"And so, in 1954 we were already operating ...(a maser[4]). Shortly after that I went to a conference in England on microwave spectroscopy, and Prokhorov was there. It was a remarkable privilege to meet a Russian scientist. At those times it was extremely complicated and hard for American and Russian scientists to meet — at those times, in the 50s. And, indeed, they arrived. At first, they did not announce what they would talk about. But they spoke precisely about the maser, they were making a maser. The idea was the same: molecular beams. An idea very similar to mine. They had not yet obtained the final results, but they had almost completed their experiment, and they perfectly understood me and we discussed it.

"And so I told them what I was doing. I said: 'we, too, are working on this... .' We talked, talked, shared experience. It was wonderful — talking with them, comparing notes and exchanging ideas.

"But they did not admit the possibility of... focusing. Later they used it, got a good maser, and then they developed this idea to make octopole focusing to improve it. It was truly a better result. They started from this idea, refined it, and on the basis of this idea they conceived another idea. They worked. And we used their octopole focusing later. Well, they had very similar ideas, very... ."

I have reproduced in this article everything I spoke of in my address to the Scientific Session of the Physical Sciences Division which was held at the P N Lebedev Physics Institute on 2 June 2004 and was dedicated to the fiftieth anniversary of quantum electronics. Of course, I realize that attempts to adequately reproduce the events that took place in the first years of the formation of quantum electronics 50 years ago involves a certain risk. What encourages me is the fact that after my speech I have not heard remarks from my colleagues which might be regarded as a reproach about violating the truth. This removed my doubts as to the possibility of publishing this article in *Uspekhi Fizicheskikh Nauk*.

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Solid state lasers: a major area of quantum electronics

I A Shcherbakov

The thesis appearing in the title is illustrated as follows:

(i) the world's first laser was a ruby laser, although this is a purely historical aspect of the problem;

(ii) today, rather compact solid-state laser setups provide cw radiation ranging up to ten kilowatts in power and, what is more important, the pulse power is approaching the petawatt level due to the use of femtosecond pulse duration. When such a pulse is focused into a spot measuring about ten micrometers, the peak at-focus intensity amounts to 10^{21} W cm^{-2}. The physics of interaction of these pulses with atoms, molecules, and clusters, as well as solid and gaseous targets, is of great interest.

Even for a radiation intensity on the order of 5×10^{16} W cm^{-2}, the peak field intensity at the focus is equal to the intra-atomic field intensity, i.e., to the intensity of the Coulomb field of the nucleus of a hydrogen atom at a distance equal to the Bohr radius (5×10^9 V cm^{-1}). In this intensity range there emerge numerous unique effects devoid of analogs in the weak-field case. For instance, the generation of very high-order harmonics of laser radiation during atom ionization (with harmonic numbers up to 300 and above), a complete restructuring of atomic spectra, and so forth. It has been proposed that such extraordinary effects which accompany the atom ionization in a strong laser field may be used to advantage to generate even shorter (attosecond, 10^{-18} s) radiation pulses. It is conceivable that many interesting phenomena in this area still remain outside the province of contemporary notions.

The next threshold of significance is the so-called relativistic intensity, whereby the velocity of electron oscillations in the light field is around the speed of light. For the neodymium-laser radiation frequency this condition is fulfilled when the at-focus laser radiation intensity is on the order of 5×10^{18} W cm^{-2}, which corresponds to a field of about 5×10^{10} V cm^{-1}. The observation of nonlinear quantum-electrodynamic effects, such as multiphoton Compton scattering, which is responsible for the radiation of hard gamma-ray quanta, the subsequent electron-positron pair production in the laser field, and so forth, is made feasible at these intensities.

The interaction with gaseous targets may give rise to effects like the self-trapping of laser beams in a medium due to the rapid ionization of target atoms and the ejection of electrons from the focal region under the action of ponderomotive forces in the nonuniform laser field. This effect may be accompanied by subsequent ion ejection interpreted as the Coulomb explosion.

A further increase in intensity in the above-specified range may lead to the discovery and investigation of new quantum-electrodynamic effects, to the performance of experiments on the laser excitation of nuclei, and to many other new results which now are hard to predict.

Therefore, there emerges a new area of physics, whose advances will enable us to develop radically new technologies for the 21st century. Ultrahigh power densities with relatively small energy densities sharply intensify different kinds of nonlinear processes without leading to material damage. These unique possibilities are difficult to overestimate. They may be employed in the development of volume optical storage elements, which will revolutionize computer engineering.

The above experiments can be staged with the use of solid-state lasers. That is why the occasionally voiced statement that solid-state lasers may be replaced with other types of lasers is unlikely to be borne out in the foreseeable future.

A M Prokhorov, one of the founders of quantum electronics, gave much consideration precisely to the development of solid-state laser technology in our country. He was the one who worked out its strategy. It involved, in particular, the unity of the activities of technologists, spectroscopists, and laser scientists. A wealth of examples can be provided to confirm the realization of this statement both in the Academy and at the industrial level. The results discussed in this report were obtained in the framework of this strategy in the General Physics Institute with the participation of a number of other organizations, including foreign ones.

For a rather long time, solid-state lasers possessed an immanent drawback — a low efficiency normally not

[4] Indecipherable in the verbatim report, supposedly, a maser. (*Author's note.*)

exceeding 3%, which is explained by a poor overlapping of the emission spectrum of pumping lamps and the narrow absorption lines of the laser medium. A natural way to eliminate this drawback was to harness the effect of luminescence sensitization. The fundamentals of this effect — the energy transfer from particles of one type to particles of the other — were laid by S I Vavilov's school. In particular, one should mention the classical works by M D Galanin. The energy transfer probability was shown to be proportional to the overlap integral of the donor emission spectra and the acceptor absorption spectrum. However, in the case of laser crystals use is normally made of the working particles possessing a large number of narrow lines, so that measuring the overlap integral over these lines was strongly problematic. For this reason, a purposeful search for efficient donor–acceptor pairs was impossible.

In the investigation of transfer processes, use was also made of kinetic techniques reliant on the tau-approximation, i.e., the transfer law was assumed to be exponential. Nevertheless, it was clear that this approximation is not always valid.

Our measurements of donor luminescence kinetics in a dynamic range amounting to five orders of magnitude revealed its rather complex nonexponential form. The corresponding empirical formula was obtained, which described the nonradiative decay of the donor subsystem. This formula contained no fit parameters and all measured quantities were underlaid by the corresponding theoretical interpretation. Therefore, it has been possible to measure several parameters describing the energy transfer and, in particular, the quantity proportional to the overlap integral, whose physical meaning is the probability that two particles spaced at 1 cm interact in a given medium.

Knowing the form of decay of the donor subsystem, it is possible to derive the temporal evolution of the acceptor one, i.e., the temporal evolution of the upper laser level population, which is of interest here. Experimental and theoretical results agreed nicely. It has been possible to establish the condition for the efficient energy transfer from the broad absorption bands of trivalent chromium ions to the narrow levels of trivalent rare-earth ions. This condition is determined by the positional relationship of the excited states ^2E and $^4T_2$ of trivalent chromium ions. The efficient energy transfer takes place only when the energy gap between these states does not exceed kT. This explained the inefficient operation of the above donor–acceptor pairs in crystals known at that time.

A variety of new crystals were proposed (and their growth technology was developed), in which the aforementioned condition was met. Furthermore, the co-activation with chromium ions in the framework of the technology elaborated did not impair the optical quality of the crystals. This resulted in a several-fold increase in the population density of the upper laser level of neodymium ions due to efficient transfer of the energy absorbed in the broad spectral lines of chromium ions. For instance, on the basis of chromium- and neodymium-doped yttrium-scandium garnet crystals it has been possible to develop lasers offering an efficiency of 11% in the free-running mode and up to 9% in the Q-switched mode. These results remain record-high even today.

Also proposed and realized were more complex schemes. Specifically, the arrival of excitation at the upper laser level in a chromium-thulium-holmium system is preceded by seven nonradiative energy transfer events. To describe the energy transport in this system requires knowledge of over ten parameters, which were measured in various ways in different crystals. By the corresponding selection of crystal composition, the energy transport was optimized for obtaining the maximum population density in the upper laser level of holmium. As a result, a cw laser was developed on the basis of the yttrium–scandium garnet with chromium, thulium, and holmium in the two-micrometer range, which offered an efficiency up to 50% for a selective excitation in the arsenide absorption band of chromium ions. We note that, from general considerations, this laser might not exceed 30% in efficiency. The result obtained is attributed to the fact that one of the energy transfer events possesses a quantum yield of 2.

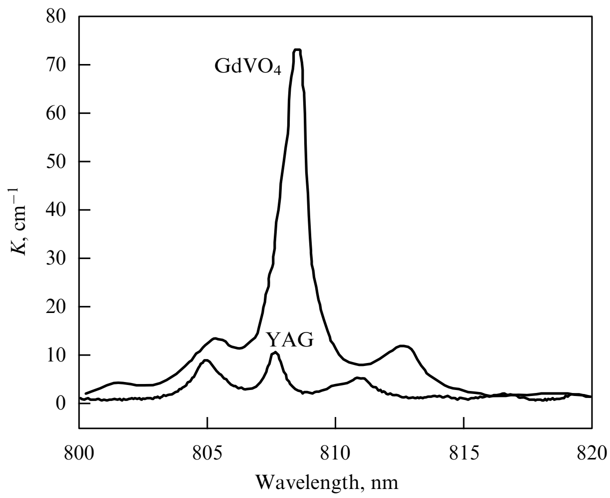

Figure 1. Neodymium ion absorption spectra of yttrium–aluminum garnet and gadolinium vanadate crystals in the region of excitation by gallium arsenide diodes.

In the early 1990s, papers concerned with the physics of lamp-pumped lasers nearly disappeared from solid-state laser conferences. There dawned the time of so-called diode pumping, i.e., pumping solid-state lasers by semiconductor lasers. In A M Prokhorov's laboratory this technology was taken up in collaboration with the 'Start' works in the early 1960s. At that time, diodes possessed a low output power and were operated at nitrogen temperature. That is why attempts to obtain lasing did not meet with success, but the promise of this method was clearly realized. Even much later, many were skeptical about this approach: why pump a laser with a laser?

Prokhorov and collaborators and Zh I Alferov and collaborators suggested specific laser diodes to pump neodymium ions. By that time, diodes with a sufficiently high power had been made and the realization of the idea of diode pumping became feasible. This was preceded by basic works on the selective excitation of lasing in solid-state lasers by the radiation of krypton, argon, and other lasers.

Two types of diode pumping are recognized. It can be transverse, where thousands of differently arranged semiconductor light sources which radiate incoherently are placed against the crystal. In this case, the crystal fulfils the function of phase locking with an efficiency up to 80%. Evidently, the task of synchronizing the radiation of so great a number of sources is hardly attainable in any other way. In precisely this way it has been possible to generate cw radiation with an output power ranging into the kilowatts. Unfortunately,

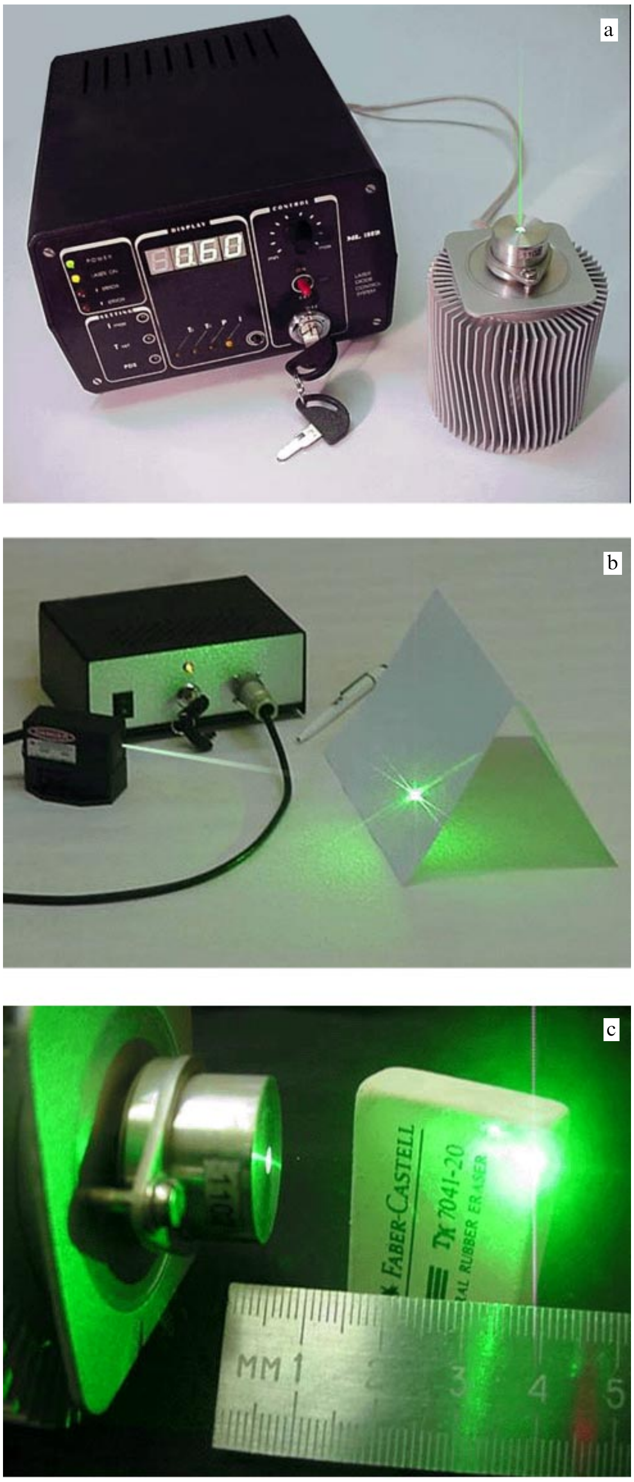

Figure 2. (a – c) Photos of single-frequency lasers radiating in the green spectral range.

under our present circumstances this is 'objective reality not given in sensation' to us because high-power diode matrices are unavailable in appropriate numbers.

As regards longitudinal pumping, when the crystal is excited by a small number of radiators through its face, our position is 'sound'. New crystals have been proposed and elaborated on for these purposes; the requirements imposed on these crystals are significantly different from those imposed on lamp-pumped crystals.

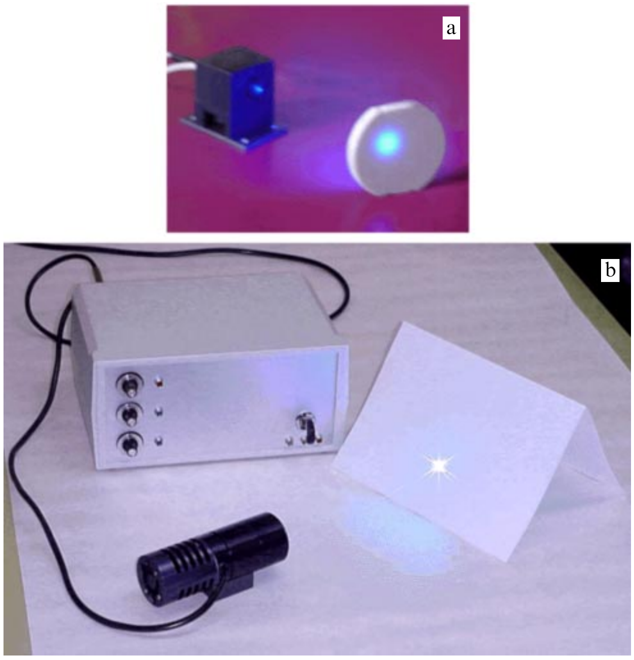

Figure 3. (a, b) Photos of single-frequency lasers radiating in the blue spectral domain.

The longitudinal diode-pumping technology necessitates a strong selective absorption at the wavelength of laser diode emission. This significantly facilitates the laser design and obtaining high-quality radiation. One of these crystals is the gadolinium vanadate crystal. Figure 1 shows the absorption spectra in the domain of emission of gallium arsenide-based laser diodes. One can see that the neodymium absorption coefficient in this crystal is many times higher than in the yttrium – aluminum garnet crystal. So strong an absorption permits using crystals with a thickness of about 1 mm or less. Even the first experiments with a laser of extremely simple design utilizing the gadolinium vanadate crystal yielded an efficiency of 57%.

The diode-pumping technology substantially broadened the spectral range of efficient lasing. Specifically, for neodymium ions alone it extends from 0.45 to 1.5 μm, i.e., from the blue to the infrared spectral region. It is significant that the last two to three years have seen the appearance of domestically produced semiconductor-laser pump sources with an output power from several to dozens of watts, including those with a fiber radiation output. This has enabled a major expansion of research in the field of diode-pumped laser physics.

On the basis of the newly developed crystals it has been possible to realize the doubling of the intracavity frequency and to obtain single-mode single-frequency lasing in the green spectral range with an output power ranging into the watts and an efficiency of up to 25%. The external appearance of these lasers is shown in Fig. 2.

Lasing has been obtained on the weak neodymium transition at 1444 nm with an output power up to 7 W and an efficiency of 19%. For a number of reasons this wavelength is of great interest for a wide range of practical applications.

Also developed was a high-efficiency laser utilizing the 912-nm transition to the ground state of neodymium ions having an efficiency of 48%. Intracavity frequency doubling

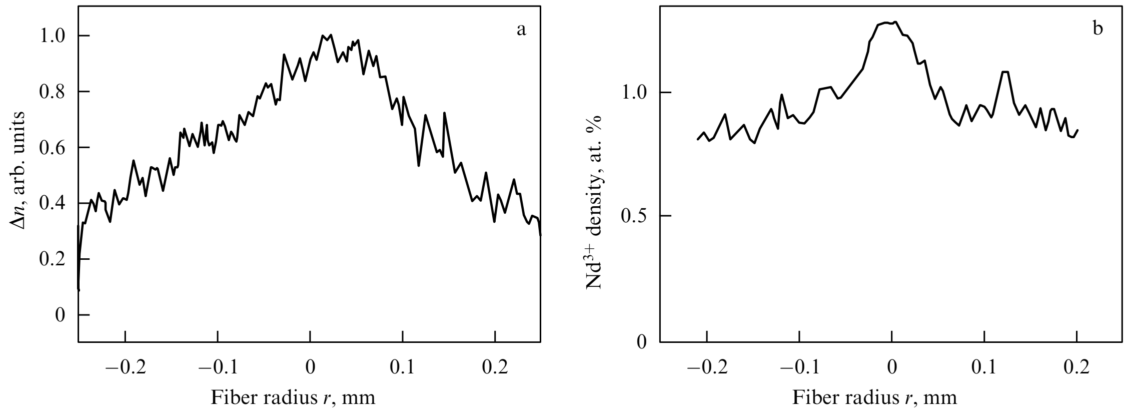

Figure 4. (a) Radial profile of the refractive index in the crystal fiber of neodymium-doped yttrium – aluminum garnet. (b) Neodymium ion density distribution over the fiber section.

of this radiation has led to the design of a laser in the blue spectral region (456 nm) with an efficiency of 18% and an output power up to 250 mW. It is pertinent to note that the output power of all lasers listed above can be substantially increased by increasing the pump power. Some photos of the blue lasers are shown in Fig. 3.

We now briefly dwell on a new type of crystal laser, specifically, crystal fiber lasers with a transverse gradient of the refraction index. A fabrication system was elaborated and realized for crystal fiber growth. A CO_2 laser serves as the heating source. An original part of this system is an element of computer optics — the so-called 'fokusator', which transforms the beam of CO_2-laser radiation into a ring. It is worthy of mention that the computer optics itself has a relatively brief history. Its founders were Prokhorov, I N Sisakyan, and V A Soĭfer. In this fabrication system, the 'fokusator' enables producing a strictly symmetric heating of annular shape about 1.5 mm in diameter on the material. The crystal fiber is pulled out from the center of this ring. By selecting the material composition and the corresponding processing conditions it has been possible to produce a crystal fiber of neodymium-doped yttrium-aluminum garnet with a significant radial gradient of both the neodymium ion density and the refractive index (Fig. 4). As a result, a waveguide lasing mode was realized in this fiber for an active medium length of about 1 cm. An obvious virtue of this laser is that the diode pump fills the entire fiber aperture (500 μm) and the lasing takes place in only its central part measuring about 40 μm.

The efficiency of diode-pumped lasing in the waveguide mode amounts to 25%, and there is also significant improvement of radiation brightness and quality. This active medium is a crystal analog of a laser utilizing a double-cladded quartz fiber. However, realizing efficient lasing in the double-cladded quartz fiber requires a 30 – 100 m-long active medium because of the low density of active particles and the consequential low absorption of exciting radiation.

In summary, I would like to draw a conclusion not relating to the results outlined. The author of this report is not entitled to judge them. The conclusion is thus. Following the development strategy and respecting the traditions laid by the great teachers, the founders of quantum electronics, our research teams manage to perform internationally recognized works, including experimental ones, even at the present time, which is by no means favorable for the science of our country. May I bow low with gratitude to those who have gone before and to those who are still heartily working.

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From quantum electronics to laser technology (first steps in application)

A L Mikaelyan

1. Introduction. 'Prelaser period' (the 1950s)

The development of society is accompanied by a constant increase in the body of information which we encounter in different fields of our activity. The requirements imposed on data processing and transfer rates become progressively more demanding. It becomes necessary to operate with huge data files for a high degree of concurrency of calculations etc.

The history of development shows that the aforementioned problems of information transfer, processing, and storage are most advantageously solved by mastering new, shorter-wavelength ranges of electromagnetic radiation.

The 1940s were marked by the pioneering works in the microwave wavelength range (decimetric and centimetric waves). This led to the development of waveguide and semiconductor technologies, as well as to their numerous applications in communication and radar systems, computer engineering, and systems for data processing and storage.

The development of microwave technology was characterized by a wide use of the methods of classical optics. For instance, multireflector antennas, which received wide acceptance (A A Pistol'kors, L D Bakhrakh), artificial-dielectric lens microwave antennas with a varied refractive index (W Kock, A L Mikaelyan), geodesic microwave lenses (A A Pistol'kors, Ya N Fel'd, L E Zelkin), and so forth were proposed and developed. Of special significance for radar and radio relay systems was the development of 'nonreciprocal' waveguide-ferrite elements (including the isolator based on a 'cutoff waveguide'), which make use of magnetooptic effects in ferromagnetic media much studied in optics. These devices (proposed by the author in 1951) were developed on