# *COHERENCE AND TIME SCANNING OF THE EMISSION SPECTRA OF A RUBY LASER*

V. V. KOROBKIN and A. M. LEONTOVICH

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

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It is shown that the radiation from a ruby laser is coherent in all directions. Regular oscillation is obtained with the ruby at −165°C. The spectra and beam divergence in separate pulses were studied. It is shown that although the generated frequency corresponds to the axial modes, this is not true for the beam divergence; nor is it due to optical inhomogeneity of the crystal.

IT has been shown[1,2] that the radiation from a ruby laser is coherent over the entire end surface, i.e., the generation occurs in the kinds of vibration (modes) that are excited in the whole volume of the crystal. These modes are most likely to be the so-called axial modes,[3,4] which satisfy the condition

$$2L\mu = l\lambda, \qquad (1)$$

where L is the distance between the mirrors, $\mu$ is the index of refraction of ruby, $\lambda$ is the wavelength of the radiation, and $l$ is an integer. At each "burst" in the time of generation there are excited simultaneously several of these modes,[4] a fact which is not completely understood in the case of ruby, where there is homogeneous line broadening.

The aim of this paper is to explain the time dependence of the excitation of these modes (under pulsed operation). For this, the coherence was investigated, and a time scan of the emission spectrum at different temperatures was obtained.

## 1. COHERENCE

The investigation was carried out both at room temperature and at −165°C. This temperature was obtained in a stream of dry, cold nitrogen and was measured by means of a copper-constantan thermocouple affixed to the ruby.

The coherence of the radiation was studied by observing the interference of the radiation with a Michelson interferometer that had one of its mirrors replaced by a prism (Fig. 1). In the focal plane F of the objective O one obtains two pictures of the angular distribution of the radiation on top of each other, one from the mirror M, the other from the prism P. If the light coming from different directions is coherent and falls in the same place in the plane F, interference bands will be found there.

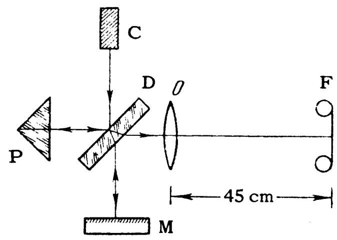


FIG. 1. Arrangement for observing interference.

Similarly, one can study the coherence of the radiation from different parts of the end surface. For this, it is necessary to place between the crystal C and the beam divider D (Fig. 1) another objective at its focal distance from the end of C. In this case, one obtains two superposed images of the end in the plane F. This method makes it possible to investigate the coherence over the whole field at once.

Figure 2 is a photograph taken in this interferometer over one pump pulse ("integrated") with the ruby at room temperature. The picture shows interference bands; hence the rays going in different directions are coherent with one another. This means that the emission of each mode is propagated in different directions, i.e., the conclusion arrived at in [2], that the wave front is not plane, is confirmed. This result disagrees with theoretical notions,[6] according to which the modes excited in

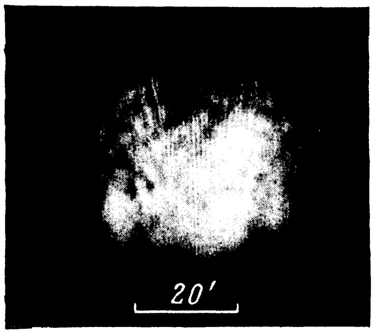


FIG. 2. Interference of radiation being propagated in different directions.

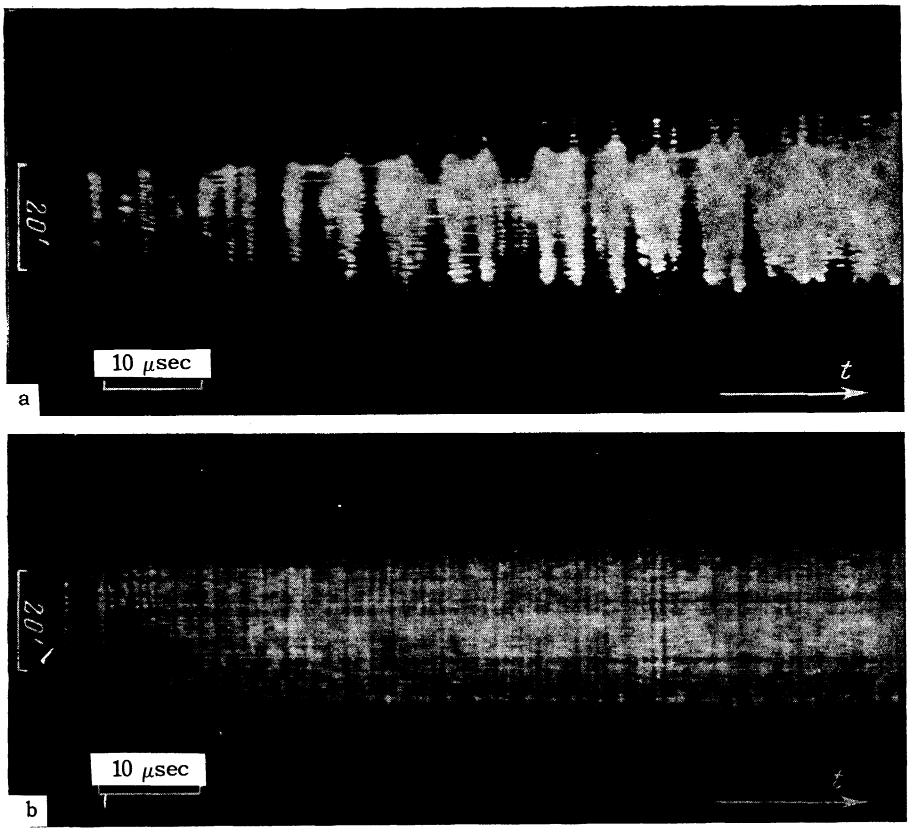


FIG. 3. Time scan of the directional distribution of the radiation. Ruby at a Cr concentration of 0.05%, c axis perpendicular to cylinder axis, L = 76 mm, diameter 11 mm. a – temperature of the ruby, 20° C; b – temperature of the ruby, −165° C.

a plane-parallel resonator should be propagated in the form of plane waves.

When the ruby is at a temperature of − 165°C, the interference bands are less sharp.

In a similar way it has been shown (as in [2]) that the emission is coherent over the entire radiating surface.

Interference phenomena are obtained only when the pump energy is not greatly in excess of the threshold (not more than 2%). For pump powers greater than this the interference bands fade and disappear. This is explained by the fact that the integrated interference pattern is made up of the interference patterns obtained from the individual flashes. Hence if the interference patterns differ for the different flashes, the integrated bands will be smeared out. When the threshold is exceeded by a large amount, modes with various lateral characteristics are generated in the different flashes,[7] and these give different interference patterns.

## 2. SCANNING

Time scanning of the generated radiation was carried out with a type SFR fast camera operating as a photorecorder. In Fig. 3a is shown one of the scanning photographs, obtained with the ruby at 20°C. The slit of the camera was placed in the focal plane of an objective on which the generated light was incident such that the photograph gives a time scan of the distribution of radiation over directions lying in a vertical plane. It can be seen from Fig. 3a that the radiation in each burst is propagated in a certain discrete number of directions with a total divergence 30—40′. A measurement of the angular difference between adjacent directions gives a quantity of the order λ/D, where D is the diameter of the radiating end face.

Pictures taken with the ruby at − 165°C (Fig. 3b) show that in this case the pulsations are completely regular—the radiation consists of a regular chain of pulses following each other at regular time intervals. Only now and then are these oscillations seen to "break." The discreteness of the propagation directions becomes less well-defined. At both temperatures the divergence at the start of generation (a few bursts) is small (about 8′) and then increases.

## 3. EMISSION SPECTRA

Emission spectra were studied with a Fabry-Perot etalon, both integrated over one pulse and time-scanned. In the integrated photographs with the ruby at 20°C, it has been found, as in [3], that the generation occurs at several frequencies separated by an interval (in $cm^{-1}$) of $1/2L\mu$, i.e., probably in axial modes. This means that during the time of generation the optical length of the crystal changes less than $\lambda/2$ because of changes in crystal temperature; this follows from condition (1): $\Delta(L\mu) < \lambda/2$ (otherwise the shift in the frequencies of the axial modes would exceed the interval between them and the pattern would be smeared out in the integrated picture). Choosing the values of $dL/dT$ and $d\mu/dT$ from [8], we find that $\Delta T < 0.3°C$, i.e., during the entire time of generation the crystal is not heated by more than 0.3°C.

Time-scanned spectra were also produced with the SFR instrument used as a photorecorder (Fig. 4). For this, the end surface of the crystal was projected onto the slit of the SFR by means of the two objectives $O_1$ and $O_2$, with a Fabry-

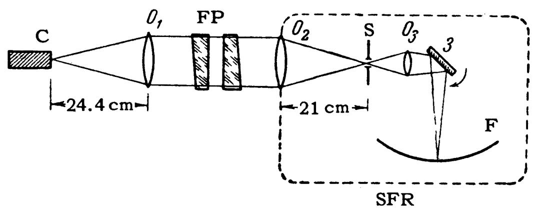


FIG. 4. Arrangement for time-scanning the emission spectra.

Perot interferometer (FP) between them. The objective $O_1$ was placed at its focal distance from the end of C and objective $O_2$ at its focal distance from the slit S. In this case, an image of the end, crossed by Fabry-Perot rings, was obtained in the plane of S. This indicated that a frequency specified by the Fabry-Perot interferometer conditions was present in the radiation coming from the corresponding place on the end. The slit cut out a vertical strip from the total image, and the light of this strip was scanned. In this way, the spectrum of the light coming from some vertical band on the end surface of the crystal was scanned.

If the objective $O_1$ is removed then a scanning of the spectrum of light propagating in different directions is similarly obtained. Figure 5 shows the results of this kind of scan. It can be seen that several frequencies are emitted simultaneously in each burst, and these frequencies are the same in different directions (this is seen from the fact that the spots repeat in the same way along the verticals). The difference between adjacent frequencies is equal to $1/2L\mu$ (in our case 0.04 $cm^{-1}$), i.e., these frequencies correspond to the excitation of axial modes. In each burst there is observed a set of axial modes, usually different from the set for another burst. At room temperature up to 5—8 axial modes (spectral interval 0.3

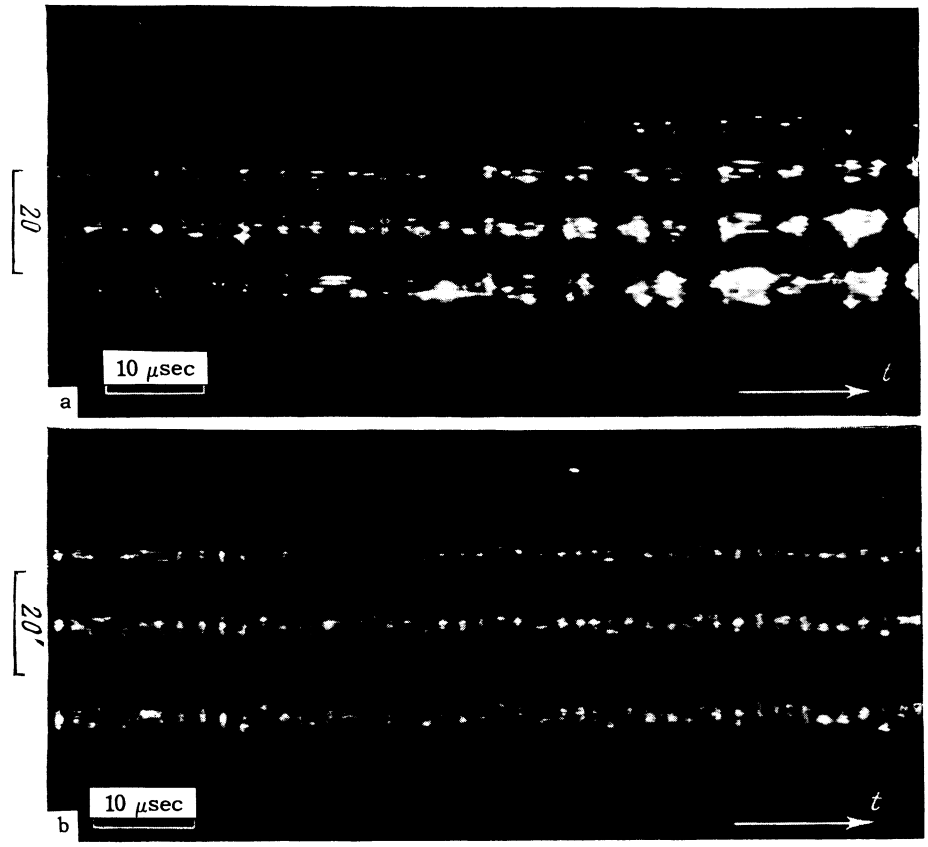


FIG. 5. Scan of the spectra of radiation being propagated in different directions. The same ruby as in Fig. 3. Separation between Fabry-Perot plates, 5 mm. a – temperature of the ruby, 20° C. Initiation of generation. b – temperature of the ruby, –165° C. Thirty microseconds after initiation.

$cm^{-1}$) can be generated simultaneously. The total width of the band of emission in our experiments amounted to 1 $cm^{-1}$ (the luminescence line width is 10 $cm^{-1}$).

At −165°C, 3 or 4 axial modes are generated simultaneously, and the total bandwidth is 0.25 $cm^{-1}$ (luminescence linewidth at this temperature is 0.6 $cm^{-1}$[9]). Whereas at room temperature generation occurs only at frequencies corresponding to axial modes, with nothing between them, at low temperatures there is a rather marked background, i.e., there are some additional frequencies besides the axial modes.

By photographing the distribution of the spectrum over the end, it was found that different points of the end surface radiated the same frequencies.

## 4. DISCUSSION

The following conclusions may be drawn from the experiments described. The scanning of the spectrum shows that in the individual bursts generation occurs in several modes having different axial characteristics. The lateral characteristics of the excited modes must be the same, otherwise in the investigation of interference they would give different interference bands, which would smear the interference pattern. The modes are excited in the entire volume of the generating portion of the crystal. In different bursts generation occurs in different modes.

The emission of excited modes is not propagated in a single direction with a diffracted divergence $\lambda/D$, as it would be in a plane-parallel resonator, but in a certain set of directions with a total divergence of 30—40′. This large divergence cannot be explained on the basis of optical nonuniformities of the crystal, since we verified the uniformity of the crystal with a Michelson interferometer (similar to the method used in [10]); it was found that the total deviation from plane-parallelism was not greater than 1 $\mu$. For the diameter of our crystals (up to 1 cm), the divergence caused by such a nonuniformity could not be greater than 30″ rather than 30′. Besides this, a consideration of the photographs in Fig. 3 shows that for the same crystal the divergence of the beam for different bursts is different—it occasionally reaches 1′, but the effect of nonuniformities should be the same. For the same reason, the divergence cannot be attributed to scattering of light in the crystal. The only possible explanation is a change in the properties of the resonator brought about by the generation process itself.

The change in temperature of the crystal during generation is very small, as has already been stated, and can be neglected.

A possible explanation could be the following. During generation the index of refraction of ruby in the $R_1$ line changes on account of the change of population of the upper level. In this case the properties of the resonator change, and this can lead to a change in the characteristics of the divergence of the radiation. Modulation of the optical length during a pulse can also lead to modulation of the emitted frequency; this is a possible explanation for the presence of a background between axial modes, as observed at −165°C.

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293