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FROM THE HISTORY OF PHYSICS

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CELEBRATING 50 YEARS OF THE LASER

Development history of the laser

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Abstract. An attempt is made at objectively assessing the contribution made by Soviet scientists to the origination of laser physics, which the author believes tends to be underestimated abroad. Together with the concept of induced radiation, the three-level method and the open resonator were to become cornerstone proposals for laser physics, as were semiconductor active media, carrier injection through a p–n junction, double heterostructure lasers, and laser fusion.

Science being as it is an international and cooperative endeavor, it does not really matter who personally contributes most to a new discovery, not even a world-changing one. But because there are such things as feeling obliged to one's teacher and to those gone and, of course, scientific results are so fascinatingly unpredictable, it is hardly possible to impartially separate a discovery from its authors. This paper has been presented at a number of international conferences and attracted considerable interest because some key facts from the history and development of the laser are interpreted in it differently from the way they are seen by scientists from abroad at conferences marking the 50th anniversary of the laser. While constantly more or less present, the trend of underestimating the contribution of Russian researchers became especially strong in the anniversary year of the laser (see, e.g., Ref. [1]). I am far from thinking that this is intentional. The real likely reason is that Russian-language scientific publications receive less-than-adequate attention from foreign scientists, even though Soviet physics journals started to be translated into English as far back as the second half of the 1950s (by the American Physical Institute) [2] and have had high impact factors (according to the founder of the Institute for Scientific Information, see Ref. [3, p. 189]) and hence high international citation rates (see Ref. [4], p. 568]). The task the author sets for himself in this paper — and he apologies beforehand to those who will find him fully or partially not up to it — is to be as objective as possible in presenting and interpreting historical facts.

To begin, then, the birthday of the laser should be taken to be 16 May 1960, or such is the date of the lab notebook entry by T M Maiman (1927–2007), arguably the father of the laser. Unlike a child, however, the laser has more than one father: a scientific discovery never comes from nowhere but is always preceded by the fundamental research by many scientists. Anyway, priority for the end result, a source of coherent optical radiation, is universally ascribed to Maiman. This result was published in Ref. [5] dated August 1960 (Fig. 1). Maiman observed, correctly interpreted, and estimated the narrowing of a spectral line and an orders-of-magnitude increase in the radiation intensity. The device he developed contained all three components necessary and sufficient for producing coherent optical radiation: an inversely populated active medium (a synthetic ruby crystal), an optical pumping system, and an open resonator that provides positive feedback and changes the optical radiation amplifier into a generator.

Somewhat later, 18 September 1961, a laser was launched at the Lebedev Physical Institute (FIAN), then in the USSR [6], by Galanin, Leontovich, and Chizhikova (see Fig. 2). Statements by some witnesses about an earlier laser launch at the State Optical Institute (GOI) have, to our knowledge, no documentation support.* Galanin's group had been determined to create a ruby laser, and they conducted pioneering studies of laser radiation.

It is worth noting that the crystal of ruby became a quantum electronics material even before the advent of the laser, in large part due to the fundamental work of Manenkov and Prokhorov [7] on the spectroscopy of this crystal (in particular, on the fine structure of the paramagnetic resonance of the Cr^{3+} ion in ruby).

In further work, a paramagnetic amplifier and a generator, both based on ruby, were proposed and developed by Zverev, Kornienko, Manenkov, and Prokhorov [8].

As already noted, the laser did not come from nowhere and was by no means fathered by a single individual. Although the reference point is here difficult to locate, the first stone was arguably laid by Albert Einstein in 1916 [9] in his study of statistical equilibrium between molecules and thermal radiation with the spatial spectral energy density U_ω determined by Planck's formula. Einstein introduced the following probabilities for each pair of energy levels E_1 and $E_2 = E_1 + \hbar\omega$ in a molecule: $B_{12} U_\omega$ for absorption and A_{21} and $B_{21} U_\omega$ for spontaneous and induced (or stimulated) radiation; here, the quantities A_{21}, B_{21}, and B_{12} (which came to be known as Einstein coefficients) are defined by

$$
\begin{aligned}
\mathrm{d}n_1 &= B_{12} U n_1 \,\mathrm{d}t\,, \\
\mathrm{d}n_2 &= (A_{21} + B_{21} U)\, n_2 \,\mathrm{d}t\,,
\end{aligned}
$$

* Archive materials on the launch of a ruby laser at GOI in June 1961 are featured in this *Uspekhi* issue; see page 73. (*Editor's note*.)

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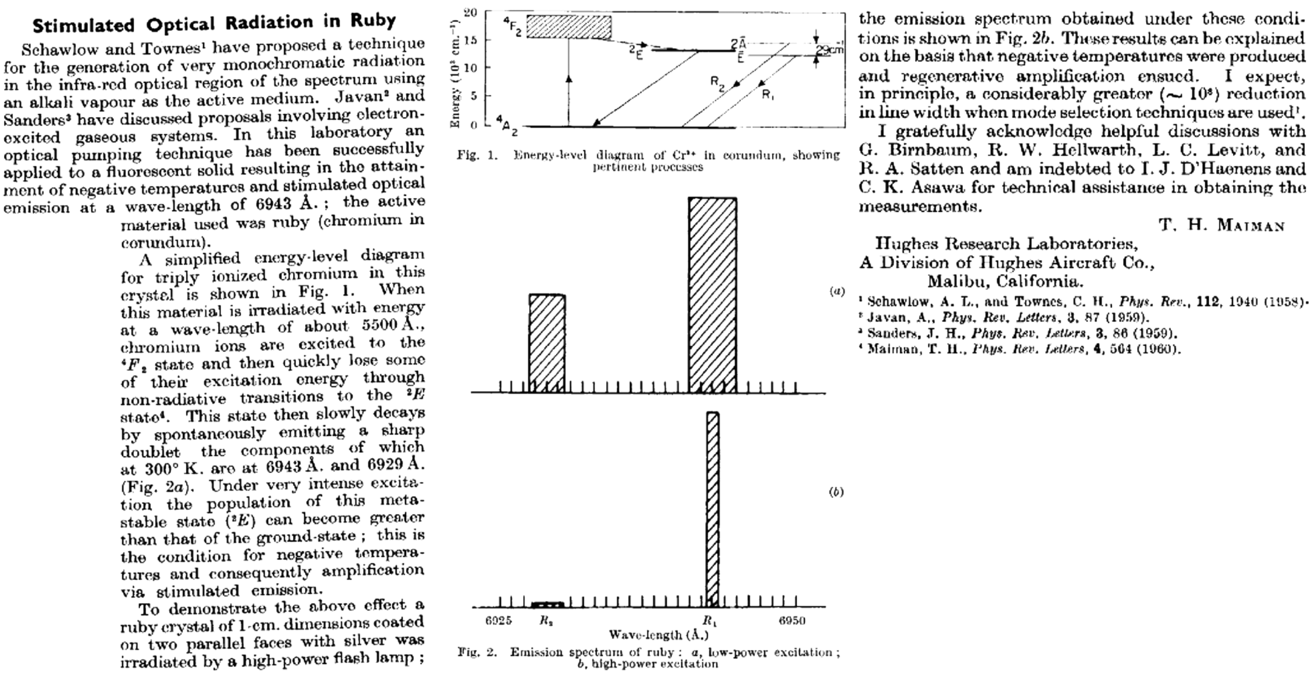

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the $^4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the ^2E state[4]. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2*a*). Under very intense excitation the population of this metastable state (^2E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp; the emission spectrum obtained under these conditions is shown in Fig. 2*b*. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater (~ 10^8) reduction in line width when mode selection techniques are used[1].

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Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

Fig. 2. Emission spectrum of ruby: *a*, low-power excitation; *b*, high-power excitation

Figure 1. Photocopy of Maiman's 1960 paper "Stimulated Optical Radiation in Ruby" [2].

Figure 2. The creators of the first ruby laser in Moscow. From left to right: M D Galanin, A M Leontovich, and Z A Chizhikova.

where n_1 and n_2 are the numbers of particles in the first and second state, A_{21} is the probability of the spontaneous transition $E_2 \to E_1$, and B_{12} is the probability of the stimulated transition $E_1 \to E_2$, B_{21} $(E_2 \to E_1)$ (we note that $B_{21} = B_{12} = B$ and $B = \pi^2 c^3/(h\omega^3)\,A$).

Einstein's treatment corresponds to the equilibrium case, that is, stimulated radiation is a necessary condition for equilibrium between a system governed by the Boltzmann distribution and radiation described by Planck's formula. The nature of spontaneous and simulated radiation is discussed in detail in Ginzburg's methodological note [10]. Ginzburg states that spontaneous radiation is not quantum in nature, and moreover, that "it by all means occurs in classical theory and cannot generally be considered a quantum phenomenon, certainly no more so than absorption or stimulated emission." Stimulated radiation is one of the cornerstone concepts of quantum electronics and laser physics.

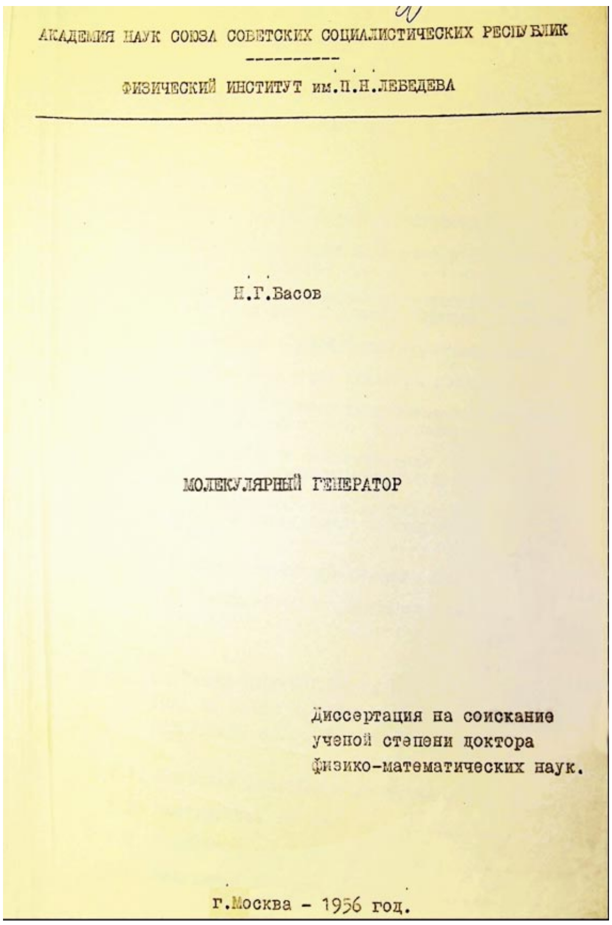
P Dirac in his mid-1920s work developed the detailed theoretical understanding of light emission and absorption processes, in particular, providing a rigorous grounding for the existence of stimulated radiation.

V A Fabrikant, a Soviet optics scientist, was the next to contribute. In his 1939 FIAN doctoral dissertation on emission mechanisms in a gas discharge, in particular, he discussed experimental evidence for the existence of negative absorption and for the possibility of increasing the radiation intensity in the direction of the exciting beam.

Later, Fabrikant, Bugaeva, and Vudynskii filed a claim (1951) and were granted an authorship certificate (1959) [12] for the invention of the optical amplifier. The team was also granted the State Committee for Inventions diploma No. 12 with the priority date 18 June 1951; the discovery was formulated as follows: "A hitherto unknown phenomenon is discovered in which electromagnetic waves amplify when passing through a medium in which the concentration of particles or of their systems at upper energy levels that correspond to excited states is excessive compared to the concentration in the equilibrium state." Therefore, the idea of inverse population as a necessary means for amplifying optical radiation was around long before the concept of the laser was realized. While necessary, however, the inverse population requirement is not sufficient to produce lasing. Positive feedback was an unfamiliar concept to opticians, which is the reason why the laser was not developed at that time. Radiospectroscopists, on the other hand, knew well that the way to turn an amplifier into a generator was to introduce positive feedback, which is exactly what was done (first, in the radio wavelength range) using a volume resonator. Moreover, the above-cited studies by Fabrikant contain no mention of the fact that stimulated radiation is a coherent process, which is yet another reason why the principles of microwave quantum electronics were applied to the optical range later than they could have been. Further details in this regard can be found in Ref. [13].

A crucial milestone in the development and maturation of laser physics was the creation of the maser. The idea that it is in principle possible to create a molecular generator is due to Basov and Prokhorov [14], whose work [15] discussed the great application potential of this device. However, American scientists Gordon, Zeiger, and Townes created the first molecular generator [16]. The development of the maser was the subject of Basov's doctoral dissertation, titled "The Molecular Generator" (Fig. 3).

The necessary point to note is that Basov's dissertation contains references to the work of Townes's team, thus countering occasional statements in the Russian literature to the effect that the laser precursor, the quantum generator of microwave radiation, was created by Basov and Prokhorov at the same time as by Townes. It is Townes's team to whom the priority of the direct experimental realization of the maser belongs.


АКАДЕМИЯ НАУК СОЮЗА СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК

ФИЗИЧЕСКИЙ ИНСТИТУТ им.П.Н.ЛЕБЕДЕВА

Н.Г.Басов

МОЛЕКУЛЯРНЫЙ ГЕНЕРАТОР

Диссертация на соискание ученой степени доктора физико-математических наук.

г.Москва – 1956 год.

Figure 3. The first page of Basov's dissertation "The Molecular Generator."

The history of how quantum electronics emerged and has developed was discussed in a quite objective way in papers in a special issue of the *Journal of Modern Optics* [17], timed to coincide with the 50th anniversary of quantum electronics. The recent work of Karlov, Krokhin, and Lukishova [18] evaluates and abundantly references the contributions of Soviet researchers. The 2010 collection on the field [19] also contains references to Soviet scientists' pioneering and seminal contributions to laser physics.

After the source of microwave coherent radiation was created, the question of moving into the short-wavelength and, in particular, visible range naturally arose. It was clear that the key barrier to this was a sharply increased probability of spontaneous transitions, a factor that makes inverse population difficult to achieve and positive feedback unrealizable by known methods.

In their work [20] (submitted on 1 November 1954), Basov and Prokhorov suggested a method in which, in contrast to the molecular generator, inverse population is achieved not by selecting excited and nonexcited molecules in molecular beams but by exposing molecules to external electromagnetic radiation at a resonance frequency. This method, which later came to be known as the three-level method, proved to be universal in the sense that under some requirements, any multilevel system can be made inverse-populated, irrespective of the energy of the quantum used (Fig. 4a).

A similar idea was later proposed by Bloembergen [21]. The three-level method is at the heart of operation of all the so-called optically pumped lasers.

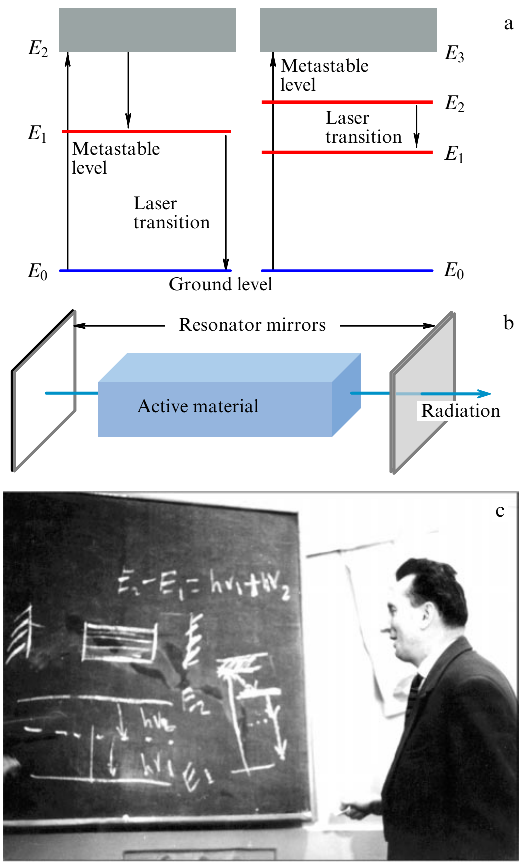


Figure 4. (a) Schematic principle of three-level pumping. (b) Open resonator. (c) A M Prokhorov delivering a talk on the working principle of the laser.

The second barrier — the lack of suitable optical resonators — was overcome with equal success. At the time, volume resonators were widely used in radio physics, but their optical analogs, with a size below 1 μm (this is a typical optical wavelength, and a volume resonator should of course have a size of the order of the wavelength it produces), were still technologically impossible (unlike today). In 1958, Prokhorov proposed using a pair of plane parallel mirror-reflecting plates as a resonator; this system was called an open resonator [22]. For this system, with the radiation wavelength much less than the resonator size, the conditions for self-excitation were obtained and an expression for the quality derived. Viewed differently, this system is the so-called Fabri–Perot interferometer, a well-known optical device, albeit used for totally different purposes. The idea of an open resonator was proposed a few months later by Shawlow and Townes [23] and patented independently by Dicke [24].

The creation of the open resonator removed the last obstacle to moving into the optical region of the spectrum and in fact completed the foundation of laser physics. Thus, pioneering theoretical work on creating the laser was done in the 1950s [22, 23, 25].

As already noted, the first laser, based on a ruby crystal, was built in the USA in 1960 [5]. Shortly afterwards, the helium–neon gas laser of Javan, Bennett, and D Herriott appeared [26], and then, within a mere year, dozens of other lasing systems were reported. Although mainly concerned with the demonstration of the effect and with the fundamental properties of the radiation, this earlier work allowed realizing, at least in part, how enormous the application potential of the laser was. However, fundamental research alone was insufficient for lasers and their unique properties to be put into wide application. The challenge was to develop totally new technologies that were then unavailable, either in the USSR or in any other country, including the USA.

It was necessary, first, to organize a search through all the existing aggregate states — solid (crystals and glasses), liquid, gaseous, and plasma — for materials with energy level arrangements and relaxation rates suitable for lasing; and, second, to develop fabrication methods for the materials found, methods capable of meeting unprecedentedly high chemical purity and structure uniformity requirements. These new materials, of course, required the development of high-precision techniques for their processing (for example, for polishing optical surfaces with an unprecedented precision), as well as for making their surfaces strictly flat and keeping these surfaces strictly parallel. Also to be developed were sources for optical pumping and precision techniques for mirror deposition. These technological problems brought a host of other problems in their wake, including the design of new technological equipment, the manufacture of special-purity chemicals, the development of methods and tools for controlling and monitoring material properties, and many other necessary aspects. All this meant entering the realm of what is called high technologies. All in all, the development of laser technology and its introduction into practice required a highly ramified infrastructure, in both research and industry.

Accordingly, within a record one decade, a network of new research institutes, design bureaus, and production facilities was set up and specialists in lasers and related areas were trained in the USSR [27], making the country one of the two (with the USA) laser superpowers.

a

b

Figure 5. 1964 Nobel prize laureates in physics awarded for "fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser–laser principle." From left to right: C Townes, N G Basov, and A M Prokhorov. (b) Prokhorov's Nobel medal.

The 1964 Nobel Prize in physics went to Nikolai Gennadievich Basov and Aleksandr Mikhailovich Prokhorov of the USSR and Charles Hard Townes of the USA (Fig. 5). The often made statement that this award was for the invention of the laser is, to say the least, incorrect. It was in fact awarded "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle." The Nobel Committee's choice of people to be made laureates appears to be fully justified and correct.

It is hard to think of any devices other than the laser that, while working on a common principle, vary so immensely in appearance and size, ranging from hundred of meters (the order of the size of the Japanese neodymium glass laser facility; see Fig. 6a) to a few millimeters (a typical semiconductor laser, Fig. 6b) (semiconductor quantum dot structures brought about by the advent of nanotechnologies allow even more impressive miniaturization).

Semiconductor lasers, which, of all lasers, have the most numerous (including daily) applications, are worth special attention. The idea of a semiconductor active medium was first published by Basov, Vul, and Popov [25] in 1959, even before the ruby laser, and was registered by the State Committee for Inventions and Discoveries of the USSR Council of Ministers with the priority date 7 July 1958. Reference [25] examined the possible use of transitions between the conduction (valence) band and donor (acceptor) impurity levels in a semiconductor for obtaining electromagnetic radiation using the simulated radiation mechanism as in the molecular generator. It was also proposed to use an electric current to obtain inverse population.

In 1961, Basov, Krokhin, and Popov published the study titled "Production of Negative-temperature States in p–n Junctions of Degenerate Semiconductors" [28]. The term 'negative temperature' was used in early laser physics to describe the nonequilibrium inverse state of a system. The method, suggested by the team, of injecting carriers through a

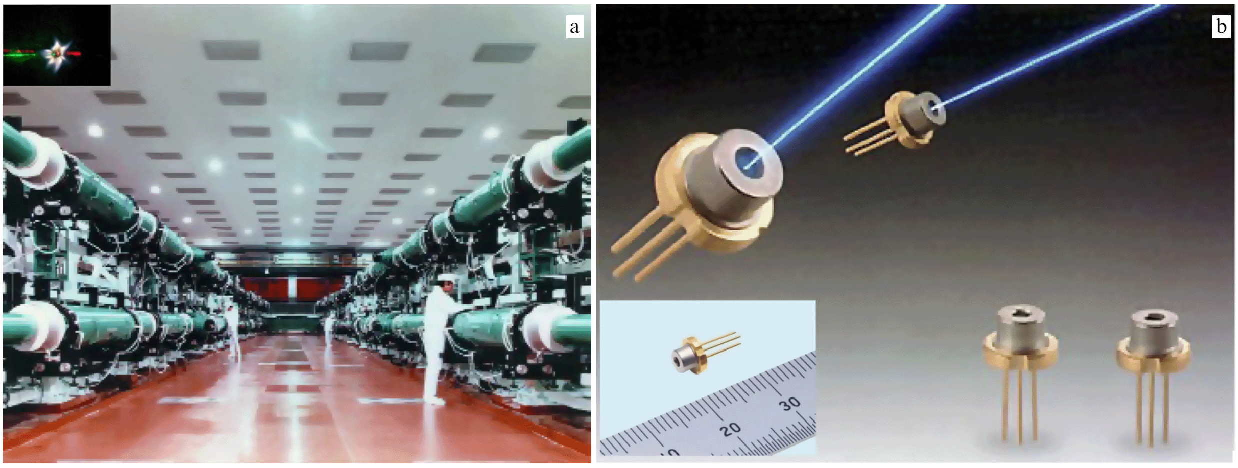


Figure 6. (a) Gekko laser, Japan. (b) Semiconductor lasers.

p–n junction proved to be very useful and led to the creation of laser diodes, devices that have found wide practical application.

As it happened, though, the first semiconductor laser was launched by Hall in the USA [29]. A Soviet team reported a narrowing of a luminescence line [30], apparently due to stimulated radiation. However, because of the lack of feedback (i.e., of mirrors), no lasing effect was observed.

Alferov and Kazarinov proposed a semiconductor laser based on a double heterostructure; this idea has been put into wide practice and the authors were awarded the certificate of authorship [31] (No. 181737, the priority date 30 March 1963). The idea of a laser based on a double heterostructure was also proposed independently by Kroemer some months later [32]. In 1970, Alferov's group reported the continuous room-temperature operation of the first AlGaAs–GaAs double-heterostructure laser. Pioneering work in the field of information and communication technologies earned Zh Alferov, H Kroemer, and J Kilby the Nobel prize in physics in 2000. Alferov and Kroemer were awarded the Nobel prize "for developing semiconductor heterostructures used in high-speed- and opto-electronics."

Over the last fifty years, a wide variety of types of lasers have been developed and realized:

— solid state lasers;
— semiconductor lasers;
— gas lasers;
— dye lasers;
— metal vapor lasers;
— excimer lasers;
— chemical lasers;
— free electron lasers;
— diode pumped lasers, including fiber lasers.

Despite their diversity, all these lasers have three components: an active medium, a pumping system, and positive feedback.

It is hard to imagine modern life without lasers. In particular, lasers are highly popular for use in medical applications, such as general surgery, urology, and ophthalmology [33].

Taking medical lasers as an example, laser parameter ranges are typically as follows:

— the spectral range, from UV (≈ 0.1 μm) to IR (≈ 10 μm) (three orders of magnitude);

— the energy density range, from 1 J cm^{-2} to 10^3 J cm^{-2} (three orders of magnitude);

— the power density range, from 10^{-3} W cm^{-2} to 10^{15} W cm^{-2} (18 orders of magnitude);

— time range, from continuous radiation (≈ 10 s) to femtosecond pulses ($\approx 10^{-5}$ s) (16 orders of magnitude).

The photos in Fig. 7 show two medical devices, the femtosecond ophthalmological laser Femto Visum and the laser surgery system Lazurit, both developed at the Prokhorov General Physics Institute of the Russian Academy of Sciences (GPI RAS). Short-duration laser pulses stimulate a range of nonlinear processes when interacting with biological tissue, such as optical breakdown, multiphonon absorption, and the formation and development of plasma. With the laser, due to the diversity of interaction mechanisms between laser radiation and biological tissue, unique and otherwise impossible operations have become possible. Pioneering the use of laser in Soviet medicine were Basov and Prokhorov, who developed very close cooperation with medical professionals.

A major recent development is the introduction of fiber lasers, which were proposed by Snitzer in the USA soon after

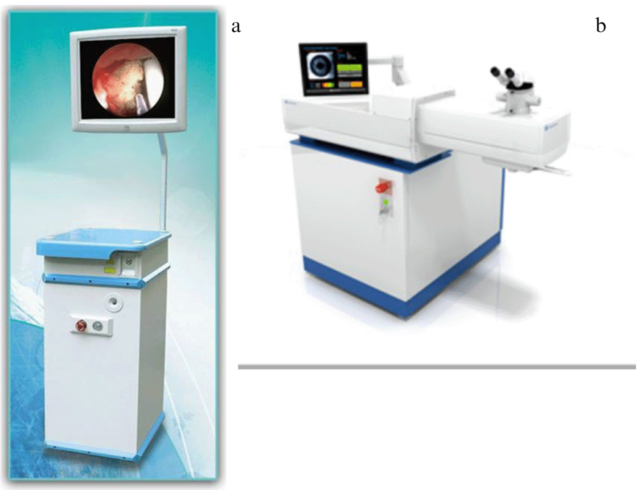


Figure 7. Laser developments at GPI RAS: (a) Laser surgery system Lazurit, (b) Femtosecond ophthalmological laser Femto Visum.

Figure 8. Laser technology system using a high-power fiber-optic laser from IPG Photonics (www.ipg photonics.com).

the invention of the ruby laser [34] but which originally received little or no application due to the inefficient bulb pumping method then in use. The 1974 development of using a laser diode to pump a fiber laser had a major impact on the field of fiber lasers [35]. Currently, fairly compact, highly reliable, and easy-to-operate fiber lasers with the diod pumping up to 50 kW are being mass produced by IPG Photonics, an international corporation founded and led by the Russian scientist V P Gapontsev [36] (Fig. 8). Also, diode pumping brought about a revival of solid state lasers by considerably enhancing their reliability and efficiency.

Over the last thirty years, fiber optical communication has come into wide use, leading to a billion-km fiber-light-guide network operated under the support of semiconductor lasers and fiber amplifiers. While commercial communication lines currently support information transfer rates 1–2 Tbit s^{-1}, their experimental counterparts reach 70 Tbit s^{-1}, with the 2030 target 1 Pbit s^{-1} (10^{15} bit s^{-1}). In 2009, the Chinese scientist Charles Kao was awarded the Nobel prize in physics for his outstanding contribution to research on fiber light-guides for optical communication.

The leading country in manufacturing high-power solid state lasers is the USA. The Lawrence Livermore National Laboratory developed large-size lasers up to 70 kW in power with active elements made of optical ceramics, a new material whose composition is similar to that of yttrium–aluminum garnet with neodymium [37].

In another major development, Northrop Grumman has built a demonstration prototype of a transportable laser system with a lasing power in excess of 105 kW and with the beam quality better than three diffraction limits [38, 39].

The status of a separate and independent field can be claimed by laser thermonuclear fusion. The creation of modulated-quality nanosecond pulsed lasers [40] allowed a new approach to producing high-temperature plasma, in which the heating is done by a short pulse of high-power spatial coherent radiation focused onto a small-size target containing hydrogen isotopes. This proposal, made by Basov

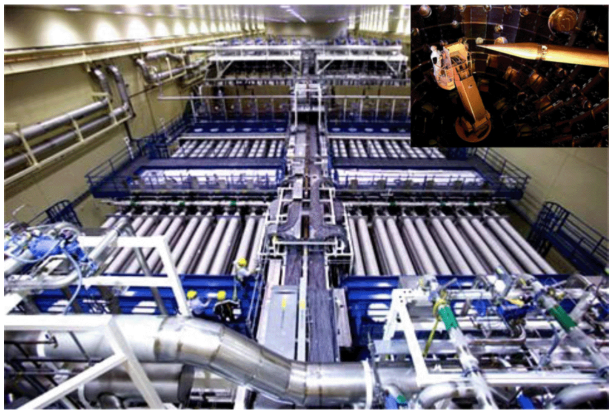


Figure 9. Laser facility for research in laser fusion (National Ignition Facility at Lawrence Livermore National Laboratory, USA).

and Krokhin in 1963 [41], gave rise to the field of inertial thermonuclear fusion. The most powerful laser for this purpose was built at Livermore. Presently, a single few-nanosecond pulse in the UV range (the third harmonic of neodymium laser radiation) has the energy 1.8 MJ, possibly enough for igniting a fusion reaction (Fig. 9).

In Russia in the 1990s, the work on laser fusion was to a large extent curtailed. Today, a program has been set up to develop the UFL-2M mega-Joule facility for a 3 ns pulse at the second neodymium laser harmonic [42]. The planned construction site is the Russian Federal Nuclear Center "All-Russian Scientific Research Institute of Experimental Physics" (RFNC ARSRIEP) in Sarov, an organization that was able to maintain and even develop its experimental resources during those years that were unfriendly (to put it mildly) to Russian science.

Lasers are ubiquitous in everyday life. No lasers means no Internet, no devices for recording, reproducing, and reading information.

Interestingly, the word laser is an acronym for "Light Amplification by Stimulated Emission of Radiation," which was coined by Gould in 1959 [43], even before this remarkable device was actually invented.

Figure 10 is an attempt to trace, if only in sketch form, how laser physics evolved. Efforts by radiospectroscopists and opticians equipped with fundamental physical knowledge led to a new field of science, quantum electronics. Quantum electronics gave rise to laser physics, which in turn gave birth to new fields in science and technology. Today, it is

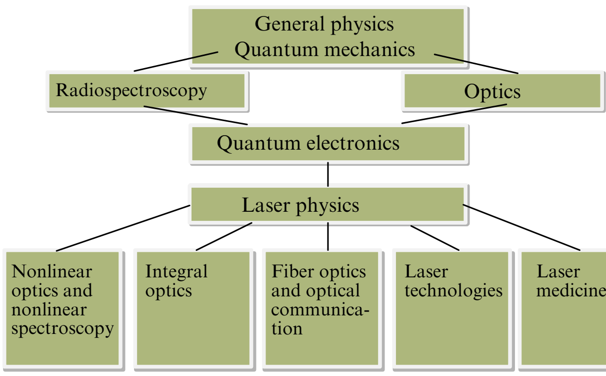


Figure 10. Genesis and development of laser physics.

undoubtedly clear that the Nobel prize winning achievements of Basov, Prokhorov, and Townes have changed the face of the world we live in. In addition, their Nobel prize led to about a dozen further Nobel prizes related to some extent or another to the laser.

As a final remark, the popular science cliché of a laser as a horrible and devastating weapon (see *Star Trek*, for example) is totally misleading. Laser energy is clever and elegant. The laser is not a means of destruction; it is a means of creation.

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