NOTATION

D, thermal diffusivity of active element; c, $\varkappa$, d, average specific heat, thermal conductivity, and density; c_1, $\varkappa_1$, d_1, h_1 and c_2, $\varkappa_2$, d_2, h_2, specific heat, thermal conductivity, density, and thickness of semiconductor layer and substrate respectively; r_0, radius of central disk portion; T_0, temperature of surrounding medium; R, disk radius; ε, disk emissivity; σ, Stefan–Boltzmann constant; W, radiant power incident per unit area; t_{set}, sensor time constant; x_1, first root of zeroth-order Bessel function; C, disk heat capacity; G_{rad} and G_{therm}, heat liberation coefficients related to radiation and thermal conductivity; J_0 and J_1, zeroth- and first-order Bessel functions; x_n, roots of zeroth-order Bessel function; S, voltage–power sensitivity of thermoelectric sensor; ΔT, temperature differential between "hot" and "cold" thermoelectric sensor junctions; m, number of thermoelements in sensor; $\alpha_{p,n}$, thermo-emf coefficient of individual element; F, area of sensitive region; T, temperature of surrounding medium; R, disk radius; ε, disk emissivity; E_{N-E}, U_{N-E}, electric field strength and output emf produced by Nernst–Ettingshausen effect; $Q_\perp$, transverse Nernst–Ettingshausen effect coefficient; l, h, length and height of thermomagnetic sensor working element; ∇T, temperature gradient; μ_1, first root of some dispersion equation.

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GRAIN IN A CO_2-GDL MEDIUM WITH WEDGE AND PROFILED NOZZLES, PART I. APPARATUS AND PULSE GAIN MEASUREMENT SYSTEM

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The apparatus is described together with the gain-measurement scheme. Weak shock waves are identified in the flow picture and probe locations are defined that are free from local inhomogeneity.

The weak-signal gain k_0 is one of the most important laser parameters [1]. Determination of the maximum gain constitutes a multifactor optimization on the stagnation parameters, the molar composition of the working mixture, and the geometrical dimensions and profile of the supersonic GDL nozzle. The nozzle produces the supersonic flow in the cavity, and its design features are sources of various gasdynamic inhomogeneities: shock waves, hot boundary layers, and wakes behind the edges. All these factors influence the state of inversion in the active medium and may increase or decrease the gain in accordance with the various line-broadening mechanisms [2].

There are many papers (see [1, 3] for reviews) on the theoretical and experimental multifactor optimization of the gain, and recently there have been papers [4-6] concerned with calculation and measurement for k_0 in a flow of a markedly inhomogeneous gas containing solid particles and shock waves.

There are several methods of measuring k_0 [7]. The maximum-loss method is based on measuring the absorption of calibrated attenuators introduced into the cavity that cut off the lasing, and the magnitude of the loss is identified with the gain. This method requires high accuracy in measuring the introduced loss and does not make allowance for the line width, which substantially reduces the accuracy in determining k_0. The

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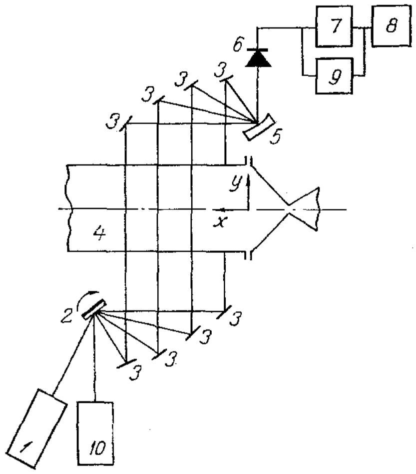

Fig. 1

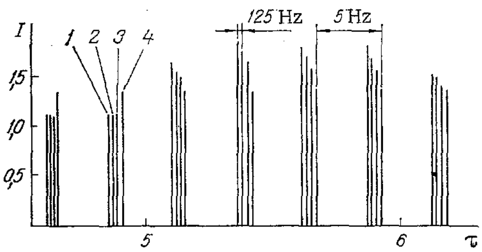

Fig. 2

Fig. 1. Pulse-modulated gain-measurement system.

Fig. 2. Typical form of oscillogram in measuring k_0: nozzle lattice, mixture 10% CO_2+ 45% N_2+45% He; T_0 = 1700°K; $P_0 \simeq$ 1.4 MPa, I transducer signal in relative terms, τ gas flow time, sec; 1) channel No. 1; 2) No. 2; 3) No. 3; 4) reference channel; 5) start of gas flow and plasmotron switched on; 6) plasmotron switched off.

spectroscopic cavity method is based on recording the resonant and nonresonant intensities when the medium is placed in a Fabry–Perot interferometer, where all forms of loss are incorporated by a single parameter, and the difference between the actual reflection coefficient of the mirrors and the loss acts as an error source.

In experiments with laser systems, the amplifier method is commonly used, which is based on probing the medium with a beam of monochromatic radiation from a quantum transition identical with that in the active medium. According to the Bouguer–Lambert Law [8], when monochromatic radiation passes through an infinitely thin layer of gas the change in intensity is proportional to the thickness of that layer, the concentration, and the optical density. The coefficient of proportionality in the expression k_0 is called the integral absorption or gain coefficient in accordance with the result of interaction between the radiation and the medium:

$$I(\nu) = I_0(\nu)\exp(k_0 L). \tag{1}$$

The amplifier method gives a value of k_0 averaged over the probe length. In particular experiments one usually employs some modification of this method. We have measured the gain in a CO_2-GDL medium by means of a pulse-train system with a scanning unit of passive type [8], which enables one to perform repeated measurements in a single run at several points in the channel simultaneously along or transverse to the supersonic flow (Fig. 1).

The radiation from the probe CO_2 laser 1 is directed by the rotating mirror 2 onto the rotating reflecting mirrors 3 and passes through the volume 4 to be collected by the spherical mirror 5, whose focal point contains the IR detector 6. The electrical signal from the IR detector 6 is passed to the amplifier 7 and is recorded by the loop oscillograph 8, and it is also displayed on the screen of the storage oscilloscope 9. The lasing line for the probe CO_2 laser is displayed by the spectrum analyzer 10, while the necessary interrogation frequency in the measurement channels is obtained by adjusting the rotational speed of mirror 2. One of the measurement lines is used as a reference one to monitor the probe-laser intensity.

An Ariman 2 gas-discharge CO_2 laser with a feedback stabilization system was used, which provides single-mode operation and tuning and has a beam power of about 1-3 W, beam diameter about 2 mm. The feedback stabilization system works on the P20 line of the 00°1-10°0 vibrational–rotational band of the CO_2 molecule. The test laser power is maintained at a level less than the saturation power of the detector and also less than the saturation power in the active medium, in which case the signal from the detector exceeds by an order of magnitude the signals from the noise and the thermal background, which are usually present around an apparatus of GDL type.

To determine the working vibrational–rotational transition in the probe CO_2 laser, a spectrum analyzer type 16 A made by Optical Engineering was used, which is a spectroscope with a diffraction grating. In the wavelength range 9.1-11.3 μm, the analyzer can identify up to 140 transitions in three different laser bands of

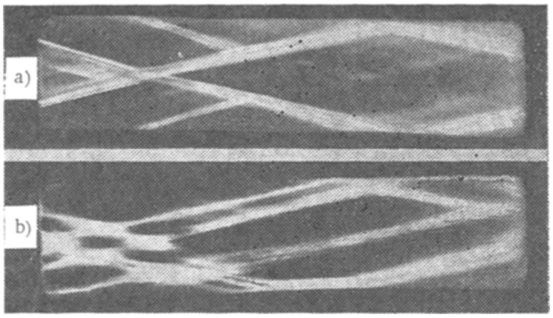

Fig. 3. Gas-flow pictures in cavity unit (gas flow from left to right). The center of the Töpler picture is in the middle of the cavity: a) wedge nozzle; b) profiled nozzle.

the CO_2 molecule (00°1-02°0, 00°1-10°0, and 01^11-11^10) with an accuracy of 0.003 μm (0.3 cm^{-1}). The recorded lines are displayed on the phosphor screen with a decay time not exceeding 0.25 sec.

Adjustment of the mirror speed provided measurement of k_0 on each channel with an interrogation frequency of about 5 Hz, while two adjacent channels were interrogated with a frequency of 125 Hz; therefore, the IR detector worked with frequency modulation close to the maker's value, and far from the frequencies of the possible interference, which in our case could have come from the plasmotron. A Ge–Au photoresistor cooled by liquid nitrogen (Svod) was used as the detector [9]. The linear range has previously been determined and the working point of the IR detector had been selected by means of calibrated ZnSe, NaCl, and Ge plates, which in various combinations provided stepped attenuation of the test laser beam by a factor 10. In accordance with the recommendations of [10], the receiving area in the photoresistor was placed behind the focus of the spherical mirror in order to provide uniform illumination and to prevent local damage. The circuit was assembled in accordance with [9, 10]. The signal level was usually too low to operate the final recorder directly, so a single-channel pulse amplifier was included, whose linear range was identified before the start of the experiment. The output signal was recorded by a loop oscillograph type K-115.

The radiation input and output windows perpenducular to the flow of active medium were closed by NaCl plates of thickness about 4 mm and were placed directly at the wall of the cavity unit, which reduced the effects of spaces with absorption when experiment indicated that there was considerable absorption for the probe radiation, which reduced the measured value of the gain appreciably.

The gain k_0 was calculated from (1), where L is the characteristic dimension of the active medium (L = 0.378 m), $I_0(\nu)$ and $I(\nu)$ are the signals before the working medium began to flow and when it was flowing. Formula (1) does not include a factor for the intensity change in the reference signal, because the test lase provided high power stability and worked on the selected vibrational–rotational transition throughout the experiment. Figure 2 shows typical oscillograms in the measurement of k_0 along the length of the flow in one of the experiments.

All the gain measurements were made with the CO_2-GDL apparatus of [11], which was an aerodynamic tube with quasicontinuous operation ($\tau \leq 3$ sec) in which the working gas mixture was heated in a three-phase plasma source.

The flow part of the GDL system could be assembled with three different forms of nozzle. In the first, a nozzle of wedge geometry had a critical section of 0.95 mm and a degree of expansion of 31.6. The supersonic part of the nozzle had a semivertex angle of 13° and a width transverse to the flow of 378 mm, while the subsonic part was formed by planar converging walls with a semivertex angle of 45°.

The second form of nozzle was a profiled one with a central body in the flow, and it had a two-slot geometry with a critical section of 2 × 0.5 mm and a degree of expansion of 25.8. The subsonic part consisted of planar converging walls with a semivertex angle of 30°, while the supersonic part was made with a kink in the contour in the throat. The calculation on the supersonic part was performed by the characteristics method, and the maximum semivertex angle was 39°. Nozzles of this type are often used in GDL to provide the most effective freezing of the vibrational level of nitrogen $N_2(v = 1)$ and the upper 00°1 level of the CO_2 molecule [1].

The third form was a nozzle lattice as usually employed in a GDL with large gas flow rates [1, 3]. The lattice used in the experiments consisted of 40 planar profile blades in which the degree of expansion in a single nozzle with a critical section of 0.3 mm was 29.6, semivertex angle 37°, length of the supersonic part of a blade along the flow 21.7 mm [12].

The wedge and profiled nozzles were first blown with air ($T_0 \approx 300°K$) to visualize the flow picture and determine the static pressures in the supersonic flow. The pressure transducers were placed on the central axis of the channel at distances of 50 and 150 mm from the end of the nozzle apparatus.

Töpler patterns for the gas flow beyond the nozzles showed that there was a complex structure of intersecting oblique shock waves (Fig. 3), which arose because of the nonideal junction between the nozzle and the cavity of constant cross section. In the profiled-nozzle case (Fig. 3b) the shock-wave structure was accompanied by a boundary layer flowing from the central body and the pattern was substantially more complicated. The shock waves could be traced throughout the cavity up to distances of about 200 mm. Figure 3a shows that weak compression waves arise within the wedge nozzle, which was due to inaccuracy in making the supersonic part and also to differences in the adiabatic parameters of the air and the laser mixture for which the nozzle was designed. It was characteristic that the compression waves arising within the nozzle were extensively disrupted and completely vanished over a length of about 90 mm. Although the shock waves recorded in our case may be classified as weak, they can affect the gasdynamic and population-inversion characteristics of the supersonic flow in the GDL.

The Töpler patterns beyond the nozzles led to selection of the following points in the GDL channel for probing with the test laser beam, which were free from shock waves: at a distance of 10 mm from the end of the nozzle in an unperturbed zone of the flow, and at distances of 100 and 144 mm in a zone beyond the first intersection of the oblique shock waves. When the GDL system was assembled with the nozzle lattice, the points of measurement lay on the axis of the channel at distances of 35, 79, and 122 mm from the end of the lattice.

To measure the profile of k_0 over the height of the channel (for the case of the wedge nozzle) we selected a section at 35 mm from the end of the nozzle, and the middle point of measurement lay on the axis $y = 0$ (where y is the coordinate along the height of the channel), while the top one lay at $y = 5$ mm from the axis and the lower one at $y = 10$ mm from it (the position of the shock wave was determined in this section as $y = 8$ mm), which enabled us to measure the distribution of the gain over the height and to estimate the effects of local inhomogeneities on k_0.

The results on the gain in the CO_2-GDL active medium for these nozzles are given in the second part of this paper.

NOTATION

k_0, total weak signal gain, m^{-1}; $I_0(\nu)$, $I(\nu)$, probe signals before and at the moment of gas efflux, V; L, characteristic dimension of the active medium, m; τ, gas efflux duration, sec; T_0, stagnation temperature, °K; P_0, stagnation pressure, Pa; y, coordinate along channel height, mm.

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