Distributed feedback in lasers with nonstationary pumping; possibility of resonatorless generation in the ultraviolet

S. A. Akhmanov and G. A. Lyakhov

Moscow State University
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We consider certain new applications of distributed feedback (DFB) due to spatial modulation of the gain in laser systems. We investigate nonstationary DFB in gas systems, determine the oscillation transient times, and the energy gain due to the DFB. The possibility of using DFB in lasers for the ultraviolet band is discussed.

1. The purpose of this article is to analyze a number of new possibilities of using distributed feedback (DFB) in laser systems.

In the presence of DFB, the opposing-wave interaction that leads to self-excitation is effected by spatial modulation of the amplification, with a period $\sim\lambda$. It is thus possible to get rid of a mirror-based resonator, a factor of particular importance for short-wave lasers.

We describe below the results of a theory developed by us for nonstationary DFB due to the time-dependent inhomogeneity of the amplification. The concrete results are connected with the analysis of hitherto unstudied transient processes in systems with DFB and with an estimate of the gain in the output energy of gas laser, particularly UV lasers with two-photon optical pumping, resulting from the use of DFB.

2. The simplest realization of DFB is by using inhomo-

geneous optical pumping; the pertinent experiments were performed with dye lasers.[1,2] The most recent investigations have shown that coherent optical pumping is quite effective (it is in fact not inferior to pumping with an electron beam) in high-pressure gas lasers in the IR band[3] and in the vacuum ultraviolet.[4] It seems natural to use DFB in such systems, but for concrete estimates it is necessary to have a nonstationary DFB theory that takes the diffusion of the active particles into account.

3. If we disregard saturation effects, the equations of a laser medium in which the periodicity of the inverted population is due to interference of crossed beams of coherent optical pumping reduce to a system of equations for the amplitudes $A_{1,2}$ of the opposing waves[5]:

$$\left(\frac{1}{v}\frac{\partial}{\partial t} \pm \frac{\partial}{\partial z}\right)A_{1,2} = \alpha(t)A_{1,2} + \beta(t)A_{2,1}, \tag{1}$$

where the gain and coupling coefficients α and β are specified functions of the time.

The boundary and initial conditions for (1) are $A_1(t,0) = A_2(t,l) = A_{1,2}(0,z) = 1$ (l is the length of the active medium, and the values of $A_{1,2}$ are normalized to the rms amplitude of the spontaneous emission).

The system (1) is reduced by the Riemann method to a system of integral equations, for which no solution can be obtained in general form.[6] We succeeded in investigating these equations by using the natural assumption that the coupling is weak, $\beta l \ll 1$. In many cases of practical interest there are no saturation effects at all, and we can determine from (1) not only the increment and time of the transient, but also the energy of the generated pulse.

Assume that α and β are turned on at $t=0$. We then have for the output field amplitude $A_1(t,l) = A_2(t,0) = E(t)$

$$E(t) = F(t)\exp\left[v\int_0^t \alpha(x)dx\right], \tag{2}$$

$$F(t) - \frac{v}{2}\int_{t-l/v}^{t+l/v} \beta(x)F(x)dx = \exp\left[-v\int_0^{t-l/v} \alpha(x)\,dx\right]. \tag{3}$$

If $\alpha(t)$ and $\beta(t)$ are step functions, then it follows from (3) that up to the instant $t = l/v$ there is no DFB and $E(t) = \exp(\alpha v t)$. At $t > l/v$ we have

$$E(t) = \exp(\alpha l)\left\{1 - \frac{\alpha_{\rm thr}}{\alpha}\exp\left[(\alpha - \alpha_{\rm thr})vt\right]\right\}\left[1 - \frac{\beta}{2\alpha}\exp(\alpha l)\right]^{-1}, \tag{4}$$

where the threshold gain $\alpha_{\rm thr}$ is the root of the transcendental equation

$$\exp(\alpha_{\rm thr}l) = 2\alpha_{\rm thr}/\beta. \tag{5}$$

At $\alpha < \alpha_{\rm thr}$ Eq. (4) describes regenerative amplification of the spontaneous noise. If $t \to \infty$, then $A(t) \to \exp(\alpha l)/[1 - (\beta/2\alpha)\exp(\alpha l)]$. At $\alpha > \alpha_{\rm thr}$, self-excitation of oscillations takes place

$$E(t) \approx \exp[\alpha_{\rm thr}l + v(\alpha - \alpha_{\rm thr})t]. \tag{6}$$

The transient time is thus $t_{\rm tr} = l/v + \Delta t$, where $\Delta t = \ln A_{\rm tr}/v(\alpha - \alpha_{\rm thr})$.

4. In UV lasers the gains are relatively small, so that (3) can be used to calculate the generated pulse. For a rectangular pumping pulse we must match together the solutions (4). The corresponding plots are shown in Fig. 1. Of primary interest is the energy gain due to the use of the DFB, namely the ratio of the energy W_1 in the presence of DFB, to the superradiance energy $W_0(\beta=0)$, $\eta = W_1/W_0$. At $\alpha = \alpha_{\rm thr}$ and a pump pulse duration $t_p > l/v$, we have $\eta = (vt_p/l)^2/3$. At $\alpha > \alpha_{\rm thr}$

$$\eta \approx [2(\alpha - \alpha_{\rm thr})(vt_p - l)]^{-1}\exp[2(\alpha - \alpha_{\rm thr})(vt_p - l)]. \tag{7}$$

5. Diffusion of the active particles in a gas medium causes, generally speaking, the grating to be "smeared out," This process is described by an equation for the inverted population in the form

$$\frac{\partial N}{\partial t} + \frac{N - N_0}{T_1} = D\frac{\partial^2 N}{\partial z^2} + \Theta(t)[a + b\cos(2kz)], \tag{8}$$

where D is the diffusion coefficient. If $\Theta(t)$ is the step function, we obtain for the alternating part of N

$$\tilde{N} = b\tilde{T}\cos(2kz)[1 - \exp(-t/\tilde{T})], \tag{9}$$

where $\tilde{T} - T_1/(1 + 4Dk^2T_1)$.

According to (9), the time of establishment of a "grating" in a medium with diffusion of active particles is $\tilde{T} \leqslant T_1$. For a gas at room temperature and atmospheric pressure we have $D \sim 1$ cm^{2}sec^{-1}; at $k \sim 10^5$ cm^{-1} and $T_1 \sim 10^{-8}$ sec we have $\tilde{T} \sim 10^{-2}\,T_1$; in high-pressure lasers, however, $\tilde{T} \sim T_1[D \sim (T^0)^{3/2}/P]$. Plots of the buildup and decay of homogeneous (N^0) and periodic ($\tilde{N}$) inversion are shown in Fig. 2.

6. Let us apply the obtained formula to a molecular xenon laser with two-photon pumping (superradiance was observed in this system by Harris and co-workers[4]).

The Bragg conditions are satisfied here for the second spatial harmonic of the population difference. Inasmuch as the gain is proportional in this case to the square of the pump intensity, an intense spatial harmonic is produced also far from saturation.[5] The threshold gain $(\alpha/l)_{\rm thr} = 4$ at $\beta l = 0.1$ (since $b/a = 1/3$ in the case of two-

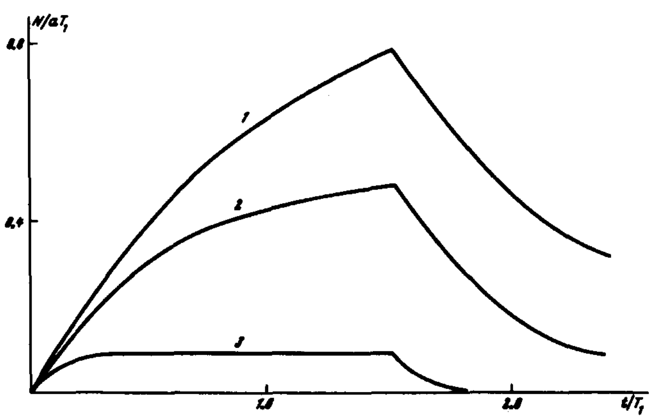

FIG. 1. Waveform of pulse excited in a system with DFB by a rectangular pump pulse of duration $t_p = lx_p/v$: 1—$x_p < 1$, $\beta = 0$; 2—$x_p < 1$, $\beta \neq 0$; 3—$x_p > 1$, $\beta = 0$; 4—$x_p > 1$, $\alpha > \alpha_{\rm thr}$; 5—$x_p > 1$, $\alpha > \alpha_{\rm thr}$.

photon pumping, this corresponds to $\tilde{T} \approx 2\times 10^{-2}\ T_1$, i.e., we are dealing with conditions that are easy to satisfy). Taking values $\alpha l = 5$ and $t_p = 5l/v$, which are close to the experimental ones, we get $\eta \approx 300$. Thus, even under such relatively inconvenient conditions the energy gain due to the use of DFB is large enough. What is quite important is also the corresponding improvement in the spatial coherence of the generated radiation.

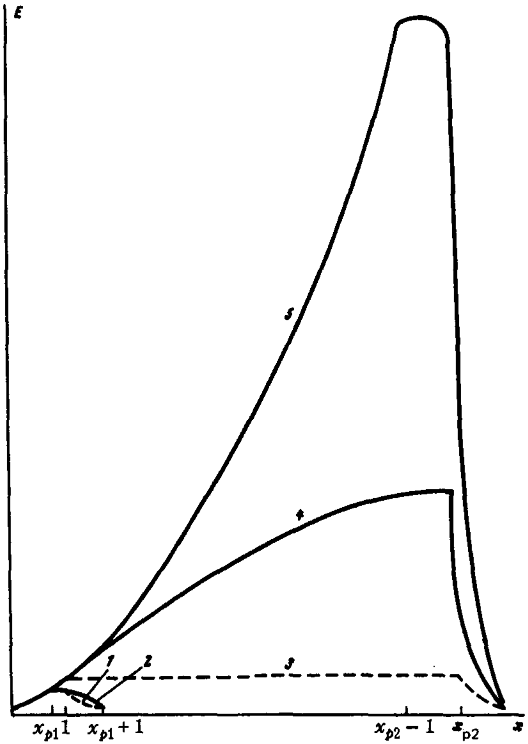

FIG. 2. Buildup and decay of homogeneous (N^0) and periodic (N) inversion in a gas medium: 1—$N^0/\alpha T_1$; 2—$\tilde{N}/\alpha T_1 \cdot 2b\tilde{T} = \alpha T_1$; 3—$\tilde{N}/\alpha T_1$, $10bT = aT_1$. Pump pulse durations $t_p = 1.5\ T_1$.

7. The use of optical pumping, according to[3,4], is particularly promising in high-pressure laser. An attractive feature of the latter is the possibility of tuning the frequency. In a system with DFB, it is possible to tune the frequency by varying the angle between the crossed pump beams.[2]

8. Interference of coherent optical pumping beams is not the only way of effecting DFB. In plasma lasers, the grating can be the result of nonlinear effects excited by a laser in the plasma.

The interaction of opposing beams in amplifying media can be stimulated also by an auxiliary light wave that experiences three- or four-photon coherent scattering in the active medium.

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