Pages from the history of quantum electronics research in the Soviet Union*

SERGEI BAGAYEV‡, OLEG KROKHIN§ and ALEXANDER MANENKOV¶†

‡Institute for Laser Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia
§Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia
¶Prokhorov General Physics Institute of Russian Academy of Sciences, Moscow, Russia

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1. Introduction

50 years of quantum electronics is an outstanding event in the history of modern science. Having started in 1954 in two countries, the Soviet Union at Lebedev Physical Institute and in the United States at Columbia University, with proposals for a new concept of amplification and generation of electromagnetic radiation based on using stimulated emission of radiation by atomic systems, this field nowadays has become a very developed multidiscipline science with very broad applications.

Outstanding contributions of many scientists to the development of quantum electronics and related fields were awarded with the Nobel Prize. Among these scientists, Nikolai Basov, Alexander Prokhorov and Charles Townes, who shared the Nobel Prize in 1964 for their pioneering works founding quantum electronics (QE), should be emphasized especially.

Unfortunately two of QE’s co-founders, Nikolai Basov and Alexander Prokhorov, were not present among us at this session: they passed away some time ago, in 2001 (Basov) and 2002 (Prokhorov). For this reason the authors of this paper, as their successors, take responsibility to present here the history of QE in the Soviet Union. Of course, we understand how extremely hard it is to speak about QE history in a brief presentation, since so many research groups and persons in the Soviet Union contributed significantly to the development of QE. For this reason, we will limit ourselves by speaking very briefly, almost schematically, only on

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†Corresponding author. Email: manenkov@kapella.gpi.ru
¶In particular, Alexander Manenkov was a graduate student of Professor Prokhorov at the Lebedev Institute in 1953–1955 and collaborated with him over the following years for almost 50 years. Also Oleg Krokhin tightly collaborated with Professor Basov over a long period of time since 1959.
selected fragments of the history of QE in the Soviet Union. Our presentation will include the following aspects:

(a) an initial stage of quantum electronics: key ideas, formulation of basic principals and first experiments,
(b) development and applications of microwave EPR solid-state masers and
(c) laser research in some institutions of the Soviet Union.

2. Initial stage of quantum electronics: key ideas, formulation of basic principals, and first experiments

At the end of the 1940s, A. Prokhorov organized at the Lebedev Physical Institute a research group on microwave spectroscopy of gases. Very soon, in 1952–1953 A. Prokhorov and his student N. Basov came up with the ideas of using molecular beams and stimulated emission (instead of absorption) for increasing spectral resolution and detection sensitivity. In 1954 they published a comprehensive analysis of these ideas and formulated a molecular oscillator concept based on stimulated emission and electromagnetic radiation feedback [1]. As is well known, a similar approach was independently developed by Townes and his group at Columbia University who published their results in the same year, 1954, demonstrating the first molecular (ammonia) oscillator operation [2]. So, these two pioneering works [1, 2] may be considered as the starting point of QE and 1954 as its birth year.

A further significant development of QE principals was a proposal in 1955 by Basov and Prokhorov of the electromagnetic (e-m) pumping method (so-called ‘three level scheme’) for population inversion [3]. This method turned out to be a very effective and universal one for population inversion in various atomic–molecular systems in different spectral ranges, from microwaves to UV. In particular, it was used in 1956 by N. Bloembergen in his proposal for a solid-state EPR maser [4]† and became one of the key components of the first optical maser, demonstrated later, in 1960, by T. Maiman [5].

Electronic paramagnetic resonance (EPR) studies of crystals, including ruby [6, 7], led A. Prokhorov and A. Manenkov in 1956 to a proposal of the ruby crystal for solid-state EPR masers [8]. The first ruby maser, operated in cm wavelength range, has been demonstrated in 1958 by Kornienko and co-authors [9]. Since that time studies of solid-state EPR masers and their applications as low-noise amplifiers were a significant part of research programs headed by Prokhorov, whereas Basov and his group mostly concentrated at that time on ammonia molecular beam masers and their applications as frequency standers and atomic clocks.

†The outstanding contributions of Professor Nicolaas Bloembergen to quantum electronics was recognized by awarding him, jointly with Professor Arthur Schawlow, the 1981 Nobel Prize for the development of laser spectroscopy.
Figure 1. Molecular oscillator (ammonia maser) built at Lebedev Physical Institute (September 1995).

Figure 2. First ruby maser ($\lambda_{\text{signal}} = 15\,\text{cm}$, $\lambda_{\text{pump}} = 2.21\,\text{cm}$) built at Lebedev Physical Institute (1958): left-General view of an experimental setup for testing of the maser right-Fragments of the maser: signal and pump wave guides, two-frequency cavity.
3. Development and applications of microwave EPR masers

Studies of EPR masers carried out at the Lebedev Physical Institute have shown that ruby is the most effective material for maser amplifiers over a wide microwave range. In particular, a series of ruby maser amplifiers operated at several wavelengths in the cm–mm range have been created and installed on radio astronomical and far-space communication antennas [10].

Many R&D laboratories in the Soviet Union were involved in these works under the general supervision of Professor Prokhorov. Application of these maser amplifiers in radio astronomy and planet radar has provided significant scientific results. In particular, a detailed study of Galactic hydrogen radiation at 21 cm and the discovery of new radiation lines in the 8 mm range of highly-exited hydrogen (R. Sorochenko et al., 1969) [11] has given valuable data on the distribution and characteristics (temperature, density and dynamics) of hydrogen in the Galaxy. Observation of maser radiation from space at 1.35 cm (L. Matvienko et al., 1980 [12–14], after the discovery by C. Townes et al., 1969 [15]) has given very interesting data on the water content in some space sources.

Maser amplifiers were also used in radar studies of Mercury, Venus, Mars and Jupiter allowing one to obtain new data on characteristics of these planets (V. Kotelnikov et al., 1962–1964) [16].

4. Transition from maser to laser

Successful development of microwave masers stimulated advancement of maser principals to shorter wavelength domain. A significant step in this direction was a proposal by A. Prokhorov in 1958 of the ‘open resonator’ for e-m feedback at short wavelengths [17]. This type of resonator was analysed in detail by A. Shawlow and C. Townes for an optical range [18]. Using this type of resonator in combination with two other key maser components, an e-m pump and ruby as an active medium, T. Maiman successfully demonstrated in 1960 the first optical maser [5] named later as a laser. (Note that before the first ruby laser was demonstrated N.G. Basov and his co-authors considered in 1958 semiconductor materials as a laser medium [19]. The significance of their approach is that it permitted employing an electric current as a direct pump source for a population inversion.)

Since that time many academic, university and R&D laboratories in the Soviet Union were involved with laser research in various directions, including physics of different types of lasers, the search for new laser materials and their technology, development of high-power lasers, physics of the laser–matter interaction, nonlinear optics and various practical applications. Significant contributions to these directions were performed by many Soviet institutions. However, here it is impossible, of course, to describe, even briefly, all such contributions. For this reason we will point out below only some of the most significant pioneering results, in our view, obtained at several Soviet academic institutions.
5. Contribution of some Soviet institutions to laser fields

5.1 Lebedev Physical Institute and General Physics Institute

Among the most significant contributions to the development of laser fields (besides those mentioned in previous sections) done at the Lebedev Physical Institute and General Physics Institute†, we would like to point out the following.

(1) New methods for population inversion in different laser media have been proposed:

(a) carrier injection through a p-n junction in semiconductors (N. Basov, O. Krokhin, Yu. Popov, 1961 [20]): this method became the most effective one for population inversion in semiconductor lasers (diode lasers);
(b) electron beam pumping of different media (N. Basov et al., 1961 [21]): usage of this method resulted in the creation of excimer lasers [22], semiconductor lasers [23] and high-pressure gas lasers [24];
(c) photodissociation in molecular gases (S. Rautian and I. Sobel’man, 1961 [25]);
(d) heating-fast cooling of molecular gases—‘thermal pump method’ (N. Basov and A. Oraevsky, 1963 [26]).

(2) New types of lasers were proposed and realized:

(a) a high-power cw gas dynamic laser which combines a fast flow of an active medium through an optical resonator and the thermodynamic method of population inversion (Konyukhov and Prokhorov, 1966–1971 [27, 28]);
(b) various types of chemical lasers (N. Basov, A. Oraevsky, et al., 1963–1971 [29–32]);
(c) a high power molecular laser, based on photodissociation by a shock wave-produced radiation at an explosive blasting, with the output laser pulse energy up to 1 MJ (N. Basov, O. Krokhin, V. Zuev, S. Kormer, G. Kirillov, et al., 1969) [33, 34].
(d) a large variety of new solid-state lasers based on rare earth and iron group-doped glasses and crystals (A. Prokhorov, E. Dianov, V. Osiko, I. Scherbakov, et al. [35–38]);

†The General Physics Institute was established in 1982 by Professor A.M. Prokhorov on the base of the Oscillation Laboratory of the Lebedev Physical Institute. In honour of its founder, it has been named since 2003 as the A.M. Prokhorov General Physics Institute.
(3) Significant results were obtained on high-power laser–matter interaction and in nonlinear optics:

(a) a laser-induced heating of nuclear targets was proposed for inertial confinement fusion (N. Basov and O. Krokhin, 1963) [41];
(b) fundamental mechanisms of laser-induced damage in transparent solids (bulk optical materials, surfaces and coatings) at various laser parameters (radiation frequency, pulse width, etc.) and experimental conditions were determined on a basis of comprehensive experimental and theoretical studies (A. Prokhorov, A. Manenkov, Yu. Danileiko, A. Epifanov, M. Koldunov, et al., 1970–2003, see reviews [42, 43]);
(c) a possibility was pointed out of a wave guiding propagation and elimination of geometric and diffractional divergence of an electromagnetic beam in gases and plasma—a phenomenon called self-focusing (G. Askar’yan, 1961 [44]);
(d) an adequate theory of self-focusing of laser beams in nonlinear media—multi-focus and moving foci models—was developed [45, 46] and experimentally verified [47, 48] (V. Lugovoi, A. Prokhorov, et al., 1967–1970);
(e) phase conjugation of laser beams in nonlinear media (at stimulated light scattering) was discovered (Ragul’sky, et al.—experimental observation, 1971 [49], Zel’dovich, et al.—theoretical explanation, 1972 [50]);
(f) first ideas on sub-Doppler narrow nonlinear spectral resonance (saturated absorption inverted Lamb dip) and laser trapping of cold atoms in a standing wave were proposed (N. Basov, V. Letokhov, 1967–1968) [50–53].

5.2 Moscow State University

Professors Rem Khokhlov and Sergei Akhmanov organized in the 1960s at Lomonosov Moscow State University a research school which is well known in the quantum electronics community for pioneering works on nonlinear optics and laser physics. Among many outstanding results of this school we would like to point out the following.

(a) Various schemes for optical parametric amplifiers and oscillators with a smoothly tunable frequency were proposed and realized (Khokhlov, Akhmanov, Kovrigin, et al. [54–56]).
(b) Coherent light scattering active spectroscopy with use of tunable lasers was developed and successfully applied for studies of intermolecular interaction in different media including biological objects (S. Akhmanov, et al. [57]).
(c) A new direction in nonlinear optics—nonlinear polarization optics—was developed (S. Akhmanov, et al. [58–60]).

A significant contribution of MSU to the organization of the International Conferences on Coherent and Nonlinear Optics, initiated by Rem Khokhlov in 1965,
should be noted. Since that time these conferences have become very popular, with a high-quality reputation international forum in the field of Nonlinear Optics. The next *XVIII Conference* of this series will be held in May 2005 in St. Petersburg, Russia.

### 5.3 Institute of Spectroscopy

The Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region has been involved in laser research since its foundation (1968). Among the important contributions of this institute to laser physics, we would like to point out the pioneering works performed by V. Letokhov and co-authors in the 1970s on the trapping and cooling of atoms by laser light: trapping spectroscopy of laser-cooled atoms [61], a theory of Doppler cooling of atoms [62] and the first experiment on laser cooling of atoms [63].

### 5.4 Institute of Laser Physics, Siberia

A research activity in quantum electronics in Siberia started at the beginning of the 1960s, practically just after the first ruby laser demonstration. At first a laser group (Drs G.V. Krivoschekov, V.P. Chebotayev, *et al.*) was organized at the Institute of Radioelectronics, Siberian Branch of USSR Academy of Sciences (Director Professor Yu.B. Rumer) and then, in 1991, Professor Veniamin Chebotayev established the Institute of Laser Physics (since 1992 headed by Professor S. Bagayev).

Among many pioneering works, done by scientists of this institute in quantum electronics and laser physics, investigations resulting in the creation of a new direction in optical spectroscopy—nonlinear super high-resolution laser spectroscopy—should be emphasized especially. They proposed and realized several methods for nonlinear laser spectroscopy: saturated absorption [64, 65], two-photon absorption in standing wave fields [66], separated optical fields [67], and others (see [68]). These methods became basic ones for creating ultra stable laser frequency standards (see the review paper [69]). In 1972 they demonstrated the most monochromatic source of coherent electromagnetic radiation with a line width of 0.05 Hz [70]. With the use of super high-stability lasers, unique optical experiments were carried out for the first time which resulted in the observation of the recoil effect [71], the quadratic Doppler effect [72], a selection of cold atoms in gases with very low effective temperature (~10 mK) [73, 74] and the anomalous Zeeman effect [75]. In 1981 Siberian scientists created for the first time in the world an optical clock with an accuracy of $10^{-14}$ [76]. Further development of these works resulted recently in the creation of femtosecond optical frequency standards with the highest accuracy $10^{-15}$–$10^{-16}$ [77].

### 5.5 Ioffe Physico-Technical Institute

Among the significant works carried out in the field of quantum electronics at the Ioffe Physico-Technical Institute, Leningrad (now St. Petersburg) we would like to point out especially the works of Professor Zheres Alferov and
Figure 3. Nobel prize winners of 1964 in physics: (on the left) Ch. Townes, A.M. Prokhorov, N.G. Basov

Figure 4. A.M. Prokhorov (left), C.H. Townes (center) and N.G. Basov in the Lebedev Physical Institute (1965).
his collaborators on semiconductor heterostructures [78] which became the basis for the development of modern electronics, including various types of semiconductor lasers (quantum well and quantum dots lasers, etc.). For achievements in this field Professor Zh. Alferov was awarded the Nobel Prize in 2000.
Figure 7. N.G. Basov (center) with his laboratory co-workers (from left to right): O.N. Krokhin, E.G. Gamaly, Yu.V. Afanasyev, V.B. Rozanov (1970).

Figure 8. Alexander Prokhorov and Charles Townes (center) among the participants of the Conference on Laser Optics (St. Petersburg 1995) Sergey Bagayev (left), Tina Karu and Alexander Manenkov (right).
5.6 Institute of Physics, Byelorussia

Byelorussian physicists contributed considerably to the different directions of quantum electronics and laser physics. In particular, A.N. Rubinov, B.I. Stepanov and V.A. Mostovnikov, of the Institute of Physics, Minsk, proposed and realized in 1965–1966 [79] the first dye lasers (independently from P. Sorokin et al. and P. Schafer et al. [80, 81]).

6. Conclusions

Summarizing the above review we would like to conclude the following. Soviet scientists contributed significantly to quantum electronics including the foundation of its basic principals, creation and development of different directions of this very wide field of science and engineering. Provided with relevant references to original publications this brief review gives, as we believe, some general view on this contribution.

We would like to point out also that the huge progress in quantum electronics during its 50 year history has been due to the contribution and international cooperation of scientists and engineers of many countries. In this context a stimulating role of International Conferences on Quantum Electronics (IQEC) established by C.H. Townes in 1959, and many ‘daughter conferences’, like CLEO and QELS, conducted in the US, and similar conferences, conducted in Europe and in the Pacific Rim, should be especially emphasized.

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Note

Figures 1–8 inserted to the text above show the retrospective photographs related to some events, mentioned in the text of the history of quantum electronics. We believe that figure captions explain sense of the events clearly enough. The photographs were reproduced from institute’s archives and from private collections.

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