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120th anniversary of the birth of Sergei Ivanovich Vavilov (Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 30 March 2011)

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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) dedicated to the 120th anniversary of the birth of Sergei Ivanovich Vavilov was held in the Conference Hall of the P N Lebedev Physical Institute, RAS, on 30 March 2011.

The following reports were put on the session's agenda posted on the web site www.gpad.ac.ru of the Physical Sciences Division, RAS:

(1) **Masalov A V** (P N Lebedev Physical Institute, RAS, Moscow) "S I Vavilov and nonlinear optics";

(2) **Basiev T T** (Laser Materials and Technology Research Center, A M Prokhorov General Physics Institute, RAS, Moscow) "Luminescent nanophotonics and high-power lasers";

(3) **Vitukhnovsky A G** (P N Lebedev Physical Institute, RAS, Moscow) "Advances in luminescent light sources and displays";

(4) **Aleksandrov E B** (Ioffe Physical Technical Institute, RAS, St. Petersburg) "Sergei Ivanovich Vavilov and the special theory of relativity";

(5) **Bolotovsky B M** (P N Lebedev Physical Institute, RAS, Moscow) "Vavilov–Cherenkov effect";

(6) **Vizgin V P** (S I Vavilov Institute of the History of Natural Sciences and Technology, RAS, Moscow) "Sergei Ivanovich Vavilov as a historian of science";

(7) **Ginzburg A S** (Knowledge Society) "Academician S I Vavilov — a devotee of the enlightenment and the first president of the Knowledge Society of the USSR".

The papers written on the basis of reports 1–4 and 6 are given below. The main contents of report 5 is reflected in the paper "Vavilov–Cherenkov radiation: its discovery and application" [*Usp. Fiz. Nauk* **179** 1161 (2009); *Phys. Usp.* **52** 1099 (2009)] published earlier by B M Bolotovsky.

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S I Vavilov and nonlinear optics

A V Masalov, Z A Chizhikova

Sergei Ivanovich Vavilov was a distinguished Russian physicist, outstanding organizer, eminent teacher, and enlightener. It was precisely his activity that promoted the revival and progress of physics research in our country after the devastation of the 1920s. Owing to his efforts as a scientist and organizer, our country became a world power with regard to scientific investigations.

While on the subject of S I Vavilov's scientific heritage, he greatly advanced the science of luminescence in various media, to begin with. In I M Frank's apt remark [1], Vavilov transformed the knowledge about luminescence from a description of a collection of facts to a rigorous science. In particular, he gave a more exact definition of the phenomenon of substance luminescence, introduced the notions of the energy and quantum yields of luminescence of substances, ascertained that the quantum yield is independent of the wavelength of the exciting light (Vavilov's law), elaborated the techniques for measuring the luminescence yield, and studied polarization characteristics of luminescent radiation and its relation to the density of luminescent particles. Proceeding from this knowledge, jointly with his colleagues he developed the luminescence method of substance analysis. This method, which received ample recognition even in his lifetime, is also topical today, especially so in the study of the properties of nanoparticles.

Much has been well written about S I Vavilov's role in the discovery of the Vavilov–Cherenkov effect. However, as regards the history of the invention of fluorescent lamps — daylight lamps — it has not been adequately covered. This history dates back to the time when S I Vavilov introduced the notion of luminescence yield and first revealed by direct measurements that the quantum yield of luminescence may approach 100% in a number of media. It is precisely the high quantum yield of luminescence that underlies the several-fold energy superiority of fluorescent lamps over ordinary incandescent lamps. In modern times, when we attempt to consider scientific investigations from the standpoint of

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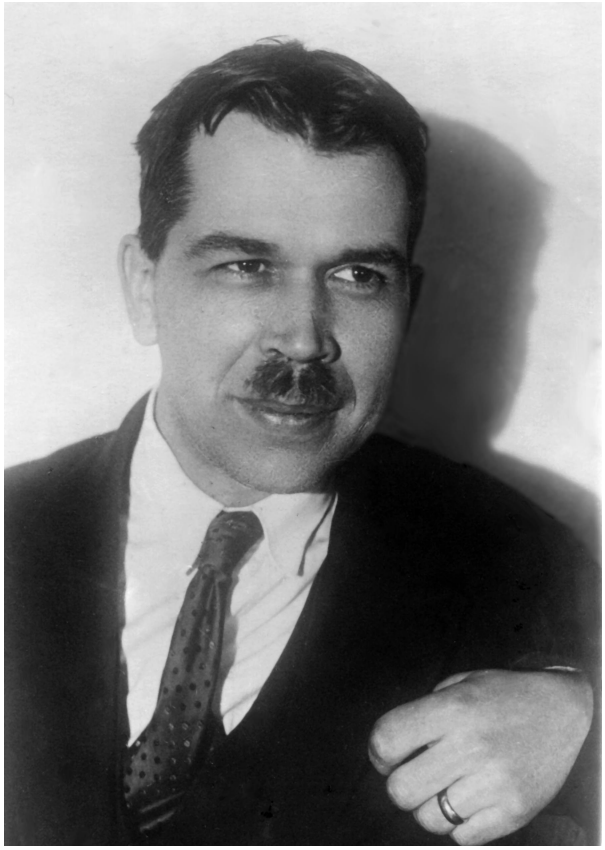

S I Vavilov in 1925–1926, when the first experimental investigation in nonlinear optics was carried out.

financial advantage, it would be instructive to give an estimate of the savings which fluorescent lighting (i.e., research on the fluorescence yield) has given our country over the past decades.

The fact that media with a high quantum yield of luminescence exist favored the advent of lasers. T Maiman, the inventor of the first ruby laser, reminisced [2] that he was dissatisfied with the available data about the low quantum yield of optical luminescence in ruby, because a high quantum yield would be natural and only special reasons could be responsible for lowering it. In the USSR program of creating lasers [3], luminescent crystals were highest on the list of the most promising laser media. It also comes as no surprise that the first lasers in our country were made from ruby crystals in institutions which were S I Vavilov's 'offsprings' — at the P N Lebedev Physical Institute of the USSR Academy of Sciences (FIAN) and the State Optical Institute (GOI) [3].

The story of the first experimental investigation performed by S I Vavilov (in collaboration with V I Levshin) in nonlinear optics is well known. This investigation was carried out in 1925, and its results were presented in Ref. [4]. (S I Vavilov's portrait displayed on this page dates back to precisely that time.) However, the essence and details of the experiment are little known. Here, we report on several features and details of Vavilov's first experiment mentioned above and give more information about nonlinear optical studies conducted by M D Galanin — S I Vavilov's pupil and disciple, who supervised for many years the Laboratory of Luminescence established by S I Vavilov at FIAN.

S I Vavilov's and V I Levshin's paper [4] is often cited as the first observation of a nonlinear optical effect. This is precisely the paper which tells us about the lowering of absorption in a medium with increasing light intensity. Such a statement is undoubtedly true, with the reservation that S I Vavilov pondered and wrote notes about the limits of the validity range of the Bouguer–Lambert–Beer law of 'linear' light absorption back in 1919. One can read about it in the materials collected in the RAS Archive. The paper "O sootnoshenii mezhdu flyuorestsentsiei i fosforestsentsiei v tverdykh i zhidkikh sredakh" ("On the relation between fluorescence and phosphorescence in solid and liquid media") [4] was submitted for publication in December 1925. Different experiments were described in that paper. Its Section 4, entitled "On the feasibility of absorption lowering in fluorescent or phosphorescent media irradiated by the light of a spark", was concerned with the violation of the 'linear' light absorption law. Premising the description of their experiment, Vavilov and Levshin distinctly formulate the mechanism responsible for the expected lowering of substance absorptivity with increasing incident radiation intensity. This lowering must take place because of the reduction in the number of absorbing molecules in the ground state due to the light absorption. The authors of Ref. [4] devised the formula for the intensity of radiation transmitted through the medium, which should quantitatively describe the effect: $J = J_0 \exp\left[-N(1-x)\,\alpha\right]$. Here, x describes the fraction of molecules that are 'out of the game' due to the absorption of light, and α and N are the absorption cross section of the molecules and their number per unit cross section of the sample (the product of molecular concentration and the sample thickness). Should we describe the effect in present-day terms, we would write out precisely the same formula (to within the notation). Also given was an estimate of the fraction x under continuous irradiation in the limiting case of the weak effect: $x = J_{\text{abs}}\tau/(Nh\nu)$, where J_{abs} is the absorbed light flux, τ is the lifetime of excited molecules of the absorbing substance, and $h\nu$ is the photon energy. Simultaneously, the authors of Ref. [4] consider, apart from the case of continuous irradiation, the special case wherein the light source emits pulses of a duration shorter than the molecular lifetime. As a result, they draw a conclusion that maximizing the effect requires selecting a medium with the longest possible lifetime. They select uranium glass (in modern sets of color optical glass samples, uranium glass is designated as JS19). Uranium glass possesses a very long lifetime of the excited state ($\sim 10^{-5}$ s). For a light source they employed a spark with a glow duration of $< 10^{-6}$ s — supposedly the highest-power source available at that time. To verify the role of lifetime, the authors prepared a second sample — a cell with a solution of fluorescein. The lifetime of fluorescein molecules in a solution is shorter than the duration of a spark flash, and under these conditions one would expect a linear character of light absorption, i.e., the absence of the sought-after effect. Proceeding from the data about the spark light energy, the authors estimated the sought-after effect of the lowering of uranium glass absorptivity at 2%. The setup for observing light absorption in uranium glass and fluorescein employed a noteworthy layout. The latter was not given in the paper, but it was described in sufficient detail.

Figure 1 represents a schematic of the setup reconstructed from its description in Ref. [4]. The light of a spark was focused on a sample in such a way that one half of the image of the spark passed through the medium under investigation, and the other half passed by the medium. The transmitted light of the spark was focused on the slit of a spectro-

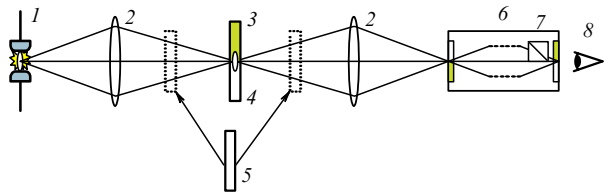

Figure 1. Schematic representation of the setup for observing light absorption in uranium glass: *1* — spark, *2* — lenses, *3* — uranium glass or a cell with fluorescein, *4* — sample-free region, *5* — attenuation filter, *6* — spectrophotometer, *7* — polarizer, and *8* — observer's eye.

photometer so that the light passing through the sample was focused onto one half of the slit height, and the other half was illuminated by the light that passed by the sample. The spectrally decomposed radiation at the output of the spectrophotometer was analyzed by the human eye. In the spectrophotometer, a polarizer was mounted in the path of the light transmitted through the sample, which made it possible to attenuate this light to the intensity level of the light that passed by the sample. As is well known, in the visual comparison of two illuminated fields observed in one field of view, it is possible to discern a very small difference in visual field illuminances and thereby equalize the illuminances to at least within several tenths of a percent.

Therefore, the observer's task during repetitive spark flashes was to equalize, by way of polarizer rotation, the fields of the light passed through the sample and the light passed by it. This procedure was repeated for each sample in two series of 50 measurements. In one series, an attenuation filter was introduced into the light beam in front of the sample to lower the intensity of sample irradiation; in this case, the nonlinear effect according to estimates would not be expected to occur. In the second series, the same attenuation filter was placed after the sample, and the light of the highest possible intensity passed through the sample. In this case, one would expect a manifestation of absorption nonlinearity for uranium glass, i.e., a disturbance of the balance in illuminance of the light fields under observation. The observer restored the balance of illuminances by slewing the polarizer and reading its new position. The difference between the readings of the angular polarizer positions in the two series was converted to a change in absorption. The authors estimated the reproducibility of these absorption measurements at $\pm 0.3\%$ (this was done from the results of measurements with fluorescein; most likely the accuracy was limited by the instability of the spark discharge). Transposition of the attenuation filter resulted in a lowering of the absorptivity of the uranium glass by 1.5% with an increase in light intensity. The sign of the effect, like its magnitude compared to the estimate (2%, see above), testifies to the validity of the result. Also, it is amazing how reasonably and optimally the measurements were made: a comparison object was utilized, intensity measurements relied on equalization of illuminances, and the trick of transposing the attenuation filter was taken advantage of. As a consequence, the experimental observations proved to be a success, despite the absence of photoelectric recorders. In modern nonlinear optics, the trick of attenuation filter transposition has come to be generally accepted.

S I Vavilov described in full measure the significance of this investigation in his book *Mikrostruktura Sveta* (*The Microstructure of Light*) [5], which was published late in 1950. He saw an advance copy of the book not long before his death. The book [5] gave a very vivid and complete picture of how the properties of separate radiators — atoms and molecules of a substance — form the characteristics of the emitted light. In his book, S I Vavilov once again addressed the mechanism of absorption lowering in a medium with increasing light intensity; nowadays we call this mechanism the population saturation of absorbing molecules and its corresponding manifestation is termed the bleaching of the medium. S I Vavilov also introduces the term nonlinear optics. He writes: "The greater the number of molecules in an excited state in the propagation of light through the medium, i.e., the higher the light power, the greater must be the lowering of the absorbed energy fraction, because the excited molecules cease to absorb the light in the previous manner prior to returning to their normal state. Absorption must therefore depend on the power of the light flux.... 'Nonlinearity' in an absorbing medium should be observable not only in relation to light absorption. The latter is related to dispersion, and therefore the velocity of light propagation through the medium, generally speaking, should also depend on the light power. In the general case, the dependence on the light power, i.e. the violation of superposition principle, should be observable for the same reason in other optical properties of the medium as well — in birefringence, dichroism, optical rotation, etc." Here, S I Vavilov generalizes the manifestation of nonlinearity and predicts other nonlinear phenomena. Much more recently, with the advent of lasers, appropriate effects were discovered and studied in different media in the course of their radiation-induced bleaching (for the accompanying nonlinearities in dye solutions, see, for instance, Ref. [6]).

It is noteworthy that, in his reasoning about nonlinear optical effects, S I Vavilov unequivocally associates 'nonlinearity' with the violation of the superposition principle: the action of several light waves on a medium in the mode of nonlinear interaction is not reduced to the sum of the individual actions of these waves. By this reasoning, S I Vavilov foresees the foundation for the future mathematical description of nonlinear optical phenomena. Indeed, when diverse nonlinear optical phenomena were discovered in the 1960s, owing to the advent of lasers, and the construction of an adequate mathematical apparatus for their description became a necessity, the first and supposedly the most important step of theoretical nonlinear optics involved the formulation of the nonlinear relationship between the medium polarization and the light wave field inducing the latter. It is precisely this relationship that S I Vavilov's reasoning about the violation of the superposition principle is fully applicable to.

It should be noted that S I Vavilov also analyzed the opposite limiting case of weak light fluxes when discussing the applicability problem for the law of linear light absorption — the Bouguer–Lambert–Beer law — at high radiation intensities. In doing so, he took advantage of a quantum treatment of radiation and considered light as a flux of rare single photons [7].

The birthday of a new field of physics — nonlinear optics — may be dated to either 1925, when the first experimental work [4] was carried out, or 1950, when the book *Mikrostruktura Sveta* was printed, in which the term 'nonlinear optics' was introduced and important generalizations were made. We emphasize that physics in 1950 and, in the first place, optics were on the eve of revolutionary changes: four years remained before the emergence of

quantum electronics, and ten years before the advent of lasers. It so happened that the breakthrough in the development of coherent radiation sources in the optical range, i.e. lasers, was made using luminescent crystals. By that time, information about the luminescence of substances made up a mature field of knowledge with a wealth of experimental data; at FIAN and other research institutions there were teams of experienced experts in luminescence — the pupils and disciples of Vavilov's scientific school. It is safe to say that the way to success in the implementation of the first lasers in our country was paved not only by the insight of the founders of quantum electronics, N G Basov and A M Prokhorov, and their organizational activity, but also by the achievements of S I Vavilov's school in the area of luminescence.

With the advent of lasers, research in the field of nonlinear optics substantially broadened in scope. A great variety of new nonlinear effects were discovered, their nonlinearity mechanisms being different from that in S I Vavilov's first experiment. In modern nonlinear optics, it is possible to single out the two biggest classes of nonlinearity mechanisms: the mechanisms with a nonlinear electronic response, and those with the response of atomic and molecular nuclei. Electronic nonlinearities are characterized by an anharmonic response of electrons in substances to the action of a harmonic light field. The class of electronic nonlinearities may be subdivided into the groups of resonance and nonresonance nonlinearities (depending on the ratio between the frequency of the light field and atomic transition frequencies). The nonresonance electronic nonlinearity is responsible for second harmonic generation, the generation of sum and difference frequencies, multiphoton absorption, and several other nonlinear phenomena. The resonance electronic nonlinearity is primarily responsible for the bleaching of a medium, as well as for other nonlinear effects. S I Vavilov's and V L Levshin's experiment [4] demonstrates the manifestation of precisely the resonance nonlinearity of substance molecules. In the nonlinear mechanisms involving responses of atomic and molecular nuclei, the field-induced motion of electrons remains harmonic, but this motion is the reason for the displacement of atomic cores, which shows up as a change in optical properties of substances. Among these mechanisms, mention should be made of electrostriction, orientation of optically anisotropic molecules, excitation of molecular vibrations, and some others. These mechanisms are responsible for the nonlinearity of the refractive index of a medium, induced birefringence, stimulated light scattering, and other effects. It is valid to say that S I Vavilov's first experiment turned out to be merely a window on the world of diverse nonlinear optical phenomena.

After the creation of lasers, experimental work on nonlinear optics poured forth as from a horn of plenty. It was evident that nonlinear mechanisms are highly diverse and go beyond the scope of the effect of light on energy level populations in a substance. Many nonlinear effects occurred with no light absorption at all (second harmonic generation, nonlinear refractive index, etc.). A breakthrough in the theoretical description of nonlinear optical effects was made in our country by R V Khokhlov, S A Akhmanov, and their collaborators: a nonlinear material equation was introduced to relate the response of a medium in the form of polarization to the magnitude of the electric field strength in a light wave: $P = P(E)$. In this case, of fundamental importance for the theory was going over from the radiation intensity (as with S I Vavilov) to the electric field strength of the wave, and from energy level populations to the polarization of the medium. This made it possible to construct a consistent theoretical description of a wealth of diverse nonlinear optical effects, in which the differences between nonlinearity mechanisms were 'concealed' in the form of the material equation $P = P(E)$. Methods for the solution of Maxwell equations with one type of the material equation or another were also elaborated. Furthermore, the material equation permitted reformulating the superposition principle making it possible to differentiate linear and nonlinear optical effects. Among the nonlinear effects are those wherein the polarization of a medium exposed to the sum of different fields is not equal to the sum of polarizations induced by each of the fields separately.

S I Vavilov's merit in the formation of nonlinear optics as a new avenue in light–matter interaction science is marked by the fact that the regular International Conference on Nonlinear Optics in Novosibirsk bears his name.

At FIAN, S I Vavilov set up the Laboratory of Luminescence, which he supervised until the last days of his life. After 1963, this laboratory was headed by his pupil and disciple M D Galanin (S I Vavilov's last postgraduate student). In mid-1961, Moscow's first laser was put into operation in Galanin's team — a ruby laser [8]. After the creation of lasers, M D Galanin, along with Z A Chizhikova and other members of the Laboratory of Luminescence, undertook in the period from 1963 to 1973 the 'development of Vavilov's nonlinear optics' and performed many pioneering studies with the employment of laser radiation. They published more than ten papers concerned with the observation of new nonlinear effects. They discovered two-photon absorption and dichroism in liquids, luminescence quenching by intense light fluxes, and anti-Stokes Raman light scattering by the electronic levels of dye molecules; they investigated superluminescence in molecular crystals under laser irradiation and the luminescence of dyes from the second excited level, and they studied the features of luminescence under excitation by picosecond light pulses. These papers were published in scientific journals of the highest prestige at that time, including *Pis'ma Zh. Eksp. Teor. Fiz.* (*JETP Lett.*) [9]; many of them are appropriate for citation in textbooks.

M D Galanin's closest colleague, who worked with him on the making of the ruby laser — A M Leontovich — also carried out several important nonlinear optical studies, in particular, on the resonance interaction of short light pulses with ruby and neodymium ions in crystal matrices [10]. Together with his colleagues, he succeeded in realizing the mode of coherent light pulse amplification, wherein the pulse duration is shorter than the period of medium phase memory; this mode is no longer described in terms of the populations of the ground and excited ion states.

In the organization of research at the Laboratory of Luminescence of FIAN, S I Vavilov attached special significance to the work of scientific seminars. Regular seminars in the Laboratory of Luminescence, or colloquia, as they were called at that time, were conducted jointly with the meetings of the Commission on Luminescence of the USSR Academy of Sciences beginning from 1945. Reports about these seminars have been retained since January 1947. The records were made by seminar secretaries for almost 65 years, and for the last 24 years the records were made by Z A Chizhikova. The seminars are described in greater details in Ref. [11]. Here are examples of scientific reports borrowed from these records. At the seminar of 5 October 1949, S I Vavilov and M D Galanin gave a report entitled

"Izluchenie i pogloshchenie sveta induktivno svyazannykh molekul" ("Emission and absorption of light by inductively coupled molecules"). This work was among the first in a long series of investigations into the migration of excitation energy in substances. Held in June of 1949 was a seminar with five reports on the subject of luminescent light sources; among the speakers was V A Fabrikant with a report "Raboty VEI po lyuminestsentnym lampam" [1] ("Work on luminescent lamps at VEI"). The seminars were held regularly on Wednesdays at 10 a.m. A regular seminar was conducted by S I Vavilov on Wednesday, 24 January 1951 — on the day before his death. Since S I Vavilov's death, the seminars of the Laboratory of Luminescence have been held on Wednesdays as before. The 1900th seminar was held in October 2010. Beginning from 1976, Vavilov Readings are held annually in honor of S I Vavilov's birthday late in March, at which reports on topical subjects of modern optics are given by leading scientists from FIAN and other institutes. Nobel Prize Laureates I M Frank, N G Basov, A M Prokhorov, and V L Ginzburg, as well as other famous scientists from Moscow research institutes and from institutes in other cities of our country, have participated in the work of the seminars and Vavilov Readings. This year saw the 35th Vavilov Readings. The seminar of the Laboratory of Luminescence is a special monument to its founder — S I Vavilov — and is undoubtedly among the unique phenomena of FIAN.

In a brief report, it is impossible to overview the numerous achievements made in nonlinear optics over the past years. We shall merely cite several examples where nonlinear optics 'work'.

(1) First of all, this is the development of laser technology. Each time a new laser medium emerges or a laser is designed to provide specific radiation parameters, there is a need to calculate its operating conditions. This may only be done by using balance equations, which is nothing but a description of the resonance nonlinearity of the active medium. In this case, the nonlinear optical description acts as an engineering science.

(2) Special nonlinear media ensure laser operation in unique lasing modes. For instance, in lasers which generate pulses of picosecond and femtosecond duration, use is made of bleachable media and media with a nonlinear refractive index. To amplify short pulses, advantage is taken of parametric crystals whose operation is underlain by the mechanism of nonresonance electronic nonlinearity. The duration of picosecond and femtosecond laser pulses is measured exclusively with instruments which rely on nonlinear optical phenomena, because the methods of direct photodetection do not offer the requisite time resolution.

(3) Nonlinear media make it possible to substantially broaden the wavelength range in which coherent radiation may be obtained. In this case, wide use is made of crystals which generate the second optical harmonic, and of converting media utilizing stimulated Raman light scattering. To continuously tune the wavelength of laser radiation, advantage is taken of parametric crystals with a nonresonance electronic nonlinearity.

(4) The spectroscopic technique of ultranarrow atomic resonances, which is applied in the development of optical frequency standards and precise clocks, is inseparably linked with resonance nonlinear phenomena. Owing to the narrowness of the atomic resonances, the nonlinearity of the interaction with light manifests itself even for milliwatt radiation power.

(5) Lasers and the nonlinear media capable of ensuring optical rectification and differential frequency generation find application in the modern technology of generating and detecting terahertz radiation.

(6) Nonlinear interaction effects that emerge in the data transmission by light pulses in optical fiber communication lines restrict the technical communication capabilities. In this case, even a weak nonlinearity of the refractive index of the light guide material has an adverse influence owing to accumulation of the disturbing effect over a long propagation path. However, 'useful' nonlinearity — optical pulse amplification due to stimulated Raman scattering in the light-guide material — also finds use in light guides.

(7) Optical memory cells developed for quantum computers rely exclusively on the resonance nonlinearity effects in different media.

(8) To generate optical radiation in nonclassical quantum states (sub-Poissonian, squeezed, etc.), only nonlinear processes that ensure the multiphoton nature of an elementary act of interaction with light are suitable. This light is requisite for unique instruments intended for ultrasensitive optical measurements, permitting one to overcome the standard quantum sensitivity limit.

(9) Among the spectroscopic methods for studying a substance, supposedly only one nonlinear optical method has gained acceptance — the technique of coherent Raman spectroscopy. Its realization necessitates two laser sources, one of which is continuously tuneable in wavelength.

(10) To record weak infrared (IR) radiation, use is sometimes made of the mixing of IR waves with visible radiation in a nonlinear medium. In this case, the IR frequency is transferred to the visible range in the course of sum (or difference) frequency generation, where the means of high-sensitive photodetection is available.

The above examples do not exhaust the subject of the role and place of nonlinear optics in modern science and technology.

During the years of the 'laser boom' in the 1960s and 1970s, FIAN and several academic institutes expanded to take on the graduating students of the Moscow institutes of higher education, who improved laser technologies and discovered new nonlinear optical effects. A considerable portion of them was made up of the graduating students of the Moscow Institute of Physics and Technology (MIPT). At this point, there is no escape from recalling a little-known aspect of S I Vavilov's activity — his participation in the establishment of MIPT. As President of the USSR Academy of Sciences, he advocated the idea of organizing in our country a highest-level educational institution aimed at preparing research physicists, which was expressed by P L Kapitza and like-minded scientists. In this connection, in 1946 S I Vavilov become president of the board of the Higher Physicotechnical School of the USSR (later MIPT). Academician G S Landsberg — S I Vavilov's fellow scientist — was assigned to organize the teaching of optical disciplines there. During the period of the laser boom, hundreds of graduating students from MIPT joined FIAN, the Institute of Spectroscopy, and other research centers of the USSR Academy of Sciences and ensured a world level of achievements in the laser area.

To summarize, it is valid to say that the advancement of the science of luminescence in media, which is due to a great extent to S I Vavilov and his successors, was conductive to the

[1] All-Union Electrotechnical Institute (VEI in *Russ. abbr.*), Moscow.

successful development of laser research in our country. The pioneering experiments performed by S I Vavilov and V L Levshin opened the window onto the world of diverse nonlinear phenomena in optics. Thanks to the application of laser light sources, S I Vavilov's pupils and successors made a major contribution to the discovery and investigation of new nonlinear optical effects. The spirit of devotion to science displayed by S I Vavilov and his personal example of selfless labor under incredibly difficult conditions are still helpful in retaining the high scientific level of optical research in our country.

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Luminescent nanophotonics, fluoride laser ceramics, and crystals

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When taking up some of Sergei Ivanovich Vavilov's scientific publications and his fundamental work — the book *Mikrostruktura Sveta* (*The Microstructure of Light*) [1] — one arrives at the conclusion that they laid the foundation for the modern nanophotonics of laser and luminescent materials.

Sergei Ivanovich stated that any light source may be characterized by three attributes: radiation energy, spectrum, and the state of polarization. In this regard, he emphasized that they are nothing more than average macroscopic characteristics. Concealed behind them is an extremely complicated microoptics world, due to which these average characteristics are formed. To investigate the nature of light and expose the relation between its properties and the properties of the elementary emitters generating light field, it is necessary to penetrate into this world of microoptics (or nanophotonics, as it is customarily called nowadays).

S I Vavilov assigned to microoptics (nanophotonics) the properties of very small emitters, the manifestations of the lifetimes of excited molecular states and, lastly, the interactions of luminous molecules with the surrounding medium. He placed special emphasis on the fact that the neighboring molecules determine the initial, principal, chain of optical excitation energy transfer (migration) in the medium [1].

Being aware that an increase in the particle concentration results in a shortening of the distance between optically active molecules and, accordingly, in a strengthening of the interaction between them, S I Vavilov and his collaborators studied this phenomenon in detail and discovered characteristic 'nontrivial' concentration dependences of the excited state lifetime, the polarization, and the yield of luminescence. As far back as the 1930s, S I Vavilov and his colleagues discovered that the concentration dependences of the excited state lifetime and the quantum yield were different; this was a direct indication that the kinetic curves of luminescence decay measured in their work were nonexponential.

Unfortunately, in those distant years there was technically no way of instantaneously exciting phosphor and measuring with high precision the kinetics of luminescence decay; nor was there a theory providing a quantitative description of the decay kinetics of a particle ensemble with the inclusion of microinteractions.

The first expressions for the decay kinetics of a statistical ensemble of luminous particles (donors) were due to Förster [2] (1948) and Galanin [3] (1955) in the form of a square-root dependence for the two-particle dipole–dipole quenching

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