, where L is the length of the discharge, H is the inter-electrode distance, and B is the width of the discharge (the discharge dimension along the gas-flow direction).

As in Ref. [6], the UV pre-ionisation was performed by an additional discharge that crept along the surface of a sapphire plate located near the region of the main discharge. The pulsed-pumping circuit of the laser contained a storage capacitor C_s, which was switched by a TGI-1000/25 thyratron and charged the peaking capacitor C_p connected to the discharge electrodes with the minimum inductance. The capacitors C_s and C_p were assembled of TDK ceramic capacitors with capacities of 2 and 0.34 nF, respectively. The capacitor C_s was charged using the pulsed resonant-diode charging scheme [8].

At the first stage of the experiments, we searched for the optimal gas mixture, the capacities C_s and C_p, and the charging voltage that would maximise the output energy E and the laser efficiency η and minimise the standard deviation σ of the laser energy. The standard deviation σ determines the stability of the output energy from pulse to pulse, which is very important for technological applications. On the other hand, the standard deviation σ reflects the preservation of the discharge uniformity in different lasing regimes [9, 10].

Our experiments have shown that the gas discharge with the dimensions $500 \times 14 \times 2.8$ mm provides the best lasing properties in the case of the gas mixture $F_2 : Xe : Ne = 3.2 : 16 : 2750$ mbar, which we used in all the subsequent experiments. The capacities $C_s = 10$ nF and $C_p = 7.8$ nF proved to be optimal for maximising the output energy and mean power.

Fig. 1 shows the dependences of E, η, and σ on the charging voltage U_0 that were measured for the pulse repetition rate 100 Hz under the above conditions. One can see that the output energy increases with increasing U_0 and, accordingly, increasing energy supply $C_s U_0^2/2$ to the discharge. However, the laser efficiency is maximal at a low charging voltage $U_0 = 15$ kV. It also follows from Fig. 1 that the best output stability corresponding to low values of σ is achieved at high values of U_0, which is explained by the great overvoltage on the discharge gap.

Fig. 2 shows the dependences of the mean output power P and σ on the pulse repetition rate f for the voltage $U_0 = 19.5$ kV, which provides relatively high lasing stability and an acceptable efficiency of the XeF laser ($\eta \approx 1\%$). One can see from Fig. 2 that, for $f < 1$ kHz, P increases linearly with f and the output energy is relatively stable from pulse to pulse ($\sigma \leqslant 0.5\%$). However, for $f > 1$ kHz, the increase in P is no longer linear, while σ increases monotonically. For

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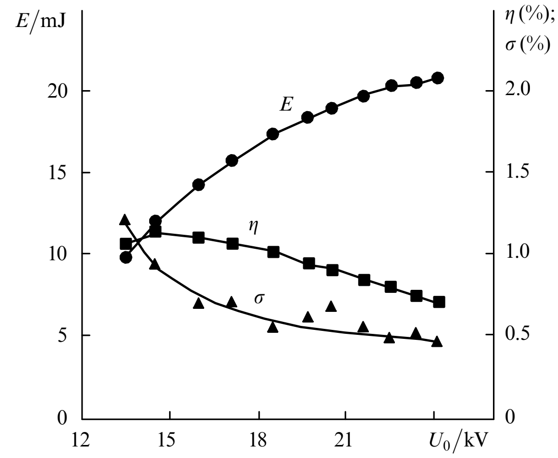

Figure 1. Dependences of the output energy E of the XeF laser, its efficiency η, and the standard deviation σ of the output energy on the charging voltage U_0 for $C_s = 10$ nF and $C_p = 7.8$ nF.

$f \geqslant 4.5$ kHz, P decreases, while σ drastically increases, reaching 3.7% for $f = 5$ kHz.

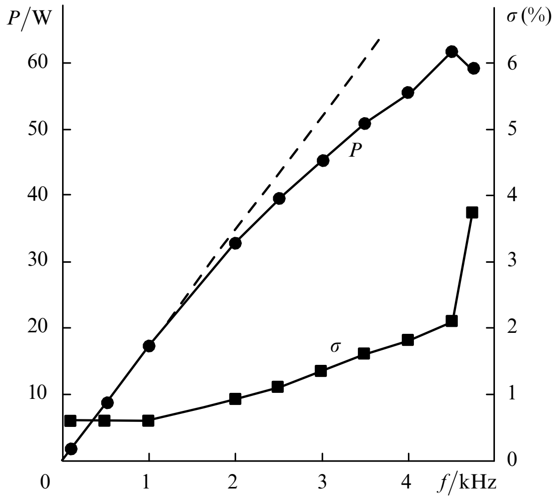

Figure 2. Dependences of the mean output power P of the laser and the standard deviation σ of the output energy on the pulse repetition rate f for $C_s = 10$ nF and $C_p = 7.8$ nF.

The deviation from the linear dependence of P on f and the increase in σ for $f > 1$ kHz can be explained by the following reasons:

(1) The incomplete removal of the 'gas plug', which has been nonuniformly heated by the preceding gas discharge, from the discharge volume [8–10].

(2) The influence of acoustic vibrations appearing in the gas-dynamic circuit of the laser [8–10], which do not have enough time to decay at pulse repetition rates $f > 1$ kHz. This results in a nonuniform distribution of the gas density inside the discharge gap at the onset of the next discharge pulse and, therefore, in a nonuniform distribution of the energy supply to the discharge.

(3) Deteriorating characteristics of the power supply of the laser. A TGI-1000/25 thyratron operates in an uncertified regime, and the energy loss in it may increase for $f > 1$ KHz. As a result, the energy supply to the discharge would decrease uncontrollably. The use of more powerful thyratrons increases the time of the energy transfer from C_s to C_p, which reduces the output energy in our experiments.

Note that the first factor is relatively easy to identify and can be removed by increasing the gas circulation velocity. In contrast, it is hard to separate the influence of the second and the third factors. However, the relative contribution of the second factor can obviously be reduced by reducing the energy stored in C_s and, therefore, the energy supply to the discharge. This can be done, for example, by reducing the capacities C_s and C_p. Fig. 3 shows the dependences of E, η, and σ on U_0 for $C_s = 4.6$ nF and $C_p = 3.8$ nF. Comparing Figs 1 and 3, we see that the reduction of the energy supply E_s ($E_s = C_s U_0^2/2$) to the discharge naturally decreases the output energy E but does not reduce the lasing efficiency η. The maximum value $\eta \approx 1\%$ is reached in the region of higher values of U_0.

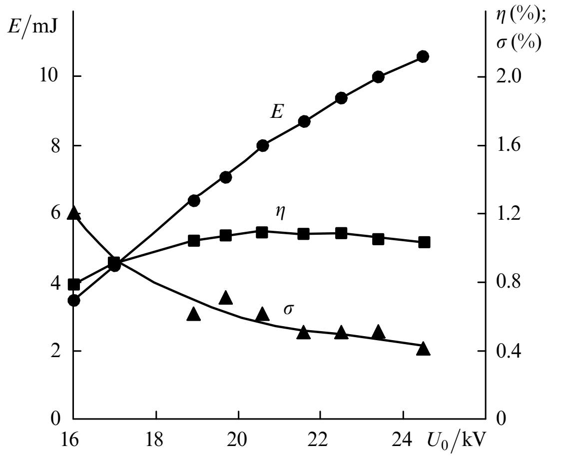

Figure 3. Dependences of the output energy E of the XeF laser, its efficiency η, and the standard deviation σ of the output energy on the charging voltage U_0 for $C_s = 4.6$ nF and $C_p = 3.8$ nF.

Curve *1* in Fig. 4 shows the dependence of σ on the energy supply to the discharge in the case of the fixed pulse repetition rate $f = 3$ kHz. The energy supply E_s was varied by changing C_s and U_0 in such a way that the lasing efficiency η remained maximum possible (1%). One can see that σ remains approximately constant (1.8%) as E_s varies from 0.8 to 2 J. Therefore, the influence of acoustic vibrations on σ and, therefore, on the discharge characteristics [8–10] is insignificant for the considered energies E_s.

The dependence of σ on the gas flow velocity V for $E_s =$ 1.38 J (curve *2* in Fig. 4) shows that, for the considered f, the increase in the gas flow velocity V above a certain V_a does not reduce σ and, therefore, does not improve the discharge uniformity ($V_a \approx 27.5$ m s^{-1} for $f = 3$ kHz).

Fig. 5 shows the dependences of P and σ on f for a reduced energy supply to the discharge ($C_s = 4.6$ nF and $C_p = 3.8$ nF). Comparing Figs 2 and 5, we see that the reduction in the energy supply makes the dependence of P on f virtually linear; the maximum pulse repetition rate $f \approx$ 5.5 kHz is reached in this case as well. The proximity between the values of σ in Figs 2 and 5 and the dependences of σ on f confirm our assumption that the laser characteristics are not affected by the acoustic vibrations as strongly as by the dete-

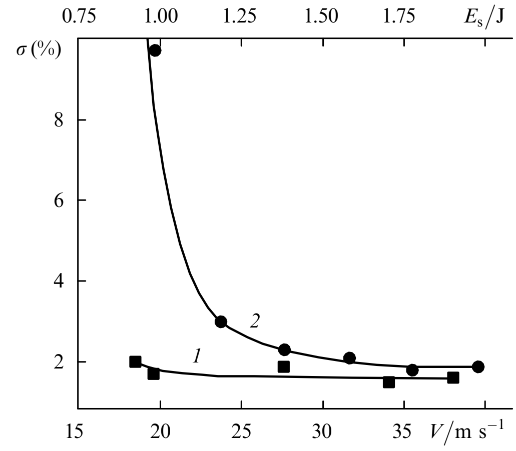

Figure 4. Dependences of the standard deviation σ of the output energy on the energy supply to the discharge E_s (*1*) and the gas flow velocity V (*2*).

riorating characteristics of the pumping circuit at high pulse repetition rates.

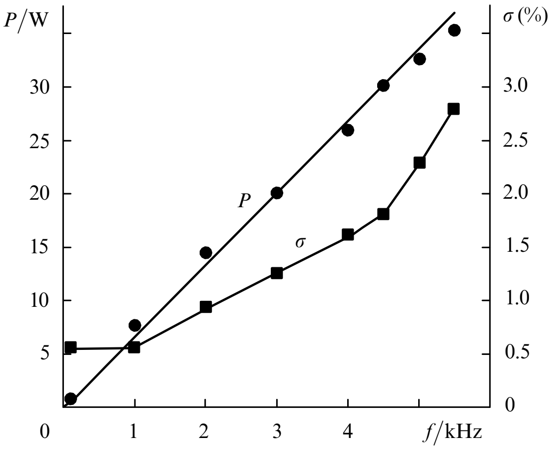

Figure 5. Dependences of the mean output power P of the laser and the standard deviation σ of the output energy on the pulse repetition rate f for $C_s = 4.6$ nF and $C_p = 3.8$ nF.

3. Conclusions

In this work, we determined the ultimate pulse repetition rate in a electric-discharge XeF laser. The mean lasing power ~ 60 W was reached for the pulse repetition rate $f \sim 4.5$ kHz. By reducing the energy supply to the discharge, we obtained an almost linear increase in the mean lasing power up to the pulse repetition rate $f \approx 5.5$ kHz with an acceptable instability of the output energy (less that 2.7%). To the best of our knowledge, this is the first time that the pulse repetition rate $f = 5.5$ kHz was achieved in a compact XeF laser with a closed gas-dynamic circuit. The weakness of the acoustic vibrations in the laser indicates that the utilisation of more efficient pumping schemes based on semiconductor switches rather than thyratrons [3–5] would permit even higher pulse repetition rates.

References

1. Burnham R, Djeu N *Appl. Phys. Lett.* **29** 707 (1976)
2. Baranov V Yu, Borisov V M, Kiryukhin Yu B, Stepanov Yu Yu *Kvantovaya Elektron.* **5** 2285 (1978) [*Sov. J. Quantum Electron.* **8** 1287 (1978)]
3. Bragin I, Klaft I, Kleinschmidt K, Osmanov R, Schroeder T, Vogler W, Zschocke W, Blasting D *Proc. SPIE Int. Soc. Opt. Eng.* **3679** 1050 (1999)
4. Enami T, Nakano M, Watanabe T, Ohba A, Hori T, Ito T, Nishisaka T, Ssumitani A, Wakabagashi O, Mizoguchi H, Narakai H, Hisagana N, Matsunaga T, Tanaka H, Ariga T, Sakanishi S, Okamoto T, Nondomi R, Sazuki T, Takabagashi Y, Tomaru H, Nakao K *Proc. SPIE Int. Soc. Opt. Eng.* **3679** 1025 (1999)
5. Myers D, Watson T A, Das P P, Partlo W N, Hofmann T, Padmabandu G G, Zambon P, Hysham C, Dunning R *Proc. SPIE Int. Soc. Opt. Eng.* **3679** 114 (1999)
6. Borisov V M, Vinokhodov A Yu, Vodchits V A, El'tsov A V, Ivanov A S *Kvantovaya Elektron.* **30** 783 (2000) [*Quantum Electron.* **30** 783 (2000)]
7. Borisov V M, Borisov A V, Bragin I E, Vinokhodov A Yu *Kvantovaya Elektron.* **22** 446 (1995) [*Quantum Electron.* **25** 421 (1995)]
8. Baranov V Yu, Borisov V M, Stepanov Yu Yu *Electric-discharge lasers on halides of inert gases* (Moscow: Atomizdat, 1988)
9. Borisov V M, Vinokhodov A Yu, Vodchits V A, El'tsov A V, Basting D, Stamm U, Foss F *Kvantovaya Elektron.* **25** 126 (1998) [*Quantum Electron.* **28** 119 (1998)]
10. Borisov V M, Vinokhodov A Yu, Vodchits V A, El'tsov A V, Basting D, Stamm U, Foss F *Kvantovaya Elektron.* **25** 131 (1998) [*Quantum Electron.* **28** 123 (1998)]