DYNAMICS OF THE RADIATION FIELD, SPECTRUM, AND COHERENCE IN A GIANT RUBY-LASER PULSE

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An image converter was used to study the time-resolved spreading of the radiation field over a mirror and also the development of the divergence, spectrum, and coherence of emission from a fast Q-switched ruby laser. The streak-camera photographs show that the radiation field originates at the center of the ruby cross section and spreads across the entire cross section in 15-25 nsec. During this time the divergence increases up to 15—30′ and the frequency increases by 0.017—0.023 cm^{-1}. The frequency increase appears to result from the spreading of the radiation field. Space coherence, which was studied by means of Young's two-hole interference experiment, persists during the first 15—20 nsec, after which the radiation phases at two points of the wave vary incoherently during 2.5—3 nsec.

THE field and frequency dynamics as well as radiation field coherence have been well studied in spontaneously operating ruby lasers,[1] but not for the giant-pulse mode. It is very important to know these properties both for purely scientific purposes and for applications to nonlinear optics, holography, etc.

In the present work we have studied the dynamics of the field, frequency, and space coherence in a giant pulse from a ruby laser. In [2] we published pertinent preliminary data on the generation of a giant pulse in a laser operating with a passive shutter containing a solution of cryptocyanine in ethanol. The same letter[2] reported our experimental study of laser dynamics with fast Q switching. A corresponding theoretical discussion in [3] enables us to compare the experiment with a theory.

The shutter used for Q switching was a 3-nsec Pockels cell consisting of a potassium dihydrogen phosphate crystal and a polarizer (a stack of glass plates). The cell was placed between the ruby crystal and a plane mirror with a 98% reflection coefficient for the 6943-Å wave. The second plane mirror, having a 30% reflection coefficient, was located 79 cm from the first mirror. Ruby rods 12 cm long and 11.5 mm in diameter with roughened sides were used. Pumping was performed by means of an illuminator with two linear IFP flash lamps.[1)]

[1)]One of the ruby rods, the illuminator, and the mirrors had been used previously for the work reported in [2].

The energy of the giant pulse reached 1.5 J. For the different crystals the total pulse duration varied within the range 40—60 nsec; the duration at half-power level was 16—28 nsec. The pulse shape was monitored by means of an FÉK-14 coaxial photocell and an S1-10 oscillograph. Streak-camera photographs of the radiation field patterns, spectra, and interference bands were obtained, as in [2], by means of an image converter operating in the slit-sweeping mode with 0.5-nsec resolution in a total sweep of 100 nsec.[4] The image-converter sweep was calibrated by means of recorded beats between the axial modes of a spontaneous laser with a semiconfocal resonator.

DYNAMICS OF THE RADIATION FIELD

When photographing both the near-field and far-field patterns, the end surface of the crystal or the field distribution in the focal plane of the objective lens (of 70-cm focal length) was projected on the slit of the image converter. Figure 1a shows a streak photograph of the near-field pattern. Oscillation begins here in the central region; the field then spreads to the crystal edges within 15—25 nsec in the course of a pulse whose total duration is 40—60 nsec. The most intense lasing regions are shifted to the edge of the crystal face (Fig. 1a).

The field boundaries moved at speeds of 0.8 $\times 10^7$—3×10^7 cm/sec in different photographs. The speed was greatest, on the average, for the ruby of poorest optical quality. Unlike the case of a laser with a saturable filter, which is character-

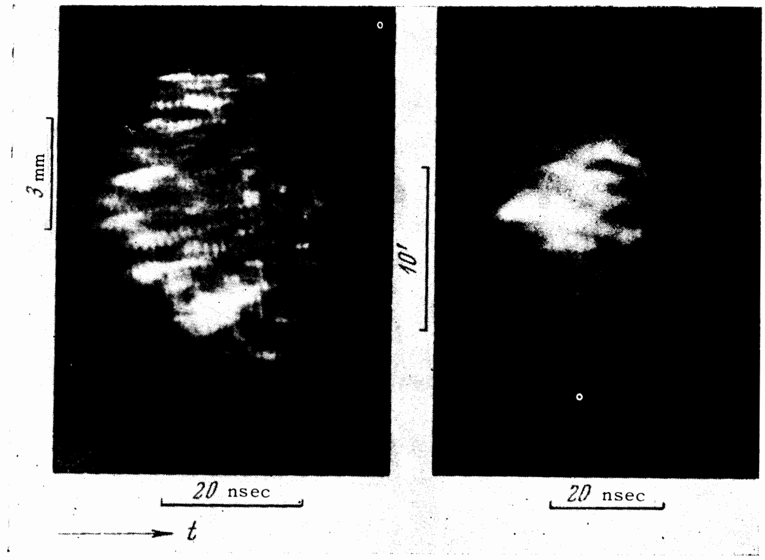

FIG. 1. Streak photograph of radiation field pattern. a – near-field (crystal end face), pulse energy 1.2 J; b – far-field (directional distribution), pulse energy 1.2 J.

ized by prolongation up to 12 nsec of the initial oscillating stage within a small central region (the "leader"), [2] we could not detect such a "leader" in the fast Q-switched laser for any position of the image converter slit on the image of the crystal end face.[2)] The spreading of the near-field area was also investigated with one of the resonator mirrors inclined at an angle of 5′. The initial lasing spot was then observed to be shifted 2.7 mm from the center toward the side of the greater mirror separation, and the subsequent spreading of the field was asymmetrical. The photographs show an irregular, granular, structure of the field over the ruby cross section, with individual spots varying in size from 0.1 to 1.0 mm, as was mentioned in [6]. This effect probably results from the small optical inhomogeneities in the form of striations that are usually present in rubies. This interpretation is supported by the fact that the most finely granular field structure was found for the ruby of poorest quality.

Some streak photographs of the field (Fig. 1a) revealed intensity fluctuations that probably resulted from beats between modes of identical transverse orders but different axial orders. The beat frequency was equal to the frequency difference between adjacent axial modes multiplied by $c/2L$, where L is the optical length of the resonator.

Figure 1b is a typical photograph of the far-field development (the directional distribution of emission). This field is observed to expand, like the near-field; divergence up to 20–34′ occurs within 15–25 nsec. These values pertain to the total divergence, whereas in the most intense portion of the emission (at about half-maximum intensity) the divergence is 8–16′ (Fig. 1b). The rate of increase of the divergence (1×10^5–3×10^5 rad/sec) was the same as for a laser with a saturable filter.[2]

The following statements must be made regarding a comparison of our results with the theoretical treatment in [3], where the spread of the field was calculated for the case of fast Q switching. The theoretical calculations pertained to nearly plane-parallel resonators. It was found that when the active medium possesses inhomogeneities resembling a diverging lens, oscillation begins at points of maximum inversion; thereafter the lasing region and the divergence increase during a time that is comparable with the pulse duration. The authors of [3] neglected to consider small striated optical inhomogeneities that cause scattering which somewhat resembles the effect of a diverging lens; like the latter, these inhomogeneities result in an electrodynamical relationship between separate portions of the resonator. Since the results of these theoretical calculations do not depend very strongly on the focal length of an inhomogeneity, it is possible to compare our results at least qualitatively, if not quantitatively, with the theory of Letokhov and Suchkov in [3].

The large inhomogeneities of our rubies resembled negative lenses; however, the rubies were not heated up enough through the absorption of pumping light to convert the resonator from negative to positive. We verified this fact earlier[7] by an in-

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[2)]The lag of pulses from the edges of the ruby face behind the pulse from the center, resulting from the spread of the field, has also been observed photoelectrically.[5]

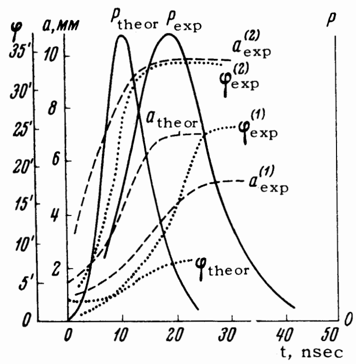

FIG. 2. Development of a giant light pulse. P – power (in relative units); a – near-field diameter (in the laser cross section); b – total divergence of generation. The theoretical values pertain to the case of a crystal resembling a diverging lens, with $\Delta L/L = 6 \times 10^{-8}$, where L is the optical length of the resonator and ΔL is the difference between the optical lengths at the center and edge of the crystal. The superscripts (1) and (2) denote the extreme values obtained in the photographs of field development. P_{exp} was obtained by averaging many oscillograms.

terference method under pumping conditions similar to those prevailing in the present work.

It was verified by the same means that a ruby is heated most at its center. This means that maximum population inversion occurs at the center, where, therefore, oscillation begins and spreads to other regions of the ruby. The hypothesis that lasing occurs independently in the different regions of a ruby conflicts with the space coherence of emission during the first 15–20 nsec (to be discussed here subsequently).

Figure 2 shows the curves calculated in [3] for the field diameter (the near-field) on the crystal end face, for the divergence, and for the generated power as functions of time; the extreme experimental values are also shown. We observe, for example, that for the speed of near-field development there is an average spread of 40% between experiment and theory; this represents qualitative agreement. In the case of inclined resonator mirrors qualitative agreement is also observed.[3]

It should be noted that when the field density at the lens focus is calculated it is important to take into account the variation of divergence. When this is done the average calculated density is increased by a factor from 2 to 10. The fine granular structure of the field must also be taken into account in calculating the maximum field density.[6]

If we neglect the existence of a "leader," which occurs specifically in cases with a saturable filter, the field development does not proceed differently for the two methods of Q switching. Unfortunately, no theory for the dynamics of a passive shutter was developed in [3]. Our results suggest that identical physical factors are involved in the field dynamics of both cases (except during the initial instants of field development).

COHERENCE

To investigate space coherence we studied Fraunhofer diffraction using a diaphragm with two holes having 0.2–0.3-mm diameters, located directly behind the laser mirror (Young's experiment). In integral photographs of the diffraction pattern the interference bands were indistinct and greatly smeared. For streak-camera photography the pattern was projected on the image converter slit in such a way that the interference bands were perpendicular to the slit. The photographs obtained with different separations of the holes (0.3, 1.2, and 5 mm) in Young's experimental scheme showed that

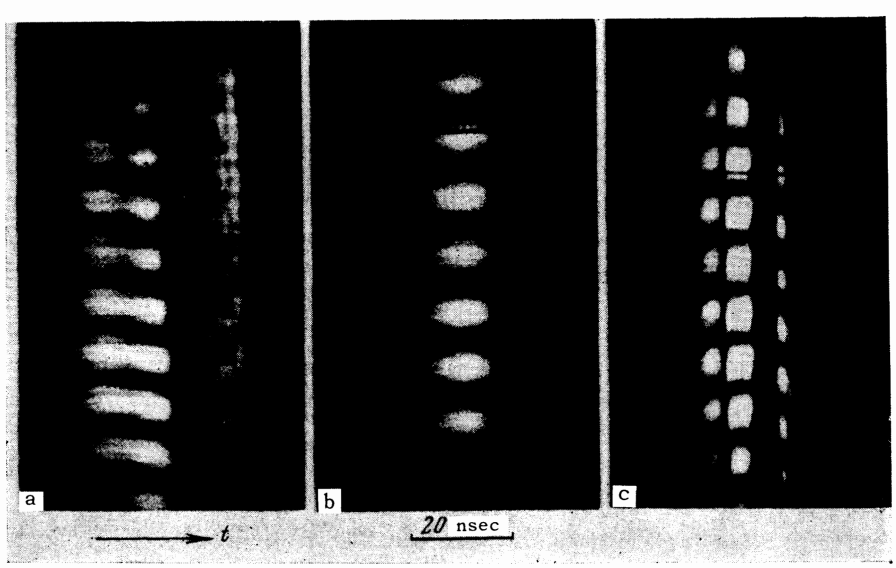

FIG. 3. Streak photograph of two-hole interference pattern. a – 1.2-mm hole separation, in resonator with 0.7-mm diameter diaphragm, pulse energy 0.02 J; c – 0.3-mm hole separation, without diaphragm, pulse energy 0.6 J.

the bands remain almost motionless during the first 15—20 nsec. Field coherence persists here in the cross section of the laser; sometimes only breaks in the bands are observed (Fig. 3c).

The persistence of space coherence in the cases of the 1.2- and 5-mm hole separations, which exceed the diameters of individual spots in the near-field spots (0.1—1 mm), indicates that oscillation occurs independently at the different spots but at identical frequencies. During the remaining time of a pulse the photographs show jumps and shifts of the bands; this means that coherence does not persist during the entire duration of a pulse. A change of 180° in the difference between the phases of a wave at two measured points (corresponding to a band shift equal to half the band separation) takes place during a time of the order 3 nsec and does not depend on the separation of the holes. These phase changes are obviously associated with a shift in the near-field structure; the characteristic time constant of the change is of the same order.

When a diaphragm of 0.7-mm diameter was inserted into the resonator (which is about one-fourth of the diameter of the first Fresnel zone) and the hole separation in Young's experiment was 0.3 mm, the emission coherence persisted during an entire pulse (Fig. 3b). In the absence of the diaphragm but retention of the same hole separation coherence did not persist (Fig. 3c). We can therefore conclude that only pure axial modes are generated in the presence of a diaphragm.

Our experiments have thus shown that the phase relationship of two different field points varies greatly during the entire period of a giant pulse. However, the theory of Letokhov and Suchkov [3] would permit only small phase differences (< 180°), which could not be abrupt. Their theory is based on the assumption of a resonator having good optical homogeneity; this condition would lead to uniform depletion of the inverted population. In real lasers this depletion evidently proceeds nonuniformly because of the small inhomogeneities of the ruby. The resulting phase differences between any two field points are equivalent to the destruction of coherence.

OSCILLATION FREQUENCY

The radiation spectra were studied with Fabry-Perot interferometers having 30- and 150-mm plate separations. Complete photographs of the interferometer rings for an 0.6-J pulse indicated oscillation line widths that were ordinarily within the range 0.015—0.019 cm^{-1}. With enhanced pumping and 1.3-J pulse energy the line width was increased to 0.024 cm^{-1}. The principal emission line was then often accompanied by extra lines that were ordinarily narrower.[3)]

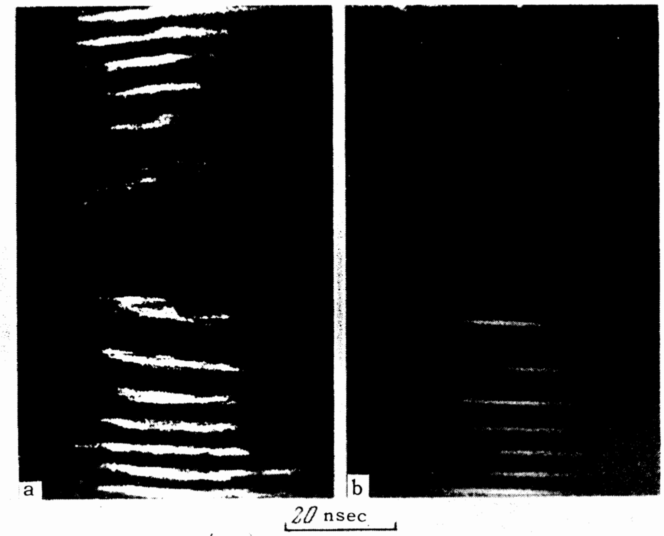

FIG. 4. Streak photograph of the emission spectrum, obtained with 150-mm plate gap in the Fabry-Perot interferometer. The internal fine structure of the lines resulted from the spatial distribution of the emission, not from the structure of the spectrum (lines in the different orders have different structures). a — without a diaphragm inside the resonator, pulse energy 1.2 J; b — with a diaphragm of 0.7-mm diameter inside the resonator, pulse energy 0.2 J.

In the streaking procedure the Fabry-Perot rings were projected on the slit with the latter at the center of the rings; one such streak photograph is shown in Fig. 4a. Here, as in the case of a laser with a saturable filter, [2] the frequency is shifted in the short-wave direction. This shift (0.017—0.023 cm^{-1}) occurs during the first 15—20 nsec (the time required for the build-up of the radiation field). During the later portion of the oscillation period the average frequency does not vary and the oscillation line-width is 0.011—0.016 cm^{-1}. This is consistent with the width that should be induced by the phase changes observed in experimental studies of coherence and by changes of field intensity that occur during a time of the order 3 nsec. The streak photographs showed that the extra frequencies are generated during a time of from 4 to 30 nsec (as in the case of the work done with a saturable filter [2]).

Two causes of the frequency increase that occurs during a pulse are (1) reduced optical length

[3)]We must emphasize that all our data pertain to a laser that operated with a Pockels cell. When a Kerr cell is used the spectrum consists of a broad line having a width up to 1 cm^{-1}, representing stimulated Raman scattering from low-frequency vibrations of nitrobenzene molecules.[8]

of the resonator due to changes in the refractive index, and (2) build-up of the radiation field.

The following mechanisms can theoretically account for the change in the refractive index:

1. Heating that results from the absorption of emitted light within the ruby itself. However, heating will increase the refractive index of the ruby,[2] which will diminish rather than enhance the frequency.

2. Heating of other elements inside the resonator by emitted light. For example, in the case of a laser with a passive shutter containing a solution of cryptocyanine in ethanol such heating could reduce the refractive index of ethanol, which possesses a negative temperature coefficient. However, direct interferometric measurements of the optical length of the resonator have shown[10] that the optical length does not change.

3. Nonlinear increase of the ruby's refractive index in a strong radiation field; this should produce a shift in the red direction.

4. Change of the refractive index caused by a reduction of the population inversion during oscillation as a result of anomalous dispersion. This effect occurs only when the laser does not oscillate at exactly the line center.[12] This hypothesis cannot account for a higher frequency; instances of reduced frequency would also be observed, because it is unlikely that the oscillation frequency would always be shifted to the right of the line center. Direct measurements comparing the oscillation frequency in a giant pulse with the mean luminescence frequency, using a single Fabry-Perot interferometer,4) have shown that the oscillation frequency is not shifted more than 0.3 cm from the luminescence line center. In this case the frequency shift resulting from change of the refractive index brought about by anomalous dispersion[13] will not exceed 3×10^{-7} cm^{-1}.

To account for the frequency change we investigated the spectrum after inserting a diaphragm of 0.7 mm diameter into the resonator. Practically no frequency increase was found in this case (Fig. 4b); the shift was at most 0.005 cm^{-1} and the line width was of the same order. This line width is almost the limiting value determined by the pulse duration of 15 nsec. On the other hand, pulse energy measurements obtained with different diaphragms showed that the field density does not depend on the size of the diaphragm in the resonator. This indicates that the frequency shift observed in the absence of a diaphragm cannot be accounted for, generally speaking, as a field-density effect.

It appears that the frequency change is induced by the field build-up process and the accompanying enhancement of radiation divergence. From the expressions for the frequencies and divergence of modes in flat or nearly flat spherical resonators[14,15] we easily derive an approximate formula relating the frequency and divergence: $\Delta\nu/c = \varphi^2/4\lambda$, where $\Delta\nu/c$ is the frequency difference between a mode exhibiting the divergence φ and the fundamental mode among modes of identical axial orders. This equation yields a frequency shift of the order 0.025 cm^{-1}, which agrees with experiment.5) A precise calculation of the frequency shift could be based on the theory of Letokhov and Suchkov, who unfortunately did not use it for that purpose.[3]

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4)The authors are indebted to V. N. Smorchkov for these measurements.

5)In [2] the value 0.3 cm^{-2} given for $\Delta\nu/c$ was one order larger, because the total divergence $\approx 30'$ was used in the calculations instead of the divergence ($\approx 10'$) of the most intense part of the radiation, which should have been used.

[1] V. V. Korobkin, A. M. Leontovich, and M. N. Smirnova, Zh. Eksp. Teor. Fiz. **48**, 78 (1965) [Sov. Phys.-JETP **21**, 53 (1965)].

[2] V. V. Korobkin, A. M. Leontovich, M. N. Popova, and M. Ya. Shchelev, ZhETF Pis. Red. **3**, 301 (1966) [JETP Lett. **3**, 194 (1966)].

[3] V. S. Letokhov and A. F. Suchkov, Zh. Eksp. Teor. Fiz. **50**, 1148 (1966) and **52**, 282 (1967), [Sov. Phys. JETP **23**, 763 (1966) and **25**, 182 (1967)].

[4] V. V. Korobkin, L. P. Malyavkin, and M. Ya. Shchelev, PTÉ **4**, 129 (1965).

[5] R. V. Ambartsumyan, N. G. Basov, V. S. Zuev, P. G. Kryukov, V. S. Letokhov, and O. B. Shatberashvili, Zh. Eksp. Teor. Fiz. **51**, 406 (1966) [Sov. Phys.-JETP **24**, 272 (1967)].

[6] T. M. Barkhudarova, G. S. Voronov, V. M. Gorbunkov, and N. B. Delone, Zh. Eksp. Teor. Fiz. **49**, 386 (1965) [Sov. Phys. JETP **22**, 269 (1966)].

[7] A. P. Veduta, A. M. Leontovich, and G. A. Matyushin, ZhPS (Journal of Applied Spectroscopy) **6**, 401 (1967).

[8] F. J. McClung and R. W. Hellwarth, Proc. IEEE **51**, 46 (1963).

[9] M. A. Jeppesen, J. Opt. Soc. Am. **48**, 629 (1958).
[10] A. P. Veduta, A. M. Leontovich, and M. N. Popova, ZhPS (Journal of Applied Spectroscopy) **6**, 401 (1967).
[11] L. V. Keldysh, Dissertation, Physics Inst., AN SSSR, 1964.
[12] D. F. Bradley, G. Magyar, and M. S. Richardson, Nature **212**, 63 (1966).
[13] N. K. Bel'skiĭ and A. M. Leontovich, Zh. Eksp. Teor. Fiz. **48**, 752 (1965) [Sov. Phys.-JETP **21**, 497 (1965)].
[14] A. L. Schawlow and C. H. Townes, Phys. Rev. **112**, 1940 (1958).
[15] G. D. Boyd and J. P. Gordon, Bell System Tech. J. **40**, 489 (1961).

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