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PACS numbers: **01.65.+g**, 42.55.Px, **42.60.–v**
DOI: 10.3367/UFNe.0180.201101l.0102

The early history of the injection laser

Yu M Popov

One of the spectacular achievements of world science, which strongly affected the technological level of modern society, is the generation of optical radiation in semiconducting materials. The concept of a semiconductor laser and the first studies in this area were initiated at the Lebedev Physical Institute, RAS (FIAN in *Russ. abbr.*), where a group of young scientists organized by N G Basov was engaged, beginning from 1957, in the problem of creating a semiconductor laser. These were pioneering investigations not only in our country but also in the world, along with the studies of C Townes and A Schawlow in the USA.

Although molecular generators operated on gases, the paramagnetic amplifiers of stimulated emission already utilized crystals, confirming the possibility of obtaining inverted population in solids. Semiconductors as active media attracted our attention because they have high absorption (amplification) coefficients. This opened up the possibility of constructing resonators of a small size. At FIAN, the properties of semiconductors in strong electric fields were studied at the Laboratory of Semiconductor Physics headed by B M Vul. N G Basov and his collaborators discussed with B M Vul and his colleagues the possibility of obtaining the inverted population required for light amplification in semiconductors. In 1958, N G Basov, B M Vul, and Yu M Popov filed an application for a patent and published a paper on using short current pulses for the avalanche multiplication of charge carriers from the valence band (or from impurities), and producing the inverted population due to cooling carriers by a lattice after the instant removal of the field [1]. The patent was recorded in the State Register by the Committee on Inventions and Discoveries of the Council of Ministers of the USSR on 7 July 1958. N G Basov reported this work at the first conference on quantum electronics in the USA in 1959.

Because the production of interband avalanche multiplication in germanium and silicon required high electric field strengths, whereas optical interband transitions were indirect, we decided to experimentally study the ionization of impurities in these materials and to use narrow-gap semiconductors with direct optical transitions for interband ionization. At that time, the best studied semiconductor of this type was indium antimonide which was grown at the Leningrad Physicotechnical Institute (LFTI in *Russ. abbr.*) at the laboratory headed by D N Nasledov, with whom we made friends. A group at the FIAN Laboratory of Semiconductor Physics studied the recombination emission of electrons ionized from shallow impurities in germanium, while a group at the Laboratory of Oscillations investigated emission observed during avalanche multiplication in indium antimonide. However, although some interesting results were obtained in these studies, no evidence of stimulated emission was observed. The main difficulties were the requirement to obtain current pulses with very short fronts and the complexity of performing measurements in the infrared region. Later on, already after the creation of semiconductor lasers by other methods, the inverted population between the energy levels of donor impurities in silicon was achieved using emission from a CO_2 laser.

In 1960, we published a long paper in *Usp. Fiz. Nauk* (*Sov. Physics–Uspekhi*) presenting both a review of the main methods and media for the creation of lasers and a number of original concepts about the use of semiconductors for this purpose [2]. In particular, the inverted population was formulated as a condition for the nonequilibrium distribution functions in bands, and we proposed forming a resonator by means of parallel output facets of semiconducting crystals having reflection high enough for providing the feedback. At the beginning of 1961, we proposed a method for producing the inverted population in semiconductors by fast electrons, and in March the concept was suggested and the main conditions were formulated for bringing about the inverted population by injecting nonequilibrium charge carriers through the p–n junction in degenerate semiconductors [3]. As a result, the fundamentals of the theory of semiconductor lasers were developed by the early 1960s. Consider in detail paper [3] where the possibility of creating an injection (diode) laser was proposed and substantiated in the world first (the paper was submitted to *JETP* on 18 April 1961 and published in June 1961). The main results of paper [3] are as follows.

(1) When a forward voltage is applied to the p–n junction in a semiconductor, the concentration of minority charge carriers near the p–n junction increases due to a decrease in the potential barrier formed by a spatial charge in the p–n junction. The maximum concentration of these carriers corresponds to the complete removal of the potential barrier by the external electric field and is on the order of their concentration in the part of the crystal where they are majority charge carriers (we assume that the p–n junction is sharp). The negative temperature in interband transitions appears only when the Fermi quasilevels corresponding to the nonequilibrium electron and hole concentrations satisfy the following condition

$$F_e + F_p > \Delta\,, \qquad (1)$$

where F_e and F_p are the Fermi quasilevels for electrons and holes, and Δ is the band gap. When a forward voltage is applied to the p–n junction, the Fermi quasilevel of minority carriers near the p–n junction will be close to the Fermi level in the part of the crystal where they are majority. In this case, it follows from inequality (1) that the carriers should be degenerate at least in one part of the p–n junction. Semiconductors with such p–n junctions are termed tunnel

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Yu M Popov Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russian Federation. E-mail: ympopov@sci.lebedev.ru

Uspekhi Fizicheskikh Nauk **181** (1) 102–107 (2011)
DOI: 10.3367/UFNr.0180.201101l.0102
Translated by M Sapozhnikov; edited by A Radzig

diodes. However, this mechanism of producing the negative-temperature states corresponds to the diffusion part of the current–voltage characteristic of a tunnel diode rather than to the tunnel part. In the p – n junctions of strongly degenerate semiconductors, the negative-temperature state appears before the complete removal of the potential barrier, which allows one to make quantitative estimates by applying the diffusion theory of the current flowing across the p – n junction.

(2) It is easy to show that the minimal external voltage U producing the negative-temperature state is given by

$$U_{\min} = \frac{\varDelta}{e}\,, \tag{2}$$

where e is the electron charge. The current density I (for example, the electron component) is on the order of

$$I = \frac{enL}{t}\,, \tag{3}$$

where t is the lifetime, L is the diffusion length, and n is the degenerate concentration of electrons.

(3) Analysis of formula (3) shows that the current density decreases with decreasing temperature of a sample. This circumstance permits the production of the negative-temperature state in the stationary regime. However, due to various radiation absorption mechanisms in a semiconductor, the negative absorption coefficient may appear at comparatively high (10^{15} cm^{-3}) nonequilibrium concentrations of minority carriers, which excludes operation at very low current densities. A spatial region, where the negative-temperature state occurs, is formed in a layer near the p – n junction with a thickness on the order of the diffusion length.

(4) The high densities of majority charge carriers in degenerate semiconductors, surrounding the negative-temperature region, can probably be used as surfaces reflecting radiation, i.e., can form a ‘resonator’.

(5) Notice that the current density can be reduced when semiconductors forming the p – n junction have different band gaps.

Thus, we obtained in paper [3] the main conditions for creating an injection laser and outlined ways for refining it:

- the condition for a distance between Fermi quasilevels was obtained (expression (1)). This condition was later refined by replacing $\varDelta$ by $h\nu$ in paper [4] published at the end of 1961;
- we made a remark on condition $U_{\min} = \varDelta/e$ (2) that, in the case of indirect transitions at low temperatures of a sample, $\varDelta$ in formula (2) should be replaced by $\varDelta - E_{\rm ph}$, where $E_{\rm ph}$ is the emitted photon energy, i.e., we considered direct interband transitions in condition (2);
- we expressed the hope that continuous-wave lasing is possible;
- it was pointed out that the waveguide properties of the active region can reduce diffraction losses and the threshold current;
- it was also pointed out that the threshold current can be reduced using different band gaps forming the p – n transition.

In our earlier paper [2], we proposed making a resonator formed by parallel output facets of a semiconductor sample, which have reflection high enough for providing the feedback.

A structure with two heterojunctions constructed by Zh I Alferov with his collaborators in 1970 reduced the active region width (expression (3)) and enhanced the waveguide effect, which resulted in continuous lasing at room temperature [5]. Note that the concept of a laser diode operating in the forward direction seemed even to us extremely unusual, and at the same time too simple. Interestingly, during the discussion of this work reported at a seminar, it was even questioned whether or not this concept contradicts the second law of thermodynamics. B M Vul suggested that we not publish this work before obtaining experimental results. Nevertheless, we published our proposal in *JETP* in June 1961, although experimental studies in this line of inquiry were also started.

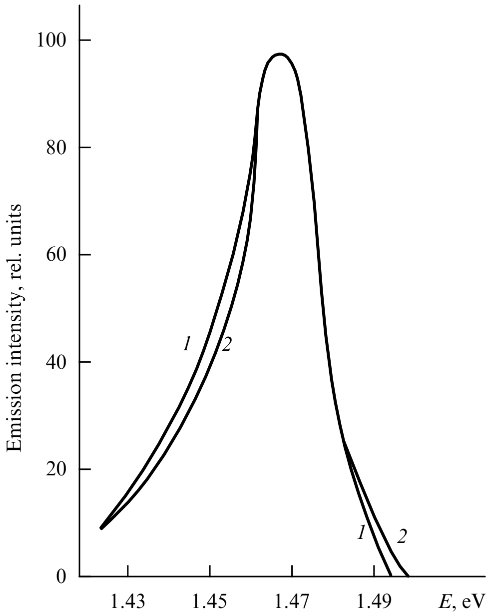


Figure 1. Spectral distribution of recombination intrinsic emission of gallium arsenide at 77 K: (1) low current density (10 A cm^{-2}), and (2) high current density (1.5×10^3 A cm^{-2}).

We reported the concept of a p – n junction laser at many places during 1961–1962. When I was on temporary duty from October 1961 to March 1962 in the USA, I gave a talk at a seminar at Harvard University, where N Bloembergen asked me questions about the selection of oscillation modes, and I told B Lax about the concept of an injection laser. In January 1962, after my report at Columbia University, I had a long discussion with IBM researchers P Sorokin and M Nathan, who was one of the first to obtain stimulated emission from the p – n junction in gallium arsenide at the end of 1962. Later on, G Burns and M Nathan mentioned in review [6] in 1964 our papers as pioneering papers in which the utilization of semiconductors for the generation of light was proposed, and our paper [3] as the world's first proposal to create an injection laser.

In October 1961, after his report at a conference in Tashkent, O N Krokhin discussed with LFTI researchers the arrangement of experiments with an arsenide gallium diode available at LFTI. They performed these experiments in January 1962. In April 1962, D N Nasledov, A A Rogachev, S M Ryvkin, and B V Tsarenkov reported in *Fiz. Tverd. Tela* (*Solid State Physics*) [7] the narrowing of a spontaneous emission line upon increasing the pump current. Curves *1* and *2* in Fig. 1 [7] correspond to current densities of 10 and 1.5×10^3 A cm^{-2}, respectively (the curves were obtained at

77 K). The authors gave the following possible explanations of this result:

(a) the narrowing of the intrinsic emission line observed in experiments can be due to two reasons. First, the inverse filling of the bands can occur at high current densities in the p – n junction wherein the lower states of the conduction band are filled with a higher probability than the upper states of the valence band, which corresponds to the so-called 'negative-temperature' state. The possibility of obtaining such a distribution of carriers in the p – n junction was discussed in Ref. [3];

(b) however, another process is also possible, which is not related to induced recombination and can explain the small narrowing of the spectrum on passing to the injection level sufficient for producing the degenerate occupation, at least in one of the semiconductor bands. Indeed, an increase in the current and, hence, in the carrier concentration cannot considerably change the occupation of states in the region adjacent to the band edge where the degeneration already exists. For this reason, the long-wavelength part of emission spectrum increases more slowly with increasing current than the short-wavelength part. However, the observed short-wavelength edge of the spectrum cannot considerably shift to the blue range because the main amount of radiation emerging from a sample is filtered by the material wherein the carrier concentration is close to the equilibrium value. Accordingly, if the optical absorption edge is sharp enough (which is the case in gallium arsenide), the emission spectrum can exhibit some narrowing. Notice that this mechanism requires degenerate distribution only in one of the bands (the conduction band in gallium arsenide). A large ratio between the effective masses of carriers in gallium arsenide indicates that the inverse occupation and especially negative absorption should probably occur here at much higher concentrations of injected carriers than those required for the degeneration in only one of the bands. Therefore, we can assume that the latter explanation is most probable.

As will be seen from the following, shortly before the creation of the first injection laser [8], R Hall and collaborators received a translation of the paper by D N Nasledov et al. and understood that the researchers at LFTI could not obtain lasing because the feedback (mirrors) was absent in their experiments, the more so that the authors themselves preferred a different explanation of the spectrum narrowing, not related to stimulated emission.

The history of the creation of the world's first injection laser was described in detail (in my opinion, interesting and instructive) by Hall, the head of a group at General Electric, in his paper "Injection lasers" devoted to the 25th anniversary of this event [9]. Below, I briefly present the content of this paper.

R Hall writes that, before the summer of 1962, he did not believe that a semiconductor laser could be created, although he knew about several proposals to obtain coherent radiation in semiconductors. In his opinion, the reason had to do, as was already known for existing lasers, with the necessity to have a highly reflecting resonator and a long optical path, which was inconsistent with a strong absorption by free carriers. Also, a broad band corresponding to the energy levels involved in spontaneous emission was unusual. But the most serious problem resided in the low efficiency of radiative recombination in semiconductors. However, the situation drastically changed in the summer of 1962 after the reports by Keyes and Quist of the Massachusetts Institute of Technology [10], and Pankove and Berkeyheiser of RCA (Radio Corporation of America) [11]. Both these reports described optical transitions in gallium arsenide producing edge luminescence with an efficiency close to 100% at pump power densities on the order of 1 kW cm^{-2}. Thus, the most important obstacle was eliminated, but other obstacles still remained and required attention. The energy levels were smeared near the band edges. Although Hall and his collaborators gained experience in operating with tunnel diodes, they did not know how it would affect the probability of optical transitions. The optical properties of the n- and p-sides were different, but how would it influence the emission efficiency, and what is more in the presence of the concentration gradient? It was not certain whether the utilization of zinc diffusion only, as Keyes and Quist did, was sufficient. All this remained uncertain before the beginning of the work.

By using the already known data at that time concerning the fact that the separation between Fermi quasilevels should be larger than the band gap, i.e., both sides of the p – n junction should be degenerate, the lifetime is very short, the active region is smaller than the diffusion length, and, to provide optical feedback, a Fabry–Perot resonator is necessary, Hall sketched in his notebook the initial considerations on the possibility of constructing the injection laser. When Hall discussed these considerations with his colleagues, many of them decided to take part in the forthcoming studies, even simultaneously with their previously planned duties at General Electric. The administration (Roy Apker) of GE agreed that this project was not the major one, and four–five researchers, devoting half their working time to this project, could determine the validity of this concept in a few months. Then, Hall wrote, "we believed that the chance of success was one in five. But even if we never obtain coherent radiation, we will know much about the efficient luminescence reported earlier. This was sufficient to justify our investigations — even if we fail to create the laser, we will feel satisfaction with our research. In addition, the fulfillment of this concept did not require paying for the research."

Because Hall knew that investigations in this area were also being performed and had started even earlier at the Lincoln Laboratory and RCA, he decided to act rapidly, despite the factors mentioned above, assuming that solutions for overcoming encountered difficulties would be found in the course of the studies. Hall describes in detail the individual contributions from each of the members of his group (G Fenner, J Kingsley, T Soltys, and R Carlson), which is not inherent in papers with several authors published in Russia. Technological studies and electric, optical, and other measurements were performed.

A large batch of cubic samples (probably about 100) with 0.4-mm facets and two plane–parallel facets perpendicular to the p – n junction was fabricated. The p – n junction was prepared by the diffusion of zinc into n-type gallium arsenide at different temperatures. Because the efficiency of spontaneous emission was expected to be high, the researchers decided to detect the onset of lasing not by a sharp increase in the emission intensity but by a change in the far-field emission pattern on a remote screen. Experiments were performed with samples placed in liquid nitrogen. Part of the samples proved to be unsuitable at once, while other samples became unsuitable upon increasing current. However, some samples emitted intense spontaneous radiation. At this time, the group received the translation of paper [7] (published in *Fiz. Tverd. Tela* in April 1962). As mentioned

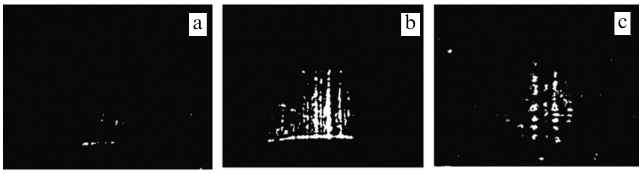


Figure 2. Far-field laser radiation patterns at different distances D from the p–n junction (L-69 diode): below the threshold (a), above the threshold for $D = 6$ cm (b), and $D = 15$ cm (c).

above, the group at General Electric concluded that the researchers at LFTI could not have obtained lasing in the absence of feedback and abandoned by themselves the possibility of obtaining stimulated emission in their paper.

After a month of investigations, the control of the parallel alignment of mirror facets and their quality were improved using an interferometer, and the duration of current pulses was reduced from a few milliseconds to a few microseconds.

Hall writes that important news appeared on the Sunday morning when the project has been developed only for two months. One diode (L-52), for which a linear dependence of the light response to the current was observed under changes of current below 6 A, began to show a much stronger increase in the light intensity upon increasing the current amplitude above 12 A. For currents below 12 A, only scattered far-field radiation was observed on a remote screen. However, as the current was further increased, 'patterns' in the form of bright horizontal lines appeared suddenly, which could not be caused by spontaneous emission (Fig. 2). These interference fringes proved the existence of coherent radiation emitted from the p–n junction region.

After this event, many diodes were intensively studied for several weeks and all the possible data were accumulated for publication of the results. At the same time, an application for patent protection was prepared, which was necessary before the publication of the paper.

Paper [8] was published in *Physical Review Letters* on 1 November 1962 (submitted 24 September 1962). Hall wrote that "it was a surprise to us that a group at IBM also obtained coherent emission in the p–n junction of gallium arsenide [12]. However, this primary paper described a structure that did not provide mode selection, but the spectral narrowing was observed and it was clear that stimulated radiation was emitted." Somewhat later, other papers appeared in which lasing was reported upon injection of carriers through the p–n junction in semiconductors [13, 14].

Soon after the information about the creation of the injection laser in the USA, the first injection laser in the USSR was created at FIAN in December 1962 by collaborating researchers of the Laboratory of Semiconductor Physics and the Laboratory of Quantum Radiophysics (Fig. 3). The parameters of this laser were described in paper [15] and reported at the Third International Congress on Quantum Electronics [16], where extensive information was presented about the first stage in the history of semiconductor lasers — the theoretical substantiation of the possibility of creating the injection laser and its experimental implementation.

About 50 years have passed since that time (the first injection laser began to operate within two years and four months after the creation of the world's first laser based on a ruby crystal). During these years, none of the other lasers have experienced such cardinal transformations which have made injection lasers the main devices in laser technologies, determining modern scientific and technical progress. Such transformations include first of all the employment of heterojunctions [5], which allowed the room-temperature operation of these lasers, and the development of new technological epitaxial processes for their fabrication, which increased their output power up to a few dozen watts, their efficiency up to 70%, and their operating life up to a few decades. The wavelength range covered by modern injection lasers extends from the IR to the UV spectrum. Monolithic diode bars and diode arrays have been developed for the efficient pumping of solid-state lasers. It is difficult to overestimate the immense contribution made to the creation

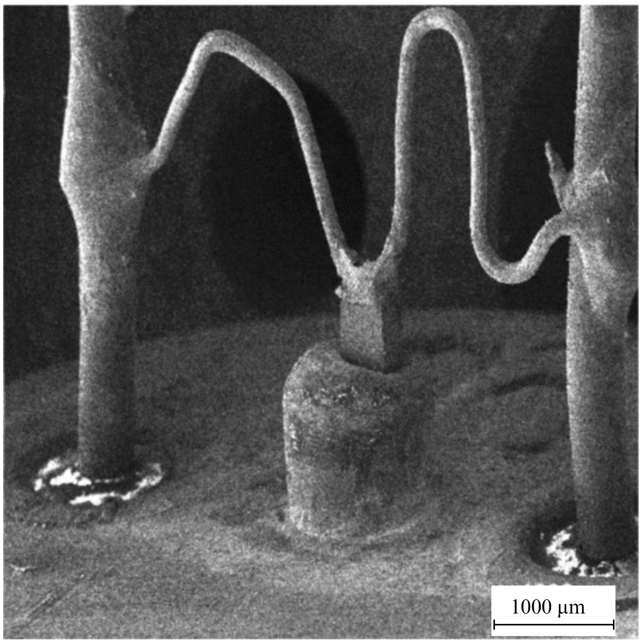
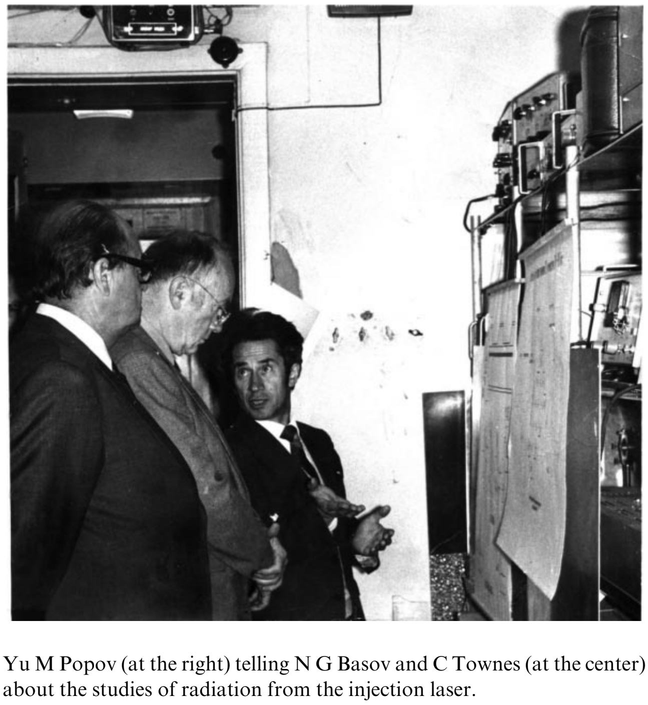
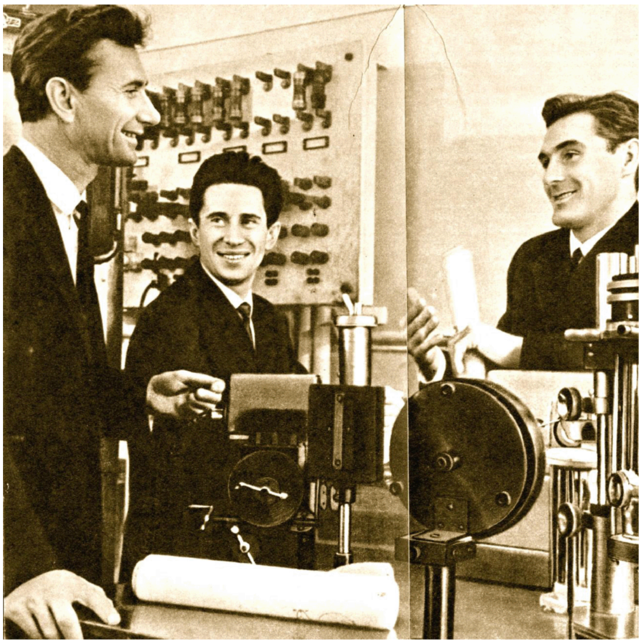


Figure 3. Photograph of the first injection laser made in the USSR (FIAN, December 1962).



Yu M Popov (at the right) telling N G Basov and C Townes (at the center) about the studies of radiation from the injection laser.



A P Shotov, Yu M Popov, and O N Krokhin (from left to right), 1964 Lenin Prize Laureates for fundamental studies which led to the creation of semiconductor lasers.

and development of semiconductor lasers by researchers working under the scientific leadership of N G Basov and Zh I Alferov at FIAN and LFTI, respectively.

The role of injection lasers in our lifetimes is well known. They are used in fiberoptic communications, laser printers, high-capacity memory on optical discs, numerous medical devices, and technological devices for laser processing of various materials. It should be expected that their importance will further increase in the near future, especially in the production of light sources and displays, including high-quality three-dimensional televisions.

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PACS numbers: **01.65.+g**, **42.60.–v**, **42.65.–k**
DOI: 10.3367/UFNe.0180.201101m.0107

Self-focusing of laser pulses: current state and future prospects

A A Manenkov

1. Introduction

The self-focusing of laser beams in their propagation through nonlinear media is among the fundamental phenomena of nonlinear optics. At the heart of this phenomenon lies the variation of the spatial beam profile owing to the dependence of the refractive index of a medium on the radiation intensity. The character of this variation depends on the amplitude-temporal beam parameters and the optical properties of the medium. The significance of the self-focusing effect is underlain by its strong influence on the interaction of high-power laser radiation with optical media (ionization, damage) and on other nonlinear effects (stimulated scattering, harmonic generation, phase self-modulation, etc.). In relation to the discovery of the self-focusing of femtosecond (fs) laser beams in the air, considerable recent interest has been generated by the prospect of practical applications of this phenomenon (remote sensing of the atmosphere, control of electric discharges, etc.).

In connection with the foregoing, investigation of the mechanisms of self-focusing in different media and different frequency and pulse-duration ranges, as well as elucidation of adequate models of the phenomenon, are among the most important areas of laser physics and nonlinear optics.

The aim of this report is to outline the main results of investigations into the self-focusing effect obtained to date, and to analyze the prospects of further research. It should be emphasized that the self-focusing effect, since its prediction in 1962, has been the subject of a wealth of investigations, which have been discussed in numerous reviews, monographs, and other publications. Published in 2009, for instance, was a book [1] containing a vast collection of 24 chapters, which were written by well-known experts in this area, covering different theoretical and experimental aspects of the problem. In what follows we shall discuss only the main — in our view, fundamental — aspects of the problem.

2. History of self-focusing research: main stages

The following main stages may be distinguished in the development of investigations into the phenomenon of self-focusing of laser beams.

- Prediction of the effect, introduction of the term ‘self-focusing’, a qualitative analysis of self-channeling (diffraction-free beam propagation) (Askar'yan [2], 1962).
- First observations of self-focusing: discovery of filamentary damages in solids (Hercher [3], 1964), and self-focusing in liquids (Pilipetskii, Rustamov [4], 1965).

A A Manenkov A M Prokhorov General Physics Institute,
Russian Academy of Sciences, Moscow, Russian Federation
E-mail: manenkov@kapella.gpi.ru

Uspekhi Fizicheskikh Nauk **181** (1) 107 – 112 (2011)
DOI: 10.3367/UFNr.0180.201101m.0107
Translated by E N Ragozin; edited by A Radzig