RUBY LASER WITH GENERATION DURATION OF ~10 MILLISECONDS

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The spectrum of a ruby laser is measured for a generation duration $\tau \sim 10$ msec and at temperatures ~ 77—$110°K$. The time variation of the spectrum is explained. A method for measuring the crystal temperature during generation is developed, based on the shift of the generated frequency. The amount of heat absorbed by the ruby lattice is determined.

INTRODUCTION

WE have investigated the spectral composition and several other characteristics of a ruby laser at $T \sim 80$—$100°K$ operating with a generated pulse length of $\tau \sim 10$ msec. The spectrum of a ruby laser at low temperatures and with $\tau \sim 1$ msec consists of two components separated by 0.38 cm^{-1}. [1,2] They correspond to transitions from the metastable level $\bar{E}(^2E)$ to the sublevels $\pm 1/2$ and $\pm 3/2$ of the ground state $^4A_2$. The spectrum was photographed during a single flash, the length of exposure coinciding with the duration of generation τ. We shall call this spectrum the complete spectrum. It is found that as the generation time is increased the complete spectrum broadens toward the red and at $\tau \sim 10$ msec it occupies a band 1—2 cm^{-1} wide with no definite structure. The abrupt expansion of the total spectrum toward one side can be explained by the gradual change in the generated frequency toward the red due to heating of the ruby crystal. An experiment the results of which substantiate this assumption is described below.

DESCRIPTION OF APPARATUS AND METHOD OF MEASUREMENT

The measurements were carried out in the apparatus depicted schematically in Fig. 1. The ruby crystal 1, of length 60 mm. diameter 7 mm, and with dulled lateral surfaces, was placed in the dewar 2 containing liquid nitrogen. The ruby was excited by means of the helical flash lamp 3, through which the capacitor bank 4 was discharged. The light generated by the ruby was reflected from the mirror 5 into the lens 6 (f = 94 mm), in the focal plane of which was situated a disk with an opening in it. The motor 7 rotated the disk with

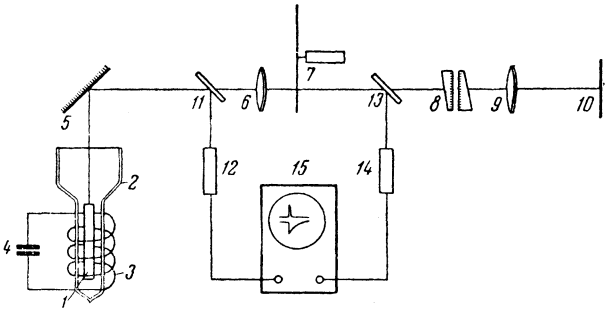

FIG. 1. Experimental arrangement.

a period of 20 msec, so that the opening in the disk opened the light path for about 0.1 msec. The light passing through the opening in the disk fell upon a type IT51-30 Fabry-Perot interferometer 8 with a 1 cm^{-1} dispersion range, and then on the camera 9 (f = 800 mm). The rings from the Fabry-Perot interferometer were recorded on the photographic plate 10, which was located in the focal plane of the camera. The shutter in the form of a disk with an opening could be opened with variable delay with respect to the initiation of generation; thus, the spectrum could be photographed at the very start of generation, at the end, or any time in between. The part of the light deflected by the plane-parallel plate 11 fell on a photomultiplier 12, type FÉU-14B, while the part passing through the opening in the disk was split by the plane-parallel plate 13 and fell upon another photomultiplier 14, of the same type.

The signals from the photomultipliers were fed into a type DÉO-1 dual-beam oscilloscope 15. The duration of generation and the moment at which the photographic plate was exposed could be determined from the oscillogram. Such an oscillogram is shown in Fig. 2. The Fabry-Perot interference patterns were read with an IZA-2 comparator. The diameters of the rings of equal angle for different

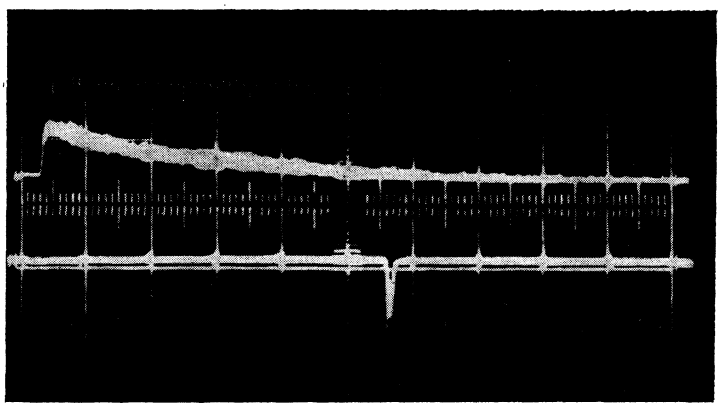

FIG. 2. Oscillogram of the complete generated pulse (upper trace) and the light pulse incident on the photographic plate (lower trace). Scan is from left to right, and each square on the horizontal axis corresponds to 1 msec. The photographic plate was exposed 5 msec after the start of the generated pulse.

orders of interference were measured for both components or for the average frequency when the two components fused together. Further, the differences in the squares of the diameters of corresponding orders for different plates were found; from these the shift in frequency in going from one plate to another was determined in the usual manner. Then the frequency shifts and splittings were averaged over all measured orders of interference. The total change in the diameters of the rings over the whole time of generation equalled approximately two orders of interference. Possible changes due to fluctuations in ambient temperature amount to 0.1 order per degree. No effort was made to stabilize the temperature of the interferometer.

The instrumental constant a of the Fabry-Perot etalon was calculated from the well-known formula:

$$a = \frac{\Delta\nu}{\pi}\frac{1-R}{\sqrt{R}} = 0.05 \text{ cm},$$

where $\Delta\nu = 1$ cm^{-1} is the dispersion range of the etalon and R = 0.85 is the reflection coefficient of the mirrors. The observed width of the spectral components was ~ 0.1 cm^{-1}. When we refer to the width of the spectral components below we shall mean this observed width.

EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

The evolution of the spectrum over the generation time can be described in the following way. From the initial moment until t = 5 msec there are two spectrum components, $\nu_{1/2}$ and $\nu_{3/2}$, with width ~ 0.1 cm^{-1}. The separation between them, initially equal to (0.37 ± 0.01) cm^{-1}, diminishes in the course of time. For t > 5 msec, the components fuse together into a single line ~ 0.2 cm^{-1} in width. In addition, the mean frequency $\nu_{av} = \frac{1}{2}(\nu_{1/2} + \nu_{3/2})$ drifts toward lower frequencies, moving by about 2 cm^{-1} during the generation time.

Figure 3 shows the change in average frequency $\Delta\nu_{av}$ with time. If the curve is extended to the origin (dashed line), the shift in average frequency at the start of generation amounts to 0.2 cm^{-1}; consequently, the frequencies in generation should be shifted relative to the frequencies of these same components in luminescence by an amount ~ 0.2 cm^{-1}. The direct measurement of this shift, carried out by D'Haenens and Asawa,[1] gave the value 0.18 cm^{-1}.

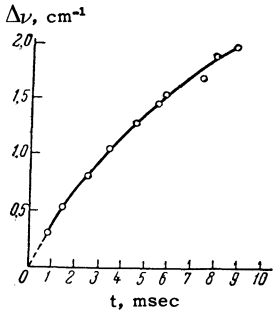

FIG. 3

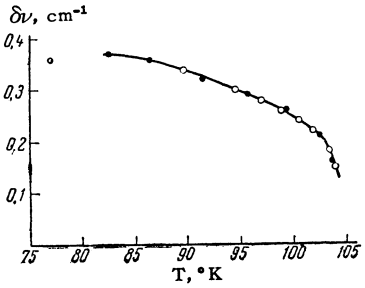

FIG. 4

FIG. 3. Change in the average frequency $\Delta\nu$ in the generation process.

FIG. 4. Separation $\delta\nu$ between the components in the generation spectrum as a function of crystal temperature. The experimental points are denoted by the black circles.

The change in temperature of the ruby lattice in the generation process can be judged from the change in average frequency ν_{av}. The frequency scale in Fig. 3 can be converted into a temperature scale. The numerical value of the conversion coefficient $\Delta T/\Delta\nu = 17$ deg/cm^{-1} for T ~ 100°K is found from the dependence of the frequency of luminescence of ruby on temperature.[3] The temperature scales in Fig. 4 and Fig. 5 were obtained by this conversion.

At the initial moment of generation there are two distinct components in the spectrum. As the temperature is increased, these components, as has already been mentioned, come together and then fuse into a single line. The graph in Fig. 4 shows the dependence of the separation between

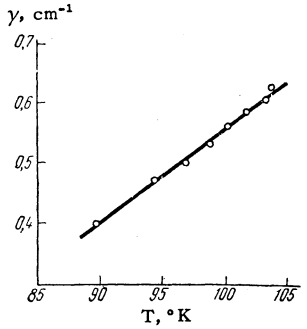

FIG. 5. Half-width γ of the luminescence components $\pm 1/2$, $\pm 3/2$ of the R_1-line of ruby. The values of γ were obtained from Fig. 4 by means of the function $l(\gamma)$.

the components on the temperature of the ruby lattice. The approach of the two components toward each other as the crystal is warmed is explained in the following way. The spectral components $\pm 3/2$ and $\pm 1/2$, into which the R_1 line is split at low temperatures, have approximately the same intensity in absorption and the same polarization in luminescence. The spectral width γ of the components increases with temperature, and at T $\sim$ 80—100°K the components overlap to a considerable extent. At inversion, each component has its own amplification factor $\alpha_{3/2}(\nu)$ and $\alpha_{1/2}(\nu)$, and the total amplification factor $\alpha(\nu)$ in the crystal is the sum of both factors:

$$\alpha(\nu) = \alpha_{3/2}(\nu) + \alpha_{1/2}(\nu).$$

Self-excitation occurs at the points of greatest value of the amplification factor $\alpha(\nu)$, in other words, at the peaks of both components in absorption. The separation l between the peaks depends strongly on the spectral width γ of the components, and so the magnitude of the splitting in the spectrum of the laser output should depend on the temperature of the radiating ruby. To confirm our explanation we calculated the function $l(\gamma)$ and compared with the data in Fig. 4 under the following assumptions: both components have the same intensity in absorption, Lorentzian shape, the separation between maxima $\nu_1 - \nu_2 = 0.38$ cm^{-1} for $\gamma \to 0$, and thus

$$\alpha(\nu) = \frac{\alpha}{1 + \frac{4}{\gamma^2}(\nu - \nu_1)^2} + \frac{\alpha}{1 + \frac{4}{\gamma^2}(\nu - \nu_2)^2}.$$

Using the function $l(\gamma)$, we calculated the value of γ corresponding to each experimental point in Fig. 4. The results are given in Fig. 5. The absolute values of γ agree within the limits of accuracy of our method with the known half-widths of the R-lines at T $\sim$ 80—100°K.[4] One expects the dependence $\gamma(T)$ to be linear over a temperature interval that is not too large.

The possibility of measuring the lattice temperature of a lasering crystal permits calorimetric experiments to be carried out at 77—110°K. The long duration of generation provides nearly steady-state conditions. The graph in Fig. 6 is constructed on the basis of the same data as the graph of the shift of average frequency with time (Fig. 3), but instead of $\Delta\nu_{av}$, the energy Q absorbed by the crystal lattice as heat is plotted along the ordinate axis. The enthalpy $H = \int_0^T C_p dT$ for low temperatures was taken from the work of Furukawa et al.[5]

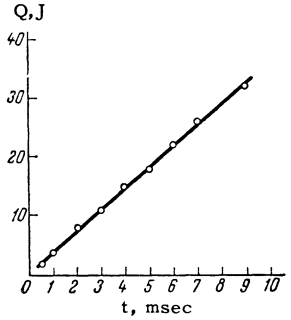

FIG. 6. Quantity of heat Q absorbed by the crystal lattice of ruby as a function of the time after the moment of firing of the flash lamp.

We assume that the principal amount of thermal energy goes into the lattice in nonradiative transitions of the particles from the absorption bands of the chromium ion. We shall use as a measure of the heat energy q the energy liberated in the lattice as a result of the transition to the metastable level of all the particles in the sample, the number of which is $N_0 = 2.7 \times 10^{19}$.

If the ground state $^4A_2$ of the chromium ion is thought of as degenerate, then to "charge up" the crystal at the generation frequency requires the transfer of $2/3$ of all the particles in the crystal to the metastable levels $\bar{E}(^2E)$ and $2A(^2E)$. Thus an energy $2q/3 = 1.9$ J enters the lattice. In our apparatus the generation begins 0.5 msec after the flash lamp lights up (t = 0). From Fig. 6 it is seen that 2J of heat is evolved in the lattice in t = 0.5 msec, which agrees with the value 1.9 J obtained in the calculation. Over the entire generation time, 32 J of thermal energy is given off in the lattice; consequently, each chromium ion has, on the average, been lifted by the flash lamp radiation to the metastable levels and returned to the ground state 11 times. The average flux of heat energy into the lattice is 4 kW. During generation of light pulses of long duration each particle can take part in the process several times.

In our experiments, the flux of particles leaving

the metastable levels was determined by the spontaneous emission. The flux of particles to the ground level, caused by the generation of coherent light, can be neglected in the total heat balance of the crystal. It is possible to calculate the average power P of spontaneous emission and the average heat flux into the lattice W under the condition that the number of particles in the metastable levels remains approximately equal to $\frac{2}{3}$ of the total number of ions during generation, with a lifetime $\tau_0 = 4.3$ msec [6]:

$$P = \frac{2}{3}\frac{N_0\hbar\omega}{\tau_0} = 1.2\,\text{kW}, \quad W = 0.43\,\text{kW}.$$

The calculated value of W should be compared with the average heat flow into the lattice, equal to 4 kW, found from experiment. We attribute this order-of-magnitude difference between the values to the sharp shortening of the lifetime of the particles in the metastable levels upon inversion. The actual lifetime is $\frac{1}{10}$ of the lifetime τ_0 in the absence of inversion. One of the possible reasons for the shortening of the lifetime in our experiments is the induced amplification of the spontaneous emission upon inversion. Another possibility is the excitation in the ruby rod of electromagnetic modes that cannot leave its boundaries.

Shortening of the lifetime of the metastable levels of the chromium ion to 0.4 msec at room temperature has been observed by McClung and Hellwarth. [7]

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