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Quantum electronics and the R V Khokhlov – S A Akhmanov school of coherent and nonlinear optics at Moscow State University

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The formation of the R V Khokhlov – S A Akhmanov scientific school of coherent and nonlinear optics is inseparably linked with the onset and progress of quantum electronic research in Russia. Moreover, it has been universally recognized that R V Khokhlov and S A Akhmanov are among the few founders of contemporary nonlinear optics.

Figure 1. S A Akhmanov and R V Khokhlov in the early 1960s.

At present, by nonlinear optics is meant the field of physics that studies optical phenomena in which the response of the matter exhibits a nonlinear dependence on the amplitudes of electromagnetic waves incident on it. Under these conditions, parameters like permittivity, conductivity, and magnetization are no longer material constants but depend on the field intensities. This in turn has an effect on the propagation of electromagnetic (light) waves in the medium. Among the most simple and well-known nonlinear effects are harmonic generation and frequency mixing, when the propagation of light waves in the medium gives rise to new waves, whose frequencies are equal to the doubled or tripled frequency of the incident radiation or are the sum or difference of the initial frequencies. Always present are the effects of self-action of light waves, when a light beam changes the refractive index of the medium (increases or decreases it) owing to the nonlinearity of response and thereby forms new conditions for its propagation. This manifests itself in the self-focusing or self-defocusing of light beams, in the self-modulation and self-compression of light pulses. The course of all these effects depends on the coherence properties of the incident radiation and in turn may significantly alter them.

The history of more than forty years of nonlinear optics development has shown that harmonic generation, frequency mixing, and the effects of self-action of light waves by no means exhaust the list of possible nonlinear effects. The realm of nonlinear phenomena is much more rich, diversified, and interesting than the 'linear' one.

To date, nonlinear optical effects have become a methodical and instrumental basis for investigation and diagnostics in various areas of science and technology, in biology, chemistry, and even mineralogy. Nonlinear optics has opened up radically new possibilities for the spectroscopic investigation of matter.

An attempt is made here to briefly outline more than the forty-year history of the formation and development of the Khokhlov and Akhmanov scientific school of coherent and nonlinear optics at Moscow State University (MSU). During the past years, the tree of this school grew thickly, and its scientific 'children' and 'grandchildren' are fruitfully working in educational and scientific institutions in Russia and all over the world. The moderate volume of this paper allows us to dwell on the accomplishments of only those scientists who had thrown in their lot with the Chair of General Physics and Wave Processes and the International Laser Center (ILC) at Moscow State University and whose work admittedly has largely predetermined the pattern of contemporary nonlinear optics as a whole and reflects the heart and character of the school's scientific activity. That is why the author does not carry on polemics as to the priority of one discovery or another in the area of nonlinear optics, which revived in connection with the celebration of the fiftieth anniversary of quantum electronics in Russia.[1] Given at the end of my paper are some of the most brilliant recent results obtained at MSU by scientists who associate themselves with this scientific school. The case in point is more than 70 candidates and doctors of sciences who teach, irrespective of their position, both general and special courses, supervise the scientific work of approximately one hundred students and forty post-graduate students, and annually publish about 100 papers in prestigious refereed journals. Unfortunately, owing to volume limitations, there is no way of recounting all these wonderful people, who maintain the creative atmosphere of scientific research generated by Khokhlov and Akhmanov.

It is pertinent to note that the origins of nonlinear optics date back to 'pre-laser' times. Specifically, even in 1926 S I Vavilov and V L Levshin discovered, during their work at the Physics Department of MSU, the saturation of light absorption in uranic glasses. Recorded somewhat later was the moderate nonlinearity of luminescence depolarization and the radiation-induced absorption dichroism. These were pioneering works undertaken in those years when physics had at its disposal only modest experimental capabilities. Thus, the results obtained in those remote years appear all the more valuable.

Khokhlov repeatedly emphasized the significance of Vavilov's role in the origin and subsequent formation of nonlinear optics: "It is well known that S I Vavilov is the progenitor of nonlinear optics. His work in this field began long before the advent of lasers. The first nonlinear effect was discovered by S I Vavilov and V L Levshin in 1926 and consisted of the saturation of light absorption in uranic glasses" [1]. The term *nonlinear optics* is also attributable to Vavilov.

[1] For the reader concerned with the history of discoveries and investigations of the principal nonlinear optical effects it would undoubtedly be interesting to read the corresponding section in the recently published book by V G Dmitriev and L V Tarasov entitled *Prikladnaya Nelineĭnaya Optika* (Applied Nonlinear Optics) (Moscow: Fizmatlit, 2004).

Many considerations and ideas on the limitations of linear optics and the necessity to investigate nonlinear effects are found in Vavilov's monograph *Mikrostruktura Sveta* (Microstructure of Light), marked with a first-degree Stalin Prize. Vavilov wrote: "The nonlinearity in an absorbing medium should be observable not only with respect to absorption. The latter is related to dispersion, and therefore the velocity of light propagation in the medium should, generally speaking, also depend on the power of light. For the same reason, the dependence on the light power, i.e., superposition violation, should also be observable in the general case in other optical properties of the medium — in birefringence, dichroism, rotatory power, etc." [2].

At that time, however, these ideas and predictions were merely of theoretical significance, for observing the effects required high-power sources of light radiation, which were then nonexistent. Immediately after the advent of lasers, an avalanche of new nonlinear-optical effects followed. Of special note are the works of the P N Lebedev Physics Institute of the USSR Academy of Sciences, the Institute of Physics of the BSSR Academy of Sciences, and the S I Vavilov State Optical Institute.

In 1961, a start was made on theoretical and experimental investigations on nonlinear optics at MSU. These investigations were led by the then young staff members of the Physics Department, and later the outstanding professors at Moscow State University, Rem Viktorovich Khokhlov (1926 – 1977) and Sergeĭ Aleksandrovich Akhmanov (1929 – 1991). Their fundamental contribution to the progress of this area of physics has gained worldwide recognition and was marked with the Lomonosov and Lenin Prizes. They wrote the world's first monograph *Problemy Nelineĭnoĭ Optiki* (translated into English as *Nonlinear Optics*), which has largely retained its significance up to the present time.

As far back as 1962, Khokhlov and Akhmanov were the first to suggest the idea and propose specific schemes of parametric oscillators and amplifiers of light. Brilliant results on the theory of nonlinear interaction of electromagnetic waves and performance of a series of pioneering experiments on the nonlinear transformation of laser radiation frequency to the 2nd, 3rd, 4th, and even 5th harmonic (with an efficiency unparalleled in those days) brought worldwide fame to the Laboratory of Nonlinear Optics of MSU.

The areas of the laboratory's theoretical and experimental research widened rapidly. Also expanding was the circle of staff members, post-graduates, and students of the Physics Department of MSU. A logical consequence of this evolution was the establishment of the Chair of Wave Processes in 1965. It was headed by Khokhlov. In a literal sense, under his leadership the chair became one of the world's leading research centers on nonlinear optics, nonlinear acoustics, laser physics, and nonlinear spectroscopy, a center for the preparation of high-level specialists in these new branches of science. Furthermore, it is difficult to overestimate the role played by Khokhlov and Akhmanov in the development of research on nonlinear optics and laser physics in our country. As a rule, all new significant ideas in those years were discussed at the famous seminar of the Chair of Wave Processes, which was invariably supervised by Khokhlov.

In 1974 Akhmanov became head of the Chair of General Physics for the Department of Mechanics and Mathematics, having moved there from the Chair of Wave Processes together with a group of research fellows and faculty members. From that time began the renovation and broadening of the research pursued in this chair. A prominent place was occupied by research on nonlinear optics, laser physics, the use of lasers in biophysics, etc. Both chairs — of Wave Processes and General Physics for the Department of Mechanics and Mathematics — were closely related by the proximity of the scientific interests of their staff members, the common scientific and engineering facilities, and even 'kinship', for a significant part of the staff members of both chairs were alumni of the now-mature Khokhlov – Akhmanov scientific school.

In 1977 the necessity arose to reorganize these two chairs. It was caused by the tragic death (as a result of a mountaineering accident) of the head of MSU Khokhlov in August of 1977. In 1978 Akhmanov became the head of the joint Chair of General Physics and Wave Processes, which remained under his charge until his death in 1991. The chair came to be among the biggest in the Physics Department of MSU. A small group of scientists of the former Chair of Wave Processes formed a new Chair of the Radiophysics Division — the Chair of Quantum Radiophysics (presently the Chair of Quantum Electronics) headed by L V Keldysh, who had been reaching at the Chair of Wave Processes on Khokhlov's invitation since the late 1960s. Since 2002 the Chair of Quantum Electronics has been under the charge of V I Panov.

Both of these chairs are now accommodated in the Nonlinear Optics Building of Moscow State University, built in 1980 according to Khokhlov's plan. It is noteworthy that the construction of this building is largely the handwork (in a literal sense) of Khokhlov and Akhmanov's disciples. The building would have become a glaring example of a protracted construction activity of the late 1980s were it not for the doctors and candidates of sciences, students, and post-graduate students, who actually abandoned scientific activity for more than two years to turn into professional construction workers to finish the building. Here they continued their research. The elder generation remembers that time quite well and regards the Nonlinear Optics Building as their second home.

On Akhmanov's initiative, an International Educational and Scientific Laser Center (ILC) was organized at Moscow State University. In 1989 – 1998, the ILC was directed by N I Koroteev (1947 – 1998), Akhmanov's disciple. Organizationally and structurally, the ILC is a subdivision of MSU in its own right. It is concerned with the organization of research at the junction between laser physics and other natural sciences, as well as with retraining and the professional development of scientists, physicians, engineers, and other specialists who apply laser techniques and laser systems in their work. The ILC participates in the execution of big interdisciplinary scientific and technical programs and projects in the field of laser physics and nonlinear optics, as well as in the organization of international scientific conferences and symposia. In its scientific and educational work, the ILC is intimately related to the Chair of Wave Processes and General Physics. This association is in fact a unique focus of the research and educational activity of the scientists of Moscow State University in 'laser' areas of modern physics, including nonlinear optics.

After Akhmanov's death, the Chair of Wave Processes and General Physics was under the charge of Koroteev, an outstanding specialist in nonlinear spectroscopy and the physics of the interaction of high-intensity light radiation with matter, who did much to engage the chair and the ILC into efficient international scientific cooperation. At present, the chair and the ILC are under the charge of V A Makarov, a scientific 'grandson' of Akhmanov.

All these organizational transformations were eventually helpful in the retention and strengthening of the position of the Khokhlov – Akhmanov school of coherent and nonlinear optics. Some of the scientific accomplishments of this school have been mentioned in the foregoing. In reality they are immeasurably greater in number. We will primarily enlarge on the accomplishments which have admittedly determined to a large measure the appearance of contemporary nonlinear optics as a whole and reflect the essence and character of the school's scientific activity.

The mathematical basis for linear and nonlinear modern wave optics (excluding the optics of extremely short pulses) is the method of slowly varying amplitudes proposed by Khokhlov in 1959 – 1961. He clearly marked out two limiting cases of nonlinear wave theory: nonlinear waves in media with a strong dispersion and nonlinear waves in a dispersion-free medium. He proposed two methods of simplifying the partial differential equations that describe the wave propagation through nonlinear media, which are adequate for these two cases. For strong-dispersion media he developed the method of slowly varying amplitudes. Khokhlov was the first to develop the theory of second harmonic generation in wave systems and pointed to the possibility of total energy conversion to the harmonic under phase-matching conditions.

The method of slowly varying amplitudes was further developed in the works of Khokhlov, Akhmanov, and their disciples, among whom mention should first of all be made of A P Sukhorukov. Until 1987 he worked in the Chair of General Physics and Wave Processes, and at present is the Head of the Radiophysics Chair of the Physics Department of MSU. The equations derived in these works, which include the diffraction of interacting beams, the heating of a medium, relaxation processes, and many other effects, form the basis of the nonlinear quasioptics of dispersive anisotropic media. It is noteworthy that the method of slowly varying amplitudes is now also applied in several other branches of physics, including the analysis of wave processes in plasmas.

In 1962 Khokhlov and Akhmanov came up with the idea of parametric amplification and generation of light waves, which have underlain numerous theoretical and experimental works. In our country, the first parametric light oscillator started working in 1965. The decisive contribution in its implementation was made, apart from the authors of the idea, by their disciple and friend A I Kovrigin (1936 – 1996). The world's first parametric oscillator emitting picosecond pulses was made in the Chair of Wave Processes in 1968. A significant contribution to the realization of this project was made by A Piskarskas, Akhmanov's and Kovrigin's disciple, presently Professor at Vilnius University. It is pertinent to note that researchers, with the advent of parametric oscillators, had at their disposal a unique device, which makes it possible to obtain continuously frequency-tunable radiation with a pulse duration ranging from several nanoseconds to picoseconds and even femtoseconds.

Akhmanov laid the foundations of statistical nonlinear optics, which studies nonlinear interactions with an account for statistical radiation properties as well as random variations of the parameters of the medium. A large contribution to the development of this area was made by A S Chirkin, Akhmanov's disciple, presently Professor at the Chair of General Physics and Wave processes. The results of the first stage of advancement of this science were outlined in the book *Statisticheskie Yavleniya v Nelineĭnoĭ Optike* (Statistical Effects in Nonlinear Optics), which was written by Akhmanov and Chirkin in 1971. At the present time, Chirkin is also a worldwide-recognized expert in quantum optics. His work possesses one of the highest citation indices.

Of special note is the active application of the ideas and methods of nonlinear optics in laser spectroscopy and material diagnostics, which was initiated by Akhmanov. Together with his disciples, Akhmanov elaborated in detail a radically new spectroscopic technique — spectroscopy of Coherent Anti-Stokes Raman Scattering (CARS). It relies on the investigation of four-wave mixing processes under the conditions when two pump waves excite a wave in the medium at the difference or sum frequency, which then scatters the probe wave. As a result, signal radiation at the combination frequency is generated. There are several versions of this method: amplitude, polarization, and time-resolved techniques. At present, each of them is extensively used for the investigation of excitation spectra in a wide diversity of media, for the spectral analysis of materials, and for the diagnostics of various processes, which range from technological ones to those assuring the vital activity of living organisms. The basic principles of this kind of spectroscopy and the scientific results obtained at the initial stage of its development are outlined in Akhmanov and Koroteev's monograph *Metody Nelineĭnoĭ Optiki v Spektroskopii Rasseyaniya Sveta* (Methods of Nonlinear Optics in Light Scattering Spectroscopy), published in 1981.

A large contribution to the development of different versions of multiwave mixing spectroscopy was made by D N Klyshko, A N Penin, Akhmanov's disciples Koroteev and V G Tunkin, as well as Khokhlov's pupil V V Fadeev. It was precisely the last of these who undertook laser spectroscopic investigations of natural water and natural organic complexes in 1974.

Also noteworthy is the accomplishment of the Khokhlov – Akhmanov school which actually opened up new broad avenues in nonlinear optics and laser physics. Among them is the discovery by Klyshko, Fadeev et al., with priority of November 1965, of the effect of spontaneous three- and four-photon parametric scattering of light in solids†. Subsequently, the authors of this discovery employed this effect for the absolute calibration of photodetectors. The theoretical and experimental investigations of the optical fields generated in spontaneous parametric light scattering have been pursued by Penin, G Kh Kitaeva, S P Kulik et al. at the Quantum Electronics Chair of MSU for more than 15 years.

The effect of nonlinear optical activity predicted by Akhmanov and V I Zharikov fostered a consistent development of nonlinear polarization optics in our country and abroad. The theoretical and experimental investigations conducted at MSU (N I Zheludev, Makarov and their pupils) allow a definite conclusion that the effects of wave polarization self-action and interaction are subtle and yet widely occurring effects of nonlinear optics, while the assumption of polarization invariance in the course of wave propagation, which is made in theoretical calculations, is an ill-founded approximation and constitutes merely the first

† Three-photon spontaneous parametric scattering of light is known in the English-language literature as spontaneous parametric down-conversion (SPDC). (*Editor's note.*)

Figure 2. Nobel Prize winner N Bloembergen (on the right) is Khokhlov and Akhmanov's (sitting by the table) guest. On the left by the wall is É S Voronin.

step on the way to a consistent description of nonlinear optical effects.

In the late 1960s, Khokhlov initiated a series of investigations involving a resonance selective action of high-power laser radiation on matter. This work has played a significant role in the formation of laser photochemistry and photobiology. He was enthusiastic about the idea of producing population inversion due to direct conversion of the energy released in the course of a chemical reaction to the energy of coherent radiation, thereby omitting other forms, i.e., due to the energy transfer from 'hot' molecules to 'cold' ones. With his active support, this research was undertaken at the Institute of Mechanics and at the Chemistry Department of MSU, where a Chair of Laser Chemistry was organized in 1988.

On Akhmanov's initiative, his colleagues and disciples, of whom mention should be made of V T Platonenko, V Ya Panchenko, and V M Gordienko, investigated nonlinear processes in vibrational-translational relaxation and intermolecular vibrational energy exchange in the gas of strongly excited molecules. In mid-1980s at MSU, under Akhmanov's and Gordienko's supervision it was possible for the first time to accomplish the generation and amplification of subpicosecond UV radiation pulses with the aid of excimer lasers. The laser system made in those years was aimed at the study of the interaction between superstrong light field and matter. Akhmanov initiated the development of powerful computational methods for solving the problems of statistical nonlinear optics of inhomogeneous media, as well as research in the field of laser optoacoustics. The latter research, developed by MSU professors O V Rudenko and A A Karabutov and their pupils, led to the advent of laser optoacoustic diagnostics of biological tissues and the laser optoacoustic spectroscopy of solids.

The school's work was not only highly appreciated by the world scientific community, but was honored with a series of high awards. Lenin Prizes were conferred on Khokhlov and Akhmanov "For the Investigation of nonlinear Coherent Interactions in Optics" and on Sukhorukov (and co-authors) "For the Discovery and Investigation of the Effects of Self-Focusing of Wave Beams". Furthermore, a USSR State Prize was conferred on Khokhlov and Akhmanov's team-mates É S Voronin (1928–1981) and V S Solomatin (with co-authors) for works in applied nonlinear optics, namely, for a series of investigations aimed at the development of nonlinear-optical translators of IR signals and images to the visible range. A USSR State Prize was conferred on Klyshko (1929–2000), Penin, and Fadeev for the discovery and investigation of the effect of parametric scattering of light and its application in spectroscopy and metrology. A USSR State Prize was conferred on Sukhorukov and Kovrigin, among others, for a series of works on "High-Efficiency Nonlinear Frequency Converters in Crystals and Development of Tunable Sources of Coherent Optical Radiation".

Figure 3. Discussion of scientific results in Khokhlov's office. In the background are K N Drabovich, A I Kovrigin, and Akhmanov.

Many of Khokhlov's disciples subsequently abandoned coherent and nonlinear optics by changing their research area. The development of the physical foundations of nonlinear acoustics and its applications, as well as the investigation of the dynamics of high-intensity noise waves and nonlinear structures in dispersion-free media may be the subject matter of separate interesting papers. Khokhlov, Sukhorukov, and Chirkin made a huge contribution to these works, which were rewarded with USSR and Russian Federation State Prizes.

A series of works entitled "Electronic and Atomic Processes on the Surfaces of Solids" [O A Aktsipetrov (Khokhlov's disciple), V I Panov, P K Kashkarov et al.], which was awarded a State Prize of the Russian Federation, contains a large section concerned with the nonlinear optics of metal and semiconductor surfaces. It includes the results of experimental research, which was conducted at MSU, on optical harmonic generation, as well as of the investigation of nonlinearity and nonlocality of the electronic response of semiconductor and metallic nanoparticles and of planar nanostructures.

At different times, several alumni of the Khokhlov–Akhmanov school were awarded with Leninist Komsomol Prizes. Six of them are now working at MSU — they are A V Andreev (Khokhlov's disciple), the author of several pioneering works on X-ray optics, an expert on coherent and cooperative processes in optics and on the physics of strong light fields, and the author of several monographs; A M Zheltikov and A B Fedotov (Koroteev's disciples), specialists on nonlinear laser spectroscopy and the optics of spatially periodic media and photonic crystals; V N Zadkov

(Koroteev's disciple), an expert on the interaction of laser radiation with atoms and molecules, on quantum optics and quantum information theory; Karabutov (a disciple of Khokhlov and Rudenko), an acknowledged expert in the field of nonlinear and laser acoustics; and S A Shlenov (V P Kandidov's disciple), a specialist on atmospheric optics.

Many alumni of the Khokhlov – Akhmanov school were honored with a Lomonosov Prize — the highest MSU award for scientific work. Apart from the aforementioned (Akhmanov, Karabutov, Koroteev, Rudenko, Khokhlov, and Chirkin), among the Laureates of this Prize are: V I Emel'yanov, a recognized specialist on coherent and cooperative effects and on laser radiation action on solids, and the author of several monographs; V P Kandidov, the author of several powerful computational methods, and an expert on electromagnetic wave propagation in nonlinear inhomogeneous media; and V A Aleshkevich (Sukhorukov's disciple), who achieved substantial results in the investigation of the laws of light field statistics transformation in nonlinear processes.

The indisputable recognition of the scientific achievements and accomplishments of the Khokhlov – Akhmanov school is also demonstrated by the fact that its participants are regularly invited to the program committees of the most prestigious international conferences. Moreover, organizing and holding several such conferences has been a task of the school.

In particular, since 1965 the Chair of Wave Processes and later the Chair of General Physics and Wave Processes, and since 1990 also MSU ILC have invariably been the base for organizing and holding the International Conferences on Coherent and Nonlinear Optics (ICONO) — the main professional forums on basic laser physics and nonlinear optics on the Eurasian continent. Khokhlov and Akhmanov were always the recognized leaders of these Conferences.

The 17th Conference, the latest in this series, was held under the direction of S N Bagaev in Minsk (Belarus) in 2001. Its chief organizers were the MSU Chair of General Physics and Wave Processes, MSU ILC, and the Institute of Physics of the Belorussian Academy of Sciences. It is noteworthy that about 700 scientists from the world's leading research centers participate in these conferences. The next (18th) conference will be held in St. Petersburg in May 2005.

In 2002, IQEC-2002, the most significant international conference on laser physics and nonlinear optics, was held in Moscow for the first time in its almost forty-year long history. And again among the principal organizers were members of the Khokhlov – Akhmanov school. To appreciate the scope of work we give only two figures: over 1200 people from 40 countries around the world participated in the IQEC-2002 Conference and its attendant Conferences on Lasers, Applications, and Technologies (LAT 2002) and for Young Scientists and Engineers (IQEC/LAT-YS 2002).

Noteworthy also is the active role the Chair and ILC played in conducting the International Conferences on Laser Applications in Life Sciences (LALS), which originated through Akhmanov's initiative, international conferences on laser physics (Laser Physics Workshops 2002, 2003, 2004), and a series of other international symposia and seminars.

Since 1997, the MSU scientific school on coherent and nonlinear optics has been officially classified with the leading scientific schools of Russia. Several staff members of the Chair of General Physics and Wave Processes and of MSU ILC who associate themselves with this school have been awarded grants from the corresponding Federal Program.

Figure 4. V N Zadkov, N I Koroteev, and S N Bagaev during a break between sessions of the XVIth International Conference on Coherent and Nonlinear Optics (Moscow, 1998).

They make every effort to ensure that the best graduates of the Physics Department supplement the ranks of Russian scientists. At the heart of education of students and postgraduates lies the system of special courses whose principles were laid more than 30 years ago. Its immanent feature is that the students are afforded the opportunity to study special courses on nonlinear optics and laser physics (they exceed 40 in number) at their option, depending on their scientific interests and specialization. Furthermore, students engage in research right away. Teaching via investigation — Khokhlov and Akhmanov considered this to be the most efficient way to train specialists.

In recent years, a computer-based textbook entitled *Nelineĭnye Volny i Nelineĭnaya Optika* (Nonlinear Waves and Nonlinear Optics) (author: K N Drabovich) and a multimedia syllabus of the lecture course "Introduction to Laser Physics" (author: V V Shuvalov) have been created, and the "University Laser Practical Work" has been totally modified. Collaboration in the frame of the educational and scientific center "Basic Optics and Spectroscopy", which the Chair has been affiliated with since 1998, is fruitfully developing.

Thanks to various contracts and grants, as well as to support from MSU President V A Sadovnichiĭ, in recent years the possibility of replenishing the scientific park of the Chair of General Physics and Wave Processes and of ILC with expensive new equipment has opened up. As an example, we refer to a chromium-forsterite laser system including a regenerative amplifier, a multipass amplifier, an optical parametric oscillator, and a pump laser (1 mJ, 1236 nm, 120 fs, 50 Hz, 10^{17} W cm^{-2}), a terawatt femtosecond laser system based on titanium:sapphire crystals (40 mJ, 800 nm, 70 fs, 10 Hz, 10^{18} W cm^{-2}), a picosecond diode-pumped Nd : YAG laser system, and a laser optical-acoustic system for the ultrasonic defectoscopy of products made of metals, alloys, and composite materials.

Unfortunately, the limited space of this article does not allow us to outline all the results obtained by all of Khokhlov and Akhmanov's scientific 'children' and 'grandchildren' working in the Chair of General Physics and Wave Processes and ILC. Among them are, apart from the aforementioned, I V Golovnin, M S Dzhidzhoev, Yu E D'yakov, T M Il'inova, S A Magnitskiĭ, V B Morozov, S Yu Nikitin, D Yu Parashchuk, V M Petnikova, A B Savel'ev-Trofimov,

Figure 5. Head of MSU V A Sadovnichiĭ and Chairman of the Council of Federation of the Federal Assembly of the Russian Federation S M Mironov in the Laboratory of Superstrong Light Fields of the Chair of General Physics and Wave Processes of MSU. In the background is V A Makarov, on the right is V M Gordienko.

Figure 6. In the Laboratory of Ultrafast Processes in Biology.

D A Sidorov-Biryukov, V D Taranukhin, A P Shkurinov, and A Yu Chikishev. We briefly outline only some of the results.

It has been shown that the excitation of low-lying nuclear levels and thermonuclear reactions may occur in the high-temperature plasma produced when a target is irradiated with a femtosecond laser pulse with an intensity up to 10^{17} W cm^{-2}. A complex of techniques was developed for the diagnostics of the hot electron component of high-temperature femtosecond laser plasma, which ranges from direct measurements of the electron energy spectrum to the evaluation of the average energy and density of hot electrons from X-ray and ion time-of-flight measurements.

A new scenario was proposed for the distillation of requisite enantiomers of chiral molecules from a racemic mixture by way of producing a quantum entangled state (by configuring exciting laser fields) of the internal rotation of molecules and their rotation in space.

A method was proposed for charged-particle acceleration in a vacuum. With the use of modern lasers, it allows the acceleration of electrons (during many optical cycles) to energies on the order of 1 GeV.

A theory of laser-induced self-organization of nanometer periodic defect-deformation structures and solitons on the surface of solids was elaborated. An interpretation was made of the effects of surface nanostructuring in the laser-controlled deposition of Ga atoms, thin film recrystallization, and the etching of semiconductors.

An investigation was made of the variation of the transverse spatial distribution of light polarization in the second harmonic and the sum frequency generation in the reflection of elliptically polarized light beams with a Gaussian profile and a uniform transverse polarization distribution from the surface of an isotropic medium with a spatial dispersion of cubic nonlinearity, as well as in self-focusing, sum frequency generation, and some other nonlinear optical effects in the bulk of such a medium. It was found that in the course of nonlinear optical interactions there emerges a clearly defined axial dissymmetry of the transverse spatial distribution of the intensity and polarization of the interacting waves; in particular, there emerge regions with different directions of rotation of the electric field vector.

A stochastic simulation was made of the formation of many filaments in laser pulse propagation through a medium with random fluctuations of the refractive index. A model was elaborated to provide a quantitative description of the initial stage of many-filament formation in a turbulent atmosphere. The statistical characteristics of the filament beam were investigated as functions of atmospheric turbulence parameters and the power of the femtosecond laser beam.

The feasibility of making, on the basis of photonic crystals, efficient compact nonlinear optical devices — compressors, frequency multipliers, and optical switches — was demonstrated. The principles for near-field microscopy and atomic motion control through the use of the effect of light field localization were worked out.

The idea of phase-matched generation of the second harmonic of ultrashort laser pulses in photonic crystals filled with a nonlinear medium with a virtually arbitrary dispersion law was proposed. The use of waveguides with a photonic-crystal cladding to improve the efficiency of nonlinear optical processes, in particular, the generation of a supercontinuum, was demonstrated to be feasible.

An experimental demonstration was made of the feasibility of radically improving the efficiency of four-wave interactions in hollow fibers with a photonic-crystal cladding. For the $3\omega = 2\omega + 2\omega - \omega$ process, where ω and 2ω are the fundamental frequency and second harmonic frequency of the picosecond pulses of a neodymium-doped garnet laser, an 800-fold increase in signal power was achieved in comparison with the regime of tight focusing.[2]

Classical and quantum theories of successive quasi-phase-matched interactions of light waves in periodically inhomogeneous nonlinear optical crystals were constructed. For such crystals, it was shown for the first time that it is possible to obtain polarization-entangled states of light for a collinear interaction geometry and for a simultaneous realization of two nonlinear optical processes.

Molecular spectra near the critical point of a substance were measured for the first time employing the technique of stationary CARS spectroscopy. An additional broadening was recorded for the Q-band spectra of the 1285-cm^{-1} vibrational transition of the CO_2 molecule, which arises

[2] The results of latest research in this area have been described in A M Zheltikov's monograph *Optika Mikrostrukturirovannykh Volokon* (Microstructured Fiber Optics) (Moscow: Nauka, 2004).

from the increase in density fluctuations near the critical point of carbon dioxide gas.

Employing polarization-sensitive CARS spectroscopy revealed the spectral components of broad (on the order of 40 – 50 inverse centimeters) bands in the vibrational spectrum of a protein which are defined by the normal vibrations of the amide group. It was thereby possible to realize a new method of diagnostics of the secondary structure of protein molecules which does not rely on a priori assumptions about the band structures.

It was found out that the nonlinearity of strongly correlated systems leads to the spontaneous formation of a laser-induced 'metastable' order in them. The occurrence of phase transitions of this type accounts for the 'anomalous' results in the non-stationary laser spectroscopy of conjugate polymers, ferromagnetic films, and in a series of other objects. The spatially nonuniform excitation of ferromagnetic films by a train of ultrashort laser pulses makes it possible to 'write' in them regular domain structures defined by the light intensity distribution. A technique was realized for a non-destructive optical-acoustic verification of the state of construction materials (metals, composites) for double-sided and single-sided accesses to the object under investigation. An optical-acoustic tomograph for the early diagnosis of breast cancer was developed and fabricated.

Nonlinear-optical analogues of the Faraday and Kerr effects were discovered in the second and third magneto-induced harmonic generation at the surface of ferromagnetic materials. A giant enhancement (by 4 – 5 orders of magnitude) of the intensity of radiation at the second and third harmonics was recorded in the excitation of localized plasmons in nanostructures, as well as in porous silicon-based photonic crystals. The effect of optical Casimir nonlocality was discovered in semiconductors of a new type.

An investigation was made of the second harmonic and sum frequency generation in the reflection of femtosecond pulses from the free surface of a solution containing noncentrosymmetrical molecules. The cases of collinear and noncollinear schemes of excitation of surface electromagnetic waves of different types, which enhance nonlinear optical interaction, were considered.

A self-consistent theory of the optical response of thin and ultrathin (1 – 10 nm) metallic films was constructed. It was shown that a metallic nanometer-thick film can, under conditions of excitation of odd longitudinal collective modes, exhibit an almost total reflection of incident laser radiation.

With the aid of Raman spectroscopy, photo-induced spectroscopy, photo-induced polarimetry, and other techniques, several priority results were obtained concerning the properties and the nature of the ground and lower excited states of trans-polyacetylene on nanopolyacetylene samples, diagnostics were performed of the anisotropy of optical transitions from long-lived photo-induced states on time scales ranging from hundreds of femtoseconds to milliseconds.

An investigation was made of the feasibility of phase control of above-threshold tunnel ionization and subsequent control of the parameters of recombination radiation with the use of two-frequency laser fields. It was shown that in these fields it is possible to control both the instant of ionization (within an optical cycle) and the instant of recombination. Phase control makes it possible to generate the recombination radiation with selection of a narrow spectral range and the mode of 'enhancement' of high-order harmonics. The generation of coherent attosecond electromagnetic pulses was shown to be possible with the use of a special two-frequency pump and elliptically polarized radiation.

The scientific school of coherent and nonlinear optics created by Khokhlov and developed by Akhmanov is indeed part of the national heritage of Russia, one of the pearls of Moscow State University. In the context of the continuing deep crisis in science and education in our country, preserving this and other equally unique scientific schools is the primary concern of the MSU staff.

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Fiber lasers

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1. Introduction

The creation of fiber lasers is one of the most brilliant accomplishments of quantum electronics.

The first-ever fiber laser was made by Snitzer in 1963 [1]. As an active element he used an optical glass fiber containing neodymium ions. However, at that time this avenue of laser physics was not pursued and it is evident why. The advent of modern high-efficiency and compact fiber lasers was possible only owing to the development of low-loss optical glass fibers ($\leqslant 1$ dB km^{-1} in the near-IR range) in the early 1970s and the subsequent rapid development of optical fiber communication. The latter became the decisive factor in the development and industrial production of long-lived high-brightness laser diodes and a series of special optical fibers. Among them are optical fibers doped with rare-earth elements and nonlinear, photosensitive, infrared, and several other fibers. This elemental base underlay the production of fiber lasers. Of special note is the development of the technology for writing the Bragg gratings of the refractive index in photosensitive optical fibers, which are employed as distributed reflectors in fiber lasers (see, for instance, Ref. [2]).

At the same time, progress in fiber-optic communication systems with a high data transfer rate (over 1 Gbit s^{-1}) called for the development of efficient fiber lasers and amplifiers compatible with these systems. This accounts for the pursuit of extensive research and large investments for solving the problem.

The fundamental advantage of fibers as a laser medium in comparison with bulk active media resides in low optical losses, a large interaction length, and the small diameter of the fiber core (typically 4 – 20 μm), which ensures the high efficiency of pumping by the radiation of laser diodes. The large ratio between the surface area and the volume of a fiber