SOME PROPERTIES OF A SOLID-STATE LASER WITH A LONG RESONATOR

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Abstract

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SOME PROPERTIES OF A SOLID-STATE LASER WITH A LONG RESONATOR

1. The properties of lasers with a resonator length of the order of several meters have been studied fairly well. The investigation of generation at large resonator lengths L is of great interest in connection with the following effects, which increase as L increases.

Owing to the decrease in the frequency of intermode beats $\Omega = \pi c/L$, as L increases the amplitude of modulation of the population inversion at the frequency Ω increases, which leads to a strengthening of the coupling between the generated modes and to the establishment of a mode-locking regime. Strengthening of the coupling between modes may also lead to ordering of the spiking regime in a solid-state laser.

One should expect a substantial change in the spectral characteristics of solid-state lasers as L increases. The results of works ([1], [2]) concerning the width of the generation spectrum prove inapplicable at larger resonator lengths, since the calculations did not take into account the coupling between modes, which leads to their self-locking, and it was assumed that the active medium completely fills the resonator.

With increasing L, as will be shown below, one can substantially increase the ratio M of the resonator bandwidth $\delta\omega = \omega/Q$ to the frequency interval between longitudinal modes Ω. For sufficiently large L, a substantial overlap of the resonator bands for longitudinal modes occurs ($M > 1$). This should lead to significant changes in the spectrum of natural fluctuations of the amplitudes and phases of the modes. In addition, for $M > 1$, because of the strong overlap of modes one may expect that the properties of such a laser will be close to those of a laser with nonresonant feedback.

2. A substantial increase in the resonator length (up to values of L of the order of a kilometer) can be achieved under laboratory conditions by introducing an optical delay line (o.d.l.) into the laser resonator. The scheme of such a generator is shown in Fig. 1, where 1 and 6 are the laser resonator mirrors; 2 and 3 are the o.d.l. mirrors; 4 is the crystal; 5 is the illuminator with pump lamps. The use of an o.d.l. makes it possible not only to substantially reduce the

Fig. 1

Figure 1: Fig. 1

dimensions of the experimental setup, but also to considerably reduce diffraction losses in comparison with the losses of a linear laser of the same length L.

For a resonator with an o.d.l., in the case of small diffraction losses, the formula for the quality factor has the form

$$Q = \frac{L_{\text{eff}}\omega}{2c\,(\ln 1/r_0 + n\ln 1/r)}; \tag{1}$$

here $L_{\text{eff}} = l_0(2n+1) + l_1 + l_2$ is the effective length of the resonator with the o.d.l.; n is the number of beam reflections at each o.d.l. mirror, and r_0 and r are the reflection coefficients of the external laser mirrors and the o.d.l. mirrors, respectively.

For sufficiently small n, the quality factor grows approximately linearly with increasing L_{eff}, whereas for large n $\left(n \gg \ln\frac{1}{r_0}\Big/\ln\frac{1}{r}\right)$, Q does not depend on L_{eff}. In this case $M \simeq L_{\text{eff}}(1-r)/\pi l_0$ increases linearly with increasing L_{eff}.

3. Some qualitative conclusions about the properties of a long laser can be obtained by considering the interaction of three longitudinal modes (with amplitu-

amplitudes E_{-1}, E_0, E_1 and phases $\varphi_{-1}, \varphi_0, \varphi_1$. For simplicity we shall assume that the central mode E_0 oscillates at the center of the luminescence line and that the active element of length l is located near the external mirror of the resonator. Taking into account the modulation of the population inversion for the phase angle $\psi = 2\varphi_0 - \varphi_{-1} - \varphi_1$, we obtain, for $L \gg l$,

$$\dot{\psi} = \Omega_0 \sin\psi, \qquad \text{where } \Omega_0 = \frac{\omega}{Q}\eta\frac{\gamma^2}{\gamma^2+\Omega^2}\left(1 - \frac{3}{2}\frac{\Omega^2}{\gamma\gamma_{ab}}\right) \tag{2}$$

(γ_{ab} is the width of the luminescence line; $\gamma = \tau^{-1}$; τ is the effective relaxation time of the population inversion; η is the excess of the pump level over threshold). It follows from (2) that the width of the self-locking band Ω_0

Fig. 1

for small lengths $\left(L \leq L_{\text{cr}}^{(1)} = \pi c\sqrt{\frac{3}{2} - \frac{1}{\gamma_{ab}\gamma}}\right)$ decreases as L increases, going to zero at $L = L_{\text{cr}}^{(1)}$. For lengths $L > L_{\text{cr}}^{(1)}$, Ω_0 increases monotonically with increasing L, approaching, at $\Omega \simeq \gamma$, the value $\frac{\omega}{Q}\eta$. Upon passing through $L = L_{\text{cr}}^{(1)}$, the value of the phase difference of the synchronized modes changes (for $L < L_{\text{cr}}^{(1)}$, $\psi = 0$, and for $L > L_{\text{cr}}^{(1)}$, $\psi = \pi$). For a ruby OQG, $L_{\text{cr}}^{(1)} \sim 50$ m, and for a YAG:Nd^{3+} OQG, $L_{\text{cr}}^{(1)} \sim 30$ m.

Analysis of the excitation condition for the three-mode regime shows that it depends only weakly on the coupling between the modes arising from modulation of the population inversion, and approximately has the form: a) for a resonator completely filled with active medium, i.e., for $L = l$ ([1]), $\eta > 3\Omega^2/\gamma_{ab}^2$; b) in the case $l \ll L$

$$\eta = \frac{9}{2}\frac{\Omega^2}{\gamma_{ab}^2}\left(\frac{L}{\pi l}\right)^2 = \frac{9}{2}\left(\frac{c}{l\gamma_{ab}}\right)^2. \tag{3}$$

It is clear from (3) that for $L \gg l$ the excitation condition for three modes does not depend on the resonator length.

The coupling between modes due to modulation of the population inversion substantially affects the distribution of the intensities of individual modes in the lasing spectrum. In the limiting case of sufficiently large resonator lengths satisfying the inequality

$$L \gg L_{\mathrm{cr}}^{(2)} = \pi\sqrt{cl/\gamma}, \tag{4}$$

and under the assumption of three oscillating modes, we obtain for the ratio of the mode intensities

$$k = \frac{E_1^2}{E_0^2} = \frac{2}{9}\left(\frac{\pi l}{L}\right)^2\left(1 + \frac{4\Omega^2}{\gamma^2}\right)\left[\eta - \frac{9}{2}\left(\frac{c}{l}\frac{1}{\gamma_{ab}}\right)^2\right]/\eta. \tag{5}$$

When (4) is satisfied, $k \ll 1$ and continues to decrease with increasing length as L^{-4}. It follows from this that, for large resonator lengths $\left(L \gg L_{\mathrm{cr}}^{(2)}\right)$, the depth of radiation modulation at the frequency Ω should decrease (as L^{-4}), since the intensities of the side modes decrease. For $l = 10$ cm, for a ruby laser $L_{\mathrm{cr}}^{(2)} \sim 600$ m, and for a YAG:Nd^{3+} laser $L_{\mathrm{cr}}^{(2)} \sim 250$ m.

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Note: Figure translations are in progress. See original paper for figures.