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CELEBRATING 50 YEARS OF THE LASER

On the creation of the first ruby laser in Moscow

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Abstract. **The paper describes the history of the creation of the first ruby laser in 1961 at the Lebedev Physical Institute (FIAN), the USSR Academy of Sciences, Moscow. Appendices present an excerpt of FIAN's 1961 annual report and a talk at the Third International Congress on Quantum Electronics (1963), in which one of the first scientific results obtained with a laser is described.**

In 1958, Schawlow and Townes [1] and Basov and co-workers [2] published articles on the potential of obtaining generation in the optical spectrum range by means of induced radiation. In June 1960, American scientist Maiman [3] published promising results (a noticeable increase in the population of the upper metastable level in Cr^{3+}) obtained with a ruby crystal in April 1960. On 7 July 1960, Maiman spoke at a press conference about his discovery of 'light amplification.' The next day, *The New York Times* published an article "Light Amplification Claimed by Scientist." Only on 6 August did the article by Maiman on the narrowing of a chromium atom luminescence line in ruby due to induced radiation (that is, superfluorescence) appear in *Nature* [4]. The first article describing the operation of a ruby laser was published by Schawlow et al in *Phys. Rev. Letters* [5] on 1 October 1960. An oscillogram with spike generation was presented in the article.

The work on lasers at FIAN was initiated by N G Basov in 1960 at the Laboratory of Luminescence in the framework of the project 'Photon.' Basov suggested to M D Galanin to perform the work. It is remarkable that Basov addressed just the Laboratory of Luminescence, where specialists in luminescence skilled in optical methods of investigations worked. S I Vavilov, who was a founder of FIAN, laid a foundation for the polyphysic character of investigations, which played a great role in the story. Galanin readily adopted the suggestion and started the work jointly with Z A Chizhikova and A M Leontovich. First, we followed the path of the Americans, namely, we observed a change in the population of an upper chromium level under optical pumping by a flash lamp. In spring 1961, our group independently created a laser setup in which the ruby sample with the chromium concentration 0.05% and length 4 cm was pumped by two xenon pulsed IFK-2000 lamps in a case deposited with MgO. A photograph of the unit is given in Fig. 1. With this setup, we obtained generation on 18 September 1961 (a month after the article by Maiman was published on 15 August 1961 in *Phys. Rev.* [6], where he described the laser construction). Our laser was thoroughly described in a FIAN report in December 1961. Pages of the report describing the creation of the ruby laser are presented in Appendix I. At that time, we persuaded Galanin to publish an article about the creation and operation of our laser, which might appear just in 1961. But Galanin said: "We will publish the results as soon as we finish the scientific work with the laser!"

We published an article in *JETP* [7] after we studied the coherent properties of the radiation of our laser. In Fig. 2,

Galanin's group (from left to right): A M Mozharovskii, O P Varnavskii, A M Leontovich, M D Galanin, Z A Chizhikova, and A N Kirkin (in the 1960s). Collage by A M Leontovich.

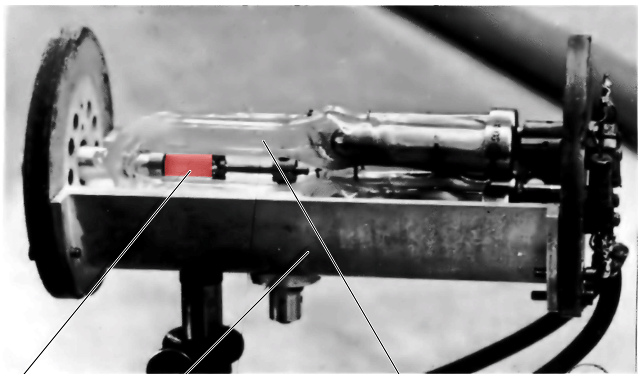

Figure 1. In 1967, for the 50th anniversary of Soviet power, FIAN organized an exhibition of the institute scientific advances for 1934–1967, at which our first real ruby laser was submitted. Later it was moved to the Polytechnic Museum, in the section of the history of physics.

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КОГЕРЕНТНОСТЬ И НАПРАВЛЕННОСТЬ ИЗЛУЧЕНИЯ ОПТИЧЕСКОГО ГЕНЕРАТОРА НА РУБИНЕ

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Направленность излучения оптического генератора на кристалле рубина обычно хуже дифракционного предела, определяемого размерами кристалла. Это обусловлено оптическим несовершенством кристаллов. Нельсоном и Коллинсом [1] было показано, что излучение когерентно на протяжении малых областей торцевой поверхности кристалла. Предполагалось, что дифракция на границах этих областей и обусловливает угловое расхождение генерируемого пучка излучения. Однако, как было показано Мастерсом и Паррентом [2], излучение когерентно на участках, отстающих друг от друга более чем на 3 *мм*.

Описываемые ниже опыты имели целью исследовать соотношение между когерентностью и направленностью излучения рубинового генератора. Прежде всего было показано, что пульсации излучения при генерации возникают одновременно по всей излучающей поверхности кристалла.

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k-е кольцо соответствует условию $2nl\cos\theta_k = (m-k)\lambda$, где l — длина кристалла, n — показатель преломления, θ_k — угол между нормалью к фронту волны внутри кристалла и нормалью к плоскости торца. Измерение диаметров подтверждает это соотношение.

Авторы выражают благодарность А. С. Бебчуку и Ю. Н. Соловьевой за предоставление исследованных кристаллов, а также В. Н. Луканину и Н. Е. Щелкалину за обработку кристаллов.

Авторы благодарны также Н. Г. Басову за постоянное внимание и обсуждение этой работы.

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18 мая 1962 г.

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Figure 2. The first and last pages of the first publication on ruby laser operation in the USSR [7].

the first and last pages of the article are reproduced. This was the first publication in the USSR concerning experiments with optical generators. Continuing the work, we also published an article about the spiking character of ruby laser generation in *Optics and Spectroscopy* [8]. In this and the following study [9], which were reported at the Third International Conference on Quantum Electronics in Paris, February 1963, we showed that the spike operation and coherence of the radiation are interrelated [10]. The text of report [10] is presented in Appendix II.

Oscillograms of the chaotic pulsations are shown in Fig. 3. Later, we also took 'mode pictures,' that is, a cross-section distribution of the radiation intensity generated in a single mode for each particular spike (Fig. 4). It agrees well with the theoretical distribution if we assume the cavity to be similar to that with spherical mirrors. The 'sphericity' originated from initial optical inhomogeneities in the ruby samples and thermo-optical distortions caused by pumping radiation.

In addition to the specialists mentioned above, young researchers and postgraduate students from both our laboratory and other laboratories were involved in these and later investigations, as well as those devoted to the giant pulse generation mode: M Popova, A Veduta, V Korobkin, M Shchelev, A Mozharovskii, and others. Based on the

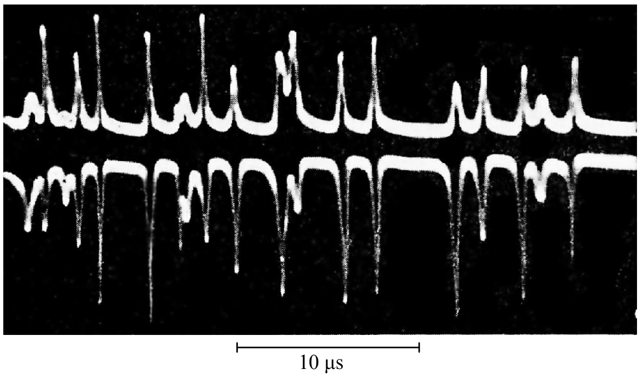

Figure 3. Oscillogram of the radiation from two different areas of a laser crystal face.

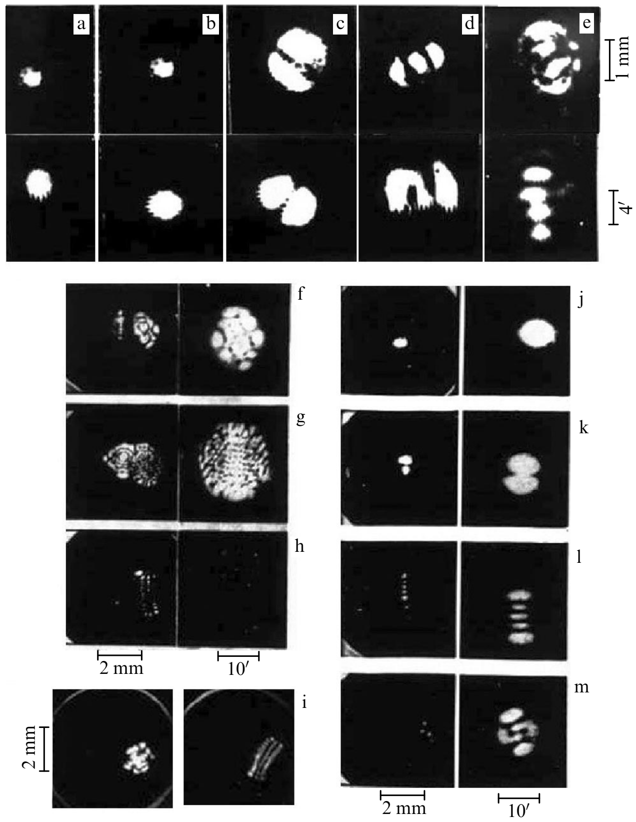

Figure 4. Simultaneous photographs of the far-field (angular) radiation distribution and the distribution on a sample face: (a–e) face distribution (the upper row of the shots), angular distribution (the lower row); (f–i) (both columns) and (j–m) face distribution (left column), angular distribution (right column).

material of this work, they all defended their PhD (and later DSc) theses. For example, V S Zuev, a collaborator of Basov, and young P G Kryukov mastered a laser technique with our help and then published an article about a ruby laser with Q-switching. Later on, such 'public friendship' in FIAN became uncommon. At the first stages of our work, much attention was paid to the quality of ruby samples (optical properties and purity), on which heavy demands were imposed. No appropriate techniques for producing ruby crystals were available at FIAN, and we obtained samples from two places: the Institute of Crystallography and a 'closed organization,' Special Design Office 311 of the State Committee on Electronic Engineering (OKB-311 GKET). They were fabricated by A S Bebchuk and Yu N Solov'eva, who previously did work on masers. We tested both types of samples. We had no success with the samples from the Institute of Crystallography. The content of Cr^{3+} in those samples was 0.5% rather than 0.05%, and the optical quality was poor. Laser generation was obtained with the samples from the closed organization.

In autumn 1961, we started more thorough tests of the optical properties of ruby crystals (mainly by means of a Michelson interferometer) and succeeded in obtaining generation, first with low energy and then with an energy capable of burning a hole in a razor blade. At that moment, a sample of ruby from the USA was at our disposal (obtained via an intelligence service). The generation obtained with that sample had parameters similar to those for our samples. There was a prejudice concerning the sample shape — both our and the American initial samples were parallelepipeds in shape, probably a vestige of the maser era. Then it became clear that the shape of the samples is meaningless and only the alignment of the crystal faces, on which silver mirrors were deposited, is important. Later on, cylindrical samples were used. When external mirrors appeared, ruby faces were cut at the Brewster angle.

As noted above, we started investigations of chaotic pulsations in generated radiation. It was found that chaos in the pulsations was related to the heat instabilities of thermal and optical–mechanical properties caused by the heat from the same lamp that was used for optical pumping [11].

Putting our first laser into operation became *the* event in the existence of FIAN. Room 356, in which the first laser was created, became a kind of a 'laser center' at FIAN. Many visitors were coming to see the laser in operation. It all looked much like a fragment of the 1962 film "Nine Days of One Year," with all those shouts "Gusev has got plenty of neutrons!" I E Tamm was happy for us. The FIAN Director D V Skobeltsyn was constantly inquiring about the progress. The prestige of FIAN and of Soviet science was at stake. Our work has allowed reducing the gap between our work on lasers and the work in the USA to a minimum. Physicists from FIAN, from other institutes in Moscow, and from laboratories in Kiev, Minsk, Gorkii, Leningrad, and other cities were coming for advice. Those were unforgettable days of our group. High-profile visitors were also present: academic authorities, the chair of the Department of Science of the CPSU Central Committee academician V A Kirillin. Sometimes N G Basov accompanied the guests. Once, Basov was taking around D F Ustinov who, not yet minister of defense, was a chair of the Committee for Military Equipment and a vice-chair of the Council of Ministers of the USSR. We burned a hole in a razor blade for him that time. Maybe at that time they were already discussing the possibility of using high-power laser beams in anti-missile facilities.

The first thorough description of our ruby laser was given in the report "Employment of quantum systems for generation, amplification, and indication of optical radiation" dated 30 December 1961. The text of the report was not lost due to the publication of the digest *Memoires of an Archivist* [12]. In the introduction to the report, it is declared that "*results of the experiments on creating a generator of optical radiation on ruby* (*the wavelength* 6943 Å), *performed at the Laboratory of Luminescence by M D Galanin, A M Leontovich, Z L Morgenshtern, and Z A Chizhikova are presented. Optical properties of a ruby crystal near the threshold pumping are thoroughly* *studied and the generated radiation is investigated. The technology of creating the generator is presented.*" Section 1 of the report is devoted to the use of luminescent crystals. A ruby laser is described in Chapter 1 of the section "Optical generator on a ruby crystal." In Chapter 1, both preliminary investigations and the observation of the generation are thoroughly described. The titles of sections are quite informative: § 1. *Some optical properties of ruby*. § 2. *Crystal treatment and surface control*. § 3. *Spectral dependence of the quantum yield for ruby luminescence*. § 4. *Silvering of ruby faces*. § 5. *Optical pumping system*. § 6. *Observation of laser generation*. § 7. *Generation energy measurements*. § 8. *Kinetics of luminescence, induced emission, and generation*. In Appendix I, sections 5, 6, and 8 are represented along with figures and references from the digest *Memoires of an Archivist* (by kind permission of the author A N Starodub). In Appendix II, report [10] of the Third International Conference on Quantum Electronics (Paris, 1963) is given.

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Appendix I

Employment of quantum systems for the generation, amplification, and indication of optical radiation

(Excerpts from FIAN report, 30 December 1961)

§ 5. Optical pumping system

For optical excitation (pumping) of the generator, we used two xenon flash lamps IFK-2000 connected in series (the characteristics are given in [12]). The schematic of our setup is shown in Fig. 5. The value of capacitors supplying the lamps was 900 μF and the voltage was up to 3 kV. This is not a nominal regime for the lamps and their service period was shorter than indicated in the manual. Usually, the voltage applied across the lamps for exciting generation was from 1.5 to 3 kV. The U-shape lamps were placed into a cylindrical laser pumping cavity of a special construction (Fig. 6). A short-duration high-voltage pulse for initiating the lamps was applied directly to the case.

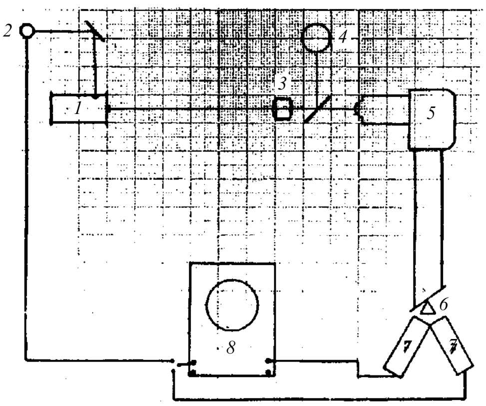

Figure 5. Schematic diagram of the setup for observing an induced luminescence and generation of a ruby crystal. *1* — optical generator, *2* — STsV photo cell, *3* — condenser, *4* — FEU-27, *5* — ISP-51 spectrograph with UF-84 camera, *6* — separating prism, *7* — FEU-12, *8* — DEO-1.

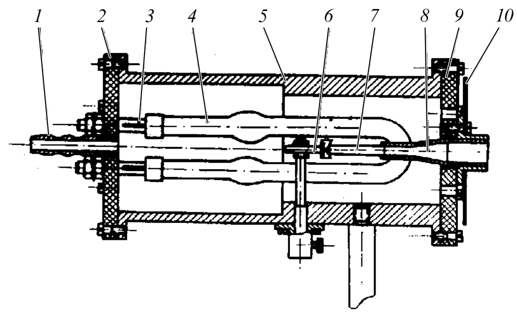

Figure 6. A pumping cavity of the optical generator. *1* — cooling tube, *4* — IFK-2000 lamp, *5* — laser pumping cavity, *6* — ruby holder, *7* — ruby crystal, *8* — light-preserve tube.

The internal surface of the pumping cavity was deposited with magnesia. In the process of deposition, the case was kept at a voltage of 4 kV. This provided a stronger magnesium layer and higher albedo. The sample was mounted between the lamps.

Each flash of the lamps slightly heated the sample. In order to cool it, the case was blown with cold air. A light-preserve tube was used to prevent waste of the scattered light from flash lamps, which leaves the cavity along with luminescence and laser radiation. The top cover had a hole through which the light of the flash lamps passed to a photocell (through an SZS-18 light filter, which cut the ruby luminescence) used for light detection. A signal from the photocell was reproduced on an oscilloscope.

§ 6. Observation of laser generation

Luminescence or induced radiation from the ruby sample passed through a condenser to a slit in the ISP-51 spectrograph coupled with a UF-84 camera. In the focal plane of the camera, where lines R_1 and R_2 were focused, a slit 1.3 mm wide was placed. A prism with an edge facing the slit was used for separating the lines. The rays passing from different sides of the edge refracted on prism faces in different directions; thus, lines R_1 and R_2 could be distinguished. Each of the lines passed to its particular photomultiplier. For detection, we used FEU-12A photomultipliers. Signals from the load resistors of two photomultipliers passed to the DEO-1

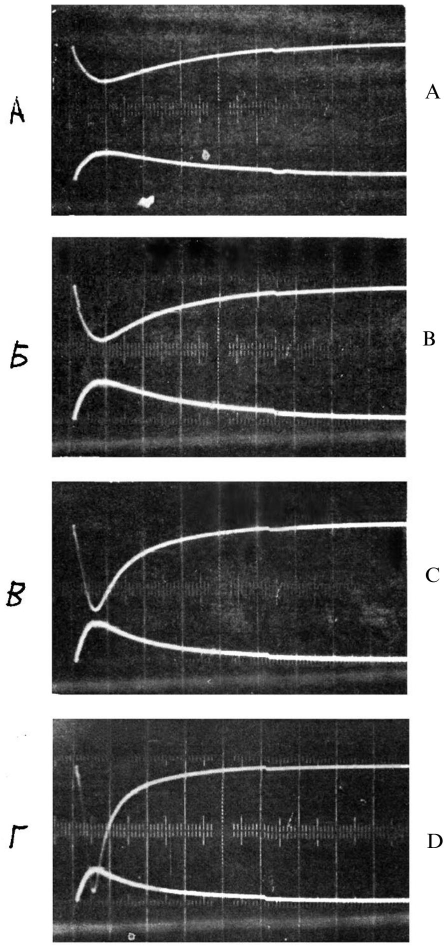

Figure 7. Oscillograms of luminescence kinetics of R_1 and R_2 lines at various pumping energies. In all the images, top rays refer to the R_1 line and the bottom rays correspond to R_2. The scale is 1 ms/div. The voltages across the lamps are: (A) $U = 1000$ V, (B) $U = 1100$ V, (C) $U = 1200$ V, (D) $U = 1300$ V.

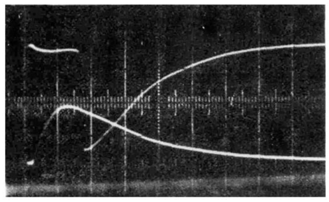

Figure 8. Oscillogram of luminescence kinetics of the R_1 line (induced emission). The top ray is the R_1 line, the bottom ray is the glow of a pumping lamp. The scale is 100 μs/div.

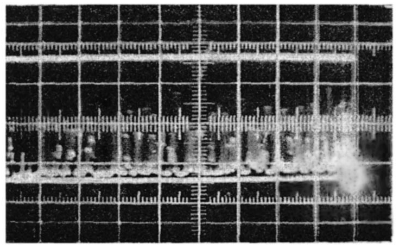

Figure 9. Generation kinetics. The oscillogram is taken 300 μs past the flash-lamp ignition. The scale is 25 μs/div.

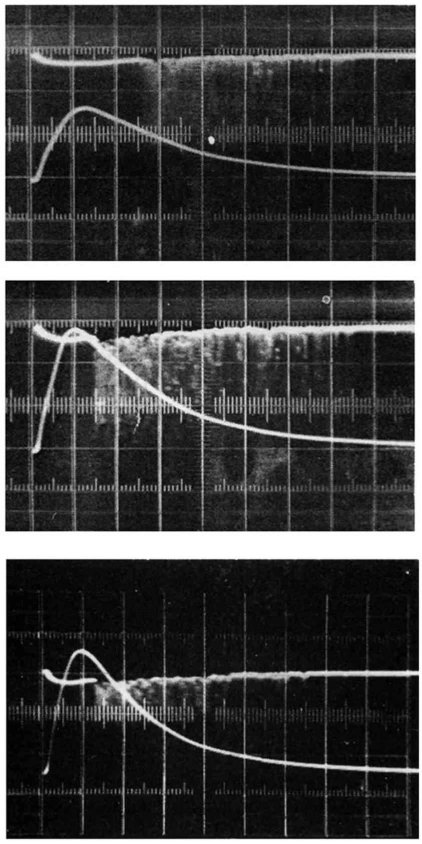

Figure 10. Generation kinetics at various pumping energies. Upper rays correspond to the R_1 line, lower rays refer to pumping lamp operation. The scale is 100 μs/div.

double-beam oscilloscope. The load resistor for a photomultiplier varied from 20 kΩ to 1 kΩ, depending on whether a luminescence or generation signal was observed. The supply voltage for the photomultipliers was 1.5 kV.

In such a setup, no scattered light from the flash lamp reached the output slit of the device, even in observing luminescence. The setup provided simultaneous observation of luminescence in both the R lines, generation in the R_1 line and luminescence in the R_2 line, and so on. Generation could also be observed without the spectrograph. In that case, radiation from the ruby crystal passed directly to the FEU-27 with an interference filter transparent to the R-line wavelength.

§ 8. Kinetics of luminescence, induced emission, and generation

In the installation described above, we observed and reproduced luminescence pulses on the oscilloscope separately for the R_1 and R_2 lines. At a low energy of the pumping lamps, we observed damped luminescence processes that were absolutely identical for the R_1 and R_2 lines described by the exponential law with $\tau = 3.5$ ms.

Upon a gradual increase in the pumping energy, the crystals, as in the study by Maiman [5], separated into two groups: some crystals exhibited only induced emission, whereas real optical generation occurred in other crystals.

Induced emission was revealed in that, starting from some energy value, the intensity ratio for the R_1 and R_2 lines

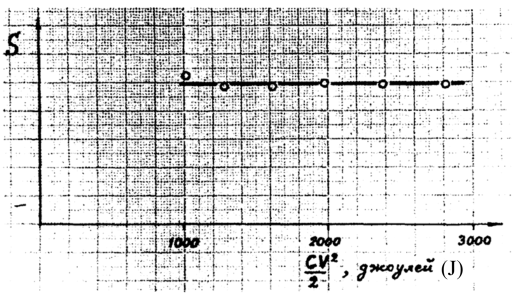

Figure 11. The pumping energy needed for starting generation versus the total energy of a flash lamp. *S* is the area under the oscillogram of the pumping lamp burning until the start of generation.

changed: the intensity of the R_1 line strongly increased, its damping kinetics drastically changed, and the damping was much faster. In Fig. 7, a variation of the relation between R_1 and R_2 versus the pumping energy is shown. A more thorough study of the intensity behavior for the R_1 line on faster scans has shown that it sharply jumps ≈ 250 μs after the onset of flash-lamp radiation (Fig. 8).

After reaching the threshold pumping value, the crystals in which optical generation was observed demonstrated a very sharp increase in the radiation intensity in the direction normal to the crystal face. The radiation kinetics drastically changed: the radiation was observed in the form of separate short spikes with a duration shorter than 1 μs (Fig. 9). The greater the energy excess over the threshold value was, the higher the repetition frequency of the spikes. The generation started 100–500 μs after the beginning of flash-lamp operation depending on the pumping energy (Fig. 10). The energy of flash-lamp radiation required for initiating generation, which is determined by the area under the oscillogram of pumping lamp intensity, was found to be constant (Fig. 11).

Therefore, the results exhibit the specific picture of pulsed ruby generation, which agrees with that described in [5, 7].

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* The volume number is indicated in accordance with the new system adopted on the Wiley site. The original volume number is 14.

Appendix II

Coherence, time scanning of the spectrum, and pulsations of laser radiation*

Z A Chizhikova, M D Galanin, V V Korobkin, A M Leontovich, V N Smorchkov

Academy of Sciences of the USSR

I. COHERENCE AND SPECTRUM OF RADIATION

It was shown in [1, 2] that the radiation of a ruby laser is actually coherent over the whole emitting face of the ruby crystal, that is, the radiation occurs in the modes excited in the bulk of the crystal. Most probably, these are so-called longitudinal modes [3] satisfying the equation

$$2L\mu = l\lambda \,, \tag{1}$$

where L is the distance between mirrors of the cavity, μ is the refractive index, λ is the radiation wavelength, and l is an integer. Several longitudinal modes are excited in each generation pulse [4], and this fact has no theoretical interpretation for ruby, which possesses a homogeneous broadening of gain [5].

In the present study, a time evolution of the radiation of these modes is studied in a pulsed mode of laser operation. Correspondingly, we studied coherence and obtained time scans of laser radiation spectra at various temperatures of ruby.

A. Coherence

Experiments were carried out at various temperatures of a ruby rod (+20 °C to −165 °C). Low temperatures were provided by blowing dry cold nitrogen and were controlled by a thermocouple attached to the ruby.

Radiation coherence was studied by observing an interference with the Michelson interferometer, one of whose mirrors was changed to a prism (Fig. 1). In the focal plane F of lens O, we observed two superimposed far-field images. One image originated due to a reflection from prism P and the other from mirror M. If the beams in the different arms are coherent and fit the same point in plane F, interference fringes arise at the point. In the same way, we studied the radiation coherence at various points of the ruby face. In that case, a lens was placed at the focal distance from the crystal face between crystal C and splitting plate D. In plane F, we then observed a superposition of two images of the crystal face. Thus, we could study the entire area simultaneously. In Fig. 2,

* A report at the Third International Conference on Quantum Electronics (Paris, 1963). (The original text of the report was edited for the present publication.)

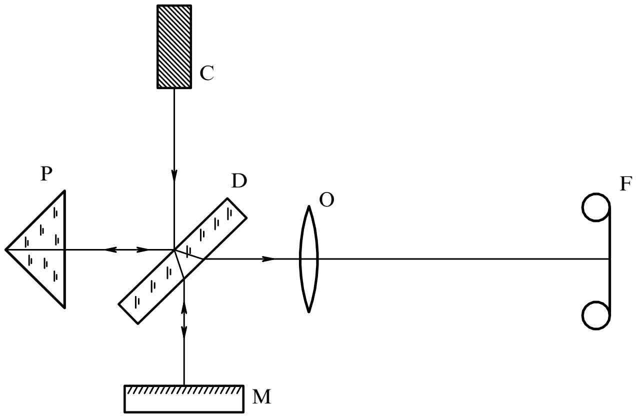

Figure 1. Schematic for observing interference.

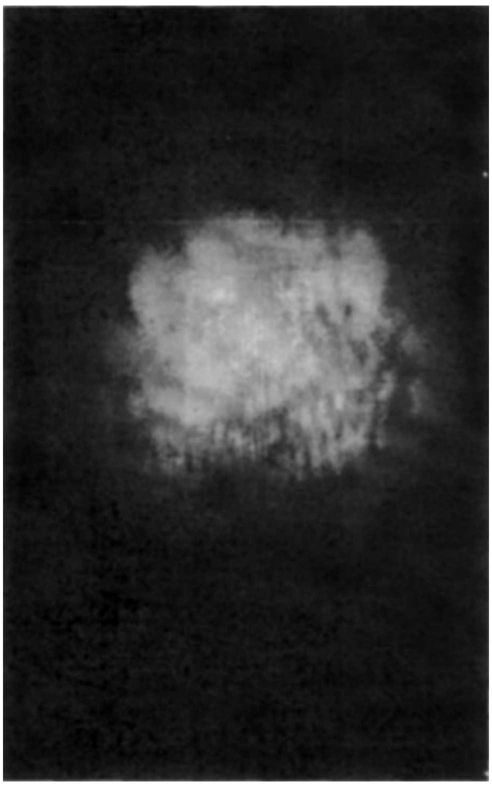

Figure 2. Interference of radiation propagating in various directions.

a photo of the interference observed for a single pumping pulse of a ruby rod at room temperature is shown. One can see the interference fringes on it; therefore, the rays propagating in different directions are coherent. This means that radiation in different modes propagates at different angles, that is, the wave front is not a plane (similarly to [2]), in contrast to the theoretical prediction [6] for a plane-parallel cavity.

At the ruby temperature $-165\,^{\circ}$C, the interference fringes are less pronounced.

In a similar way, it was found that the laser radiation is coherent over the whole emitting surface of the ruby face (similarly to [2]).

Interference fringes were only observed at a small (approximately 2%) excess of the pumping power over the threshold value. At higher excess, the fringes blurred and

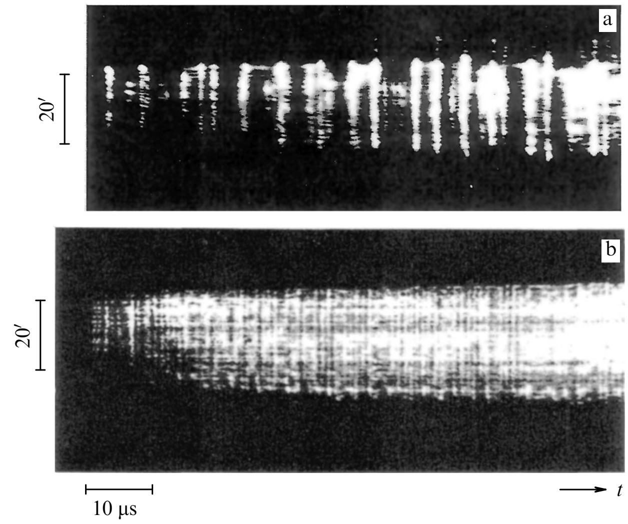

Figure 3. Time evolution of radiation with angular spread. Ruby: chrome concentration 0.05%, the optical axis is perpendicular to the crystal axis, $L = 76$ mm. (a) Ruby temperature $+20\,^{\circ}$C, (б) ruby temperature $-165\,^{\circ}$C.

disappeared. This can be explained by the fact that the integral inference picture comprises interference pictures from separate radiation spikes. If the pictures of separate spikes differ, the total interference picture is blurred. At a greater excess of pumping over the threshold value, modes in different spikes have different cross-section characteristics [7], which may lead to different interference pictures in different spikes.

B. Time scan

Time scans of laser radiation were taken with a high-speed SFR camera (speed photo recorder) with mirror scanning (in a slit photo-recording mode). In Fig. 3a, a photograph that was taken at the ruby temperature $+20\,^{\circ}$C is shown. The slit S of the camera was placed in a focal plane of a lens, where laser radiation passes. The photograph hence shows a temporal evolution of a far-field pattern. In the photograph, one can see that the radiation in each spike spreads out to a discrete set of angles with the total divergence of $30'-40'$ (it differs for different spikes). A measured difference in adjacent directions was of the order of λ/D, where D is the diameter of the ruby face.

Photographs of radiation time evolution obtained at the ruby temperature $-165\,^{\circ}$C (Fig. 3b) show that in this case, the generation spikes become almost regular, and the radiation consists of regular chains of pulses with equal interleaving time lapses between them. In some cases, a kind of beating between the pulsations is observed. The discrete directions are not so pronounced as in the case of room-temperature ruby. At all temperatures, the total beam divergence is usually less at the start of generation [8] than at later stages.

C. Radiation spectrum

Spectra of laser radiation for a single pumping pulse were studied by means of a Fabry–Perot interferometer with and without time scanning. From integral shots without time scanning, it was found that the generation occurs in longitudinal modes similarly to [3]. The mode separation is $1/(2L\mu)$ (in wave numbers, cm^{-1}). This means that during a pulse of generation, the change in the crystal optical length

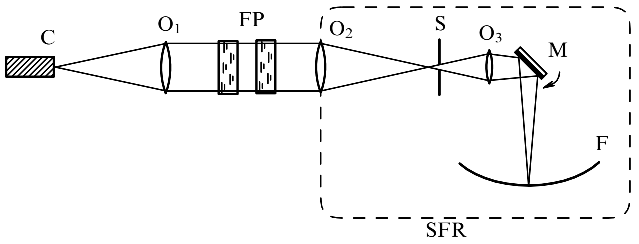

Figure 4. Schematic diagram of time scanning of spectra.

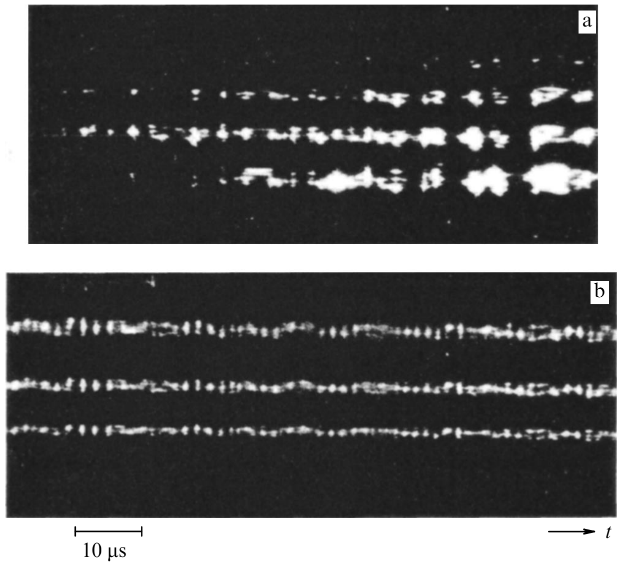

Figure 5. Time scan of the spectrum of radiation propagating in different directions. The ruby crystal is the same as in Fig. 3. The separation between the plates of the Fabry–Perot etalon is 5 mm. (a) The temperature of the ruby crystal is 20 °C, the start of generation. (b) The ruby temperature is −165 °C, 300 μs after the start of generation.

due to temperature expansion does not exceed $\lambda/2$, which follows from condition (1). Otherwise, the change in the longitudinal mode frequency would be greater than the mode separation and the integral image would spread. With the values of $\partial L/\partial T$ and $\partial\mu/\partial T$ taken from [8], we obtained $\Delta T < 0.3\,°\mathrm{C}$, that is, the increase in temperature in the course of generation does not exceed 0.3 °C.

Time scanning of laser radiation was performed with the same high-speed SFR camera with a rotating mirror (Fig. 4). An image of the ruby face was projected to the SFR slit by two lenses O_1 and O_2, between which a Fabry–Perot interferometer was placed. Lens O_1 was mounted at the focal length from the ruby face C and lens O_2 was at the focal length from slit S of the SFR. In this case, the image of the ruby face was projected to the slit plane and rings of the Fabry–Perot interferometer were observed. Slit S cut a vertical strip from the whole image of the rod, the radiation from which was scanned. Thus, we observed a time scan of the radiation emitted by the vertical strip of the ruby face.

By removing lens O_1, it is also possible to observe a time scan of a radiation spectrum in various directions. In Fig. 5, a time scan of the spectrum is shown for this last case. Several generation frequencies in each pulse can be seen, which are similar for different directions. The measured difference between neighboring frequencies was found to be $1/(2L\mu)$ cm^{-1} (in our case, 0.04 cm^{-1}), and hence the frequencies correspond to longitudinal modes. Longitudinal mode sets differ for different spikes. At room temperature of the ruby crystal, the number of longitudinal modes was $5-8$ (the corresponding spectral interval was 0.3 cm^{-1}). The total width of the generation spectrum was 1 cm^{-1} (the width of luminescence was 10 cm^{-1}). At the ruby temperature $-165\,°\mathrm{C}$, generation occurs in $3-4$ longitudinal modes at the total generation width ~ 0.25 cm^{-1} (at this temperature, the luminescence band is 0.6 cm^{-1} [9]). At room temperature, ruby generation only occurs in longitudinal modes, between which no generation is observed. However, at a low temperature of the ruby crystal, a noticeable background between longitudinal modes is observed (see Fig. 5), which corresponds to radiation at intermediate frequencies.

Discussion

Time scans of spectra show that in different spikes, the radiation intensity is modulated in several modes, which have different longitudinal parameters. The transverse characteristics of the modes are similar, which is confirmed by the experiment; otherwise, the interference fringes would blur. These modes are excited in the bulk of an emitting ruby crystal.

The modes emit in several directions with a total divergence of $30'-40'$ rather than in a single direction with the divergence λ/D ($20'$), as would be the case with a plane-parallel cavity. Therefore, high beam divergence cannot be explained by optical inhomogeneities because we have tested the internal homogeneity of the crystal with a Michelson interferometer (similarly to [10]), which was no worse than $1\,\mu$ ($1.5\,\lambda$). It would give a resulting divergence better than $30''$ instead of $30'$. In addition, it can be seen from Fig. 3 that the beam divergence varies in different spikes, whereas the effect of inhomogeneity should be similar for different spikes. For the same reason, light scattering cannot result in beam divergence. The only explanation is that the cavity characteristics change in the course of generation. As we have seen, the temperature variation is too small to be taken into account.

A possible explanation is that the refractive index in the R_1 ruby line changes during generation due to a variation of the population of the upper laser level. In this case, the cavity characteristics would change, which affects the beam divergence. At low temperatures of the ruby crystal, a modulation of the optical length of the cavity may itself result in a frequency modulation, which might explain the emission at intermediate frequencies between longitudinal modes.

II. PULSATIONS OF RADIATION

The theory of laser emission pulsations (spikes) developed in several studies [10–15] is not yet completed. This may be explained by insufficient experimental data on the spikes. We have experimentally measured the dependence of the average frequency for the spikes on the pumping power and ruby temperature. The spikes differ dramatically in amplitudes and follow each other irregularly. We measured the average time for 20–30 spikes, calculated the average repetition frequency for them, and compared it with the average power of pumping for the same time interval. These experiments were performed by using both a photomultiplier and time scanning. The data usually refer to the start of generation.

In Fig. 6, the average spike repetition frequency is shown versus the pumping power. It can be seen that the spike repetition frequency is a linear function of the pumping

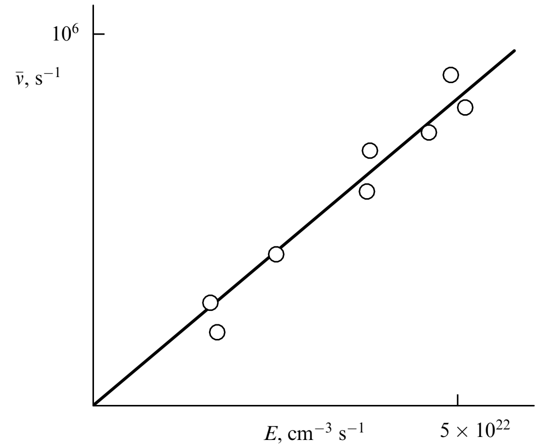

Рис. 6. The dependence of the average frequency of the peaks on the pumping power E.

power. The average amplitude of the spikes also increases linearly and their width, respectively, reduces.

We have already mentioned that at low temperatures, the pulsations are almost regular and a background emission is observed between them. At the temperature $-165\,^{\circ}$C, the pulsation frequency increases thrice compared to the case of a room temperature ruby crystal. The dependence of the pulsation repetition frequency on pumping is superlinear.

A simple theoretical scheme of pulsations leads to the equations [13]

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{N}{\tau} + bnN\,, \qquad \frac{1}{2}\frac{\mathrm{d}n}{\mathrm{d}t} = -bnN + E\,, \qquad (2)$$

where N is the energy density in a crystal expressed in terms of the number of photons, n is the number of active atoms, $b = Bh\nu$ is the Einstein coefficient, E is the pumping energy (the number of photons absorbed in 1 cm^3 for 1 s), and τ is the radiative lifetime of a photon inside the crystal. The solution of (2) yields damped pulsations (if $bE\tau^2 < 2$; in our cases, this parameter is of the order of 10^{-3}). The pulsation repetition frequency obtained from (2) is proportional to $\sqrt{bE}$ and does not agree with the experimental linear and superlinear (at low temperatures) dependence on E mentioned above. Probably, the pulsations are not the damped pulsations of an equilibrium state, but are relaxation auto-oscillations. This means that Eqns (2) are not appropriate for explaining the pulsations of radiation. Probably, as noted in [16], the pulsations and their irregularity at room temperature are connected with fluctuations of spontaneous emission. Actually, despite a sufficiently high photon density immediately prior to the start of emission, the number of spontaneous photons per mode is small (~ 100).

Fluctuations in the number of spontaneous photons with a frequency near the maximum luminescence may excite different modes in different spikes.

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