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Fig. 1

Figure 1: Fig. 1

Abstract

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V. K. KONYUKHOV, L. A. KULEVSKII, Corresponding Member of the Academy of Sciences of the USSR A. M. PROKHOROV, A. K. SOKOLOV

SPECTRUM OF AN OPTICAL RUBY GENERATOR WITH EXTERNAL SPHERICAL MIRRORS

In a ruby generator with external spherical mirrors operating at room temperature, under certain conditions a regime of regular undamped oscillations of the generator-radiation intensity is realized, as well as a regime of damped oscillations with a transition to a stationary regime ([1,2]). Similar regimes have also been observed by other authors both in ruby generators ([1–5]) and in a glass generator activated with neodymium ([6]).

Fig. 1. Interferograms of the emission spectrum of a ruby optical generator at room temperature with external spherical mirrors.
a –concentric resonator, **b** –confocal resonator. The time sweep runs from left to right; total generation time ~ 2.5 msec; resolving time 0.1 msec; interferometer dispersion range 2.5 cm^{-1}.

We have carried out an investigation of the emission spectrum of a ruby generator with external spherical mirrors operating in the regime of undamped intensity oscillations, and also in the quasi-stationary generation regime.

In the work a ruby crystal was used, 12 mm in diameter and 120 mm long, with the optical axis directed perpendicular to the geometrical axis of the crystal. The spherical mirrors had a radius of curvature of 500 mm and were installed either at a distance of 1000 mm (concentric resonator) or at a distance of 500 mm (confocal resonator). The emission spectrum was investigated with the aid of a Fabry–Perot interferometer with a time sweep of the spectrum.

Figure 1 shows typical interferograms for concentric and confocal resonators, and Fig. 2 shows a plot of the change in generation frequency with time, obtained by processing one of the interferograms. In contrast to a ruby laser with plane mirrors ([7,8]), where several spectral components are generated simultane-

Fig. 2

Figure 2: Fig. 2

ously with frequencies that vary chaotically in time within a spectral interval of ~ 1 cm^{-1}, the emission spectrum of a ruby laser with external spherical mirrors consists of one component with a width of no more than 0.1 cm^{-1}. The generation frequency decreases monotonically with time, but along with the smooth change there are sharp frequency jumps of several tenths of cm^{-1} toward lower frequency. We propose the following explanation of the motion of the generation frequency in time. We relate it to the change in the optical properties of the ruby rod, caused by an increase in its temperature during operation of the optical laser.

Fig. 2. Generation frequency of a ruby optical laser with external concentric mirrors as a function of time

The generation frequency is determined by two factors: the position of the R_1-line on the frequency scale and the set of eigenfrequencies of the optical resonator. As the temperature of the ruby crystal is raised, the R_1-line shifts toward lower frequencies; the magnitude of this shift is ~ 0.14 cm^{-1} per degree (^{9}). The eigenfrequencies of the optical resonator also decrease with increasing temperature of the ruby crystal because of the increase in its linear dimensions and refractive index. The magnitude of the shift $\Delta\nu_p$ of the eigenfrequencies due to an increase in the optical path length in the resonator can be calculated from the relation

$$l_0 + l_{\text{cr}}(n-1) = q\frac{\lambda}{2},$$

where l_0 is the distance between the mirrors and q is the number of half-waves fitting along the length of the resonator; they do not depend on temperature, while l_{cr}, the crystal length, n, its refractive index, and λ, the wavelength, depend on temperature. We obtain:

$$\Delta\nu_p = -\frac{l_{\text{cr}}}{l_0 + l_{\text{cr}}(n-1)}\left[(n-1)C_\perp + \frac{dn}{dT}\right]\Delta T = \begin{cases} -0.029\,\Delta T\ \text{cm}^{-1} & \text{(concentric)}, \\ -0.048\,\Delta T\ \text{cm}^{-1} & \text{(confocal)}, \end{cases}$$

where $\lambda = 0.694\,\mu$, $C_\perp = 5.85 \cdot 10^{-6}$ deg^{-1} is the coefficient of linear expansion of ruby in the direction perpendicular to the optical axis (^{10}), and $dn/dT = 13 \cdot 10^{-6}$ deg^{-1} is the temperature change of the refractive index of the ordinary ray in a ruby crystal (^{11}). Comparing the magnitude of the shift of the eigenfrequencies of the optical resonator with the displacement of the maximum of the R_1-line, we conclude that the motion of both the resonator eigenfrequencies and the R_1-line occurs toward longer wavelengths, but the drift rate with temperature for the luminescence line is ~ 5 times greater than for the resonator eigenfrequencies.

The plot of the motion of the generation frequency is explained in the following way (see Fig. 2). In the intervals with a smooth change in frequency, the set of generated oscillation types does not change, but, together with the slow increase in the optical length of the resonator, their eigenfrequencies decrease···

frequencies. As the crystal is heated, the oscillation frequency shifts from the center of the R_1-line, where it arose, to the short-wavelength part of the contour until the self-excitation condition is no longer satisfied. After this, oscillation of the given set of oscillation types breaks off, and near the center of the R_1-line oscillation arises on another set of oscillation types; this explains the frequency jumps. The appearance of oscillation, after the oscillations have broken off, each time at another, lower frequency is evidence of motion along the frequency scale of the luminescence spectrum.

From the drift rate of the oscillation frequency, which is caused by an increase in the optical length of the resonator, one can determine the rise in the temperature of the crystal. Independently of this, the rise in the crystal temperature can be determined from the frequency difference at the beginning of neighboring sections with a smooth change of frequency, assuming that after the jump oscillation begins at the center of the R_1-line. A comparison of the heating values obtained from several interferograms is given in Table 1, which indicates the rise in temperature of the ruby crystal per millisecond of oscillation. It follows from the table that the agreement of the heating values is fairly good. The discrepancy between the values can be explained by the absence of a linear dependence of the change in crystal temperature on time, on the assumption of which the data in Table 1 were calculated. The rise in the crystal temperature over the full oscillation time, calculated from the interferogram, agrees in order of magnitude with the rise in the crystal temperature determined independently from calorimetric measurements.

Table 1

Rise in temperature of the ruby crystal, in degrees per 1 msec of oscillation, calculated from the increase in the optical length of the resonator (a) and the motion of the maximum of the R-line along the frequency scale (b)

Excitation energy, kJ	a	b
Concentric resonator	Concentric resonator	Concentric resonator
11	4.4	4.9
13	5.9	6.0
16	6.9	6.4
Confocal resonator	Confocal resonator	Confocal resonator
9	1.9	2.1

Excitation energy, kJ	a	b
13	4.5	5.1
16	2.9	4.0

The change in the refractive index at the frequency of the R_1-line due to a change in the number of particles in the upper level during oscillation, or due to a mismatch of the oscillation frequency with the maximum of the line, has, according to estimates, a value an order of magnitude smaller than the change in refractive index due to heating.

Other factors besides temperature can also affect the optical path length in the crystal, for example internal stresses that arise because of nonuniform heating of the crystal over its volume; however, the influence of these factors is not determining.

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