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Development of high-power KrF lasers with a pulse repetition rate up to 5 kHz

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Abstract. An experimental investigation was made of the principal factors that determine the possibility to increase pulse repetition rates in high-power KrF lasers. Two prototypes of a compact industrial KrF laser were considered. The first one produces a maximum average output power of $\sim$ 620 W for a pulse repetition rate of 4 kHz; the second, a more compact prototype, yields a maximum pulse repetition rate of 5 kHz for an average output of 200 W.

1. Introduction

Excimer KrF lasers with an output wavelength of $\lambda \approx$ 248 nm are widely used in diversified technological applications, such as microprocessing of different materials, UV lithography, and marking. It is evident that the productive capacity of the engineering process involving a laser may be improved by increasing its average output P and/or the pulse repetition rate f, and thereby the efficiency of the use of the laser may be improved. The average output power attained in commercially available KrF lasers to date is no greater than $\sim$ 300 W [1].

Recent studies [2 – 4] pursued to develop laser sources for UV lithography by leading laser manufacturers, such as Lambda Physik [2], Komatsu [3], and Cymer [4], have demonstrated the feasibility of raising the KrF-laser pulse repetition rate up to 2 kHz. The average output power of the KrF lasers cited in the above papers was $\sim$ 20 W for a spectral width of $\sim$ 0.6 pm, which is quite acceptable for use of the lasers in UV lithography. The attainment of a repetition rate $f \sim 2$ kHz in Refs [2 – 4] was primarily due to a relatively small discharge width $b = 3$ mm. So small a discharge width allowed, in principle, the gas in the discharge volume to be changed by the onset of the next discharge pulse for moderate velocities of the gas flow in the interelectrode gap.

In Ref. [5], a KrF laser with an output power $P \approx 600$ W obtained for $f \sim 620$ Hz was described. The laser discharge volume measured $d \times b \times l = 28 \times 8 \times 800$ mm, where d is the interelectrode gap and l is the discharge length. Here, we continue the KrF-laser research commenced in Ref. [5]. The aim of our investigation is to produce the discharge conditions required to raise the pulse repetition rate in a KrF laser by retaining a high average output.

2. Experimental results

It is evident that the pulse repetition rate of a repetitively pulsed laser may be augmented primarily through a reasonable increase in the velocity of the gas flow in the interelectrode gap. In the laser described in Ref. [5], the maximum velocity of the gas in the interelectrode gap was $\upsilon = 45$ m s^{-1} for the interelectrode distance $d = 28$ mm.

At the first stage of the research, we reduced d down to 20 mm in order to increase the velocity υ. However, our measurements showed that υ reduced to 30 m s^{-1} for $d \approx 20$ mm, which did not allow an increase in the pulse repetition rate. The last circumstance is axplained by the fact that the laser employed a diametrical fan with a wheel diameter of 150 mm which, as was disclosed by extensive measurements of the main gas-dynamic characteristics of the circuit, is not optimal when d is reduced below 28 mm.

The next stage of our investigation involved reduction of the discharge width from 8 mm [5] to 3 mm, which was accomplished through the use of new modified electrodes with a sharper profile (the first prototype of a KrF laser). Fig. 1 shows the laser output E, the laser efficiency η, and the relative roote-mean-square pulse-to-pulse variation σ of the output energy as functions of the charging voltage U

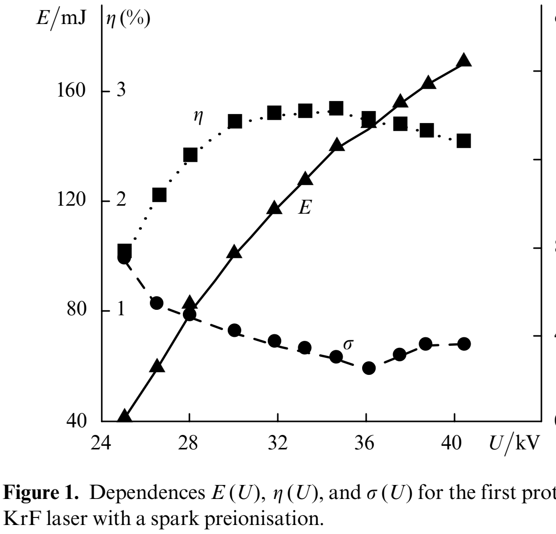

Figure 1. Dependences $E(U)$, $\eta(U)$, and $\sigma(U)$ for the first prototype of a KrF laser with a spark preionisation.

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obtained for $f \approx 100$ Hz. In these experiments, the discharge width was ~ 3 mm and the interelectrode gap was ~ 28 mm. We used a spark UV preionisation in the laser. One can see from Fig. 1 that the output energy of the modified laser may be as high as 160 mJ for $U = 40$ kV and the maximum lasing efficiency may amount to $\eta = 2.8\,\%$ with respect to the energy initially stored in the storage capacitors of the *LC* oscillator of a power supply. The highest stability in output energy ($\sigma = 2\,\%$) was reached in the range $U = 34 - 38$ kV.

The dependence of the average output power P of the KrF laser on the pulse repetition rate is plotted in Fig. 2. One can see that the maximum pulse repetition rate attained and the maximum average output power are 4 kHz and 630 W, respectively. The experimental results show [6] that the parameter σ, which characterises the pulse-to-pulse stability of the laser output, is a rather definite, though indirect, characteristic of the degree to which the uniformity of the volume discharge is retained during lasing. The behaviour of $\sigma(f)$ (Fig. 2) suggests that the discharge uniformity is adversely affected for $f > 3500$ Hz. This correlates with the behaviour of P_f (Fig. 2), which is also illustrative of the fact that the growth of P with f significantly slows down for $f > 3500$ Hz. The curves in Fig. 2 were obtained for a highest velocity of the gas flow $\upsilon \simeq 45$ m s^{-1} possible for the first prototype of the KrF laser.

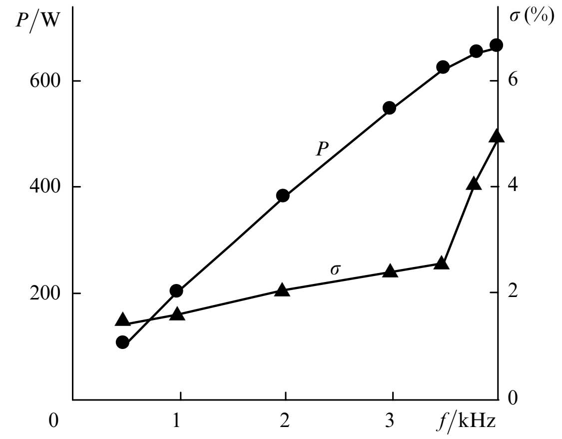

Figure 2. Dependences $P(f)$ and $\sigma(f)$ for the first prototype of a KrF laser with a spark preionisation.

Subsequently, our effort went into the development of a compact gas dynamic KrF-laser system for $d = 16 - 20$ mm. We elaborated a new system based on the recommendations given in Ref. [7]. In particular, our calculations showed that it is more advantageous to use a diametrical fan with a wheel diameter of no greater than 120 mm at a rotational speed $\omega \approx 4000$ rpm to ensure high values of υ for the interelectrode gap $d = 16 - 20$ mm. We carried out numerous model experiments to reveal the gas-dynamic circuit that is optimal for attaining maximum velocity. As a result, velocities υ up to 55 m s^{-1} for $\omega \approx 4000$ rpm were attained in the interelectrode gap of the new version of a KrF laser (second prototype) with $d = 16 - 20$ mm. Furthermore, we managed to reduce significantly the dimensions of the second prototype of the KrF laser compared to those of the first one. The laser chamber of the second prototype was made of a 700-mm-long aluminium tube of internal diameter 380 mm.

The role of the gas velocity υ in the interelectrode gap in the attainment of the maximum pulse repetition rate is clearly demonstrated by Fig. 3, which depicts the dependence $\sigma(f)$ for different υ. One can see that the deviation σ for $\upsilon = 8$ m s^{-1} is acceptably low ($\sigma \leqslant 1\,\%$) up to only $f \approx 1100$ Hz. When this repetition rate is exceeded ($f \geqslant 1100$ Hz), σ rises steeply, which is indicative of a significant impairment of the discharge uniformity. A visual observation of the integral discharge glow revealed downstream-shifted spark channels for $f > 1100$ Hz. This means [8] that the gas, in which there appeared significant (over $2\,\%$) fluctuations of the gas density caused by the current of the 'previous' discharge, had not fully escaped from the discharge gap region by the onset of the next discharge pulse.

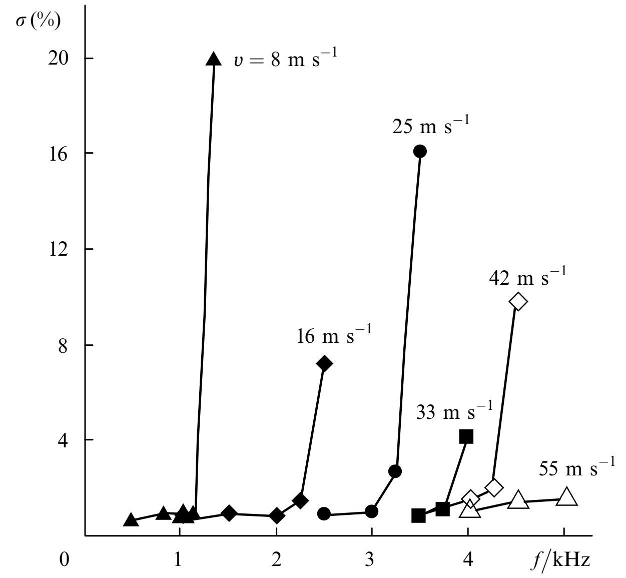

Figure 3. Dependences $\sigma(f)$ for the second prototype of a KrF laser preionised by a dielectric-surface discharge for different υ.

By increasing υ above 16 m s^{-1}, we obtained higher pulse repetition rates f. For $\upsilon = 55$ m s^{-1}, a gas in the interelectrode gap is completely changed by the onset of the next discharge pulse even for the highest (5 kHz) pulse repetition rate. The highest pulse repetition rate attained in our experiments (~ 5 kHz) was limited by the range of stable thyratron operation. Note that the so-called gas replacement coefficient $K = \upsilon/fb$ in this experiment increased monotonically from 2.2 for $\upsilon = 8$ m s^{-1} to 3.6 for $\upsilon = 55$ m s^{-1}. This fact suggests that the higher is the pulse repetition rate, the further downstream should the unperturbed gas region be shifted.

Fig. 4 gives the dependences of P and σ on f obtained for the second prototype of the KrF laser with a spark UV preionisation. A series of UV preionisation sparks was automatically produced upon charging the peaking capacitors of the laser pump circuit. In this experiment, the sparks ~ 2 cm apart were located on one side of the discharge electrodes, so that a new portion of gas passed first through the spark region and then, the region of the volume discharge (location of the sparks 'upstream' of the discharge). It would be natural to assume that improving the uniformity of UV preionisation would improve the uniformity of the main (volume) discharge current and thereby reduce σ and raise the maximum pulse repetition rate. However, our experiments showed that the use of two spark arrays located in staggered order on both sides of the electrodes did not result in a reduction of σ or an increase in f in compared to the use of only one spark array. Moreover, for $f \approx 4$ kHz, the emergent high-current channels are 'attached' to precisely the downstream-located ionisation sparks.

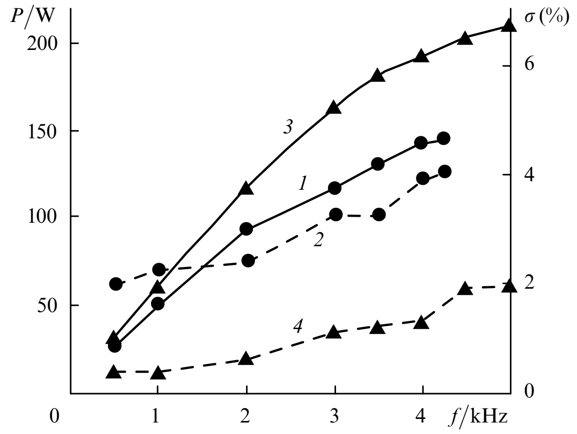

Figure 4. Dependences $P(f)$ (*1*, *3*) and $\sigma(f)$ (*2*, *4*) for the second prototype of a KrF laser with the use of spark preionisation (*1*, *2*) and the preionisation by a dielectric-surface discharge (*3*, *4*).

To improve the uniformity of UV preionisation, we developed a system of UV preionisation on the basis of a sliding discharge on the surface of a dielectric. Such a discharge, which uniformly covers the surface of an extended dielectric [9], ensures naturally a high uniformity of preionisation of the main volume discharge.

The dependences of P and σ on f for this system are also given in Fig. 4. A comparison of curves *1* and *3* shows that the average output power of the KrF laser for $f = 500$ Hz with preionisation by a spark array or by a sliding discharge are the same. However, the UV preionisation by a sliding discharge permits a four-fold improvement of the laser output stability (curve *4*) as compared to the preionisation by a spark array (curve *2*).

One can also see from Fig. 4 that P grows with increasing f much slower in the system with spark preionisation (curve *1*) than in the system with uniform preionisation by a sliding discharge (curve *3*). The behaviour of σ in these systems (curves *2* and *4*) shows that the magnitude of σ in the system with preionisation by a sliding discharge (curve *4*) for a high $f = 4$ kHz, too, remains several times lower than in the system with a spark UV preionisation (curve *2*).

Thus, the dependences presented in Fig. 4 show that a more uniform preionisation by the UV radiation of a sliding discharge is favourable to the formation of a volume discharge which retains a reasonably high uniformity even for maximum pulse repetition rates.

Another attractive feature of the discharge system with preionisation by a sliding discharge is that the average output of the KrF laser $P \approx 200$ W can be obtained by using for the preionisation only a small fraction ($\sim 1\,\%$) of the electric energy stored in the power supply. By contrast, in a system with a spark preionisation, all the stored energy usually passes through the sparks. Therefore, the use of UV preionisation by the radiation of a sliding discharge allows us to reduce the sputtering of the electrodes of the preionisation system and thereby lengthen the operating life of both the gas mixture and the laser system as a whole.

The dynamics of the pulse-to-pulse variation in the KrF laser output is presented in Fig. 5 for different pulse repetition rates. One can see that the laser output E remains invariable for about 50 pulses, after which it lowers to some new value that can persist for long ($\sim 10^7$ pulses).

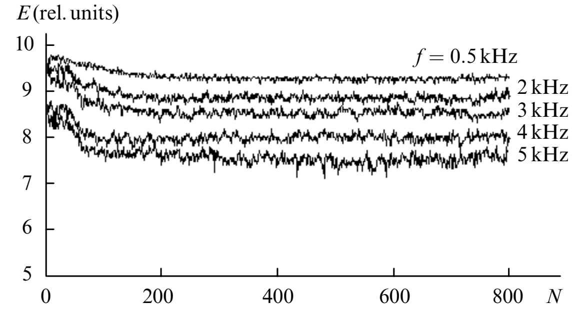

Figure 5. Variation in the energy of output laser pulses from the pulse number N for the second prototype of a KrF laser with preionisation by the discharge over a dielectric surface for different f.

The system for monitoring the pulse energy E was so designed that every pulse was recorded for $f \leqslant 1$ kHz, every second pulse for $f = 2$ kHz, every third for $f = 3$ kHz, etc. Therefore, as is clear from Fig. 5, the characteristic time, after which there occurs a lowering of E, remains approximately constant for an invariable flow velocity $\upsilon = 55$ m s^{-1}. According to our estimates, this time coincides with the average time required for a portion of gas to travel through the entire gas-dynamic laser circuit and is equal to ~ 30 ms. The latter circumstance may signify that the first portion of gas, in which a discharge had already occurred and some products were formed that adversely affect the efficiency of lasing in KrF molecules, re-enters the discharge gap in 30 ms to cause a significant lowering of the laser output. Then, a dynamic equilibrium is established between the production and diminution of these products, whose stationary density determines the form of the dependences in Fig. 5.

Note that the degree to which the effect under discussion reveals itself depends on the duration of both the active and passive fluorine passivations of the laser, as well as on the dielectric material used in the laser design. A more comprehensive investigation of this effect is planned for the future, especially in the context of lasing on ArF* molecules, where this effect is more pronounced.

3. Conclusions

Therefore, it is possible to sharply increase the maximum pulse repetition rate by optimising the width of the volume discharge, the velocity of the gas flow in the interelectrode gap, and the uniformity and location of UV preionisation. The dependences of the average output laser power on the pulse repetition rate in the $1-5$ kHz range do not differ qualitatively from those previously obtained for the repetition rates below 1 kHz. Hence, they can be interpreted in the context of the notions developed, e.g., in Refs [5, 8]. However, the passage to repetition rate above 1 kHz revealed a new interesting effect which determines the dynamics of the pulse-to-pulse variation of the laser output (see Fig. 5).

The practical outcome of this work was the development of two prototypes of a KrF laser with an average output power of 600 and 200 W and a maximum pulse repetition rate of 4 and 5 kHz, respectively. Long-term runs in different operating modes have shown the above prototypes to be highly reliable, which permits high-power industrial KrF lasers with a high repetition rate to be made using the prototypes as the base.

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