Quantum electronics at the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR (FIAN) [Text of an address presented March 21, 1985 at the International Conference on Lasers and Electrooptics (CLEO '85) Baltimore, USA, dedicated to the 25th anniversary of quantum electronics]

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A review is given of the history of, and progress in the field of quantum electronics at the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR (FIAN). The paper was presented on March 21, 1985 at the International Conference CLEO '85 dedicated to the 25th anniversary of quantum electronics, Baltimore, USA.

The 25 years that have passed since the invention of the laser may, without exaggeration, be called the "golden age" of quantum electronics. The creation of the laser has not only radically changed the science of optics, but also has had a tremendous influence on many fields of modern physics, chemistry, cybernetics, biology, medicine, and technology. We are now aware that the availability of coherent light has opened up new and totally unexpected possibilities for solving many fundamental problems of our rapidly developing civilization—problems in energy, information, and technology. The wide use of lasers has meant a qualitative transformation in the production segment of society similar to that brought about by the introduction of electricity into industry and human activity.

The many aspects of modern quantum electronics do not allow me to structure this talk in a logical closed classical form even if I restrict the topic to a historical review of the work done at the P. N. Lebedev Physics Institute.[1)] Like an impressionist painter, I will have to sketch in the full picture by the use of nonlogical daubs here and there. It is clear that in this phase of development science for its self expression must borrow the form from art. In any event new forms are needed. First of all, I would like to show a slide that reflects the "ancient" history of quantum electronics—a list of scientific ideas and events (Table I).

All the scientists listed there I know either personally or by their work. In the past years quantum electronics has been enriched by innumerable achievements and the tremendous number of people that have entered the field. For instance, in the Physics Institute of the Academy of Sciences (FIAN) there are about a thousand people working at the present time in the area of quantum electronics, and I am not acquainted, either personally or by their work, with most of the contributors to this conference. Such familiarity is not within the power of a single individual. Quantum electronics has acquired a multitude of faces in the literal meaning of the phrase.

At what point did we begin to work on making lasers at our Physics Institute? It was after the idea of the quantum was firmly established in radio engineering (1956) and gen-

TABLE I.

1900	M. Planck	Hypothesis of the quantum of radiation.
1913	N. Bohr	Quantum nature of the spectra.
1916	A. Einstein	Concept of stimulated emission.
1927	P. A. M. Dirac	Quantum interpretation of the effect of stimulated emission.
1940	V. A. Fabrikant	Idea of the possible observation of stimulated emission in a discharge in a gaseous system.
1950	E. Purcell and R. Pound	Experimentally obtained stimulated emission by inversion of nuclear spins.
1953–1954	N. G. Basov, A. M. Prokhorov, J. Gordon, C. Townes, H. Zeiger	Developed the physical principles of masers; obtained generation in the centimeter range with ammonia molecules.
1955	N. G. Basov, A. M. Prokhorov	Idea of using a three-level system and optical pumping to obtain inversion.
1957	H. Scovil, G. Feher, H. Seidel	Development of paramagnetic amplifier in a crystal.
1958	C. Townes, A. Shawlow, N. G. Basov, A. M. Prokhorov, A. Javan	Idea of stimulated emission effect in the optical range.
1959		1st conference of quantum electronics.
1960	T. Maiman	Developed the ruby laser.
1960	P. Sorokin, M. Stevenson	Developed the fluorite laser.
1960	A. Javan, V. Bennett, D. Herriott	Developed the He-Ne laser.
1961	E. Snitzer	Developed the Nd laser.
1958–1962	N. G. Basov, B. M. Vul, O. N. Krokhin, Yu. M. Popov	Developed theory of various types of semiconductor lasers.
1962–1964	GE, IBM, MIT, FIAN USSR	Developed semiconductor lasers

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erators and amplifiers in the centimeter wavelength range were developed, that the directly opposite idea occurred to us. What if, on the other hand, the ideas of radio engineering were extended to the truly quantum world—to optics. We thought a great deal about the use of a three-level system and optical pumping to obtain inversion. We also clearly understood that in order to produce a generator in the optical range quantum systems with inversion and positive feedback in the optical channel were needed. The optical resonator, proposed by A. M. Prokhorov, is the analog of the tank circuit or the cavity resonator. For us remained the obvious problem of finding a luminescing material and a method of exciting it in order to obtain inversion and generation. It is in just this stage of the investigation that radio physics must be united with optics. At FIAN this unification occurred naturally. The Academy of Sciences Optics school that existed at that time (the S. I. Vavilov Luminescence Laboratory and the G. S. Landsberg Optical Laboratory) and the Spectroscopy Laboratory together successfully effected this union and were transformed respectively to radiophysics (which obtained the modifier "quantum") and to optics (which obtained "laser"). Today all these laboratories are actively occupied with lasers and their application.

To begin with, we studied the possibility of making lasers based on semiconductors. We were attracted to semiconductors as the active medium by their high absorption (amplification) coefficients. This opened up the possibility of making resonators of small dimensions. The physics of semiconductors at that time was studied at FIAN in the laboratory of B. M. Vul (later Academician). The results obtained in this laboratory allowed us to develop a method of producing inversion in semiconductors. The method was based on impurity ionization during interband electrical breakdown, with the subsequent instantaneous removal of the field. This suggestion was reported in June, 1958 (the authors were N. G. Basov, B. M. Vul, and Yu. M. Popov[1]) under the title "Quantum mechanical semiconductor generator and amplifier of electromagnetic oscillations". I spoke of this work at the first conference on quantum electronics in the USA.

Later, in 1960–1961, we succeeded in developing other methods of exciting semiconductor lasers: pumping with a beam of fast electrons, optical pumping, and charge carrier injection through a p-n junction (the authors were N. G. Basov, O. N. Krokhin, and Yu. M. Popov[2–4]). In this period a number of basic ideas for the physics of future semiconductor lasers were put forward in our work: the possibility of obtaining cw operation, the waveguide nature of the active region of a diode, the possibility of reducing the threshold current density for a p-n junction with different band gaps for the semiconductors forming the junction (heterojunctions), and the possibility of using the specimen itself as the resonator. As a result, the basic theory of semiconductor lasers was essentially worked out at the beginning of the 1960s. At the same time, beginning in 1959, under my direction at FIAN the "Photon" program got under way; this was the first Soviet scientific program for the development of lasers. The first publication, a review "Generation, amplification, and detection of infrared and optical radiation by quantum-mechanical systems",[2] contained the basic ideas of this program. Many of the currently existing types of lasers were proposed under the institution of this program.


FIG. 1. N. G. Basov and A. Javan chat during the 1st International Conference on Quantum Electronics (USA, September 1959).

In January, 1962, a group of workers at the A. F. Ioffe Physicotechnical Institute, Leningrad, observed experimentally the effect of line narrowing in a gallium arsenide diode. Lasing in gallium arsenide diodes was achieved for the first time by the group of R. Hall (General Electric) and almost simultaneously by the group of M. Nathan (IBM). A short time later we achieved this result at FIAN (V. S. Bagaev, N. G. Basov, B. M. Vul, B. D. Kopylovskiĭ, O. N. Krokhin, Yu. M. Popov, A. P. Shotov, *et al.*[5]). So, by means of a combined effort, the first semiconductor lasers were created. These results were discussed at the 3rd conference on quantum electronics in 1963 in Paris. Thus, the first quantum generators based on semiconductors were created by the union of several sciences—radiophysics, optics, solid state physics and atomic physics. The success of this work was, to a considerable degree, made possible by the varied nature of the investigations that are traditional in our Institute and that make it possible to unite the strengths of the scientists working in various fields. Moreover, we tried to understand as much as possible the physical picture of the phenomena before doing the experiments, a strategy that allowed us to take the shortest route to our goal.

Subsequently, in the 1960s and the beginning of the 1970s investigations were carried out at FIAN on various types of semiconductor lasers: the dynamic operating ranges of different diodes were studied, fast-acting optical switches

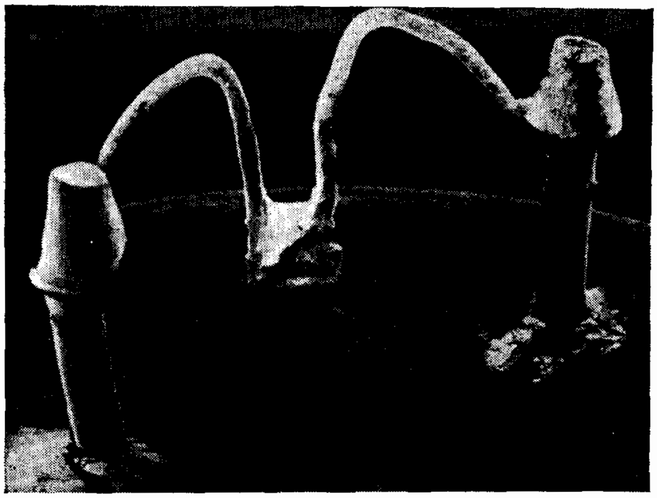

FIG. 2. One of the first gallium arsenide injection lasers (P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR, 1962).

were developed, and optical logical elements were produced (the authors were N. G. Basov, P. G. Eliseev, V. N. Morozov, V. V. Nikitin, *et al.*, 1963–1965).[7] Along with the group of Zh. I. Alferov from the Leningrad Physicotechnical Institute, work was carried out on optimizing the characteristics of gallium-aluminum-arsenic heterolasers,[6,33] the first laser based on cadmium sulfide, excited by fast electrons and operating at $\lambda = 0.5\,\mu$m, was devised (1964),[34] laser electron beam tubes were developed for three-color projection television, and address tubes for optical memories were developed (authors, N. G. Basov, O. V. Bogdanovich, A. S. Nasibov, and A. N. Pechenov[8]), and semiconductor lasers with one- and two-photon excitation by the radiation of ruby and Nd lasers were studied.[9,10]

In 1974, in a combined investigation by FIAN and the State Rare Metals Institute, injection lasers were devised, based on a four-component gallium-indium-aluminum-arsenic heterostructure whose emission was tunable over a wide frequency range, depending on the composition (authors, A. P. Bogatov, L. M. Dolginov, L. V. Druzhinina, P. G. Eliseev, *et al.*).[11]

The work on semiconductor lasers enabled us to create excimer lasers (authors, N. G. Basov, V. A. Danilychev, Yu. M. Popov, and D. D. Khodkevich, 1970)[12] and lasers with combined electroionization excitation (authors, N. G. Basov, V. A. Danisychev, E. M. Belenov, and A. F. Suchkov, 1971).[13] At FIAN, chemical, gas dynamic, and photodissociation lasers were proposed and then successfully developed.[14–19,35,36] In 1984 a high-pressure (2–3 atm) He-Ne laser operating in the visible red and yellow region of the spectrum was developed (authors, N. G. Basov, V. A. Danilychev, O. M. Kerimov, *et al.*).[20] At the present time a project has been started involving an oxygen-iodine laser for investigations in the area of nuclear fusion. Today, all these types of lasers are associated with applications of the highest importance in various fields of science and technology.

At the end of the 1960s work was begun in the optical laboratory of FIAN on the development of effective lasers based on metal vapors. In 1972 a self-heating copper vapor laser was made (authors, A. A. Isaev, M. A. Kazaryan, and G. G. Petrash)[37] and on the basis of this laser a laser projection microscope was devised, which made it possible to obtain on a large screen a brightness-enhanced image of a microscopic specimen (authors K. I. Zemskov, A. A. Isaev, M. A. Kazaryan, and G. G. Petrash, 1974).[40]

At the beginning of the 1970s in the quantum radiophysics laboratory (Physics Institute of the Academy of Sciences) work was begun on finding ways to make lasers that operate in the far ultraviolet and soft x-ray regions of the spectrum. A number of theoretically possible schemes were suggested for producing inversion on the transitions of multiply charged ions in a laser plasma (authors, A. V. Vinogradov, I. I. Sobel'man, and E. A. Yukov).[21] Two schemes were considered as being the best: creating inversion via electronic excitation in the transitions of Ne-like ions, and the method of selective photopumping. At the same time, experimental efforts to achieve amplification and generation on the transitions of the neon-like CaXI were begun. In 1977 preliminary positive results were obtained for the first time in the range $\lambda \approx 600$ Å (authors, G. V. Peregudov, E. N. Ragozin, I. I. Sobel'man, *et al.*).[22] In 1984, in Livermore (USA), stimulated amplification on the transitions of the Ne-like ions of selenium ($\lambda = 206$ Å and 209 Å) and yttrium ($\lambda = 155$ Å and 157 Å) was obtained (authors, D. L. Matthews, *et al.*, 1984).

Clearly, one of the most important areas of application of lasers is inertial-containment nuclear fusion. The laser nuclear fusion "fever", which began in 1962, very quickly grew to be an independent field in the physics and technology of thermonuclear fusion. Today it is possible to speak separately of a history of laser thermonuclear fusion (Table II).

Of course, this historical reference does not contain many important theoretical and experimental incidents that arose on the route to laser thermonuclear fusion, incidents such as the generation of fast electrons and ions, the discovery of numerous laser-plasma effects, the evolution of the problem of target compression stability, the competition of long wavelength and short wavelength lasers, etc.

The properties of laser light—evolution of a substantial amount of energy in a short time and high energy flux densities—make it possible to attain specific energy deposition rates of 10^{18} W/g. From this stems the possibility of heating a material to thermonuclear temperatures and compressing it to high densities in consequence of the high pressure that results from the reduction in size. O. N. Krokhin and I called attention to this circumstance in 1962 (report to the Presidium of the Academy of Sciences of the USSR, March, 1962), and in 1963 the first theoretical estimates were reported at the 3rd conference on quantum electronics (Paris).[23] Theoretical and experimental investigations, on the interaction of high-power laser radiation with a plasma, were begun at this time at FIAN. In the course of carrying out the experimental program we developed ruby and Nd lasers with record power parameters for that time.

In the fall of 1962 the method of Q-switching for increasing the power of a ruby laser was conceived at FIAN.

TABLE II.

1962	N. G. Basov, O. N. Krokhin	Proposed use of lasers in controlled thermonuclear fusion.
1968	N. G. Basov, P. G. Kryukov, Yu. V. Senatskiĭ, S. D. Zakharov	Detected thermonuclear neutrons in a laser plasma.
1972	N. G. Basov, O. N. Krokhin, G. V. Sklizkov, S. I. Fedotov	Developed the first multichannel laser apparatus "Kal'mar" (Russian Monster), carried out experiments on laser compression of a target. Obtained nuclear densities 30 g/cm^3.
1972	E. Teller, J. Nuckolls, L. Wood, G. Zimmerman	Proposed scheme of laser supercompression of uniform thermonuclear targets.
1974	P. N. Lebedev Physics Institute, Academy of Sciences USSR; M. V. Keldysh Institute of Applied Mathematics, Academy of Sciences of the USSR	Proposed the idea of low-entropy supercompression of high-aspect-ratio multilayered targets.
1975–1978	P. N. Lebedev Physics Institute, Academy of Sciences of the USSR	Experimentally attained thousandfold laser compression of shell targets.
1978	Lawrence Livermore Laboratory (LLL)	Fired 20-channel laser apparatus "Shiva"; obtained neutron output $3\cdot10^{10}$.
1978	Los Alamos Laboratory	Fired 8-channel CO_2 laser "Helios".
Beginning of the 1980s	Institute of Laser Technology (Osaka)	Suggested the idea of x-ray targets and targets of the type "cannonball" attained density of DT combustion ~ 30 g/cm^3.
1982	P. N. Lebedev Physics Institute, Academy of Sciences of the USSR	Fired 108-channel apparatus "Del'fin" attained density 8 g/cm^3 in compression of high-aspect-ratio shell targets.
1983	LLL	Fired apparatus "Novetta" attained DT density ~ 50 g/cm^3.
1983	Institute of laser Technology (Osaka)	Fired apparatus "Gekko"; attained neutron output $4\cdot10^{10}$
1983–1984	P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR	Experimental demonstration of compression stability of targets of high ($\sim 10^2$) aspect ratio.
1985	LLL	Fired apparatus "Nova".

This idea was implemented experimentally with the use of a rapidly rotating disk with an aperture at the focal plane of two confocal lenses. In the USA *Q*-switching was obtained with the use of an electrooptical Kerr cell shutter (authors, McClung and Hellwarth).

Later, for the purpose of developing laser sources to produce plasmas, work begin at FIAN on the amplification of nanosecond pulses in traveling wave amplifiers. The experimental and theoretical studies of the amplification processes in the saturation regime allowed us to reduce further the laser pulse length and bring the emitted power up to several gigawatts. Study of the amplification of pulses with a complex multimode structure led to the construction of a model of solid state lasers with passive mode locking (authors, N. G. Basov, P. G. Kryukov, V. S. Letokhov, *et al.*, 1969).[24] Self-mode-locking in neodymium glass lasers was first observed at the optical laboratories of FIAN (authors, V. I. Malyshev and A. S. Markin, 1965).[41] At the same time diagnostic methods having unique spatial and temporal resolution were devised for hot laser plasmas. Many of these methods, for example, laser interferometry and schlieren photography, are now numbered among the classical ones. A significant advance in our experimental efforts was the observation of the first thermonuclear neutrons in a plasma formed by a Nd laser.[25] This result was duplicated within a year at Limay and it demonstrated the possibility of laser-induced nuclear fusion.

At the beginning of the 1970s the time for laser compression of irradiated targets arrived. In 1972, at FIAN, the nine-channel laser apparatus "Kal'mar" for spherical irradiation of targets was fired up. In this apparatus the first experiments were carried out with spherical homogeneous targets, where the generation of D-D neutrons, and later also secondary D-T neutrons, were observed (authors, N. G. Basov, O. N. Krokhin, G. V. Sklizkov, S. I. Fedotov *et al.*, 1972).[26,27] The secondary D-T neutrons gave evidence for the existence of a compressed nucleus. In this same year, at the Montreal conference the group of E. Teller, at Livermore, advanced the beautiful physical idea of supercompression by means of time-profiling the laser pulse (authors, E.

FIG. 3. At a seminar on quantum electronics at the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR (September 1965).

Teller, J. Nuckolls, L. Wood, and G. Zimmerman). However, in our view, there were at least two circumstances that made implementation of this scheme quite difficult. The first of these clearly indicated that "it is impossible to shoot a gun slowly". This scheme required super-high radiation flux densities in the final stages of the pulse, which must inevitably cause preliminary heating of the compressed material by fast electrons and hard photons from the hot "crown". The second difficulty associated with this compression scheme involved the instability against a transition from the isentropic mode to a mode with strong shock waves.

In 1974, with workers from the M. V. Keldysh Institute of Applied Mathematics, we proposed an alternative plan for low-entropy compression with the use of a constant-intensity laser pulse and nonuniform targets of high aspect ratio (authors, Yu. V. Afanas'ev, N. G. Basov, P. P. Volosevich, E. G. Gamaliĭ, O. N. Krokhin, S. P. Kurdyumov, E. I. Levanov, V. B. Rozanov, A. A. Samarskiĭ, and A. N. Tikhonov).[28,29] During the following years we carried out a large series of experiments on the compression of shell-structured targets, in the "Kal'mar" apparatus, completely corroborating the ideas that we had worked out (authors, N. G. Basov, G. V. Sklizkov, A. S. Shikanov, *et al.*).[30] Of course, we clearly understood that the main problem of laser-induced nuclear fusion using thin shells had to do with the stability of the compression. Together with a theoretical-numerical series of investigations at the end of the 1970s and the beginning of the 1980s,[31] we carried out experiments on the compression of shells with an aspect ratio $\sim 10^2$ with the 108 channel apparatus "Del'fin", which was constructed in 1982.[32] In these experiments we were able to achieve compression by a factor of $3\cdot 10^3$, an indication of the possibility of stable compression of these targets (authors, N. G. Basov, G. V. Sklizkov, S. I. Fedotov, *et al.*, 1983)[50] Today the main problems in this area, we believe, are the further development of the physics of thermonuclear targets, particularly in the range of compression 10^4, the choice and construction of a driver for laser-induced thermonuclear fusion, the engineering and technological development of a laser thermonuclear reactor, and finally a design for a laser thermonuclear power station that is technologically feasible, economically viable, and safe for the population and the environment.

Beginning in 1963, at the astrophysics laboratory (FIAN Crimea), investigations of laser tracking of the moon have been carried out. The distance to the moon has been measured to great accuracy, making it possible to improve the accuracy of the parameters of the Earth-moon system by several orders of magnitude. In 1978 measurement of the Earth-moon distance achieved a precision of 10 cm. Such precision measurements make it possible to measure accurately the distances between various points on the Earth. For instance, in 1984 the distance between the MacDonald observatory (Texas, USA) and the Crimean laboratory was measured to an accuracy of ~ 70 cm.

From the beginning of the 1960s, at the quantum radiophysics laboratory, work was started in connection with the laser-induced thermonuclear fusion problem, on the conversion of laser radiation for the purpose of increasing its density and directionality and broadening its spectral range. The final goal was to achieve diffraction-limited divergence (10^{-5}–10^{-6} radians for a device operating at the kilojoule level). It was proposed that this problem could be solved with the use of stimulated Raman scattering or stimulated Mandel'shtam-Brillouin scattering (authors, N. G. Basov and I. I. Sobel'man).

The work carried out thereafter at FIAN allowed us, with the use of converters based on stimulated Raman and Mandel'shtam-Brillouin scattering, to increase the brightness of pumping lasers by several orders of magnitude in the lasing mode, while for the case of amplification of a single-mode Stokes emission in a spatially nonuniform pumping field with stimulated scattering, practically 100% photon conversion was attained while preserving the diffraction-limited directionality of the amplified radiation. The principal results are summarized in an article by N. G. Basov.[38]

Stimulated Mandel'shtam-Brillouin scattering experiments carrier out at the quantum radiophysics laboratory under a program for developing converters led in 1971 to the experimental observation of wavefront self-reversal by stimulated light scattering (authors, V. V. Ragul'skiĭ, V. I. Popovichev, and F. S. Faĭzullov). The first publication, containing also a preliminary theoretical interpretation of the phenomenon of wavefront self-reversal appeared in 1972 (authors, B. Ya. Zel'dovich, V. I. Popovichev, V. V. Ragul'skiĭ, and F. S. Faĭzullov).[39]

In 1978 at the quantum radiophysics laboratory, a broad experimental program for the investigation of this phenomenon as applied to the problem of high-power lasers for controlled thermonuclear fusion was started. An effective divergence $\sim 2\cdot 10^{-5}$ radians, equal to the diffraction-limited divergence, was obtained experimentally for the first time in 1979 in a single channel of an apparatus of the "Del'fin" type.

In 1962 at FIAN, the possibility of a self-focusing laser was put forth (author, G. A. Askar'yan[51]); this phenomenon plays an extremely important role in the problem of high-power lasers.

We attach a great deal of importance to the problems of laser technology at FIAN. Laser technology (annealing, hardening, welding, etc.) is the principal task of the branch of the Physics Academy of Sciences set up in Kuybyshev.

At the physics Institute of the Academy of Sciences we also develop new types of technological lasers. In recent years we have developed electric ionization lasers ($\lambda = 1.73$ μm) with an energy 80 J (8 J/liter), a pulse duration $4\cdot 10^{-6}$ sec, efficiency ~ 2–3%, and a divergence $\sim 5\cdot 10^{-5}$ radians (authors, N. G. Basov, V. A. Danilychev, I. V. Kholin, *et al.*).[43]

In speaking of the development of quantum electronics at FIAN it is impossible not to touch upon the problem of optical frequency standards. The principal task of changing over from high-stability generators in the uhf region to the optical region was begun by the work carried out in FIAN back in the 1950s.

In 1967–1968 at the quantum radiophysics laboratory, the main directions for the development of this problem were laid out (authors, N. G. Basov, V. S. Letokhov, and A. N. Oraevskiĭ, 1968).[44,45]

In 1969–1970 narrow resonances were detected in He–Ne ($\lambda = 3.39\,\mu$m) and CO_2 ($\lambda = 10.6\,\mu$m) lasers with internal and external absorption cells. The frequency stability of the emission makes possible a long-term stability $\sim 10^{-11}$, exceeding by 3–4 orders of magnitude the stability of any system known to that time (authors, N. G. Basov, I. N. Kompanets, O. N. Kompanets, V. S. Letokhov, and V. V. Nikitin).[46]

At the end of the 1960s we undertook a series of studies of the interaction of colliding pulses in ring gas lasers with nonlinear absorption, and a method was proposed for narrowing the reference resonances by 2–3 orders of magnitude relative to the homogeneous width of the spectral line.[47] In 1970 these resonances (30 kHz width) were first observed in a He-Ne/CH_4 ring laser (authors, N. G. Basov, E. M. Belenov, M. V. Danileĭko, and V. V. Nikitin).[48] Further development of the method of competing resonances in ring lasers led to the creation of a compact optical frequency standard with a long-term stability $\sim 10^{-13}$.

New possibilities for increasing the resolving power of precision laser spectroscopy and the stability of optical frequency standards are provided by the method of frequency resonances of a two-mode laser with nonlinear absorption, a method worked out together with coworkers of FIAN and the Moscow Engineering Physics Institute. The distinctive feature of this method is its high sensitivity to detecting very narrow spectral lines. At the present time, at FIAN we have produced stabilized He–Ne/CH_4 lasers, based on the two-mode frequency method, that have a narrow emission spectrum (~ 10 Hz) with long-term stability $2\cdot 10^{-14}$, and spectral lines separated with a Q of 10^{11}. Characteristic features of these systems are their small size, ease of operation, and reliability, such that we can regard this method as one of the most promising ones for attaining long-term stability at the 10^{-15}–10^{-16} level and frequency reproducibility of 10^{-14}–10^{-15} (authors, N. G. Basov, M. A. Gubin, V. V. Nikitin, E. D. Protsenko, *et al.*).[49]

In 1970 at FIAN, there was proposed (author, A. F. Suchkov)[52] and implemented high-sensitivity intraresonator laser spectroscopy (authors, E. A. Sviridenkov, A. F. Suchkov, *et al.*[53]) permitting study of trace amounts of material (down to 10 atoms/cm^3) by virtue of the fact that the material is located within the resonator, and the multiple passages of the light through the material results in an equivalent path length of the order 10^7–10^9 cm.

I would like also to speak of the use of lasers in medicine.

In 1982, the laboratory for laser sugery was organized at FIAN. Today this laboratory operates in close collaboration with the All-Union Cardiological Center, the All-Union Laser Medicine Center, the Institute for Gastroenterology, and the Kaunas Medicine Institute. As a result of these efforts laser operations on the heart and vascular system have been incorporated into medical practice: this includes the creation of a new vascular system for the myocardium by the laser formation of channels, and controlled damage to the conduction paths of the heart (His' bundles) for the purpose of preventing arrythmia.

Lasers are widely used in stomach resectioning operations, for treating trophic ulcers (CO_2 laser, 60 W), for stopping stomach hemorrhage, for removing polyps, for the sterilization of wounds, with the consequent enhancement in the effect of antibiotics (Ar laser, 10 W). The effectiveness of laser therapy is evidently connected with the great brightness of the laser light. For example, it was observed by R. V. Ambartsumyan in 1985 that the effect of small doses is governed by processes at the celluar level, and is related to the formation of singlet oxygen.

In conclusion to my talk I would like to speak of the foremost task in quantum electronics that faces our combined efforts in the foreseeable future. Of the use of lasers, especially semiconductor lasers, with their "unpretentiousness", their compactness, simplicity, economy, and very high efficiency, in optical systems there is no doubt. Therefore the development of permanent and operating optical memories, optical coupling lines, optical integrated microcircuits based on semiconductor lasers, and other optical elements, for instance controllable transparencies, should lead to the appearance of ultrafast computers. Their stability against noise and the consequent reliability of operation may prove to be better than that of the most modern electronic computers.

Another problem associated with semiconductor lasers is that of creating a spatial lattice of synchronized lasers.

In laser thermonuclear fusion the problem is obvious: a 10 MJ driver is needed. It may be in the final analysis that we shall turn to the glass laser, in spite of the great competition to it afforded by the excimer and the chemical laser. Neither can we exclude the possible recourse to the first plan involving the CO_2 laser, if it is possible to overcome the physical barrier associated with fast electrons. The problems are many, the promises are great, and I am deeply convinced that at our next jubilee quantum electronics will be enriched by a new series of remarkable discoveries.

In conclusion I would like to thank Yu. V. Afanas'ev, I. G. Zubariv, Yu. M. Popov, and F. S. Faĭzullov, for help in preparing this talk.

A great deal of work in the field of quantum electronics has been carried out by Division A of FIAN, and on the basis of this work the Institute of General Physics, Academy of Sciences of the USSR was organized in 1983.

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