Mechanism for the formation of a plasma mirror in a resonator

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The time evolution of the reflectance of a resonator plasma is analyzed. The motion of the plasma in the intense multimode light field, the reflection of the light and its amplification are analyzed in a self-consistent way. The evolution of the reflectance is related to the time evolution of the light intensity only through the hydrodynamics of the plasma. The operating principle of a plasma shutter is determined. The structure of the train of laser pulses is found. Some behavior observed experimentally is explained.

The advantages of open resonators with plasma optics—the simplicity of design, the stability of the operating regimes, the high efficiency, and the high light intensity—have been pointed out in many studies.[1–13] Oscillators with plasma elements are simple to control. A plasma layer combines the functions of resonator mirror, optical shutter for Q switching, and nonlinear element for mode locking. Plasma optics makes it possible to develop simple and efficient lasers of large aperture for Q-switched operation. A plasma shutter has an unlimited radiation strength. It makes it possible to synchronize several laser channels and to superimpose the beams on the target. Experiments have also demonstrated that it is possible to replace both resonator mirrors with plasma reflectors.

Experimental results show that resonators with plasma optics are promising. Some interesting possibilities for practical use of such resonators have been discussed in several papers.

The experiments with resonator plasmas have concentrated on the temporal structure of the laser light. The operating principles of the plasma mirror (or shutter) have not been determined. There have been several suggestions regarding the physical mechanisms which determine the time evolution of a plasma mirror: stimulated Brillouin scattering, self-focusing, and the formation of a crater in the target.

In the present paper we derive a theory for the events which occur in a resonator with a plasma mirror. The calculations on the plasma in the intense multimode light field, the reflection of the light, and its amplification are treated in a self-consistent way. We determine the structure of the train of laser pulses, and we explain some behavior which has been observed experimentally.

THE GASDYNAMICS OF A PLASMA MIRROR

Figure 1 shows the equivalent optical diagram of a resonator with a plasma mirror. The mirror M_1 has a reflectance $R_1 = 100\%$. The plasma mirror, M_2 is in a plasma-optics cell S. The chemical composition and pressure of the gas in this cell strongly influence the structure of the light field. The reflectance of the plasma mirror, $R(t)$, and the optical thickness $\Lambda(t)$ are to be calculated. The time t is reckoned from the time at which the plasma appears. The plasma can be produced through optical breakdown of the gas, by an electric discharge, or by burning through thin films with a laser beam. The metallized film can be one of the resonator mirrors at $t < 0$ (Ref. 14). A good model of a plasma-optics elements, which can explain all the operating principles of a mirror and of a shutter, is a plane plasma slab which is formed at the caustic F of the focusing system at the time $t = 0$ and which then expands into the surrounding gas.

Under the conditions of this problem, the electron and ion-atom subsystems can be assumed locally equilibrium subsystems, characterized by temperatures T_e and T. The plasma motion obeys the laws of hydrodynamics:

$$\frac{\partial v}{\partial t} = \frac{\partial u}{\partial m}, \quad \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial m}, \quad u = \frac{\partial x}{\partial t},$$
$$\frac{\partial \varepsilon_i}{\partial t} = -p_i \frac{\partial v}{\partial t} + \Pi_{ei},$$
$$\frac{\partial \varepsilon_e}{\partial t} = -p_e \frac{\partial v}{\partial t} - \Pi_{ei} + v\mu_\omega q_\omega - v \sum_j I_j G_{je}. \tag{1}$$

Here v is the specific volume of the plasma; u is the velocity of a mass element; x is an Euler coordinate; m is the Lagrange mass coordinate $(\partial m = \rho \partial x)$;$\rho = v^{-1}$ is the density; $p = p_e + p_i$ is the total pressure; ε_e and ε_i are the specific internal energies of the electron and ion subsystems; Π_{ei} is the rate at which energy is transferred from the electron subsystem to the ion subsystem; μ_ω is the bremsstrahlung coefficient corrected for stimulated emission; and q_ω is the radiation intensity at the frequency of the working transition. The last term in the equation for ε_e is the specific energy expanded by the electron subsystem on the ionization of atoms and ions by electron impact. The index $j = 0,1,2,\ldots$corresponds to atoms and to ions of charge j; I_j is the ionization potential of ion j; G_{je} is the rate at which the ions j are ionized by electron impact (the number of ioniza-

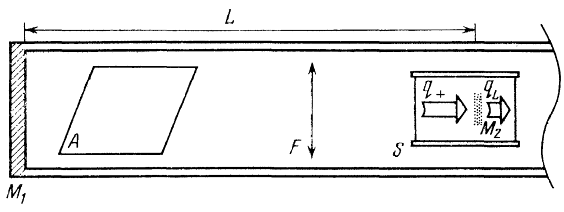

FIG. 1. Equivalent diagram of a resonator with a plasma mirror.

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tion events per cm^3 per second); and

$$p_i=\frac{\rho T}{M},\quad p_e=\frac{\rho T_e}{M}\alpha_e,\quad \varepsilon_i=\frac{3T}{2M},\quad \varepsilon_e=\frac{2T_e}{2M}\alpha_e,$$

$$\alpha_e=\frac{n_e}{n_a+n_i}\quad \alpha_j=\frac{n_j}{n_a+n_i}\quad n_i=\sum_{j=1} n_j,$$

$$\Pi_{ei}=(3m_e/M^2)\nu_e\alpha_e(T_e-T),\qquad \mu_\omega=2\omega\varkappa_\omega/c,$$

$$n_\omega=2^{-1/2}\{\varepsilon_\omega+[\varepsilon_\omega^2+(4\pi\sigma_\omega/\omega)^2]^{1/2}\}^{1/2},$$

$$\varkappa_\omega=2^{-1/2}\{-\varepsilon_\omega+[\varepsilon_\omega^2+(4\pi\sigma_\omega/\omega)^2]^{1/2}\}^{1/2},$$

$$\varepsilon_\omega=1-\frac{\omega_p^2}{\omega^2+\nu_e^2}\qquad \sigma_\omega=\frac{\omega_p^2}{4\pi}\frac{\nu_e}{\omega^2+\nu_e^2},\qquad \omega_p^2=\frac{4\pi e^2 n_e}{m_e}.$$

Here α_e is the degree of ionization of the plasma; n_e, n_a, and n_j are the numbers of electrons, atoms, and ions j per cm^3; ν_e is the effective rate of elastic collisions of electrons with atoms and ions[15]; m_e is the mass of the electron; M is the mass of the atom; n_ω and $\varkappa_\omega$ are the refractive index and absorption coefficient of the plasma[15]; ε_ω and σ_ω are the dielectric constant and electrical conductivity of the plasma at the frequency ω; and ω_p is the electron plasma frequency.

The hydrodynamic equations are integrated along with the ionization kinetic equation. In a Lagrange description of the motion, the kinetic equations can be put in the form

$$\frac{\rho}{M}\frac{\partial\alpha_e}{\partial t}=G_{ph}+\sum_{j=0}(G_{je}-G_{j+1,e}^-),$$

$$\frac{\rho}{M}\frac{\partial\alpha_0}{\partial t}=-G_{ph}-G_{0e}+G_{1e}^-,$$

$$\frac{\rho}{M}\frac{\partial\alpha_1}{\partial t}=G_{ph}+G_{0e}-G_{1e}^--G_{1e}+G_{2e}^+,$$

$$\frac{\rho}{M}\frac{\partial\alpha_j}{\partial t}=G_{j-1,e}-G_{j,e}-G_{j,e}^-+G_{j+1,e}^-,\quad j\geqslant 2,$$

written for each element of mass. Here $G_{\rm ph}$ is the rate of photoionization of the atoms by the ultraviolet emission from the plasma; G_{je} and G_{je}^- are the rates at which ions j are ejected from the subsystem by ionization ($j\to j+1$) and recombination ($j\to j-1$); and $G_{j-1,e}$ and $G_{j+1,e}^-$ are the rates at which ions j appear in the system as a result of ionization ($j-1\to j$) and recombination ($j+1\to j$). The rate at which ions are photoionized is negligibly small. The recombination rates are calculated from the ionization rates and from the ionizational-equilibrium constants.[16] In these calculations we use the impact-ionization rates calculated in Refs. 17 and 18 and the rates of photoionization of atoms calculated in Refs. 19 and 20. The diffusion of electrons can be ignored.

REFLECTION AND AMPLIFICATION OF THE SIGNAL

Electromagnetic radiation $q_+(t)$ is directed toward the plasma from the active medium. The plasma absorbs part of the radiation and is heated. This heating is accompanied by an expansion. Shock waves are excited in the surrounding gas. An inhomogeneiety of the refractive index $n_\omega(x,t)$ results in the reflection of part of the radiation back toward the active element: $q_R(T)=R(t)q_+(t)$. The most intense bursts of reflection occur during collisions of shock waves. The reflected signal $q_R(t)$ passes through the active medium twice, is amplified, and strikes the plasma slab again after a time $\Delta t=2L/c$. Figure 2 shows some typical profiles of the dielectric constant. At an initial gas pressure on the order of atmospheric in the cell, the following condition holds quite accurately at the frequency of a neodymium laser:

$$\partial\varepsilon_\omega/\partial x\ll\varepsilon_\omega^{3/2}/\lambda_0. \qquad (2)$$

Under this condition the relectance can be calculated in the first geometric-optics approximation[15] (here $\lambda_0=\lambda\sqrt{\varepsilon_\omega}$ is the wavelength in vacuum). Going through calculations analogous to Ref. 15, but incorporating absorption, we find

$$R(t)=\mathrm{th}^2\left|\int_{-\infty}^{\infty}\frac{1}{2k_\omega}\frac{\partial k_\omega}{\partial x}\exp\left[-2i\int_{-\infty}^{x}k_\omega(y)\,dy\right]dx\right|, \qquad (3)$$

$$k_\omega(x,t)=(\omega/c)(n_\omega-i\varkappa_\omega).$$

Of the radiation intensity incident on a unit area of the plasma mirror, $q_+(t)$, a fraction $R(t)q_+(t)$ is reflected and amplified again, while the remainder, $(1-R)q_+$ is partially absorbed by the plasma slab and partially transmitted. This part represents the laser output intensity $q_L(t)$. In the geometric-optics approximation the transparency of the mirror can be characterized by an optical thickness

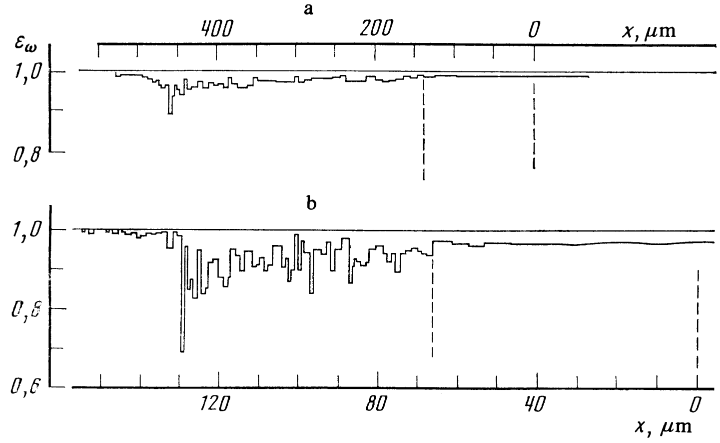

FIG. 2. Dielectric constant of a plasma mirror ($p_0=1$ atm, $l_0=0.1$ mm, $L=1$ m, $W=200$). a—hydrogen, $t=20$ ns; b—argon, $t=21$ ns. The dashed line at the center marks a mass element through which the plasma-gas interface passed at $t=0$; the dashed line at the right shows the position of this element at $t=0$.

$$\Lambda(t) = \frac{2\omega}{c} \int_{-\infty}^{\infty} \varkappa_\omega(x, t)\, dx ,$$

and we can write

$$q_L(t) = q_+(t)\,[1 - R(t)\,]\,e^{-\Lambda(t)}.$$

Beginning with the second pass through the resonator ($t > 2L/c$), the radiation intensity $q_+(t)$ can be written

$$q_+(t) = W^2 R(\tau)\, q_+(\tau), \qquad (4)$$

where $\tau = t - 2L/c$, and W is the power gain of the signal per passage through the active medium.[1]

During the first passage through the resonator ($0 \leqslant t < 2L/c$), the radiation cannot be written in the form (4), since we have $R \equiv 0$ at $\tau < 0$. The shape of the signal $q_+(t)$ at $t < 2L/c$ is determined by events which occur in the system before the formation of the plasma mirror, so that this shape should be specified along with the initial conditions of the problem. We assume that the higher-order transverse modes of the resonator are suppressed. We assume that the inhomogeneous broadening ($\Delta\nu_\omega$) of the working transition is significantly greater than the intermode beat frequency $\Delta\nu_m = c/2L$. The resultant field, in the resonator can be written as a superposition of N_m longitudinal modes, where[21] $N_m \approx \Delta\nu_w / \Delta\nu_m$:

$$E(t) = \sum_{m=m_c-N_m/2}^{m_c+N_m/2} E_m \sin\{[\,\omega + 2\pi(m - m_c)\,\Delta\nu_m\,]\,t + \varphi_m\}.$$

Here $m_c = 2L/\lambda_0$ is the index of the longitudinal mode which corresponds to the center of the line, and φ_m are the random phases of the independent oscillators. The radiation intensity is

$$q_+(t) = (c/8\pi)\,E^2(t), \qquad 0 \leqslant t < 2L/c.$$

FORMATION OF A PULSE TRAIN

The time evolution of the reflectance $R(t)$ is determined by the motion of the plasma, the time evolution of the refractive index, and the absorption. The motion of the plasma is determined to a large extent by the light absorption $q_-(t)$, while the light intensity $q_+(t)$ is expressed in terms of the reflectance. To find the shape of the output signal we must therefore solve the self-consistent problem of the expansion of a plasma slab and the formation of the radiation field.

The problem has been solved numerically for argon and hydrogen. The initial state of the plasma is specified as an immobile plane slab of thickness $l_0 = 0.1$–0.3 mm, with a temperature $T_0 = T_{e0} = 3$–5 eV, and with the density of the surrounding gas. For the passage through the resonator, the light $q_+(t)$ is specified as a superposition of 20 longitudinal modes. All the amplitudes E_m are specified equal, while random numbers are chosen for the phases φ_m.

At $t > 0$ the plasma slab begins to expand into the surrounding gas. Two shock waves are formed. The gas around the plasma absorbs part of the ultraviolet emission from the plasma and undergoes a slight (nucleating) ionization. The electron temperature in the immobile gas is determined primarily by the intensity of the laser light.[22] The rate of impact ionization depends exponentially on the electron temperature, and it varies over a broad range in an alternating field $q_+(t)$. Progressively new portions of gas and plasma are continuously entrained in the hydrodynamic motion. A series of shock waves and rarefaction waves is formed. The velocities of these waves differ, because of differences in the plasma density, the degree of ionization, and the fraction of the laser light which is absorbed. Because of this difference in velocities, the shock fronts collide. These collisions are accompanied by high gradients of the variables and bursts of reflection.

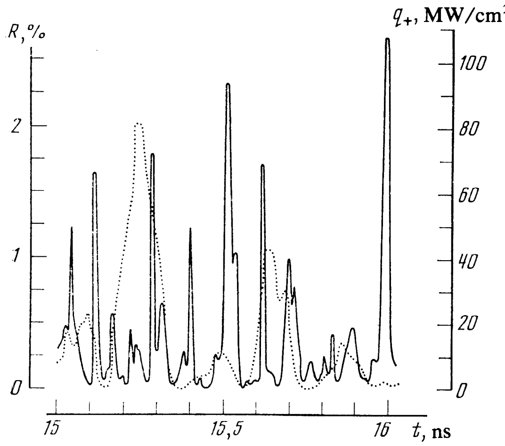

FIG. 3. Reflectance of a plasma mirror (argon, $p_0 = 0.7$ atm, $l_0 = 0.2$ mm, $L = 1$ m, $W = 200$]. The dotted curve shows the intensity of the light incident on the mirror.

Figure 3 shows a typical fragment of the $R(t)$ record. The length of a burst (at its base) is $\tau_R \sim 50$ ps, equal to the scale time for the collision of shock waves in the plasma, $\tau_{\rm coll} \sim l_s/D_s$ (the width of the shock front is $l_s \sim 1\,\mu$m, and the velocity of the shock wave is $D_s \sim 10$ km/s). The stage of maximum compression is slightly shorter. The stage corresponds to a maximum reflection. Figure 3 compares the pulsed reflectance $R(t)$ with the intensity of the incident laser light, $q_+(t)$. We see that the bursts of reflection do not correlate with intensity peaks. Furthermore, the peaks in $q_+(t)$ are several times wider than those in $R(t)$. In one of the simulations, a slab of argon plasma was bombarded by a constant intensity $q_+ = 600$ MW/cm^2. Again in this case the reflectance has a peak structure with typical peak half-widths ~ 20–50 ps. It can thus be asserted that the reflectance of the plasma mirror is coupled with the laser light only through the hydrodynamics.[2]

The peak values of the reflectance $R(t)$ depend on the pressure and chemical composition of the gas in the plama-optics cell and also on the thickness of the plasma slab and the rates of processes which occur in the plasma: the rate of ionization and the velocities of the shock waves. In calculations carried out for a neodymium laser the reflectance in the picosecond pulses, R, reaches a few percent (argon; $p_0 = 1$ atm, $l_0 = 100\,\mu$m and $p_0 = 0.7$ atm, $l_0 = 200\,\mu$m), in agreement with the experimental results of Refs. 11 and 12. Geometric-optics condition (2) is violated for the light of a CO_2

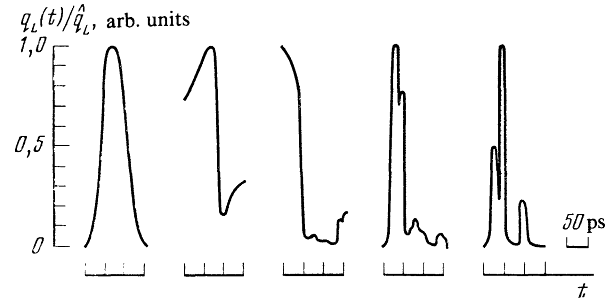

FIG. 4. Change in the shape of the signal during four successive traversals of the resonator (argon, $p_0 = 1$ atm, $l_0 = 0.1$ mm, $W = 200$, $L = 1$ m).

laser, but in this case the gradient $\partial \varepsilon_\omega / \partial x$ is large, and we can expect the Fresnel formulas to be satisfactorily accurate.[26] Calculations carried out for a CO_2 laser (argon, $p_0 = 1$atm, $l_0 = 0.1$ mm) show that the reflectance can reach 25% in some pulses. In the experiments of Ref. 5 the reflectance was 15–20%.

In the experiments of Refs. 11 and 12 the structure of the laser pulse was measured with a picosecond time resolution. Those measurements showed that a typical peak has half-width $\tau_L \approx 20$ ps. Some narrower peaks are also found ($\tau_L < 5$ ps). It was also noted that (1) the peaks become narrower when they are reflected from the plasma mirror and (2) some of the peaks are not reflected at all.

The experimental results can be explained in a natural way on the basis of the problem solved here. Let us examine the changes in the shape of some peak over several passes throught the resonator (Fig. 4). From the complete laser pulse $q_L(t)$ found in the numerical simulation we select five fragments: a peak of regular shape with a half-width $\tau_L = 70$ ps and four of its "resonances": four signals which are successively reflected and amplified, and which are separated by time intervals $\Delta t = 2L/c$. For convenience in comparing the shapes of the signals, the intensities are given in arbitrary units. These results imply that over several traversals of the resonator the time evolution of the radiation $q_L(t)$ becomes similar to that of the reflectance $R(t)$. A wide light pulse of regular shape becomes a haphazard sequence of peaks with a half-width $\tau_L \sim 20$ ps (Refs. 11 and 12). There may also be a further contraction of a peak if, upon reflection, it is displaced slightly along the time scale from the $R(t)$ burst.

The calculations show that at certain times the plasma loses its ability to reflect (Fig. 3). The light peaks which arrive at the plasma at such times do not contribute to the reflected signal $q_R(t)$, in agreement with experimental observations.[11,12]

The lasing regime is basically governed by the gain of the active medium.[5,10] This conclusion can also be drawn from the numerical simulations. As an example, Fig. 5 shows the structure of two trains of laser pulses produced in a resonator with a plasma mirror. In the first case ($W = 300$) the condition for self-pumping, $R(t)W^2 > 1$, holds nearly continuously. The contrast between the peaks and the background is small (~ 30), since the background and the peaks are amplified identically (without discrimination), on the average. In the second case ($W = 150$) the self-pumping condition holds much less frequently than in the first case, so that the background is, on the average weakened with each transit of the resonator. The light peaks $q_+(t)$ which are incident on the mirror at the time $R(t)W^2 < 1$ are also weakened, but a fraction of the $q_+(t)$ peaks is reflected and amplified when the self-pumping condition holds. The contrast of several peaks thus increases, and the pulse train thins out. In this particular calculation, the peak contrast with respect to the background was ~ 200. In the experiments of Ref. 10 the contrast of the light produced in a resonator with a plasma mirror was 100–1000. The reason for the comparatively low contrast is that the plasma mirror is not a discriminator. It cannot respond instantaneously to the intensity of the incident light, since the reflectance is related to the intensity through the hydrodynamics. This property cannot be called a disadvantage of the plasma mirror, since the contrast of the light can be increased substantially throught the use of saturable absorbers.[10]

The contrast cannot be increased through a further reduction of the gain of the active medium. At $W = 80$, for

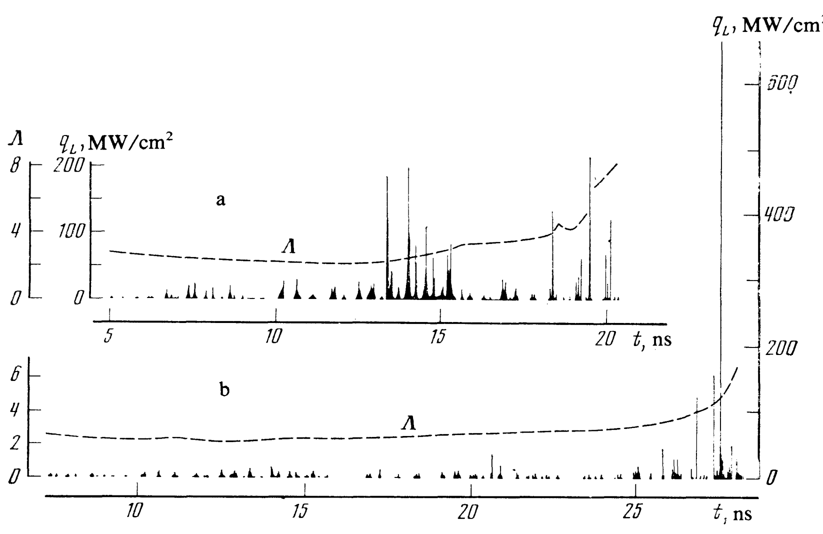

FIG. 5. Temporal structure of the laser light (argon, $p_0 = 1$ atm, $l_0 = 0.1$ mm, $L = 1$ m. a—$W = 300$; b—$W = 150$.

example (with otherwise the same parameters; Fig. 5), the self-pumping condition is satisfied so infrequently that the light has become weaker than it began after six back-and-forth traversals of the resonator.

We might also note that in the calculations carried out for hydrogen ($p_0 = 1$ atm, $l_0 = 0.3$ mm and $p_0 = 0.7$ atm, $l_0 = 0.1$ mm) the signal is not amplified even at $W = 300$ (six back-and-forth traversals of the resonator, $L = 1$ m). Under otherwise equal conditions, a hydrogen plasma is not ionized as extensively as an argon plasma is, so that the relative oscillations of the optical parameters are smaller in the case of hydrogen (see, for example, the dielectric constant in Fig. 2). The reflectance is low (in comparison with that of argon), and the self-pumping condition is satisfied only infrequently.

The reflectance of a plasma mirror can be increased by increasing the initial gas density or the initial thickness of the plasma slab, l_0, but this approach results in an increase in the optical thickness of the mirror,

$$\Lambda_0 \sim \mu_{\omega,0} l_0 \sim n_e n_i l_0 \sim p_0^2 l_0 ,$$

and an exponential decay of the laser light.

If the self-pumping condition, $R(t)W^2 > 1$ holds sufficiently frequently during the operation of the plasma mirror, the light intensity in the resonator will progressively increase. As the intensity increases, there are also increases in the plasma temperature, the rate of impact ionization, the velocities of the shock wave, and the energy with which shock fronts collide. At $q_+(t) > 1\text{GW/cm}^2$ ($\lambda_0 = 1.06$ μm), the reflection increases, and the self-pumping condition is satisfied nearly continuously: $\overline{R}W^2 > 1$. The Q of the resonator increases. In this stage of the formation of the pulse train, the plasma slab serves as a mirror and as an optical shutter for Q switching. The optical thickness of the plasma slab, $\Lambda(t)$, which increases as new layers of the gas are ionized, has an important effect on the shape of the train of laser pulses, $q_L(t)$ (Fig. 5). Most of the light incident on the plasma from the side of the active medium is absorbed.[4]

When any optical shutter is used, the giant light pulses produced in Q-switched operation deplete the upper level of the active medium in a time $\sim 2L/c$, and the train is cut off. In this calculation, the energy stored in the active medium was assumed arbitrarily large (a linear gain). This assumption leads to a clear picture of the particular features of a plasma shutter. A plasma shutter has a mechanism of its own for cutting off a pulse train, and it can do this before the population inversion is completely depleted. Let us examine this mechanism in more detail.

In Q-switched operation the light intensity in the resonator, $q_+(t)$, increases sharply and reaches the threshold for the excitation of a fast ionization wave.[27] The plasma front goes from an optical detonation regime to a fast-wave regime. This "superdetonation" regime is characterized by a smooth profile $\alpha_e(x)$ against the background of the immobile gas: $\rho(x) = \rho_0$. The absorption of the laser light on this profile occurs without reflection: The plasma loses its ability to reflect, and the resonator disappears. By this time, the population inversion in the active medium can be depleted only partially.

The expansion and cooling of the plasma are accompanied by its recombination, and the optical thickness of the slab decreases. If the laser system has mirrors in addition to the pair M_1–M_2, the lasing may begin again. A second train of laser pulses will be generated. This train, like the first, is cut off either by the plasma shutter or by the depletion of the upper level in the active medium. In experiments with plasma mirrors, several trains of nanosecond laser pulses are usually observed.[10–12]

We might note in conclusion that this self-consistent model can explain all the behavior which has been observed in experiments with an in-resonator plasma.

I wish to thank S. I. Anisimov and P. P. Pashinin for useful discussions in various stages of this study.

[1)] The shape of the signal is not distorted during the amplification, since the optical system F spreads the intensity $q_+(\tau)$ over the surface of the active element. Over the duration of the lasing, a comparatively small amount of radiant energy is taken from a unit area, and the amplification can be treated as linear.

[2)] A gaseous medium imposes a limitation on the intensity q_+. Specifically, the radiation intensity must not exceed the threshold for picosecond (many-photon) breakdown of the gas,[23] $q^* \gtrsim 10^{13}$ W/cm^2. This limitation rules out consideration of stimulated Brillouin scattering, since the threshold for this scattering is even higher.[24,25]

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