THE CHANGE IN THE EMISSION SPECTRUM OF A RUBY LASER DURING GENERATION

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The coefficient relating the frequency shift of the stimulated radiation of ruby to the change in temperature was determined experimentally. It is shown that the change in the emission frequency of a ruby laser during generation cannot be explained solely by an increase in the crystal temperature.

1. The paper of Konyukhov, Kulevskiĭ, and Prokhorov[1] presents some results of the experiments in which the red shift of the emission spectrum of ruby was observed during prolonged (10 msec) generation. This change in the frequency was explained by a continuous rise in the crystal temperature, and on this basis a method was proposed for measuring the crystal temperature during generation using the frequency shift. The coefficient relating the generation-frequency shift to the change in the crystal temperature, at temperatures close to 100°K, was taken to be equal to 17 deg/cm^{-1}.

However, the value of this coefficient (which we shall denote by γ), found from the formulas of McCumber and Sturge,[2] differs greatly from 17 deg/cm^{-1} (it is found to be 31 deg/cm^{-1} at T = 100°K) and its temperature dependence is so considerable that the coefficient cannot be regarded as constant in the temperature range 80—110°K, as was done in[1,3]. The validity of the formulas obtained by McCumber and Sturge[2] has been confirmed by the measurement of the temperature dependence of the fluorescence frequency of ruby.

In the present study, we determined experimentally the coefficient γ from the frequency shift of the stimulated radiation of ruby for a given change in temperature. The results obtained were in satisfactory agreement with the calculations carried out using the formulas of McCumber and Sturge.[2]

Moreover, it is shown that the change in the emission frequency during generation cannot be explained solely by a rise in the crystal temperature. While a temperature rise should only reduce the emission frequency, experiments show an increase in the frequency during generation (the violet shift). In particular, the nature of the change in the spectrum during generation[1)] depends on the Q-factor of the resonator in which ruby is placed (i.e., on the transparency of the mirrors).

2. The method used in the experiments discussed in the present paper was analogous to that described earlier.[4] The ruby was cooled by means of nitrogen vapor passing through a quartz Dewar tube containing the crystal. By varying the amount of the vapor passing through the tube, we established different initial crystal temperatures. The temperature of ruby when the pumping illumination commenced, T_b, and at the end of the illumination, T_e, was measured by means of a copper—constantan differential thermocouple.[2)] For the same illumination pulses, the difference $T_e - T_b$ remained constant, being 18 deg in our case. If we assume that ruby is heated mainly by the radiationless transitions of chromium ions from the absorption bands,[1] then the temperature rise during an illumination pulse is approximately proportional to the consumed pumping energy.[3)] Since the generation began at a moment when about half the energy stored in the capacitors had been expended on illumination, we may assume the crystal temperature at the beginning of the generation to be equal to $T = T_b + 9°$, with an error not exceeding 2—3 deg.

Employing the system described in[4], consisting of an objective, a Fabry-Perot interferometer with a working distance of 9 mm, and a rapid-response photorecorder (SFR-2M), we recorded the variation of the emission spectrum of ruby with

[1)]Duration of the generation pulse was close to 1 msec in most of the experiments described.

[2)]The temperature of boiling nitrogen was used as the reference temperature.

[3)]Heat transfer from the crystal during the illumination pulse was assumed to be negligibly small.

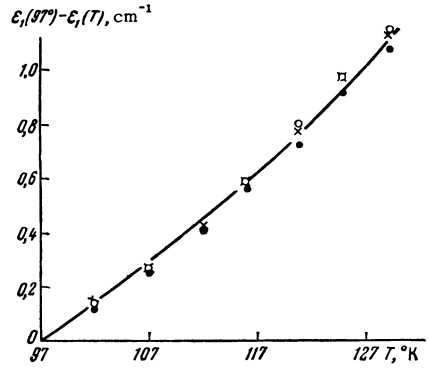

FIG. 1. Reduction in the frequency of the stimulated radiation with increase in the temperature of the ruby, relative to the frequency at 97°K: × – transition $\bar{E}(^2E) \rightarrow \pm\frac{1}{2}(^4A_2)$ in crystal No. 1 at transparencies of the silver coatings of the ends of 0 and 3%; ○ – transition $\bar{E}(^2E) \rightarrow \pm(3/2)(^4A_2)$ in crystal No. 1 at transparencies of 0 and 3%; ● – transition $\bar{E}(^2E) \rightarrow \pm\frac{1}{2}(^4A_2)$ in crystal No. 2 at transparencies of 0 and 10%.

time on cine film. Using photographs obtained at different temperatures (T = 97—130°K), we measured the diameters of the Fabry-Perot rings at the beginning of the generation and determined the frequency shift [4)] at each temperature with respect to the frequency at T = 97°K. In those cases when two generation lines were observed at the beginning of the generation period (due to the splitting of the ground energy state of ruby), we measured the temperature shift of each line with respect to its position at T = 97°K.

Figure 1 gives the results of some experiments with two crystals whose ends had silver coatings with different transmission coefficients. Crystal No. 1 was 60 mm long and 10 mm in diameter; it contained ≈ 0.04% of chromium ions and had 90° orientation of the optical axis. Crystal No. 2, 50 mm long and 6 mm in diameter, had a chromium ion concentration of ≈ 0.04% and 60° orientation of the optical axis. The continuous curve in Fig. 1 shows the results of calculations of the energy shift of the R_1 line at temperatures T = 97—130°K with respect to its position at T = 97°K, obtained from the formula (cf.[2])

$$\varepsilon_1(97°) - \varepsilon_1(T) = -\alpha_1\left\{\left(\frac{T}{T_D}\right)^4 \int_0^{T_n/T} dx \frac{x^3}{e^x - 1} - \left(\frac{97}{T_D}\right)^4 \int_0^{TD/97} dx \frac{x^3}{e^x - 1}\right\} \quad (1)$$

where T_D = 760°K and $\alpha_1 = -400$ cm^{-1}.

As is evident from Fig. 1, a satisfactory agreement is obtained between the experimental and calculated results, and the coefficient γ, found experimentally at T = 100°K, is close to 30 deg/cm^{-1}.

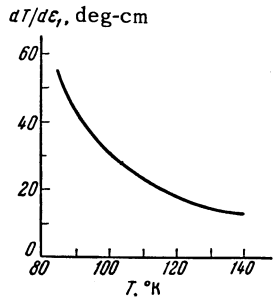

FIG. 2. $dT/d\epsilon_1$ as a function of temperature.

The expression for γ as a function of temperature can be obtained by differentiating Eq. (1). The function $\gamma(T) = dT/d\epsilon_1(T)$ is shown graphically in Fig. 2, which indicates that the coefficient γ at 85°K is approximately twice its value at 110°K.

3. In an investigation of the time dependence of the emission spectrum of two rubies with different transmission coefficients of their end coatings, it was found that the nature of the change in the spectrum during the period of generation depended, as mentioned earlier, not only on temperature but also on the transparency of the coatings.

Thus, for example, the following results were obtained for crystal No. 1. When one of the coatings was opaque and the other had transparencies of 3 and 5%, and the pumping energy was 1.4 times the threshold energy (we shall call this the strong illumination condition), simultaneous generation was observed at both the transitions (Fig. 3a) $\bar{E}(^2E) \rightarrow \pm\frac{1}{2}(^4A_2)$ (the long-wavelength line) and $\bar{E}(^2E) \rightarrow \pm\frac{3}{2}(^4A_2)$ (the short wavelength line) over the whole range of temperatures. On reducing the pumping energy, the intensity of the long-wavelength line decreased so that near the emission threshold the short-wavelength line was mostly emitted and the long-wavelength emission was observed only briefly (10—20 μsec) at the beginning of the generation.

When the transparencies of the coatings of the other end were 16 and 20%, only the long-wavelength line was generated near the threshold (Fig. 3b). If the illumination intensity was increased, then, some time after the beginning of the generation, the short-wavelength line appeared in addition to the long-wavelength one and the intensity of the former rose during generation while the intensity of the latter decreased to zero (Fig. 3c). When the illumination intensity was increased, the duration of the period of the simultaneous generation of the two lines decreased and the point where the lines interchanged shifted toward the onset of the generation. It is interesting

[4)] Since the generation lines had a finite width, the average generation frequency was measured.

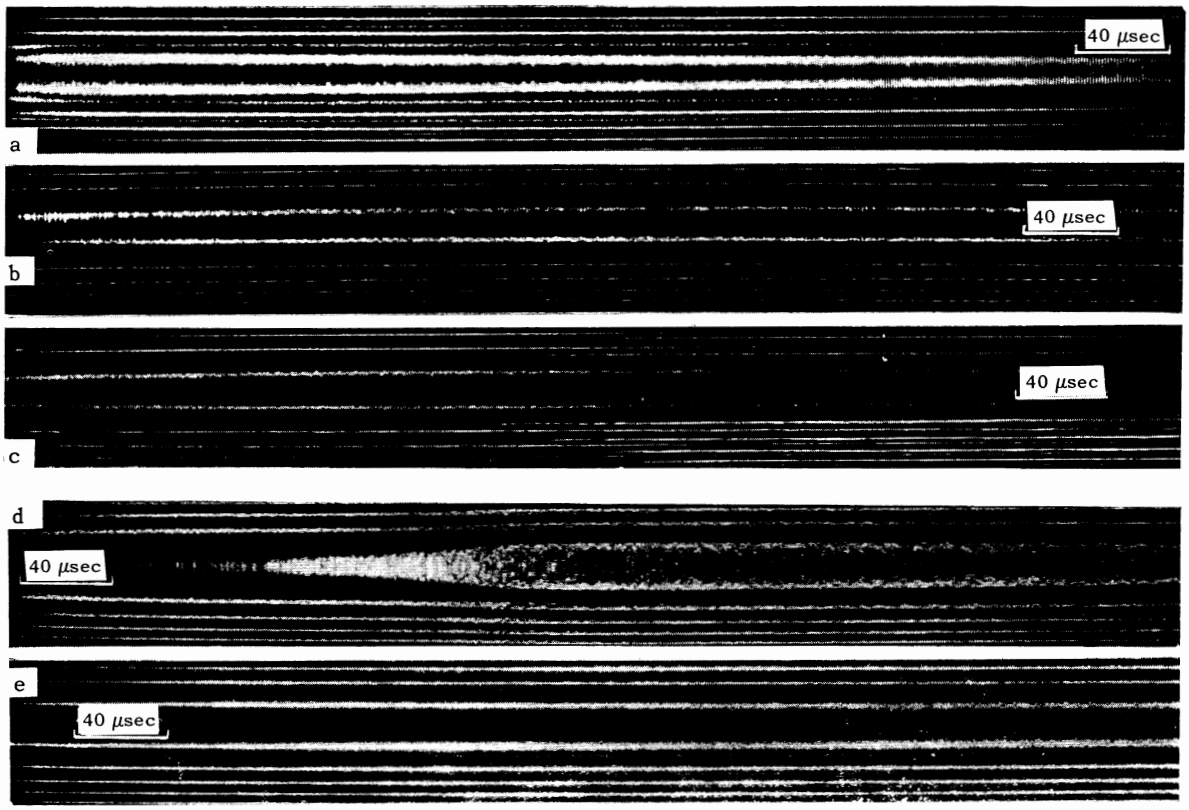

FIG. 3. Time-resolved emission spectrum of crystal No. 1: a) coating transparencies 0 and 3%, T = 116°K, pumping energy $1.4E_{thresh}$; b) coating transparencies 0 and 20%, T = 105°K, pumping energy $1.05E_{thresh}$; c) coating transparencies 0 and 20%, T = 105°K, pumping energy $1.4E_{thresh}$; d) coating transparencies 0 and 20%, T = 128°K, pumping energy $1.4E_{thresh}$; e) coating transparencies 0 and 41%, T = 98°K, pumping energy $1.4E_{thresh}$.

that the long-wavelength line exhibited the violet shift during generation, and the short-wavelength line exhibited the red shift, as is clearly evident from Fig. 3d.

When the transparencies of the coatings were 25, 41, and 57%, the short-wavelength line was obtained near the threshold at T_b = 88—98°K and the long-wavelength line was obtained at T_b = 110—130°K. Under strong illumination ($1.4E_{thresh}$) at T_b = 110—130°K, the generation lines were interchanged but otherwise the behavior was similar to that shown in Fig. 3c. Under strong illumination at T_b = 88—98°K, the short-wavelength line was accompanied by weak generation of the long-wavelength one (Fig. 3e).

In experiments on two crystals having coatings of different transparencies, we noted the following relationship. If only the long-wavelength line was emitted, then the violet shift was observed during generation; if only the short-wavelength line was emitted, the shift was toward the red side.

When the generation lines were interchanged (Figs. 3c and 3d), the long-wavelength line was emitted first and it had the violet shift, and then the short-wavelength line appeared as well. Initially, both lines had the violet shift, which was gradually replaced by the red shift, so that at the moment when the long-wavelength generation ended the red shift was always observed.

When the short-wavelength line was the first to be generated (Fig. 3e) and then the long-wavelength line appeared, both lines had the red shift during the whole generation period.

A theoretical explanation of the dependence of the laser generation frequency on the resonator Q-factor has been given in Freĭdman's work.[5]

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[1] Konyukhov, Kulevskiĭ, and Prokhorov, JETP 45, 857 (1963), Soviet Phys. JETP 18, 588 (1964).

[2] D. E. McCumber and M. D. Sturge, J. Appl. Phys. 34, 1682 (1963).

[3] Konyukhov, Kulevskiĭ, and Prokhorov, DAN SSSR 154, 1072 (1964).

[4] A. M. Kubarev and V. I. Piskarev, JETP 46, 508 (1964), Soviet Phys. JETP 19, 345 (1964).

[5] G. I. Freĭdman, Izv. vyssh. uch. zav., Radiofizika 8, 272 (1965).

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