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DESIGN AND OPTIMIZATION OF RUBY LASERS IN THE USSR

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PREFACE

In January 1968, the Soviet Physics Uspekhi had published a voluminous review of solid state lasers.[1] This date marks essentially the passing of a decade of laser research[2] and marks the eighth anniversary of development of the first solid state laser--Maiman's ruby.[3] Late in coming, the Soviet review of the then state-of-the-art was based on 300 reference sources of which 130 were Soviet and Soviet Bloc. The authors of the review article--Mak, Anan'yev and Yermakov -- are actively engaged in the laser research and are affiliated with the State Optical Institute im. S.I. Vavilov in Leningrad, a major Soviet laser research center which is heavy committed to developing high-intensity solid state lasers.[4] The rapidly proliferating field of solid state laser research in the West has been the subject of a recent review[5] which only briefly touches upon the development of counterpart lasers in the Soviet Union. The intent of this 4-part paper is to summarize the most recent (1968 through 1969) Soviet solid state laser research, as reflected in the open scientific literature published in the USSR, and to identify the responsible groups and their affiliations. Part 1 is strictly devoted to ruby lasers. Parts 2-4 will deal with neodymium glass, YAG and flouride lasers, respectively. The application of solid state lasers throughout the Soviet technology was the subject of a recent comprehensive study.[6] In this summary, only those Soviet papers which are directly involved in the problem of optimal laser design will be discussed.

ABSTRACT

A comprehensive review is made of Soviet research on ruby lasers as reflected in the open scientific literature for the period from January 1968 through December 1969. It is shown that in the laser power sweepstakes, the Soviets have fielded some of their best researchers at several facilities to optimize the design of optically-pumped solid state devices. Research groups and their specialized areas of interest are identified and, in some instances, the Soviet and Western results are juxtaposed.

CONTENTS

I. RUBY LASERS

In a recent comparability study it was shown that the number of papers on ruby lasers published during the last two years was greater in the Soviet open literature than in American.[6] The Soviet output in that field is being generated at three major and, at least, a dozen minor laser research facilities. The major centers are: the Lebedev Institute, Institute of Physics Academy of Sciences BSSR, and the Vavilov Institute.

A. INSTITUTE OF PHYSICS im. P.N. LEBEDEV, Academy of Sciences USSR

By far the leading Soviet laser R&D facility, the Lebedev Institute has been heavily committed during the early laser days to semiconductor laser research, essentially by virtue of Basov's interest in them. However, in the last three years there has been a noticeable departure from this status, with a considerable effort going into studies of high-intensity solid state lasers and their application in the beam matter interaction problems. As a result of this, three groups are now generating ruby laser work at the Lebedev.

1. Basov's Group

Basov's group is vigorously pursuing its research dealing with the generation of plasma by a giant-pulse laser focused on a solid target. In this connection, the group is interested in the generation of ultrashort (picosecond) optical pulses in two-component systems consisting of an amplifying medium (ruby) and a saturable absorber (dye). In 1968, Letokhov published several papers on the dynamics of pulse shortening in such a system.[7,8,9] The more recent spectral studies examine the fluctuations of the multimode ruby laser radiation (input) propagated through such a system and the occurrence of high-intensity spikes in the output after multipass propagation through the absorber (kryptocyanine).[10,11] The experiments point to the fact that a two-component system can indeed be used to transform fluctuating multimode noise into mode-locked ultrashort pulses. The authors claim that in principle, single ultrashort pulses can be obtained from a high-intensity noncoherent super-radiant radiation using these methods.

2. Prokhorov's Group

In what appears to have been an effort totally independent of the Letokhov studies, Academician Prokhorov was the first to generate ultrashort pulses in a mode-locked ring ruby laser with a saturable absorber.[12] Writing at the time when Nd-glass and Nd-garnet mode-locked lasers (pulse duration 2×10^{-12} sec) were already in operation in the West, Prokhorov obtained a train of 10 mode-locked pulses, each with duration of $\sim 0.9 \times 10^{-11}$ sec and peak power of 2.5×10^{9} w. The divergence of his mode-locked laser was 3 arc min.

Some time later, Prokhorov carried out essentially the same measurements of pulse duration and energy on the same laser as above, using, however, a different measuring technique.[13] Whereas the pulse duration in Ref. 12 was measured by superimposing two time-shifted optical pulses in CdS and Iceland spar crystals, the new experiments were carried out using Giordmaine's method based on two-photon excitation of fluorescence by mode-locked pulses in a nonlinear medium. The pulse duration and peak power were 2.4×10^{-11} sec and $\sim 1.2 \times 10^{9}$ w, respectively.

The experimental results of Malyshev et al, which are based on the measurement of spectral width of a mode-locked ruby laser, yield comparable pulse duration values of $(1.1 - 2.4) \times 10^{-11}$ sec.[14]

Malyshev is also trying to clean up the output of a ruby laser. His theoretical and experimental studies, in collaboration with Markin and Sychev, are programmed to look at the spectral and temporal characteristics of free-running ruby (and Nd-glass) lasers.[15,16] Their earlier studies with passively Q-switched and single-spike free-running lasers showed that the structure and width of spectra are determined to a great extent by mode discrimination by the various elements of a cavity.[4] They have also proposed a ruby laser cavity without a mode discrimination.[4] This has led them to look more recently at a multi-spike free-running laser, disallowing for mode discrimination in the cavity which tends to camouflage other effects. Their results appear to be useful in the study of relaxation process in the active medium which govern the kinetics of generation spectrum.

In order to optimize the rod lengths of the oscillator and amplifier sections of a solid state laser amplifier, Karlov and Konev have made calculations for two cases of homogeneously and nonhomogeneously-broadened laser lines.[17] They found that for a given L (length of active medium) and $\beta\ell \ll 1$ (where β are the distributed losses and ℓ is the length of amplifier), the separation into the oscillator and amplifier sections is desirable in the case of homogeneous broadening of the laser line and is not in the case of inhomogeneously broadened lines. Where $\beta L \gg 1$, both methods yield the same results in either case of broadening. Their analysis also showed that the improvement of spatial and spectral emission characteristics of high-power lasers by means of single-mode oscillators which are used in conjunction with power amplifiers, did not decrease the output power.

3. Galanin's Group

The mode discrimination in a ruby laser cavity was also the subject of experimental studies carried out by members of a group headed by M.D. Galanin. Through 1967, this group was primarily interested in the kinetics of giant-pulse ruby lasers and in nonlinear optics.[4] Korobkin and Shchelev showed that the best mode discrimination could be achieved if one of the resonator mirrors were replaced by an active Fabry Perot interferometer.[18]

In 1965, Veduta observed that the laser rod continues to heat up even after the end of the pumping pulse, and this changes the optical properties of the rod (ZhETF 48, 1965, 87). A more recent study carried out on ruby (and Nd-glass) rods under anisotropic pumping conditions (2 lamps) shows that the heating is due to infrared radiation emitted by the flash lamp shortly before and after the end of the pumping pulse (for 1.5 to 150 μsec).[10] This effect was observed for water- or air-cooled rods except for rubies with leucosapphire jackets whose absorption bands are outside the pumping range. The study shows that the most intense heating in the rod occurs in the plane of the two flashlamps and the least, in the upper and lower edges of the rod cross section.

The temperature and energy distribution in air-cooled polished cylindrical ruby rods under isotropic pumping were also studied by Veduta.[20] Disallowing for losses, he had calculated the maximum possible generation energy and rod effectiveness and showed, expermentally, the effectiveness of an illuminator used in conjunction with a spiral IFK-1500 flashlamp. Veduta's results show that due to the excited state absorption in the UV region the temperature of the upper rod layer 0.1-mm thick increases by 25°.

The degradation of ruby-laser output energy as a result of color center production was shown recently by C.M. Stickley et al.[21] Studies of this problem have been conducted within Galanin's group by Arkhangel'skiy, Morgenshtern and Neustruyev since 1965.[4] In 1968, on the basis of the literature data and some experimentation of their own carried out on optically- and γ-irradiated rubies, these researchers concluded that the basic color centers in a ruby are the Cr^{2+} and Cr^{4+} ions.[22] The additional absorption caused by these centers was shown to lead to a reduction of the quantum yield in the R-line region which, in turn, increases the generation threshold of the ruby laser.[23] In addition to the above changes, the nascent Cr^{2+} and Cr^{4+} centers interact with the Cr^{3+} spectrum.[24] This interaction leads to an increase in the oscillator strength of the $^4A_2 \rightarrow {}^2E$ and $^4A_2 \rightarrow {}^2T_2$ transitions, a decrease in the fluorescence, and the broadening of certain EPR spectral lines. These effects are presumed to be the result of the higher probability for the forbidden transitions from the $^4A_2 \rightarrow {}^2E$ and $^4A_2 \rightarrow {}^2T_2$ of a Cr^{3+} ion in the corundum lattice.

B. STATE OPTICAL INSTITUTE im. S.I. VAVILOV

The high-intensity solid state laser studies at the Vavilov Institute have been always in the forefront of its R&D activities.[4] Although the bulk of that effort has been in the Nd-glass and fluoride lasers, recently published papers indicate a rising interest in the ruby laser. The dominant figure in the Institute's solid state laser research (particularly glass) had been M.P. Vanyukov, at least until the end of 1967. In the last two years (68/69), Vanyukov's name has not appeared in print as often as it did before.

As far as the publishing activity is concerned, his place appears to have been filled, at least for the time being, by B.A. Yermakov and A.A. Mak. Except for having co-published (with Anan'yev) a review of solid state lasers,[1] Yermakov and Mak appear to be working independently of each other on two different aspects of the same optimal design problem.

1. Yermakov's Group

Yermakov's principal collaborators are: V.N. Andreyev, I.F. Balashov, V.A. Berenberg, B.G. Berezin, and V.V. Blagoveshchenskiy. One area of their interest is the modulation of ruby laser radiation. In this connection, they have performed experiments to achieve single pulse generation of a Q-switched ruby laser in which power limitations are overcome not by increasing the speed of a rotating prism but by the introduction of additional total-internal-reflection plates into the cavity.[25] They first established the relationships between the prism rotation speed, the (minimal) number of reflections at the plates, the polarization of light, the losses and other factors in order to ensure maximum power extraction and single pulse operation. These relationships were then verified experimentally using a ruby laser with a prism rotating at $3\text{-}6 \times 10^4$ rpm and plates having 4 and 8 reflections. The results show that the first-pulse energy is nearly doubled by introduction of a multiple-reflection plate, but is still approximately one half of the value attainable with instantaneous Q-switching.

The generation of micro- and nanosecond pulses in a ruby laser by means of novel Q-switching techniques, is another area of the group's interest. Balashov et al has generated highly stable rectangular pulses of 4 - 10 μsec duration in a feedback-controlled fully-pumped Q-switched ruber laser.[26] Unlike in the system proposed by Thomas and Price (j. of QE, 2, 9, 1966, 617) which used a photodiode feedback, Balashov used a 100 mm long benzene-filled cell in the cavity to achieve negative feedback, due to SRS losses. In so doing, he claims to have eliminated the high-frequency pulse amplitude instability which occurred in the Thomas-Price experiments. His spherical resonator was Q-switched by a rotating total-internal-reflection prism (at $15\text{-}25\times10^3$ rpm) and the energy of pulses amplified in a 1.6x12 cm rod was 0.8 - 1 j.

A method of generating powerful pulses with durations less than the two-pass time of a photon is a resonator $\left(\frac{2L}{c}\right)$ was shown experimentally by Yermakov et al.[27] It is based on the principle of rapidly increasing the transmission of one mirror (up to ~100%) at the instant of a field maximum and was demonstrated earlier in the West (J. Ernest et al, Phys. Lett., 22, 2, 1966, 147; W.R. Hook et al, Appl. Phys. Lett. 9, 3, 1966, 125). However, whereas the Western experiments used an electro-optic shutter and a polarizing prism for Q-switching, Yermakov used a Kerr cell filled with a saturable absorber (vanadium phthalocyanine in nitrobenzene) and a simple pulse system with a laser-fired discharger in order to be able to Q-switch precisely at the generation maximum for the most efficient energy extraction. With this system (60-cm cavity and a 7x80 mm ruby rod) he obtained a 3.5-nanosec ~ 6-Mw pulses.

An improvement of gain effectiveness of weak (less than 0.5j) optical signals was investigated by Balashov and Berenberg theoretically and experimentally[28] in terms of a more complete utilization of the excitation energy by way of increasing the length of the signal path in the amplifying medium. The theoretical paper provides relationships between the input and output signal energies in the absence of losses for a single-pass regenerative amplifier and a double-pass amplifier. The results indicate that a two-pass amplifier is considerably more effective than the present-day single-pass TW and regenerative amplifiers. However, losses tend to make two-pass amplifiers less eff tive for large signals. The experiments verify that the maximum energy extraction from a two-pass amplifier occurred at 0.1 - 0.2 j input signals when nearly all of the energy in a fully-pumped rod was extracted. Greater than 30-fold gain was observed for a 0.025j input signal ($\sim$ 10-fold single-pass gain) in a 10x120 mm ruby with 30-mm long sapphire end pieces which was pumpted by a 7x120 mm ruby laser oscillator. The oscillator and amplifier rods were placed $\sim$ 40 cm apart and the spatial separation of the two opposed beams in the amplifier rod was accomplished by tilting the latter by an angle of $\sim$ 30 arc min. The maximum beam displacement of the return signal in the amplifier rod with respect to the forward pass was $\sim$ 1.5 mm. Practically all of the rod volume was filled with the signal and the energy losses due to lateral extraction were less than 30%.

The third aspect of ruby laser research in the Yermakov group are the experimental studies of active rod deformation due to heating and the means of its prevention.[20] It was shown that a nonsymmetrical metalic heat sink attached to not more than 25% of the rod lateral surface provides an effective cooling for a laser operating in a single-pulse regime with a repetition frequency not greater than 3-5 sec^{-1} when the amount of heat through the sink is 10-50 w and the thermal deformation of the rod between pulses is negligible.

2. Mak's Group

The emission spectrum of a ruby laser is characterized normally by three regimes: chaotic spikes, a smooth pulse, and periodic pulsations. In all three, the spectrum is comparatively wide (0.02 - 1Å) and in the case of pulsed operation its stability is normally low.

While studying the spectrum kinetics of a ruby laser with plane and concentric resonators, Mak and Sedov claim to have observed a new generation regime characterized by high monochromaticity ($\Delta\lambda \approx 5 \times 10^{-4}$ Å) and laser frequency stability.[30] The remarkable feature of this regime is the independence of the laser wavelength from the temperature changes ($\Delta T \approx 4 - 5^{\circ}C$) in the active medium and the corresponding thermal deformation of the resonator. The frequency stabilization effect was observed in a ruby with a sapphire jacket placed inside a resonator. A jacketless ruby continued to generate a high monochromatic output, although not without a certain frequency drift. A similar effect was observed in sapphire-clad rubies whose ends formed the resonator cavity. In this case, however, the laser frequency remained stable during periods not longer than 100-200 μsec. In between these, the frequency follows essentially the temperature drift of the fluorescence line.

Mak's experimental results of the dependence of the width of emission spectra of solid state lasers (ruby, Nd-glass, fluoride) on the parameters of the active medium, the pump and the resonator (plane only) are compared against those calculated from a formula advanced in an earlier Soviet paper (DAN SSSR, 168, 1966, 72).[31] Results show that at temperature $T > 100^{\circ}K$ the broadening of the fluorescence line is essentially homogenous, while below those it is overwhelmingly inhomogenous. In the first case, the experimental and theoretical data basically agree, although the latter are somewhat higher. The axial mode intensity distribution is frequently non-Gaussian as postulated by the Tang-Statz condition, and can be attributed to insufficiently "averaging" the spectrum over the spikes.

Outside of the Mak and Yermakov groups several Vavilov Institute researchers are also involved in ruby laser studies. The studies of Muzhdaba et al[32], and Ageyeva and Kolyadin[33] of small-angle scattering of light in corundum crystals are an extension of a series of earlier Soviet studies in this area which were carried out to establish the effect of scattering on the generation characteristics of a ruby laser. The results show that: (1) in the corundum crystals with the orthogonal optical and crystal growth axes the scattering index in the direction of the beam and in an angle from 2' to 3° is $0.01 - 0.1\ cm^{-1}$, and $1\text{-}6 \times 10^{-4}\ cm^{-1}$ at 90° to the beam; (2) the principal crystal defect which leads to light scattering at large angles is the occurrence of "fog" in the central portion of a crystal; and (3) small-angle light scattering in the Verneuil crystals is caused by structural scattering ($\sim 10^{-2}\ cm^{-1}$) and the non spherical components of the refractive index gradient due to nonuniform distribution of Cr ions in the matrix.

Ageyeva has also carried out measurements to establish the dependence of the degree of polarization of light propagated through a (synthetic) ruby crystal on the losses due to small-angle scattering.[34] The degree of polarization is a useful parameter in determining the optical quality of a crystal. The measurement of this parameter is considered useful insofar as it reveals two basic rules for ruby crystals: (1) for each individual polarization incident on a crystal the degree of polarization decreases from sample to sample with increasing losses due to small-angle scattering, and (2) the relationship between depolarization and scattering losses for different beams in the same sample is an inverse function.

Veyko and Suslov made a comparative study of ruby and Nd-glass lasers with regard to the thermal effects arising in them from a periodic operation, which change the energy, pulse duration and divergence of the laser beam.[35] This appears to be a routing study, culminating in a conclusion that Nd-glass is superior to ruby as a laser material at pumping rates of ~ 1 Hz, while the ruby performs better than Nd-glass at higher pumping rates with intense cooling.

C. INSTITUTE OF PHYSICS, ACADEMY OF SCIENCES BSSR

The solid state laser research at the Institute of Physics AN BSSR in Minsk is largely theoretical, a trend which was established several years ago by Academician B. I. Stepanov, its most prominent advocate.[4] Although Stepanov's interests have resulted in the last two years in several experimental studies (notably stimulated emission of ruby- and glass-laser-pumped organic dyes), the nature of the solid state laser research remains essentially theoretical. Nowadays, Stepanov publishes infrequently, but his guidance and sponsorship of other authors is evident in the numerous salutatory statements in their articles.

1. Stepanov's Group

The *de facto* leader of this group appears to be A.M. Samson whose 1966 studies of amplified fluorescence in ruby (and glass) rods and other loss-mechanism studies, have established him firmly as one of the leading experts in the optimal laser design at Minsk.[4] Samson's more recent co-publishing collegues are: Kotomtseva, Karamaliyev, Chekalinskaya, Katseva, Rybakov, Stashkevich and Chechenina.

One of the recent studies is on the noise in solid state lasers which increases with the rod size causing a degradation of the output energy.[36] This work evaluates noise originating from the pump radiation penetrating into and being amplified by the active medium. As an example, a cylindrical ruby rod with opaque lateral surfaces is considered under the conditions of generation. Under these conditions, the laser gain can be considered independently of the pumping, radiation noise and generation. This, in turn, makes it possible to distinguish pump-radiation noise independently of other noise (such as due to fluorescence and/or scattering).

Another theoretical study employs the rate equation approach to a model of a laser with a split metastable level.[37] Samson had shown that laser action occurs at two different frequencies which correspond to transitions from both metastable states.

The kinetic equations were used by Samson in the theoretical analysis of the operation of a ruby laser with a ruby filter.[38] Such a system appears to be of interest since it may serve as a model for the study of the properties of a laser with an inhomogeneously excited rod. An analysis of the system's properties tends to explain the role of a nonlinear absorption of stimulated emission by the non-active centers in the active medium in the course of formation of the non-stationary generation. The study shows that the instability of the stationary regime can occur only in a laser with a saturable filter, but not in one where the filter acts as an amplifying medium. A computer solution of the kinetic equations is given for the entire stability domain.

Samson's most recent study uses the balance equations to look at the temporal development of a single pulse in a ruby laser with a saturable absorber.[39] In it, Samson derived analytical expressions for the time required to form a single pulse and the spectral width of radiation. His calculations for modes with a different gain have shown that the spectral width of a laser pulse varies by approximately one order of magnitude in the process of pulse formation from noise. Subsequent development of the giant pulse under the generation conditions leads to even greater narrowing of the spectrum.

Chekalinskaya used wave optics to calculate the frequencies and the loss coefficients of axial modes for a ruby amplifier consisting of two rods in series and operating in the stationary regime.[40] Unlike in the earlier works of Birnbaum (J.Appl.Phys. 34, 1963, 3414; 37, 1966, 531), her calculations allow for wave interference in the intermediary layer and place no restrictions on the magnitude of loss coefficients. Particular attention is paid to two specific cases: a symmetrical laser (both rods have identical lengths and reflection coefficients of output ends) and an asymmetrical laser (lengths identical, one rod end fully reflective). The study proceeds from a derivation of an equation for the stationary generation of the composite system when the lasing condition is satisfied for the intermediate layer between the rods. Calculations by means of this equation show that the loss coefficient of a composite laser is the same for all the natural frequencies and is determined only by the reflection coefficient at the output faces of the composite system. The presence of the intermediate layer has no effect on the radiation loss, and the laser frequencies depend on the optical lengths of the active medium and the intermediate layer, and also on the change of phase upon reflection from the output face. The average number of modes generated by a symmetrical laser in a certain interval is approximately equal to the number of modes of a simple laser having an optical length equal to the total optical length of a composite laser. Calculation of the frequency characteristics of the asymmetrical laser and of the generation threshold shows that, unlike in a symmetrical laser, each natural frequency has its own loss coefficient. An exception is the case when the change of phase on the reflecting face equals an even number of periods, in which case the loss coefficient of the asymmetrical laser is the same for all frequencies and depends neither on the reflection coefficient of the intermediate layer nor on its optical length. The mode selection is determined by the frequency dependence of the gain of the active medium. The loss of an asymmetrical laser depends not only on the coefficient of reflection from the output face, but also on the coefficient of reflection from the boundary of the intermediate layer and on the optical length of the latter. Chekalinskaya's results show that in the case of an asymmetrical laser the values of loss coefficients obtained in the geometric-optics approximation are nearly the same as the minimum loss coefficients obtained by wave calculations. In the case of a symmetrical laser, the loss coefficients obtained by geometric- and wave-optics approximations are fully identical.

Chekalinskaya's more recent study concerns the effect of the intensity of an amplified signal and the resonator parameters on the frequency characteristics of regenerative laser amplifiers with simple and complex resonators.[41] The computer study considers the amplification of a monochromatic beam in which allowance is made for the gain saturation in the active medium in the case of homogenous line broadening. The results indicate that the frequency dependence of gain is most noticeable near the generation threshold at small input signals. As the intensity of the input signal increases, the gain decreases and the gain line shape broadens. If the single-pass gain in the active medium is greater than $r_2^{-1/2}$ (where r_2 is the coefficient of reflection at the output end) then the gain at the natural frequencies in an amplifier with feedback is a maximum; however, if such a condition is not satisfied, the gain is a minimum. The gain of a single-pass amplifier is always maximum at the natural frequencies and is independent of the amplitude of the input signal.

In addition to Samson and his coworkers, Stepanov supports two other teams within his laboratory, which consist of A.N. Rubinov and T.I. Smol'skaya, and A.S. Rubanov and A.V. Chaley. All four are experimentalists. Rubinov and Smol'skaya are concerned with studying the generation characteristics of multi-rod ruby (and Nd-glass) lasers,[42,43] and the energy losses which occur in optically inhomogenous rods due to edge effects[44] and radiation noise.[45] Rubanov and Chaley are continuing their earlier experimentation on the heating effects in a ruby laser.[46]

In support of Rubanov's research are V.P. Gribkovskiy and F.K. Rutkovskiy. The first has done some experimental work on the effect of rod surface finish on optical pumping.[47] Rutkovskiy's computer studies examine the distribution of population inversion and the extent of pump radiation absorption in a ruby rod.[48] Rutkovskiy had derived formulas which interrelate the radiation density in a laser, the absorption coefficient, the level population and the pumping rate, from which the distribution of population inversion and the absorption across a ruby rod can be calculated for a given temporal shape of the pump intensity. He had shown that the most uniform distribution of population occurs when the optical thickness $\delta \approx 4$, and had determined the coefficients which indicate the amounts of pump radiation being utilized for producing the population inversion and heating.

2. Independent Groups

Besides the strong Stepanov group, the Institute's ruby-laser research is conducted by several considerably smaller author groups without well-defined leaderships. These groups do not appear to collaborate with each other or with Stepanov, and the bulk of their work concerns the generation dynamics of solid state lasers.

Thus, Boyko et al have proposed and experimentally tested a ruby laser in which the active medium forms the total-internal-reflection cavity.[49] The most distinct advantage of such a resonator is its near-total resistance to deformation caused by the thermal inhomogeneities of the active medium. DeMaria was the first to propose such a laser (Proc. IEEE, 53, 1965, 1757). However, unlike Boyko's, his ruby was immersed in liquid nitrogen, a feature which Boyko considers problematic. Boyko's ruby (10×80 mm) had yielded 0.8-j per pulse energies for a pumping energy of 800j.

One way to compensate for the optical inhomogeneity of the laser rods, which is unlike the existing methods (introduction of a positive lens into the resonator, the use of a spherical mirror in the resonator) is to use, according to Boyko, a "capped (beveled) prism" as the opaque mirror, in which one of the reflective sides is spherical.[50] Such a reflector acts in a manner of an elliptical mirror. In fact, in rubies with a 90^{o} orientation of the optical axis, optical inhomogeneities in the rod cause an elliptical rather than spherical lensing effect, and the proposed compensation method is even more effective. Tests were made using capped prisms with different radii of curvature of the spherical side (R = 15, 9.5, and 7.6 m). Results show that the smaller the R, the lower the threshold energy and the higher the output energy. For the optimal R (9.5m), the beam divergence decreases by a factor of 2 (to 2.35 min of arc) in comparison with a regular-prism resonator.

Boyko has also carried out an experiment (which he claims to be the first of its kind) of the effect of a magnetic field on the absorption spectrum of a ruby in the R-line region at the room temperature.[51] The study has established that at the temperature of $30^{o}C$ and field intensity of ~ 70 koe and 100 koe, the absorption coefficients at the R_1-line maximum were 0.15 cm^{-1} and 0.11 cm^{-1}, respectively, i.e., ~ 1/2 and 1/3 the value in the absence of a field. He also observed a change in the shape of the absorption spectrum, a fact which can be used for gain control in ruby lasers at the room temperature.

There are two routine experimental studies of the properties of saturable filters and their effect on the parameters or ruby laser emission.[52,53]

D. LASER RESEARCH INSTITUTES IN THE CITY OF KIEV

Kiev is the home of several laser research establishments whose solid state laser programs are far less ambitious than those of the preceding institutes. For that reason Kiev-based facilities are grouped in this chapter and a brief description of the ruby-laser design activity is given.

1. Kiev State University

Kondilenko and Koshel' have experimented with continuously-tunable two frequency giant-pulse multirod ruby lasers which can be used in the study of the fine structure of nonlinear filters.[54,55]

Anisimov, Gorban' and Kononchuk are continuing their earlier (1967) work on the changes in the refractive index of ruby under strong pumping in the 650-680 nm region. They have shown that the refractive index of ruby changes not only due to heating but also the high density of the excited chromium ions.[56,57] They have also proposed a method of determining the gain and the internal losses of a ruby laser with a polarized superradiance.[58] The method is based on introducing a half-wave plate into the resonator which changes the light polarization in the laser and, thus, its gain in a normal manner. This permits measurements of the loss coefficient in terms of known laser parameters.

2. Physics Institute, Academy of Sciences Ukr SSR

In 1967, M.S. Soskin et al showed that self-disruption of generation occurs in a ruby laser with plane mirrors upon introduction of various liquids (glycerine, benzene, nitrogen) and/or transparent solids (plastic glasses) into the cavity.[4] This line of research has been pursued for the case of a ruby laser with spherical mirrors.[59] The study shows that the relative increase in the output energy due to self-disruption of generation in a spherical cavity over the plane-mirror cavity indicates that a considerable portion of the stimulated emission energy is scattered in the liquid (glycerine). This energy is then returned into the resonator by virtue of its sphericity.

Soskin and V.S. Mashkevich have acted in an advisory capacity in some low-temperature experimental studies of ruby lasers by Danileyko et al.[60] Whereas in earlier investigations it was assumed that the dependences of the threshold pump power on the transparency of the resonator are the same at $300^{O}K$ and $78^{O}K$, Danileyko found that at $78^{O}K$ the Q of the resonator has very little influence on the threshold power, making it possible to work with ruby rods without special high-reflectivity coatings. The analysis shows that this phenomenon is connected with the great predominance of reabsorption losses over the losses due to the resonator transparency. By comparing the distribution pattern of the axial modes in the emission spectrum of the laser at $300^{O}K$ and $78^{O}K$, it is concluded that when the ruby is cooled the mode competition decreases and may be the cause of the observed quasi-cw emission.

E. INSTITUTE OF SEMICONDUCTOR PHYSICS, SIBERIAN BRANCH OF THE ACADEMY OF SCIENCES USSR

At one time a predominantly gas-laser research facility,[4] the Institute of Semiconductor Physics has given considerable support to ruby laser studies in the last two years. The work there is essentially experimental and the result of a team effort by A.N. Bondarenko, G.V. Krivoshchekov, K.G. Folin, V.A. Smirnov and V.V. Antsiferov, who publish in various co-author configurations, with the exception of Bondarenko and Antsiferov who have not co-published since 1967.

Bondarenko et al have looked at the spectral characteristics of a Q-switched ruby laser pumped by Q-switched[61] and free-running[62,63] ruby lasers. The purpose of these experiments appears to be the production of frequency-tunable high powers from the R_1 and R_2 lines. The results indicate that for a given intensity of the pump signal, the generation and pump signal spectra are identical.

The same authors have also described a method for the stabilization of the time pulse duration in a Q-switched ruby laser.[64] Bondarenko has also examined experimentally the gain distribution in a solid state laser as a function of time.[65] Knowledge of the gain distribution makes it possible to calculate the field in the laser cavity and to diaphragm in a suitable manner the laser rod in order to effect mode selection. It also makes it possible to confine the laser action to the most effectively generating central section of the rod.

Antsiferov, working with the same people as Bondarenko, has carried out a number of experimental studies involving the internal frequency modulation[66] and generation dynamics[67,68] of a ruby laser. The spectral, angular and temporal characteristics of a TW ruby laser are the subject of another experimental study by the Antsiferov group.[69]

F. INSTITUTE OF CRYSTALLOGRAPHY, ACADEMY OF SCIENCES USSR

The Institute of Crystallography is the principal grower and supplier of laser crystals to the Soviet laser R&D community.[4] By virtue of its role, the Institute conducts a small-scale research program to improve the rod quality and to devise analytical methods of determining the various crystal properties.

Until her recent death in September 1969, S.V. Grum-Grzhimaylo was one of the Institute's better-known investigators of ruby crystals. She was the editor of a volume of collected works on the quality of ruby crystals.[70] This work is a very thorough review of the structural, chemical, optical, thermal and mechanical characteristics of the ruby crystals and an equally extensive description of the various macro- and microscopic defects. The book also reviews the internal stresses, orientation and distribution of active impurities (Cr^{3+}), refractive index inhomogeneity and the control methods of growing ruby crystals.

In addition to the late Grum-Grzhimaylo, other researchers at the Institute have studied, in collaboration with the Lebedev Institute's Prokhorov and Manenkov, the relationship between the optical homogeneity of ruby crystals and the laser beam divergence.[71] Their results show that from among the various sources of the optical inhomogeneity in ruby crystals -- bloc structure, slip planes, chromium concentration nonuniformity, macrostrains -- the latter exhibit the greatest effect on the distribution of laser energy in the far field. The presence of macrostrains in the crystal causes wavefront deformations, which cannot be corrected by the optical systems.

G. TOMSK INSTITUTE OF RADIO ENGINEERING AND ELECTRON TECHNOLOGY

The Institute of Radio Engineering and Electron Technology at Tomsk has emerged only recently (1967) as a laser R&D facility.[4] Its modest laser research program is apparently the responsibility of Ye. S. Kovalenko.

In 1968, Kovalenko described a method which makes it possible to improve greatly the temporal characteristics of solid state lasers and to eliminate the spiking present in the output.[72] The method consists of increasing the rate of pumping by limiting the transverse dimensions of the generation region, followed by displacement of the latter over the transverse cross section of the active medium. This is done either mechanically or electrically by means of a shutter having a movable transmission region and placed inside the cavity. Owing to the smallness of the spatial diffusion of the population investion, this causes different regions of the active medium to generate at different times. If the scanning rate is high enough, spikeless generation can be obtained. This method can also produce quasi-cw operation or any combination of smooth laser pulses with duration from several to several tens of microseconds.

More recently (1969), Kovalenko and his group have published two experimental papers[73,74] and one theoretical.[75] The experimental papers deal with h-f modulation of the spatial field structure in a ruby laser[73], and the effect of crystal orientation in the cavity on the generation spectrum of a ruby laser.[74] In the first case, two modulators (KDP crystals) were placed on each side of a ruby rod inside a Fabry-Perot cavity in order to introduce phase shifts (same amplitude, opposite sign). This led to a periodic longitudinal displacement of the field's nodes and loops in the crystal at the modulation frequency (7.5 MHz), without the detuning of the resonator. Under such conditions, the de-excitation of the upper level proceeds uniformly, the spatial inhomogeneity of the population difference decreases, resulting in a substantial (not less than 10-fold) narrowing of the output spectrum.

Kovalenko's theoretical paper is a quantitative analysis of the possibility of obtaining the population inversion of the ground state sublevels in the case of the generation of a single spectral line.[75] The internal optical pumping appears to have several advantages. In view of the large volume of the active medium (5-10 cm^3), high amplifier gains or oscillator output powers are possible. Losses which arise due to elements of external pumping systems are eliminated by the internal pumping (only one working crystal is used).

H. SIBERIAN PHYSICO-TECHNICAL INSTITUTE im. V.D. KUZENTSOV

This Institute is better-known for its laser studies in the area of optical beam propagation in air and other particulate media.[4]

Two recent (1969) papers on the temperature measurement of the ruby laser wavelength,[76,77] suggest a broadening of interests at that facility. These experimental papers by Kokhanenko and Antipov are an attempt to observe the temperature shift of the R_1-line from the absorption, fluorescence and generation spectra of a ruby laser at temperatures (surface) from 12 to 135°C. The measurement of the ruby laser wavelength is refined to within 0.3Å.

I. MOSCOW SCIENTIFIC-RESEARCH INSTITUTE OF INSTRUMENT MANUFACTURE

The solid state laser research at the above institute is headed by A.L. Mikaelyan, the co-author (with his younger brother M.L. Mikaelyan and Yu. G. Turkov) of a concise monograph on that subject,[78] and a frequent visitor to the USA (IQE Conferences--Phoenix, Miami, etc.).

In fact, during his 1968 visit to the Fifth IQE Conference in Miami, Mikaelyan presented a paper which was subsequently published in the Soviet literature.[79,80]

The main intent of this work was to observe changes in the field pattern of a single-mode pulse from a ruby laser which was amplified in a TW ruby laser amplifier. The input signal was an 8-ns 0.02-j pulse with a width of 0.8 mm. The near field pattern showed that the initially circular input beam was distorted into an elliptical cross-section with the axes ratio being dependent on the magnitude of inversion and determined by the geometry of the pump system and ruby crystal. The far field structure also had axes oriented like those of the near field pattern but not perpendicular as might be expected. This is due to thermal distortion of the crystal input force, which is maximum in the direction perpendicular to the plane of incidence. The divergence measured along the minor axis was 0.62 $\times 10^{-3}$ rad at the 0.5 level, while in the perpendicular direction, 12×10^{-3} rad, i.e., nearly three times greater than the diffraction limit. With an 0.8-mm diameter input beam and 1300-j pump energy, the amplifier gain was 3.2. When the input was expanded to a 6-mm diameter so as to use more of the amplifier rod cross-section, the gain increased to 7. The near-field expansion and the decreasing divergence were attributed to the gain saturation at high radiation intensities (output energy density ~ $4 j/cm^2$).

A rigorous solution of a ruby laser problem which allows for changes in the population and field along the resonator length, was offered by Mikaelyan et al with an intent to reveal certain new effects arising during the generation of short pulses.[81] The following laser parameters were considered at $77^{\circ}K$: $\ell = 2cm$, $L = 4cm$, $\beta = 0.03\ cm^{-1}$, $\tau = |R|^2 = 0.5$, $\Delta_o = 10^{19}\ cm^{-3}$, $\Delta\nu = 0.3 cm^{-1}$. In this case, the emission of active atoms occurred during a time shorter than the photon transit time in the resonator. During that time a short pulse was formed in the cavity which lost a portion of its energy as a result of multiple reflections from the mirrors. This made the output appear modulated and was the result of a strong interaction between the field and the active medium which, in turn, acted on the traveling signal causing its distortion. As a result of such a "self-modulation", the emission spectrum exhibited several longitudinal modes, although the initial conditions corresponded to the excitation of a single mode. The second effect observed was the oscillations of population inversion which also attained negative values. This effect is a result of the high field intensity and leads to output oscillations which are superimposed on oscillations due to the "self-modulation".

More recently (July 1969), Mikaelyan had proposed a new method of achieving an unidirectional ring ruby laser.[82] The method is based on using a Faraday rotator with a small angle of rotation of the polarization plane (~5°). The stability of the elements inside the cavity of such a laser is considerably higher than that of ring lasers employing Faraday cells with a 45° rotation.

J. YEREVAN STATE UNIVERSITY

The Yerevan State University supports a relatively small laser research program which, although not lacking in variety, provides for only a limited backing for the solid state lasers.[4] Three papers only were retrieved on ruby laser design for the two-year period covered by this summary.

Kostayan, Pogosyan and Papazyan made a theoretical study, and followed it experimentally, of the effect of coherence on the energy characteristics of a ruby laser.[83,84] The studies were prompted by the fact that laser calculations based on the equations of equilibrium theory fail to allow for the phase relationships between the photons. Yet, these relationships are important in feedback-type cavities, and the quasi-classical approach, used by the Armenian group, indicates that the coherence of radiation has a significant effect on the energy characteristics of lasers or laser amplifiers with feedback. Their numerical results show that the deviation of the energy characteristics from the equilibrium theory calculations due to coherence are of the order of 60-70%. However, under the experimental conditions, the maximum deviation of the output energy due to the interference of waves traveling in opposed directions occurs when the pump energy exceeds the threshold energy by a factor of 1.25, and it amounts to 25-40%.

Gevorkyan et al have carried out an experimental study to determine the dependence of the width and length of the R-lines on chromium concentrations (0.006-0.28%) for various ruby temperatures (room - 240°C), and also the R-line length on the crystal length (5 and 80 mm) for a 0.05% Cr^{3+} concentration.[85] Their results show a decrease in the length (fluorescence time) of the R-lines with increased Cr^{3+} concentrations up to 0.02%. However, subsequent increases in the Cr^{3+} concentration, result in an increase in the fluorescence time due to the effects of reabsorption. The width of the R-lines also increases with increasing chromium concentrations due to, for one reason, interactions between the impurity ions.

K. MOSCOW ENGINEERING PHYSICS INSTITUTE

Davidenko et al have investigated pulsations of the laser output on the basis of the quantum mechanical Hamiltonian for two-level systems interacting with the radiation field.[86] They obtained a system of differential equations for the field amplitude and population inversion, allowing for many modes. Using as an example the interaction between two modes of nearly equal intensities, they showed that the system of equations has solutions corresponding to the undamped output pulsations. Another purpose of the work was to study the effects of the weak spatial inhomogeneity of the pumping power. The results of the numerical analysis were found to be in a good agreement with the experiment.

L. MOSCOW POWER ENGINEERING INSTITUTE

The scope of the ruby laser research at the Moscow Power Engineering Institute is far from extensive. Nevertheless, the important factor is that the four scientists who generate the work there (Korneyev, Folomeyev, Tarasov, and Pavlov) appear to have the attention of and guidance from V.A. Fabrikant-frequently touted today as the father of the gas laser.[4] In 1968, Korneyev and Folomeyev proposed using a spherical cavity to obtain a single mode output from a Q-switched ruber laser.[87] To achieve this (single longitudinal and transverse mode), they used various ruby rods 120mm long and 7-8mm in diameter, with and without sapphire ends. The rods were low quality (5-10 interference rings), with chromium concentration of 0.05%. The 50-cm long resonator consisted of concave and convex mirrors with a 50-cm radius of curvature. The ruby rod was pumped by two linear flashlamps and two coupled elliptical illuminators whose axes were parallel with the ruby crystal. The system was water cooled and the Q-switching was done by means of a saturable absorber. The spatial coherence of a 5.5mm beam was 5.8×10^{-4}rad. The maximum power was 2.5Mw and the pulse duration 20nsec (at half power). The pulse-to-pulse reproducibility of results was high, the changes in pulse width and amplitude being less than 3-4%. When two ruby rods (120mm long and 7 and 8mm in diameter) were coupled in series and placed inside separate but similar illuminators as those in Ref. 87, in a convex mirror resonator Q-switched by a saturable absorber, one longitudinal and one transverse mode were generated in a smooth single pulse of 10nsec duration and 0.4j maximum energy, corresponding to a peak power of 40Mw.[88] The presence of several additional reflecting surfaces and saturable absorbers between the rods has made it possible to obtain one axial mode with the pump up to 50% above threshold (total threshold for both rods was 3kj).

The same experiments as those in Ref. 87 were repeated a year later in which single mode selection was achieved by placing the ruby rod between focus of the confocal resonator and the output mirror (99.8%) so as to fill the entire crystal by the single mode.[89] The ruby rod length and diameter were 120 and 8mm respectively, and a 4-Mw 40-ns (at half power) pulse output was reported.

Shortly thereafter, the experiments were repeated again, using a different illuminator (a silver-coated quartz block 150mm long and 30mm in diameter).[90] The sapphire-ended ruby rob (120mm long and 6.5mm in diameter) and a xenon flashlamp were placed inside the block in two circular hollow cylinders and were water cooled. Because of the generation threshold being lower in the quartz illuminator than in Ref. 87, the conditions for isolating a single mode were better, although not as stable. The distribution of population inversion was not as uniform as in the case of two elliptical illuminators. Two different cavities were used. The first consisted of one convex mirror with a 2 or 5-m radius of curvature and a plane mirror. The second, used two convex mirrors with 2 or 5-m radii. In the first case, single mode generation with a 5.3mm beam diameter occurred, although under above-threshold conditions two or more modes were observed. In the second--spherical--case, stable single-mode generation with a uniform field distribution ensued. In the case of 99.5% and 56% reflective mirrors with the 5-m radii of curvature, the maximum pulse energy was 60mj and the pulse duration was 35-40 ns at half power. In the case of a single mode operation using the spherical resonator, the maximum pulse power was 1.7 Mw.

M. PHYSICO-TECHNICAL INSTITUTE OF LOW TEMPERATURES

The ruby laser work at this Khar'kov facility is mainly due to A.M. Ratner. In a recent paper, co-published with Korzhenevich, Ratner showed that excitation diffusion in the active medium of a solid state laser affects the mode kinetics, leading to additional damping of the relaxation modes of intensity.[91] He also showed that the dependence of damping on the excitation diffusion is stronger than the dependence on spectral width. In the physical sense, the damping is due to the fact that in relaxation modes only those excited active centers take part which are located near the intensity maxima of the longitudinal mode; active centers located close to the modes do not directly contribute to generation or, consequently, oscillations. The excitation transfer between the two active-center groups leads to mode damping. A strong damping of relaxation modes was demonstrated earlier by Konyukhov et al (DAN.SSSR, v. 149, 1963, 571) in experiments with a ruby laser at liquid nitrogen temperatures. Considering that the damping was shown to be practically independent of pumping, Ratner assumed that damping was related to excitation diffusion.

N. NON-AFFILIATED AUTHORS

The publication of articles without indicating the author's institutional affiliation occurs frequently in the Soviet literature for a variety of reasons.[4] There are only a few unaffiliated authors with ruby laser interests and this section deals with their work.

Andriyakhin et al have studied theoretically the problem of a regenerative laser amplifier capable of producing a highly stable monochromatic signal.[92] The paper concluded that the low efficiency of such amplifiers at high gains can be explained by the inability to sufficiently saturate the active medium at low input signal levels and the relatively low resonator Q which is limited by the sub-threshold conditions.

Shcherbakov and Berezhnaya have derived an analytical solution of a problem of the spectral efficiency of a pumping system which uses a coaxial flashlamp as the source.[93] Their calculations are based on the theory of multiple reflections and make use of the generalized angular coefficients which characterize the energy (radiation) transfer in the system of coaxial-cylindrical Lambert surfaces. Using ruby as a model active medium, a number of conclusions were made: (1) the efficiency of the system increases with a decreasing cross section of the lamp internal bore; (2) the region of the effective operation of a pumping system is defined by $0.8 \le r/R \le (r/R)$ for cases where $k \geq 1$ (where k is the coefficient of absorption of a plasma, r/R ratio of lamp radii), and the upper bound (r/R_{cr}) is determined by the durability of a lamp; (3) the efficiency of a system is nearly directly proportional to the ratio of radii of the rod and the internal wall of a lamp, thus suggesting a close coupling of rod to the inner lamp surface; and (4) the presence of an immersing medium enhances the pump efficiency, which is particularly noticeable for high absorption parameters and small dimensions of the active rod. Knowing the temperature dependence of the coefficient of absorption and the gas-discharge plasma conductivity one may use, the authors claim, the results of their work to determine the overall efficiency of any coaxial-cylindrical pumping system.

Valyashko and Timoshenkov have investigated experimentally the absorption spectra of regular and "orange" rubies in the excited and non-excited states at temperatures of 295 and 90°K.[94] The "orange" rubies consisted of Cr-doped Al_2O_3 single crystals and differed from "regular" rubies by an orange hue. The latter can be induced in "regular" rubies by γ- or optical radiation. In the excited state "orange" rubies exhibit a wide, highly dichroic absorption band in the optical range with a maximum at ~610 and ~580 nm for ordinary and extraordinary waves, respectively. A decrease in the ruby temperature to 90°K causes an increase in the intensity of excited absorption, the bandwidth remaining practically unchanged. After γ- irradiation the intensity of the absorption band increased considerably, although the coloration was unstable. The crystals color rapidly under pulsed optical excitation. A strong dependence of the relaxation of the excited state absorption on the temperature was evident. As the temperature increased (to the room temperature), the relaxation time (τ) decreased markedly. The relaxation of the metastable Cr^{3+} ions was 3.6×10^{-3}sec and 7×10^{-3}sec at 295°K and 77°K, respectively. The authors concluded that this indicates that the excited state absorption is independent of the metastable ions. A similar excited absorption band was not observed for regular rubies. A comparison of spectra of both regular and "orange" rubies up to and after γ-irradiation, showed that the excited state absorption in the latter is nearly twice that in the regular rubies, in which it was not registered at all. This shows, the authors concluded, that the Cr^{2+} and Cr^{4+} ions which give irradiated regular rubies an "orange" hue, do not constitute in themselves the excited absorption centers. They conjectured that apparently, there exists some impurity, most probably two- or single-valent "colorless" cations, which at the time of crystal growth contributes to a change in chromium valence and increases the lattice defect. Similar wide dichroic absorption bands in the excited state were observed by the same authors (with Rashkovich) in $LiNbO_3$[95] and in certain leucosapphires. Crystals in which the excited state absorption occurs either fail to lase or require high generation threshold.

Razumova and Rubanova have studied the kinetics of the metastable level population and the resonator losses in a single-pulse ruby laser with plane mirrors.[96] The square-cross section (1cm side) ruby rod was 7.5 cm long and was terminated with sapphire ends. It was placed in an elliptical illuminator and pumped by two linear flashlamps. The Q-switching was done by means of either a rotating prism or the KS-19 glass. The transmission of the output mirror was varied from 0.1 to 78% in both cases. The population kinetics and the internal resonator energy were studied from the transmission spectra of the sample. This method appears to be both more convenient and accurate than the method based on the fluorescence spectra, since in the first case the magnitude of the transverse absorption cross section is independent of the excitation density. In the fluorescence method, however, the time-dependent relationship between the spontaneous and stimulated fluorescence should be taken into consideration in the case of large-size rods. The results of the study show that considerable losses (up to 70%) may occur in cavities switched with KS-19 glass.

LIST OF ABBREVIATIONS

Soviet publications cited frequently have been abbreviated in order to save time and space. A list of these abbreviations and their expanded forms follows:

ZhETF	Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhETF, PvR	Zhurnal eksperimental'noy i teoreticheskoy fiziki, Pis'ma v redaktsiyu
ZhTF	Zhurnal tekhnicheskoy fiziki
ZhPS	Zhurnal prikladnoy spektroskopii
UFZh	Ukrayins'kyy fizychnyy zhurnal
UFN	Uspekhi fizicheskikh nauk
FTP	Fizika i tekhnika poluprovodnikov
FTT	Fizika tverdogo tela
OMP	Optiko-mekhanicheskaya promyshlennost'
PTE	Pribory i tekhnika eksperimenta
O & S	Optika i spektroskopiya
R & E	Radiotekhnika i elektronika
DAN SSSR	Akademiya nauk SSSR. Doklady
DAN BSSR	Akademiya nauk Belorusskaya SSR. Doklady
IVUZ Radiofizika	Izvestiya vysshikh uchebnykh zavedeniy. Radiofizika
IVUZ Fizika	Izvestiya vysshikh uchebnykh zavedeniy. Fizika
Vestnik AN SSSR	Akademiya nauk SSSR. Vestnik

REFERENCES

1. Mak, A. A., Yu. A. Anan'yev and B. A. Yermakov, "Solid State Lasers," UFN, Vol. 92, Nos. 3, 4, pp. 373-426, 1968.

2. Schawlow, A.L. and C. H. Townes, Physics Review, Vol. 112, pp. 1940-1949, 1958.

3. Maiman, T.H., Brit. Commun. and Electr., Vol. 7, pp. 674-675, 1960.

4. Ksander, Y., ATD Reports 66-97, 1966; 67-61, 1967; 68-5-14-1, 1969; and 69-95-14-1, 1969.

5. Stickley, C.M., "Ruby and Nd: YAG Lasers," Proc. SPIE (soon to be published).

6. Asmus, J.F., Laser Applications: A Comparison of U.S. and Soviet Technology, IDA Research Paper P-506, December 1969.

7. Letokhov, V.S., "Generation of Ultrashort Light Pulses in a Laser with a Saturable Absorber," ZhETF, Vol. 55, No. 3, pp. 1077-1089, 1968.

8. Letokhov, V.S., "Generation of Ultrashort Coherent Optical Pulses," ZhETF, PvR, Vol. 7, No. 1, pp. 35-38, 1968.

9. Letokhov, V.S., "Fluctuating Ultrashort Light Pulses in a Laser," ZhETF, Vol. 55, No. 5, pp. 1943-1946, 1968.

10. Basov, N.G., P.G. Kryukov, V.S. Letokhov, and Yu.A. Matveyets, "Investigation of the Formation of an Ultrashort Light Pulse Propagating in a Two-Component Medium," ZhETF, Vol. 56, No. 5, pp. 1546-1556, 1969.

11. Basov, N.G., Yu. A. Drozhbin, P.G. Kryukov, V.B. Lebedev, V.S. Letokhov, and Yu. A. Matveyets, "Fluctuation Structure of a Giant Optical Pulse and its Variation During a Passage Through a Saturable Absorber," ZhETF, PvR, Vol. 9, No. 7, pp. 428-432, 1969.

12. Krasyuk, I.K., P.P. Pashinin, and A.M. Prokhorov, "Ring Ruby Laser for Ultrashort Pulses," ZhETF, PvR, Vol. 7, No. 4, pp. 117-119, 1968.

13. Kaytmazov, S.D., I.K. Krasyuk, P.P. Pashinin, and A.M. Prokhorov, "The Characteristics of a Mode-Locked Laser," DAN SSSR, Vol. 180, No. 6, pp. 1331-1332, 1968.

14. Malyshev, V.I., A.S. Markin, A.V. Masalov, and A.A. Sychev, "The Calculation of the Critical Duration of Ultrashort Pulses in Ruby and Nd-Glass Lasers with Passive Q-Switching," ZhPS, Vol. 11, No. 4, pp. 655-661, 1969.

15. Malyshev, V.I., A.S. Markin, and A.A. Sychev, "The Spectral Kinetics of a Free-Running Ruby Laser Disallowing for Mode Discrimination," ZhTF, Vol. 39, No. 2, pp. 334-340, 1969.

16. Malyshev, V.I., A.S. Markin, and A.A. Sychev, "The Spectral Kinetics of a Free-Running Traveling-Wave Solid State Laser Disallowing for Mode Discrimination," ZhETF, PvR, Vol. 9, No. 1, pp. 3-6, 1969.

17. Karlov, N.V. and Yu. B. Konev, "Laser Output Power," R & E, Vol. 13, No. 4, pp. 749-750, 1968.

18. Korobkin, V.V. and M. Ya. Shchelev, "Investigation of Axial Mode Discrimination in a Ruby Laser," ZhTF, Vol. 38, No. 3, pp. 497-505, 1968.

19. Veduta, A.P., A.M. Leontovich, and G.A. Matyushin, ZhPS, Vol. 8, pp. 238-243, 1968. "Changes occurring in the active element of a solid-state laser heated by the pump light."

20. Veduta, A.P., "Temperature and Population Distribution in Ruby Rods During Pumping," ZhPS, Vol. 9, No. 6, pp. 964-968, 1968.

21. Stickley, C.M., H. Miller, E.E. Hoell, C.C. Gallagher, and R.A. Bradbury, "Color Centers and Ruby-Laser Output-Energy Degradation," J. Appl. Optics, Vol. 40, No. 4, pp. 1792-1802, 1969.

22. Arkhangel'skiy, G. Ye., Z. L. Morgenshtern, and V. B. Neustruyev, "Color Centers in Ruby Crystals," AN SSSR, Izvestiya, Ser.fiz., Vol. 32, No. 1, pp. 2-5, 1968.

23. Morgenshtern, Z.L. and V.B. Neustruyev, "Effect of Color Centers on the Generation Threshold of Ruby," AN SSSR, Izevstiya, Ser. fiz., Vol. 32, No. 1, pp. 6-7, 1968.

24. Arkhangelskiy, G. Ye., Z.L. Morgenshtern, and V.B. Nevstruyev, "Effect of Color Centers on the Cr^{3+} Spectrum in Ruby," AN SSSR, Izvestiya, Ser. fiz., Vol. 33, No. 5, pp. 875-878, 1969.

25. Balashov, I.F., V.A. Berenberg, and B.A. Yermakov, "Single-Pulse Operation of a Ruby Laser with Opto-Mechanical Shutters," OMP, No. 3, pp. 1-5, 1968.

26. Balashov, I.F., V. A. Berenberg, and B.A. Yermakov, "Production of Microsecond Pulses in a Ruby Laser," ZhTF, Vol. 38, No. 5, pp. 928-930, 1968.

27. Andreyev, V.N., I.F. Balashov, B.G. Berezin, and B.A. Yermakov, "A Method of Producing Nanosecond Laser Pulses," ZhTF, Vol. 38, No. 5, pp. 941-943, 1968.

28. Balashov, I.F., V.A. Berenberg and V.V. Blagoveshchenskiy, "Laser Amplifier with a Two-Pass Signal in the Amplifying Medium," ZhTF, Vol. 39, No. 5, pp. 926-928, 1969.

29. Balashov, I.F., B. G. Berezin, E. Ya. Veselov, B.A. Yermakov, and E.A. Izupak, "Cooling of an Active Laser Material by Means of Metallic Heat Conductor," OMP, No. 4, pp. 5-8, 1968.

30. Mak, A.A. and B. M. Sedov, "Effect of Stabilization of the Emission Frequency of a Solid State Laser," ZhTF, Vol. 38, No. 12, pp. 2119-2122, 1968.

31. Mak, A.A., D.S. Prilezhayev, B.M. Sedov, V.I. Ustyugov, and V.A. Fromzel, "The Width of Generation Spectra of Solid State Lasers," O & S, Vol. 26, No. 2, pp. 276-283, 1969.

32. Muzhdaba, A.A., N.P. Tikhonova, and Ye. A. Korelev, "Scattering of Light in Corundum Crystals," OMP, No. 1, pp. 14-19, 1968.

33. Ageyeva, L. Ye., and A.I. Kolyadin, "Rational Characteristics of Small-Angle Indicatrices of Light Scattering in Ruby Crystals," OMP, No. 8, pp. 5-8, 1969.

34. Ageyeva, L. Ye., "Depolarization of Light Scattered at Small Angles in Synthetic Ruby Crystals," FTT, Vol. 10, No. 9, pp. 2836-2838, 1968.

35. Veyko, V.P. and G.P. Suslov, "Characteristics of a Ruby Laser in a Periodic Operation Mode," Fizika i khimiya obrabotki materialov, No. 6, pp. 21-26, 1968.

36. Samson, A.M. and L.A. Kotomtseva, "Analysis of Noise in an Opaque Laser Rod Due to the Penetration of Pump Radiation," AN BSSR, Vestsi, Ser. fiz-mat navuk, No. 3, pp. 76-83, 1968.

37. Samson, A.M. and R.A. Karamaliyev, "Two-Frequency Generation in a Medium with a Split Metastable Level," ZhPS, Vol. 8, No. 1, pp. 56-66, 1968.

38. Samson, A.M., V.A. Rybakov, and N.K. Stashkevich, "Nonstationary Generation of a Ruby Laser with a Ruby Filter," ZhPS, Vol. 10, No. 2, pp. 236-243, 1969.

39. Kotomtseva, L.A. and A.M. Samson, "Temporal Development and the Spectral Width of a Single Pulse From a Laser with a Bleachable Filter," ZhPS, Vol. 10, No. 3, pp. 443-448, 1969.

40. Chekalinskaya, Yu. I, and I.R. Katseva, "Calculation of Axial Model Frequencies of a Laser Consisting of Two Series-Coupled Active Rods," ZhPS, Vol. 9, No. 4, pp. 575-584, 1968.

41. Chechenina, Ye.P., and Yu.I. Chekalinskaya, "Frequency Characteristics of a Laser Amplifier with Simple and Complex Resonators," ZhPS, Vol. 11, No. 2, pp. 242-252, 1969.

42. Smol'skaya, T.I. and A.N. Rubinov, "Experimental Study of Composite Lasers with Series-Coupled Rods," ZhPS, Vol. 8, pp. 938-942, 1968.

43. Smol'skaya, T.I. and A.N. Rubinov, "Spectral, Temporal and Angular Characteristics of the Emission of a Multi-Rod Ruby Laser," ZhPS, Vol. 10, No. 3, pp. 433-438, 1969.

44. Rubinov, A.N. and T.I. Smol'skaya and V.I. Tomin, "Experimental Determination of the Energy Parameters of A Ruby Laser," AN BSSR, Doklady, Vol. 13, No. 2, pp. 113-117, 1969.

45. Rubinov, A.N. and T.I. Smol'skaya, "Experimental Determination of the Energy Parameters of a Ruby Laser," AN BSSR, Doklady, Vol. 12 No. 9, pp. 781-785, 1968.

46. Rubanov, A.S. and A.V. Chaley, "Effect of Heating on the Operation of a Ruby Laser," AN BSSR, Vestsi, Ser. fiz-mat. navuk, No. 2, pp. 80-85, 1968.

47. Sypchenko, L.V., V.P. Gribkovskiy and L.A. Kravtsov, "Effect of Dulling the Finish of the Lateral Rod Surfaces on Optical Pumping of Lasers," ZhPS, Vol. 8, No. 3, pp. 421-424, 1968.

48. Rutkovskiy, F.K., "Nonstationary Distribution of Population Inversion and Absorbed Pump Radiation Power in Ruby," ZhPS, Vol. 8, No. 1, pp. 32-41, 1968.

49. Boyko, B.B., N.S. Petrov, V.V. Valyavko and I.M. Vashkevich, "A Two-Dimensional-Resonator Laser," ZhPS, Vol. 8, No. 2, pp. 351-353, 1968.

50. Boyko, B.B., V.A. Andreichev and V. Ye. Matyushkov, "A Method of Compensating for the Optical Inhomogeneity of Active Laser Elements," ZhPS, Vol. 10, No. 5, pp. 744-747, 1969.

51. Boyko, B.B., V.V. Valyavko, N.I. Insarova and N.S. Petrov, "Effect of a Magnetic Field on the Ruby Absorption in the R-Line Region," ZhPS, Vol. 11, No. 5, pp. 933-939, 1969.

52. Kovalev, A.A., V.A. Pilipovich, L.A. Bogdanovskaya, and L.S. Murashko, "Effect of Spectral Characteristics of Possive Shutters on the Parameters of Ruby Laser Emission," ZhPS, Vol. 9, No. 1, pp. 71-76, 1968.

53. Kovalev, A.A., V.A. Pilipovich and Yu. V. Razvin, "Dependence of Certain Parameters of Single-Pulse Ruby Lasers on the Initial Transmission of Passive Shutters," AN BSSR, Vestsi, Ser. fiz-mat. navuk, No. 4, pp. 92-101, 1968.

54. Kondilenko, I.I., P.A. Korotkov and O.N. Koshel', "Investigation of Two-Frequency Continuously Tunable Generation of a Two-Component Ruby," ZhPS, Vol. 8, No. 6, pp. 1048-1049, 1968.

55. Kondilenko, I.I., P.A. Korotkov and O.N. Koshel', "Study of Generation of a Composite Ruby Element," UFZh, Vol. 13, No. 12, pp. 1983-1988, 1968.

56. Gorban', I.S. and G.L. Kononchuk, "Variation of the Refractive Index of Ruby During Optical Pumping," ZhPS, Vol. 8, No. 5, pp. 864-866, 1968.

57. Anisimov, N.A. and G.L. Kononchuk, "Variation of the Refractive Index of Ruby Due to Population Inversion," FTT, Vol. 10, No. 10, pp. 3150-3153, 1968.

58. Gorban', I.S. and G.L. Kononchuk, "Determination of the Internal Losses of a Ruby Laser," ZhPS, Vol. 11, No. 3, pp. 450-455, 1969.

59. Soskin, M.S., Ye.N. Sal'kova and P. P. Pogoretskiy, "Special Features of Automatic Disruption of Generation in a Spherical Ruby Laser," UFZh, Vol. 13, No. 9, pp. 1567-1569, 1968.

60. Danileyko, M.V., Ye.O. Tikhonov and M.T. Shpak, "Special Features of the Operation of a Ruby Laser at 78°K," UFZh, Vol. 13, No. 3, pp. 390-395, 1968.

61. Bondarenko, A.N., G.V. Krivoshchekov, V.A. Smirnov and K.G. Folin, "Study of Temporal Characteristics of a Q-Switched Ruby Laser Pumped by a Laser," ZhETF, Vol. 55, No. 1, pp. 111-114, 1968.

62. Bondarenko, A.N., G.V. Krivoshchekov and V.A. Smirnov, "A Single Frequency Ruby Laser with Active Q-Switching," ZhETF, PvR, Vol. 9, No. 2, pp. 100-102, 1969.

63. Bondarenko, A.N., G.V. Krivoshchekov and V.A. Smirnov," A Single Frequency Ruby Laser with a Tunable Emission Frequency and Operating in a Giant-Pulse Mode," ZhETF, Vol. 56, No. 6, pp. 1815-1818, 1969.

64. Bondarenko, A.N., G.V. Krivoshchekov, V.A. Smirnov and K.G. Folin, "Ruby Laser with an Electrooptic Q-Switch and Saturable Absorber in the Cavity," IVUZ, Radiofizika, Vol. 11, No. 2, pp. 1909-1911, 1968.

65. Bondarenko, A.N. and I.V. Yeremina, "Experimental Study of Nonuniform Distribution of Gain in the Active Laser Element," ZhPS, Vol. 8, No. 4, pp. 599-603, 1968.

66. Antsiferov, V.V., G.V. Krivoshchekov and K.G. Folin, "Narrowing of a Ruby Laser Spectrum in the Case of Internal Frequency Modulation," O & S, Vol. 24, No. 3, pp. 454-456, 1968.

67. Folin, K.G. and V.V. Antsiferov, "Generation Kinetics, Spectrum and Directivity of a Ruby Laser with Spatially Homogeneous Population Inversion," ZhETF, Vol. 55, pp. 122-129, 1968.

68. Antsiferov, V.V., G.V. Krivoshchekov and K.G. Folin, "Effect of Nonuniformity of the Radiation Field in the Active Rod on the Ruby Laser Dynamics," ZhETF, Vol. 56, No. 2, pp. 526-535, 1969.

69. Antsiferov, V.V., G.V. Krivoshchekov, V.S. Pivtsov and K.G. Folin, "Experimental Study of Spectral, Angular and Temporal Characteristics of a Traveling-Wave Ruby Laser," ZhTF, Vol. 39, No. 5, pp, 931-934, 1969.

70. Grum-Grzhimaylo, S.V., Metody i pribory dlya kontrola kachestva kristallov rubina (Methods and Instruments for Controlling the Quality of Ruby Crystals), M., Izd-vo "Nauka", 1968.

71. Danileyko, Yu.K., A.A. Manenkov, A.M. Prokhorov and V.Ya. Khaimov-Mal'kov, "Optical Homogeneity of Ruby Crystals and Its Relationship to the Divergence of Laser Beams," FTT, Vol. 10, No. 9, pp. 2738-2744, 1968.

72. Kovalenko, Ye.S., K.V. Pak and A.V. Pugovkin, "Internal Scanning in a Ruby Laser," IVUZ, Fizika, No. 4, pp. 153-154, 1968.

73. Kovalenko, Ye.S., A.V. Pugovkin, G.G. Kushch, and S.M. Shandarov, "H-f Modulation of the Spatial Field Structure of a Ruby Laser," IVUZ, Fizika, No. 1, pp. 81-86, 1969.

74. Pugovkin, A.V., "Effects of Orientation of an Active Crystal in the Resonator on the Generation Spectrum of a Ruby Laser," ZhPS, Vol. 10, No. 1, pp. 149-151, 1969.

75. Kovalenko, Ye.S. and A.A. Tikhomirov, "Possibility of Producing the Population Inversion Between Ground-State Sublevels of a Laser," IVUZ, Fizika, No. 1, pp. 125-127, 1969.

76. Kokhanenko, P.N. and A.B. Antipov, "Possibility of Determining the Ruby Laser Wavelength from the Rod Temperature. I," IVUZ, Fizika, No. 5, pp. 33-36, 1969.

77. Kokhanenko, P.N. and A.B. Antipov, "Possibility of Determining the Ruby Laser Wavelength from the Rod Temperature. II," IVUZ, Fizika, No. 5, pp. 37-40, 1969.

78. Mikaelyan, A.L., M.L. Ter-Mikaelyan and Yu.G. Turkov, "Opticheskiye generatory na tverdom tele (Solid State Lasers), Izd-vo "Sovetskoye Radio", M., p. 384, 1967.

79. Mikaelyan, A.L., V.G. Savel'yev and Yu.G. Turkov, "Propagation of a Highly Coherent Ruby-Laser Beam Through an Optical Amplifier," R & E, Vol. 13, No. 10, pp. 1819-1823, 1968.

80. Mikaelyan, A.L., V.G. Savel'yev and Yu.G. Turkov, "Reduction in Laser Beam Divergence in the Case of Propagation Through an Optical Amplifier," ZhETF, Vol. 55, No. 5, pp. 1687-1689, 1968.

81. Mikaelyan, A.L., V.G. Savel'yev and Yu.G. Turkov, "A Strict Calculation of a Q-Switched Laser," R & E, Vol. 13, No. 9, pp. 1719-1721, 1968.

82. Mikaelyan, A.L., Yu.G. Turkov, V.F. Kunpishov, V. Ya. Anton'yants and V.I. Kruglov, "A Method of Designing an Unidirectional Ring Laser," ZhETF, Vol. 57, No. 1, pp. 38-41, 1969.

83. Kostanyan, R.B. and P.S. Pogosyan, "Effect of Coherence on the Process of Light Amplification," R & E, Vol. 14, No. 4, pp. 730-733, 1969.

84. Kostanyan, R.B., T.A. Papazyan and P.S. Logosyan, "Effects of Coherence on the Energy Characteristics of a Laser," AN ArmSSR, Doklady, Vol. 48, No. 5, pp. 273-276, 1969.

85. Gevorkyan, V.A., K.A. Madatyan, E.A. Kochinyan and V. Kh. Sarkisov, "Dependence of Width and Length of the R-Lines in Ruby on Chromium Concentrations," ZhPS, Vol. 8, No. 5, pp. 742-745, 1968.

86. Davidenko, D.F., T.N. Zubarev and Yu.A. Tarasov, "Pulsations of Output Power in Lasers," O & S, Vol. 26, No. 5, pp. 801-808, 1969.

87. Korneyev, N. Ye. and A.V. Folomeyev, "A Single-Mode Ruby Laser," ZhPS, Vol. 8, No. 3, pp. 503-504, 1968.

88. Korneyev, N. Ye. and Yu. I. Pavlov, "High-Power Single-Mode Ruby Laser," ZhETF, PvR, Vol. 8, No. 6, pp. 309-312, 1968.

89. Korneyev, N. Ye., Ye. A. Tarasov and Yu. I. Pavlov, "Saturation of an Optical Resonator with a Single Mode in a Ruby Laser," ZhPS, Vol. 10, No. 3, pp. 439-440, 1969.

90. Korneyev, N. Ye., Yu. I. Pavlov and A.V. Folomeyer, "A Single-Mode Ruby Laser," ZhPS, Vol. 10, No. 6, pp. 924-927, 1969.

91. Korzhenevich, I.M. and A.M. Ratner, "Damping of Laser Relaxation Mode Connected with Excitation Diffusion," O & S, Vol. 26, No. 1, pp. 108-110, 1969.

92. Andriyakhin, V.M., A.G. Basiyev, V.V. Lebedeva and A.I. Odintsov, "A Regenerative Laser Amplifier," R & E, Vol. 12, No. 4, pp. 743-746, 1968.

93. Shcherbakov, A.A. and V.P. Berezhnaya, "The Problem of the Optimal Coupling of the Optical Pumping Source (coaxial lamp) to the Active Laser Medium," ZhPS, Vol. 11, No. 2, pp. 260-265, 1969.

94. Valyashko, Ye. G. and V.A. Timoshenkov, "Absorption Spectra of "Orange" Rubies in the Excited State," ZhPS, Vol. 11. No. 1, pp. 73-75, 1969.

95. Valyashko, Ye.G., L.N. Rashkovich and V.A. Timoshenkov, "Absorption Spectra of Excited $LiNbO_3$ Single Crystals," O & S, Vol. 24, No. 4, pp. 637-639, 1968.

96. Razumova, T.K. and G.M. Rubanova, "Investigation of Population Kinetics of the Ruby ^2E Metastable State and Resonator Losses in a Laser with Pulsed Q-Switching," O & S, Vol. 25, No. 4, pp. 530-535, 1968.

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13. ABSTRACT

A comprehensive review is made of Soviet Research on ruby lasers as reflected in the open scientific literature for the period from January 1968 through December 1969. It is shown that in the laser power sweepstakes, the Soviets have fielded some of their best researchers at several facilities to optimize the design of optically-pumped solid state devices. Research groups and their specialized areas of interest are identified and, in some instances, the Soviet and Western results are juxtaposed.

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