ON THE NATURE OF SPIKING LASER GENERATION

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Fig. 1

Figure 1: Fig. 1

Abstract

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ON THE NATURE OF SPIKING LASER GENERATION

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As many years of research have shown, chaotic spiking generation is a fundamental property of solid-state lasers. However, its cause has not yet been established.

In 1966 the author and co-workers discovered (^{1}) that in "traveling-medium" lasers an evolution of spiking generation into continuous generation is observed if, along with the motion of the body along the laser axis, a diaphragm of sufficiently small size is introduced into the resonator. Subsequent systematic studies (^{2}) of the conditions necessary for obtaining spike-free radiation in traveling-medium lasers, the results of which are set out below, make it possible to draw unambiguous conclusions about the nature of spiking laser generation.

Figure 1 shows the scheme of a traveling-medium laser. The velocity of motion v in the active medium (the rod C in the form of a right circular cylinder) relative to the plane mirrors of the resonator in all the cases given below was ~ 50 cm/sec. The optical length of the resonator was about 70 cm. The reflection coefficients of mirrors Z_1 and Z_2, with wedge-shaped substrates, were respectively 99.5 and 85%. The circular diaphragm D was placed several millimeters from mirror Z_2.

Fig. 1

The experiments were carried out on three media at room temperature: ruby, neodymium glass (rods of the LGS-5 type), and $CaWO_4 : Nd^{3+}$ crystals. Spectra were recorded with a DFS-13 spectrograph with a linear dispersion of 4 Å/mm. Time scanning was performed with an SFR-2M ultrafast photorecorder.

Figure 2 presents time-resolved distributions of the laser-radiation intensity at mirror Z_2, obtained in the slit-scan mode (slit width 0.2 mm, with the light beam moving on the photographic film at 750 m/sec). The resolution of the

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

SFR-2M was $\sim 10^{-6}$ sec, so that assertions about the continuous generation observed in the indicated operating mode of the ultrafast photorecorder are valid only in this approximation.

Figure 2a shows the generation of a traveling-medium laser on neodymium glass with a 2 mm diaphragm. It can be seen that it still has a spiking character, with a changing diameter of the generation spot on mirror Z_2. The introduction into the resonator of a smaller, 1.5 mm diaphragm leads to the radiation of the traveling-medium laser becoming continuous in time and spatially unchanged; this is recorded in Fig. 2b. Figure 2c shows that a 1.5 mm diaphragm placed in the resonator of an ordinary laser (with an immobile active medium) does not change the spiking character of the generation.

Fig. 2

Fig. 3

A similar picture is also observed in other active media. In this case, the only difference in the conditions for achieving spike-free emission lies in the maximum size of the diaphragm diameter that ensures a continuous generation regime. Thus, in a $CaWO_4$:Nd^{3+} crystal the diaphragm diameter must be less than 1 mm, and in a ruby crystal less than 0.7–0.8 mm.

In all the cases cited above, the pumping was within 1.3–1.4 of threshold. It should be noted that increasing the pumping does not affect the time dependence of the radiation intensity of traveling-medium lasers, so that the results obtained apply to a broad range of generation-power values.

From the foregoing, two main conclusions follow:

1. If the active medium moves in the axial direction of the laser at a velocity of ~ 50 cm/sec, and its working part is simultaneously limited in the transverse direction, then chaotic spiking emission is replaced by continuous and spatially invariant generation, corresponding in its intensity to the time dependence of the pump power.

2. The minimum transverse size of the working region of the active medium that ensures continuous generation in traveling-medium lasers is specific to the given medium. For neodymium glass it is ~ 1.5 mm, for a $CaWO_4$:Nd^{3+} crystal ~ 1 mm, and for ruby ~ 0.7 mm.

To understand the essence of these regularities, one must take into account that in traveling-medium lasers there occurs a regularization of their emission spectra ([2],[3]). Figure 3 presents time sweeps of the emission spectra. Comparing Figs. 3a and 3b for an ordinary laser and a traveling-medium laser, respectively, we see that, when the active medium moves, the laser emission spectrum becomes continuous (within the resolution of the spectrograph, equal to 0.1 Å), with a smooth distribution of intensity. Conversely, in an ordinary laser the spectrum has a discrete structure, sharply fluctuating in time (from spike to spike).

Keeping in mind that, according to the theory ([4]), the form of the generation spectrum is determined by the relation between the gain and loss curves as functions of the frequency of the laser modes, one may assert that the shape of these curves in ordinary lasers with an immobile solid-state medium fluctuates in time. Specifically, fluctuations of the spatially distributed parameters of the active medium lead to fluctuations of the gain and loss coefficients of individual modes ([3]). It can be shown that, for single-mode generation,

$$\ddot{y} + \alpha/\tau_{\mathrm{n}}\dot{y} + (\alpha - 1)/\tau_{\mathrm{n}}\gamma_0 y = \xi\Omega\cos\Omega t - \beta_1 y^2 - \beta_2 y^3,$$

where $y = \ln[N(t)/N_{\mathrm{st}}]$, $N(t)$ and N_{st} are the numbers of photons of the generated mode, respectively for variable ($\gamma(t)$) and constant (γ_0) loss coefficient ($\gamma(t) = \gamma_0 - \xi\sin\Omega t$); the anharmonicity constants are $\beta_1 = \omega_r^2/2$, $\beta_2 = \omega_r^2/6$, $\omega_r = \sqrt{(\alpha-1)\gamma_0/\tau_{\mathrm{n}}}$ is the resonant (relaxation) frequency of oscillations of the laser intensity. According to ([7]), for certain Ω and $\xi > \xi_{\mathrm{k}}$ the laser intensity may undergo unstable resonant oscillations at the frequency $\omega_0 \sim \omega_r$. The study shows that in ruby lasers the critical values of the relative fluctuations of the loss coefficient with frequencies $\Omega \sim \omega_r$ and $\Omega \sim 2\omega_r$ are $\xi_{\mathrm{k}}/\gamma_0 \sim 10^{-5}$-$10^{-4}$. For fluctuations of the inverse population n_0 created by the pump, the corresponding critical values are $\delta n_0/n_0 \sim 10^{-3}$-$10^{-2}$. Since in the frequency spectrum of fluctuations there is always a resonant or doubled resonant frequency for y, chaotic spiking generation must be observed, and is almost always observed, in solid-state lasers characterized by substantial instability of the parameters of the active medium.

Multimode generation has a spectrum of resonant frequencies $\omega_r^i \leq \omega_r$ ([5]). Since, when the active medium moves, fluctuations of the parameters of the laser system are modulated with frequency $\omega_{\mathrm{k}} = 2\pi 2v/\lambda$ ([3]), it may be assumed that in a traveling-medium laser $\Omega \sim \omega_{\mathrm{k}}$. In the region of velocities $v \sim 10^2$ cm/sec the frequency $\omega_{\mathrm{k}} \sim 10^7$ sec^{-1}, whereas ordinarily $\omega_r \sim 10^5$–10^6 sec^{-1}. Consequently, since $\Omega \sim \omega_{\mathrm{k}} \gg \omega_r \geq \omega_r^i$, multimode generation should be stable.

Since motion in traveling-medium lasers occurs in the axial direction, the influence of spatial fluctuations is not thereby eliminated completely, if the presence of transverse structure in the generated modes is taken into account. Since the spatial inhomogeneity of a mode in the transverse direction has a size on the order of the diameter of the working part of the active medium, any appearance of inhomogeneity of pumping or losses in this direction will affect the transverse structure of the mode. This means that modulation of the gain coefficients and of the Q-factors of the modes will arise and, as a consequence, disruption of their oscillations. Therefore, introducing into the resonator a diaphragm that selects from the pumped region of the active medium a sufficiently homogeneous section stabilizes the oscillatory system of the laser and, in combination with motion of the active medium, reproduces the conditions of sufficient constancy of the parameters of the laser system, which, in accordance with the kinetic theory, leads to stability of multimode generation (5).

The fact that the minimum size of the diaphragm ensuring continuous generation of a traveling-medium laser depends on the nature of the active medium is consistent with the role that the diaphragm plays in eliminating the causes of spiking generation, since the sizes of inhomogeneities vary from medium to medium. And it is no accident that for glass, as the most homogeneous of the media investigated in this work, the largest maximum size of the diaphragm required for continuous generation of a traveling-medium laser was obtained.

Thus, analysis of the conditions for spike-free generation of traveling-medium lasers leads to the conclusion that chaotic spiking generation of solid-state lasers is caused by space-time fluctuations of losses and pumping within the active media.

Until recently, attempts were made to seek an explanation of spiking generation within the framework of a dynamic model that takes into account the interaction of laser modes. However, as follows from the results of the present work, the cause of spiking generation in lasers is nondynamic in nature. It is rooted in statistical wanderings of the principal parameters of the laser system.

It may therefore be considered that the main hypothesis of multimodeness as the cause of spiking generation in lasers has also been refuted. This is also indicated by the experiment of Dzhibladze, Murina, and Prokhorov (6), who showed that single-mode laser generation also has a spiking character (a laser on $CaF_2 : Dy^{2+}$ with such small linear dimensions of the resonator and mirror diameters that only one mode enters into generation).

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