

PACS numbers: 42.55.Lt; 42.60.Lh; 52.80.–s
DOI: 10.1070/QE2013v043n07ABEH014928

Lasing in the UV, IR and visible spectral ranges in a runaway-electron-preionised diffuse dischrage

P.O. Vil'tovskii, M.I. Lomaev, A.N. Panchenko, N.A. Panchenko, D.V. Rybka, V.F. Tarasenko

Abstract. **Lasers on the mixtures of inert gases, H_2, D_2, and nitrogen with NF_3 and (or) SF_6 are studied under pumping by the volume (diffusive) discharge formed in a nonuniform electric field due to runaway-electron preionisation. Generation in the IR, visible and UV spectral ranges is obtained on atomic transitions of neon (λ = 585.3 nm), argon (750.3 nm) and fluorine (712.8 and 731.1 nm), and on molecular transitions of N_2 (337.1 nm), XeF^* (351 and 353 nm), HF (2.8–3.2 μm) and DF (3.8–4.2 μm). It is shown that in N_2–SF_6, H_2–SF_6 and D_2–SF_6 mixtures the generation efficiency approaches the limiting values.**

Keywords: *pulsed gas IR, visible and UV lasers, run-away-electron-preionised diffuse discharge, high efficiency.*

1. Introduction

It was shown [1–4] that gas mixtures at elevated pressures pumped by a runaway-electron-preionised volume (diffuse) discharge (REP DD) exhibited lasing in the IR [1], visible [2] and UV [3, 4] spectral ranges. In those works, runaway electrons and laser radiation were generated in the same discharge gap. Runaway electrons formed in a separate gap were used for preionising the main lasing gap, in which the generation on molecules N_2 [5] and CO_2 [6] was realised. In addition, the voltage pulses used for obtaining runaway electrons in atmospheric air were also employed for pumping a laser on ZnSe crystals [7]. The runaway-electron beams formed in a separate gap by kilovolt voltage pulses were used to pump gas lasers in the IR range at low and moderate pressures [8–10].

Analysis of popular works shows that the pumping of lasers efficiently operating at elevated pressures of working mixture [11, 12] is more promising if the diffuse discharge is formed by a runaway electron beam. The duration of the current pulse of runaway electrons formed in gases at pressures of hundred Torr and higher is comparatively small (~100 ps) and the current density of the beam at atmospheric pressure usually does not exceed several A cm^{-2} [13, 14]. Such values are explained by the mechanism of forming the runaway electron beam at elevated pressures [13]. In these conditions, most of runaway electrons are produced between the front of the ionisation wave and the anode, and the current pulse duration of the beam is limited, in particular, by the wavefront of the ionisation wave arriving at the anode.

The aim of the present work is to study the parameters of generation in the IR, visible and UV spectral ranges on transitions of atomic neon, argon and fluorine, on molecular transitions of HF, DF, N_2 and XeF_* pumped by REP DD, and to determine most promising gas mixtures for realising efficient generation. The present work is the continuation of investigations started in [1–4].

2. Experimental setup and measuring methods

Lasing in various gas mixtures was studied under pumping by the voltage pulses of nanosecond duration formed by a RADAN-250 generator [15] (installation 1) with a wave resistance of 20 Ω in the forming line. Constructions of the output generator cascade and discharge chamber were presented in [4]. The breakdown voltage of the peaker was ~250 kV, which corresponded to the energy stored in the forming line of 1.5 J. The half-height voltage duration on the matched load was ~2 ns and the front duration of a voltage pulse in the forming line was approximately 0.5 ns. With connected discharge chamber, the front duration of the voltage pulse increased to ~2 ns, the half-height pulse duration also increased. The duration of the current pulse depended on the pressure and type of gas and at low helium and neon pressures reached several hundred nanoseconds in the oscillating regime. In these experiments the discharge gap between the anode and cathode was 2 cm. The both electrodes were shaped as blades. The length of the discharge domain was 20 cm. The cavity comprised plane mirrors placed on end walls of the discharge chamber. The highly reflecting mirror was made of a plate with an aluminium coating. For the output mirror we used the plane-parallel plates made of quartz, CaF_2, KRS-5, KRS-6 or Ge. We also used plane mirrors with dielectric coatings and the reflection coefficients in the UV and visible ranges R = 20%–80%. The chamber was evacuated by a diffusion pump and was filled with various gases. Its side wall had an additional window for shooting the discharge and detecting the pulses of spontaneous emission.

The amplitude–time characteristics of visible and UV radiation were detected with a FEK-22SPU photodiode, the IR radiation was detected with a FSG-23 photoresistor. The lasing domain was determined by luminescence on the screen placed on the output mirror. The discharge glow and screen luminescence were photographed by a Sony A100 digital camera. The spectra of radiation were recorded with a StellarNet EPP2000-C25 spectrometer with calibrated spectral sensitivity in the wavelength range λ = 200–850 nm at a

P.O. Vil'tovskii, M.I. Lomaev, A.N. Panchenko, N.A. Panchenko, D.V. Rybka, V.F. Tarasenko Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, Akademicheskii prosp. 2/3, 634055 Tomsk, Russia;
e-mail: VFT@loi.hcei.tsc.ru, alexei@loi.hcei.tsc.ru

Received 27 June 2012; revision received 6 March 2013
Kvantovaya Elektronika **43** (7) 605–609 (2013)
Translated by N.A. Raspopov

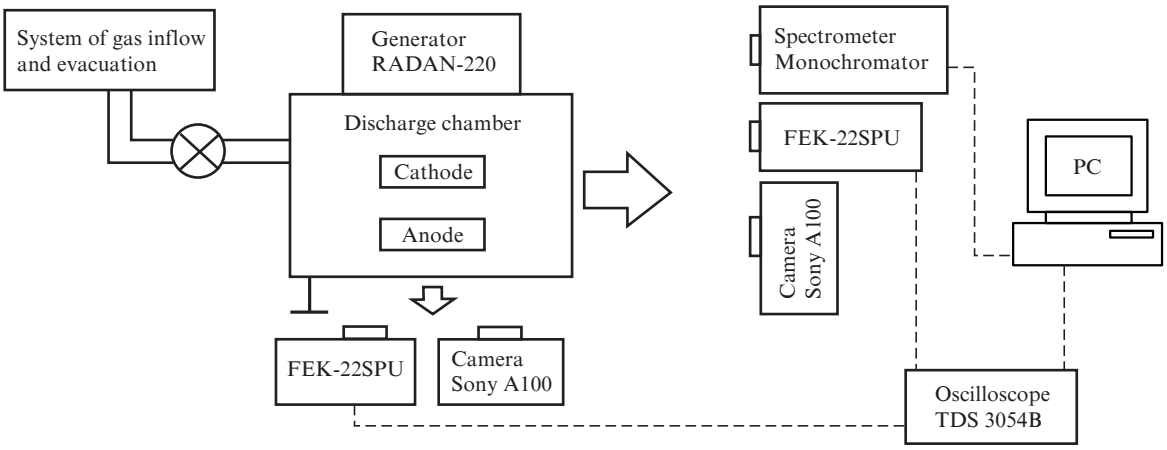

Figure 1. Schematic diagram of experimental setup and measurement of the laser generation parameters.

resolution of 0.75 nm. Spectra in the range $\lambda = 2.8-4.2$ μm were recorded by using an MDR-23 monochromator equipped with a 300 lines mm^{-1} grating and FSG-23 photoresistor. In performing the measurements, the photodetectors operated in a linear regime, which was provided by attenuating the laser radiation by a series of metal meshes. The energy of laser radiation was measured by an Ophir device with a PE-50BB measuring head. The electrical signals were recorded with a TDS-3054B oscilloscope (0.5 GHz, 5 samples per 1 ns). The schematic diagrams of installation 1 and measuring system are shown in Fig. 1.

The characteristics of the discharge pumped by the REP DD were studied in our earlier works [1, 4] and on installation 2, which utilised a SLEP-150 generator and a chamber with a capacitive divider and shunt. On installation 2 it was also possible to place a sub-nanosecond-resolution collector [13, 14] behind the anode foil for measuring the parameters of the runaway electron beam. The discharge gap was formed between the cathode made of a 100-μm-thick foil with the sharp edge of length 2.2 cm and the plane anode arranged at a distance of 1.3 cm.

In the present work much attention was paid to investigation of peculiarities of laser radiation in mixtures of various gases with NF_3 and SF_6. Earlier it was established that addition of electro-negative gases substantially, by the order of magnitude [3], increases the radiation energy and power of the laser operating on the second positive system of nitrogen. The increase in the radiation energy in the mixtures comprising electro-negative gases is mainly explained by the increased gap breakdown voltage on the installations with the electrodes of a small radius of curvature.

The following mixtures with electro-negative gases were employed in the experiments: $N_2-NF_3(SF_6)$, $H_2-C_2H_6-SF_6$, $H_2(D_2)-SF_6$, $He-NF_3$, $Ne-NF_3$ и $Ar-NF_3$, as well as $Ne(He)-Xe-NF_3$. The generation parameters of those mixtures were studied earlier under the excitation by a transversal volume discharge and electron beam [11, 12, 16–18].

3. Experimental results and discussion

3.1. Nitrogen laser ($\lambda = 337.1$ nm)

For obtaining the generation on the UV transition of nitrogen molecule ($\lambda = 337.1$ nm) the value of the 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 nanoseconds. Correspondingly, for increasing the efficiency of generation on nitrogen molecules the discharge current pulses should have the duration shorter than 10 ns. Hence, the pulse generator used in the experiments is optimal for pumping a nitrogen laser and the employment of nitrogen mixtures with SF_6 provides matching the discharge resistance with generator impedance, which increases the pump power and energy of the UV radiation. In this case, the diffuse discharge without gap preionisation was formed in nitrogen and its mixtures with SF_6 at pressures of up to several atmospheres.

The results obtained are shown in Fig. 2. Under REP DD pumping, simultaneous lasing on the second ($\lambda = 337.1$ nm) and first ($\lambda = 865-1048$ nm) nitrogen systems was observed, which started 3 ns after the breakdown of the discharge gap. The generation domain width was 0.5 cm with the uniform distribution of laser radiation power over the discharge aperture, the peak radiation power reached 0.7 MW. The maximal energy of the UV radiation was 3.1 mJ at the electrical efficiency (with respect to the energy stored in the forming line of the RADAN-220 generator) $\eta_0 \approx 0.2\%$. Such an efficiency is close to the limiting theoretical value for this type of the laser [19] and to maximal efficiencies obtained experimentally [19, 20]. In the nitrogen mixtures with NH_3, the radiation energy of the nitrogen laser was no greater than 0.5 mJ.

3.2. Non-chain chemical HF(DF) lasers

An interesting feature of SF_6 mixtures with hydrocarbons is the possibility of forming the volume discharge without preionisation [21]. However, the discharge in the SF_6 mixtures with H_2 or D_2 in conventional excitation regimes is unstable and hence the electrodes are required capable of providing the uniform electrical field in the discharge gap [22]; the maximal efficiency in non-chain HF(DF) lasers in the mixtures with $H_2(D_2)$ was obtained with short pump pulses (~20 ns) [23].

The characteristic oscillograms of the voltage across the discharge gap, REP DD current, and the time dependence of power deposited into the discharge plasma are shown in Fig. 3; those were obtained on installation 2 with the discharge gap separation of 1.3 cm and electrode length of 2.2 cm at the SF_6-pressure of 0.6 atm. At increased gap separation and length of the electrodes (installation 1) the dura-

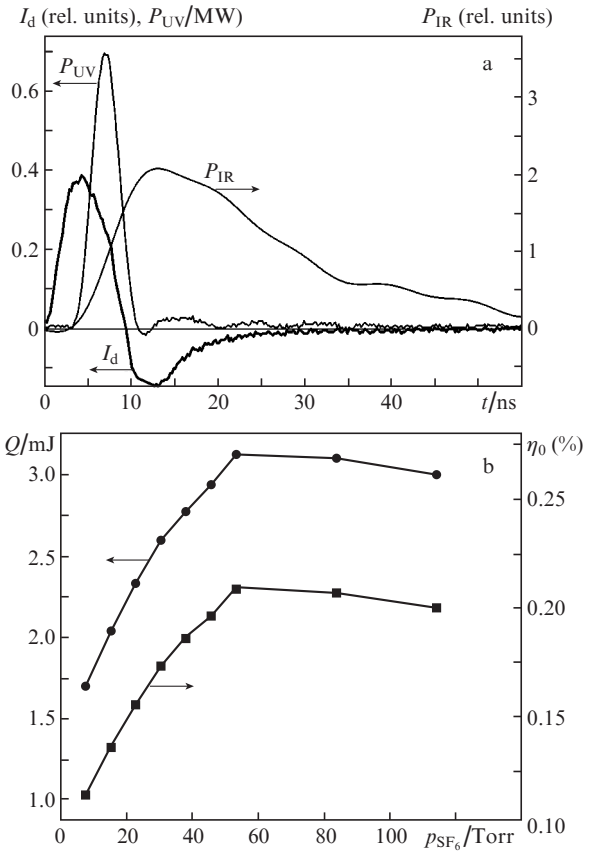

Figure 2. (a) Oscillograms of REP DD current pulses I_d and generation in the mixture $N_2:SF_6 = 300:45$ Torr in the first (P_{IR}) and second (P_{UV}) positive bands of nitrogen and (b) dependences of radiation energy Q at $\lambda = 337.1$ nm and electrical efficiency of nitrogen laser η_0 on pressure of SF_6 at the nitrogen pressure 300 Torr.

tion of the discharge current pulse increased to 10 ns, and the measured energy deposition into the laser active medium was ~0.7 J. At the volume of the laser active medium ~10 cm^3 such energy deposition corresponds to the specific pump energy of 70 J L^{-1}, which is optimal for a non-chain electrodischarge HF laser [24]. The pump power under these conditions reached 20–30 MW cm^{-3}.

Figure 4 shows the generation energy for HF(DF) lasers versus the reflection coefficient of the output mirror. The maximal radiation energy of the HF laser (65 mJ) was obtained, similarly to [24], in a mixture with hydrogen. It corresponds to the internal (relative to the energy deposited into the discharge plasma) generation efficiency η_{int}, which is close to the limiting value ~10%. The radiation energy of the DF laser raised linearly with increasing cavity Q-factor and at the reflection coefficient of the output mirror $R = 55\%$ reached 45 mJ. The obtained generation efficiency ($\eta_{int} = 6.5\%$) is also close to the limiting value for the DF laser (~8%). One may expect a further increase in the radiation energy and efficiency at greater R. Similarly to [24], the integral, with respect to spectrum, radiation pulse of non-chain lasers with the REP DD pumping had a single peak (Fig. 5a) and intensive cascade transitions were observed in the generation spectrum. The maximal radiation energy of HF and DF lasers was observed in the bands P_1 and P_2 (Fig. 5b), respectively. This fact proves the high uniformity of energy deposition into the active medium under REP DD pumping. It is common knowledge that cascade transitions do not occur in a non-uniform discharge and the radiation pulse exhibits the well pronounced spike-mode character [24, 25]. Cascade transitions increase the efficiency of energy extraction from the active medium of non-chain chemical lasers, because a single excited molecule $HF^*(v \leqslant 3)$ or $DF^*(v \leqslant 4)$, where v is the vibrational quantum number, may emit up to three–four photons. In addition, due to the powerful pump pulse, lasing in separate lines started within 15–20 ns after the discharge gap breakdown with a jitter of ~5 ns, which reduced the energy losses to attaining the generation threshold. These factors provide the high efficiency of the non-chain laser upon REP DD pumping. Note that the distribution of radiation power over the aperture of lasing spot was also comparatively uniform.

The high REP DD power at maximal Q-factors of the cavity resulted in appearance of weak lines in the generation spectrum of HF and DF molecules in the P_4 and P_5 bands with $v = 4$ and 5, respectively. Lasing in these lines started

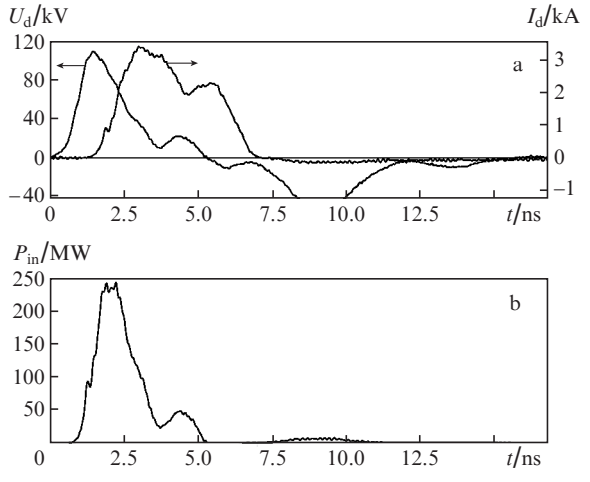

Figure 3. Typical oscillograms of voltage across the discharge gap, REP DD current (a), and power deposited into the discharge plasma (b) obtained on installation 2. The gap separation is 1.2 cm, cathode length is 2.2 cm; the discharge chamber is filled with SF_6 at the pressure of 0.6 atm.

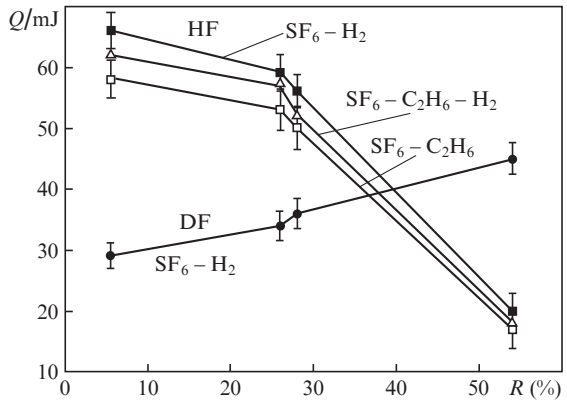

Figure 4. Generation energy Q of laser on molecules HF and DF vs. the reflection coefficient of the output mirror of cavity R for the mixtures $SF_6:H_2(D_2) = 8:1$, $SF_6:C_2H_6:H_2 = 44:3:1$, and $SF_6:C_2H_6 = 20:1$ at the pressure of 275 Torr.

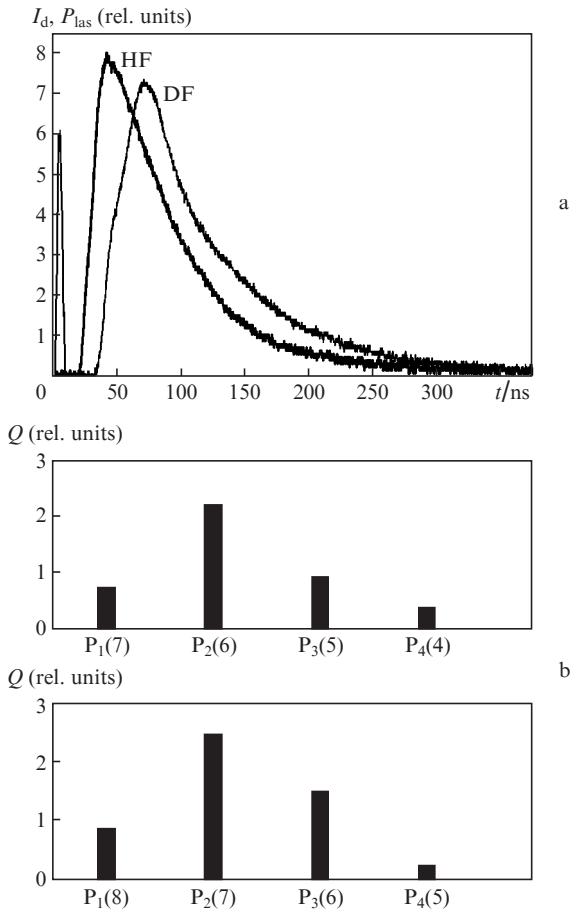

Figure 5. Oscillograms of a current pulse of REP DD and integral over spectrum pulses of laser generation on molecules HF and DF at the reflection coefficient of output mirror $R = 25\%$ and 55%, respectively (a); distribution of generation energy of DF-laser over cascade transition lines at the reflection coefficient of output mirror $R = 55\%$ (b). The pressure of the gas mixture $SF_6 : H_2(D_2) = 8 : 1$ was 275 Torr.

within ~75 ns after the onset of the discharge current, their intensity was weaker by 2–3 orders of magnitude than that of other lines. The excited molecules HF (DF) with the vibrational quantum number $v > 3$ ($v > 4$) are formed in a 'hot' reaction H(D) + F_2, whereas the generation in the P_4–P_6 bands of HF molecules is usually observed under the powerful uniform electron beam pumping [26]. If the mixtures are excited by a conventional transversal self-sustained discharge, the generation threshold in the transitions of HF (DF) molecules with $v > 3$–4 is not attained.

3.3. Laser on Ne–NH_3 mixtures

Generation in the mixture Ne–NF_3 was earlier obtained at the wavelength of 585.3 nm (the transition 3p–3s of a neon atom) under pumping by a transversal discharge; the uniformity of the latter was provided by the preionisation from additional spark gaps [16]. Employment of the REP DD in the present work gave the chance to increase the optimal pressure of working mixture and the pressure of electro-negative gas NF_3. The generation pulses were observed with one or two peaks depending on the pressure of the mixture. The maximal power of radiation was 180 W. The double-peak generation was observed from the entire interelectrode gap at the pressure of mixture less than 100 Torr without bright spark channels in the gap. The power of the second generation peak was lower and it had a delay of ~10 ns relative to the first peak and was detected from a discharge domain near the anode. Appearance of the second peak may be explained by an increased pump power at the instant of second half-period of the discharge current. The half-height duration of the first (main) generation peak was ~3.5 ns at the optimal pressure. Disappearance of the second generation peak at an elevated pressure may be explained by contraction of the discharge. After the first generation peak, the intensity of the discharge emission detected through a lateral window of the discharge chamber increased and bright spark channels were observed in the gap.

3.4. Laser on Ar–NF_3 mixtures

Generation in Ar–NF_3 mixtures at the wavelength λ = 750.3 nm (the transition 4p–4s of atom) was obtained earlier [16] under pumping by a transversal discharge with the spark preionisation as in the mixture Ne–NF_3. The REP DD has increased the optimal pressure of the mixture and the pressure of NF_3. Generation of two radiation peaks was also observed in this mixture. The half-height duration of the first peak of a lower power was ~5 ns at optimal pressures.

3.5. Laser on He–NF_3 mixtures.

In the mixture He–NF_3 the generation threshold on the transition 3s–2p (λ = 706.5 nm) was not attained, probably due to the shorter (by four times) active length of the laser (~20 cm) as compared to that in [16] where pumping was made by a transversal discharge.

However, under REP DD pumping the generation was obtained in the range λ = 620–760 nm on the lines of atomic fluorine, which were earlier observed in the mixtures of helium with various fluorine donors excited by the self-sustained volume discharge [17]. Up to seven generation lines were observed at an elevated helium pressure. The generation power also increased with pressure. Most intensive were the atomic fluorine lines at λ = 712.8 and 731.1 nm. In all the lines the half-height duration of the generation pulse depended on the pressure and for the mixture $He : NF_3 = 99 : 8$ Torr it was ~10 ns.

3.6. XeF laser

The highest generation power under REP DD pumping of the mixtures of inert gases with NF_3 was obtained in the conditions of our experiment on transitions of XeF^* molecule. At the mixture pressure of 4 atm and lower, the radiation power in the mixture with buffer helium gas was higher than in the mixture with the neon buffer gas and reached 30 kW. No measurements were performed at higher pressures because of the pressure limitation for the mixture in the installation. The half-height duration of generation pulse decreased from 8.5 to 5.5 ns if the mixture pressure increased from 1.2 to 2.6 atm. The generation spectrum depended on the contents of the working mixture. In the He–Xe–NF_3 mixture, the laser radiation was mainly observed at λ = 351 nm, whereas in the Ne–Xe–NF_3 mixture it was observed at λ = 351 nm and λ = 535 nm. The power of radiation at λ = 535 nm was twice greater.

Not high values of generation parameters of various lasers on the mixtures with NF_3 are explained by the low resistance

of the discharge because attempts to increase the concentration of this additive resulted in a fast loss of uniformity of the REP DD due to its stratification. The mechanism of this phenomenon was thoroughly considered in our work [27].

4. Conclusions

Thus, the investigations conducted show the promising prospects of REP DD employment for exciting a series of gas lasers. Generation was obtained on molecules N_2, HF, and DF with the efficiency close to the limiting value. It was established that the REP DD is most efficient for pumping lasers with the mixtures comprising electro-negative gas SF_6. The addition of SF_6 increases the breakdown voltage in the gaps with electrodes having the shape of blades and makes the pump power higher. Under REP DD pumping the generation on transitions of helium, neon, argon, and molecules XeF^* was obtained in the mixtures of inert gases with NF_3 also in visible and UV spectral ranges. However, in those mixtures the generation efficiency was comparatively low, seemingly, due to the loss of discharge uniformity at increased contents of NF_3 in the mixture.

Acknowledgements. The work was supported by the Russian Foundation for Basic Researches (grant No. 10-08-00556-a).

References

1. Alekseev S.B., Gubanov V.P., Kostyrya I.D., Orlovskii V.M., Skakun V.M., Tarasenko V.F. *Kvantovaya Elektron*., **34**, 1007 (2004) [*Quantum Electron*., **34**, 1007 (2004)].
2. Tarasenko V.F., Baksht E.Kh., Burachenko A.G., Rybka D.V., Lomaev M.I., Tel'minov A.E. *Izv. Vyssh. Uchebn. Zaved., Ser. Fiz*., (5/2), 5 (2011).
3. Baksht E.Kh., Tarasenko V.F., Burachenko A.G., *Kvantovaya Elektron*., **39**, 1007 (2009) [*Quantum Electron*., **39**, 1007 (2009)].
4. Tarasenko V.F., Tel'minov A.E., Burachenko A.G., Rybka D.V., Baksht E.Kh., Lomaev M.I., Panchenko A.N., Vil'tovskii P.O. *Kvantovaya Elektron*., **41**, 1098 (2011) [*Quantum Electron*., **41**, 1098 (2011)].
5. Khomich V.Yu., Yamshchikov V.A. *Prikl. Fiz*., (6), 77 (2010).
6. Orlovskii V.M., Alekseev S.B., Tarasenko V.F. *Kvantovaya Elektron*., **41**, 1033 (2011) [*Quantum Electron*., **41**, 1033 (2011)].
7. Berezhnoi K.V., Nasibov A.S., Shapkin P.V., Shpak V.G., Shunailov S.A., Yalandin M.I. *Kvantovaya Elektron*., **38**, 829 (2008) [*Quantum Electron*., **38**, 829 (2008)].
8. Azarov A.V., Mit'ko S.V., Ochkin V.N. *Kvantovaya Elektron*., **32**, 675 (2002) [*Quantum Electron*., **32**, 675 (2002)].
9. Bel'skaya E.V., Bokhan P.A., Zakrevskii D.E. *Kvantovaya Elektron*., **40**, 599 (2010) [*Quantum Electron*., **40**, 599 (2010)].
10. Bel'skaya E.V., Bokhan P.A., Zakrevskii D.E., Lavrukhin M.A. *Kvantovaya Elektron*., **42**, 99 (2012) [*Quantum Electron*., **42**, 99 (2012)].
11. Mesyats G.A., Osipov V.V., Tarasenko V.F. *Pulsed Gas Lasers* (Washington: SPIE Press, 1995).
12. Endo I., Walter R.F. *Gas Lasers* (New York: CRC Press, 2007).
13. Tarasenko V.F. *Fiz. Plazmy*, **37**, 444 (2011).
14. Kostyrya I.D., Rybka D.V., Tarasenko V.F. *Prib. Tekhn. Eksper*., (1), 80 (2012).
15. Yalandin M.I., Shpak V.G. *Prib. Tekhn. Eksper*., (3), 5 (2001).
16. Lomaev M.I., Tarasenko V.F. *Kvantovaya Elektron*., **15**, 1978 (1988) [*Sov. J. Quantum Electron*., **18**, 1237 (1988)].
17. Koprinkov I.G., Stamenov K.V., Stankov K.A. *Appl. Phys. B: Photophys. Laser Chem*., **33** (4), 235 (1984).
18. Burnham R., Powell F.X., Djeu N. *Appl. Phys. Lett*., **29** (1), 30 (1976).
19. Tarasenko V.F. *Kvantovaya Elektron*., **31**, 489 (2001) [*Quantum Electron*., **31**, 489 (2001)].
20. Iwasaki C., Jitsuno T. *IEEE J. Quantum Electron*., **18** (3), 423 (1982).
21. Apollonov V.V., Belevtsev A.A., Kazantsev S.Yu., Saifulin A.V., Firsov K.N. *Kvantovaya Elektron*., **30**, 207 (2000) [*Quantum Electron*., **30**, 207 (2000)].
22. Bulaev V.D., Gusev V.S., Kazantsev S.Yu., Kononov I.G., Lysenko S.L., Morozov Yu.B., Poznyshev A.N., Firsov K.N. *Kvantovaya Elektron*., **40**, 615 (2010) [*Quantum Electron*., **40**, 615 (2010)].
23. Midorikawa K., Sumida S., Sato Y., Obara M., Fujioka T. *IEEE J. Quantum Electron*., **15** (3), 190 (1979).
24. Panchenko A.N., Orlovskii V.M., Tarasenko V.F. *Kvantovaya Elektron*., **34**, 320 (2004) [*Quantum Electron*., **34**, 320 (2004)].
25. Baranov V.Yu., Vysikailo F.I., Dem'yanov A.V., Malyuta D.D., Tolstov M.V. *Kvantovaya Elektron*., **11**, 1173 (1984) [*Sov. J. Quantum Electron*., **14**, 791 (1984)].
26. Erofeev M.V., Orlovskii V.M., Skakun V.S., Sosnin E.A., Tarasenko V.F. *Kvantovaya Elektron*., **30**, 486 (2000) [*Quantum Electron*., **30**, 486 (2000)].
27. Genin D.E., Panchenko A.N., Tarasenko V.F., Tel'minov A.E. *Kvantovaya Elektron*., **41**, 360 (2011) [*Quantum Electron*., **41**, 360 (2011)].