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Aram V. Papoyan
Editor

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Introduction

This volume includes oral and poster presentations reported at the International Conference on Laser Physics 2010 (Ashtarak, Armenia, 12–15 October 2010). The conference is held annually by the Institute for Physical Research of the National Academy of Sciences of Armenia (IPR NAS, http://www.ipr.sci.am) in Ashtarak for presentation and discussion of the latest progress in fundamental and applied research in laser physics and closely related fields. The conference is open for participants from research and industry centers of Armenia and foreign countries.

The principal objectives of the conference are promotion of laser physics in Armenia; revealing and coordination of perspective directions of investigations; further cooperation and integration of Armenian scientists with the international laser physics community; promotion of innovation and commercialization activities; encouraging and promotion of young scientists in their professional activity. As a means to reach these goals, the organizers emphasize unconstrained, informal discussion of the results of ongoing studies, and live communication of Armenian scientists from different institutions with each other and with foreign participants.

The conference program covers all the aspects of laser physics with the focus on new and exciting developments and results in physics of coherent light sources, nonlinear and quantum optics, laser spectroscopy of atoms and condensed matter, laser instrumentation, crystal growth and thin film preparation of inorganic materials for quantum electronics and integral optics, and industrial applications.

The conference included 110 registered researchers, including 19 from abroad. Eighty-five works were reported, including 28 oral talks and 57 poster presentations. Sixty-six papers were submitted for publication in these Proceedings. Fifty-five papers have been selected for publication based on results of double reviewing by expert referees assigned by the program committee.

Laser Physics 2010 was dedicated to the 50th anniversary of lasers, and the regular scientific contributions presented in this volume are preceded by an introductory article, "50 years of lasers: the achievements of the Institute for Physical Research," reported by the Conference Chair at the opening session. The regular contributions presenting recent scientific results are presented in the seven topical sessions held at the conference.

The organizers believe that the publication of conference papers in the Proceedings of SPIE series will promote the annual Laser Physics conference, and will facilitate further integration of Armenian research centers with international scientific community.

I would like to express my special gratitude to the International Science and Technology Center (ISTC) for supporting scientific research at the IPR NAS and sponsoring the Laser Physics 2010 conference, which in particular made it possible to publish this Proceedings volume. Support of the State Committee of Science of Armenia in organizing the

conference is also gratefully acknowledged. I would like to mention the valuable role of members of the organizing and program committees, and, in particular, Vahagn Petrosyan, the conference secretary for his generous contribution in organizing the conference and preparation of this volume.

Aram V. Papoyan

50 years of lasers: Achievements of the Institute for Physical Research (introductory article)

2010 was the year of commemoration of *50-th anniversary of lasers*. Invention of lasers had a significant impact on development of science and technology. The Institute for Physical Research (IPR) of National Academy of Sciences of Armenia, one of the key Armenian scientific institutions, is a worldwide-known leader of laser physics in Armenia. The present paper is based on unpublished manuscript of Prof. **M.L. Ter-Mikaelian** (1923-2004), the founder of laser physics in Armenia, and first director of IPR. The manuscript entitled **"Optical Quantum Electronics and Nonlinear Optics in Armenia in 1962-1987"** was translated to English by V. Chaltykyan. Below we present a concise version of the manuscript. The full text with detail references list, photographs and photocopies of records of prominent scientists in the IPR guestbook, as well as an article presenting further achievements of IPR in laser physics covering "better visibility" period of 1987 – 2011 will appear soon at the IPR web page: http://www.ipr.sci.am.

"Optical Quantum Electronics and Nonlinear Optics in Armenia in 1962 – 1987" by M.L. Ter-Mikaelian

1. Introduction

In early 60-s of the last century, pioneering studies of N.G. Basov, A.M. Prokhorov, and Ch. Townes have lead to creation of the first optical quantum generators, which started immediately to be employed in various fields of science stimulating development of a number of new scientific directions. Soon after the first experiments with the lasers, many physicists and technologists from different fields of physics got involved in development of optical quantum electronics and nonlinear optics, which appeared as a separate field.

At that time, a problem arose of extending physical research within the Republic's Academy of Sciences, and increasing scientific and pedagogical activities at the Yerevan State University (YSU). In this context, intense discussions took place in 1961-1962 at the newly opened Chair of Nuclear Physics of YSU on the choice of new scientific directions. There were several suggestions, one of which was optical quantum electronics. At that time the Chair had neither specialists in the field, nor corresponding equipment, i.e., actually nothing but great interest towards the new field of investigations, which was rather far from the nuclear physics.

Our suggestion was approved by the President of the Academy of Sciences of Armenian SSR V.A. Ambartsoumian, Rector of the YSU Academician I.Kh. Harutyunyan, and supported by the Corresponding Member A.L. Mikaelyan, who rendered considerable assistance, involving us in the first government decrees on the development of quantum electronics.

In the sequel we had always thorough support from both the Presidium of Academy of Sciences of Armenian SSR and the Administration of Yerevan State University. So, from the very inception of the activities in quantum optoelectronics and nonlinear optics, they were performed by joint efforts of all professionals working in the Republic, regardless of their affiliation. This predetermined the success and rapid development of these areas.

In order to begin with the experimental work, it was necessary to organize a laboratory equipped with modern facilitiest, to engage to new studies specialists working in Armenia, and to train needed personnel.

This task was implemented as soon as possible. We were joined by a group from the Solid State Chair, headed by a corresponding member of the Academy of Sciences of Armenian SSR, M. Movsesian, who marked the beginning of experimental work on nonlinear optics in the Republic and established their high scientific level.

Then, at the Chair of Nuclear Physics the Problem Radiation Laboratory was organized and the staff of the Chair was reoriented to the research into quantum electronics.

After that the Chair of Radiophysics and Electronics was engaged, headed by a corresponding member of the Academy of Sciences of Armenian SSR R. Kazaryan, who introduced radiophysical ideas and methods into the investigations on quantum electronics, and, finally, in 1963, the theoretical and quantum electronics departments were organized within the Academy of Sciences of the Armenian SSR, which helped us to significantly accelerate the development of new directions.

All research in the field of quantum electronics and nonlinear optics in Armenia were concentrated in the above-mentioned units, which were merged into a single research center, known as the Joint Laboratory of the Academy of Sciences and YSU (JLASYSU). Scientific Council and research plans were approved by joint decision of the Academy and University. This system of organization and development of quantum electronics in the Republic lasted up to 1972; it created, on the one hand, favorable opportunities for development of the new direction, and helped, on the other hand, to significantly strengthen the pedagogical activity at the University. During these years YSU was developed remarkably: the number of students graduating from the Physics Department was doubled.

At the end of 1967 academic units working in the fields of quantum electronics and solid state physics were transformed into the Institute for Physical Research of AS of Armenian SSR (IPR AS); construction of a new complex began in Ashtarak, and then in 1970 all the above laboratories moved to Ashtarak. This strengthened significantly the resource basis and concentration of forces on the basic directions of scientific development, but separated geographically from the University Chairs. However, this did not change the established tradition of joint research.

In addition to the continuing joint research on quantum electronics and nonlinear optics by academic laboratories and university chairs within JLASYSU, creation of IPR AS enabled the development of a new scientific field of study of the processes of growth and investigation of materials for laser technologies. In 1968, at the Kirovakan Chemical Plant (KCP) a department of IPR AS was organized, which played a crucial role in the development of investigation of materials for laser technology. On the basis of physical-chemical laboratory of the KCP and Kirovakan department (KD) of IPR AS Joint Laboratory was organized for developing new and improving existing materials for laser technology.

In 1972 JLASYSU was closed and the Problem Radiation Laboratory of YSU moved back to Yerevan, and in 1978 on its basis the Institute of Condensed Matter Physics (CMP) of YSU was organized. At that time optical quantum electronics and nonlinear optics were developing also in other centers of the Republic. New scientific directions appeared at the chairs in the universities of Armenia; for example, at the Chair of Optics of YSU liquid crystals were studied, the Chair of General Physics of the Polytechnic Institute performed theoretical study on the interaction of laser radiation with semiconductors, the Chair of Radiophysics and Electronics of YSU worked on generation of laser radiation in the millimeter frequency range, at the Institute of National Economy theoretical research on optical properties of doped crystals was conducted, Yerevan Physical Institute developed theory of free electron lasers, etc. The elemental basis for quantum electronics and its applications were developed also in a number of enterprises of the Republic, among which we should note the KCP, the "Kristall" association, which included Arzni plant of precise technical stones (APPTS), Polytechnic Institute, as well as a number of sectoral institutions and laboratories. In order to intensify the applied research and to create facilities for laser technology and single crystal growth, the pilot plant "Kristall" was organized at IPR AS in 1986, and the Research Institute of CMP with the SDO and pilot production were in 1987 transformed into the SPA "Laser Technology".

In what follows we will describe the basic directions and results of works, which in our opinion contributed significantly to the development of quantum electronics and nonlinear optics in the Republic.

2. Optical quantum electronics

a) Optical quantum generators

In 1962, together with the Research Institute of Radiooptics of MRI USSR, studies began on the creation of ruby generators. This first comprehensive work has initiated the development of quantum electronics and nonlinear optics in the Republic and included a wide range of problems, beginning with the formulation of basic equations of the theory of solid-state generators to the creation and development of industrial ruby lasers. In the theory of quantum generators and amplifiers the limits of validity of the rate equations for calculation of the laser intensity versus time and position along the laser propagation were formulated. Basic characteristics of steady and pulsed regimes were considered: dependence of the output energy on non-resonant losses, transparency of mirrors, pumping, the properties of the active material, etc. Depending on these parameters, optimum conditions for generators and amplifiers were found. In particular, we showed that due to non-resonant losses the increase in linear dimensions of the active element in amplifier or oscillator has a limit beyond which increasing the length of the active element does not lead to increase in radiation. The effective size of the active element, above which the amplification is saturated, was determined.

This theory formed the basis for all subsequent engineering calculations for designing solid-state generators. Also quasiclassical theory of laser radiation was developed, which takes into account the coherence effects in the amplification and lasing.

The first experimental work on lasers related to the studies of ruby lasers. Measurements of luminescence and optical characteristics of ruby, studies of characteristics of generators and amplifiers, research into output and efficiency depending on the transparency of mirrors, non-resonant losses, pumping, sizes of ruby elements, construction of the cavity, this is a part of the list of works that was performed for creation of the first models of ruby generators.

Works performed by JLASYSU employees in these areas by 1967 were included into the monograph. Also a special issue of the Scientific Notes of YSU was devoted to these works.

Work on ruby lasers led to the development and industrial launcing in the Republic of a series of quantum optical generators "Arzni", the first models of which were demonstrated at the Leipzig Fair as early as in 1965.

For the cycle of the above-mentioned works on study, development, and industrial launching of pulsed solid-state lasers for scientific research and technological purposes, the team of authors from Arzni Production Association "Kristall", Moscow Institute of Radiooptics of MRI USSR, and IPR AS was awarded the Science and Technology State Prize of the Armenian SSR in 1980.

In the sequel, investigation and designing of various types of generators have been expanded and continued. In particular, the influence of coherence on the operation of ruby lasers was experimentally studied.

One of the last works of IPR AS of that time was creation of a pulse generator on garnet with a power of about 10 MW and a very narrow width of radiation equal to 0.025 cm^{-1}, as well as an erbium doped garnet laser at three microns.

In the field of picosecond generators we proposed and implemented two new ways of realization of tunable picosecond generators based on the stimulated Raman scattering (SRS): by inclined polaritons and by the mixing of two laser waves in a crystal of lithium iodate. In IPR AS, in colaboration with the Hungarian Central Research Institute, a new method was proposed and implemented for measuring the duration of ultrashort pulses; the method is based on noncollinear second harmonic generation in a nonlinear crystal. Proposed and implemented was the method of smooth control of the sweeping duration; the method extends the limits of measurement by an order of magnitude both upward and downward. Proposed and realized was a nonlinear optical spectrochronograph with subpicosecond (0.2 ps) resolution, which allows measuring the frequency chirp of laser radiation in the limits from 10^{-2} to 10^{-3} cm^{-1}/ps in a wide range of wavelengths. Generation of tunable ultrashort laser pulses in the range of 1.046 - 1.09 microns was realized using phosphate neodymium glasses. Generated ultrashort pulses are close to spectral-limited and may be varied in duration in the range 6-250 psec and, correspondingly, over spectrum in the range 0.15 - 6 cm^{-1}. YAG neodymium based picosecond laser generating at four different wavelengths was developed.

Tunable dye laser with an active medium in the form of a thin (several microns) layer of solution with a narrow (about 0.01 nm) line of tunable radiation was created. On the basis of performed srydies also a two-frequency tunable laser with distributed feedback (DFB) in a quasi-waveguide layer of dye solution was realized. Tunable DFB generation was also implemented in the picosecond regime (with pumping of 35 ps duration). It was shown that in the case of employing a quasi-waveguide active layer as an amplifier a multiply (up to 1000 times) amplified signal with improved spatial parameters and distributed over several fixed directions may be obtained.

In eighties, works began on studies of the possibilities of obtaining stimulated emission in vacuum ultraviolet. This new direction was based on the use of anti-Stokes Raman scattering from high-lying metastable states of atoms excited in the gas-discharge plasma.

New emission lines have been recorded in the range of 50 - 80 nm in the autoionization spectrum of atomic potassium and spontaneous Raman scattering on metastable helium atoms at the wavelength of 56.9 nm and on neon at 628 nm was realized; the spectral brightness of these lines exceeded the brightness of existing sources of synchrotron radiation, these studies were preceded by investigations of the gas discharge, which were attended by Czechoslovak scientists and focused on the study of ionization waves. The study of gas discharge led to the creation of gas lasers in a mixture of He-N_2. Interesting works were carried out on generation of submillimeter waves, new theoretical ideas were proposed on the generation of radiation, and study of motion of electrons in the electromagnetic wave were performed. Laser based on the phenomenon of phase conjugation was created. A large series of works on semiconductor lasers were conducted.

b) Propagation of laser radiation through turbulent atmosphere

Large series of studies on the propagation of optical laser radiation in the atmosphere was performed at the Department of Quantum Electronics of IPR AS. In Armenia, between Yerevan and the Byurakan Observatory one of the first experimental telephone line using modulated radiation of helium-neon laser was launched. On this line, our scientists performed studies on optimization of transmitting and receiving optical signals in the atmosphere and, in collaboration with the Institute of Physics of Atmosphere of AS USSR, on propagation of laser beam in the atmosphere; this work continued in a number of expeditions (Lakes Sevan and Ladoga, Black and Japan Seas, Tsimlyanskoe reservoir, and polygon of IPR).

We studied statistical characteristics of a laser beam passed through atmosphere in different geographical and climatic conditions. The longitudinal and transverse correlation functions of intensity fluctuations in a turbulent atmosphere were for the first time studied experimentally on real lines. Quasioptimum, optimum, and adaptive optical systems of information transfer via atmospheric channel with both direct and heterodyne detection and in both visible and infrared spectrum were experimentally and theoretically studied. An original method of compensation of phase fluctuations of the optical signal in the atmosphere at homodyne reception was proposed and investigated. Different variants of diversed reception raising the noise immunity of communication were realized. In late eighties, the possibility of compensation, by means of phase conjugation, for the distortions introduced by the atmosphere was studied experimentally on real lines. Phase conjugation was excited by SBS in a liquid or fiber. It was shown that this dramatically increases the effectiveness of photomixing, and also a partial restoration of wavefront of second harmonic of the probing radiation takes place. Channels with scattering were studied, in particular those beyond-the-horizon. The performed studies allowed us to develop units of operative control of the state of atmosphere, the system of diversed reception of a weak optical pulse, and a technique for rapid estimation of the distortions of the wavefront of laser beam in atmosphere.

3. Growth and study of crystals for quantum electronics

a) Introduction

Ruby was a basic material for quantum electronics at the initial stage of its development. In the sixties in Armenia (Kirovakan) an industrial center on growth of synthetic ruby already existed. They were processed at the APPTS, whose production was widely used in jewelry and clock industry. This circumstance stimulated the development of works on quantum electronics and created an opportunity to involve the enterprises above into scientific activity. The first joint works were launched in 1962, when the main working element of a laser was ruby. The first element grown by the Verneuil method in Kirovakan and processed at Arzni, gave generation in JLASYSU at the end of 1962. Scientific contacts with physicists of JLASYSU prepared industry of Armenia to carry out a large complex of works on production of ruby elements for optical quantum generators. A major role in organizing these activities played the Institute of Crystallography of AS USSR, which introduced at the KCP the method of directed crystallization for the growth of active laser elements of ruby and garnet.

Many years KCP and APPTS were the main suppliers of ruby active element for the research institutions of the Republic. This played a great role in the development and establishment of quantum electronics and nonlinear optics in USSR. A group of engineers of Kirovakan and Arzni plants were awarded in 1975 the State Prize of the Republic for the works on industrial development and production of wares of corundum. However, the development of quantum electronics and nonlinear optics stimulated new studies and search for more effective materials for quantum electronics.

Works on search for new materials began to develop intensively after the KD of IPR AS was opened in 1968 at the KCP. There, studies on a variety of single crystals with industrial value have been initiated. Studies on the growth of single crystals for quantum electronics and nonlinear optics were concentrated in the Joint Laboratory, which included Physical-Chemical Laboratory of the KCP and the KD of IPR AS. Great help in organization of these works made Presidium of the AS of Armenia and the Administration of the KCP.

In late eighties an extended complex of works were performed on development and industrial production of materials for quantum electronics.

Development of works on the creation of single crystals has stimulated new research in the field of solid state physics. These included theoretical and ESR studies of energy levels of rare-earth ions in different crystalline matrices, studies of polaritons by means of SRS, etc. Annual meetings organized by IPR AS, devoted to the problem of crystals for quantum electronics, as well as periodic scientific-technological conferences organized by the KCP were evidence of recognition of the Republic as one of the centers on these problems in USSR.

b) Nonlinear and acousto-optical crystals

The techniques of growth of a number of nonlinear and acousto-optic crystals for laser technology and research were elaborated. Some of them were introduced and are produced in the Republic. The main scientific direction of these works was to study the phase states, the kinetics of solid-phase interactions, the doping process, the influence of electric fields on the growing process, etc; the purpose was to achieve reproducible high-quality crystals and to develop other methods.

As a result of these investigations, new acousto-optic crystals were elaborated, such as large samples of lead molybdate and calcium molybdate and crystals of alpha-iodine acid. Also the technique for growing crystals of diplumbum molybdate and lead germanate and barium lithium niobate were developed.

A new nonlinear optical material for information recording, iron-doped lithium niobate was elaborated. By means of double impurities introduced into lithium niobate, this material has been significantly improved and is used for research and hologram recording.

The technology of growing large-size high-optical-quality crystals of lithium iodate was elaborated; on their basis garnet lasers were developed and produced in the green spectral region with characteristics exceeding international standards. This traditional for the Republic crystal was produced at the KCP.

A technique for growing crystals of potassium pentaborate from aqueous solution by solvent evaporation was developed and the first report on this crystal was made on the Conference on Nonlinear and Coherent Optics in Tbilisi in 1976. Large series of works was devoted to the study of photorefractive and photochromic effects in single crystals of lithium niobate; also the influence of γ-irradiation on the photorefractive properties of lithium niobate was studied.

At that time also theoretical investigations started on the structure and growth of single crystal.

b) Active crystals

In IPR AS techniques were created for obtaining crystals of yttrium aluminum garnet with neodymium, lutetium-aluminum garnet with neodymium, holmium, erbium, thulium and ytterbium, and yttrium aluminate with neodymium and chromium, their physical and chemical properties, mechanisms of formation of defects and problems associated with inhomogeneity of distribution of activator ions were studied in detail. The results of these studies significantly extended the class of grown materials and improved their quality.

Research work led to a number of promising new materials for quantum electronics, in particular, erbium and holmium garnets for the three micron range with "concentration" tuning of the lasing wavelength. At "crystallochemical" design of these materials the possibility of shifts of energy levels of activator ions with variation of chemical composition and structural parameters of the lattice was used. This effect is at most displayed in the crystals of solid solutions based on lutetium and gadolinium garnets.

In 1979-1981 new materials were elaborated with valuable technical and decorative properties: garnets with a predetermined optical absorption and color changing gradually from violet to red; these materials were patented in the USA, Japan, France, and Switzerland. We studied the properties of garnets with trivalent zirconium and divalent lanthanides.

In 1983-1986 high-quality crystals of a series of complex oxides (garnets, orthorhombic aluminates, compounds with complex anions - tungstates, and niobates) with praseodymium ions were obtained. Studies of their spectroscopic properties and solution of the problem of raising the crystal stability towards shortwavelength radiation of pumping lamps allowed us to develop on their basis new low-threshold laser materials which generate at room temperature in orange and dark red spectral regions.

A large cycle of works was devoted to the theoretical study of the spectra of impurity ions in the active materials.

By ESR technique and involving, as a rule, the data of optical absorption, the impurity ion valence, sites of substitution, the parameters of the crystal field and spin Hamiltonian, the times of spin-lattice relaxation, the initial splitting, etc., were determined for a) laser crystals doped with transition elements of the palladium group and b) nonlinear crystals doped with iron group elements.

The technology of growing high-optical-quality crystals of high-concentration solid solutions based on calcium fluoride (concentration up to 30 mole%) was developed in CMP of YSU. Conditions of formation in crystals of characteristic inhomogeneities, cellular substructure, and growth bands, were studied. Solid solution $Ca_{1-x}Er_xF_{2+x}$, $Ca_{1-x}Ho_xF_{2+x}$ ($0<x\leq0.3$) crystals with sizes up to 15×70 mm, in which the change in the index of refraction did not exceed $5\cdot10^{-5}$, were obtained. In these crystals stimulated emission of Er^{3+} and Ho^{3+} ions was recorded at the wavelengths of 2.1, 2.7-2.8 μm. We have also developed methods of growth of lithium-yttrium fluoride crystals doped with Er^{3+}, Ho^{3+}, Nd^{3+}, and generating stimulated emission in the IR range. This material is considered as one of the most promising for creating powerful solid-state lasers. The mechanism of trapping of microparticles during the growth of crystals is considered.

3. Resonant nonlinear optics

This area of nonlinear optics is by its appearance and development associated mostly with the works of scientists of the Republic. Weekly workshops devoted to discussion of some phenomena in gaseous media were well known among specialists and enjoyed high recognition.

a) Nonlinear processes at propagation of radiation in a resonant medium

The first works on the study of nonlinear phenomena, carried out in JLASYSU, were devoted to fashionable in the sixties studies of stimulated scattering processes in liquids and solids.

However, a few years later, opticians of JLASYSU switched to a new area of research and began the first experiments related to the study of stimulated electronic Raman scattering (SERS) in metal vapors near resonance.

In connection with the development of lasers and amplifiers, JLASYSU at that time made intensive research into the theory of propagation of laser radiation in resonant media. We formulated the semiclassical equations describing the propagation of laser radiation through a system of resonance atoms and showed that the usual process of amplification, with the intensity increasing exponentially when passing through a resonant medium, is replaced by an oscillatory regime if relaxation phenomena have no time to establish. These theoretical works were done earlier than the well-known works of American physicists on the coherent propagation of so called 2π-pulses in the medium. They laid the foundation for a large series of experimental and theoretical research in many laboratories, both in our country and abroad.

The success of further studies on the passage of radiation through a resonant atomic gas was due to close contact of theorists and experimentalists.

As a result of using propagation equations for interpretation of experiments, a new series appeared of important works on resonant interaction of radiation with alkali metal vapors, which studied in detail three-photon and parametric effects, Raman scattering, broadening of the spectrum, etc. In particular, the phenomenon of transition from usual amplification process to the regime of the shock wave of light was predicted. These results were then refined and parametric and polarization phenomena were examined in detail theoretically.

This direction continued developing rapidly in the IPR AS and the PCM YSU, both experimentally and theoretically. In IPR AS, SERS on magnetic sublevels of potassium atoms was studied in detail. For the first time, the dynamics of evolution of nonlinear multiphoton processes was investigated. Stimulated resonant emission at adjacent transitions in the presence of a buffer gas was studied and, finally, a new phenomenon of "magnetization" (more exactly, appearance of emf in the winding of a coil around the cell with the studied gas) of a resonant medium at passing through it of linearly polarized light was discovered. The induced rotation of the polarization plane of resonance radiation passing through alkali metal vapors was studied in detail in PCM YSU. On the basis of this phenomenon, a method for determining relaxation times and the magnetic field strength was proposed. A large variety of phenomena of nonlinear polarization spectroscopy were theoretically studied. Finally, IPR AS performed studies on resonant interaction of picosecond pulses with metal vapors.

Considerable progress was achieved in understanding relaxation-free processes in gases and the first converters of light were created on their basis. The probability of third-harmonic generation was theoretically calculated without use of perturbation theory and the theory of hyper-Raman scattering and four-wave parametric processes in gases was developed.

b) Nonlinear resonant processes on a single atom

A large number of theoretical studies on the resonant interaction of laser radiation with atomic systems were carried out in the Republic. This series of works was concerned with the studies of collisionless resonance phenomena occurring in the interaction of one or more laser beams resonant with electronic transitions in atoms. In particular, scattering of an intense wave by an atom near the resonance was considered and the well-known Kramers-Heisenberg formula was generalized for the case of presence of strong scattered field. Scattering spectrum was shown to consist of three lines: the central line at the frequency of incident radiation (Rayleigh scattering) and the lines of three-photon scattering and absorption symmetric with respect to the central line. The probabilities of these processes were calculated by neglecting the relaxation processes. Subsequently, this technique was extended for the processes taking into account relaxation effects and the known formulas for the resonance fluorescence were obtained in a simple way.

After that three- and four-level systems interacting with resonant laser fields were investigated. Phenomenon of self-induced inversion of atomic level population was discovered. The probability of third-harmonic generation and the fine structure of its lines for a single atom were calculated. Of the works of general theoretical significance we should note studies of interaction of coherent radiation with atoms where the concept of quasi-energy in the strong fields was developed, as well as a series of studies on quantum electrodynamics in the presence of a strong resonance field. A number of publications were devoted to the second-order effects on "dressed atoms". Series of papers was devoted to the interaction of electrons with an atom in the presence of intense resonance radiation, including multiphoton ionization in strong fields. Several theoretical works performed the classification of two-photon states of polarization. A series of theoretical works dealt with the nonlinear Faraday and Paschen-Back effects.

4. Nonlinear Optics of Condensed Matter

The first works in this area were made at the dawn of nonlinear optics in the Republic. These included the study of Raman scattering in pyridine solutions. A large number of works were performed in late eighties on laser interaction with crystals. Up-conversion of ultrashort pulses in potassium pentaborate was studied and the theoretically predicted competition of nonlinear processes was experimentally observed. The causes of so-called OH absorption in lithium niobate were revealed.

A separate direction was development of works in the field of nonlinear properties of liquid crystals; special monographs were devoted to these studies.

This is far not full list of works performed in the Republic on the nonlinear optics of condensed matter. The references of this list may be found in books and reviews [1-5].

1. Mikaelian A.L. and Ter-Mikaelian M.L., *On the theoty of laser radiation* [*in Russian*], DAN USSR, v.155, p.1298, 1964.
2. Mikaelian A.L., Ter-Mikaelian M.L., and Turkov. Yu.S., Solid state optical generators [*in Russian*], Moscow: Radio, 1967.
3. Mikaelian A.L., Ter-Mikaelian M.L., *Quasi-classical theory of laser radiation*, in: Progress in Optics, North Holland Publishing, v.7, p.231, 1969.
4. Arakelyan S.M. and Chilingaryan Yu.S., Nonlinear optics of liquid crystals [*in Russian*], Moscow: Nauka, 1984.
5. Ter-Mikaelian M.L., *Nonlinear resonant optics*, Preprint IPR AS No.11, parts 1-3, Ashtarak, 1974.