Experimental investigation of the generation kinetics of a ruby laser with a nonstationary resonator

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A ruby laser with a modulated resonator length is investigated experimentally. Regular kinetic conditions are attained in a plane-and-sphere resonator laser. In the case of a plane-parallel resonator a sequence of pulses is observed for which the repetition frequency is equal to the modulation frequency. The experimental results are discussed and compared with available data.

INTRODUCTION

One of the important applied problems of quantum electronics is that of stabilizing the spectral and temporal characteristics of the emission of solid-state lasers in cw and quasi-continuous lasing regimes. Theoretical and experimental investigations[1-4] have shown that the main physical factors that determine the temporal and spectral characteristics of the radiation are relaxation processes, the longitudinal and transverse inhomogeneities of the population inversion in the working medium, and random mode selection in the optical resonator. Great interest attaches therefore to an investigation of the dynamic methods of stabilizing the characteristics of the laser emission[5-7], one of which is to use nonstationary resonators in the laser.

Ruby lasers with nonstationary resonators have been the subject of a number of studies[8-10], but their results are not sufficient to clarify the entire picture of the generation kinetics in the laser. Thus, in[8] they obtained a regime of regular damped pulsation of ruby-laser emission by using strong low-amplitude flexural vibrations of the resonator reflecting surface, after satisfying a number of additional requirements, which reduced to creating "strong mode degeneracy" conditions[9]. Groups of spikes following one another at double the frequency of motion of the reflecting surface, were obtained in[9] at large amplitudes and low oscillation frequency. Finally, a regime of regular undamped pulsations was obtained in[10]. Principal attention of the investigators was focused in[8-10] on the temporal characteristics of the intensity of the laser emission and there are practically no data on the kinetics of the generation spectrum or on the changes in the distribution of the radiation field. Nor are there any data on the influence of the parameters of the optical resonator (length, radius of curvature of the mirror) on the generation kinetics of a laser with a nonstationary resonator.

The present paper is devoted to the kinetics of the generation of a ruby laser with a nonstationary optical resonator. (A resonator is called "nonstationary" if one of its reflecting surfaces executes reciprocating motion.)

EXPERIMENT

We used in the experiment ruby rods of medium quality (7 mm diam and $l = 70$ mm) with polished lateral surfaces. The end faces of the rod were perpendicular to the crystal axis. The working rod was placed in a single-lamp illuminator (IFP-800 lamp) with maximum dense packing and with water cooling. The accuracy of the setting and the stability of the pump level amounted to ~1%. The pump energy was varied during the course of the experiments from P_{thr} to $2P_{thr}$. The illuminator and the mirrors were placed on an optical branch, making it possible to regulate the length of the optical resonator from 0.35 to 1.5 m. The output mirror of the resonator was either flat or spherical (R_{sph} = 0.5, 1, and 2 m). The maximum resonator length in the latter case was $\leq 0.9R_{sph}$. The reflection coefficient of the output flat mirror ranged from 0.4 to 0.95. The total-reflection flat mirror of the optical resonator was an integral piezo-optical modulator (IPM)[11]. We used in the experiments IPM with substrate resonant frequencies from 0.3 to 3 MHz. The amplitude of the oscillations of the reflecting surface of the IPM varied during the course of the experiments from 0 to 0.7 μ. The amplitude was monitored and measured with a two-beam interferometer. The time variation of the laser intensity was monitored with a photomultiplier and OK-17 oscilloscopes used to register the entire generation pulse, and with the aid of an S1-11 oscilloscope to investigate the fine structure of the emission (spike duration, repetition period). The distribution of the emission in the far zone was investigated with a high-speed SFR-2M camera. The kinetics of the spectrum were investigated during the course of lasing by recording the scanned image of a Fabry-Perot interferometer with a dispersion range 1.67 cm^{-1} and a resolution 0.05 cm^{-1}. The emission energies were compared by integrating the signal at the photoreceiver output.

EXPERIMENTAL RESULTS

A. Plane-and-sphere resonator. In the case of a stationary resonator, the laser emission takes the form of irregular pulsations that fluctuate greatly in ampli-

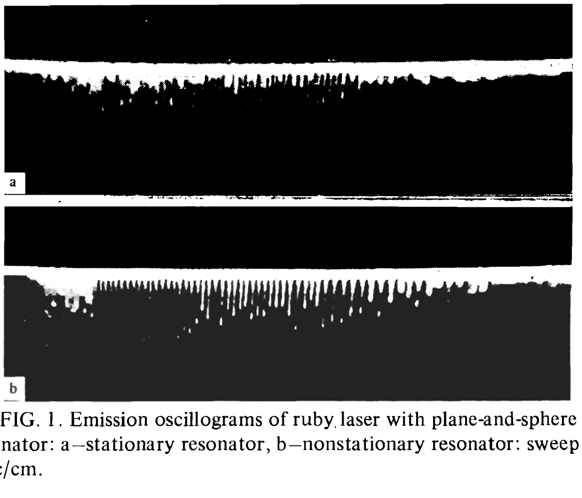

FIG. 1. Emission oscillograms of ruby laser with plane-and-sphere resonator: a—stationary resonator, b—nonstationary resonator: sweep 125 μsec/cm.

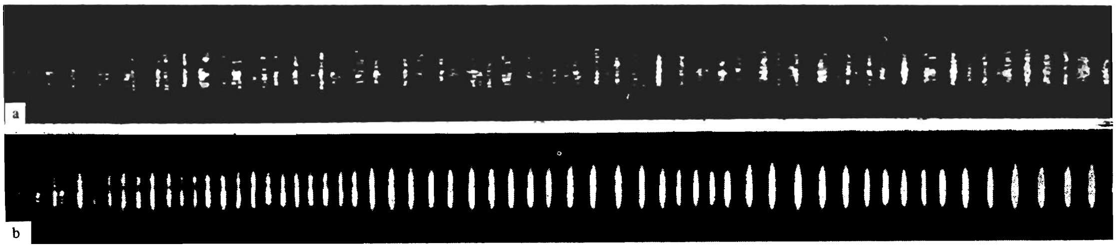

FIG. 2. Time scans of the radiation distribution in the far zone for a ruby laser with plane-and-sphere resonator: a—stationary resonator, b—nonstationary resonator; sweep 25 μsec/cm.

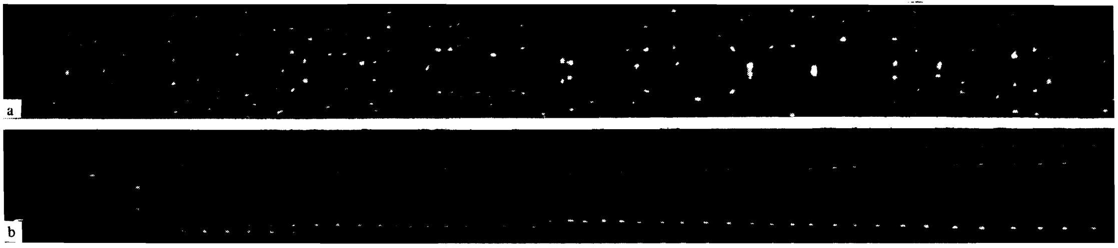

FIG. 3. Time scans of interference patterns of ruby laser radiation with plane-and-sphere resonator: a—stationary resonator, b—nonstationary resonator; sweep 25 μsec/cm.

tude and in repetition frequency. The pulsation envelope duplicates the variation of the pump pulse—see Fig. 1a. When the IPM excitation voltage is turned on, a change takes place in the temporal and spectral characteristics of the radiation. As seen from Fig. 1b, the radiation pulsations become regular. The repetition frequency (<100 kHz) is much lower than the average frequency of the spikes in the free-generation regime. At the same time, the emission intensity in each individual spike is increased. With increasing pump energy, the spike repetition frequency increases, and the duration of the spikes decreases. The form of the laser spike envelope coincides qualitatively with the waveform of the pump pulse. The threshold pump level and the total emission energy at the laser output do not depend on the amplitude of the IPM oscillation.

As seen from Fig. 2b, in one generation spike, in a laser with nonstationary resonator, there are simultaneously excited many transverse modes, in comparison with the non-modulated regime (Fig. 2a). The distribution of the radiation field in the far zone varies little from spike to spike during the entire time of laser generation. The beam divergence increases to 70′.

It is seen from the scanned emission spectrum of a laser with nonstationary resonator (Fig. 3b) that at the start of the generation there are excited several modes with different longitudinal indices. This is followed by a fast decrease (within <100 μsec) of the width of the generation spectrum to a value <0.05 cm^{-1}. At the same time, the average laser frequency shifts towards larger wavelengths by an amount 0.5 cm^{-1}, after which it remains constant during the subsequent generation process, but a monotonic increase of frequency from spike to spike is observed in this region, followed by a jumplike return of the generation frequency to the mean value. This return to the mean value spans several spikes, in which simultaneous generation of two spectral components separated by an interval of 0.4 cm^{-1} takes place. The foregoing emission characteristics are consistently reproduced when the pump energy is increased from threshold to maximum.

The regular kinetics regime is easiest to attain when the active medium is placed near the IPM. When the ruby is brought closer to the output mirror, the emission becomes less regular, and to restore the emission it is necessary to increase the IPM vibration amplitude. When the curvature radius of the output mirror is increased to 2 m it becomes necessary to increase the IPM vibration amplitude in order to obtain the same regularity of laser emission. Transverse-mode selection effected by introducing diaphragms with openings from 1 to 3 mm into the resonator leads to irregular kinetics of the lasing.

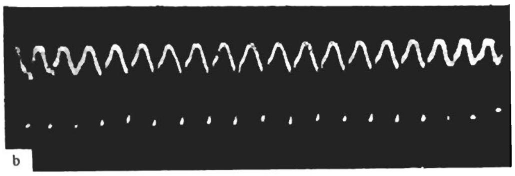

FIG. 4. Emission oscillogram of ruby laser with plane-parallel nonstationary resonator. Sweep duration 50 μsec.

B. Plane-parallel resonator. As seen from Fig. 4, the emission of a laser with a plane-parallel nonstationary resonator constitutes a sequence of spikes that are rigidly connected, in phase and frequency, with the motion of the IPM reflecting surface (sinusoid at the base of the spikes in Fig. 4). The amplitudes of the spikes are much larger than in the case of the free-generation regime. However, the amplitude fluctuations typical of the free-generation regime continue to exist. The spike duration in this lasing regime is less than 0.1 μsec and is practically independent of the modulation frequency. The modes excited in a laser with a plane-parallel resonator have lower transverse indices, as is clearly seen from the field distribution in the far zone (Fig. 5a). When the resonator length is modulated (Fig. 5b), the angular divergence decreases further, indicating an even greater suppression of modes with transverse indices in the nonstationary plane-parallel resonator. At the same time, a study of the interference patterns has shown that no essential changes occur in the generation spectrum.

The processes described above are regularly reproduced when the reflection coefficient of the output mirror is varied from 0.4 to 0.95. An increase of the pump level

FIG. 5. Time scan of radiation distribution in far zone of a ruby laser with plane-parallel resonator: a—stationary resonator, b—nonstationary resonator; sweep duration 150 μsec.

leads to an increase of the threshold of the reflecting-surface vibration amplitude at which a transition to synchronous generation takes place.[1)]

DISCUSSION OF RESULTS

A. Plane-and-sphere resonator. The presented experimental data can be satisfactorily explained with the framework of the existing theories of ruby-laser generation kinetics[1-3,5], and coincide in many respects with the experimental results obtained in[5] after removal of the spatial inhomogeneity of the population inversion.

The reciprocating motion of the reflecting surface leads to motion of the mode field relative to the active medium, and the displacement is maximal near the moving mirror and decreases as the immobile mirror is approached. This explains why the effectiveness with which the modulation of the resonator length affects the generation kinetics depends on the position of the active medium in the resonator. To smooth the longitudinal inhomogeneity of the population in version, the velocity of the mode field relative to the working medium should exceed 0.3 m/sec[6] at a double displacement amplitude equal to $\lambda/2$. These conditions are satisfied at a reflecting-surface oscillation frequency ~0.3 MHz. At the same time, owing to the change of the relative position of the reflecting surfaces in the laser generator, the parasitic mode selection becomes smoothed out.

The field distribution in the far zone becomes uniform in this generation regime. This uniformity shows that many modes with different transverse indices are generated simultaneously. In this case excitation of a large number of transverse modes and the effective elimination of the transverse inhomogeneity of the inversion are due to frequency modulation of the laser radiation[5]. The sideband components of the spectrum of the frequency-modulated signal play in this case the role of the external "primer" in the excitation of modes with large transverse indices. When the amplitude of the reflecting-surface displacement is $\geq\lambda/4$, the spectrum of the frequency-modulated oscillation spans the entire intermode interval and ensures excitation of all the modes corresponding to the given section of the luminescence line of the active medium.

Thus, modulation of the resonator length gives rise to simultaneous smoothing of the longitudinal and transverse inhomogeneities of the population inversion and eliminates the parasitic mode selection. It is the joint action of these factors which leads to the regular kinetics of the ruby-laser generation.

The fact that the emission spectrum varies with time indicates that a regime with gradual change of modes, in accordance with the classification proposed in[5], takes place in a ruby laser with a nonstationary plane-spherical resonator.

In the initial stage of the generation (Fig. 3b) one observes a relatively rapid shift of the average generation frequency towards lower frequencies, amounting to 0.5 cm^{-1}. This decrease in frequency is attributed to heating of the ruby by the pump. Since the rate of thermal drift of the ruby luminescence line is approximately 0.13 cm^{-1}/deg, this corresponds to a rise of about 4° C[12]. Taking into account the structural features of the illuminator, it can be assumed that the thermal shift of the luminescence line plays the decisive role in this region. During this stage, the emission line has the maximum width, ~0.15 cm^{-1}. In the entire remaining generation region there is a monotonic increase of the emission frequency. The frequency increases from the center of the luminescence line, corresponding to the temperature of the central part of the ruby rod. A similar frequency change was observed in[5] and was attributed to the difference between the mode excitation volumes and the temperature gradient of the working medium. As shown by calculation[4], the difference between the diameters of the central cross sections of the excited modes with different transverse indicates is ≈0.5 mm at the optical-resonator parameters indicated above. Consequently, the gradual transition of the generation from modes with small excitation volume to modes with large excitation volume, and accordingly with small thermal shift of the luminescence line, determines in this case the direction in which the generation frequency shifts. This is followed again by a jumplike transition to generation of modes with small excitation volume. This transition is due to accumulation of active particles in the central part of the active medium. A characteristic feature of such a transition is that it takes place in the course of several lasing spikes. An additional confirmation of this mechanism of generation-frequency variation is the change in the laser beam divergence (Fig. 2b).

B. Plane-parallel resonator. In a laser with a plane-parallel resonator, the modes excited have small transverse indices. The longitudinal mode-field shift due to the motion of the reflecting surface eliminates the longitudinal inhomogeneity of the population inversion in the active medium. At the same time, the weak mode degeneracy in the plane-parallel resonator cannot ensure elimination of the transverse inhomogeneity and a transition to the regime of regular kinetics, as in the plane-and-sphere resonator. Under these conditions, the decisive role in the generation kinetics is assumed by effects that lead to Q-switching of the nonstationary optical resonator. When the reflecting surface of the IPM vibrates, Doppler shifts take place in the frequencies of the traveling opposing waves, and this leads to modulation of the field amplitude inside the resonator. This effect is analogous to kinematic modulation of laser emission[7]. Additional modulation of the field in the resonator is caused also by the uneven distribution of the vibration amplitude over the IPM surface[11]. The existence of such a phenomenon is evidenced by the decrease in the laser beam divergence (Fig. 5b), which is due to the lowering of the Q of modes with transverse indices. Similar effects of suppression of modes with large transverse indices is observed in He-Ne lasers with IPM[11]. Calculations show that the relative depth of laser Q switching due to the joint action of the indicated factors is $\sim 10^{-4}$. Taking the multimode character of the laser emission into account[13], this depth of Q switching can lead to generation of spikes that are in synchronism with the modulation frequency. An additional confirmation of this phenomenon is that the laser generation spectrum remains unchanged when the amplitude of the IPM reflecting-surface vibration decreases.

The reported experimental research allows us to draw the following conclusions:

1. Periodic modulation of the length of a plane-and-sphere laser resonator ensures smoothing of the longitudinal and transverse inhomogeneity of the population inversion in the active medium and eliminates the parasitic mode selection. This leads to regular kinetics of ruby-laser generation, with gradual alternation of the generating modes, and ensures stabilization of the field distribution in the far one and a narrowing of the generation spectrum.

2. Periodic modulation of the length of a plane-parallel laser resonator leads to a periodic Q switching and to a simultaneous smoothing of the longitudinal inhomogeneity of the population inversion in the active medium. This leads to generation of a regular sequence of spikes, in synchronism with the frequency of the reflecting surface. At the same time, the duration of each individual lasing spike decreases (< 100 nsec) and the laser beam divergence is reduced.

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1) Analoguos results were obtained by us with a YAG laser with a plane-parallel nonstationary resonator.

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