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Radiation intensity distribution in a nuclear-pumped gas-flow laser

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***Abstract*. It is shown experimentally that two lasing regions, displaced directly towards the entrance of the laser channel, are formed in gas-flow lasers pumped by the fission fragments of uranium nuclei. As the pump power is increased, these regions merge into a single region that expands towards the exit section of the channel. The time dependence of the lasing power qualitatively repeats the shape of the exciting neutron pulse.**

Keywords: *gas-flow lasers, nuclear-pumped lasers, application of a nuclear reactor*.

1. Introduction

The laser medium in a nuclear-pumped gas-flow laser is excited by the fission fragments of uranium nuclei, leaving the uranium layers covering the inner surface of the cell walls [1 – 4]. Lasers excited by the fission fragments have usually the form of an extended cylinder [1, 2] or a rectangular channel [3, 4]. In the former case, a thin layer ($\delta_U \sim 1 - 10$ μm) of the active fissionable material is deposited on the inner surface of the cylindrical laser casing, while in the latter case the deposition is carried out on two opposite parallel inner surface walls of a rectangular channel.

Studies of the evolution of optical inhomogeneities in sealed nuclear-pumped gas-flow lasers [5, 6] have led to the conclusion [7] that gas circulation is a necessary condition for continuous generation in stationary or quasi-stationary excitation regimes. As a result, a system of transverse gas mixture circulation (relative to the optical axis) was proposed. Such a system consists of a set of rectangular laser channels with $\sim$ 10 cm-long plane uranium layers in the direction of the gas flow. The layers are deposited on the inner surface of the side walls of the channels that are parallel to the direction of the gas flow. A radiative cooler consisting of a set of thin metal plates arranged parallel to the gas flow and perpendicular to the uranium layers is installed at the channel exit in order to cool the heated gas mixture in the channel. An identical radiator is installed at the channel entrance so that the required temperature of the gas mixture entering the channel is ensured and its velocity is levelled out as a result of the heat exchange between the gas and the plates. For the next laser channel that can be installed behind the output radiator, the latter plays the role of the input radiator, and so on. Thus, a chain of laser channels combined into a single gas circuit can be constructed. Such a circuit was realised in the LM-4 four-channel laser module (Fig. 1a) employed in the BIGR pulsed reactor complex [8].

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In the experiments with hermetically sealed laser cells, lasers are excited by pulsed thermal neutron flows with a half-amplitude pulse duration $\tau \leqslant 3 \times 10^{-3}$ s. In experiments with LM-4 gas-flow modules, the duration of the exciting neutron quasi-pulse was $\sim$ 1.5 s. The lasing duration was also of the same order.

The intensity distribution of laser radiation, shape and area of the light spot at the surface of the resonator mirror in a sealed laser with plane – parallel uranium layers were studied in [4]. It was shown that at the instant corresponding to the beginning of lasing, the emitting region is concentrated near the axis of the laser cell; then it begins to expand and acquires a nearly rectangular shape at the laser pulse peak. The intensity distribution of laser radiation is symmetric relative to the symmetry planes $y = \text{const}$ and $x = \text{const}$ passing through the optical axis. The active generation volume may occupy up to $\sim 60\,\%$ of the laser cell volume.

Such a behaviour is determined by the dynamics of evolution of gas density inhomogeneities and spatial intensity redistribution of the specific energy input to the hermetically sealed laser cell during pulse pumping. Naturally, lasers with a transverse pumping of the gas mixture must have a different and more complex dynamics. Hence the intensity distribution of laser radiation over the channel cross section will also be different.

2. Evolution of inhomogeneities

The evolution of inhomogeneities in hermetically sealed nuclear-pumped lasers excited by $\sim$ 3-ms neutron pulses, as well as in the channels of stationary and quasi-stationary transverse gas-flow lasers, was studied experimentally and theoretically in [5, 6, 9, 10]. The results of these investigations indicate that a gas region is formed in the immediate vicinity of the uranium layer deposited on a metal substrate, from which heat is removed intensely to the substrate itself. This region is characterised by very large positive density gradients and refractive index ($\nabla n \sim 10^{-4}$ cm^{-1}). Light beams directed parallel to the optical axis of the channel at any point in this region are deflected towards the substrates; hence, this region must not be a part of the lasing region. Outside this (passive) region, the transverse components of the gradients of density and refractive index in the central (active) region of the gas volume are negative and have relatively small magnitudes ($\nabla n \sim 10^{-6}$ cm^{-1}).

The passive region is confined by the laser channel wall on one side and by a surface in the gas at a distance l from the wall on the other side. A typical feature of this region is that $\partial T/\partial y < 0$ and $\partial \rho/\partial y > 0$ in it, while $\partial T(x,l)/\partial y = \partial \rho(x,l)/\partial y = 0$ at the surface lying in the gas (here, T is the gas temperature and ρ is its density).

The size of the passive region in pulsed sealed lasers increases with time as [9]

$$l(t) \approx A_1\sqrt{at}, \quad (1)$$

where a is the thermal diffusivity of the gas. For sealed laser cells with plane – parallel uranium layers, the numerical factor A_1 is approximately equal to three.

A passive region is also formed in the gas-flow channels of a laser whose walls are at a temperature lower than that of the gas flow [9 – 11]. However, this region is formed not only as a result of heat exchange with the walls, but also due to the formation of a viscous boundary layer at the wall. In the steady state, the transverse size of the passive region at a distance x from the entrance to the gas channel of the laser is approximately determined by the equality [10]

$$l(x) \approx A_2(ax/u)^{1/2}, \quad (2)$$

where u is the velocity of the gas flow away from the wall, the numerical factor A_2, which depends on the Prandtl number $\mathrm{Pr} = \nu/a$ (ν is the dynamic viscosity), lies in the range $1.4 < A_2 < 1.9$ [10]. Since x/u is the mean time of residence of a portion of gas in the channel, the passive region in a gas-flow laser is about 1.5 – 2 times smaller than in hermetically sealed non-circulating type lasers.

3. Experimental

In our experiments, we used a gas mixture of composition Ne : Ar : Xe = 300 : 100 : 1 circulating under a pressure of 1 atm through the laser channel of the LM-4 module with a velocity of 7.2 m s^{-1}, the average thickness δ_U of the uranium metal layers (with 90 % enrichment in ^{235}U) being 2.67 μm. These layers were deposited on 4-mm thick aluminium substrates and covered by a thin (0.5 μm) aluminium film on the side exposed to the gas mixture in order to prevent the ejection of ^{235}U nuclei to the gas [12, 13]. As in the experiments with hermetically sealed laser channels [4], the separation between layers was equal to 2 cm, while the length of the channel was 6 cm along the gas flow and 1 m along the optical axis. A totally reflecting dielectric spherical mirror (with radius of curvature 20 m) and a semitransparent flat dielectric mirror served as the cavity mirrors.

Neutrons from the active region of the BIGR reactor were used for excitation. Figure 1 shows the schematic arrangement of the laser module and BIGR reactor, as well as the direction of gas flow. The duration of the exciting quasi-pulse from the reactor was ~ 1.5 s, while the average power release in the gas per unit length of the laser channel at the peak of the exciting pulse was ~ 6.2 W cm^{-3}. The lasing threshold was ~ 35 % of the maximum neutron flux, while the maximum laser radiation power was 12 W.

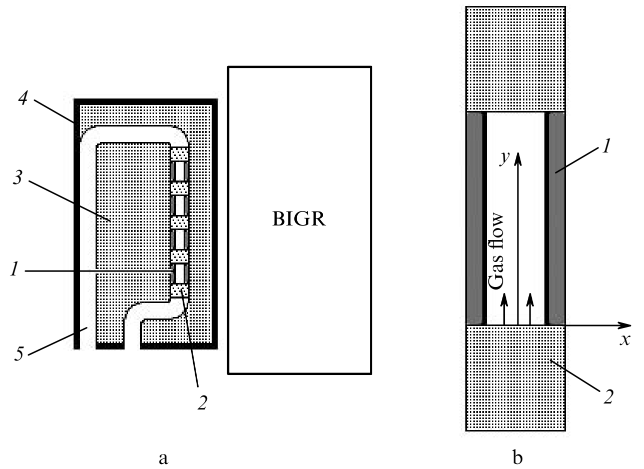

Figure 1. Cross sections of (a) the LM-4 laser module combined with the BIGR reactor and (b) laser channel; (*1*) aluminium substrate with uranium layer; (*2*) cooling radiator; (*3*) graphite; (*4*) casing; (*5*) gas channel.

The image of the laser spot was recorded by a CCD camera working in the IR spectral region. The image of the laser beam cross section obtained from one channel of the laser module was formed on the sensitive element of the camera with a pixel size of 0.1 mm. The camera worked in the recording mode during neutron pumping and registered the laser spot images at an interval of 30 ms. 25 frames showing the evolution of the laser spot in chronological order were registered during one pulse. The laser radiation power was measured with FSA-G1 sensors with a lead-sulphide-based photoresistance and IMO-3I optical radiation power meters.

4. Results

Figure 2 shows the experimental time dependences of the neutron flux density and laser radiation power. Lasing begins when the threshold is attained, and its subsequent time dependence is practically a complete repetition of the analogous dependence of the neutron flux density.

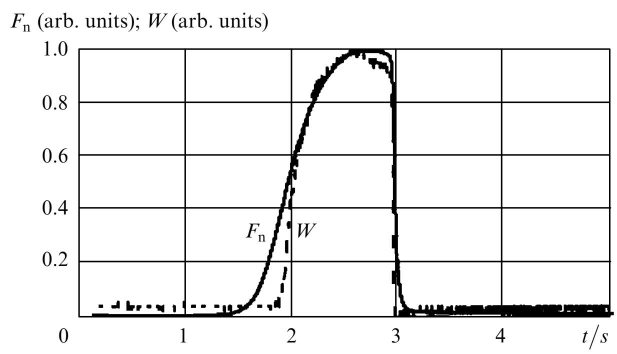

Figure 2. Time dependences of the flux density F_n of the exciting pulse neutrons and the lasing power W.

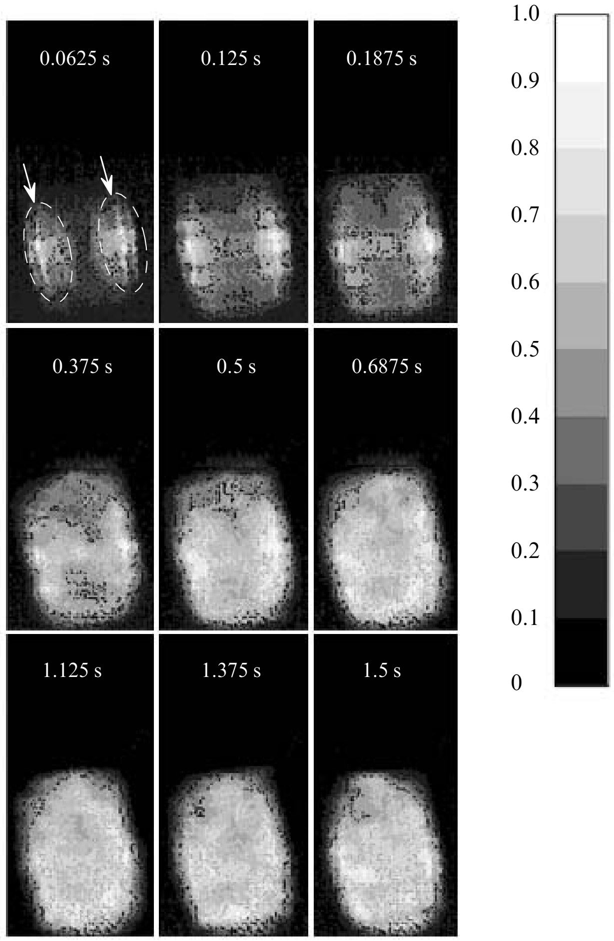

Figure 3. Distribution of radiation intensity (in relative units) over the cross section of the laser channel at the output mirror. The dashed outlines show two regions corresponding to lasing initiation.

Figure 3 shows the radiation intensity distribution at the output mirror over the laser channel cross section for several successive instants of time. The dashed curves show the onset of two lasing thresholds. The relative distribution of the laser radiation intensity in directions perpendicular and parallel to the gas flow direction is shown in Fig. 4.

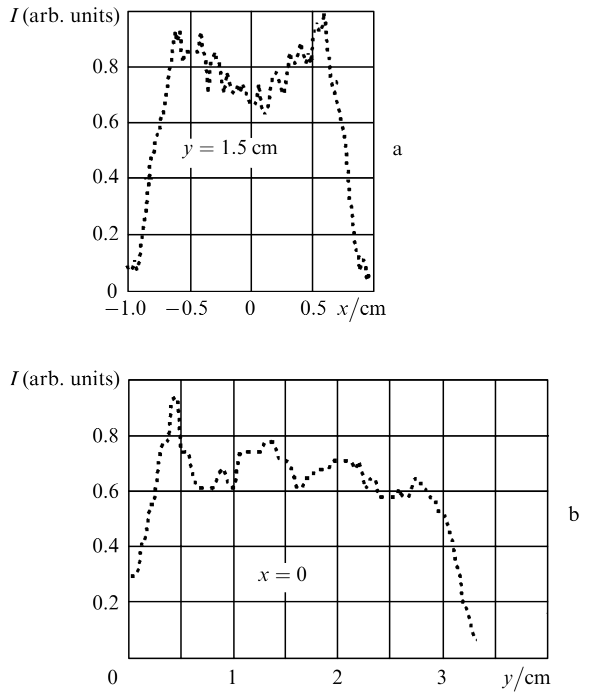

Figure 4. Relative distribution of the laser radiation intensity I in transverse (a) and longitudinal (b) directions for $y = 1.5$ and $x = 0$.

For a velocity $u \sim 7$ m s^{-1} and a channel length $b = 6$ cm in the direction of gas flow, the characteristic residence time of a gas portion in the channel τ_0 is $\sim b/u \sim 10^{-2}$ s, which is much shorter than the duration of the neutron pulse. This fact allows us to calculate the spatial distributions of the gas density and specific output power in the laser channel at each instant of time by using the method described in [11] for calculating the gas-dynamic characteristics for the

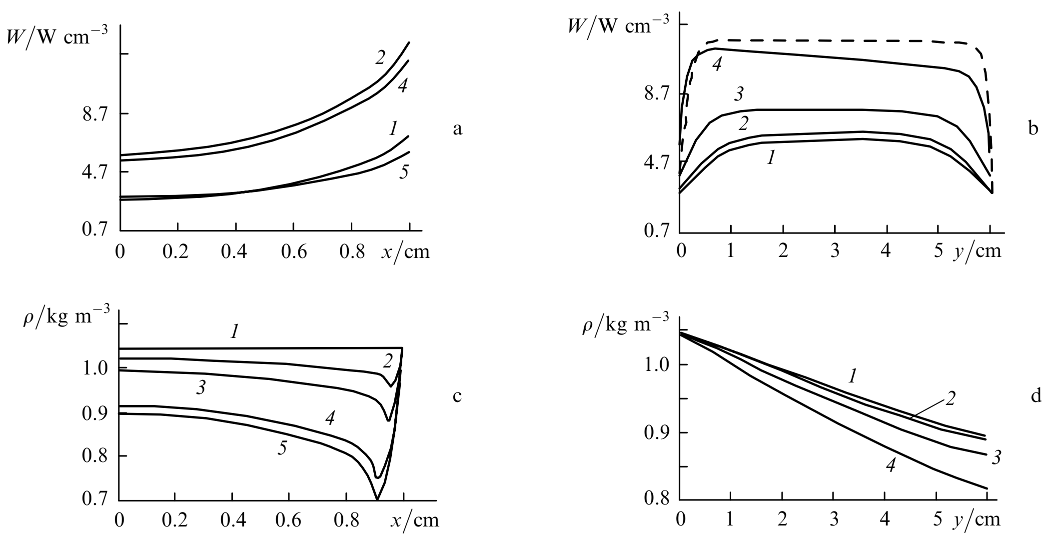

Figure 5. Spatial distribution of the specific power input W (a, b) and gas density ρ (c, d) in transverse (a, c) and longitudinal (b,d) directions for $y = 0$ [curve (*1*)], 1 (*2*), 2 (*3*), 5 (*4*) and 6 cm (*5*) (a, c) and $x = 0$ [curve (*1*)], 0.3 (*2*), 0.6 (*3*), and 0.9 cm (*4*) (b, d) at the instant of time corresponding to the peak of the exciting pulse. The solid and the dashed curve correspond to calculations with and without gas circulation, respectively.

steady-state excitation regime. The results of calculations are shown in Fig. 5. The dashed curve in Fig. 5b is the result of calculation of the specific output power in a hermetically sealed laser (without gas circulation) for $x = 0.9$ cm. The difference between the specific output powers in gas-flow and sealed gas laser systems does not exceed $\sim 2\,\%$ on the average in the central region ($x < 0.7$ cm).

The experimental results together with the results of calculations (Fig. 5) made by using the technique described in [11] under the same excitation conditions and for the same geometry as in the experiments unequivocally indicate that:

(i) in nuclear-pumped gas-flow lasers, lasing is 'initiated' in two symmetric regions (relative to the longitudinal symmetry plane) adjoining the gas entrance to the laser channel, in which the specific power contribution and the gas density approach their maximum values;

(ii) narrow regions not involved in lasing exist right at the surface of the uranium layers in which the specific power contribution attains its maximum value; the existence of these regions can be attributed to the formation of passive regions;

(iii) with the growth of the power of the exciting neutron pulse, and hence the proportional increase in the specific power input at each point of the gas volume, both symmetric regions involved in lasing merge into a single region which expands in the direction of the gas flow and attains its maximum size ($\sim 60\,\%$ of the laser channel volume) at the instant of time corresponding to the peak of the exciting pulse.

5. Conclusions

The obtained experimental results on the evolution of generation in nuclear-pumped gas-flow lasers have shown that unlike the dynamics of the analogous process in sealed lasers in which a single lasing region is formed in the region around the optical axis, two regions displaced towards the channel entrance region are formed in gas-flow lasers with a Ne : Ar : Xe = 300 : 100 : 1 gas mixture circulating under a pressure of 1 atm. As the pump power increases, these regions merge into a single region which expands in the direction of the channel outlet. As the generation threshold of specific energy input is exceeded, the time dependence of the lasing power qualitatively repeats the shape of the exciting neutron pulse. The maximum volume of the lasing region is $\sim 60\,\%$ of the laser channel volume and is attained at the instant of time corresponding to the peak of the exciting neutron pulse.

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