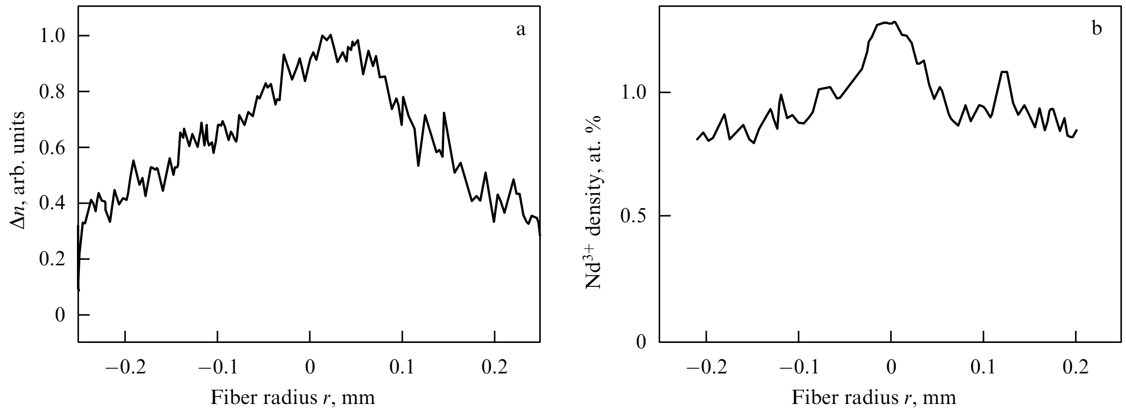

Figure 4. (a) Radial profile of the refractive index in the crystal fiber of neodymium-doped yttrium–aluminum garnet. (b) Neodymium ion density distribution over the fiber section.

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

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

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

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

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

A L Mikaelyan

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

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

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

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

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

Pistol'kors's initiative and entered into wide use in our country.

Despite the rapid progress of microwave technology, even early in the next decade (i.e., in the 1950s) an effort was mounted to advance to shorter-wavelength (millimeter and submillimeter) ranges, where a diversity of practical realizations appeared to be more elegant (for instance, sharp radiation directivity patterns for moderate antenna dimensions, broadband communication channels, etc.). However, microwave engineering did not make significant advances in these wavelength ranges for a variety of reasons (the difficulty of making low-loss waveguides, high levels of detector noise, worsening conditions for wave propagation in the atmosphere, etc.).

Concurrently with this process, the outlines of the formation and progress of quantum electronics — a new scientific field involving the use of induced emission (discovered by Einstein in 1917) for the production of coherent radiation sources in the optical wavelength range — began to emerge increasingly more clearly. Basic research in the field of quantum electronics was most vigorously pursued in our country and in the USA.

The main feature marking the research pursued under A M Prokhorov and N G Basov's supervision was that it was practically aimed at the final objective — the development of a coherent optical oscillator, which would allow making a start on mastering the optical wavelength range for a wide diversity of applications. As early as in 1955, a paper by Basov and Prokhorov on three-level pumping was published, and in 1958 the principle of using a cavity was formulated (Prokhorov). After that it became clear: the time had come to proceed directly to the development of a laser on the basis of the results accumulated in the spectroscopic investigation of crystals and gases (P N Lebedev Physics Institute, Institute of Crystallography, State Optical Institute, etc.). In 1959 the findings of Basov and Prokhorov's basic research were recognized by the awarding of the Lenin Prize, and in 1960 the first-ever ruby laser made its appearance.

2. Development of the laser — a start on the mastering of the optical range

Therefore, the 1960s may be considered the beginning of the mastering of the optical wavelength range, i.e., the commencement of the development of laser engineering. The significance of this event was estimated at its true worth by the awarding of the 1964 Nobel Prize in Physics to Basov, Prokhorov (USSR), and C Townes (USA).

It is pertinent to note that the majority of experts in the field of radar and communications did not attach proper significance to the potential of the optical wavelength range for a variety of reasons (high losses in the wave propagation through the atmosphere, lack of optical waveguides for information transmission, low efficiency of lasers, noise limitations in reception, etc.). Because of this, the Ministry of Radio Industry charged the institute in which I worked with analyzing the potential of lasers for solving radar problems, as well as the processing, storage, and transmission of information. By the end of 1961 we produced a scientific report in which we proposed and substantiated several important applications, as well as the work program for their implementation, including the formation of the requisite componentry base.

The outcome of our suggestions was the setting up of the 'Korall' research work, which concluded with several volumes of reports on the realization of different radio-optical systems.[1] In this case, apart from the analysis of obvious applications (aviation range-finders utilizing solid-state lasers, semiconductor laser-based phase altimeters, a system for aerial reconnaissance utilizing an argon laser), which were later pursued as commercial products in their own right, there were new proposals as well. One of them relied on the use of Doppler frequency shift (which is several orders of magnitude greater in the optical range than in the radio-frequency range) for raising the precision of measurements of velocity and other navigational characteristics. Another proposal involved laser techniques for data recording and processing.

In one of the volumes of reports[2] we set forth the theory of optical oscillators; also given were the resultant approximate equations in a form which enabled easy investigation of different regimes of lasing and amplification of laser radiation. One result was the understanding and optimization of the requirements imposed on different constituents (mirrors, cavity design, pump lamp spectra, design of the pump system, antireflective faces, etc.), which subsequently allowed the realization of a high radiation efficiency of ruby and garnet lasers and to achieve record-high radiation power levels, in particular, for Q-switched lasers.

At the same time, certain limitations were established for the possibility of raising power by way of amplification in the active medium (the notion of 'effective length' was introduced).

A significant outcome of the work done was the development of a componentry base in our country, which we launched on the basis of broad cooperation and close contact among physical institutes (Lebedev Physics Institute, Shubnikov Institute of Crystallography, State Research Institute for the Rare-Metals Industry, etc.) and industrial organizations of different ministries. This applies to pump lamps, crystals, mirrors, interference coatings, and other elements required for constructing efficient lasers, as well as to some laser engineering devices. Of these I would like to mention the 'optical isolator', which was made based on the Faraday effect in terbium crystal. This made it possible to realize a laser with a traveling wave optical resonator.

Among significant results is the development of a high-power ruby laser with a high pulse-repetition rate, which demonstrated the potentialities of lasers. Mention should be made of the first commercial ruby laser, whose production was launched in a plant in the town of Arzni with the aid of scientists who later joined the Physics Research Institute of the Academy of Sciences of Armenian Soviet Socialist Republic. This laser was available to organizations, which was helpful for teams starting to work in the area of laser engineering.

In the pursuit of this work there rapidly formed a new team of young researchers. As a result, by the time this work was completed, a powerful research center (subsequently transformed into the Radiooptics Institute of the Ministry

[1] The personnel of academic and industrial institutes engaged in different problems of laser technology development were fully familiarized with the results of the 'Korall' research work.

[2] It was published in the form of a book by A L Mikhelyan, M L Ter-Mikhelyan, and Yu G Turkov entitled *Opticheskie Generatory na Tverdom Tele* (Solid-State Optical Oscillators) (Moscow: Nauka, 1967), which was extensively used by physicists and other experts in the area of quantum electronics.

of Radio Industry) was formed for the development and application of laser technologies to solve problems in the radio industry. (Similar centers were established by other Ministries.) A significant part in the development of this center was played by the Affiliated Chair of the Moscow Institute of Physics and Technology, which I have headed since 1957 and which was partly reoriented to prepare young experts in the field of quantum electronics and laser engineering. This was also fostered by the rapid publication of the above-mentioned book on optical oscillators, for at that time there were no textbooks on lasers, with the exception of papers and reviews [among them I would like to note the paper by N G Basov, O N Krokhin, and Yu M Popov in *Usp. Fiz. Nauk* **72** (2) 161 (1960), in which they came up with the idea of implementing semiconductor lasers for the first time].

It is pertinent to note that after the advent of the first lasers there emerged a large number of diverse proposals about their application in different areas of science and technology. Indeed, the enormous power in a narrow spectrum and the possibility to produce short radiation pulses generated a great variety of ideas for applying lasers in technology and medicine, radar and range-finding, measuring techniques and material analysis, communication systems and television, systems for data recording and processing, and other areas. As lasers and componentry improved, different institutes came to be occupied with a whole series of applications. This applied primarily to range-finding systems and uses in technology and medicine. In parallel with this, a search was continued for novel, more exotic fields of application of high-power lasers. Mention should be made, as a case in point, of the laser fusion problem, which was first brought forth by Basov and Krokhin.

Of fundamental importance to radio electronics systems is high radiation coherence. At the same time, all lasers employ resonators with dimensions much greater than the wavelength. As a result, a large number of randomly phased eigenmodes are excited at different frequencies, which is responsible for a low spatial and temporal coherence. The radiation directivity pattern therefore turns out to be irregular and, in the case of focusing, the spot size is significantly greater than the diffraction limit. That is why our effort in the development of lasers was directed to finding and developing an efficient way of mode selection to ensure lasing at the lowest-order (transverse) mode; this was to be done without an appreciable sacrifice in output power. Such a method was borrowed from the theory of waveguide resonators close to the 'cutoff' resonator. In the regard, for the first time we obtained a single-mode (helium – neon) laser with diffraction-limited radiation divergence [1] and somewhat later a single-mode ruby laser, with which a pulsed hologram was realized for the first time [2].

3. Coordination of the work on the development of laser engineering

The early 1960s saw the establishment of an Interdepartmental Council on Quantum Electronics under the chairmanship of the Deputy Minister of the Radio Industry. The Council comprised the leading experts of the USSR Academy of Sciences and different ministries with the aim of coordinating activities on the development and application of lasers. This undoubtedly fostered close contacts between the teams of different institutions.

A certain positive part in combining efforts to develop lasers and their applications was played by the scientific conferences which were annually organized by R V Khokhlov under the auspices of the Council on Coherent and Nonlinear Optics.

In 1967, with Basov and A M Prokhorov's assistance I took upon myself the organization of the 1st All-Union Quantum Electronics Conference, which included the invitation of foreign scientists. Following that, the Conference on Coherent and Nonlinear Optics was organized by Khokhlov, helping to get the leading foreign scientists in the area of quantum electronics to take part in both conferences, and in establishing contacts which would foster the active participation of our experts in future conferences on quantum electronics regularly held abroad.

On the initiative of the Interdepartmental Council on Quantum Electronics, the first All-Union Conference of Laser Applications was held in 1968. Early in the 1970s, the first issue of a new journal, *Kvantovaya Elektronika* (Quantum Electronics), appeared (initially as a collection of papers and later as a journal of the USSR Academy of Sciences in its own right). A large role in the establishment of this monthly periodical was played by Basov, who became the first editor of this journal (along with Khokhlov and myself as associate editors).

At these conferences we came up with the idea of using lasers and holographic techniques for high-density data recording and developing new data storage systems. The line of inquiry of the Radiooptics Institute would more and more focus on data recording, storage, and processing systems employing lasers and holography principles. However, prior to turning our attention to this area of application there is good reason to outline the application of laser devices in communication systems.

4. Production of the first optical waveguide — commencement of the development of optical fiber communication lines

An important event occurred in 1968, which significantly broadened the field of application of laser technologies. The first optical waveguide realized in the form of a dielectric fiber with a varied refractive index was demonstrated in Japan. Its idea and theory were first proposed in our country in 1951 [3]; subsequently, they gained wide recognition both here and abroad.

The production of the first optical waveguide opened up the possibility for high-rate huge-volume data transmission. A large role in the development of this new avenue of laser technology was played by Prokhorov: he headed the work on developing low-loss weak-dispersion optical fibers and organized cooperation of experts in the fields of material sciences, special technologies, and physical research. The results obtained and the promise of their application underlay the subsequent establishment of an independent institute supervised by Prokhorov's disciple E M Dianov, who continues to advantageously develop this important avenue. We cannot presently follow the constant growth in data transfer rates of optical fiber communication lines and new areas of developments in lasers which harness the effects in optical fiber waveguides.

5. Production of the first holographic memory system — commencement of development of parallel techniques of information recording and processing

I will now mention briefly the progress of work on holographic methods for information recording, storage, and processing, including the development of holographic memory systems. This development work significantly outstripped similar research carried out abroad. In the first half of the 1970s we completed this development work by producing several pilot samples at a specialized factory and entered the testing phase.

The development of the first holographic memory system was from the very outset intended for a specific radio-electronic complex and therefore had to meet stringent requirements as regards not only technical characteristics, but its environment (temperature, humidity, vibration resistance, etc.) as well. This undoubtedly complicated the elaboration of the requisite new componentry but at the same time imparted finality and utility to the elements and laser devices designed, which could also be widely used for other applications.

The holographic memory system device with random access to data arrays is shown in Fig. 1. Also given is the photograph of the test sample (the lower part of the holographic device accommodates power supply units and auxiliary electronics).

The central feature of this system is a high readout rate (on the order of 10 Gbit s^{-1}), the readout of a requisite multi-digit number from an array being accomplished in only 0.1 μs using a single-mode helium – neon laser with a milliwatt output power. This was achieved by using a photodetector in the form of a special-purpose image intensifier, which enhanced the brightness of the signal readout of a microhologram and converted the signals from the red region to the green one (where the photomultiplier responsivity is most high). Then, via glass fibers, the signals arrived at a compact photomultiplier array and were read out in the form of digital signals.

The second unique optoelectronic device, made at the Radiooptics Institute, was a high-speed multistage electrooptical deflector based on lithium niobate crystals. It was necessary to significantly improve the production technology of ultrapure lithium niobate crystals, which was accomplished by other participants in the work. Figure 2 shows photographs of the laser spots made by 1024- and 4096-position

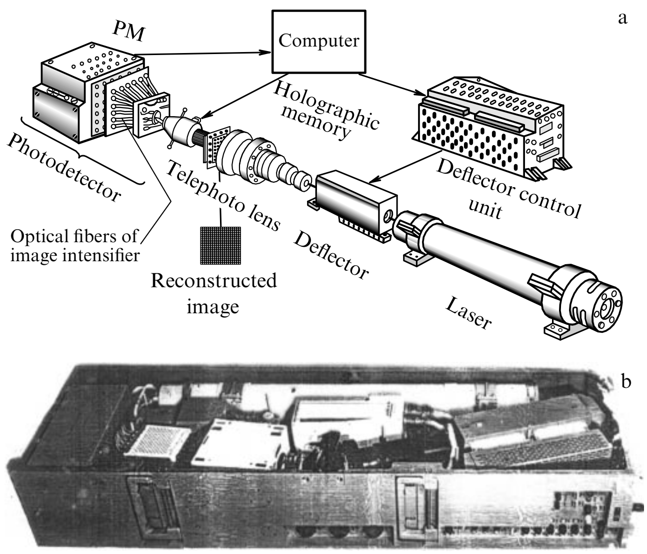

Figure 1. Schematic (a) and test sample (b) of the holographic random-access memory system.

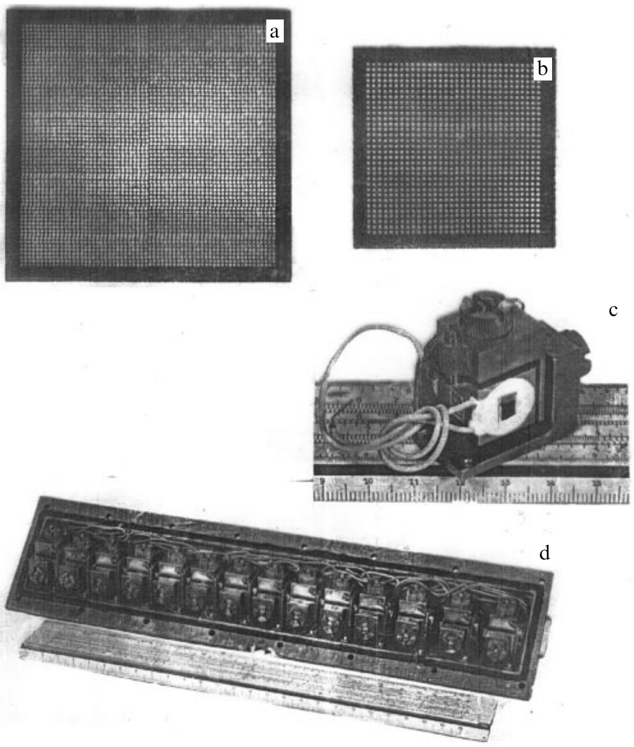

Figure 2. Photograph of the laser spots produced by 4096 (a) and 1024 (b) position deflectors and the pilot sample of the electrooptical deflector based on lithium niobate crystals with a switching time of 1 μs (c, d).

deflectors and the photograph of a pilot sample with a switching time of about 1 μs.

Finally, one more result, also significant for the advance of new applications of laser engineering, related to the development of high-speed spatiotemporal modulators for recording electrical information in the form of holograms: the existing spatiotemporal liquid-crystal modulators are very slow. The on-line data input into the memory carrier was effected with the aid of an electrically controllable two-dimensional spatial modulator employing the Faraday effect. For this purpose, special two-dimensional structures were elaborated on the basis of yttrium orthoferrite and bismuth and of garnet films. Under the action of electric signals flowing through a system of orthogonal conductors, certain cells were remagnetized, which resulted in the rotation of the plane of polarization of the transmitted light. Figure 3 shows photographs of one of the samples produced (a), the transparency (b) photographed in laser light, and the image reconstructed from the microhologram (c) in which this transparency was written. The development of magnetooptical spatiotemporal modulators called for the development of new materials: yttrium orthoferrite and garnet films with a large coercive field and a high domain-wall velocity. This enabled the realization of a data input speed of about 10^8 bits s^{-1} for a high zero – unit contrast ratio (about 300).

The new laser engineering devices were implemented in close contact of the Radiooptics Institute with numerous institutes of the Academy of Sciences and industrial ministries. This applies primarily to the development of technology for the production of ultrapure niobate lithium crystals, garnet films, yttrium orthoferrite, fine-grained low-noise photographic emulsions, special fiber elements, special low-distortion image intensifiers, photomultiplier arrays, special-

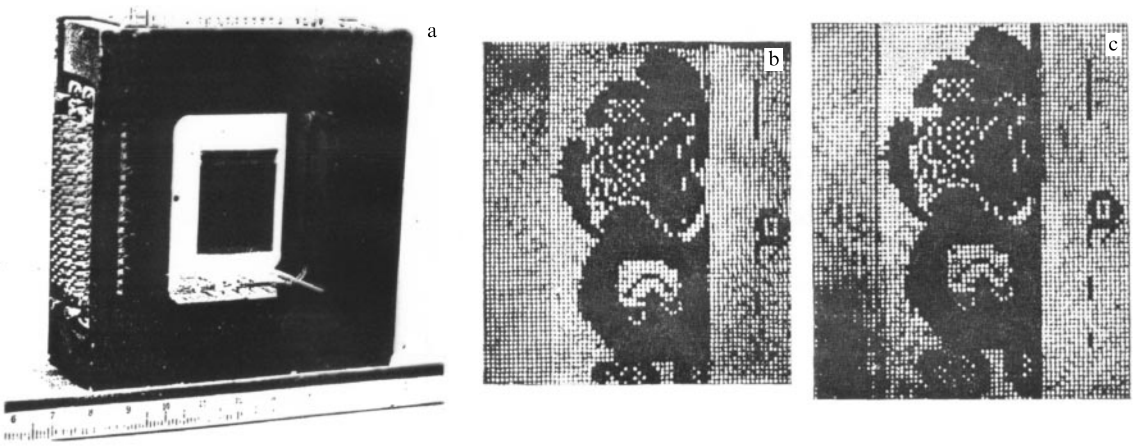

Figure 3. Two-dimensional magnetooptical controllable spatiotemporal modulator: (a) original transparency, (b) reconstructed image.

purpose wide-angle optics, new materials for rewriting holograms (bacteriorhodopsin, photochromic films, photopolymers), narrow-band filters based on reflectance holograms of iron-doped lithium niobate, volume holographic memory elements, etc.

One more, highly promising holographic memory device used the principle of recording in parallel a large number of signals on a moving carrier. In the version of the disk shown in Fig. 4, recording is performed on a wide track and has the form of one-dimensional holograms. In comparison with disks (magnetic and optical) widely used at the present time, holographic disk memory offers several advantages (higher read and write speeds, the possibility of using more informative thick carriers, etc.), which also makes them excellent candidates for neurocomputers.

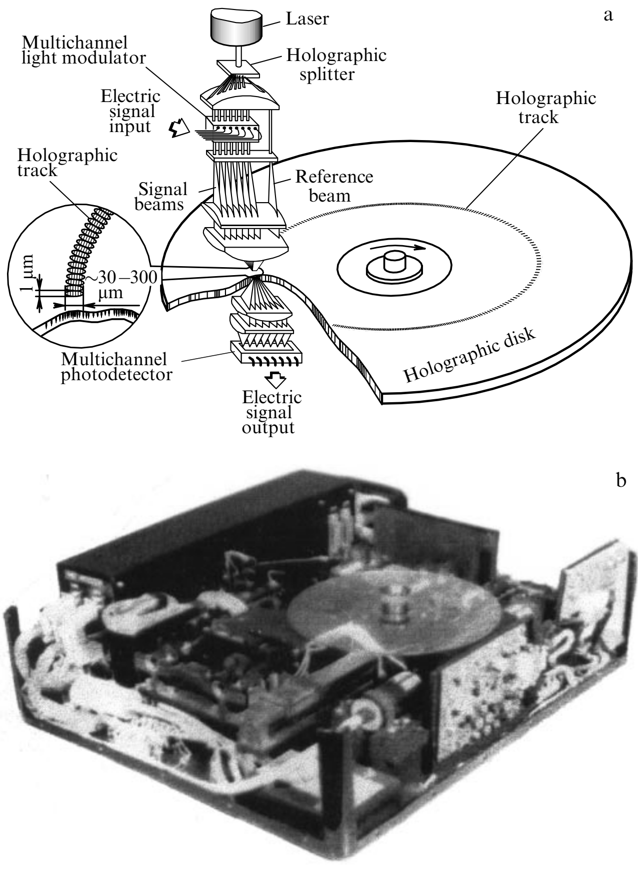

Figure 4. Schematic (a) and sample (b) of a disk memory system using one-dimensional holograms.

All the aforementioned optoelectronic devices are described in greater detail in the author's monograph *Opticheskie Metody v Informatike* (Optical Methods in Informatics) (Moscow: Nauka, 1990), which also contains references to original papers. Despite the fact that over 30 years have elapsed since the invention of some of these laser engineering devices, they are still nonexistent abroad. As to the research aimed at developing holographic memory systems, a start on it abroad was made only in the early 1990s in connection with the rapidly rising requirements on information systems. These programs are now underway in the USA and Europe.

6. Conclusion

In our subsequent activity we did not circumvent difficulties encountered by research institutes engaged in advanced development for the industry, which were no longer called for in our country.

In the mid-1990s, the Russian Academy of Sciences established the Institute of Optico-Neural Technologies with the aim of pursuing research on new methods of data processing relying on the principles of holography and neural systems. I became the Director of this institute, and several leading researchers who had been my collaborators and had a broad background in research were also included on the staff. Our task is to preserve the scientific school to develop young scientists in this highly promising field and find the areas of application of the new holographic data processing methods, mastered in our work, for the solution of problems of practical significance (not restricting ourselves only to the development problems of radio-electronic systems). We are already obtaining the first results in the development of holographic nanostructures and associated methods of data processing with the use of principles of operation of neural structures. We hope that there will be a call for these findings in our country.

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