Run-away electron preionized diffuse discharge as a source of efficient laser emission in the IR, UV, VUV

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Abstract. REP DD was suggested as an excitation source of various gas lasers. The efficient lasing was obtained in the IR, UV, and VUV spectral ranges. The ultimate intrinsic efficiency of non-chain chemical lasers on HF(DF) molecules was achieved. REP DD pumped N2 laser with an ultimate electrical efficiency of 0.2% was developed. Lasing on N2 molecules with 2 or 3 peaks in successive REP DD current oscillations was obtained for the first time. The laser action on F2* at 157 nm and rare gas fluorides (KrF*, XeF*) under REP DD pumping was obtained for the first time, as well. It has been shown that the vector stage of REP DD in mixtures with fluorine can last over 50 ns during several current half-cycles. Therewith, the efficiency and the pulse duration of lasers on rare gas fluorides and VUV F2* laser parameters under REP DD excitation are comparable with those obtained in suitable transverse discharges. The results allow the conclusion that the REP DD homogeneity in mixtures with F2 and SF6 is high enough for attaining high laser efficiency.

1. Introduction

It is known that in active mixtures, the main parameters of gas discharge lasers such as pulse duration, output, and efficiency are essentially dependent on the uniformity and stability of self-sustained volume discharge. Currently, it is generally recognized that the necessary conditions for volume discharge development are: the use of properly shaped electrodes having no strong edge effects, preionization from different sources (VUV radiation, x-rays, electron beam and so on) producing certain electron number density, over-voltage pulse applied to a laser gap [1–3].

Nevertheless, the formation of quite uniform discharges in various gases at high pressure and efficient lasing are possible even without any preionization, if voltage pulses with an amplitude over 100 kV and sub-ns rise-time are applied to needle or blade electrodes [4]. In this case, the volume discharge is formed due to preionization by the beam of run-away electrons. This discharge form is called the run-away electron preionized diffuse discharge (REP DD) [5].

The present paper reports the parameters of gas lasers pumped by REP DD.

2. Experimental set-up and measurement procedure

The discharge chamber described in detail in [4] was used in the experiments. The REP DD was formed by the nanosecond pulses of RADAN-220 generator between the blade-shaped electrodes of 30 cm length, which were placed at a distance of 1.8 cm [6]. In the impedance matched excitation
mode, the discharge current duration was 10 ns, while in the oscillating mode, it could reach 50 ns within the half-cycle of 10 ns. The active volume was usually \( V \approx 20 \text{ cm}^3 \).

The circuitry of RADAN generator includes a high voltage pulsed forming line (PFL) with the capacitance \( C=50 \text{ pF} \) and the oil insulation, which is charged from a Tesla transformer (TT) and then is switched on a load with commercial two-electrode high-pressure nitrogen spark gap R-49.

One of the basic parameters of a gas laser is its efficiency, which in turn, is dependent on the self-breakdown voltage of P-49 spark gap. Two spark gaps with breakdown voltages \( U_1=240 \pm 10 \text{ kV} \) and \( U_2=280 \pm 10 \text{ kV} \) were used in the experiments. Therewith, the energy stored in the generator transmission line was not higher than \( E_1=1.56 \text{ J} \) or \( E_2=2.1 \text{ J} \).

Optical cavity mirrors were fixed at the chamber ends; there was an additional window in the sidewall, to shoot the discharge and record the spontaneous emission spectra and pulses.

A flat cavity used in the experiment consisted of a mirror with the reflection coefficient \( R=100\% \), at the laser wavelength, or an aluminum coated mirror and MgF\(_2\) plate. Mirrors with \( R=20–90\% \) were mounted behind the exit plate.

The radiation energy was measured using an OPHIR calorimeter with a PE-50BB sensor head. The discharge current was measured using a shunt. The time variations in radiation pulses at \( \lambda=193 \text{ nm} \) were recorded using a high-speed Photek PD025 Spec.No. SPD025/S01-01 photodiode, and at \( \lambda=200–800 \text{ nm} \), with a FEK-22 SPU photodiode. The amplitude–time characteristics of IR radiation were detected using a FSG-23 photoresistor. Photodetectors were mounted close to the output mirrors.

A standard photocathode was replaced by a copper plate in the FEK-22 photodiode, to measure pulses in the VUV region. The modified photodetector was connected to the output plate and evacuated. This detector was tested using pulses of N\(_2\), XeF*, and KrF* lasers. The measured KrF* laser pulse shape coincided with the pulse shape measured using the FEK-22 SPU photodiode. The radiation at \( \lambda = 337 \) and 351 nm was not recorded by the modified photodetector.

The visible and the UV discharge radiation spectra were measured using a HR4000 spectrometer (Ocean Optics B.V.). Spectra in the IR range were recorded using an MDR-12 monochromator equipped with a 300 lines mm\(^{-1}\) grating and FSG-23 photoresistor.

The integral glow of discharge was shot using a Sony A100 digital photo camera. A TDS3054B digital oscillograph (0.5 GHZ, 2.5 × 10\(^9\) samples/s) was used for recording the electric signals.

3. Efficient lasing in REP DD

3.1. Non-chain HF(DF) lasers

The volume discharge in SF\(_6\) mixtures with hydro- and deuteron-carbons can be formed in the transverse geometry without preionization [7]. However, the discharge arising in SF\(_6\) mixtures with H\(_2\) or D\(_2\), under conventional excitation regimes, is unstable, and hence, the electrodes providing the uniform electrical field in the discharge gap and the intense preionization are required to improve the discharge stability [8]. Therewith, the maximal electrical efficiency of HF(DF) lasers in the transverse geometry in the mixtures with H\(_2\) and D\(_2\) was obtained using short excitation pulses (~20 ns) [9].

Figure 1 illustrates the laser parameters of non-chain chemical lasers under PEP DD excitation. In our experiments, the duration of REP DD current pulse was about 10 ns without any oscillations. The input electric power was as high as 15 MW cm\(^{-3}\) providing a short delay time of laser pulse appearance. Laser pulses have one peak with about 75 ns duration at half-maximum followed by an exponentially decaying tail. The maximal output of HF (110 mJ) and DF lasers (75 mJ), with the peak radiation power over 1.2 MW, was obtained, similarly to [8], in the mixtures with H\(_2\) and D\(_2\).

The energy deposited into the laser active medium was estimated from the current and voltage waveforms, and was equal to \( E_{\text{dep}}=1 \text{ J} \). This energy deposition corresponds to the specific pumping energy of 50–65 J l\(^{-1}\), which is optimal for a non-chain discharge HF(DF)-laser [8]. It is easily to see that the internal HF laser efficiency (relative to \( E_{\text{dep}} \)) is as high as \( \eta_{\text{int}}=10\% \), which corresponds to the limiting value for the discharge HF laser [8]. The obtained DF laser generation efficiency (\( \eta_{\text{int}}=7.5\% \))...
Figure 1. Waveforms of the voltage across the laser gap $U_d$, REP DD current $I_d$, and integral laser pulses on HF ($P_{\text{las}}(\text{HF})$) and DF $P_{\text{las}}(\text{DF})$ molecules (a), the power distribution $P_{\text{las}}$ over laser lines in cascade transitions of the DF laser (b). Gas mixtures SF$_6$:H$_2$(D$_2$) = 8:1 at p=300 Torr are used, $E_2=2.1$ J.

The number of lasing lines attained 16 in mixtures of SF$_6$ with hydrogen. The radiation energy distribution over HF bands was $Q(P_1):Q(P_2):Q(P_3)=1:0.62:0.1$ and intensive cascade transitions were observed in the generation spectrum. The maximal energy was emitted at the $P_1$ band of HF molecules, while up to 85% of laser output was emitted in the cascades. A number of DF lasing lines attained 26, and lines of the $P_2$ band had the maximal intensity.

Intense cascade transitions prove the high uniformity of REP DD, which provides the high uniformity of energy deposition into an active medium. It is known that the cascade transitions do not occur in a non-uniform discharge, while the integral radiation pulse in this case exhibits the well-pronounced spike-mode character [8, 10].

The cascade transitions increase the efficiency of energy extraction from the active medium of non-chain chemical lasers, because a single excited molecule HF$^*$ ($v=3$) or DF$^*$ ($v=4$), where $v$ is the vibrational quantum number, may emit up to 3–4 photons. The results allow the conclusion that the high homogeneity of a REP DD satisfies the main conditions for volume discharge development in the mixtures with SF$_6$. In this case, due to a high power pumping pulse, the lasing occurring on separate lines started 15–20 ns later than the discharge gap breakdown, with a jitter of 5 ns, which decreases the energy loss for the attainment of lasing threshold. These factors provide the high efficiency of REP DD pumped non-chain laser.

### 3.2. Nitrogen laser

For obtaining the generation on the $C^3Π_u→B^3Π_g$ transition of nitrogen molecule ($λ=337.1$ nm), the value of parameter $E/p$ in the discharge gap should be at least 100 V cm$^{-1}$ Torr$^{-1}$. Under pumping by a self-sustained discharge, the voltage across the gap falls in several ns. Thus, to obtain high efficiency under such conditions, one has to design the supply circuits providing fast ($≈10$ ns) injection of high energy ($≈0.1$ J cm$^{-3}$) into the working medium, in order to reach rapidly the lasing threshold. Hence, the pulse generator used in the experiments is optimal for pumping a nitrogen laser. However, the high impedance of generator requires the high discharge resistance, which was achieved using SF$_6$ additions into nitrogen. The high voltage pulse amplitude allows us to form a diffuse discharge without additional preionization in N$_2$-SF$_6$ mixtures at pressures up to several atmospheres.

Two operation modes of N$_2$ laser under REP DD excitation were determined from the calculations and in experiments. The ultimate electric efficiency of nitrogen laser is characteristic of the first operating mode. In this case, the main part of energy, which is stored in the PFL, is deposited into the discharge plasma during 10 ns. Under REP DD pumping, the generation domain width was 0.5 cm.
with the uniform distribution of laser radiation power over the discharge aperture. The maximal energy of UV radiation was \( Q = 4.2 \text{ mJ} \), while the peak radiation power reached \( 1.4 \text{ MW} \) with \( E_2 = 2.1 \text{ J} \). The electrical efficiency (with respect to \( E_2 \)) was as high as \( \eta_0 \approx 0.2 \% \). Such efficiency is close to the ultimate theoretical value \([11]\) and to maximal efficiencies obtained experimentally for the nitrogen laser at \( \lambda = 337.1 \text{ nm} \), pumped by the transverse discharge with UV preionization \([11, 12]\).

The characteristic feature of the second oscillation mode of \( \text{N}_2 \) laser is two or three radiation peaks during one excitation pulse (see figure 2). This operation mode can be achieved in \( \text{N}_2\text{-SF}_6 \) mixtures at pressure below \( \approx 100 \) Torr. In the case of REP DD excitation, the second and the third laser peaks appear during discharge current oscillation. It was found that the addition of \( \text{He} \) into \( \text{N}_2\text{-SF}_6 \) mixture allows to increase intensities of the second and the third laser peaks.

![Figure 2](image)

Figure 2. Waveforms of REP DD current \( I_d \), laser pulses at 337.1 nm \( P_{\text{las}} \) in mixture \( \text{N}_2\text{-SF}_6 = 30:30 \) Torr, the waveform \( P_{\text{las}}(\text{He}) \) is obtained in the \( \text{He}:\text{N}_2\text{-SF}_6 = 100:30:30 \) Torr mixture, \( E_2 = 2.1 \text{ J} \).

The REP DD in this operation mode comprises the wide diffuse streams starting for both blade electrodes, its emission spectra being typical for the volume discharge in nitrogen and consisting of the intense lines of nitrogen second positive system. It is known, that in the contracted discharge in nitrogen, the emission spectrum is dominated by broad continua, bands, and lines of the cathode-electrode material, as well as by the lines of nitrogen and oxygen atoms, and ions \([13]\). This fact shows the sufficient stability of REP DD in mixtures of nitrogen with \( \text{SF}_6 \), which volume stage duration in our experiments lasts longer than 50 ns. The radiation energy in the operation mode with several radiation peaks is about 1 mJ.

### 3.3. Excimer lasers

Gas lasers on \( \text{XeF}^* \), \( \text{KrF}^* \), \( \text{ArF}^* \), \( \text{F}_2^* \) molecules are usually pumped by the transverse volume discharge with preliminary ionization of a working volume. As a rule, duration of laser radiation pulses in mixtures of rare gases with fluorine is substantially limited by a discharge arcing or its filamentation. The discharge non-uniformities usually develop in a short time (10–30 ns) after the breakdown of laser gap \([14, 15]\). As in case of the nitrogen and non-chain chemical lasers, it leads to a need to use pumping generators forming short excitation pulses, and the set-up, on the base of the RADAN pulser, can be optimal for this laser application.

In our experiments, the maximal radiation energy was reached in mixtures with helium as a buffer gas. In mixtures with neon, the laser output decreases dramatically due to low discharge resistance and as a result, the input electric power was insufficient for attaining the efficient lasing on rare gas fluorides. Additives of argon in working gas led to REP DD transformation into a channel form.

Figure 3 shows the integrated photo of REP DD and laser spot in a typical mixture of \( \text{XeF}^* \) laser. The discharge has the form of channels, which begin at the electrodes and then quickly extended to the center of the discharge gap, forming a uniform volume glow without signs of contraction. Similar discharge view was observed in the \( \text{KrF}^* \) laser mixtures. The laser spot width of \( \text{XeF}^* \) and \( \text{KrF}^* \) lasers was 4–5 mm.
Figure 3. Integral image of REP DD and XeF* laser spot in He:Xe:F₂ = 3 atm:15:5 Torr mixture.

Experimental results describing XeF* laser operation under REP DD excitation are presented in figure 4. Mixtures with two fluorine donors, F₂ and NF₃, were used. In both cases, an oscillatory character of REP DD, with duration exceeding 50 ns, was evident. The current decay in mixtures with fluorine was faster, which meant a higher resistance of the volume discharge plasma in F₂ based mixtures.

Figure 4. Waveforms of REP DD current and integral laser pulses on FI lines and XeF* molecules for different reflectance R of the output mirror, mixture He:Xe=3.5 atm:15 Torr with 5 Torr F₂ (a) and NF₃ (b) is used, E₁=1.56 J.

In mixtures with fluorine, a short generation peak on red transitions of atomic fluorine was observed within 2–3 ns after the discharge formation. The delay time of XeF* laser pulse appearance in mixtures with F₂ increases, and the energy of the radiation was 3 times lower than in mixtures with NF₃. This is due to the fluorine absorption at 351–353 nm and quenching of XeF*molecules by F₂.

Maximal output of XeF* laser was as high as 10 mJ, which corresponded to the electrical efficiency η₀ = 0.65%. The efficiency value is close to the parameters of XeF* lasers pumped by the transverse volume discharge [16]. Laser emission was continued during 2–3 current periods, and full length of laser pulse on XeF* molecules in mixtures with fluorine reached 45 ns. In mixtures with NF₃ the radiation pulse was 10 ns shorter. This means maintaining of the REP DD diffuse phase burning even after the repeated change of current direction in the laser gap.

Laser parameters obtained in He-Kr-F₂ working mixtures are presented in figure 5. As in the case of XeF* laser, a short radiation pulse on atomic fluorine transitions was observed in few ns after the REP DD formation. Lasing on KrF* molecules started within 10 ns and lasted for two current half-cycles, while total duration of the laser pulse was as long as 30 ns. This indicates the high homogeneity and stability of REP DD in the mixtures of helium and krypton with fluoride. The radiation energy increased linearly with He pressure and reached Q=20 mJ, which corresponded to the electrical efficiency η₀=1.25%.

The input energy in our experiments was estimated to be Eᵢ=0.64 J. Hence, the internal efficiency of the KrF* laser under REP DD excitation can reach ηᵢₑ > 3%, which is comparable with the
parameters of the KrF* laser pumped by a transverse discharge with UV preionization [17]. At the same time, the input electric power into the REP DD plasma reaches 2 MW cm⁻³, which is also close to the conventional modes of KrF* lasers pumping by the electric discharge [17].

![Image](image_url)

**Figure 5.** Characteristic waveforms of the discharge current $I_d$, and laser pulses $P_{\text{av}}$ on atomic fluorine lines (FI) and at on KrF* molecules for the output mirrors with $R = 50\%$ and $70\%$, He Kr : F₂ = 3.5 atm: 100: 5 Torr gas mixture is used (a) and KrF* laser output Q and electric; the efficiency $\eta_0$, as a function of gas mixture He: Kr: F₂ = X: atm: 100: 5 Torr pressure, $R = 50\%$ (b), $E_1=1.56$ J.

![Image](image_url)

**Figure 6.** Waveforms of REP DD current $I_d$ and laser radiation on FI (curves 1, 2) and F₂ (P\textsubscript{VUV}) in He:F₂=3 atm:5 Torr mixture for R=7% (1, P\textsubscript{VUV}) and 90% (2), $E_2=2.1$ J.

A laser action on the VUV transition of F₂ molecules at 157 nm was obtained in He-F₂ mixtures for the first time, under REP DD excitation (see figure 6). The VUV laser pulse on F₂ molecules had two distinct peaks, and one weak peak during three half-periods of the REP DD current, lasing duration being as long as 25 ns. The VUV radiation power in the peaks increased exponentially with He pressure. The maximal VUV energy of 2 mJ was achieved at He pressure of 5 atm. Therewith, the electrical efficiency of F₂ laser was as high as 0.1%, which, similarly to XeF* and KrF* lasers, is comparable with the parameters of F₂ lasers pumped by the transverse discharge with preionization [18–19]. Simultaneously with VUV emission, a laser action on atomic fluorine with the maximal output of 0.25 mJ was observed.

4. Conclusion
Laser radiation parameters in mixtures of rare gases, H₂ (D₂) and nitrogen, with fluorine containing molecules, pumped by the REP DD are studied. It is shown that the stable volume discharge of long
duration can be formed in high-pressure mixtures with F$_2$, NF$_3$ and SF$_6$, in compact systems formed by the blade electrodes without additional illumination source.

Promising prospects of REP DD application for exciting series of gas lasers are demonstrated. A laser action on molecules N$_2$, HF, and DF, with ultimate efficiency, was obtained.

Novel operation modes of N$_2$ laser with two and three radiation peaks was demonstrated under pumping by the oscillating run-away electron preionized discharge.

A laser action on F$_2^*$, KrF$^*$ and XeF$^*$ was obtained in REP DD for the first time. It was shown that volume stage of REP DD in mixtures with fluorine could last >50 ns during several current half-cycles. Therewith, the efficiency and pulse duration of lasers on rare gas fluorides and VUV F$_2^*$ laser parameters under REP DD excitation are comparable with the laser characteristics obtained in a convenient transverse volume discharges with preionization.

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