ionization level. The role of plasma processes in the heat transfer is more apparent for particles of small size ($R < r_D$) because of the strong influence of the local particle electric field on the motion of the electrons and ions.

NOTATION

e, charge of the electron; $\mathcal{E}$, total energy; $E_j^{\pm}$, flux density of kinetic energy; I_i, ionization energy; $J_j^{\pm}$, number flux density of particles in the plasma; k, Boltzmann constant; ℓ_j, mean free path; m_j, mass; N_j, computed number density; p, pressure; Q_j, heat flux; r, spatial coordinate; r_D, Debye radius; R, particle radius; T_j, temperature; φ, plasma potential; φ_f, particle floating potential; Φ_e, electron work function; Ω, momentum. Subscripts: a, molecules; e, electrons; i, ions; h, heavy plasma particles (molecules and ions); r, radial component; s, surface; t, tangential component; ∞, unperturbed plasma region far from the particle; +(−), direction away from (toward) the particle.

LITERATURE CITED

1. J. E. Allen, R. L. F. Boyd, and P. Reynolds, Proc. Phys. Fluids, No. 2, 212-216 (1959).
2. I. B. Bernstein and I. N. Rabinowitz, Phys. Fluids, 2, No. 2, 2150-2167 (1959).
3. A. G. Gnedovets, A. V. Gusarov, and A. A. Uglov, Inzh.-fiz. Zh., 62, No. 1, 41-46 (1992).
4. A. G. Gnedovets, A. V. Gusarov, and A. A. Uglov, Inzh.-fiz. Zh., 62, No. 1, 47-50 (1992).
5. J. Laframboise, Rarefied Gas Dynamics, J. H. Leeuw (ed.), Vol. 2, Academic Press, New York–London (1966), pp. 22-44.

ENERGY CHARACTERISTICS OF A SOLID-STATE LASER PUMPED BY EMISSION FROM A CUMULATIVE JET

M. Kh. Vergasov, A. F. Leonov, N. A. Makarovets,
and Yu. A. Torfimov

UDC 662.017.224.2

Optical pumping of solid-state lasers by strong shock waves formed during gas cumulation is shown to be feasible.

The possibility in principle of using strong shock waves in gases as a high-temperature high-power radiator was substantiated long ago. High radiation fluxes in small devices can be obtained by using condensed explosives (EXP) to produce strong shock waves in dense gases.

Explosive charges in a cylindrical cumulative channel are used to obtain strong shock waves in gases. A cumulative jet in the channel of such charges is formed when the detonation products collapse (gas cumulation).

It was shown in [1] that the jet velocity u is related to the detonation velocity v by

$$\frac{n^2}{n^2-1} = (x-1)^2 + \frac{n^2}{n^2-1}\left(\frac{2}{\gamma+1}\right)^{\frac{1}{n}}\left[(\gamma+1)\frac{\rho_0}{\rho\,\mathrm{exp}}\right]^{\frac{n-1}{n}} x^{\frac{2n-2}{n}}, \quad (1)$$

where $x = u/v$; ρ_0 is the initial gas density; and $P = A\rho^n$.

The given solution gives a fairly correct description of the detonation processes in a charge of limited size. After initiation the detonation wave reaches the bottom of the charge channel and initiates a shock wave in the gas. As a result of the subsequent collapse of the detonation products a jet leading the detonation front is formed in the channel. The

---

St. Petersburg Mechanical Institute. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 62, No. 2, pp. 261-266, February, 1992. Original article submitted April 19, 1991.

jet velocity increases, and so does the velocity of the shock wave. Upon traveling a path equal to 8-10 times the channel diameter the shock wave reaches maximum velocity, which it maintains during its continued travel.

The propagation of a strong shock wave in the gas is accompanied by intensive luminescence. Even though the process is short, the luminescence is always observed visually as a blindingly bright flash at the time of the explosion. The gas, which had been at atmospheric pressure and room temperature, undergoes an approximately tenfold compression in the shock wave and heats up to a temperature of the order of 10^4 K, depending on the amplitude of the shock wave.

Under such conditions the air behind the shock wave front to the surface of the explosion is completely dissociated and ionized to a considerable degree [2]. The radiative properties of such a column of ionized gas coincide with those of an absolute black body up to a shock wave velocity of 30-40 km/sec, and the concept of optically dense plasma is applicable to it [1]. The high luminance temperatures (up to 70,000 K) place the shock wave among the brightest radiators. In regard to radiation power the shock wave as a light source is superior to the extensively used pulsed gas-discharge lamps, thus making it possible to create a solid-state laser with a new source of optical pumping of the solid-state medium.

Elements of the theory of pumping of a solid-state active medium and lasing have been discussed, e.g., in [3]. The solution of differential equations describing radiation transfer in the geometric approximation in an active medium operating in a four-level scheme, under the conditions of steady-state lasing, makes it possible to evaluate such laser characteristics as lasing delay time τ^*, output power P_Σ, optimum cavity transmission coefficient $r_{2\mathrm{opt}}$ as a function of the radiator temperature (the radiator in this case is shock-ionized gas with the characteristics of an absolute black body):

$$r_{2\mathrm{opt}} = \exp\left[-2\beta l\left(\sqrt{\frac{\sigma_{32}n_0}{\beta}\,\frac{w_{14}\tau_{32}}{w_{14}\tau_{32}+1}}-1\right)\right],$$

$$P_\Sigma = \frac{h\nu_{32}n_0 V\ln\dfrac{1}{r_{2\mathrm{opt}}}}{\tau_{32}(2\beta l-\ln r_{2\mathrm{opt}})}\left[w_{14}\tau_{32}-(w_{14}\tau_{32}+1)\frac{2\beta l-\ln r_{2\mathrm{opt}}}{2\sigma_{32}n_0 l}\right], \tag{2}$$

$$\tau = \frac{1}{w_{14}+1/\tau_{32}}\ln\left[\frac{1}{1-\dfrac{\Delta_*}{w_{14}n_0}(w_{14}+1/\tau_{32})}\right].$$

The characteristic and certified values of the parameters for samples of GLS-6 neodymium-activated glass, diameter 10 × 130 mm, were taken to be: $n_0 = 2\cdot10^{20}$ cm^{-3}; $\tau_{32} = 5\cdot10^{-4}$ sec; $\sigma_{32} = 1.64\cdot10^{-21}$ cm^2; $\beta = 0.57\cdot10^{-3}$ cm^{-1} for $\lambda = 1.06$ µm; $\nu_{32} = c/\lambda$; Δ_* is determined from the condition of steady-state lasing $\Delta_* = (2\beta\ell + r_{2\mathrm{opt}})/2\sigma_{32}\ell$ and is the upper limit of integration for finding τ_* from the equation

$$\frac{d\Delta}{d\tau} = w_{14}(n_0-\Delta)-\frac{\Delta}{r_{32}},$$

w_{14} is the pump rate of the active medium, considered as a parameter that determines the temperature beyond the shock wave front.

In the general case the probability of excitation of a microparticle during pumping (pump rate) is determined by the transfer of light energy from the radiator to the active element,

$$w_{14} = \int\frac{c}{h\nu}\sigma_{14}(\nu)\rho_{14}(\nu)\,d\nu, \tag{3}$$

where $\sigma_{14}(\nu) = \kappa(\nu)/n_0$ is the cross section for absorption in a unit frequency interval. In the calculations $\kappa(\nu)$ was taken from the data of [3]. Therefore,

$$w_{14} = \frac{8\pi}{n_0c^2}\int_{\nu_1}^{\nu_2}\frac{\nu^2\varkappa(\nu)}{\exp\left(\dfrac{h\nu}{RT}\right)-1}\,d\nu \tag{4}$$

and the pump rate essentially depends on the jet temperature T at the given frequency range of the absorption spectrum of the active medium ($\nu_1 = 3.35 \cdot 10^{14}$ Hz, $\nu_2 = 7.5 \cdot 10^{14}$ Hz).

With the results of numerical integration of (4), using Eq. (2) we can easily determine the main energy characteristics of a laser from the parameters of a strong shock wave during gas cumulation. In this case, the actual efficiency of light transfer by the reflecting system is interpreted as a lowering of the radiator temperature or the velocity of the shock wave.

Preliminary calculations showed that an active element of GLS-6 glass, with a dielectric coating deposited on its ends having a reflection of 99% ("opaque" mirror) and 75% (output mirror), makes it possible to obtain an output power of 136 kW with a lasing delay time of about 80 μsec at steady-state lasing, when the luminance temperature of the cumulative jet is about 17,000 K.

Figure 1 shows the design and principal dimensions of a laser device with the active element pumped by a strong shock wave, propagating ahead of a gas cumulative jet. The source of the pump radiation consists of a cumulative explosive charge 5 in an assembly with a detonator 6, which are put in a chamber with a weakened cross section 4, and a glass tube 7 pressed against it by a collar 8. The pump radiation source and the active element 3 are inside a strong casing 1. Their axes are strictly parallel. Reflector 9, which has a closed cylindrical surface with an oval cross section and is placed inside the casing, serves to transfer pump radiation energy to the active element. The casing is closed with a lid 2. The optical elements of the cavity, planar mirror coatings, are made on the ends of the active element.

The charge is made of TG 40/60 explosive. The mass and size characteristics of the charge (mass of the charge 23 g, outside diameter 20 mm, channel diameter 8 mm, channel length 40 mm) made it possible to count on obtaining a shock wave with a velocity of about 11 km/sec; the velocity of the cumulative jet is about 9.1 km/sec and the temperature of the air beyond the shock wave front is about 17,000 K according to estimates.

With the assumption that the active element is pumped only from the surface of the column of ionized air, contained between the shock wave and the detonation products of the explosion (gas cumulative jet), the lasing delay time obtained with the estimates is two to three times as long as the time taken by the ionized gas to travel through the glass tube and the laser does not manage to "luminesce." It was necessary, therefore, to experiment with photographic recording of the gas cumulative jet, the purpose being to determine the delay between the existence of radiation in the jet and the arrival of the detonation at the end of the explosive charge, after which a shock wave propagates inside the casing and shatters the active element. The photographic recording was made on a film moving at 25 m/sec, with the slit of the recorder parallel to the axis of the tube.

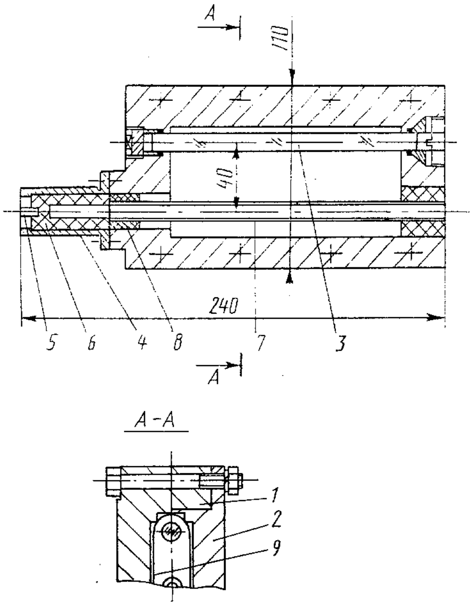

Fig. 1. Design of laser device.

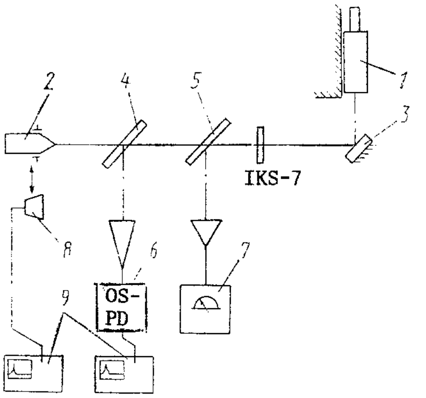

Fig. 2. Diagram of experiment to determine the energy characteristics of the laser device.

The delay between the tube luminescence and the arrival of the detonation at the end of the charge was 150 μsec, which made it possible to count on the laser attaining steady-state lasing.

Our tests of such a laser device were intended to ascertain whether pumping an active element with radiation from an ionized air shock wave is feasible and to determine the energy characteristics, i.e., the energy E, J, of a pulse of induced laser radiation and the lasing pulse length τ, μsec.

In the case of a laser device with shock-wave pumping, a time of the order of tens of microseconds is assigned for determining the parameters; this made it necessary to develop a new measuring technique that would take into account the characteristic features of the radiation diagnostics. Its first feature is a short single pulse with an unpredictable amplitude, as well as its noise protection. The second feature of the radiation diagnostics is that the main parameters of the radiation must be determined under conditions of considerable indeterminacy. This pertains primarily to determining the form of the signal and estimating its amplitude—time characteristics. The third characteristic feature is that the maximum signal must be recorded. Accordingly, prototypes, of special measuring apparatuses to record the radiation, were developed and built.

1. Optical signal-processing device (OSPD) for synchronizing the time when the induced radiation appears and when it is recorded by oscilloscope methods. The device delays the signal under study, analyzes the amplitude growth rate, regulates the gain in the measuring channel on this basis and from the leading edge of the signal forms a synchro pulse to trigger the sweep in the second channel. The signal delay is 6-10 μsec and the dynamic range of automatic regulation is 60 dB.

2. A photodetector with a preamplifier based on a small-lag silicon photodiode with a spectral characteristic such that in combination with an IKS-7 filter it can cut out a fairly narrow band near λ = 1.06 μm and thus isolate the induced radiation against the background of extraneous illumination.

3. A calorimetric instrument to measure the energy of the laser radiation with storage of the maximum value of the analog signal and automatic selection of the measuring range,

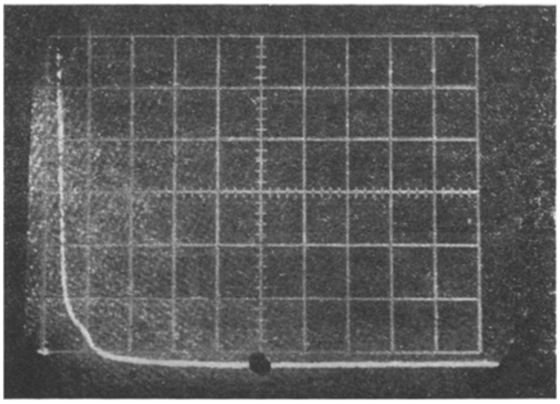

Fig. 3. Oscilloscope trace of induced laser radiation.

ensuring the following principal parameters: measuring limits 0.1, 1.0, and 10.0 J; automatic switching of the measuring ranges; electrical calibration in all ranges and analog storage of the results of the measurement for no less than 10 min.

Figure 2 shows a diagram of the experiment consisting of the laser device under study 1, mounted on a fixture, an LGN 208-B laser 2, used to align the optical system, a rotatable mirror 3, beam splitters 4 and 5, optical signal-processing device 6; and a calorimetric instrument 7 to measure the laser-radiation energy.

After the alignment the aligned laser is replaced by a photodiode 8 to duplicate the OPSD. The signal from the photodiode and the OSPD was recorded with an S8-13 storage oscilloscope 9 in two channels. Extraneous light eliminated from the optical system by the inclusion of an IKS-7 light filter, which cuts out radiation with a wavelength shorter than $\lambda = 0.90$ μm and makes it possible to identify the induced radiation.

The numerical values of the energy loss in each element of the optical system were obtained experimentally. The total attenuation of the laser radiation to the head of the calorimetric measuring instrument was 93.36%.

In tests we recorded induced laser radiation, which indicates that the laser device functioned properly. A typical oscilloscope trace of a pulse is shown in Fig. 3. The lasing pulse length was 50 ± 5 μsec. The radiation energy, determined by the calorimetric instrument, was 0.2 J, which gives a radiation pulse energy of 3 ± 0.2 J at the laser-device output when the loss is taken into account.

The experiments have demonstrated that radiation from strong shock waves that arise during gas cumulation can be feasibly applied to optical pumping of solid-state lasers; a laser device with the active element pumped by shock-wave radiation has been built; the average lasing power is of the same order of magnitude, as the estimate made on the assumption of steady-state lasing.

We thank A. N. Flerov and S. B. Leont'ev for their great assistance in developing and building the measuring apparatus.

NOTATION

u, velocity of cumulative jet; v, velocity of detonation of the explosive; x, dimensionless jet velocity; γ, effective adiabatic exponent of the shock-heated gas; ρ, density; P, pressure; T, temperature; n, exponent in the equation of state for the explosion products; τ_*, lasing time delay; P_Σ, output power of the stimulated radiation; $r_{2\mathrm{opt}}$, optimum transmission coefficient of cavity; n_0, Nd^{3+} ion concentration; V, volume of active element; ℓ, length of active element; τ_{32}, lifetime of metastable state; ν_{32}, radiation frequency; σ_{32}, interaction cross section; β, absorption coefficient of the material of the active element; Δ_*, steady-state value of the population inversion; w_{14}, pump rate of active medium; $\rho_{14}(\nu)$, spectral energy density of the absolute black body; $\kappa(\nu)$, quantity characterizing the absorption spectrum of Nd^{3+}-activated glass; c, velocity of light; τ, length of lasing pulse; E, energy of lasing pulse; and λ, wavelength of laser radiation.

LITERATURE CITED

1. M. A. Tsikulin and E. G. Popov, Radiative Properties of Shock Waves in Gases [in Russian], Moscow (1977), pp. 172-194.
2. F. A. Baum, K. P. Stanyukevich, and B. I. Shekhter, Physics of Explosions [in Russian], Moscow (1959).
3. A. L. Mikaélyan, M. L. Ter-Mikaélyan, and Yu. G. Turkov, Solid-State Lasers [in Russian], Moscow (1967), pp. 112-380.