CONFERENCES AND SYMPOSIA

PACS numbers: 01.10.Fv, **01.65.+g**, **42.50.–p**, **42.55.–f**, 42.55.Px, **42.60.–v**, **42.65.–k**, 42.72.Ai

CELEBRATING 50 YEARS OF THE LASER

Celebrating 50 years of the laser
(Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and of the Scientific Councils of the P N Lebedev Physical Institute, RAS and the A M Prokhorov General Physics Institute, RAS, 21 April 2010)

DOI: 10.3367/UFNe.0180.201101i.0093

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the scientific councils of the P N Lebedev Physical Institute, RAS and the A M Prokhorov General Physics Institute, RAS dedicated to the 50th anniversary of the advent of the laser was held in the conference hall of the Lebedev Physical Institute on 21 April 2010.

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

(1) **Alferov Zh I** (A F Ioffe Physical-Technical Institute RAS, St. Petersburg) "Semiconductor heterostructure lasers";

(2) **Bagaev S N** (Institute of Laser Physics, Siberian Branch, RAS, Novosibirsk) "Ultrahigh-resolution spectra and their fundamental application";

(3) **Masalov A V** (P N Lebedev Physical Institute, RAS, Moscow) "Optical Department of the Lebedev Physical Institute: early work on lasers";

(4) **Garnov S V, Shcherbakov I A** (A M Prokhorov General Physics Institute, RAS, Moscow) "Laser sources of megavolt terahertz pulses";

(5) **Sergeev A M, Khazanov E A** (Institute of Applied Physics, RAS, Nizhny Novgorod) "Structural functions of a developed turbulence";

(6) **Popov Yu M** (P N Lebedev Physical Institute, RAS, Moscow) "The early history of semiconductor lasers";

(7) **Manenkov A A** (A M Prokhorov General Physics Institute, RAS, Moscow) "Self-focusing laser pulses: current state and future prospects".

The papers written on the basis of reports 3, 4, 6, and 7 are published below. A comprehensive version of report 5 prepared in the form of a review paper is published in this issue of *Physics–Uspekhi* on p. 9.

Uspekhi Fizicheskikh Nauk **181** (1) 93 – 112 (2011)
DOI: 10.3367/UFNr.0180.201101i.0093
Translated by E N Ragozin, M N Sapozhnikov; edited by A Radzig

PACS numbers: **01.65.+g**, **42.55.–f**, **42.60.–v**
DOI: 10.3367/UFNe.0180.201101j.0093

Optical Department of the Lebedev Physical Institute: early work on lasers

A V Masalov

1. Introduction

After the successful creation of masers in the mid-1950s, the idea of implementation of quantum oscillators radiating in the optical range, i.e., lasers, was in the air. The term 'laser' had not yet gained acceptance by that time. Many people aspired to accept the challenge of nature, to implement population inversion in a medium, and demonstrate the light amplification in the optical wavelength range. In this case, the desire to be the very first, which is natural for researchers, speeded up the execution of such endeavors. Nowadays, too, the 'virus of priority' is a powerful incentive for the cognition of nature. Discussed in this report is the pioneering work on the development of lasers performed by the staff members of the optics-related laboratories of the Lebedev Physics Institute (LPI). Although the term 'very first' is applicable to these investigations, they are valued primarily for their impact on the future development of laser physics and laser technology.[1]

[1] Many researchers are infected with the 'virus of priority'; everyone may give examples. However, among outstanding scientists there are those who have never carried the virus of priority. An instructive example is Grigorii Samuilovich Landsberg. In the year of the discovery of combination scattering of light, when G S Landsberg and his closest colleague Leonid Isaakovich Mandel'shtam analyzed experiments on light scattering in quartz, they were perfectly aware that they were dealing with a new phenomenon of a fundamental nature. And yet they were far from the idea of 'staking out' their finding, being instead concerned with the verification

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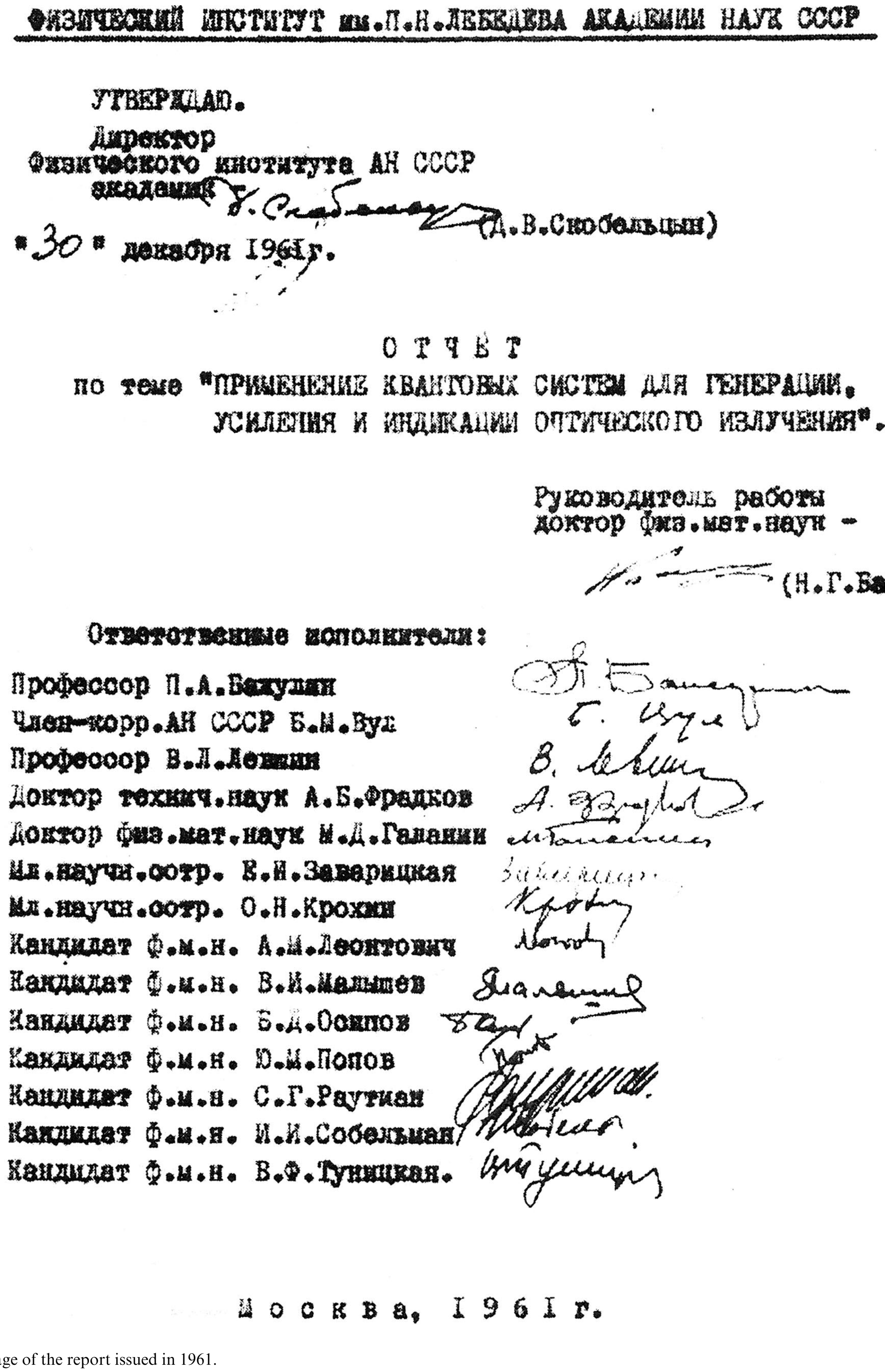
Uspekhi Fizicheskikh Nauk **181** (1) 93 – 97 (2011)
DOI: 10.3367/UFNr.0180.201101j.0093
Translated by E N Ragozin; edited by A Radzig



ФИЗИЧЕСКИЙ ИНСТИТУТ им. П.Н.ЛЕБЕДЕВА АКАДЕМИИ НАУК СССР

УТВЕРЖДАЮ.
Директор
Физического института АН СССР
академик (Д.В.Скобельцын)
"30" декабря 1961г.

О Т Ч Е Т

по теме "ПРИМЕНЕНИЕ КВАНТОВЫХ СИСТЕМ ДЛЯ ГЕНЕРАЦИИ, УСИЛЕНИЯ И ИНДИКАЦИИ ОПТИЧЕСКОГО ИЗЛУЧЕНИЯ".

Руководитель работы
доктор физ.мат.наук -
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Кандидат ф.м.н. И.И.Собельман
Кандидат ф.м.н. В.Ф.Туницкая.

Москва, 1961 г.

Title page of the report issued in 1961.

of the experiments and the consistency of the physical picture of the phenomenon. The same cannot be said about C V Raman, whose name was given to the combination light scattering. Another example of a person uninfected by the virus of priority — Mikhail Dmitrievich Galanin.

Early in 1959, Nikolai Gennadievich Basov set up a program labeled Photon at the P N Lebedev Physical Institute of the USSR Academy of Sciences, whose line of research was formulated in its title: "Application of quantum systems to the generation, amplification, and detection of optical radiation.'' N G Basov provided State support for this research, which was embodied in the relevant governmental Resolution of April 1960. By that time, N G Basov and his colleagues had already conceived the ideas of how to implement semiconductor lasers. The Photon project extended the scope of the quest for gain media suited for operating in optical quantum generators (OQGs) to include fluorescent crystals and gases. Involved in the work were highly experienced staff members — 'opticians' — now referred to as brilliant researchers and outstanding scientists, who made significant contributions to science. The photograph above shows the title page of the report written late in 1961, listing the scientists responsible for project execution. There we see the names of opticians as well: P A Bazhulin, V L Levshin, M D Galanin, A M Leontovich, V I Malyshev, S G Rautian, I I Sobel'man, V F Tunitskaya — more than half of the list.

The staff members of the optics-related laboratories at LPI performed several pioneering investigations in the development of lasers. Some of these priority achievements are listed in this paper, which may be termed either as 'the very first', or as 'the first in the USSR'.

It was in the framework of the Photon project that the first work on the list of pioneering achievements described below was carried out. The question is how the first ruby laser was developed in this country.

2. Ruby laser

The first Soviet publication about the implementation of a ruby laser and the properties of its radiation was prepared by M D Galanin and his colleagues A M Leontovich and Z A Chizhikova [1]. The paper was submitted to *JETP* on 18 May 1962. According to the authors, the ruby laser itself was brought into service in September 1961. By that time it had already been in operation in the USA. The first publication [2] about light amplification, by Theodore Maiman, was published in *Nature* in 1960. In the same year, Maiman implemented the oscillation regime [3]. Arthur Schawlow was hot on the trail and put into operation the ruby laser (also in the USA) [4]. Therefore, the paper by M D Galanin et al. may be referred to as the first one in the USSR. There is unconfirmed information about the making of a ruby laser by L D Khazov in the State Optical Institute (SOI) in mid-1961. Unfortunately, attempts to find documentary evidence of this have not met with success. [2]

The creation of the Soviet ruby laser required that crystal 'growers' synthesize ruby samples of unconventional quality. The watchmaking industry of that time made use of ruby crystals with a chromium concentration of 2.5%, and such crystals were available. However, to achieve lasing called for larger crystals with a lower chromium concentration. Such crystals were grown for the project by staff members of the Special Design Bureau (OKB-311) A S Bebchuk and Yu N Solov'eva. Ensuring optical crystal uniformity was a special concern. The circumstances were rather favorable as regards flash lamps employed for pumping ruby lasers. Such lamps were produced for airplane lights used on night flights. The mirrors of the first lasers were silver layers deposited directly on the polished ends of a ruby rod in a vacuum facility. In the LPI there were such homemade facilities, which demanded certain skills for their operation. Therefore, the first LPI ruby laser resulted from the achievements of Soviet industry and the experience of advanced science.

According to A M Leontovich and Z A Chizhikova, participants in the creation of the ruby laser who are still alive, shortly after the laser was put into operation on Soviet crystals, a specimen of American laser ruby rod fell into their hands. They obtained lasing on that rod as well.

The international scientific community was made directly aware of the Soviet ruby laser achievements at the Third International Congress on Quantum Electronics in Paris in 1963 [5]. The text of this report published in the congress proceedings is an example of an in-depth and comprehensive analysis of laser radiation (this text is reproduced in Appendix I to the paper by A M Leontovich and Z A Chizhikova published in this issue (p. 77).

Noteworthy in the history of the invention of the ruby laser is the fact that ruby — the crystal of chromium-doped corundum — had found itself in the view of American and Soviet researchers as the most attractive candidate for lasing even several years prior to their success. One may read about this both in the report on the Photon project and in N G Basov's memoirs, which were published in book [6]. The expertise and intuition of the pioneers did not let them down.

The significance of the implementation of the first laser at the LPI is hard to overestimate. A multitude of familiar and unfamiliar people came to the Laboratory of Luminescence to look at the 'ruby OQG'. Owing to the authors' openness, before long the laser was reproduced in many laboratories, and investigations of lasers and their improvement and application were placed on a broad footing shortly thereafter.

3. Photodissociation laser

Putting forward the idea of a photodissociation laser and the development of an optical quantum generator relying on the photodissociation mechanism of inversion production is the second example of pioneering laser research. The proposal to employ the photodissociation mechanism to achieve lasing was put forth by S G Rautian and I I Sobel'man [7]. They hypothesized that one of the products of molecular dissociation under short-wavelength irradiation would find itself primarily in an excited state. Broad molecular absorption lines and narrow atomic emission lines in dissociation products promised the high gain coefficients required for lasing. This idea was set forth at length in the foregoing 1961 LPI report. In the experimental quest that followed, the members of V I Malyshev's group directed their attention to the NaI and TlI molecules, which glowed rather brightly due to dissociation; these were the emission lines of sodium (yellow) and thallium (green). However, the first lasing based on the photodissociation mechanism was obtained in 1964 by J Kasper and G Pimentel with CF_3I and CH_3I molecules [8]. Kasper and Pimentel came across the high brightness of the radiation in experiments involving the analysis of infrared emission spectra of these media dissociated by ultraviolet radiation: this was the 1.315-μm emission line of atomic iodine. This 'prompt' from the Americans enabled V I Malyshev's group members to implement the photodissociation laser within a few months. That was the first work on lasers based on the photodissociation mechanism of pumping a laser medium in our country [9]. This mechanism opened up the line of research into different versions of iodine photodissociation lasers in our country,

[2] See the archival documents of the SOI first published in this issue of *Physics–Uspekhi*. (*Editor's note*.)

including those powered by explosive pumping (see the paper by V S Zuev [10]).

4. Ultrashort laser pulses

Among the important achievements in the area of laser development, mention should be made of the work of V I Malyshev and his colleagues, which lies at the origin of lasers generating ultrashort radiation pulses. The case in point is the implementation and investigation of the laser self-mode-locking regime.

It became obvious after the advent of the first ruby laser, as might be recalled, that pulsed solid-state lasers generate, as a rule, irregular sequences of laser spikes — free-running lasing spikes — for several hundred microseconds. The principle of *Q*-switching was formulated only a short time later, which made it possible upon implementation to concentrate the energy of numerous laser spikes in one high-power 'giant pulse' with a duration of several nanoseconds or tens of nanoseconds. *Q*-switched lasers promised a rise in radiation intensity by several orders of magnitude, and the development of *Q*-switching means started making rapid strides. The first *Q*-switches were electrooptical shutters, which necessitated a pulsed multikilovolt supply. To achieve *Q*-switching, advantage was also taken of a rotating reflection prism (rotation frequency amounted to several dozen kilohertz). N G Basov suggested to V I Malyshev that he should develop jointly with chemists a *Q*-switch in the form of a bleachable dye solution. On Malyshev's initiative, the staff members of the LPI Optical Laboratory A S Markin and V S Petrov also got involved in the work. By 1966, such *Q*-switches were developed in the Optical Laboratory of the LPI in collaboration with chemists of the Research Institute of the Chemicophotographic Industry (NIIKHIMFOTO), I I Levkoev and A F Vompe [11]. The *Q*-switch comprised a compact glass cell with a dye solution, which was placed into the laser cavity and did not necessitate control. Quite suitable here was the experience of chemists in developing media which darkened under high-power irradiation (primarily from the radiation of a nuclear bomb explosion). When studying lasers with a bleachable dye, they discovered the regime of self-mode-locking, i.e., the regime whereby the 'giant' pulse acquired additional structure in the form of a train of pulses of picosecond duration. The radiation intensity at the peak of a picosecond pulse was several orders of magnitude higher than the intensity of an ordinary 'giant' pulse. The implementation of self-mode-locking was first reported by American researchers in 1966 [12]. V I Malyshev and A S Markin were so close to the independent discovery of this regime that they promptly carried out research work on this subject [13] and submitted it for publication in September 1966. Among the authors of that paper was Tat'yana Ivanovna Kuznetsova, who provided the theoretical elaboration of the subject and subsequently performed numerous theoretical investigations into ultrashort light pulses. The indicated paper thereby turned out to be the first publication on the implementation of laser self-mode-locking in this country. Dye No. 3955 (a polymethine dye) developed for these purposes for neodymium lasers, which disseminated to many laboratories from Malyshev's hands, permitted executing a wealth of brilliant work with picosecond pulses. Today, after several improvements the laser self-mode-locking regime has reached the femtosecond duration range, and femtosecond lasers are employed in a diversity of domains of science and technology.

5. Copper vapor laser

After the first advances in the development of lasers, N G Basov initiated the quest for new laser media, in particular, in the gas phase. This research was taken up by G G Petrash and his collaborators in the Optical Laboratory of the LPI. They decided in favor of a copper vapor laser. The copper vapor laser with highly attractive output energy characteristics was made by W T Walter (USA) in 1967 [14]. A disadvantage of this laser was the necessity of external heating of the active medium to a temperature of 1500 °C. Petrash and his colleagues came up with the idea of a self-heating laser and implemented it. To do this they had to design a new discharge tube. Even in the first paper on the self-heating copper vapor laser they reported an average output power of 15 W [in two lines: green (510.5 nm), and yellow (578 nm)] for a pulse repetition rate of 20 kHz; the peak power ranged up to 200 kW and the practical efficiency up to $\approx 1\%$ [15]. As a result, the energy characteristics of the copper vapor laser placed it among the 'workhorses' of laser technology. In the course of subsequent development of the laser, the authors managed to attain an almost diffraction-limited radiation divergence by using an unstable cavity [16]. They also implemented a brightness amplifier based on a self-heating copper vapor tube [17], and made a laser projection microscope with a brightness amplifier as its key element [18]. The decisive contribution of G G Petrash's group to the development of the copper vapor laser has been recognized worldwide.

6. Intracavity laser spectroscopy

The idea of intracavity laser spectroscopy was conceived and realized at the LPI late in the 1960s. The idea of detecting weak spectral lines in absorption media placed into a laser cavity arose with Al'bert Fedorovich Suchkov [19], a staff member of the Laboratory of Quantum Radiophysics. A F Suchkov's proposal was underlain by the idea that laser radiation traverses a cavity several thousand (or more) times to accumulate the weak effect of absorption by the medium. Before long, the first experiment demonstrating the high sensitivity to spectral losses was carried out on A F Suchkov's initiative (and with his participation) in E A Sviridenkov's group at the LPI Laboratory of Luminescence [20]. Use was made of a neodymium laser and a V I Malyshev type diffraction spectrograph. The authors took advantage of their expertise to eliminate parasitic spectral-selective losses in the laser in order to record only the controllable losses. This result inspired the participants in the work, and they developed a high-sensitivity spectroscopic technique which has come to be known as intracavity laser spectroscopy (ILS). Numerous examples are known today of employing the ILS technique with other broadband lasers for the detection of lines in a diversity of substances. The priority of E A Sviridenkov's group in the development and dissemination of this technique has been recognized worldwide. In the 1980s, a series of studies on ILS was nominated for the USSR State Prize. However, this work was not awarded the prize owing to personal relations outside the team of authors.

7. Mechanism of CO_2 laser operation

Since its invention in 1966, the electric discharge CO_2 laser has attracted the attention of researchers due to the novelty of its spectral range (10.6 μm) and the uncommonness of the inversion production mechanism: this was a laser operating by transitions between *vibrational* levels of the molecule.

Optimization of the CO_2 laser ran into difficulties because of the lack of understanding of the mechanism responsible for the production of inversion between vibrational levels in a gas discharge. The situation became clear with the emergence of a paper by N N Sobolev and V V Sokovikov [21] and Ref. [22] that followed. The authors compared data on the average electron energy in the discharge with the energy dependence of the excitation cross section for the corresponding molecular vibrational levels and saw that the electron impact mechanism is highly efficient. In this case, the inversion between vibrational levels is produced due to collisions with atoms and molecules. When these papers appeared, a start was made on a targeted theoretical description of the CO_2 laser and a new impetus was given to experiments aimed at its improvement. Notably, the USSR's first CO_2 gas-dynamic laser was put into operation in the framework of this work [23].

8. Conclusions

Summarizing the foregoing material, one may draw a conclusion on what underlay the success of Soviet science in the development of lasers.

• In the USSR there existed a large community of highly qualified scientists, which was permanently fed by scientific personnel from institutes of higher education (the Moscow Institute of Physics and Technology (MIPT), M V Lomonosov Moscow State University, the Moscow Engineering Physics Institute, etc.). From MIPT alone (MIPT was founded for preparing researchers in physics) several hundred graduates came to the LPI during the post-war years. The leaders of the laser program, N G Basov and A M Prokhorov, could rely on the scientific schools nourished by S I Vavilov, G S Landsberg, and L I Mandel'shtam at LPI.

• A system of financing the research had functioned in the USSR. The government responded to the needs of science and stimulated scientific progress. New facilities were commissioned to promote laser research: buildings on the LPI territory, branches of the LPI in Troitsk with accommodation for scientists, the Institute of Spectroscopy, the Polyus Scientific Production Association, and other laser research institutes.

• USSR industries were capable of providing the requisite components and instruments for research; in the USSR there were works for creating big research facilities and technologies for producing unique materials.

Notwithstanding the known shortcomings of the governance of that time, a strategically weighed program of scientific and technological development existed in the country. Laser research was a part of this program.

References

1. Galanin M D, Leontovich A M, Chizhikova Z A *Zh. Eksp. Teor. Fiz.* **43** 347 (1962) [*Sov. Phys. JETP* **16** 249 (1963)]
2. Maiman T H *Nature* **187** 493 (1960)
3. Maiman T H et al. *Phys. Rev.* **123** 1151 (1961)
4. Collins R J et al. *Phys. Rev. Lett.* **5** 303 (1960)
5. Chizhikova Z A et al., in *Quantum Electronics: Proc. of the Third Intern. Congress, Paris, 1963* (Eds P Grivet, N Bloembergen) (New York: Columbia Univ. Press, 1964) p. 1483
6. Basov N G *O Kvantovoi Elektronike* (On Quantum Electronics) (Moscow: Nauka, 1987)
7. Rautian S G, Sobel'man I I *Zh. Eksp. Teor. Fiz.* **41** 2018 (1961) [*Sov. Phys. JETP* **14** 1433 (1962)]
8. Kasper J V V, Pimentel G C *Appl. Phys. Lett.* **5** 231 (1964)
9. Andreeva T L et al. *Zh. Eksp. Teor. Fiz.* **49** 1408 (1965) [*Sov. Phys. JETP* **22** 969 (1966)]
10. Zuev V S *Istoriya Nauki Tekhniki* (4) 69 (2009)
11. Malyshev V I et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **1** (6) 11 (1965) [*JETP Lett.* **1** 159 (1965)]
12. DeMaria A J, Stetser D A, Heynau H *Appl. Phys. Lett.* **8** 174 (1966)
13. Kuznetsova T I, Malyshev V I, Markin A S *Zh. Eksp. Teor. Fiz.* **52** 438 (1967) [*Sov. Phys. JETP* **25** 286 (1967)]
14. Walter W T *Bull. Am. Phys. Soc.* **12** 90 (1967)
15. Isaev A A, Kazaryan M A, Petrash G G *Pis'ma Zh. Eksp. Teor. Fiz.* **16** 40 (1972) [*JETP Lett.* **16** 27 (1972)]
16. Zemskov K I et al. *Kvantovaya Elektron.* **1** 863 (1974) [*Sov. J. Quantum Electron.* **4** 474 (1974)]
17. Zemskov K I, Kazaryan M A, Petrash G G, in *Opticheskie Sistemy s Usilitelyami Yarkosti* (Optical Systems with Brightness Amplifiers) (Trudy FIAN, Vol. 206, Ed. G G Petrash) (Moscow: Nauka, 1991)
18. Zemskov K I et al. *Kvantovaya Elektron.* **1** 14 (1974) [*Sov. J. Quantum Electron.* **4** 5 (1974)]
19. Suchkov A F, Preprint No. 126 (Moscow: Lebedev Physical Institute, 1970)
20. Pakhomycheva L A et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **12** 60 (1970) [*JETP Lett.* **12** 43 (1970)]
21. Sobolev N N, Sokovikov V V *Pis'ma Zh. Eksp. Teor. Fiz.* **4** 303 (1966) [*JETP Lett.* **4** 204 (1966)]
22. Sobolev N N, Sokovikov V V *Pis'ma Zh. Eksp. Teor. Fiz.* **5** 122 (1967) [*JETP Lett.* **5** 99 (1967)]
23. Dronov A P et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **11** 516 (1970) [*JETP Lett.* **11** 353 (1970)]

PACS numbers: **42.50.−p**, **42.65.−k**, 42.72.Ai
DOI: 10.3367/UFNe.0180.201101k.0097

Laser methods for generating megavolt terahertz pulses

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1. Introduction

The development of terahertz (THz) electromagnetic radiation sources is related to new methods and avenues of basic research in physics, chemistry, biology, and medicine, which have been making rapid strides during the last decade, as well as to new methods in different areas of applied research, including those related to new industrial technologies and security issues (see book Ref. [1] and references cited therein).

Terahertz radiation opens new paths and fresh unique possibilities for studying the properties and structure of substances and objects in the heretofore practically inaccessible spectral–temporal domain. Recording the probing terahertz pulses transmitted or reflected by an object and their subsequent amplitude–time and spectral analysis permits acquiring data about the object parameters and the substance properties in the terahertz range, as well as about the processes occurring therein, with a high (pico- and subpicosecond) temporal resolution. Along with use in basic research, terahertz pulses find practical applications in

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Uspekhi Fizicheskikh Nauk **181** (1) 97 – 102 (2011)
DOI: 10.3367/UFNr.0180.201101k.0097
Translated by E N Ragozin; edited by A Radzig

different applied areas. In recent years, in particular, several technical solutions have been proposed involving the use of terahertz radiation for microwave radar and the positioning of small-sized objects, recording microwave images of 'hidden' objects, analysis of pharmaceuticals, detection of explosives and drugs, and so forth [1].

According to the presently accepted classification, terahertz radiation (1 THz $= 10^{12}$ Hz) lies in the wavelength range from several millimeters to several dozen micrometers (from several hundred gigahertz to several dozen terahertz). Basic and applied research aimed at studying the properties of diverse objects and materials (including solids, liquids, gases, biological objects, etc.), investigating the methods of generation, propagation, and recording of terahertz radiation, and developing novel terahertz sources, terahertz vision, and radar systems is being successfully carried out in this rather broad and informative spectral range. These investigations are being pursued at leading universities and research centers in the USA, European Union countries, China, and Japan. In Russia, this work is being carried out, in particular, at M V Lomonosov Moscow State University, the Institute of Applied Physics of the RAS, the A M Prokhorov General Physics Institute of the RAS, the V A Kotel'nikov Institute of Radio Engineering and Electronics of the RAS, the Institute for the Physics of Microstructures of the RAS, the Institute of Spectroscopy of the RAS, several institutes of the Siberian Branch of the RAS, and St. Petersburg State University of Information Technologies, Mechanics, and Optics.

Terahertz research has been actively pursued since the late 1990s — early 2000s. This is due to the development of new, primarily laser-related, methods of generating pulsed and cw terahertz radiation, which enabled implementing efficient compact instruments and devices in practice.

The past years have seen the development and proposals of several methods of laser-driven generation of terahertz electromagnetic pulses (of the micro- and millimeter wavelength ranges). Among these methods are:

— the employment of ultrafast optoelectronic semiconductor switches of current and voltage (terahertz antennas, or the so-called Auston switches which were first proposed by D H Auston back in the 1970s [2]);

— the exploitation of the optical rectification effect (discovered by M Bass and P Franken [3] in 1962) and the generation of the difference frequency of ultrashort (pico- and femtosecond) laser pulses in nonlinear optical media;

— the harnessing of the spatial separation effect of charges of opposite signs (electrons and holes) occurring under optical excitation of semiconductors by pico- and femtosecond laser pulses, which is attended by the fast diffusive drift of current carriers in a thin surface layer of the material;

— the employment of quantum-cascade lasers and lasers that simultaneously generate two-wavelength radiation (carbon oxide lasers, and solid-state lasers with a broad amplification band).

Widely discussed in recent literature is the feasibility of obtaining high-intensity (with electric field amplitudes above 10^6 V cm^{-1}) ultrashort (pico- and subpicosecond) terahertz pulses and their application to the study of different nonlinear processes and phenomena in physics, chemistry, and biology, as well as in applied areas [1]. Among the rapidly advancing techniques of terahertz radiation generation in a broad frequency range (from several hundred gigahertz to several dozen terahertz) is the utilization of nonlinear interaction of femtosecond laser pulses with gaseous media (production of various laser-plasma objects, for instance, extended plasma channels — so-called filaments [1]), as well as of their interaction with nonlinear-optical crystals: the generation of terahertz laser pulses in $LiNbO_3$, ZnTe, GaAs, GaP, and GaSe crystals [1]. Another promising method of THz wave generation involves the development of new solid-state two-frequency lasers with the subsequent conversion of their difference frequency to terahertz radiation in nonlinear crystals or optoelectronic emitters.

Both of these techniques for generating pulsed electromagnetic radiation of ultrashort (picosecond) duration are being actively developed at the A M Prokhorov General Physics Institute of the RAS (RAS GPI).

2. Terahertz sources based on two-frequency lasers

Research aimed at developing new terahertz radiation sources, which is pursued at the RAS GPI, involves the production of two-frequency lasing in a diode-pumped solid-state laser with new high-efficiency active crystal media having broad overall amplification lines (gadolinium, yttrium, and mixed vanadates — Nd:$GdVO_4$, Nd:YVO_4, and Nd:$Gd_{0.7}Y_{0.3}VO_4$) and the subsequent conversion of the laser radiation to the terahertz spectral range by generating the difference frequency in the nonlinear GaP and GaSe crystals [4, 5].

Simultaneous two-frequency lasing is realized in the same active medium possessing a broad overall amplification contour (up to 5 nm in the 1-μm region), which is placed in a selective cavity of a diode-pumped solid-state laser. This approach does not necessitate additionally bringing two laser beams into coincidence and timing the operation of two independent lasers. We obtained two-frequency lasing in cw, *Q*-switching (nanosecond range), and mode-locking (picosecond range) regimes.

To maximize the peak output power of the two-frequency solid-state laser and, therefore, the peak power of the generated terahertz radiation, a picosecond Nd^{3+}:$GdVO_4$ laser with longitudinal diode pumping of the active medium was developed at the RAS GPI, which operated in a combined regime: with simultaneous *Q*-switching and active mode locking. This laser operating regime permits raising the peak output power by nearly two orders of magnitude in comparison with that for a picosecond laser operated only with active acoustooptical mode locking. The optical schematic of the laser is depicted in Fig. 1.

An Nd:$GdVO_4$ (0.5 at.%) laser crystal measuring $4 \times 4 \times 6$ mm was cut along the *c*-axis. The active element

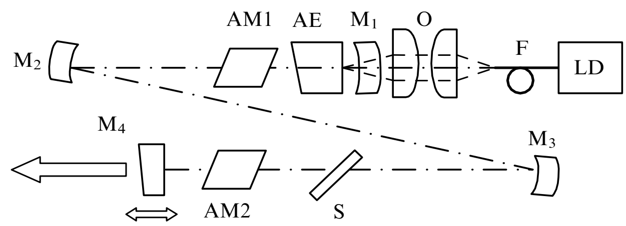

Figure 1. Schematic layout of a picosecond Nd^{3+}:$GdVO_4$ laser with simultaneous *Q*-switching and active mode locking: LD — laser diode pump; F — optical fiber (200 μm); O — objective; M_1 – M_4 — cavity mirrors; AE — active element; S — spectral selector (Fabry–Perot interferometer or Lyot filter); AM1 — acoustooptical *Q*-factor modulator, and AM2 — acoustooptical modulator intended for mode locking.

was pumped by an LIMO30-F200-DL808 linear laser diode array with a fiber radiation output ranging up to 25 W in power at a wavelength of 808 nm. The pump radiation was focused by an objective system which enabled obtaining a beam waist in the crystal from 150 to 400 μm in diameter. In experiments use was made of a Z-shaped cavity formed by four mirrors M_1-M_4. The laser generated the principal TEM_{00} mode due to an iris placed into the cavity.

To actively Q-switch the laser, advantage was taken of an acoustooptical modulator (ML-321) controlled by a high-frequency sine-wave oscillator with a peak power of 30 W.

To achieve mode locking, use was made of an acoustooptical modulator (ML-202) with an output power of 8 W and a modulation frequency of 70 MHz, which corresponded to a laser pulse repetition rate of 140 MHz.

The duration of laser pulses was measured with the help of a streak camera with a resolution of 0.7 ps.

To obtain two-frequency output, spectral-selective elements (Fabry–Perot etalons) in the form of 120- and 83-μm thick plane-parallel YAG crystal plates were placed into the cavity. These selectors enabled obtaining the two-frequency radiation spaced respectively at 2.3 and 3.8 nm in wavelength, which in turn corresponded to the generated terahertz radiation with frequencies of 0.56 and 0.92 THz.

This laser system provided stable two-frequency generation of 80–120-ns long trains of picosecond pulses containing 15–20 separate 30–40-ps long pulses following one after another at a repetition rate of 140 MHz. The average output power for a train repetition rate of 10 kHz amounted to 350 mW. The laser system developed had stable radiation parameters which did not vary for several hours of continuous running, and was employed for high-efficiency nonlinear conversion of the laser radiation to the terahertz wavelength range in GaSe crystals. In this case, the output power of the terahertz radiation amounted to several microwatts, and the energy of the terahertz comb was as high as several tenths of a nanojoule. Of course, so low an energy level of the terahertz pulses does not by itself ensure attainment of the megavolt electric fields declared. That is why, the created two-frequency laser should be regarded as the master oscillator for a high-power laser system with an energy of more than several hundred millijoules, which is intended for the subsequent conversion of its output radiation to the terahertz range employing wide-aperture nonlinear GaSe crystals. Figure 2 displays a photograph of such a crystal 50 mm in diameter intended for operation together with the high-power two-frequency laser, which presently is under development at the RAS GPI.

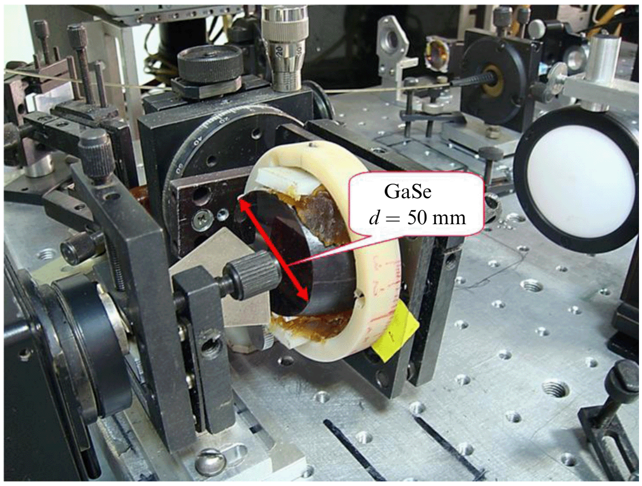

Figure 2. Terahertz converter module based on a GaAs crystal 50 mm in diameter, which is intended for operation together with the high-power two-frequency laser being developed at the RAS GPI.

3. Terahertz sources based on femtosecond lasers

Despite the long-standing successful employment of femtosecond lasers for the generation of terahertz radiation, the sources of terahertz pulses made on their bases (including commercially available ones) possess, as a rule, a low output power and a low peak intensity of the generated radiation. Typically, the generated terahertz pulses range from pico- to nanojoules in energy, their average power ranges between nano- and microwatts, and the intensities of the electromagnetic field lie in the range between several and several dozen kV cm^{-1}. Only with unique terahertz radiation sources relying on radically different generation techniques [free-electron lasers at the Budker Institute of Nuclear Physics, Siberian Branch of the RAS (Novosibirsk), the Stanford Picosecond Free Electron Laser Center (USA), the FOM-Institute for Plasma Physics (the Netherlands), etc.] has it been possible to obtain average power levels of up to several dozen watts and electromagnetic field strengths of several hundred kV cm^{-1}. Notably, the highest-energy (several dozen microjoules) and peak power (up to 100 MW) terahertz pulses were obtained in the generation of the transition radiation of relativistic electron beams of picosecond duration at the Brookhaven National Laboratory (USA). It is noteworthy that the uniqueness of such facilities (gigantic sizes and high operating costs) is a significant limitation for their wide application. As for the laser femtosecond sources under consideration, terahertz pulse energies of several dozen nanojoules and generated field intensities of several dozen kV cm^{-1} were until recently regarded as record high.

The low energy and peak power of femtosecond terahertz sources significantly limit their practical implementation. More specifically, terahertz radiation is largely attenuated in the propagation through the atmosphere due to the absorption by water vapor, which limits its practical use in radar systems for objects located at distances exceeding several dozen meters. Even in transparency windows (200–300 GHz), the attenuation is as strong as several dozen dB km^{-1}, with the consequence that the existing terahertz radiation detectors cannot ensure reliable signal detection, even at so short a distance.

However, the situation has changed radically in recent years due to the successful development and implementation of a new method of terahertz radiation generation, which is based on the optical rectification of femtosecond laser pulses with a pre-tilted wave front in stoichiometric $MgO:LiNbO_3$ crystals. This method was first proposed in 2002 by the Hungarian physicist J Hebling jointly with his colleagues from the Max-Planck-Institute for Solid State Researches in Stuttgart [6]. In 2007, in particular, scientists at the Massachusetts Institute of Technology (MIT) succeeded in reaching record high values of the energy parameters of terahertz pulses. Utilizing femtosecond laser pulses with an energy of 20 mJ, the MIT researchers obtained ultrashort terahertz pulses with an energy of up to 10 μJ and a peak power of 5 MW [7]. It was therefore demonstrated that the employment of femtosecond lasers makes it possible to generate pulsed

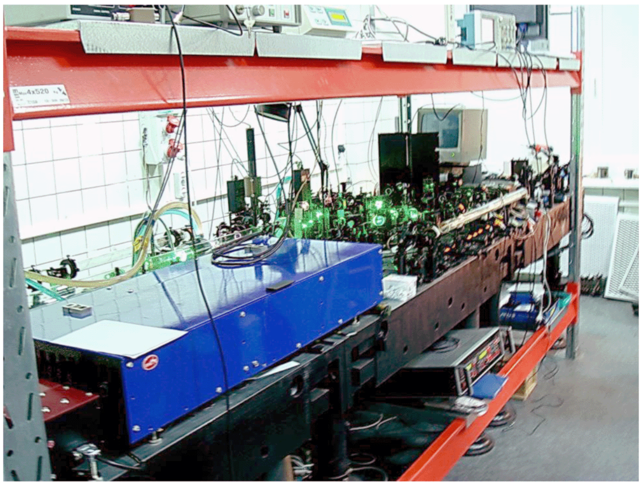

Figure 3. TERAFEM terawatt parametric laser complex.

terahertz radiation with a peak power which exceeds the peak power of the terahertz radiation generated by synchrotron sources and free-electron lasers. To state it in different terms, the technique of the optical rectification of femtosecond laser pulses with a transverse group delay in MgO:$LiNbO_3$ crystals enables obtaining the now record high energy efficiency of conversion of femtosecond laser pulses to terahertz radiation. (Specifically, the conversion efficiency of this technique is several orders of magnitude higher than the efficiency of conversion in ZnTe crystals, which are presently employed in the majority of terahertz radiation sources reliant on the optical rectification of femtosecond laser pulses.)

Femtosecond laser pulses with a tilted intensity front are required to meet the condition of their phase matching with the generated terahertz radiation. In lithium niobate crystals, the collinear matching of a wave interaction is not realized for the femtosecond laser radiation (e.g., of a titanium–sapphire laser) in use, and so Hebling et al. [6] proposed the application of noncollinear matching — the condition that the phase velocity V_{THz} of the generated terahertz wave is equal to the projection $V_{\mathrm{las}} \cos\alpha$ of the group velocity vector of the laser pulse onto the former velocity direction, where α is the in-crystal angle between the propagation directions of the laser and the terahertz radiations. This condition may be fulfilled, in particular, for laser pulses with a tilted intensity front which is easily formed, for instance, when the laser radiation is obliquely incident on a diffraction grating [6]. Interestingly, this relation for noncollinear matching is similar to the relation for the propagation direction of the Cherenkov radiation generated by a dipole traveling at a supraluminal speed through a medium — the process which was first considered theoretically by V L Ginzburg [8] in 1959, and which was not realized experimentally until 45 years after the dawn of the laser era [9].

In 2009, a laser source of high-intensity terahertz pulses, which relies on the principle proposed in Ref. [6], was devised at the RAS GPI. The source possesses the highest energy parameters in Russia: a pulse power of over 1 MW, and a field intensity above 1 MV cm^{-1}. The terahertz source comprises a terawatt laser complex (TERAFEM), whose overall view is shown in Fig. 3, and a module for generating megavolt terahertz electromagnetic pulses, whose optical scheme is depicted in Fig. 4. The peak power of the laser complex based on parametric radiation amplification [10] amounts to 1 TW at the central wavelength (910 nm) for a pulse duration of 45 fs. The module intended for the generation of megavolt terahertz pulses relies on the optical rectification of femtosecond laser pulses with a tilted intensity front in wide-aperture (measuring $30 \times 10 \times 10$ mm) magnesium-doped stoichiometric lithium niobate (MgO:$LiNbO_3$) crystals. For a laser pulse energy of 30–40 mJ, the energy of the terahertz pulses produced by the module amounts to 2–3 μJ; after focusing them on a spot 500 μm in diameter, the resultant electric field amplitude of the terahertz wave field exceeds 10^6 V cm^{-1}.

The high-intensity terahertz radiation system under consideration is intended for studying extreme states of matter in the terahertz spectral domain and for solving a number of applied problems. In this case, the laser part of the complex is independently employed for executing experiments in the production of charged particles and the generation of X-rays, and in studies of the mechanisms of plasma formation and the filamentation of laser radiation.

4. Techniques for characterizing high-intensity terahertz pulses

In the work carried out to develop pulsed terahertz sources, special emphasis was placed on the techniques and means for measuring their energy and time parameters.

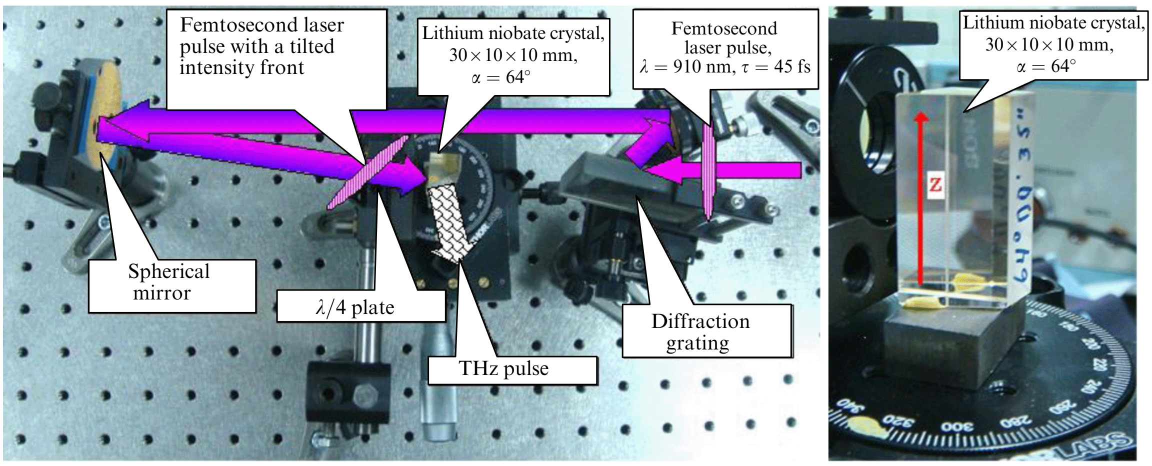

Figure 4. Optical scheme of the module for generating megavolt terahertz electromagnetic pulses. External appearance of a stoichiometric lithium niobate crystal (Z is the direction of the crystal axis).

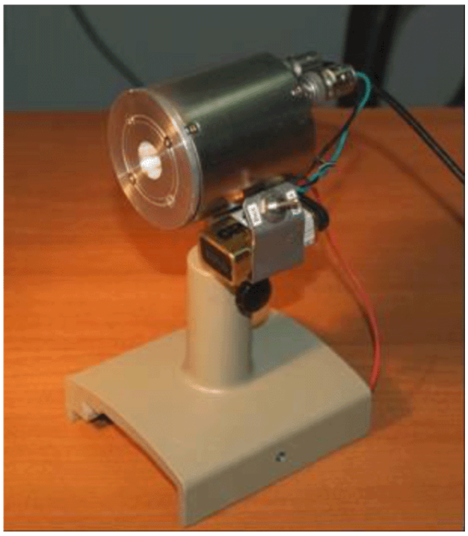

Figure 5. Pyroelectric terahertz pulse energy meter.

Table 1. Parameters of pyroelectric terahertz pulse energy meters.

Parameter	Value
Spectral range	0.1 – 3 THz
Responsivity to single THz pulses	$S_{pulse} = 1.9 \times 10^6$ V J^{-1} (±15%)
Responsivity for 22-Hz modulation frequency and 1-MΩ load	20,000 (±15%) V W^{-1} at 0.14-THz frequency 16,000 (±15%) V W^{-1} for broadband radiation in 0.2–2 THz frequency range
Dynamic range	0.1 μW – 0.35 mW
Noise level	1.0 mV

To record the energy parameters of terahertz pulses, high-responsivity (1.9×10^6 V J^{-1}) broadband (spectral range: 0.1–3 THz) pyroelectric sensors with a linear dynamic range of more than 10^3 and a detection threshold of 1 nJ were developed, fabricated, and calibrated. An external appearance of the pyroelectric terahertz pulse energy meter is given in Fig. 5, and its parameters are collected in Table 1.

To measure the amplitude–time profile of ultrashort (~ 1 ps) single (repetition rate close to 1 Hz) terahertz pulses, the method of spatial visualization of the terahertz field was selected and implemented, which is based on the electrooptical recording of the 'image' of a *single* terahertz pulse with a gating *single* femtosecond laser pulse due to the optical anisotropy in an electrooptical ZnTe crystal, induced by a terahertz field.

Figure 6 shows the schematic diagram of the method and the results of measurement of the temporal profile of a picosecond terahertz pulse.

5. Conclusions

Laser sources of pulsed terahertz radiation of ultrashort duration were devised in the laboratories of the A M Prokhorov GPI of the RAS, which make it possible to obtain record high electric field intensity — over 10^6 V cm^{-1}. The achieved megavolt intensity level of the terahertz field opens up exciting possibilities for a new line of investigation in physics — the nonlinear optics of terahertz waves, which has recently begun to progress rapidly due to the advent of new

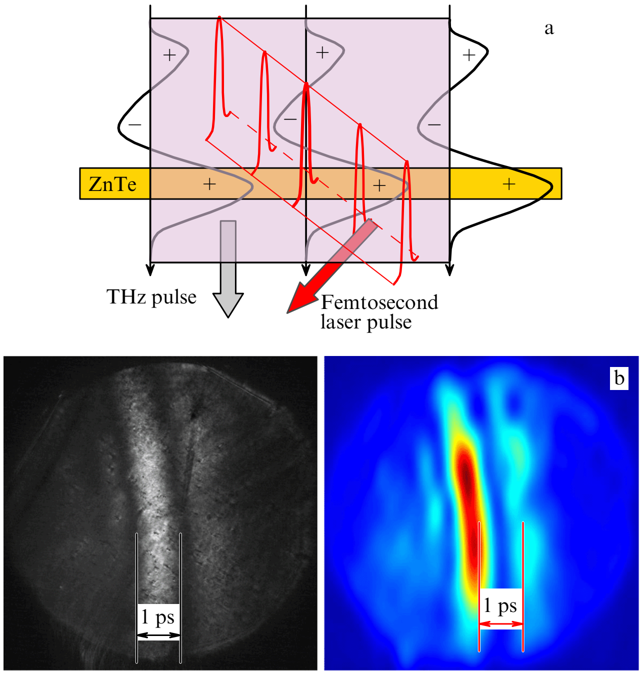

Figure 6. (a) A schematic of the technique of spatial visualization of a terahertz field. (b) Recorded temporal profiles of single terahertz pulses.

compact laser sources of high-intensity terahertz pulses. Among the problems solvable by the methods of nonlinear terahertz optics, mention should be made, in particular, of nonlinear plasma production mechanisms — ionization of substances and the 'optical' breakdown of material media; the generation mechanisms of higher-order harmonics of currents and radiation; charged particle acceleration by high-intensity terahertz fields; modulation and parametric plasma instabilities in the field of terahertz radiation, and self-focusing of terahertz pulses.

Fundamentally, the technique of the optical rectification of femtosecond laser pulses with a tilted intensity front in nonlinear crystals permits generating single-cycle picosecond terahertz pulses with an even higher energy (over 100 μJ) and higher field intensity amplitude (up to 10^9 V cm^{-1}). Such pulses may be obtained in the presently existing multiterawatt laser facilities, in particular, in the Luch facility at the Institute of Laser Physics Research of the Russian Federation Nuclear Center 'All-Russian Research Institute of Experimental Physics' (Sarov).

Acknowledgments. In summary, the authors express their deep appreciation to their colleagues who actively participated in the research conducted: to A G Stepanov (Institute of Spectroscopy, RAS), who made a significant contribution at the initial stage of the work, to RAS GPI staff members V V Bukin, A A Sirotkin, A I Ritus, and A I Zagumennyi, as well as to the Russian Foundation for Basic Research, the Presidium of the RAS, and the Physical Sciences Division of the RAS for the support of this work.

References

1. Zhang X-C, Xu J *Introduction to THz Wave Photonics* (New York: Springer, 2009)
2. Auston D H, Cheung K P, Smith P R *Appl. Phys. Lett.* **45** 284 (1984)

3. Bass M et al. *Phys. Rev. Lett.* **9** 446 (1962)
4. Vlasov V I et al. *Kvantovaya Elektron.* **37** 938 (2007) [*Quantum Electron.* **37** 938 (2007)]
5. Sirotkin A A et al. *Laser Phys.* **19** 1083 (2009)
6. Hebling J et al. *Opt. Express* **10** 1161 (2002)
7. Yeh K-L et al. *Appl. Phys. Lett.* **90** 171121 (2007)
8. Ginzburg V L *Usp. Fiz. Nauk* **69** 537 (1959) [*Sov. Phys. Usp.* **2** 874 (1960)]
9. Stepanov A G, Hebling J, Kuhl J *Appl. Phys. B* **81** 23 (2005)
10. Khazanov E A, Sergeev A M *Usp. Fiz. Nauk* **178** 1006 (2008) [*Phys. Usp.* **51** 969 (2008)]
11. Shan J et al. *Opt. Lett.* **25** 426 (2000)

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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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

$$U_{\min} = \frac{\Delta}{e}\,, \qquad (2)$$

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

$$I = \frac{enL}{t}\,, \qquad (3)$$

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 Δ by $h\nu$ in paper [4] published at the end of 1961;

• we made a remark on condition $U_{\min} = \Delta/e$ (2) that, in the case of indirect transitions at low temperatures of a sample, Δ in formula (2) should be replaced by $\Delta - E_{\text{ph}}$, where E_{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.

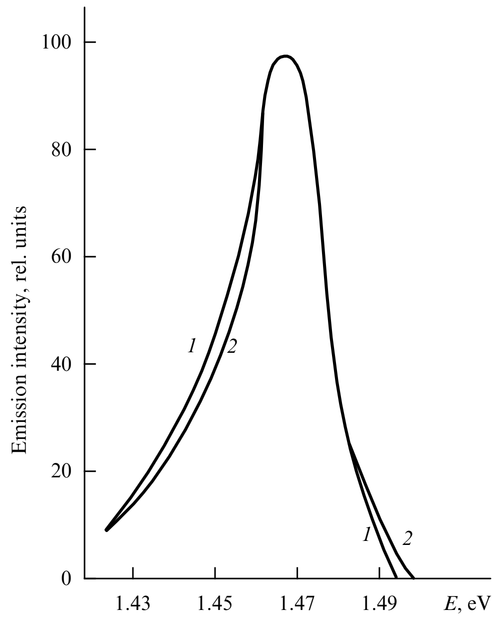


Figure 1. Spectral distribution of recombination intrinsic emission of gallium arsenide at 77 K: (1) low current density (10 A cm^{-2}), and (2) high current density (1.5×10^3 A cm^{-2}).

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

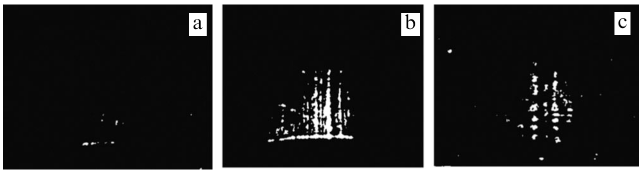


Figure 2. Far-field laser radiation patterns at different distances D from the p–n junction (L-69 diode): below the threshold (a), above the threshold for $D = 6$ cm (b), and $D = 15$ cm (c).

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

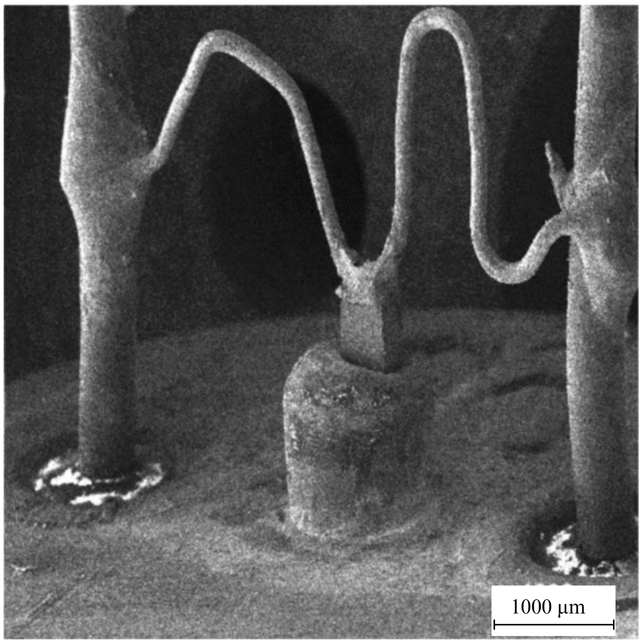
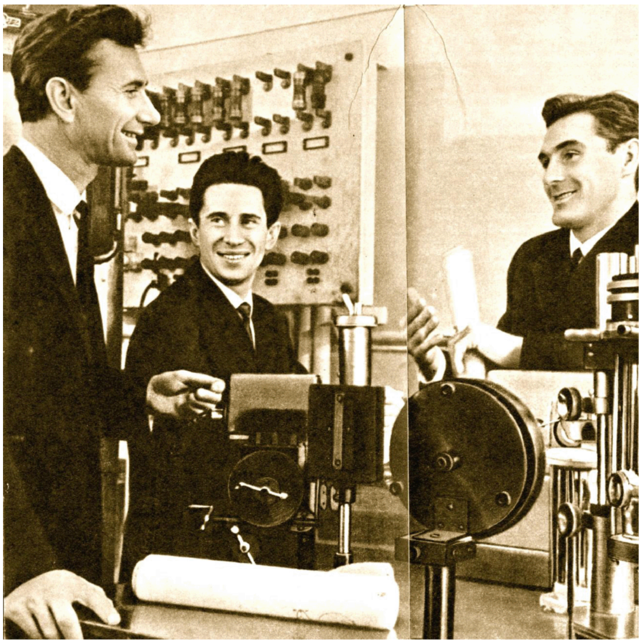


Figure 3. Photograph of the first injection laser made in the USSR (FIAN, December 1962).

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.

References

1. Basov N G, Vul B M, Popov Yu M *Zh. Eksp. Teor. Fiz.* **37** 587 (1959) [*Sov. Phys. JETP* **10** 416 (1960)]
2. Basov N G, Krokhin O N, Popov Yu M *Usp. Fiz. Nauk* **72** 161 (1960) [*Sov. Phys. Usp.* **3** 702 (1961)]
3. Basov N G, Krokhin O N, Popov Yu M *Zh. Eksp. Teor. Fiz.* **40** 1879 (1961) [*Sov. Phys. JETP* **13** 1320 (1961)]
4. Bernard M G A, Duraffourg G *Phys. Status Solidi B* **1** 699 (1961)
5. Alferov Zh I et al. *Fiz. Tekh. Poluprovodn.* **4** 1826 (1970) [*Sov. Phys. Semicond.* **4** 1573 (1971)]
6. Burns G, Nathan M I *Proc. IEEE* **52** 770 (1964)
7. Nasledov D N et al. *Fiz. Tverd. Tela* **4** 1062 (1962) [*Sov. Phys. Solid State* **4** 2449 (1963)]
8. Hall R N et al. *Phys. Rev. Lett.* **9** 366 (1962)
9. Hall R N *IEEE J. Quantum Electron.* **23** 674 (1987)
10. Keyes R J, Quist T M *Proc. IRE* **50** 1822 (1962)
11. Pankove J I, Berkeyheiser J E *Proc. IRE* **50** 1976 (1962)
12. Nathan M I et al. *Appl. Phys. Lett.* **1** 62 (1962)
13. Holonyak N, Bevacqua S F *Appl. Phys. Lett.* **1** 82 (1962)
14. Quist T M et al. *Appl. Phys. Lett.* **1** 91 (1962)
15. Bagaev V S et al. *Dokl. Akad. Nauk SSSR* **150** 275 (1963) [*Sov. Phys. Dokl.* **8** 453 (1963)]
16. Grivet P, Bloembergen N (Eds) *Quantum Electronics: Proc. of the Third Intern. Congress, Paris, 1963* (New York: Columbia Univ. Press, 1964)

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).

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

• First detailed investigation, introduction of the notion of critical power, formulation of the theoretical model of self-channeling (Chiao, Garmire, Townes [5], and Talanov [6, 7], 1964).

• Further theoretical investigations:

— establishment of the main features of the phenomenon: beam collapse, determination of the base characteristics: critical power, the self-focusing length, phase self-modulation, and spatial instability (Kelley [8], Bespalov, Talanov [9], Akhmanov, Sukhorukov, Khokhlov [10, 11], Marburger et al. [12, 13]);

— formulation of multifocus structure models (Dyshko, Lugovoi, Prokhorov [14]) and moving nonlinear foci models (Lugovoi, Prokhorov [15]). Since these two models turned out to be the most adequate and theoretically substantiated, reliably confirmed by experiments (especially in the nanosecond range of pulse durations), and provide the basis for further self-focusing research in the range of ultrashort pulses, we shall enlarge on their analysis in Section 3.

• New stage: investigations into the self-focusing of ultrashort (femtosecond) pulses:

— the first observation of the self-focusing of femtosecond pulses in the air, discovery of the 'superlong' filaments of laser radiation and plasma formations (Braun et al. [16], 1995);

— further experimental investigations of the self-focusing of femtosecond pulses in the air: elucidation of the main characteristics of the filamentation phenomenon (length and diameter, energy, spectrum of the filaments, conical emission, supercontinuum) (Nibbering et al. [17], 1996; Brodeur et al. [18], 1997);

— theoretical investigations, analysis of different models of femtosecond pulse filamentation in the air (Chien et al. [19], 1968; Mlejnek et al. [20], 1998).

In recent years, investigations into the filamentation of femtosecond pulses in the air, other gases, and condensed media are the main avenue of inquiry into the self-focusing effect. Some of the findings of these investigations are discussed below.

3. Lugovoi–Prokhorov theory: multifocus structure model and moving nonlinear foci model

In this section we briefly set out the main findings of the theoretical research through which the models of multifocus structure (MFS) [14] and moving nonlinear foci (MNF) were developed [15].

Dyshko et al. [14] considered the propagation of a light beam with a Gaussian initial intensity profile through a medium with an inertialess Kerr nonlinearity of the refractive index. Proceeding from the numerical solution of the wave equation

$$\frac{\partial^2 E}{\partial r^2} + \frac{1}{r}\frac{\partial E}{\partial r} + 2ik\frac{\partial E}{\partial z} + n_2 k^2 |E|^2 E = 0\,, \tag{1}$$

where E is the electric field strength of the light beam, r and z are the radial and longitudinal coordinates (z coincides with the direction of beam propagation in the medium), k is the wave number, n_0 is the initial refractive index of the medium, and n_2 is the nonlinearity coefficient of the refractive index, namely

$$n = n_0 + n_2 |E|^2\,, \tag{2}$$

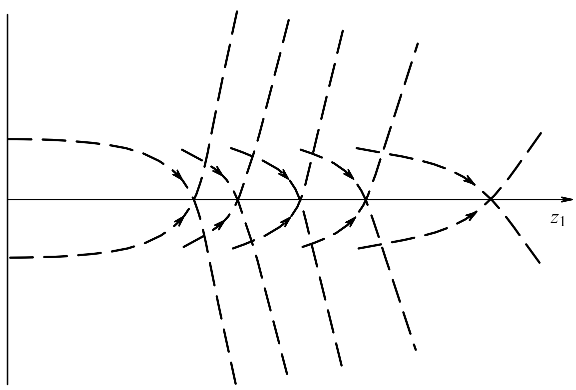

Figure 1. Schematic representation of a longitudinal section of a light beam propagating through a Kerr nonlinear medium for $P > P_{\text{cr}}$. Here, $z_1 = z/l_{\text{sf}}$, where l_{sf} is the self-focusing length.

they found that the *waveguide propagation* hypothesized in several earlier studies (see review Ref. [21] and references cited therein) did not take place when the incident beam power P exceeded some critical power $P_{\text{cr}}^{(1)} = cn_0 N_1^2/8n_2 k^2$, where c is the speed of light in a vacuum, and N_1 is the numerical coefficient equal to about 2. Instead, a *multifocus structure* formed. Figure 1 is a schematic representation of such a structure for a stationary light beam (P is time-independent). The mechanism of multifocus structure formation consists in the fact that the first focus in the paraxial beam region accumulates only a fraction of the initial beam power (this fraction is close to the critical power $P_{\text{cr}}^{(1)}$). This fraction is partly absorbed in the nonlinear focus and partly diffracts (upon transit through the focus) at relatively large angles to the beam axis. In a similar way, a fraction of the remaining part of the light beam, which passed by the first focus, detaches to produce the second nonlinear focus, etc. Therefore, the sequential formation of nonlinear foci is seemingly recurring.

The main characteristics of the MFS model are the positions of nonlinear foci and the critical powers at which they are produced [21]:

$$\xi_{\text{f}m} = \frac{\chi_m}{N_m}\frac{k\bar{a}_0^2}{\sqrt{P_0/P_{\text{cr}}^{(m)}} - 1}\,, \tag{3}$$

$$P_{\text{cr}}^{(m)} \approx mP_{\text{cr}}^{(1)}\,, \tag{4}$$

where m is the number of a nonlinear focus, $P_{\text{cr}}^{(m)}$ is the critical power of the mth focus, χ_m and N_m are numerical parameters, and $\bar{a}_0$ is the radius of the incident beam. The dimensions of the foci and their relative arrangement on the longitudinal coordinate may depend on additional physical effects (nonlinear absorption, ionization, etc.) which limit the light energy density in the nonlinear focal regions. Theoretical investigations of many of these effects have revealed, however, that the multifocus structure persists, i.e., that the MFS model is universal and may be observed under different physical conditions [21].

It is evident that nonlinear foci positions for pulsed beams with a smooth power variation in time will vary in accordance with relation (3), in which $\xi_{\text{f}m}$ and P_0 are now functions of time: $\xi_{\text{f}m} = \xi_{\text{f}m}(t)$, $P_0 = P_0(t)$. Hence, it follows that the case of nonstationary light beams will see the realization of the moving nonlinear foci model. The total number of foci in this structure at the point in time t is defined by the condition

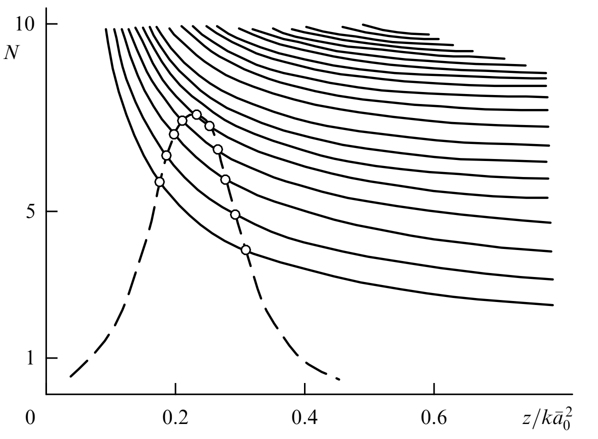

Figure 2. Positions of nonlinear foci on the $z/k\bar{a}_0$-axis (solid curves) and the shape of incident radiation pulse (dashed curve), which illustrate the formation of the structure of moving nonlinear foci in a Kerr nonlinear medium.

$P_0(t) > P_{\rm cr}^{(m)}$. Figure 2 illustrates the production of the multifocus structure of moving nonlinear foci in a Kerr medium. The positions of nonlinear foci on the beam axis (solid curves) and the shape $N(t, z)$ of the incident light pulse (dashed curve) are depicted on the $(z/k\bar{a}_0^2, N)$ coordinates. The pulse shape $N(t)$ is given by the expression [21]

$$N(t, z) = \frac{1}{E_{\rm cr}} \left| E_0 \left(t - \frac{k\bar{a}_0^2}{v} \frac{z}{k\bar{a}_0^2} \right) \right| , \tag{5}$$

where $E_{\rm cr}$ is the critical field strength corresponding to the critical self-focusing power $P_{\rm cr}$, and v is the speed of light in the medium. The quantities $z/k\bar{a}_0^2$ corresponding to the intersection of solid and dashed curves define the position of nonlinear foci on the beam axis at the time t. The model of moving nonlinear foci was first proposed by Lugovoi and Prokhorov in 1968 [15]. Subsequently, a comprehensive investigation was made of its characteristics (including the structure and velocity of movement of nonlinear foci in the case of ultrashort laser pulses) (see review [21]).

The multifocus structure model and moving nonlinear foci model were reliably borne out in purposeful experimental investigations of self-focusing in different media employing different approaches and recording techniques [22–24].

Loy and Shen [22] investigated the self-focusing of a ruby laser beam with a pulse length of 8 ns in toluene and CS_2. As they changed the power of incident radiation, which exceeded the critical power $P_{\rm cr}$, they observed a beam evolution inside and at the output end of the cell with the liquid being studied. An analysis of observed data was clearly indicative of the motion of nonlinear foci (a detailed investigation was made of the behavior of the first nonlinear focus).

Korobkin et al. [23] studied the self-focusing of the beam of a ruby laser with a 15-ns-long pulse in nitrobenzene and CS_2 to observe temporal beam evolution in the medium. In this case, they employed the techniques of recording light intensity with a high temporal resolution. For high values of incident radiation power exceeding the critical one, the authors observed the moving structure of nonlinear foci in the liquids under investigation.

The investigations reported in Refs [22, 23] were conducted using Q-switched lasers which generated conventional bell-shaped temporal pulses. This corresponded to the case of *nonstationary* self-focusing.

Lipatov et al. [24] investigated the self-focusing of a ruby laser beam with a variable temporal pulse shape (bell-shaped, saw-tooth, and rectangular) in TF-105 glass. This approach made it possible to investigate the character of self-focusing both in the *nonstationary* (the first two pulse shapes) and in the *stationary* (rectangular pulses) modes. Laser-induced damage was observed in the samples, and a study was conducted of its morphology in relation to the pulse shapes. The data of this research were unambiguously interpreted in the framework of the moving nonlinear foci and stationary multifocus structure models. It is pertinent to note that the approach involving the employment of laser pulses with a varied temporal shape in self-focusing research was first proposed and implemented in Ref. [24]. The conceptual development of this approach is discussed in the analysis of the prospects of further research into the self-focusing of ultrashort laser pulses (Section 5).

4. Self-focusing of femtosecond laser pulses

In this section we outline the main findings that have emerged from experimental and theoretical research into the self-focusing of laser beams with a femtosecond pulse duration.

4.1 Experimental data

As noted in Section 2, the self-focusing of laser beams with femtosecond-long pulses was initially observed and comprehensively studied in the air, and subsequently in other gases and condensed media. As for radiation sources, in experimental research advantage was primarily taken of Ti:Al_2O_3 crystal-based laser systems (quite frequently referred to as titanium–sapphire lasers), which lase in the ~ 800-nm wavelength range and produce pulses several tens to hundreds of femtoseconds long.

The typical characteristics of the filaments observed in such experiments in the air are as follows (see Ref. [25] and references cited therein): critical power $P_{\rm cr} \approx 3$ GW, filament length (for $P_0 \leqslant 10\,P_{\rm cr}) \approx 10$ m, filament diameter ≈ 100 μm, the energy fraction in the filament amounts to 6–10% of the total beam energy, multiple filamentation for $P_0 \geqslant 10\,P_{\rm cr}$, filament lengths for $P_0 \gg P_{\rm cr}$ may range up to 2 km, the filament emission spectrum experiences radical changes: a strong broadening (a supercontinuum in the range from 230 nm to 4 μm) and a conical emission are observed (Fig. 3).

The typical characteristics of the filaments observed in condensed media (crystals, glasses, liquids) are as follows (see Ref. [25] and references cited therein): the critical power $P_{\rm cr}$ is

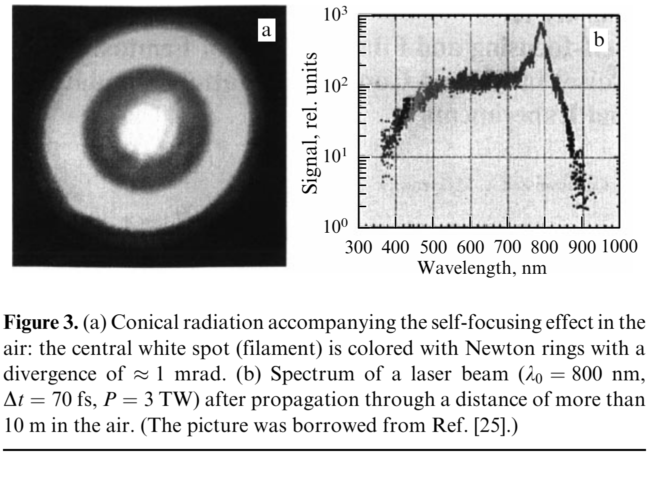

Figure 3. (a) Conical radiation accompanying the self-focusing effect in the air: the central white spot (filament) is colored with Newton rings with a divergence of ≈ 1 mrad. (b) Spectrum of a laser beam ($\lambda_0 = 800$ nm, $\Delta t = 70$ fs, $P = 3$ TW) after propagation through a distance of more than 10 m in the air. (The picture was borrowed from Ref. [25].)

by an order of magnitude lower than in gases, the filament lengths are on the order of several centimeters, and the filament diameter is about 2 μm. The diameter of a filament becomes smaller and its energy rises in the propagation of a beam through an amplifying medium (Ti:Al_2O_3 crystals, etc.).

4.2 Results of theoretical research

A large number of theoretical studies on the self-focusing of femtosecond pulses in the air have been published to date (see Refs [17–20, 25–28] and references cited therein).

All of the studies rely on the numerical solution of the wave equation with due regard for Kerr nonlinearity (responsible for self-focusing) and plasma (responsible for defocusing) produced owing to multiphoton absorption in the air. The typical system of equations used in such investigations (see, for instance, Ref. [25]) is written out as

$$2\mathrm{i}\,\frac{\partial E}{\partial z}+\frac{1}{k_0}\,\Delta_\perp E-k''\,\frac{\partial^2 E}{\partial t^2}+k_0 n_2\left(|E|^2+\tau_{\mathrm K}^{-1}\int_{-\infty}^{t}\exp\left(-\frac{t-t'}{\tau_{\mathrm K}}\right)|E(t')|^2\,\mathrm{d}t'\right)E-k_0\,\frac{\omega_{\mathrm{pe}}^2(\rho)}{\omega_0^2}\,E+\mathrm{i}\beta^{(K)}|E|^{2K-2}E=0\,,\qquad(6)$$

$$\frac{\partial\rho}{\partial\tau}=\frac{\beta^{(K)}}{K\hbar\omega_0}\,|E|^{2K}\left(1-\frac{\rho}{\rho_{\mathrm{at}}}\right).\qquad(7)$$

The first two terms in equation (6) describe the beam propagation through the medium with the inclusion of diffraction, and the third term with the inclusion of group velocity dispersion; the third and fourth terms account for the Kerr nonlinearity of the medium (the fourth term for inertialess nonlinearity, and the fifth one for the retarded part of the nonlinearity with the time characteristics $\tau_{\mathrm K}$), and the sixth and seventh terms take into account the production of plasma with a density ρ and multiphoton absorption with a probability $\beta^{(K)}$ [here, the superscript (K) indicates the number of photons in the multiphoton process].

Equation (7) describes the kinetics of the plasma produced owing to multiphoton ionization (ρ is the plasma density, and ρ_{at} is the density of neutral atoms).

The data of numerical simulations were interpreted by different authors on the basis of various models: dynamic spatial replenishment [20], moving foci and refocusing, and slice-by-slice self-focusing [18, 27].

An analysis [29] of these models revealed that they are *inherently* similar to the multifocus structure model and moving nonlinear foci model, and that they are only terminologically different from them. Indeed, the terminology employed by Mlejnek et al. [20] (for instance, 'self-guided light strings') may be misleading and create the illusion of some new concept of nonlinear light propagation. In reality, this is nothing more than another name for the trajectories of the moving nonlinear foci of the multifocus structure (involving plasma production). Similarly, there is nothing new about 'dynamic spatial replenishment' — this is just the mechanism of sequential formation of the nonlinear foci of the multifocus structure described in Section 3. The same is true of the 'slice-by-slice self-focusing' model [27], which is inherently the reformulated moving nonlinear foci model.

In an analysis of the presently available papers concerned with the self-focusing of femtosecond laser beams in the air, several of their drawbacks were noted [29], which made difficult an adequate comparison of numerical simulation results with experimental data. In particular, it was noted that experimental data were not informative enough for gaining a complete understanding of the mechanisms and processes involved in laser beam filamentation and plasma production. Specifically, the observations of filaments were time- and space-integrated, with a resolution insufficiently high to reveal the filament structure. As regards numerical simulations, it was noted, in particular, that they did not take into full account the group velocity dispersion (neglect of the contribution from the plasma component) and inadequately interpreted the retarded Kerr nonlinearity term (it was groundlessly ascribed to stimulated Raman scattering).

The imperfections of experimental works and theoretical calculations mentioned above, as well as the complexity of taking into account the strong variation of the laser radiation spectrum in the course of filamentation and the dissimilarity of the processes occurring at the leading and trailing edges of a laser pulse, call for further investigation into the self-focusing of femtosecond laser beams in different media and invite the use of new approaches. One such approach proposed in Ref. [30] — the employment of laser pulses with a varied temporal shape — will be discussed in Section 5.

5. Variation of the temporal shape of laser pulses — a promising approach to the investigation of self-focusing of ultrashort laser pulses

The conception of this approach relies on the dependence of the spatial and spectral self-focusing characteristics on the temporal pulse shape $P_0(t)$, predicted by the theory of self-focusing (the moving nonlinear foci model). For media with the Kerr nonlinearity of the refractive index, in particular, the velocity of nonlinear foci movement on the beam propagation axis is defined by the derivative

$$V=\frac{\mathrm{d}\xi}{\mathrm{d}t}\,,\qquad(8)$$

which is a function of the pulse shape $P_0(t)$ [see formula (3)]. The spectrum broadening due to phase self-modulation also depends on the pulse shape:

$$\Delta\omega=-\frac{\mathrm{d}\varphi_{\mathrm{nl}}}{\mathrm{d}t}=-\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\omega}{c}\,\frac{n_2 I(t)}{L}\right).\qquad(9)$$

Here, φ_{nl} is the radiation phase change arising from the nonlinear variation of the refractive index $n_2 I(t)$ over the propagation length L, and $I(t)$ is the intensity.

The temporal shapes of laser pulses that are of interest in the investigation of spatial and spectral characteristics of self-focusing are illustrated in Fig. 4.

The following effects are expected in self-focusing phenomenon, when the indicated pulse shapes are employed:

— for a rectangular pulse ($P_0=\mathrm{const}$): $\xi_m=\mathrm{const}$, $\mathrm{d}\xi_m/\mathrm{d}t=0$, $\Delta\omega=0$ — a stationary nonlinear foci structure (no filamentation) and the absence of spectrum broadening should be observable;

— for all other pulse shapes: $\mathrm{d}\xi_m/\mathrm{d}t\neq 0$ — a moving nonlinear foci structure and spectrum broadening whose character depends on the specific shape $P_0(t)$ should be observable.

The foregoing brief analysis shows the promise of the proposed conception for further investigations into self-

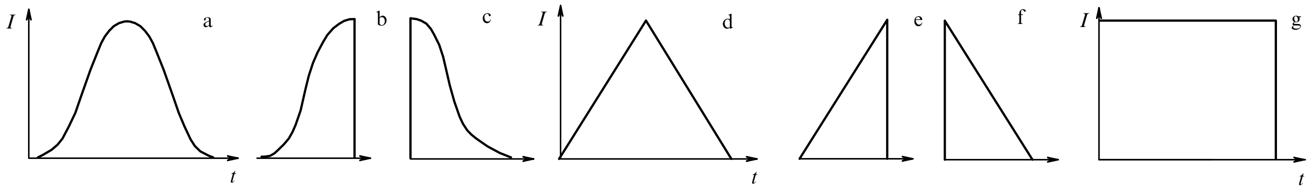

Figure 4. Temporal shapes of laser pulses: (a) symmetric bell-shaped, (b, c) asymmetric (truncated) bell-shaped, (d) symmetric triangular, (e, f) asymmetric (truncated) triangular, and (g) rectangular.

focusing and its related laser–matter interaction effects (ionization, damage, etc.) in the area of ultrashort pulse durations. To implement this approach requires solving several practical problems, namely, developing:

— methods for generating laser pulses with a prescribed temporal shape;

— methods for recording laser pulses with a high (femtosecond) temporal resolution;

— efficient techniques for recording self-focusing processes and several related effects with a high temporal resolution.

One of the promising methods for producing ultrashort laser pulses with a prescribed temporal shape — the use of volume Bragg diffraction gratings — was proposed at the A M Prokhorov General Physics Institute of the RAS. This method is presently being developed in the RAS GPI in collaboration with OptiGrate (USA).

6. Conclusions

The main results of investigations into the self-focusing effect of laser beams, performed to date, may be summarized as follows.

• Experimental research (especially comprehensive investigations in the nanosecond range of laser pulse durations) has revealed diverse effects caused by self-focusing in optical media of different kinds, which testifies to the universal nature of the phenomenon.

• Theoretical investigations have resulted in the determination of the main features and characteristics of self-focusing phenomenon common to different optical media. Different self-focusing models have been proposed; the most appropriate and best substantiated of them are the multifocus structure (MFS) and moving nonlinear foci (MNF) models.

• The MFS and MNF models have been reliably borne out by experimental data.

• The phenomenon of the self-focusing of ultrashort (femtosecond) pulses was discovered and has been comprehensively investigated in the air and other gases and in condensed media, and the features of the effect have been determined: the formation of long thin light and plasma filaments and a dramatic spectrum transformation (supercontinuum and conical emission).

• Proceeding from the data of theoretical research (numerical simulations), different ultrashort-pulse filamentation models have been proposed. An analysis of these models suggests that they correspond in essence to the MFS and MNF models, the difference being merely terminological.

• A more comprehensive explanation of the features of ultrashort-pulse self-focusing invites further experimental and theoretical investigations. A method involving laser pulses of a varied temporal shape has been proposed as a promising experimental research method.

References

1. Boyd R W, Lukishova S G, Shen Y R (Eds) *Self-focusing*: *Past and Present*. *Fundamentals and Prospects* (New York: Springer, 2009)
2. Askar'yan G A *Zh. Eksp. Teor. Fiz.* **42** 1567 (1962) [*Sov. Phys. JETP* **15** 1088 (1962)]
3. Hercher M *J. Opt. Soc. Am.* **54** 563 (1964)
4. Pilipetskii N F, Rustamov A R *Pis'ma Zh. Eksp. Teor. Fiz.* **2** 88 (1965) [*JETP Lett.* **2** 55 (1965)]
5. Chiao R Y, Garmire E, Townes C H *Phys. Rev. Lett.* **13** 479 (1964)
6. Talanov V I *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **7** 564 (1964)
7. Talanov V I *Pis'ma Zh. Eksp. Teor. Fiz.* **2** 218 (1965) [*JETP Lett.* **2** 138 (1965)]
8. Kelley P L *Phys. Rev. Lett.* **15** 1005 (1965)
9. Bespalov V I, Talanov V I *Pis'ma Zh. Eksp. Teor. Fiz.* **3** 471 (1966) [*JETP Lett.* **3** 307 (1966)]
10. Akhmanov S A, Sukhorukov A P, Khokhlov R V *Zh. Eksp. Teor. Fiz.* **50** 1537 (1966) [*Sov. Phys. JETP* **23** 1025 (1966)]
11. Akhmanov S A, Sukhorukov A P, Khokhlov R V *Usp. Fiz. Nauk* **93** 19 (1967) [*Sov. Phys. Usp.* **10** 609 (1968)]
12. Wagner W G, Haus H A, Marburger J H *Phys. Rev.* **175** 256 (1968)
13. Marburger J H *Prog. Quantum Electron.* **4** 35 (1975)
14. Dyshko A L, Lugovoi V N, Prokhorov A M *Pis'ma Zh. Eksp. Teor. Fiz.* **6** 655 (1967) [*JETP Lett.* **6** 146 (1967)]
15. Lugovoi V N, Prokhorov A M *Pis'ma Zh. Eksp. Teor. Fiz.* **7** 153 (1968) [*JETP Lett.* **7** 117 (1968)]
16. Braun A et al. *Opt. Lett.* **20** 73 (1995)
17. Nibbering E T J et al. *Opt. Lett.* **21** 62 (1996)
18. Brodeur A et al. *Opt. Lett.* **22** 304 (1997)
19. Chien C Y et al. *J. Nonlin. Opt. Phys. Mater.* **6** 485 (1968)
20. Mlejnek M, Wright E M, Moloney J V *Opt. Lett.* **23** 382 (1998)
21. Lugovoi V N, Prokhorov A M *Usp. Fiz. Nauk* **111** 203 (1973) [*Sov. Phys. Usp.* **16** 658 (1974)]
22. Loy M M T, Shen Y R *Phys. Rev. Lett.* **22** 994 (1969)
23. Korobkin V V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **11** 153 (1970) [*JETP Lett.* **11** 94 (1970)]
24. Lipatov N I, Manenkov A A, Prokhorov A M *Pis'ma Zh. Eksp. Teor. Fiz.* **11** 444 (1970) [*JETP Lett.* **11** 300 (1970)]
25. Couairon A, Mysyrowicz A, in *Self-focusing*: *Past and Present. Fundamentals and Prospects* (Eds R W Boyd, S G Lukishova, Y R Shen) (New York: Springer, 2009) p. 297
26. Zhang J et al., in *Self-focusing*: *Past and Present. Fundamentals and Prospects* (Eds R W Boyd, S G Lukishova, Y R Shen) (New York: Springer, 2009) p. 323
27. Chin S L et al., in *Self-focusing*: *Past and Present. Fundamentals and Prospects* (Eds R W Boyd, S G Lukishova, Y R Shen) (New York: Springer, 2009) p. 349
28. Kandidov V P et al., in *Self-focusing*: *Past and Present. Fundamentals and Prospects* (Eds R W Boyd, S G Lukishova, Y R Shen) (New York: Springer, 2009) p. 371
29. Lugovoi V N, Manenkov A A *Laser Phys.* **15** 1269 (2005)
30. Manenkov A A, in *7-ya Mezhdunar. Konf. "Lazernaya Fizika i Opticheskie Tekhnologii", 17–19 Iyunya 2008, Minsk, Belarus*: *Nauchnye Trudy* (7th Intern. Conf. "Laser Physics and Optical Technologies", 17–19 June 2008, Minsk, Belarus: Proceedings) Vol. 3, p. 197