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Planar Xe laser with cw radio-frequency pumping

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Abstract. **The characteristics of the radiation of a planar Xe laser excited by transverse RF discharge at a frequency of 40.68 MHz with diffusive cooling of the active medium and a nonselective optical cavity have been investigated. The spectral and power characteristics of the Xe laser have been experimentally studied as functions of the interelectrode-gap width (1.4 – 2.5 mm), composition and pressure (30 – 100 Torr) of working gas mixture, input power density (0.4 – 34 W cm^{-3}), and the electrode temperature. The output laser power was found to decrease at an interelectrode gap above 1.6 mm. The threshold pump power was 12 W (power density 0.4 W cm^{-3}). Addition of butane to the working mixture increases the output power by approximately 50 % at interelectrode gaps of 2.0 – 2.5 mm. A cw lasing power of 4 W and a maximum efficiency of ~0.7 % are obtained. Good prospects of the Xe laser operating at wavelengths of 2.03, 2.65, and 3.51 μm are shown.**

Keywords: *planar waveguide Xe laser, RF discharge, spectral characteristics, diffusive cooling, molecular ions.*

1. Introduction

Recently, increasing attention has been given to the development of laser systems of different purposes, operating in the conditionally eye-safe spectral range of 1.3 – 3.5 μm. This interest is caused by the wide possibilities of transmitting – receiving devices in this range for both research and applications (lidar complexes, distance meters, and medical tools). Studies aimed at designing diode-pumped solid-state lasers based on Ho : YAG, Tm:YLF, and Er : YLF crystals, generating in this range, are being actively developed. Gas lasers have a significant advantage over solid-state ones: high optical homogeneity of the active medium, which makes it possible to apply long optical cavities and, as a consequence, obtain highly convergent and monochromatic radiation. Among a large number of such gas lasers the following ones can be selected: overtone CO laser; iodine laser with photodissociation pumping, which makes it possible to excite very large volumes and provides record pulse energies; and chemical lasers. However, these lasers have a number of disadvantages, in particular, high aggressiveness and/or toxicity of the components of their active media or the products of chemical reactions occurring in them (chemical, iodine, and CO lasers). Development of closed-cycle (gas-dynamic) lasers meets great fundamental difficulties. Thus, an urgent problem is to design high-power laser systems free of the above-mentioned disadvantages and allowing for a wider frequency range of high power-radiation [1].

Currently, the laser on transitions in xenon atoms is considered to be a promising radiation source in the near-IR range, because it allows one to use large-volume working media and provides a high efficiency (above 1 %). The Xe laser, which generates in the wavelength range of 1.73 – 3.6 μm, operates in wide ranges of active-medium pressures (0.05 – 14 atm) and specific pump powers (1 W cm^{-3} – 10 kW cm^{-3}) in the pulsed and cw regimes [2]. Xe lasers can be pumped by electric discharge, electron beams, and nuclear reactions. There are many experimental and theoretical studies of xenon laser characteristics; however, the cw RF pumping of xenon laser has been studied poorly, and the physical principles of its operation are still not clear.

It was shown in [3] that RF pumping of the active medium of laser on the Xe – Ar – Ne gas mixture at intermediate pressures leads to a sharp increase (by three orders of magnitude) in its power in comparison with the known low-pressure lasers; therefore, it can be assigned to high-power lasers. The subsequent studies {in particular, investigation of lasers with planar active media (see, for example, [4, 5])} demonstrated good prospects of Xe lasers providing a maximum power at wavelengths of 2.03 and 2.65 μm [6, 7].

The working levels of Xe laser under cw RF pumping and intermediate pressure of working gas mixture are occupied due to the production of $ArXe^+$ and Xe^{2+} molecular ions with their subsequent dissociative recombination [6]:

$$ArXe^+ + e \rightarrow Xe^* + Ar, \tag{1}$$

$$Xe_2^+ + e \rightarrow Xe^* + Xe. \tag{2}$$

Quenching of the lower working levels of argon and xenon atoms and electronic mixing of levels determine the inversion of laser-level populations and the lasing spectrum. Figure 1 shows a schematic diagram of energy levels and the laser transitions in the xenon atom.

Planar waveguide lasers with RF discharge pumping and diffusive cooling are popular with researchers in view of the development of new generation of inexpensive compact sealed-off gas-discharge lasers generating high-quality optical radiation in the cw and repetitively pulsed regimes [7 – 9]. The planar electrode-waveguide discharge system in these lasers is generally formed by two water-cooled metal electrodes, the

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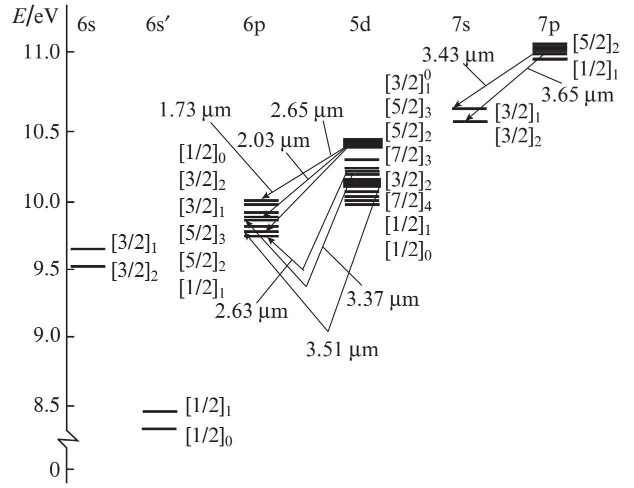

Figure 1. Schematic diagram of laser transitions in Xe.

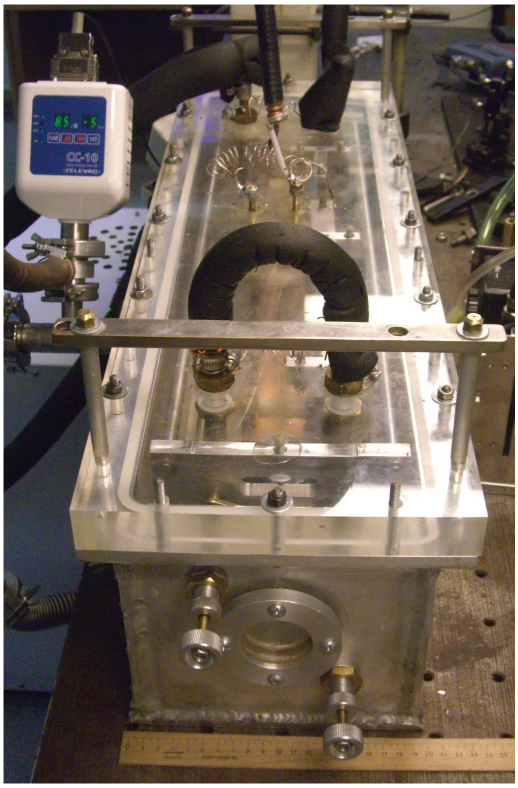

Figure 2. Photograph of RF-excited Xe laser.

working surfaces of which must be treated with high precision and can be limited by dielectric lateral walls. One of the transverse sizes of the electrode-waveguide system is small (1 – 3 mm), which provides effective diffusive cooling of gas-discharge plasma, while the other changes in a fairly wide range, due to which the active-medium volume can be scaled with preservation of the laser length.

In this paper, we report the results of studying the lasing characteristics of a planar cw Xe laser pumped by transverse RF discharge at a frequency 40.68 MHz, with diffusive cooling of the active medium and a nonselective optical cavity.

2. Experimental setup

Figure 2 shows a photograph of Xe laser. The volume of its active medium was varied from 26 to 46 cm^3 by changing the interelectrode gap from 1.4 to 2.5 mm. The working surfaces of copper electrodes were 38×485 mm in size. The RF power supply was a Cesar generator (frequency 40.68 MHz) with an output power up to 2 kW. The laser efficiency was determined as the ratio of the output laser power to the RF power introduced into the discharge.

The discharge chamber (AMG-6 alloy) had an internal volume of ~18 L and could be pumped out to a residual pressure of $\sim 10^{-3}$ Torr. Its walls had holes with flanges to be connected with the system of pumping out and puffing gas-mixture components, fittings for feeding and draining the coolant (separately for each electrode), and current leads to apply RF voltage across the electrodes. The end walls of the chamber had optical windows to extract laser radiation and adjusting devices to tune the mirrors of the optical cavity (located in the chamber). The system had two hollow copper electrodes of rectangular cross section (19 × 38 mm); two bellows tubes were attached to each of them to provide coolant circulation. The discharge gap was formed by electrodes fixed using insulating holders with adjusting screws.

The lasing spectrum was analysed by an MS-2004 monochromator (reverse linear dispersion 11.9 nm mm^{-1}) and a NOVA-2 power meter (OPHIR) with a thermoelectric head and a time constant of 1 s. We used Xe – Ar – He – M gas mixtures (M is a molecular gas) of different compositions at total pressures from 35 to 100 Torr. The optical cavity was formed by a highly reflecting mirror with a gold coating (reflectance 98 %) and a radius of curvature of 3 m. The output mirror was a plane-parallel silicon plate 2 mm thick with a transmittance of ~55% or a mirror with a multilayer dielectric coating and a transmittance of ~20% at the working wavelength. The optical-cavity length was 510 mm.

To provide efficient laser operation, it is necessary to match the RF oscillator (with an output impedance of 50 Ω) with the dynamic load: gas-discharge plasma. This was done using an adjustable U-type *LC* matching system, through which RF power was supplied to the discharge gap. Correcting inductances were mounted at the ends of the electrodes.

3. Results

The lasing characteristics of the xenon laser were analysed using a laser emitter with copper electrodes at interelectrode gaps of 1.4, 1.6, 2.0, and 2.5 mm; gas mixture pressures of 35 – 65 Torr, and RF pump powers from 150 to 350 W.

Figures 3 and 4 show the dependences of the output laser power on the interelectrode-gap width at different powers supplied to the discharge and different gas mixture pressures, respectively. It can be seen that the output laser power decreases with an increase in the interelectrode gap (i.e., with a decrease in the specific power supplied to the discharge). Some decrease in the output laser power at an interelectrode-gap width of 1.4 mm can be related to the increase in the waveguide loss, caused by insufficiently qualitative treatment of the surface of electrodes and their nonparallelity. Further experiments were performed with an interelectrode gap 1.6 mm wide.

Figures 5 and 6 present the dependences of the output laser power on the pump power supplied to the discharge and on the working mixture pressure, respectively. It can be seen in Fig. 5 that an increase in the pump power leads to an

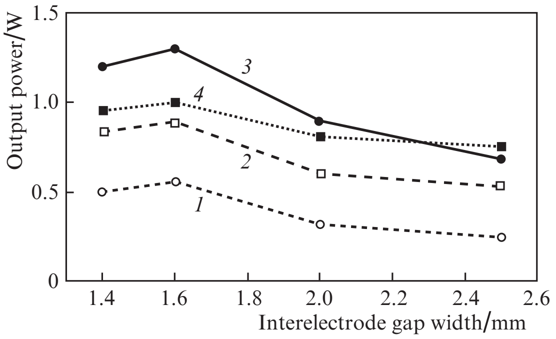

Figure 3. Dependence of the output laser power on the interelectrode gap width at RF powers of (*1*) 150, (*2*, *4*) 250, and (*3*) 350 W, supplied to the discharge, for the working mixtures (*1*–*3*) Ar : He : Xe = 60 : 39 : 1 and (*4*) Ar : He : Xe : C_4H_{10} = 59 : 39 : 1 : 1, at a pressure of 50 Torr.

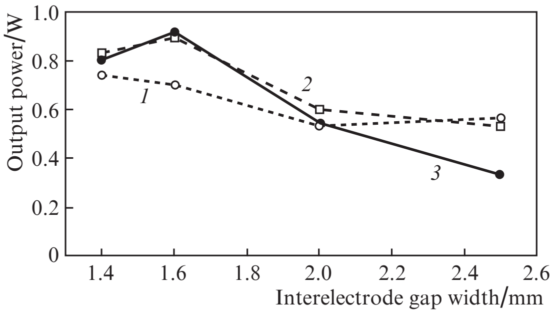

Figure 4. Dependence of the output laser power on the interelectrode gap width for the Ar : He : Xe = 60 : 39 : 1 gas mixture at pressures of (*1*) 35, (*2*) 50, and (*3*) 65 Torr and a pump power of 250 W supplied to the discharge.

increase in the optimal gas mixture pressure. More molecular ions are produced at higher pressures and, as a consequence, the occupancy of the upper working level increases, while the pump power per particle decreases. At the same time, a rise in the pump power increases the electron concentration and temperature and, therefore, the mixing rate of excited xenon levels; i.e., the laser efficiency is reduced.

Along with the purity of the initial gases, the material of electrodes is also important for implementing long-term operation of the sealed-off planar xenon laser. Fast degradation of its output power is attributed to the desorption of electrode material into the discharge [10]. For example, the output power of the laser with aluminum electrodes reduced significantly for a minute, whereas shutting electrodes with quartz plates ensured stable laser operation for 1 h with almost constant (varied by no more than 10%) output power [10, 11]. We carried out experiments using a laser with copper electrodes, partially coated (from the side of the discharge gap) by a nickel layer ~5 μm thick (nickel is widely used in vacuum instrument making due to its low vapour pressure and high melting temperature).

In comparison with the laser having purely copper electrodes, the output power of the laser under consideration in the quasi-stable range increased by a factor of three, whereas the operation time in this range increased from 3 to 16 min (Fig. 7). A possible reason for the reduction of the output power with time is that nickel only partially coated the electrodes, while during laser operation the discharge was spread to the uncoated areas. Note that the xenon laser output power is maximum when the discharge burns in the so-called γ phase; in the course of time the laser power decreases, and the discharge is reconfigured into the α phase (local α-type discharges arise along the discharge gap to capture gradually the entire area of electrodes). Thus, in contrast to the CO and CO_2 lasers, the γ-discharge phase is optimal for the xenon laser.

The dependences of the output power on the pump power supplied to discharge for the laser with nickel-coated electrodes

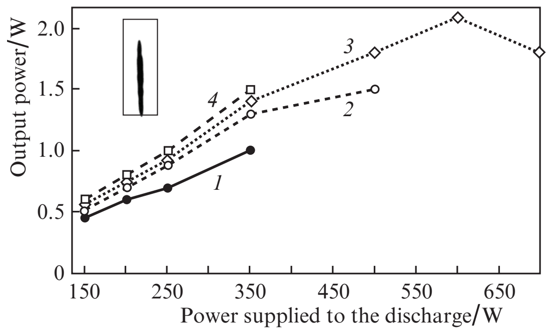

Figure 5. Dependence of the output laser power on the pump power supplied to the discharge for the working mixtures (*1*–*3*) Ar : He : Xe = 60 : 39 : 1 at pressures of (*1*) 35, (2) 50, and (*3*) 65 Torr and (*4*) Ar : He : Xe : C_4H_{10} = 59 : 39 : 1 : 1 at a pressure of 50 Torr. The inset shows a spot developed on thermosensitive paper by a laser beam with an output power of 1 W; the interelectrode gap width is 1.6 mm.

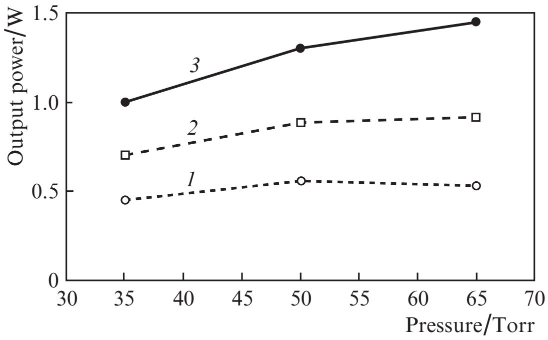

Figure 6. Dependences of the output laser power on the pressure of Ar : He : Xe = 60 : 39 : 1 working mixture at pump powers of (*1*) 150, (*2*) 250, and (*3*) 350 W and an interelectrode gap width of 1.6 mm.

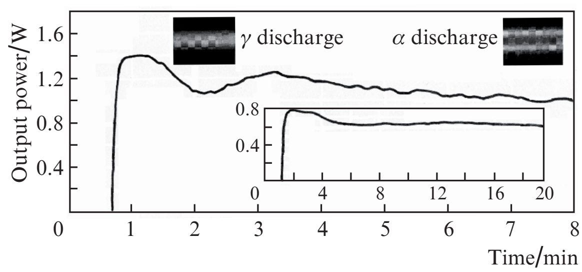

Figure 7. Time dependence of the output power of laser with nickel-coated electrodes for the Ar : He : Xe = 60 : 39.5 : 0.5 working mixture at a pressure of 50 Torr and pump power of 250 W. The insets show the time dependence of the output laser power at a pump power of 150 W and photographs of the γ and α discharges.

are shown in Fig. 8. The threshold pump power was 12 W, and the minimum output power above the lasing threshold was 4 mW. The maximum laser efficiency (~0.7%) was obtained by adding butane to the working gas mixture.

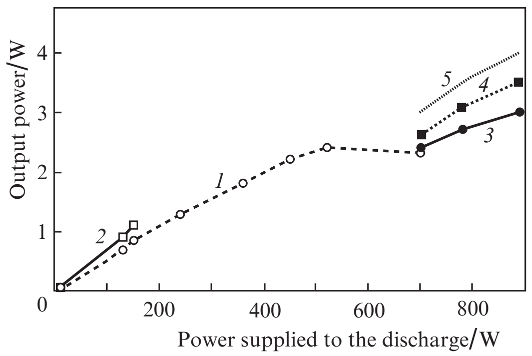

Figure 8. Dependences of the output laser power on the pump power supplied to the discharge for the (*1*) Ar : He : Xe = 60 : 39.5 : 0.5 and (*2*) Ar : He : Xe : C_4H_{10} = 59 : 39 : 0.5 : 0.5 working mixtures at a pressure of 50 Torr, (*3*, *4*) Ar : He : Xe = 60 : 39.5 : 0.5 mixture at 90 Torr, and (*5*) Ar : He : Xe : C_4H_{10} = 59 : 39 : 0.5 : 0.5 mixture at 90 Torr. The measurements were performed using (*1*–*3*) an output mirror with a multilayer dielectric coating and a transmittance of ~20% at working wavelengths and (*4*, *5*) an output mirror (45%) in the form of a plane-parallel silicon plate. The interelectrode gap width is 1.6 mm.

It is of interest to analyse the influence of molecular additives in the working gas mixture on the output laser power under cw RF pumping, because it was investigated previously for only pulsed electron-beam pumping of xenon laser [12, 13]. Table 1 contains the output powers for a laser on an Ar : He : Xe : M = 59 : 39 : 1 : 1 gas mixture with different molecular additives, at a pressure of 50 Torr. The pump power was 160 W and the interelectrode gap amounted to 1.6 mm.

Table 1. Influence of molecular additives on the output Xe laser power.

Additive	Power/mW	Additive	Power/mW
–	620	CO_2	64
C_4H_{10}	660	CH_4	539
N_2	528	CO	540
O_2	75	H_2	210

It was shown in [5, 6] that the nature of discharge in the Xe laser differs from that of discharges in planar CO and CO_2 lasers. RF pumping is most efficient in narrow near-wall regions in the active medium (because of the refractive index gradient, caused by the thermal inhomogeneity of the gas density), whose relative volume is rather small; note that the discharge has a very low impedance. The gain near the walls is larger than in the middle of the discharge gap. This is related to the lower electron concentration, which increases gain because of the decrease in the electron-impact-induced collisional mixing of laser levels [6].

Addition of gaseous butane to the working gas mixture significantly increases the output Xe laser power at large interelectrode gaps (more than 1.6 mm). Apparently, this effect is related, on the one hand, to the discharge transformation, which leads to a more uniform distribution of specific power over the laser beam cross section, and, on the other hand, to the decrease in the electron temperature, which increases the recombination rate and, possibly, the depletion rate of the lower laser level in Xe atoms [12]. A possible reason for the highest efficiency observed for butane as an additive is that a rather high energy must be applied to break bonds in the butane molecule.

Figure 9 shows the dependence of the output laser power on the amount of xenon content ε in the Ar : He : Xe = 60 : 39 : ε working mixture at a pressure of 50 Torr and a pump power of 150 W supplied to the discharge.

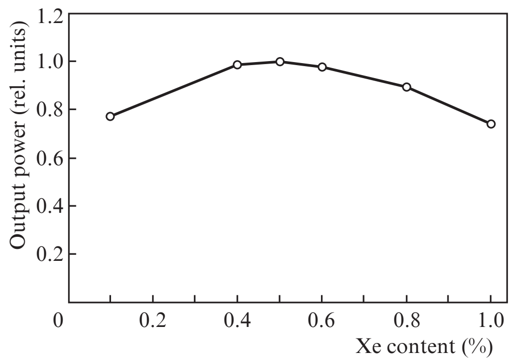

Figure 9. Dependence of the output power of Xe laser on the xenon content.

The xenon content in the working gas mixtures used in the Xe laser is generally fairly small. The presence of optimum in the Xe content is due to the competition of two processes. An increase in the Xe content, on the one hand, enhances the production of molecular xenon ions (with their subsequent dissociative recombination, which leads to occupation of the upper laser level) and, on the other hand, increases the quenching rate of the upper working levels in Xe atoms.

A change in the Xe content causes redistribution of the output laser power over the lasing wavelengths. For example, under electron-beam pumping [2], at working gas mixture under atmospheric pressure, an increase in the Xe content causes dominance of the lines with λ = 3.37 and 3.51 μm, which are due to the transitions with upper levels populated from higher lying states. In our experiments with cw pumping at intermediate working mixture pressures, the increase in the Xe content from 0.5% to 3% increases the intensity of lines with λ = 2.03 and 3.51 μm and weakens the lines with λ = 2.65 and 3.37 μm.

Figure 10 shows the Xe-laser radiation spectrum. Lasing occurs at seven wavelengths corresponding to the 5d–6p transitions in xenon atoms. The output power is maximum at λ = 2.65 μm (the $5d[3/2]_1 - 6p[1/2]_0$ transition). The normalised laser powers at wavelengths of 2.03, 2.48, 2.63, 2.65, 3.11, 3.37, and 3.51 μm are, respectively, 0.58, 0.048, 0.051, 1.00, 0.076, 0.112, and 0.16.

Note lasing at lines with λ = 2.48 and 3.11 μm of the laser transitions having a common upper level $5d[3/2]_3$ (these lines are generally absent in the emission spectra of pulse-pumped lasers) and the absence of lasing at the line with λ = 1.73 μm, which are present in the emission spectra of pulsed lasers. In addition, changing the component ratio in the gas mixture, one can redistribute the output laser power over the emission-line wavelengths [11].

The maximum output power (4 W) was obtained when supplying a pump power of 890 W to the discharge; this value

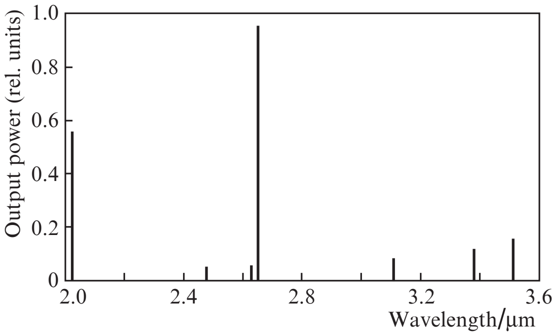

Figure 10. Emission spectrum of Xe laser for the Ar : He : Xe = 60 : 39 : 1 working mixture at a pressure of 50 Torr, a pump power of 130 W, and an interelectrode gap width of 1.4 mm.

corresponds to a specific pump power of 34 W cm^{-3}. This is less than the specific pump powers obtained in [5] and [11] (88 and 67 W cm^{-3}, respectively). Unfortunately, in view of the design features, further increase in the pump power made discharge burn between not only the electrodes but also the internal elements of the laser emitter (in particular, near the upper Plexiglas lid), which immediately caused degradation of the working mixture.

Cooling discharge electrodes to $-50\,°C$ with ethyl alcohol barely affected the output power and time of stable laser operation.

4. Conclusions

(i) The threshold pump power of Xe laser was less than 12 W (specific power 0.4 W cm^{-3}), which is indicative of a large gain of active medium (low lasing threshold).

(ii) The output laser power decreases with an increase in the interelectrode gap (a decrease in the specific power supplied to the discharge)

(iii) Coating of electrodes with nickel increases the output laser power in the quasi-stable region by a factor of 3, the laser operation time in this range increases from 3 to 16 min.

(iv) Addition of butane to the working gas mixture increases the output laser power. This is especially pronounced for wider interelectrode gaps.

(v) Lasing is obtained at seven wavelengths in the spectral range of 2.03 – 3.51 μm. The output power is maximum at 2.65 μm.

(vi) The maximum output power (4 W) is obtained when a pump power of 890 W is supplied to the discharge.

(vii) Cooling electrodes to a temperature of $-50\,°C$ barely affected the output power and time of stable laser operation.

(viii) The γ phase of discharge is optimal for the xenon laser.

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