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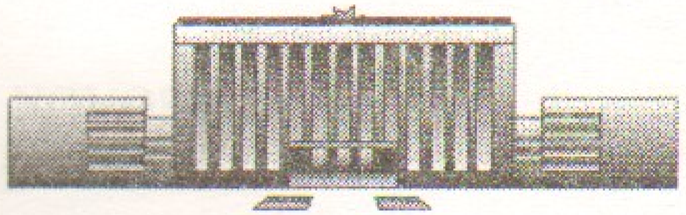
NONLINEAR DYNAMICS AND CHAOS OF THE SELF-ORGANIZATION OF THE GENERATION OF THE SOLID LASERS

Budker INP 97-84



Novosibirsk

Nonlinear dynamics and chaos of the self-organization of the generation of the solid lasers

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Abstract

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In the present paper we analyse the results of our experimental investigations of nonlinear dynamics of the free generation on the ions of chromium and neodymium in the varios media. The results of the theoretical investigations of the role of the dynamic Stark effect and stochastic factors are produced in the generation forming.

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1. INTRODUCTION

Free running lasing of solid-state Nd and Cr lasers in various active media was and is being studied in a great deal of works on experimental devices having very different technical characteristics. The reasons for arising undampled pulsations were mainly discussed on the basis of experimental results which were obtained on various, often outdated devices and, as a rule, under non-controlled conditions. The present paper presents and dicusses the experimental results of the the studies concerning the dynamics of free-running lasing of Cr and Nd lasers equipped with flat mirrors [1-7]. These results were obtained on the same experimental device under identical experimental conditions, with rough mechanical disturbances of the cavity eliminated.

2. EXPERIMENTAL DEVICE

The optical components of the cavity are positioned on rigid and massive tables, with the units for precise alignment. The parasitic selection of longitudinal modes was completely removed. The mirrors were deposited on glass 2°-wedged substrates. Active media were pumped by pulsed tubes in a monoblock quarts pump. The pumping pulse was shaped closely to a rectangular one. The energy characteristics of the laser radiation were recorded at one and the same duration of the pumping pulse 0.25 ms. The dependences on the diagrams having been constructed for energies emitted per unit volume of an active media: E_g/V_g. Active media (except rubin cooled by distilled water) were cooled by a liquid filter in order to cut off the UV radiation of pumping. The filter was pumped through a constant-temperature cabinet thermostat maintaining the temperature in active media with an accuracy of about 0.1°C.

3. EXPERIMENTAL RESULTS

3.1. Spectral-time characteristics of radiation Cr-lasers

Under usual conditions, free-running generation of TEM_{ooq} modes in rubin (Fig.1,b), alexandrite (Fig.1,c) and Cr:GSGG (Fig.1,d) lasers with flat mirrors always occurs in the regime of undamped spiking .

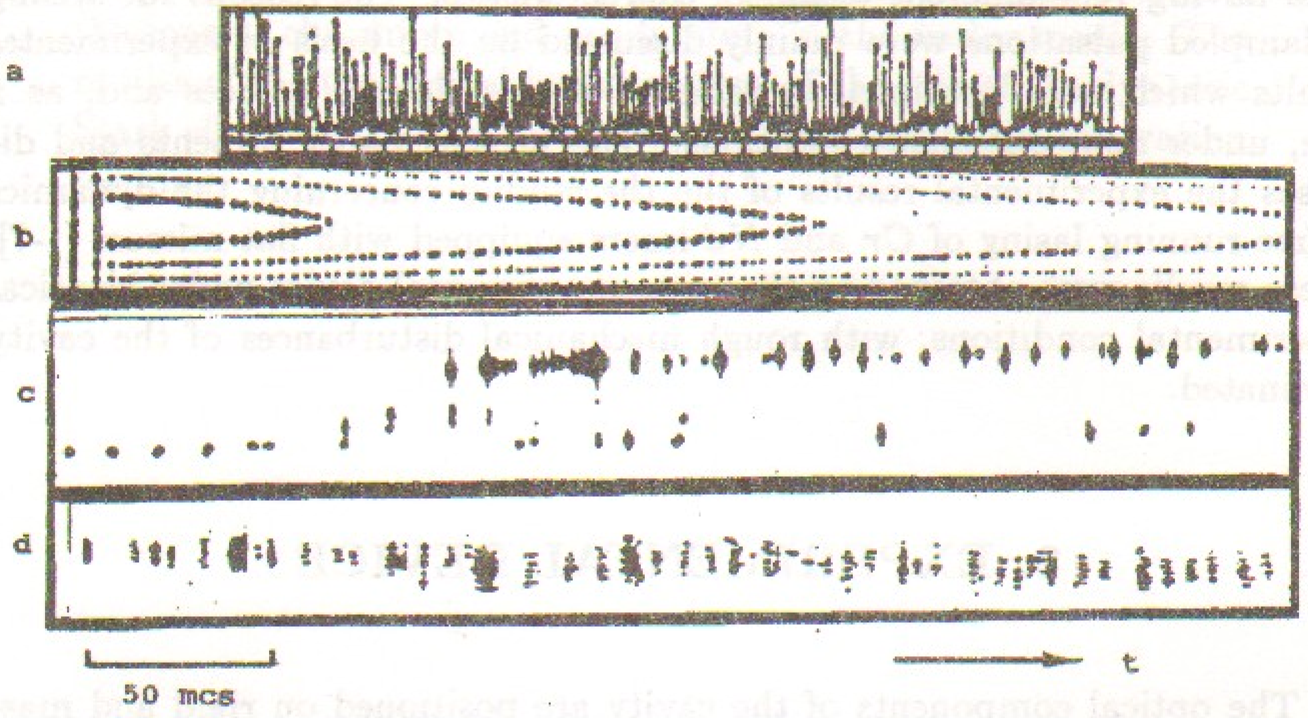

Figure 1: The parameters of lasing of Ruby(b), alexandrite (c) and GSGG:Cr (d) lasers with the influence of technical perturbations of the cavity removed: a – oscillogram of radiation intensity, labels are for 20 μs; b–d — time scanning of the radiation spectrum.

In the Ruby laser, in the presence of weak perturbations the radiation pulsations were irregular both in time and in amplitude, with periodic (in

$50 - 100\mu s$) shifts of the radiation wavelength to the short-wave spectral range (Fig.1,b). A single-directed shift of the generation wavelength to the long-wave spectral range throughout the pulse, with regular-in-time radiation pulsations was possible only after the elimination of the technical disturbances of the cavity by the above technique. Here, one longitudinal mode is excited during every spike (except for the three first ones), and the jump inthe wavelength $\Delta\lambda$ is determined, from spike to spike, by the ratio of the cavity length L to the active rod length $l(\Delta\lambda = (L/l)\delta\lambda_m$, where $\delta\lambda_m$- is the spectral interval between neighbouring longitudinal modes). The rate of wavelength self-sweaping was several times higher than the rate of thermal drift of the amplification line and linearly-dependent on the exceeding of the pumping E_p over the threshold pumping. At $E_p = 3E_t$ it was $0.12nm/ms$. The achieved mode of lasing for rubin lasers has found broad use in high-resolved express analysis of atomic and molecular objects. In the mode of undamped spiking, we failed to stabilize the radiation wavelength even with the use of a high-quality selector-etalon Fabri-Perot. Here the jumps of the wavelength from spike to spike took place within the transmission band of the selector and the integral radiation spectrum narrowed to 5 nm.

The nature of the development in time of the generation spectra for alexandrite (Fig.1,c) and Cr:GSGG (Fig.1,d) lasers depended on the crystal temperature, the presence of parasitic selection of modes and on inactive absorption at the radiation wavelength. The presence, in the cavity, of even a very weak distrimination of modes, which is introduced by illuminated crystal edges, led to the appearance of a fine discrete structure of the spectrum (Fig.1,d). Such a structure disappeared, when the selection of longitudinal modes was completely removed, i.e. when the crystal edges were cut at the Brewster angle. In this case, the oscillating structure of the radiation spectrum was observed on the background of the continuous spectrum (Fig.1,c). The spectral interval betwen the neighbouring components of the oscillating spectrum was $1.5nm$ and depended, in the range under study, on the temperature of alexandrite.

In the alexandrite laser, lasing starts at a wavelength of $750nm$ (Fig.1,c) and then, with a delay in time being dependent on the exceeding of the pumping over the threshold one, lasing successively takes place with the spikes at 745 and $734nm$ wavelengths. When alexandrite worked a prolonged period of time under the conditions of incomplete cutting off of the UV pumping radiation at a temperature over $70°C$, the lasing threshold at $\lambda = 734nm$ increased considerably and the lasing at this wavelength stopped. At low ($\sim 10°C$) temperatures and high levels of pumping ($E_p \geq 8E_t$) the integral radiation spectrum was $\sim 40nm$ wide.

In the Cr:GGSGG laser, a shift of the spectrum was observed during lasing. It is due to a high rate of thermal drift of the amplification line and also by a strong heating of the crystal because of its low thermal conductivity (Fig.1,d). The measured average rate of thermal drift of the amplification line in this laser was $0.13nm$/degree within $10 - 90$°C. When the pumping was twice as large as the threshold one, the maximum in the lasing spectrum shifted by $5nm$ for 200 ms. This corresponds to crystal heating by 40°C. Unlike the Cr:GSGG laser, the rate of thermal drift of the amplification line of alexandrite increased linearly from 0.01 to $0.13nm$/degree in the $10-50°C$ and $50 - 90°C$ ranges of temperature variation, respectively. When a prism dispersion resonator with an angular dispersion of $\sim$3 min$/nm$ is used, the instantaneous and integral spectra of radiation of Cr:GsGG and alexandrite lasers narrowed to $0.8nm$. The radiation wavelength was retuned within $700-800nm$ in the alexandrite laser and within $740-830nm$ in the Cr:GSGG laser.

In the case of a forced smoothing of the longitudinal field inhomogeneity in rubin by means of the compensated phase modulation (CPM) free-running generation of TEM$_{ooq}$ modes always occurs in stable quasi-stationary regime (Fig.2).

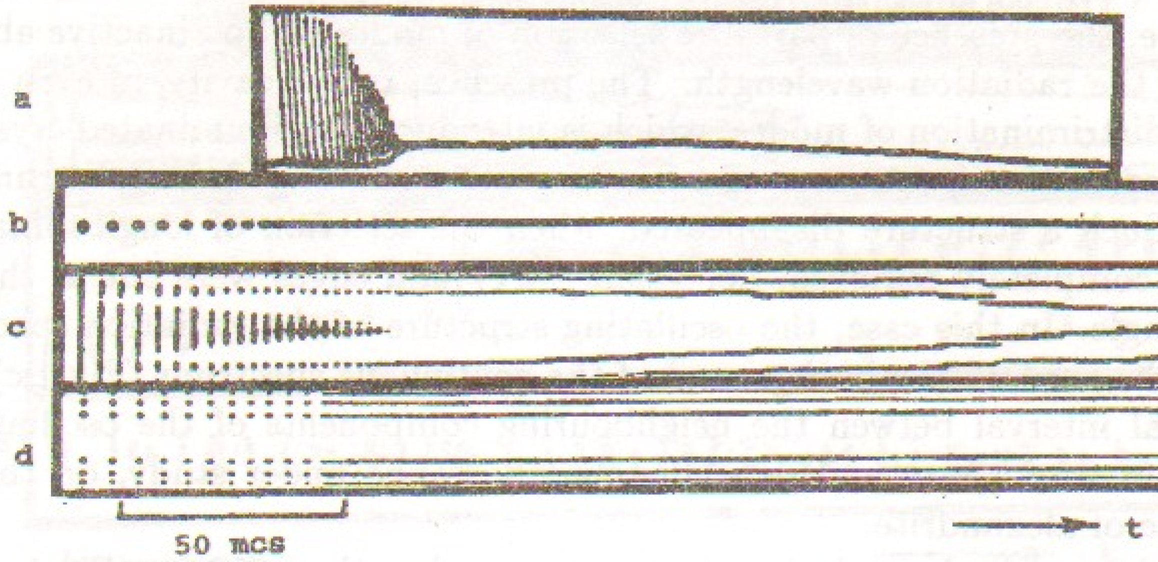

Figure 2: The parameters of TEM$_{ooq}$ mode generation by a Ruby laser with flat mirrors when smoothing the longitudinal inhomogeneity of the field by means of the compensated phase modulation and without the technical disturbances of the cavity. $E_p = 3E_t$, the dispersion regions of Fabri-Perrot interferometers are 29 pm (c) and $8pm$(d).

In the first spike a wide radiation spectrum is excited. It depends on both the shape of the amplification line and the difference between the pumping and threshold pumping values (Fig.2,c). The narrowing in this case occurs for the amount of time one order of magnitude longer as compared to the conventional conditions and is due only to the dispersion created by the shape of the amplification line, by the law defined by the relation $\Delta\lambda_g = \Delta\lambda_o\sqrt{t_p/t}$ $\Delta\lambda_o$- is the spectrum width in the first spike and t_p is the lifetime of a photon in the cavity. After the transient process finishes and the quasistationary regime reaches the spectral line displays, on some sections, inertia to the thermal drift of the amplification line: the spectrum-stable single-frequency lasing is observed in regular $50 - 100ms$ intervals. It is worth to note that in the lasing process the mode alteration, which is caused by the thermal drift of the amplification line, takes place adiabatically and is not accompanied by the radiation intensity pulsations.

In the quasi-stationary mode of lasing, the selection of longitudinal modes becomes much more efficient, i.e. at the same parameters of the selector, the radiation spectrum is easily narrowed to a single longitudinal mode and stabilized with respect to the spectrum within one intermode interval (Fig.2,d). The influence of the field inhomogeneity in active medium on the nature of lasing is clearly seen when the process of its CPM-assisted smoothing was started and finished during the lasing pulse. If the CPM was switched with a delay in time relative to the onset of a pulse, the transition from undamped spikes to quasi-stationary lasing was always observed. If smoothing was stopped after reaching quasi-stationary lasing, the inverse transition from quasi-stationary lasing to the mode of undamped spiking took place.

The stability of the quasi-stationary mode of lasing and the efficiency of the selection of longitudinal modes increased even more when the longitudinal field inhomogeneity was smoothed under the conditions of passive negative feedback . However, the adiabatic alteration of modes in the course of lasing also occurs in this case. Here the alteration is due to the retuning of the natural modes of the cavity because the active rod is heated and, as a result, the length of the cavity increases . The width of the integral spectrum of quasi-stationary lasing the rubin laser was $0.14pm.A$ smooth retuning of the wavelength of the R_1 line of rubin in single-frequency mode in the $0.5nm$ range was obtained . The reproducibility of the lasing wavelength equaled $0.5pm$ at a stabilized temperature of rubin and that of the selector was $\sim$1°C. The divergence of the radiation was close to the diffraction one, and the radiation energy in a $0.8ms$ pulse was equal to 0.1 J.

3.2. Spectral-time parameters of lasing *Nd*-lasers

In *Nd* lasers free-running lasing of TEM_{ooq} modes in all media under study always occurs in quasi-stationary regime (Fig. 3). This is achieved under usual conditions, without the forced smoothing of the longitudinal inhomogeneity of the field, but with the use of the above procedure for alignment of the cavity units. As we have already mentioned, this procedure enables us to eliminate the influence of rough technical disturbances of the cavity. At any pumpings, a steady quasi-stationary multimode lasing is reached after the transient process. In this case, the spectral width is determined by the nature of the broadening, the width of the amplification lines of active media and by the exceeding of the pumping value over the threshold value. In the quasi-stationary regime, stable single-frequency lasing is achieved in all media under study (Fig.3,h) and a smooth retuning of the radiation wavelength within the width of the amplification lines of these media.

In *Nd* lasers with YAG, BLN and KGV crystals which are highly homogeneous and possess high thermal conductivity, the stable quasi-stationary lasing of TEM_{mnq} modes is very simple to achieve, under the same experimental conditions. But the modes have small transverse indices ($m, n < 10$) in this case. In the transient process, the transverse modes with different indices alternate. Because they have different excitation volumes, and hence amplification, the transient process is of the irregular nature. In the absence of mode selection, the spectral width of quasi-stationary lasing coincides with that of TEM_{ooq} modes. With the use of a dispersion cavity, it was easy to obtain stable single-frequency quasi-stationary lasing of TEM_{mnq} modes. With increasing the indices of tranverse modes and with decreasing the length of the cavity, the spatial competition of the modes increases. This leads to the alternation of the transverse modes during the whole pulse of lasing and also to undamped pulsations of the radiation intensity.

We also designed single-frequency *Nd* ions lasers which are capable of lasing in the quasistationary regime whose pulse duration is 0.1–1.0 *ms* and the radiation energy in the pulse is 0.1–1.0 J. Besides, their radiation wavelength can be smoothly retuned in the 1050–1080 *nm* range.

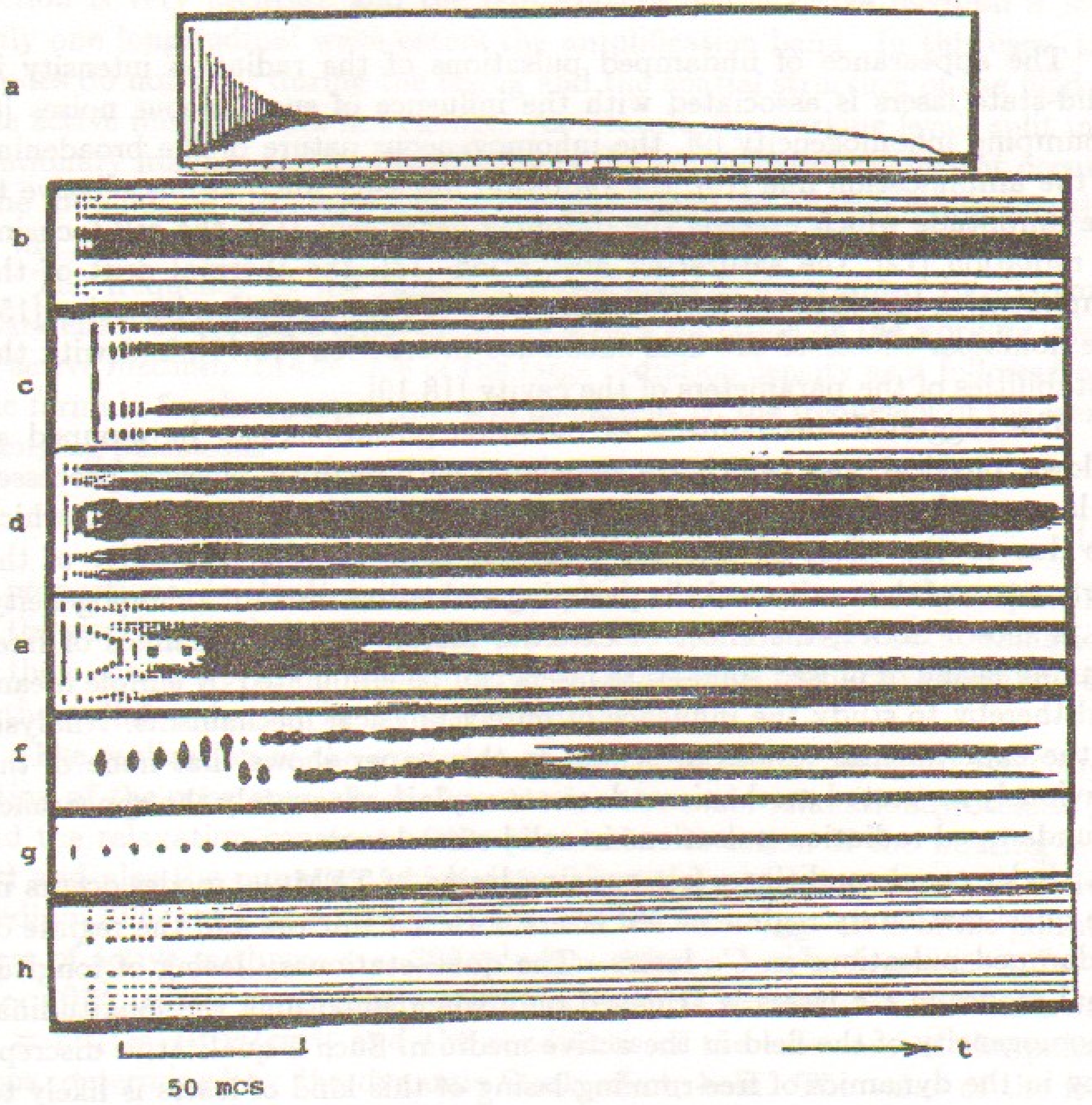

Figure 3: The parameters of TEM_{ooq} mode generation by ions *Nd* in KGV (b), BLN (c), GSGG:Cr (d), YAG (e), soda-lime (f) and phosphate (g) with flat mirrors under usual conditions and with the influence of technical perturbations of the cavity removed, h – spectrum of generation without the selection of longitudinal modes. The dispersion regions of the Fabri-Perrot interferometers: 190 (b), 286 (c), 113 (d), 70 (e) and 20*pm*(h)

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4. DISCUSSION

The appearance of undamped pulsations of the radiation intensity in solid-state lasers is associated with the influence of spontaneous noises [8] , pumping inhomogeneity [9], the inhomogeneous nature of the broadening of the amplification line [10], the radiation intensity fluctuations relative to the amplitude which exceeds the damping decrement [11], the self-focusing of radiation [12], the saturating absorption [13], the thermal drift of the amplification line [14], the periodic structure of the population inversion [15], the nonlinear effects of the field-substance interaction [16,17], and with the instabilities of the parameters of the cavity [18,19].

The suggested mechamisms of radiation pulsations can be grouped as follows: physical ones, which are associated with intrinsic physical processes in lasers rather than with a concrete device and technical processes, which are due to the effect of external technical factors - the instability of the parameters of the cavity and the pumping and active medium inhomogeneity. As is shown above, the effect of external factors on the dynamics of free-running lasing of pulsed solid-state lasers can be eliminated by simple means and thereby to study the influence of purely physical mechanisms. Analysis of the experimental results presented in this paper shows that none of the previously suggested mechanisms does not explain adequately the appearance of undamped radiation pulsations in solid-state lasers.

Under equal conditions, free-running lasing of TEM_{ooq} modes occurs in the quasi-stationary regime in Nd lasers with flat mirrors and the regime of undamped pulsations in Cr lasers. The quasi-stationary lasing of longitudinal modes in Cr lasers is achieved only when smoothing the longitudinal inhomogeneity of the field in the active medium. Such a qualitative discrepancy in the dynamics of free-running lasing of this kind of lasers is likely to be due to a considerable difference in the structure of the working levels of ions. If the emission of Nd ions is determined by the electrons of the $4f$ shell, which is deeply screened by two electron shells $5s$ and $5p$, the emission of Cr ions depends on the electrons of the outer $3d$-shell. The electromagnetic field of laser radition, which appears in the active medium, will, therefore, act only on Cr ions, giving rise to an additional splitting of the working levels of ions due to the dynamic Stark effect. In the spatially inhomogeneous field of the active medium, which is created by the standing wave whose spatial structure changes as a result of the modes alteration in the course of lasing, this effect can lead to the modulation in time of the amplification coefficient of an active medium and to the undamped pulsations of radiation intensity.

No modulation can arise, when the excitation conditions are satisfied only for one longitudinal mode. These conditions take place when the modes selection is very accurate and the temperature of the active medium is low: only one longitudinal wave enters the amplification band. In this case, the modes do not alter during the lasing and the spatial structure of the field in the active medium does not change. As a result, the working levels split in a stationary manner and no modulation of the amplification coefficient occurs. The modulation also disappears when smoothing the spatial inhomogeneity of the field in the active medium.

The frequency of the radiation pulsationns is determined by dynamic Stark effect by resonant influence of the strong radiation on the working levels of active medium. In the case of the large radiation density as it follows from the formula for the spectral Einstein coefficient B, the frequency of the weak damping pulsations

$$\nu = \sqrt{\mu\sigma B U_c} \tag{1}$$

is proportional to the Rabi frequancy, which characterizes the light splitting of the working levels by the resonant field. Here $\mu\sigma$ are losses of the radiation in the resonator, μ is the filling degree of the resonator by active medium, U_c is the radiaton density in the stationary regime.

The realization of the existence of the pulsations depends on the correlation of the constants which characterize the main relaxation processes (γ and the relaxation constant of the population inversion of the working levels) and also the pumping which determines the excitation degree of active medium. The ruby laser is characterized by the following values of the parameters of active medium: $\gamma \sim 300c^{-1}$; $B \sim 600 erg^{-1} cm^3 c^{-1}$; $\sigma \sim 5 \cdot 10^9 s^{-1}$; $\mu \sim 10^{-1}$; $\mu B U_c \sim \gamma$. There with the value U_c corresponds the intensity $I_c = cU_c \sim 10^4 w/cm^2$, and the conditions of the existence of the pulsations, determined by the dynamic Stark effect, hold. The value of the frequency of the pulsations ν and their damping constant $\tilde{\gamma}$ are estimated as follows: $\nu \sim 1.2 \cdot 10^6 s^{-1}$; $\tilde{\gamma} \sim 1500 s^{-1}$. Hence the pulsation period equals $T = 2\pi/\nu \sim 5 \cdot 10^{-6} s$, and during their characteristic damping time $\tilde{\gamma}^{-1}$ approximately 10^2 oscillations occur. This is in a good agreement with experiment.

For the neodymium laser we have $\gamma \sim \mu B U_c \sim 4400 s^{-1}$; $\sigma \sim 3 \cdot 10^8 s^{-1}$; $\mu \sim 10^{-1}$. In this laser the value of the constant $\tilde{\gamma}$ increases ($\tilde{\gamma} \sim 2 \cdot 10^4 s^{-1} 4$) with the conservation of the pulsations frequency. Thus in the laser with active medium of this type the pulsations regime transits to the stationary generation regime very quickly. This weakening of the influence of the dynamic Stark effect on the generation is related to the screening of the working levels by the outer electron shells.

The properties of the solid lasers generation are determined essentially by stochastic processes, and their investigations become particular actual last time. We consides the stochastic model of the transient processes in the laser generation. The dependence between the generation conditions and the fluctuations of the realization time of the transient processes in the approximation of the weak saturation.

From the viewpoint of practical applications, of main interest are fluctuations of the time of the increasing of the photon concentration up to some selected level η. Thiese fluctuations are characterised by the density of the appearance probability of a specific number of photonsd $\tilde{W}(t)$ in the time period from t to $t + \Delta t$.

The average time $\tilde{t}$ of the appearance of the prescribed photon concentration n, determined by the level η, and the dispersion σ_t^2 of this time are equal to respectively:

$$\tilde{t} = t_m + \frac{C}{\alpha_2}; \tag{2}$$

$$\sigma_t^2 = <(t - \tilde{t})^2> = \frac{\pi^2}{6\alpha_2^2}. \tag{3}$$

The balance equation describing the nonlinear stage of the generation has the form

$$\frac{dn}{dt} = (\alpha_2 - \gamma_0 n)n = G. \tag{4}$$

Here $C = 0.577...$ is the Euler constant; α_2 is the value of the effective coefficient of the radiation amplification α beyond the generation threshold; G is the average value of the generation velocity; has the form

$$t_m = \frac{1}{\alpha_2} ln(\eta \frac{n_s}{\tilde{n}_o}) \tag{5}$$

is the time when the distribution function $\tilde{W}(t)$ reaches its maximal value

$$W_m = \frac{\alpha_2}{e} \tag{6}$$

where $n_s = \frac{\alpha_2}{\gamma_0}$, $\tilde{n}_0 = n_1 + n_2$; $n_{1,2}$ is the initial photon concentration below (beyond) the generation threshold.

The equation for $\tilde{W}(t)$, expressed by means of the parameters W_m and t_m, has a simpler form

$$\tilde{W}(t) = W_m \exp\{-\alpha_2(t - t_m) + 1 - \exp[-\alpha_2(t - t_m)]\}. \tag{7}$$

It is possible to determine more accurately the condition for rapid connection of the excitation source taking into account the time fluctuations of the establishment of the stationary regime. It is evident that for this to happen, the variation time of the parameter α should be much smaller than $\tilde{t} \sim \alpha_2^{-1}$.

The relative fluctuations of the establishment time of the given photon concentration, determined in accordance with (2) and (3), by the relation

$$\frac{\sigma_t}{\tilde{t}} = \frac{\pi}{\sqrt{G}[C + ln(\eta n_s/\tilde{n}_0)]}, \tag{8}$$

at fixed values of $\tilde{n}_0$ and η decrease in a logarithmic manner with an increase of the stationary concentration n_2.

For the removal of the concentration fluctuations of the photons it is necessary to stabilize the number of the initial particles up to the generation excitation and on the initial excitation stage with the duration of the order α^{-1}.

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Budker INP 97-84

Ответственный за выпуск А.М. Кудрявцев
Работа поступила 28.10. 1997 г.

Сдано в набор 29.10.1997 г.
Подписано в печать 29.10.1997 г.
Формат бумаги 60×90 1/16 Объем 1.0 печ.л., 0.9 уч.-изд.л.
Тираж 100 экз. Бесплатно. Заказ N° 84

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН,
Новосибирск, 630090, пр. академика Лаврентьева, 11.