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Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation dedicated to the fiftieth anniversary of quantum electronics (2 June 2004)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation dedicated to the fiftieth anniversary of quantum electronics was held in the Conference Hall of the P N Lebedev Physics Institute, Russian Academy of Sciences, on 2 June 2004. The following reports were presented at the session:

(1) **Krokhin O N** (P N Lebedev Physics Institute, Russian Academy of Sciences, Moscow) "The early years of quantum electronics";

(2) **Ducloy M** (Universite de Paris-Nord, Paris) "Quantum electronics in Europe: from the first years to our time";

(3) **Bagaev S N** (Institute of Laser Physics, Russian Academy of Sciences, Novosibirsk) "Quantum electronics in Siberia";

(4) **Shcherbakov I A** (A M Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow) "Solid state lasers: a major area of quantum electronics";

(5) **Mikaelyan A L** (Institute of Optico-Neural Technologies, Russian Academy of Sciences, Moscow) "From quantum electronics to laser technology (first steps in application)";

(6) **Apanasevich P A** (Institute of Physics, National Academy of Sciences of Belarus, Minsk) "Development of laser physics in Belarus";

(7) **Makarov V A** (Physics Department and International Laser Center of the M V Lomonosov Moscow State University, Moscow) "Quantum electronics and the R V Khokhlov – S A Akhmanov school of coherent and nonlinear optics at Moscow State University";

(8) **Kazakov A A** (M F Stel'makh 'Polyus' Research and Development Institute (State Enterprise), Moscow) "Laser applications in defense technology";

(9) **Dianov E M** (Fiber Optics Research Center at the A M Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow) "Fiber lasers";

(10) **Popov Yu M** (P N Lebedev Physics Institute, Russian Academy of Sciences, Moscow) "On the history of the development of the injection laser".

Abridged versions of reports 1, 4 – 7, 9, and 10 are given below.

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The early years of quantum electronics

O N Krokhin

In the early 1950s, A M Prokhorov pioneered the spectroscopic investigation of molecules in the microwave range of electromagnetic radiation at the L I Mandel'shtam and N D Papaleksi Oscillation Laboratory. N G Basov, who joined the P N Lebedev Physics Institute (FIAN) as a student, willingly got into this research.†

At that time, microwave spectroscopy was a new, rapidly developing branch of physics, in which several scientific groups in different countries were engaged. Of these, first and foremost, mention should be made of C Townes's group at Columbia University, USA.

What special features and, hence, problems did the pioneers of microwave spectroscopy encounter? The subject of investigation in the microwave range is quantum transitions between rotational molecular levels. The frequencies of these transitions, for instance in ammonia molecules, lie in the submillimeter wavelength range (the highest photon energy is 2×10^{-3} eV, $\lambda \sim 0.5$ mm). One can see that the photon energy is well below the value of kT (T is the temperature), and therefore several lower rotational molecular levels are populated at normal temperature. This reduces the absorption of incident radiation at the transition frequency because absorption results from the balance between transitions up (with the loss of a photon) and down (with the emission of a photon), i.e., is proportional to the difference $N_1 - N_2$, where N_1 and N_2 are the respective population densities of the lower and upper levels. As a result, the sensitivity of the spectroscopy technique reliant on microwave absorption measurements is lowered.

Another factor which also reduces the accuracy of frequency determination of quantum transitions in the molecules of gases is the absorption line broadening due to the Doppler effect. The Doppler line broadening is present in all versions of gas spectroscopy, including, of course, the optical range spectroscopy.

Both of these problems can be solved by employing, instead of gases, the beams of molecules that are allowed to pass through a radio-frequency cavity in the direction for

† In 1949. (*Author's note to the English translation.*)

which the mode of the field oscillation in the cavity is almost 'cutoff', i.e., possesses a very high phase velocity. In this case, since the Doppler shift of the transition frequency is proportional to v/c, where v is the thermal velocity of molecules and c is the phase velocity of the wave, it is clear that the frequency shift will be small for $c \to \infty$.

Employing a molecular beam in lieu of a gas also makes it possible to enhance absorption due to the 'sorting' of molecules by level with the aid of nonuniform electric or magnetic fields. In particular, when the molecules are sorted with a nonuniform electric field (for instance, with a quadrupole capacitor made up of four metal rods parallel to the axis of beam propagation), the following occurs. When a molecule which resides, owing to thermal excitation, in several rotational quantum levels enters the sorting system, the electric field 'mixes' these states, and there emerges a dipole moment and, accordingly, a force perpendicular to the direction of molecular motion (in the direction of the gradient of the nonuniform field). Eventually, the particles residing in the neighboring levels of the transition under investigation are either focused on the axis of the system or expelled from the beam.

We see that the application of beams allowed one to solve two spectroscopically significant problems — eliminating the Doppler broadening of the transition line and improving the efficiency of absorption by way of sorting.

The maser principle was now only a short way off. Indeed, why not take advantage of radiative transitions instead of absorptive transitions for microwave spectroscopy uses? And if we attempt to trace the logic of the authors of the first publications in 1954, Basov and A M Prokhorov and Townes, J Gordon, and H Zeiger, we will see that both of these groups of microwave spectroscopists wrote in their papers primarily about improving the resolving power of radiospectrometers due to the use of induced emission in lieu of absorption, because the former should lead to the narrowing of the transition line owing to oscillation.

These two works verily marked the beginning of a new era in radiophysics — the era of applying quantum systems to the generation of electromagnetic radiation. Today, 50 years after this outstanding discovery, we amply recognize its significance for modern civilization.

Late in 1963, when it was clear that this discovery had led to the advent of a new scientific and technological area, which received the name 'quantum electronics', and the scientific circles were coming to recognize it to be an outstanding accomplishment, D V Skobel'tsyn nominated it for the Nobel Prize. In his letter to the Nobel Committee he wrote: "...when studying this issue one may recall that the first considerations on the use of induced emission for the coherent amplification and generation of electromagnetic waves were independently advanced by these researchers in the early 50s at Conferences whose proceedings, unfortunately, were never published.

"The first publications relating to quantum oscillators made their appearance in 1954. Specifically: in the January of 1954 N G Basov and A M Prokhorov submitted a paper entitled "Application of molecular beams for the radiospectroscopic study of rotational molecular spectra" to the *Journal of Experimental and Theoretical Physics*, which was published in Volume 27 on pp. 431–438 in October 1954. In the May of 1954, C Townes et al. submitted a paper entitled "Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3" to the journal *Physical Review*. This work was published in Volume 95 on p. 282–284 in July 1954."

Concluding his letter, Skobel'tsyn wrote: "The diversity of papers on quantum oscillators, which we witness today, reflect, in one way or another, the new ideas proposed and formulated independently by C Townes, N G Basov, and A M Prokhorov at one time.

"I hope that my arguments are sufficiently well-grounded for the Nobel Committee to consider my proposals advanced in this letter."

We now turn to these first papers. The paper by Townes and his collaborators Gordon and Zeiger published in Letters to the Editor of *The Physical Review* journal in Vol. 95 on pp. 282–284 in July 1954 and received by the editors on 5 May 1954 reported: "An experimental device, which can be used as a very high resolution microwave spectrometer, a microwave amplifier, or a very stable oscillator, has been built and operated. The device, as used on the ammonia inversion spectrum, depends on the emission of energy inside a high-Q cavity by a beam of ammonia molecules."

That was the first report on the realization of a molecular oscillator — a maser. The paper was entitled "Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3."

Basov and Prokhorov published a paper (submitted in January 1954) in the *J. Exp. Theor. Phys.* in Vol. 27 on pp. 431–438 in October, which ran, in particular, as follows: "Employing a molecular beam from which molecules in the lower state of the transition under consideration are missing, it is possible to make a 'molecular oscillator'. The principle of operation of the molecular oscillator lies in the following.

A sorted molecular beam wherein molecules in the lower state of the transition under consideration are absent is allowed to pass through a cavity. During the molecular time of flight in the cavity, a part of the molecules experience a transition down, giving up energy to the cavity resonator. When the power loss inside the cavity is lower than the molecular radiation power, there occurs self-excitation, whereby the power in the cavity builds up to a value determined by the saturation effect. Therefore, self-excitation will set in when ...". Next there follow formulas defining the main oscillator parameters and eventually the Q factor required for the self-excitation of the molecular oscillator is estimated. For the CsI molecule, which was investigated by Basov and Prokhorov, it turned out that the Q factor should exceed 7×10^6 (!). It gave grounds to state that self-excitation was impossible in this case (three orders of magnitude were lacking). However, considering that the beam formation system in their experiments was not efficient enough, the authors nevertheless drew an optimistic conclusion about the feasibility of oscillator implementation.

It should be mentioned here that Basov and Prokhorov were aware of this circumstance and started making a facility utilizing a formaldehyde† molecular beam, which was much more intense. However, after Townes's publication they changed to ammonia to obtain oscillation a short time later. For obvious reasons, no official publication followed, but Basov's Doctoral Thesis, which was presented at the end of 1955, contained a detailed description of the molecular oscillator harnessing the beam of ammonia molecules. In his review of the Thesis, Prokhorov wrote, in particular, that

† Private communication by A N Oraevsky. (*Author's note to the English translation.*)

"The possibility to develop a molecular oscillator was first pointed out by N G Basov in 1952."

The following should be added: the only record that has been possible to find in the archives on this subject is Basov and Prokhorov's report in the verbatim account of the Conference on Nuclear Magnetic Moments of 22–23 January 1953 (Archive of the Russian Academy of Sciences, depository No. 1522, inventory No. 1, file No. 59, pp. 36–47). The report was made by Basov, and it contains two significant messages directly related to the subject under discussion. Specifically, it runs as follows: "Once we had elucidated in general the theoretical possibilities for molecular selection, it was reasonable to turn immediately to the new technique of obtainment.[1] Specifically: to observe the emission rather than the absorption of microwaves, i.e., select the molecules residing in the upper rotational state and not in the lower rotational state. To observe the molecular emission spectrum rather than the absorption spectrum... To observe the induced emission of such a molecular beam it is allowed to pass through a resonator. With time, if the cavity Q factor is high enough, the energy stored in the cavity builds up and the probability that the molecules radiate energy approaches unity."

Another interesting statement made in that report runs as follows: "First and foremost is should be emphasized that, as shown by A M Prokhorov, the beam need not be monochromatized in velocity, because here advantage can be taken of the high-frequency field such that the Doppler broadening does not occur. If the beam propagates through the waveguide in the direction in which the phase velocity of the waves, say the E wave, is infinite, no Doppler shift occurs, because the frequency shift is determined by the ratio between the molecular beam velocity and the phase velocity of the waves in the direction of the beam propagation."

Concluding the analysis of the events that occurred in the early 1950s I will nevertheless mention that Basov and his disciples† later managed to put into operation a molecular oscillator utilizing a formaldehyde molecular beam.

Of the early works, I would like to mention the proposal of particle 'sorting' by way of pumping the active media with electromagnetic radiation — the so-called three-level scheme, which was used for developing masers, low-noise microwave amplifiers utilizing ruby crystals, and subsequently in developing lasers. That work was published by Basov and Prokhorov in the *Journal of Experimental and Theoretical Physics* in Vol. 28 on pp. 249, 250 in February 1955. The work was entitled "On the possible methods for obtaining active molecules for a molecular oscillator".

The discovery of new techniques of generating electromagnetic radiation — the realm of science and technology that has come to be known as quantum electronics — has led to rapid progress of research in this area and to an unparalleled application of these techniques to many fields of engineering. In many cases, fantastic results were obtained in engineering, which were undreamed of in those remote 1950s. For instance, radiation pulses with a duration of 4×10^{-15} s have been generated, stable oscillations whose frequency is defined with a precision of 10^{-15} have been realized, optical transmission lines with a data transfer rate of 10^{10} bits per second have been developed, and so on. That is why in concluding this article, it seems to me, there is no escape from mentioning the first papers in which attempts were made to transfer the principles of a molecular oscillator to the optical frequency range.

In June 1958 Prokhorov published a paper in the *Journal of Experimental and Theoretical Physics* in Vol. 34 on pp. 1658, 1659 (submitted in April) entitled "On the molecular amplifier and oscillator of submillimeter range". In that paper he came up with the idea of a so-called open resonator, in which a high Q factor was reached due to a short radiation wavelength: "To design a molecular oscillator, two plane-parallel mirrors can be employed as the cavity. When the mirror separation is l and the mirror reflection coefficient is k (assuming that the energy losses of the plane wave occur only at reflection from the mirror), the Q factor of such a system is

$$Q = \frac{2\pi l}{\lambda}(1-k)^{-1} \,."$$

As is commonly known, open multimode resonators are an inevitable attribute of lasers.

In December of the same year A L Schawlow and Townes published a comprehensive paper entitled "Infrared and optical masers" (*The Physical Review*, Vol. 112, pp. 1940–1949, submitted in August). That paper reported: 'The extension of maser techniques to the infrared and optical region is considered. It is shown that by using a resonant cavity of centimeter dimensions, having many resonant modes, maser oscillation at these wavelengths can be achieved by pumping with reasonable amounts of incoherent light."

Lastly, Basov, B M Vul, and Yu M Popov published in the *Journal of Experimental and Theoretical Physics* in Vol. 37, pp. 586, 587 in August 1959 (submitted in May 1959, registered in the Inventions and Discoveries Committee at the USSR Council of Ministers on 7 July 1958) the paper "Quantum-mechanical semiconductor oscillators and amplifiers of electromagnetic waves". It "...considered the feasibility of using the electronic transitions between the conduction band (the valence band) and the donor (acceptor) impurity levels of a semiconductor for obtaining electromagnetic radiation by the mechanism of induced radiation, much as is the case in a molecular oscillator."

Those were the first papers in which attempts were made to extend the principle of operation of a molecular oscillator to the infrared and optical frequency ranges. They, of course, were only laying the groundwork for such investigations and were trying to draw the attention of the scientific community to this area.

In conclusion, I would like to quote from C Townes's speech at the meeting of Nobel Laureates in St. Petersburg in the summer of 2003, which was organized by Zh I Alferov during the jubilee celebrations of the city's tercentenary.

In his speech, Townes said[2]: "And this arose, as I have already mentioned, from spectroscopy, from molecules, for here we conducted research at different places, and me, too, and Nikolaĭ Basov and Aleksandr Prokhorov in Moscow also developed their original ideas... and in Maryland there was a scientist who proposed this, and he also saw certain possibilities in this direction [3]... .

[1] Sic (*Author's note*.)

† It was realized by A Krupnov and V Skvortsov from Gor'ky. (*Author's note to the English translation*.)

[2] Translation of the unprocessed phonogram of the speech. (*Author's note*.)

[3] Supposedly J Weber is meant. (*Author's note*.)

"And so, in 1954 we were already operating ...(a maser[4]). Shortly after that I went to a conference in England on microwave spectroscopy, and Prokhorov was there. It was a remarkable privilege to meet a Russian scientist. At those times it was extremely complicated and hard for American and Russian scientists to meet — at those times, in the 50s. And, indeed, they arrived. At first, they did not announce what they would talk about. But they spoke precisely about the maser, they were making a maser. The idea was the same: molecular beams. An idea very similar to mine. They had not yet obtained the final results, but they had almost completed their experiment, and they perfectly understood me and we discussed it.

"And so I told them what I was doing. I said: 'we, too, are working on this... .' We talked, talked, shared experience. It was wonderful — talking with them, comparing notes and exchanging ideas.

"But they did not admit the possibility of... focusing. Later they used it, got a good maser, and then they developed this idea to make octopole focusing to improve it. It was truly a better result. They started from this idea, refined it, and on the basis of this idea they conceived another idea. They worked. And we used their octopole focusing later. Well, they had very similar ideas, very... ."

I have reproduced in this article everything I spoke of in my address to the Scientific Session of the Physical Sciences Division which was held at the P N Lebedev Physics Institute on 2 June 2004 and was dedicated to the fiftieth anniversary of quantum electronics. Of course, I realize that attempts to adequately reproduce the events that took place in the first years of the formation of quantum electronics 50 years ago involves a certain risk. What encourages me is the fact that after my speech I have not heard remarks from my colleagues which might be regarded as a reproach about violating the truth. This removed my doubts as to the possibility of publishing this article in *Uspekhi Fizicheskikh Nauk*.

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Solid state lasers: a major area of quantum electronics

I A Shcherbakov

The thesis appearing in the title is illustrated as follows:

(i) the world's first laser was a ruby laser, although this is a purely historical aspect of the problem;

(ii) today, rather compact solid-state laser setups provide cw radiation ranging up to ten kilowatts in power and, what is more important, the pulse power is approaching the petawatt level due to the use of femtosecond pulse duration. When such a pulse is focused into a spot measuring about ten micrometers, the peak at-focus intensity amounts to 10^{21} W cm^{-2}. The physics of interaction of these pulses with atoms, molecules, and clusters, as well as solid and gaseous targets, is of great interest.

Even for a radiation intensity on the order of 5×10^{16} W cm^{-2}, the peak field intensity at the focus is equal to the intra-atomic field intensity, i.e., to the intensity of the Coulomb field of the nucleus of a hydrogen atom at a distance equal to the Bohr radius (5×10^9 V cm^{-1}). In this intensity range there emerge numerous unique effects devoid of analogs in the weak-field case. For instance, the generation of very high-order harmonics of laser radiation during atom ionization (with harmonic numbers up to 300 and above), a complete restructuring of atomic spectra, and so forth. It has been proposed that such extraordinary effects which accompany the atom ionization in a strong laser field may be used to advantage to generate even shorter (attosecond, 10^{-18} s) radiation pulses. It is conceivable that many interesting phenomena in this area still remain outside the province of contemporary notions.

The next threshold of significance is the so-called relativistic intensity, whereby the velocity of electron oscillations in the light field is around the speed of light. For the neodymium-laser radiation frequency this condition is fulfilled when the at-focus laser radiation intensity is on the order of 5×10^{18} W cm^{-2}, which corresponds to a field of about 5×10^{10} V cm^{-1}. The observation of nonlinear quantum-electrodynamic effects, such as multiphoton Compton scattering, which is responsible for the radiation of hard gamma-ray quanta, the subsequent electron-positron pair production in the laser field, and so forth, is made feasible at these intensities.

The interaction with gaseous targets may give rise to effects like the self-trapping of laser beams in a medium due to the rapid ionization of target atoms and the ejection of electrons from the focal region under the action of ponderomotive forces in the nonuniform laser field. This effect may be accompanied by subsequent ion ejection interpreted as the Coulomb explosion.

A further increase in intensity in the above-specified range may lead to the discovery and investigation of new quantum-electrodynamic effects, to the performance of experiments on the laser excitation of nuclei, and to many other new results which now are hard to predict.

Therefore, there emerges a new area of physics, whose advances will enable us to develop radically new technologies for the 21st century. Ultrahigh power densities with relatively small energy densities sharply intensify different kinds of nonlinear processes without leading to material damage. These unique possibilities are difficult to overestimate. They may be employed in the development of volume optical storage elements, which will revolutionize computer engineering.

The above experiments can be staged with the use of solid-state lasers. That is why the occasionally voiced statement that solid-state lasers may be replaced with other types of lasers is unlikely to be borne out in the foreseeable future.

A M Prokhorov, one of the founders of quantum electronics, gave much consideration precisely to the development of solid-state laser technology in our country. He was the one who worked out its strategy. It involved, in particular, the unity of the activities of technologists, spectroscopists, and laser scientists. A wealth of examples can be provided to confirm the realization of this statement both in the Academy and at the industrial level. The results discussed in this report were obtained in the framework of this strategy in the General Physics Institute with the participation of a number of other organizations, including foreign ones.

For a rather long time, solid-state lasers possessed an immanent drawback — a low efficiency normally not

[4] Indecipherable in the verbatim report, supposedly, a maser. (*Author's note.*)