Quantum Electronics 50th jubilee

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ABSTRACT

The history of the discovery of the physical principles of the quantum electronics and the early period of its development are discussed.

Keywords: new principle of generation and amplification of electromagnetic waves, molecular oscillator, laser quantum electronics.

Looking back at the past 50 years, we clearly realize that the discovery of the physical principles of quantum electronics was one of the most outstanding achievements of science in the past century and has imparted a significant impulse to the development of modern civilization. The acme of this discovery was, по doubt, the creation in 1960 of a laser - a source of highly coherent optical radiation. [1]

The great variety of lasers, classified, for example, by aggregate state of their active medium - gas, solid state (semiconductor, crystalline, and glass-based), and liquid; by methods of excitation - "pumping" with electric current, optical radiation, and thermal excitation; and by methods of technical implementation, predetermined the unusually broad application of them in various fields of technology. Much of what seemed incredible in that comparatively not-so-distant past and evoked ironic smiles from skeptics, including physicists, has already become habitual and not surprising.

Here are some results obtained in the field of quantum electronics and laser physics, which, in my view, are very significant, although I, of course, realize that this list cannot be exhaustive. It reflects both practical or applied achievements and scientific ones that are still awaiting practical implementation.

A global system of fiber-optic communications. Today, we can assert that a fiber-optic channel capacity of up to 10^{10} bit/s has been achieved, allowing simultaneous transmission of nearly 10000 television programs. It is worthy of note that there are sizable reserves for increasing the rate of transmission through updating technical means. We may obviously state that optical communication lines will fully satisfy future societal needs for information exchange.

Frequency-time standards. The contemporary methods of stabilizing the frequency of generation of laser electromagnetic oscillations make it possible to register the frequency of these oscillations with a relative accuracy of 10^{-15} that is comparable with the accuracy of passive standards, but promising further improvement. This correlates with the same accuracy in measuring time intervals; e.g., the error of time standards is equal to 1 s over an interval of 10^{15} s, that is, over 100 million years. The problem of transferring this accuracy to microwave ranges, in which the Time Service operates, is nearing a solution.

Supershort light pulse generation. Specially designed laser systems with a wide-band spectrum are capable of generating light pulses with a minimal duration of $4 \cdot 10^{-15}$ s. The pulse is extended in space over the length of one wavelength, approximately 1 μm. Such pulses make possible to "photograph" superfast atomic-molecular processes, e.g., chemical reactions, and to obtain superhigh densities of light power in focusing radiation to small volumes.

[1] The optical range comprises infrared (with a wavelength from 10 to 0.7 μm), visible (0.7-0.3 μm), and ultraviolet (0.3-0.01 μm) radiation. The boundary between these spectral sections is quite conventional.

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Laser cooling of atoms in a gaseous state. The process essentially consists in a small quantity of atoms, which initially have thermal velocities corresponding to normal temperature, being caught in a so-called "trap" and radiated from all sides by laser emission with a frequency correlating with resonance quantum transition. In so doing, the radiation frequency should be tuned so that absorption occurs only for atoms moving toward a laser beam (due to the Doppler effect). Light absorption is accompanied by photon pulse transmission; i.e., deceleration takes place. Then, the atom returns to its basic state and the process continues. It was thus possible to cool atoms to a temperature of about 10^{-9} K and experimentally study quantum-statistical regularities in the particle-ensemble behavior (Bose−Einstein condensation).

Semiconductor lasers. In practical implementation of the new opportunities offered by quantum electronics, semiconductor (diode) lasers play a special role. This is due to the fact that electric current in them is directly converted into light, and, consequently, their efficiency reaches 70%. Moreover, they are space saving and, in recent years, their capacity has been tangibly increased almost up to 20 W from one diode. Diode lasers are predominant among quantum electronics items by the volume of sales and, particularly, by nomenclature. They are widely used in optical communication systems, information recording-playback devices on various types of compact disks, in printers, range finders, velocity meters, homing systems for high-precision weapons, etc. Recently, diode lasers have found application as effective sources of pumping crystalline, glass, and fiber lasers, which has actually led to a breakthrough in laser technology. It has become possible to create high-capacity complexes for large-scale machine building. Thus, the development of up-to-date diode lasers enabled one to overcome the basic difficulty in broad application of laser technology — low efficiency.

Highly efficient industrial laser complexes with "diode pumping." These have already been put into operation in the automobile industry, aircraft, railway cars, and shipbuilding. For example, around 600 welding laser units operate at Volkswagen plants. Laser welding has a number of essential advantages, namely, higher accuracy, an even and clean weld, and the absence of a large heating zone and, consequently, deformation. It is effective also in the manufacture of "composite" blanks in mechanical engineering, e.g., sheet products of variable thickness or materials with different mechanical parameters. Lasers also have a wide application in pattern cutting of sheet materials, including textiles, drilling of thin holes (e.g., in engine injectors), cleaning of surfaces, rapid and high-quality cutting of glass, etc.

Mass data recording and storage. It seems that today everyone knows what a compact disk—CD—is. An enormous amount of these products is sold in a network of trade outlets, ranging from conventional music disks to huge-capacity carriers of video, graphic, and text information. Here, I would like to emphasize that similar hardware is developing and improving in plain sight. This is associated with enormous technological potentialities that have not been assimilated yet. A move to shorter-wave lasers (the spectrum blue region) on gallium nitride diodes will bring about still greater recording densities, and the implementation of a multilayer recording in several different wavelengths will increase the information recording density and the speed of information readout.

Active systems of precise positioning, location, and high-precision weapons. Lasers make it possible to create active range finders, object velocity counters, and locators. It is unquestionable that all of them, such as active missile target homing systems, find their place in military equipment.

Lasers for medicine. The widespread introduction of endoscopic equipment makes it possible to use lasers in various types of major surgery. In many cases, the use of this equipment yields good results. Another field of laser application is ophthalmology, where lasers have become standard instruments for operative treatment of eye diseases.

Stimulation of thermonuclear reactions. The application of lasers to solve problems of nuclear fusion is still at the stage of research. The main scientific problem lies in finding ways to overcome gas-dynamic instabilities that accompany compression and heating of small amounts of hydrogen isotopes — mixtures of deuterium and tritium. The low efficiency of laser facilities is the original cause of the technical difficulties in solving these problems. It seems that the difficulties may be removed with a transition to "diode pumping." Nevertheless, the cost of a project (given the present-day technological level) may turn out to be high, because a "fusion" laser, unlike an industrial one, must develop a huge pulse power. There is hope that rapid development of laser technology and a parallel search for more effective methods to "ignite" fusion "fuel" will lead to the solution of this problem in the future.

I have already said that the list of the most vivid (in my view) examples of implementing the ideas of quantum electronics in science and in practice cannot, by far, be a complete one. On the other hand, there is no sense in markedly increasing this list (the question would be where to stop) because, if we go into detail, there will be a danger of boring the reader.

Since my report is devoted to the 50th anniversary of the advent of quantum electronics, it is necessary to return to the time when this remarkable discovery took place and try to recall the history of events that brought about this outstanding result.

In 1964, the Nobel Committee for Physics conferred its prize on N.G. Basov, A.M. Prokhorov, and C. Townes (Figure 1) "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle." The prize was divided into two equal parts (one went to Basov and Prokhorov and the other to Townes). It is noteworthy that investigations associated with quantum electronics won three more Nobel Prizes in subsequent years. In 1981, N. Bloembergen and A. Schawlow became Nobel Prize laureates for their research into laser spectroscopy; in 1997, the prize went to S. Chu, C. Cohen-Tannoudji and W.D. Phillips for the development of laser methods for atom cooling; and, in 2000, Zh.I. Alferov became a Nobel prizewinner for the development of heterostructures, including for semiconductor diode lasers.

Figure l. The 1964 Nobel Prizewinners in Physics (left to right): A.M. Prokhorov, C. Townes, and N.G. Basov at the P.N.Lebedev Physical Institute. October 1965.

Thus, in the early 1950s, at the Mandel'shtam and Papaleksi Laboratory of Oscillations of the P.N.Lebedev Physical Institute (FIAN), on the initiative of Prokhorov, researchers began spectroscopic investigations of molecules in the radio frequency band of electromagnetic radiation. Basov, who came to the FIAN shortly before graduation from the Moscow Engineering Physics Institute, had become actively involved in the work. At that time radio spectroscopy was a novel and rapidly advancing field of physics, in which several groups of scientists in different countries were working and among which we single out, first and foremost, the team led by Townes of Columbia University in the United States. The objective of radio spectroscopy is to study the structure of molecules. What specific features and, consequently, problems did the pioneers of radio spectroscopy face?

One subject of research in the radio frequency band is quantum transitions between rotational levels of molecules (Figures 2 and 3). The frequencies of these transitions, e.g., for ammonia molecules, lie in the field of the submillimeter wave bands (the maximum value of the quantum energy is $2 \cdot 10^{-3}$ eV and $\lambda \sim 0.5$ mm). Since the quantum energy is less than the value of $k_B T$ (T is temperature and k_B is the Boltzmann constant), several lower rotational levels of the molecule are usually filled at normal temperature. This reduces the absorption of incident radiation at the transition frequency, because it is the balance of the acts of absorption during the transition from the lower level to the upper one and induced emission in the reverse process, that is, proportionate to the difference $N_1 - N_2$, where N_1 and N_2 are the populations of the lower and upper levels, respectively. As a result, the spectroscopy method based on radio wave absorption measurement becomes less sensitive.

Another circumstance that also impairs the accuracy of determining the frequencies of quantum transitions of molecules in a gaseous state is absorption line broadening due to the Doppler effect. Doppler line broadening is present in all variants of gas spectroscopy, including, naturally, the optical range.

Both problems can be solved by using a beam of molecules instead of gas. These molecules pass through a high-frequency resonator in the direction where the type of field oscillations in the resonator is almost maximal, that is, has a very high phase velocity in this direction. It is obvious that, since the Doppler shift of the transition frequency is proportional to v/c_{ph}, where v is the molecule thermal velocity and c_{ph} is the wave phase velocity, then with $c_{ph} \to \infty$ the frequency shift will be small (Figure 4).

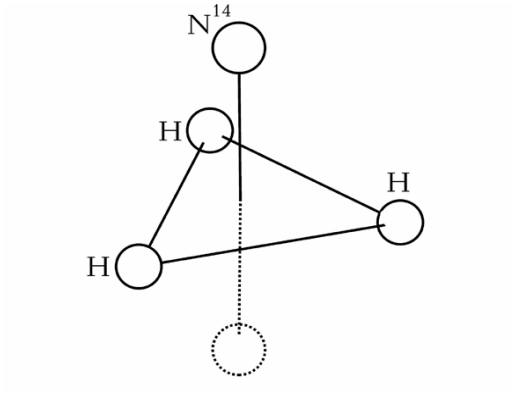

Figure 2. Ammonia (NH_3) molecule structure. The vertical axis corresponds to the molecule axis of rotation, which forms rotational quantum levels; the nitrogen atom may jump from the upper to the lower position (dotted line) and inversely ("inversion"), which results in splitting of each rotational level into two sublevels between which there may occur transition with absorption or induced radiation used in a maser.

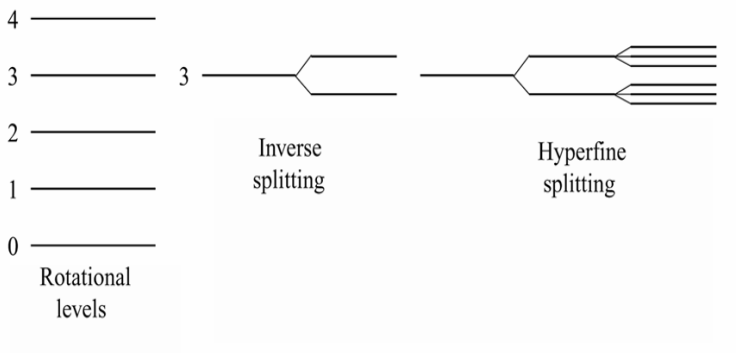

Figure 3. Spectrum of an ammonia molecule's rotational levels. Everywhere $kT \gg E_n - E_m$; population $N_n \sim \exp(-E_n/kT)$ is equal for many lower levels down to $E_n \sim kT$

The use of a molecular beam instead of gas also allows increasing the absorption efficiency owing to the "sorting" of molecules over the levels with a nonuniform electric or magnetic field. In particular, if we suppose the molecules to be "sorted" by a nonuniform electric field (for example, a quadrupole capacitor consisting of four metal rods, along the axis of which the beam propagates), then, at the input to the sorting system of the molecule that fills several

quantum rotational levels as a result of thermal excitation (in a "mixed up" state), the electric field "mixes up" these states. A dipole moment arises, and, correspondingly, a force that acts on the molecules in the direction transverse to that of the beam motion in the direction of the nonuniform field gradient. In this way, the molecules located at the levels near the transition under study are focused toward the system axis or ejected from the beam (Figure 5). Thus, application of molecular beams allowed solution of two problems important for spectroscopy, namely, ruling out Doppler broadening of the transition line and making absorption more effective due to "sorting" of molecules. The principle of maser creation was now around the corner.

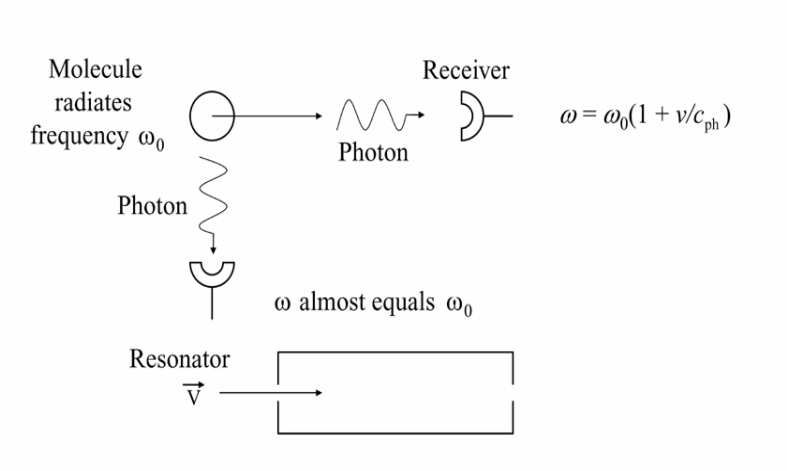

Figure 4. Doppler line broadening and exclusion of this effect. The frequency of an electromagnetic wave emitted by the molecule moving to the right at velocity v is shifted relative to the frequency of transition to the value of $\omega_o v/c_{ph}$ for the receiver arranged to the right and is almost not shifted for the receiver arranged at the bottom; an effective (phase) velocity $c_{ph} \to \infty$ can be provided in the resonator to rule out the frequency shift; field $E \sim E_0 \cos\omega t$; if E_0 does not depend on the axis coordinate, this means that $c_{ph} \to \infty$ and $\omega \to \omega_0$.

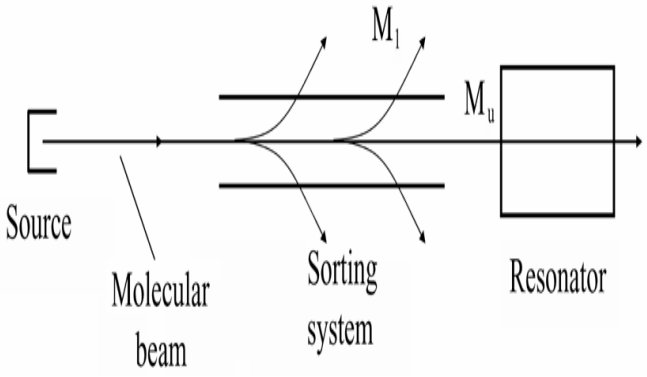

Figure 5. "Sorting" molecules by rotational levels in an electric field. The electric field on the system axis is minimal: the molecules located in the upper level (M_u) pass to the resonator; the molecules in the lower level (M_l) are ejected from the system.

Really, why not use radiative transitions instead of absorbing ones for the purposes of radio spectroscopy? If we try to follow the logic of Basov and Prokhorov, on the one hand, and that of Townes, G. Gordon, and H. Zeiger, on the other, we will be convinced that both teams of researchers in the field of radio spectroscopy wrote in their 1954 publications primarily about an increase of radio spectroscopes' resolving power owing to the use of induced emission

instead of absorption, because this emission, due to regeneration, should bring about the transition line narrowing (Figure 6). These two studies marked the onset of a new era in radio physics — the application of quantum systems for generation of electromagnetic radiation.

At the end of 1963, when it was already clear that the discovery had resulted in the formation of a new trend in science and technology that came to be known as "quantum electronics" and the scientific community viewed it as an outstanding achievement, D.V. Skobel'tsyn presented it for a Nobel Prize. In his letter to the Nobel Prize Committee, he wrote, "Investigating this problem, one can remember that the first considerations about the use of induced radiation for coherent amplification and generation of electromagnetic waves were stated independently by these researchers in the early 1950s at conferences, the proceedings of which, unfortunately, were not published later.

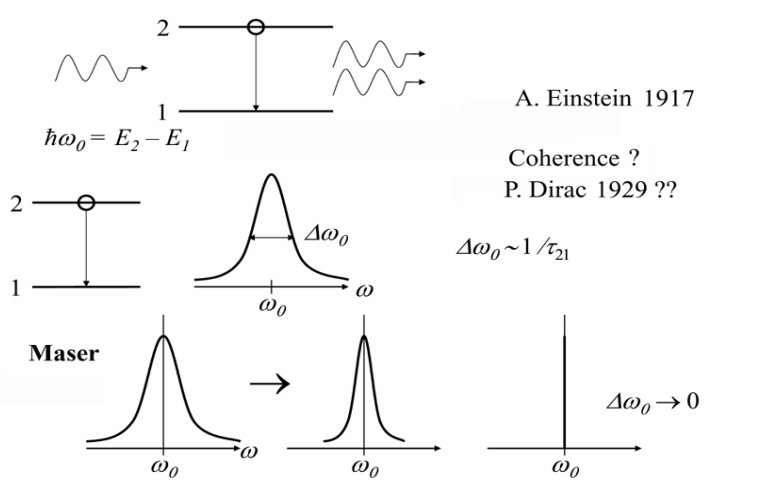

Figure 6. Induced radiation "line forms." At a single act. the probability of radiating the preassigned frequency is given by a bell-shaped function with a spectrum width $\Delta\omega_0 \sim 1/\tau_{21}$, where τ_{21} is the time of radiation from the second level to the first; with multiple induced radiation, the spectral probabilities are multiplied by as many times, and, within a great number of transitions, the spectrum will tend to be monochromatic (generation in laser); the induced radiation is coherent (identical) to an incident wave, which is corroborated by the discovery of a maser effect.

However, the first publications related to quantum oscillators appeared in 1954. In January 1954, Basov and Prokhorov contributed the article "Application of Molecular Beams for Radio Spectroscopic Investigation of Molecules' Rotational Spectra" to the *Journal of Experimental and Theoretical Physics,* where it was published in Volume 27, pp. 431-438, in October 1954. In May 1954, Townes and his colleagues sent the article "Molecular Microwave Oscillator and New Hyperfine Structure in the Microwave Spectrum of NH_3" to the journal *Physical Review,* where it was published in Vol. 95, pp. 282-284, in July 1954."

Skobel'tsyn ends his letter as follows: "That diversity of studies on quantum oscillators that we have had up to now reflects in one way or another the new ideas put forward and formulated at the same time independently by Townes, Basov, and Prokhorov. I hope that my arguments are well founded enough for the Nobel Committee to consider my reasoning outlined in this letter."

Let us now discuss those first papers on quantum electronics. An article by Townes and his colleagues Gordon and Zeiger, "Molecular Microwave Oscillator and New Hyperfine Structure in the Microwave Spectrum of NH_3," stated that

… an experimental facility has been developed and is now operating that can be used as a high-resolution microwave spectrometer, microwave amplifier, or very stable oscillator. This device, in which an inversion spectrum of the ammonia molecule is used, is based on energy emission inside the resonator with a high Q factor by the beam of ammonia molecules …

This was the first information about the development of a molecular oscillator — a maser.

Basov and Prokhorov wrote the following in their article "Application of Molecular Beams for Radio Spectroscopic Study of Molecules' Rotational Spectra":

Using a molecular beam where there are no molecules in the lower state of the transition under review, one can construct a "molecular oscillator." The principle of operation of the molecular oscillator consists in the following.

A sorted molecular beam that lacks molecules in the lower state of the transition under review is passed through a cavity resonator. Over the time of the molecules' passage through the cavity resonator, some of the molecules pass from the upper state to the lower one, giving off energy to the cavity resonator. Should the power of losses inside the resonator be less than that of the molecules' radiation, there self-excitation begins, at which the resonator power grows to the value determined by the effect of saturation. Thus, self-excitation begins if....

Furthermore, they have the formulas determining the oscillator basic parameters, and, eventually, the Q factor needed to self-excite the molecular oscillator is evaluated. For the CsJ molecule, which was investigated by Basov and Prokhorov, the Q factor should be at least $7 \cdot 10^6$ (!). This gave reasons to state that self-excitation is impossible in this case (the Q factor falls short by three orders). However, in view of the fact that the beam formation system in the experiments was not effective enough, the authors do draw an optimistic conclusion about possible realization of the molecular oscillator.

Basov and Prokhorov started developing a facility with a more intensive molecular beam — hypothetically, formaldehyde — rather than with a beam of CsJ molecules. However, after Townes' publication, they took up ammonia and soon obtained generation. Basov's doctoral dissertation, which was presented for approval in 1956, contained a detailed description of a molecular oscillator operating with an ammonia molecular beam (Figure 7). In his review of the dissertation, Prokhorov wrote, in particular, that "It was N.G. Basov who first pointed to the possibility of creating a molecular oscillator in 1952."

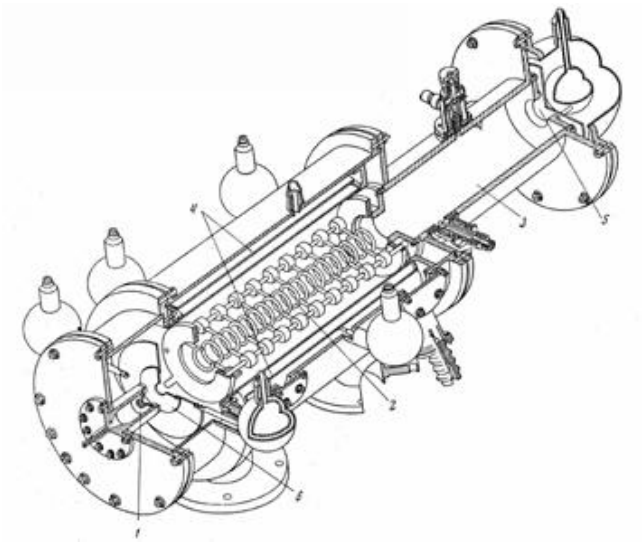

Figure 7. Molecular oscillator design. *(1)* Molecular beam source, (2) sorting system, *(3)* resonator, *(4)* vacuum jacket cooled by liquid nitrogen, (5) end trap of spent molecular beam, and *(6)* diaphragm to form molecular beam.

The report by Basov and Prokhorov was the only item that they have managed to find on this subject in the archives. The report was contained in the verbatim record of the Conference on the Magnetic Moments of Nuclei held on January 22-23, 1953 (RAS Archives, Fund 1522, Inventory 1, File 59, pp. 36-47). The report delivered by Basov contains two basic points directly relating to the subject under study. It said, in part,

After we have elucidated, in general, the theoretical potential for sorting the molecules, it was natural to switch immediately to the new method of production (the actual text— O.K.). Namely, to consider radiation rather than absorption of microwaves, that is, sort out the molecules that are not in the lower rotational state but single out the molecules that are in the upper rotational state. We are to observe already the spectrum of molecular radiation rather than the absorption spectrum .... In order to observe the induced radiation of such a molecular beam, it is passed through a resonator. With time, if the resonator's Q factor is adequately great, the energy stored in the resonator grows and the probability of molecules emitting the energy tends to unity.

Another interesting statement made in the same report says that

As A.M. Prokhorov has shown, it is not imperative to monochromatize the beam by velocities, because one can use a high frequency field so high that the Doppler expansion (the actual text — O.K.) will not be obtained. Given that the beam is passed along the waveguide in such a direction in which wave phase velocities, say, that of the E wave, equal infinity, there is no shift due to the Doppler effect, because the frequency shift is determined by the ratio of the molecular beam velocity to the wave phase velocity in the direction of the beam propagation.

I believe it unavoidable to observe that the existence of the process of induced radiation was postulated by A. Einstein in 1917 as a result of analyzing the thermal process of setting equilibrium between radiation and the atomic system. The conclusion that the quantum of induced radiation must be equal to the quanta that caused the radiation follows from quantum field theory and is usually associated with P. Dirac. However, it is not all that simple to bridge the notion of coherence in the classical understanding of this word (a type of the field oscillation in a resonator) with a contention about the identity of the quanta (they lack the notion of phase). It is precisely the establishment of coherence in molecular ("quantum") oscillators operating due to a stimulated emission that is a nontrivial fact of this outstanding discovery (see Figure 6).

Among the studies of the early period of quantum electronics, note the proposal to "sort" particles by the method of pumping active media with electromagnetic radiation, a so-called three-level diagram. It has been successfully used in creating masers — low-noise amplifiers of the microwave range in a ruby crystal — and, subsequently, in the construction of lasers. This suggestion was in the paper by Basov and Prokhorov "Possible Methods of Obtaining Active Molecules for a Molecular Oscillator," published in the *Journal of Experimental and Theoretical Physics* in February 1955 (Vol. 28, pp. 249-250).

The discovery of new methods of generation of electromagnetic radiation boosted research in the field of quantum electronics and yielded, in a number of cases, fantastic results, which in those bygone 1950s were simply impossible to imagine. Primarily, we should point out implementation of the principles of a molecular oscillator in the optical range of frequencies, in other words, the development of lasers.

In June of 1958, Prokhorov contributed the article "A Molecular Amplifier and Oscillator in Submillimeter Waves" to the *Journal of Experimental and Theoretical Physics* (Vol. 34, pp. 1658- 1659) (sent to the editors in April 1958). It presents a so-called open resonator, where a high Q factor is provided due to a short radiation wavelength. "Two plane-parallel mirrors may be used to create a molecular oscillator as a resonator. If the distance between the mirrors is l and the coefficient of reflection from the mirror is k (bearing in mind that plane wave energy losses occur only upon reflection from the mirror), then the Q factor of such a system is equal to

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

As is known, open "multimode" resonators (with a great number of various types of field oscillations having close frequencies) are an indispensable attribute of lasers.

In December of that same year, Schawlow and Townes published the large article "Infrared and Optical Masers" (it was sent to the editors in August 1958) in *Physical Review* (Vol. 112, pp. 1940-1949). The article said that "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."

And, finally, in August 1959, the *Journal of Experimental and Theoretical Physics* (Vol. 37, pp. 586, 587) carried an article "Quantum-Mechanical Semiconductor Oscillators and Amplifiers of Electromagnetic Oscillations" by Basov, B.M. Vul, and Yu.M. Popov (received by the editors in May 1959 and registered with the Committee for Inventions and Discoveries under the USSR Council of Ministers on July 07, 1958). The article dealt with "a possibility of using electron transitions between the conductivity zone (valence zone) and donor (acceptor) admixture levels of a semiconductor to produce electromagnetic radiation with the aid of an induced radiation mechanism, just as it occurs in a molecular oscillator."

All three articles attempted for the first time to extend the molecular oscillator operation principles to the region of infrared and optical frequencies. They, of course, only initiated such investigations and attracted the attention of the scientific community to the new scientific trend.

I have already said what we have received from all this. Here I consider it expedient to note that 50 years of the development of quantum electronics are a brilliant example of the importance and potential of basic science or a fundamental discovery for practical applications useful to society and the economy. Quantum electronics has actually revealed its potential over the life span of one or two generations.