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Planar multifrequency mid-IR microwave-pumped lasers

A.P. Mineev, S.M. Nefedov, P.P. Pashinin, P.A. Goncharov,
V.V. Kiselev, O.M. Stel'makh

Abstract. **The characteristics of planar repetitively pulsed diffusion-cooled HF, DF, HF–DF, Xe, and HF–DF–Xe(Kr) lasers pumped by a microwave discharge (2.45 GHz) are studied depending on the pump pulse duration (10–40 μs) and repletion rate (50–400 Hz), as well as on the composition and pressure of the working gas mixture (30–200 Torr) at low (to 0.6 L s^{-1}) gas flow rates. It is demonstrated for the first time that a HF–DF–Xe gas-discharge laser may simultaneously operate as a HF–DF chemical molecular laser and a recombination laser based on xenon atom transitions and generate broadband (octave) radiation in the range 2.0–4.2 μm with an average output power of 43 mW and an efficiency of 0.9%. With substitution of xenon for krypton, lasing in a HF–DF–Kr laser is obtained at wavelengths of 2.52–4.15 μm. Lasing in a HF–DF laser was achieved simultaneously in two spectral regions (2.7–2.9 and 3.6–4.2 μm) with an output power of ~50 mW. It is found that a decrease in the pump pulse duration with a simultaneous increase in the pulse repletion rate for retaining the average energy deposition leads to an increase in the average output power and efficiency of the laser. At low pulse repetition rates (50–100 Hz) and a low gas mixture flow rate, helium buffer gas can be effectively substituted for neon. Operation of the Xe laser was achieved in the spectral range 2.03–3.65 μm with an average output power of 580 Mw at a pump pulse duration of 20 μs, a pulse repetition rate to 10 kHz, and a maximum efficiency of 55%. The obtained experimental results demonstrate the possibility of creating broadband HF–DF–Xe lasers emitting in the frequency range 2–4 μm with a desired ratio of intensities in different spectral ranges.**

Keywords: *planar HF–DF–Xe laser, gas discharge, spectral characteristics, multifrequency lasing.*

1. Introduction

Development of broadband mid-IR lasers is of great interest for spectroscopy, monitoring of gas and aerosol impurities in the atmosphere, chemical technologies, isotope separation, and other applications. The laser spectrum in this case should contain a large number of lines in a wide wavelength range. A promising way to advance into new spectral regions is related to parametric conversion of the frequency of currently available lasers by nonlinear optics methods, in particular, by generation of sum and difference frequencies [1].

A.P. Mineev, S.M. Nefedov, P.P. Pashinin, P.A. Goncharov, V.V. Kiselev, O.M. Stel'makh Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavillova 38, 119991 Moscow, Russia;
e-mail: mineev@kapella.gpi.ru

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As mid-IR radiation sources, one can use pulsed chemical lasers emitting simultaneously at the transitions of several vibrationally excited molecules. Chemical reactions can cause excitation of a number of molecules. Most chemical lasers emit radiation at transitions between the vibrational levels of diatomic molecules. Theses lasers operate in the IR range from 1 to 10 μm.

HF (DF) molecules may form from molecular F_2 and $H_2(D_2)$ in electric gas discharges with the use of the SF_6 inert molecule as a donor of atomic fluorine, which eliminates the danger related to the work with molecular fluorine. As a result, one achieves standard conditions of operation of chemical lasers. In addition, the gas mixture contains a considerable amount of helium as a dilutant, which provides conditions for discharge maintenance and gas mixture circulation. Interaction of atomic fluorine with molecular hydrogen in a chemical laser leads to the formation of vibrationally excited HF*(DF*) molecules according to the reactions

$$SF_6 + e \to SF_5 + F + e,$$

$$F + H_2(D_2) \to HF(HD)(v) + H(D),$$

$$HF(v) \to HF(v-1) + (2.6\text{–}3.3)\ \mu m,$$

$$DF(v) \to DF(v-1) + (3.5\text{–}4.1)\ \mu m,$$

where v is the vibrational level of the molecule.

Deuterium fluoride behaves similarly to HF. A bigger mass of deuterium ensures lasing at longer wavelengths. It should be kept in mind that the complex structure of vibrational-rotational transitions in these molecules makes it possible to obtain lasing at many lines upon strong vibrational excitation. To achieve the optimal lasing conditions, the working medium should be rapidly changed for the time between pulses because the laser pulse in hydrogen halide lasers is limited in time by accumulation of the reaction products. The exhaust gas is pumped out of the discharge chamber and can be used again after separation of HF. The rotational energy levels are nonequidistant, and the laser spectrum consists of multiple vibrational-rotational lines lying in a wide spectral range, namely, in the range of 2.6–3.3 μm for the HF laser and 3.5–4.1 μm for the DF laser.

In [2], operation of HF and DF lasers was achieved under excitation in a high-power pulsed microwave discharge. The laser head consisted of a quartz tube with windows oriented at the Brewster angle, which was placed into a rectangular microwave waveguide. The active laser medium was formed in a microwave discharge under action of a pulse of a 5-kW magnetron generator. At a pump pulse duration of 3.5-μs and a pulse repetition rate (PRR) of 1 kHz, lasing with efficiency of 0.1% was observed with output powers of 6 and 1 mW at wavelength of 2.7 and 3.8 μm for mixtures with H_2 and D_2, respectively. The authors of [3] reported on lasing in the planar structure of HF and DF lasers upon discharge excitation by a pulsed microwave generator with a frequency of 30 MHz. The laser energy was 10 μJ at an efficiency of 0.1%. Lasing of HF and DF lasers in a waveguide structure with a cross section of 2 × 3 mm was obtained in [4] upon gas-discharge excitation by a pulsed microwave generator with a frequency of 150 MHz. The achieved efficiency was ≈ 5% at a pump PRR of 100 Hz and a pulse duration of 2 μs.

It is known that chemical hydrogen fluoride laser (HFLs) well operate at both hydrogen isotopes (H_2 and D_2), and the energy yield of lasers based on HF* molecules exceeds the energy yield of DF* lasers. However, the vast literature on HF and DF lasers contains only a few experimental works reporting on obtaining lasing simultaneously on HF* and DF* molecules (see, for example, [5]). This effect for a photoinduced chemical hydrogen fluoride laser was described in [6]. The data on the spectral composition of laser radiation presented in [7] testify to simultaneous excitation of vibrational-rotational transitions of HF* and DF* (2.6–3.0 and 3.7–4.1 μm, respectively) in a laser based on a gas mixture SF_6–H_2–D_2.

The laser based on atomic xenon transitions is considered today as one of the promising sources of near-IR radiation due to the possibility of using a large-volume working medium, as well as due to efficiency exceeding 1% and a low lasing threshold. Emission of Xe lasers was achieved in the wavelength range 1.73–3.6 μm at gas mixture pressures in the range of 0.05–14.0 atm and specific pump powers from 1 W cm^{-3} to 10 kW cm^{-3} for pumping varying from pulsed (10-ns) to cw regimes [8–10]. The most significant progress in the creation of these lasers was achieved in the case of their excitation by an electron beam (maximum efficiency 4.5% [11]), nuclear reactions (laser pulse energy 500 J, efficiency 3% [12]), electroionisation (efficiency 3.2% [13]), and microwave discharge [14, 15]. In particular, the authors of [14] described lasing in a high-power pulsed microwave discharge with formation of the active laser medium under action of a ~500 kW magnetron generator pulse at a pressure up to 1 atm. Lasing was observed at wavelengths of 1.73 and 2.03 μm in the gas-discharge tube centre outside the skin layer; the average laser power was 17 mW.

The aim of the present work is to study the characteristics of planar diffusion-cooled multifrequency lasers based on mixtures of HF, DF, and Xe(Kr) excited by a microwave discharge at a frequency of 2.45 GHz at intermediate pressures of the working gas mixture. An increased interest in the use of microwave discharges for pumping of lasers is related mainly to the availability of magnetrons emitting at a frequency of 2.46 GHz, which are widely used in microwave ovens [16, 17]. In addition, microwave discharge in the frequency range of 2–10 GHz has the following advantages over dc and rf discharges for pumping of lasers: high efficiency (exceeding 70%) and kilowatt powers of magnetrons (microwave sources), as well as their compactness, low cost, and the possibility of operating in pulsed regimes.

2. Scheme of a planar microwave-pumped laser

Figure 1 presents a photograph of the experimental setup. A pulsed microwave discharge was used as a source of excitation of the active laser medium. We used a 2M-130 magnetron with a pulsed output power of up to 8 kW. The laser pulse shape was controlled by a PVP-10.6 IR detector with a time resolution of 2 ns and by a LeCroy-432 two-channel digital oscilloscope with a bandwidth of 350 MHz. The laser power was measured by a NOVA-2 power meter (OPHIR). The spectra were measured using an MS-2004 monochromator with a 150-line/mm grating and an uncooled HPL-256-500 pyroelectric linear array.

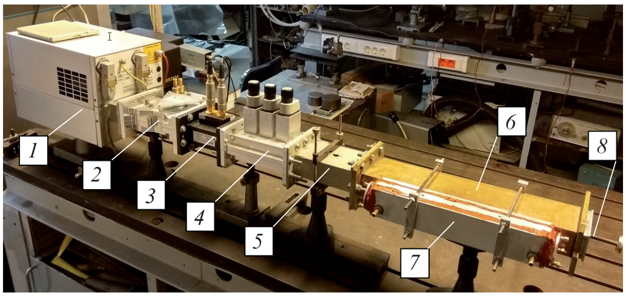

Figure 1. Photograph of the experimental setup:
(*1*) 2M-130 magnetron with a PM-740T power supply and a cooling unit; (*2*) isolator with a load; (*3*) directional coupler with a WR340-WDC0-2.0 meter of the direct and reflected power; (*4*) AG340M3 three-pin matching transformer; (*5*) waveguide adapter; (*6*) microwave resonator; (*7*) laser emitter; (*8*) short-circuiting plunger.

The output parameters of a planar laser with repetitively pulsed microwave pumping and a discharge channel length of 250 mm were experimentally studied. The optical cavity was formed by a highly reflecting mirror with a gold coating (reflection coefficient 98%, radius of curvature 3 m) and an output mirror made of a ZnSe plane-parallel plate with a dielectric coating with a transmittance of about 50% at wavelengths of 2–4 μm.

A rectangular waveguide with dimensions of 90 × 45 × 500 mm forms a microwave cavity (*6*) closed on one side and tuned by a short-circuiting plunger (*8*). From the side of the microwave power input, a magnetron (*1*) was matched with the microwave resonator using a three-pin matching transformer (*4*) through a waveguide adapter (*5*). The introduced and reflected microwave powers were controlled using a WR340-WDC0-2.0 power meter with a directional coupler (*3*). The magnetron was protected from reflected power (in the case of mismatch) by an isolator with an absorbing load (*2*). The microwave power was coupled out of the cavity through an extended slit in the narrow wall of the waveguide (analogue of a slot antenna) and directed to a laser head (*7*).

The planar laser head cross section (Fig. 2) is a gas-discharge structure formed by two profiled aluminium plates (*2*) and (*3*), which press a quartz plate (*4*) by its lateral side to the microwave resonator slit. The discharge channel (*5*) with dimensions of 2 × 25 × 250 mm was formed by the gap between the polished aluminium and quartz plates. The design provides water cooling of the aluminium plates. The use of a planar discharge offers advantages in the efficiency of heat removal from the walls and in compactness and allows one to achieve a lower breakdown threshold, a good output beam quality, and a higher laser output power per unit volume.

In this design, the electric field in the discharge region is perpendicular to the dielectric plate surface. Since the microwave power enters the discharge region only from one side, the discharge current is closed on the other side through the aluminium plate. Therefore, the microwave discharge is not concentrated only near the dielectric plate surface but is uniformly distributed over the entire thickness of the discharge region. The active medium volume was 12.5 cm^{-3}, which allowed us to achieve the input pulsed power density up to 640 W cm^{-3}. The laser design is described in detail in [16, 17].

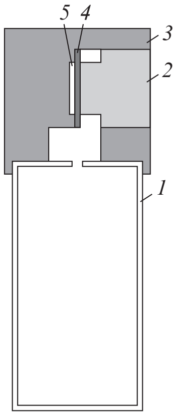

Figure 2. Cross section of a microwave-pumped planar laser: (*1*) rectangular waveguide with a cross section of 90×45 mm; (*2*, *3*) profiled aluminium plates; (*4*) $2 \times 30 \times 300$-mm quartz plate; (*5*) $2 \times 25 \times 250$-mm discharge channel.

3. Experimental results

3.1. HF and DF lasers

To obtain atomic fluorine and initiate the chemical reaction in the working gas mixture, in our experiments we used a transverse gas discharge. In preliminary experiments, we determined the optimal proportion of the working mixture components to be $H_2(D_2):SF_6:He = 1:10:89$ and found that variations in the hydrogen partial fraction (within 1–3) only slightly affect the output power.

The kinetics of chemical lasers is determined by the fact that almost all these lasers contain molecules of hydrogen halides, which are efficient quenchers for many excited molecules, first of all, for themselves. Therefore, to increase the laser output power and efficiency, it is necessary to decrease the pump pulse duration and increase the gas mixture flow rate. The laser pulse in hydrogen halide lasers is delayed from the pump pulse by ~1.5 μs (the delay time is determined by the chemical reaction rate) and is limited from above by the time of accumulation of reaction products, because deactivation by unexcited HF(DF) molecules suppresses lasing before the pump pulse termination. Note that the output laser power decreases with increasing the repetition rate and duration of laser pulses (Figs 3–5). At a working gas flow rate of ~0.6 L s^{-1} and an active medium volume of 12.5 cm^3, the total renewal of the working medium occurs for a time of ~20 ms (50 Hz). Based on our experimental data and the results obtained in [4], we may suggest that the optimal pump pulse duration under these experimental conditions should lie within the range 2–3 μs; this duration allows one to increase the pump PRR and, hence, the output power and efficiency of the laser. In particular, at the minimum pump pulse duration of 10 μs, which was limited by the technical characteristics of the used microwave generator, we achieved the average output power of 83 mW with an efficiency of 1.7% at a PRR of 100 Hz, while the substitution of helium in the gas mixture for neon allowed us to achieve an output power of 91 mW with an efficiency of 3.6% at a PRR of 50 Hz (see Fig. 4).

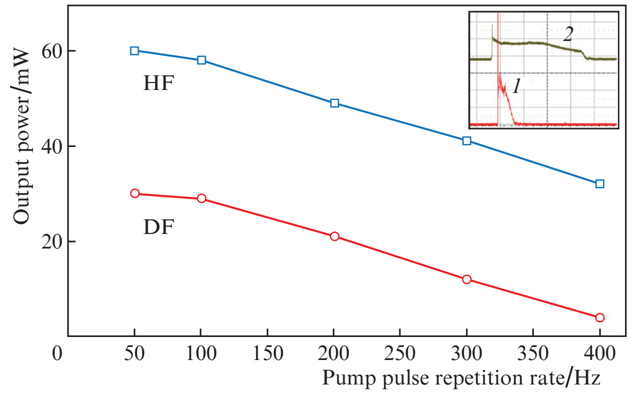

Figure 3. Dependences of the average output power of HF and DF lasers on the repetition rate of pump pulses with a duration of 20 μs and power of 5 kW in working mixtures $H_2(D_2):SF_6:He = 1:10:89$ at a gas pressure of 150 Torr. The inset shows the oscillograms of (*1*) 5-μs laser pulses and (*2*) pump microwave pulses for the HF laser.

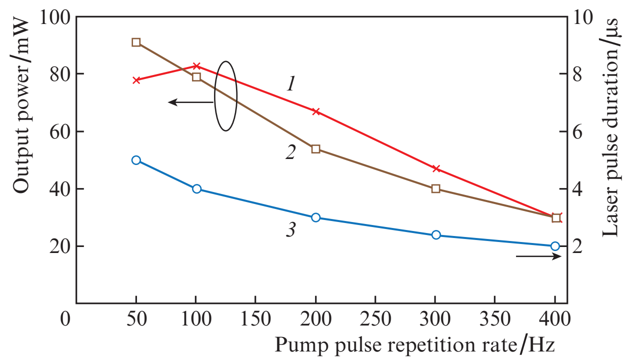

Figure 4. Average power of the HF laser for working mixtures (*1*) $H_2:SF_6:He = 2:10:88$ and (*2*) $H_2:SF_6:Ne = 2:10:88$ and (*3*) laser pulse duration versus the repetition rate of pump pulses with a duration of 10 μs and a power of 5 kW at a gas pressure of 159 Torr.

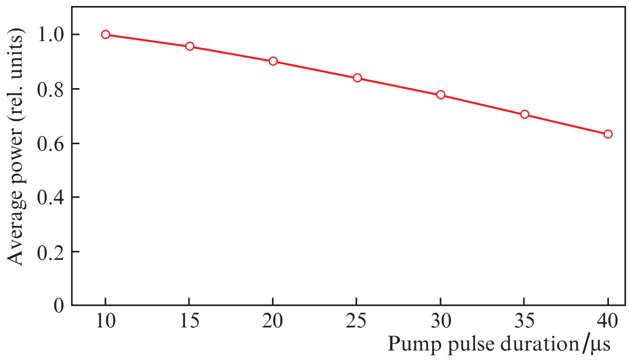

Figure 5. Dependence of the average laser output power on the pump pulse duration at a pump pulse repetition rate of 100 Hz and a pulsed pump power of 5 kW for the gas mixture $H_2:SF_6:He = 1:10:89$ at a pressure of 150 Torr.

A specific feature of the microwave discharge in the used planar structure is that, with increasing pressure, the discharge loses the necessary uniformity, concentrates near the elec-

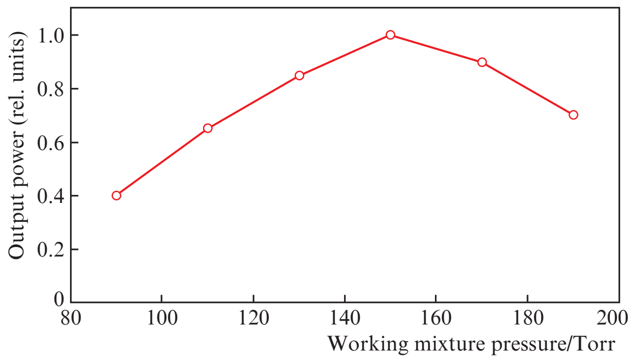

Figure 6. Dependence of the average output power of a HF laser on the pressure of the gas mixture $H_2:SF_6:He = 1:10:89$ at an average pump power of 10 W, a pump pulse duration of 20 μs, and a pump PRR of 100 Hz.

tric field strength maximum (antinode) in the waveguide cavity, and does not fill the entire discharge gap [17] (Fig. 6).

Deuterium fluoride chemically behaves similarly to HF. The advantage of the DF laser (the deuterium atom mass exceeds the hydrogen mass) is that it emits at longer wavelengths, at which the absorption by atmospheric water vapours is considerably weaker, and its emission spectrum is considerably broader. The difference between the DF and HF lasers consists in the fact that the energy accumulated in DF molecules is distributed over a larger number of vibrational levels than in HF molecules. The average output power of the DF laser was 40 mW at a pump PRR of 100 Hz and 48 mW in the case of substitution of helium for neon and a PRR of 50 Hz. The increase (almost twofold) in the output power of the DF laser compared to the HF laser can be explained by lower pump reaction rate constants for the DF laser.

3.2. HF–DF laser

In the present work, we obtained emission of a HF–DF laser simultaneously in two spectral regions using the working gas mixture $H_2:D_2:SF_6:He = 1:1:10:88$ at a pressure of 150 Torr, a pump pulse duration of 10 μs, a pump PRR of 100 Hz, and a pulsed pump power of 5 kW. The average laser power was 45 mW. In the case of the working mixture $H_2:D_2:SF_6:Ne = 1:1:10:88$ and a PRR of 50 Hz, the average laser power was 51 mW.

Analysis of the experimental results shows (similar to [5]) that simultaneous chemical reactions resulting in the formation of excited HF* and DF* molecules affect each other and proceed interdependently, which is related both to their competition and to the processes quenching HF* and DF* molecules.

3.3. Xe laser

With increasing the pump pulse duration, the authors of some works observed a decrease in the Xe laser power and even suppression of lasing long before the pump pulse termination. Theoretical concepts on the processes in the active media of lasers pumped by a hard ioniser, as well as actual numerical calculations, indicate that this is mainly caused by an increase in the concentration and temperature of electrons during the pump pulse action, which increases electronic mixing of excited levels in the Xe atom [14, 15]. As is known, lasers based on atomic xenon transitions require a high purity of initial gases, because of which, to decrease the influence of desorption of gases from the walls of the chamber during the discharge process, a slow (~0.5 L min^{-1}) working gas flow is used. The average output power of the Xe laser was 580 mW at a pump pulse duration of 20 μs and pump PRR up to 10 kHz (Fig. 7).

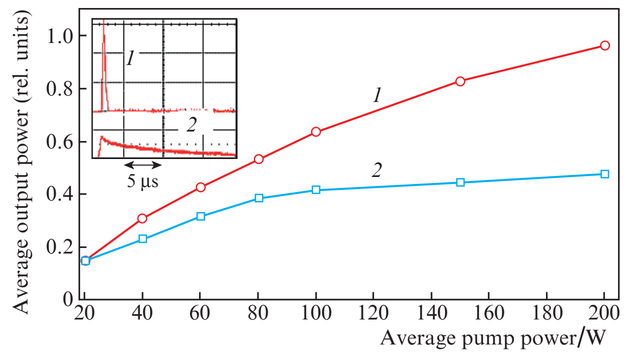

Figure 7. Dependences of the average output power of a Xe laser on the average pump power (*1*) at the pump PRR varying from 0.1 to 10 kHz and a pump pulse duration of 20 μs and (*2*) at a pump pulse duration varying from 20 to 200 μs and a pump pulse repetition rate of 1 kHz. The pulsed microwave pump power is 1 kW, the gas mixture is $Xe:SF_6:He = 1:0.2:99$, and the gas pressure is 90 Torr. The inset shows the oscillograms of pulses of Xe lasers based on (*1*) $Xe:He = 1:99$ and (*2*) $Xe:SF_6:He = 1:1:98$ mixtures at a pump pulse duration of 20 μs.

The oscillogram shown in the inset in Fig. 7 shows that a small addition of SF_6 to the working gas mixture leads to an increase in the laser pulse duration to the pump pulse duration (20 μs), which considerable increases the average output power of the Xe laser. This effect is probably caused by cooling of electrons (decrease in the electron temperature), which increases the recombination rate and, probably, the rate of depletion of the lower laser level in xenon [18].

3.4. HF–DF–Xe(Kr) lasers

To the specific features of microwave-pumped Xe laser operation (laser line 2.03 μm) one should assign the almost linear increase in the average output power with increasing the pump PRR, which is in contrast to the decrease in the power of the HF–DF laser (2.8 and 3.8 μm) observed with increasing the pump PRR at a given gas mixture flow rate. Therefore, there exist pump PRRs and gas mixture pressures optimal for obtaining a uniform distribution of the average output power over the emission spectrum in the wavelength range 2–4 μm.

Figure 8 presents the results of investigation of the amplitude and shape of pulses of Xe, HF, and HF–Xe lasers at identical main parameters, i.e., the gas mixture pressure and the duration, repetition rate, and power of the microwave discharge pulses. The obtained results testify to the possibility of simultaneous lasing in the molecular HF laser and the atomic Xe laser with comparable output powers.

In the present work, we have demonstrated for the first time the operation of a broadband HF–DF–Xe laser in the range 2–4 μm (octave) and of a HF–DF–Kr laser in the range 2.5–4 μm. The average power of a HF–DF–Xe laser based on the gas mixture $Xe:H_2:D_2:SF_6:He = 1:1:1:4:93$ was 43 mW at a pump pulse duration of 10 μs and a pump PRR of 100 Hz. The average output power of a laser based on the gas mixture $Kr:D_2:H_2:SF_6:He = 3:1:1:1:94$ was 18 mW at a pressure of 100 Torr, a pump pulse duration of 10 μs, a pump PRR of 100 Hz, and a pulsed microwave pump power of 5 kW. The output power of the laser based on the mixture with Kr rapidly decreases with increasing the SF_6 percentage.

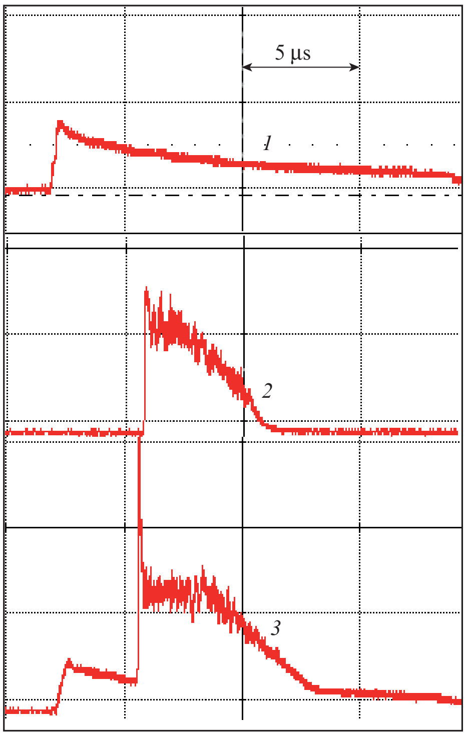

Figure 8. Oscillograms of pulses of (*1*) a Xe laser based on the gas mixture Xe:SF6:He = 1:1:98; (*2*) a HF laser ($H_2:SF_6:He = 1:4:95$), and (*3*) a HF–Xe laser ($Xe:H_2:SF_6:He = 1:1:4:94$). The gas pressure is 150 Torr, the pump pulse duration is 20 μs, the PRR rate is 100 Hz, and the pulsed pump power is 5 kW.

Table 1 lists the average output laser powers and efficiencies achieved at a pump pulse duration of 10 μs and a pulsed pump microwave power of 5 kW.

3.5. Spectral characteristics of the lasers

To study the pulsed IR lasers (based on Xe, CO, HF, DF, etc.) operating simultaneously at many lines, it is often necessary to instantaneously measure the spectral composition of radiation. To solve this problem in the mid- and far-IR regions, we developed and used a device with an uncooled HPL-256-500 pyroelectric linear array (Heimann Sensor GmbH) and an MS-2004 monochromator with a 150-line mm^{-1} grating.

It was experimentally found (Fig. 9) that the HF laser spectrum consists of 9 strong lines corresponding to the 1–0 and 2–1 vibrational transitions, while the spectrum of the DF lasers contains 11 strong lines corresponding to the 1–0, 2–1, and 3–2 vibrational transitions. To achieve the threshold of lasing at high transitions (with a large number of lines), one needs a high-Q cavity. In our case, the transmittance of the output mirror of the laser optical cavities was 50%. For comparison, Fig. 10 shows the spectrum of the HF–DF–Xe laser.

Lasing in a Xe laser based on mixtures with Ar and He occurs mainly at the 5d–6p and 7p–7s transitions. In particular, at a pulsed pump microwave power of 1 kW, a PRR of 1 kHz, and a pulse duration of 20 μm, we achieved the following average powers $\bar{P}$ at a constant pressure of 90 Torr and different working mixture compositions:

(1) $Xe:He:SF_6 = 1:99:0.2$ – $\bar{P}$ = 110 mW, normalised powers $P_{norm} = 0.59:0.26:0.03:0.12$ at wavelengths 2.03:3.43:3.51:3.65 μm.

2) $Ar:Xe:He:SF_6 = 50:1:49:0.2$ – $\bar{P}$ = 52 mW, P_{norm} = 0.52:0.28:0.20 at wavelengths 2.03:2.65:3.51 μm.

3) $Ar:Xe:SF_6 = 99:1:0.2$ – $\bar{P}$ = 25 mW, P_{norm} = 0.08:0.92 at wavelengths 2.03:2.65 μm.

According to the lasing mechanism accepted in the literature, the level that is initially populated in Xe is $5d[3/2]^0_1$, which is the upper laser level for the most intense lines at 1.73, 2.03 and 2.65 μm in the case of using different buffer gases (He, Ar, or He–Ar mixtures). The laser spectra and energy characteristics depend on the rates of collisional quenching of the lower laser levels by the atoms of Ar and He buffer gases. Lasing at wavelengths of 2.65 and 2.03 μm occurs at the $5d[3/2]^0_1 - 6p[1/2]_0$ and $5d[3/2]^0_1 - 6p[3/2]_1$ transitions, respectively. An increase in the fraction of lasing at 2.03 μm and the absence of lasing at 1.73 μm in the presence of He in the work-

Table 1.

Working gas mixture composition	Wavelength (μm); Vibrational $v-(v-1)$ and atomic $nd-(n+1)$p laser transitions	Pulse repetition rate/Hz	Average output laser power/mW	Efficiency (%)
$H_2:SF_6:He = 1:10:89$	2.6–3.0; (1–0, 2–1)	100	83	1.6
$D_2:SF_6:He = 2:10:88$	3.7–4.1; (1–0, 2–1, 3–2)	100	40	0.8
$H_2:SF_6:Ne = 2:10:88$	2.6–3.0; (1–0, 2–1)	50	91	3.6
$D_2:SF_6:Ne = 2:10:88$	3.7–4.1; (1–0, 2–1, 3–2)	50	48	1.9
$H_2:D_2:SF_6:He = 1:1:10:88$	2.6–3.0 and 3.7–4.1; (1–0, 2–1, 3–2)	100	45	0.9
$H_2:D_2:SF_6:Ne = 1:1:10:88$	2.6–3.0 and 3.7–4.1; (1–0, 2–1, 3–2)	50	51	2.0
$Xe:H_2:D_2:SF_6:He = 1:1:1:4:93$	2.6–3.0 and 3.7–4.1; (1–0, 2–1, 3–2); 2.03; $5d[3/2]^1_0 - 6p[3/2]_1$Xe	100	43	0.86
$Kr:D_2:H_2:SF_6:He = 3:1:1:1:94$	2.6–3.0 and 3.7–4.1; (1–0, 2–1, 3–2); 2.52; $4d[1/2]^1_0 - 5p[3/2]_2$Kr	100	18	0.36

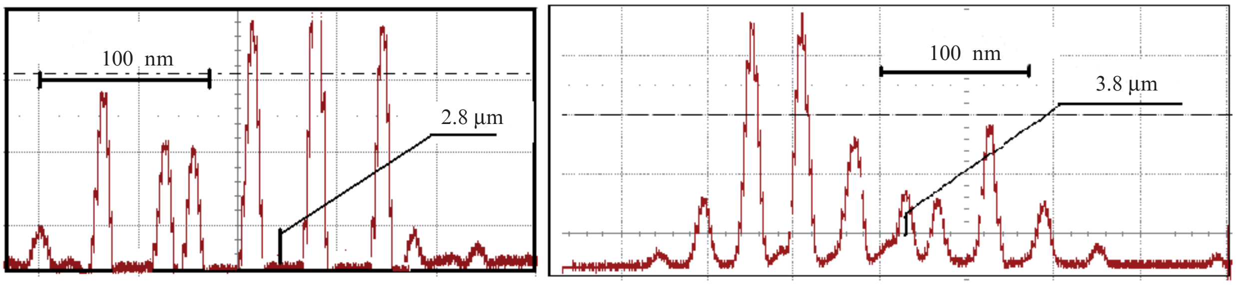

Figure 9. Emission spectra of HF (2.8 μm) and DF (3.8 μm) lasers [working mixture $H_2(D_2):SF_6:He = 1:10:89$, gas pressure 150 Torr, pump pulse duration 20 μs, PRR 100 Hz, pulsed pump power 5 kW].

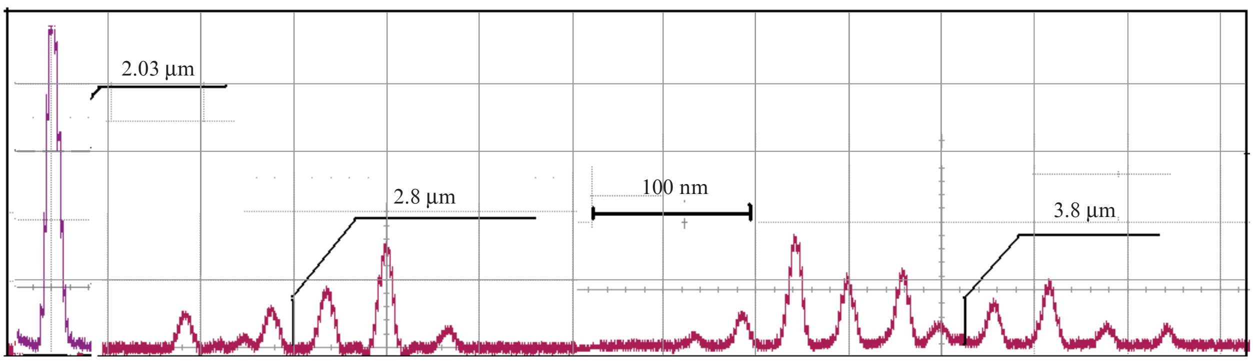

Figure 10. Emission spectrum of a HF–DF–Xe laser [working mixture $D_2:H_2:Xe:SF_6:He = 1:1:1:5:92$, gas pressure 100 Torr, pump pulse duration 20 μs, PRR 100 Hz, pulsed pump power 5 kW].

ing mixture are caused by the high rate of quenching of the lower $6p[3/2]_1$ level by collisions with helium and by the fact that this level lies above the $6s^1$ state, from which the $6p[5/2]_2$ level (the lower laser level for the 1.73-μm line) is efficiently populated [19]. The spectrum of lasing in the Xe–He mixture exhibits laser lines at 3.43 and 3.65 μm, which belong to the 7p–7s transitions of Xe atoms. The appearance of these lines is probably related to the population of the 7p level due to collisional-radiative and triple recombination [20].

One can see that the main fraction of the laser power belongs to wavelengths of 2.03, 3.43, and 3.65 μm for the mixture $Xe:He:SF_6 = 1:99:0.2$; to wavelengths of 2.03, 2.65, and 3.51 μm for the mixture $Ar:Xe:He:SF_6 = 50:1:49:0.2$; and to a wavelength of 2.65 μm for the mixture $Ar:Xe:SF_6 = 99:1:0.2$. Thus, by changing the working gas mixture composition, it is possible to redistribute the laser power between the laser lines. The Xe laser efficiency was 0.55%.

4. Conclusions

We studied the output characteristics of planar pulsed diffusion-cooled lasers with different working gas mixture compositions excited by microwave discharge at a frequency of 2.45 GHz. Lasing occurred in working gas mixtures of different compositions at average pressures in the range of 30–200 Torr. The simultaneous operation of a HF–DF chemical laser and a recombination laser based on the atomic xenon and krypton transitions in a broad (octave) range of 2–4 μm is demonstrated for the first time. The output power of the HF–DF–Xe laser was 43 mW at an average pump power of 5 W. Lasing of the HF–DF laser occurred simultaneously in two spectral regions with an output power of ~50 mW. The performed experiments on the substitution of xenon for krypton (laser line 2.52 μm) showed the possibility of the HF–DF–Kr laser operation at wavelengths of 2.52–4 μm. Further increase in the average output power and efficiency of the laser can be achieved by using pump pulses with a duration shorter than 10 μs. At low pump PRRs (and a low gas mixture flow rate, of the order of 0.6 L s^{-1}), helium can be effectively substituted for neon. The obtained experimental results demonstrate the possibility of creating a broadband HF–DF–Xe laser (2–4 μm) with a desired intensity ratio in a particular spectral range. The Xe laser emitted in the spectral range 2.03–3.65 μm with an average power of 580 mW at a pump pulse duration of 20 μs and a pump PRR up to 10 kHz. The maximum laser efficiency was 0.55%. These values are not limiting because we did not optimise the discharge gap width, the pump pulse duration, and the transmission of the output mirror of the laser optical cavity.

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