Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (31 May 1989)

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A scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR took place on 31 May 1989 in the conference hall of the S. I. Vavilov Institute of Physics Problems of the Academy of Sciences of the USSR. The following reports were presented at the session:

1. *Yu. A. Anan'ev*. The problem of the divergence of laser radiation.
2. *S. B. Novikov and A. A. Ovchinnikov*. The development and achievement of methods of optical observations with high angular resolution at the observatory on Mt. Maĭdanak.

A brief summary of the reports is presented below.

Yu. A. Anan'ev. *The problem of the divergence of laser radiation*. The history of lasers is closely connected with the history of the development of the idea of open resonators, which was formulated almost simultaneously in 1958 by Prokhorov, by Dicke, and by Schawlow, and Townes (there are bibliographies in Refs. 1 and 2 on this and other questions that are mentioned). Already in 1960, Meĭman built the first model of a ruby laser by using the simplest variant of an open resonator formed from two plane-parallel mirrors; after this, newer and newer types of lasers started to appear rapidly. The general confidence which existed then in a very quick solution of the problem of transmitting energy over very long distances and of other problems was based on the equation for the diffraction limit of the divergence $\varphi = 1.2(\lambda/D)$ (λ is the wavelength, and D is the diameter of the light beam), which predicted a very small value for the latter. However, it turned out in fact that the divergence of the radiation of those same ruby lasers was many times larger than φ.

The subsequent analysis of the situation was based in many ways on the results from the theory of hollow open resonators, which was founded in 1960 by Fox and Lee, who first showed that a two-mirror system actually possesses modes in the sense of the standard definition. This theory was mainly constructed towards the end of the 1960s (Vaĭnshteĭn's papers played a significant role here). It turned out that ideal resonators with plane and slightly concave mirrors possess whole sets of modes with small losses (high Q-factor) and various symmetric field distributions. However, such distributions were clearly observed extremely rarely in experiments with pulsed lasers because of the presence of optical nonuniformities of the medium.

A series of papers in 1963 and 1964, among which that by Leontovich and Veduta was the best, showed that the presence of even a slight non- uniformity introduced within the resonator medium is capable of fundamentally rearranging the mode structure. At approximately the same time, it became clear that the tendency of resonators with small losses to excite simultaneously a large number of modes also leads to a large value for the divergence.

Kuznetsov and Rautian showed in 1963 how a single-mode lasing regime can easily lose stability. Soon afterwards, Tang and Statts suggested a multimode lasing model for lasers operating close to the threshold regime. The author extended this model to the case where the lasing threshold was greatly exceeded, which allowed one to estimate the width of the spectrum and the divergence of radiation for real lasers. Work on the spectrum was continued by Livshits and Tsikunov, especially on the divergence; it turned out that the number of high Q-factor modes that are simultaneously excited also increases with increasing resonator cross section, and therefore, the ratio of the divergence to φ becomes larger and larger.

The results of other researchers, in particular, Basov, Belenov, Letokhov, and Suchkov, also indicated an unfavorable situation concerning divergence for large D values. Therefore, many assumed that only schemes of the type depicted in Fig. 1(a) allow one to solve the divergence problem. The laser 1 serves as a master oscillator. It has a small cross section; the value of φ turns out to be comparatively large here, which makes reaching it considerably easier (a successful method for optimizing similar lasers was suggested by Mikaélyan *et al.*). The cross section of the light beam is "spread out" during its passage through the telescope 2, and the divergence is reduced by the same factor. After the amplification stage 3, another telescope with an amplifier can be added if necessary, etc.

A much simpler alternative solution was suggested by Sigmen in 1965, who favored so-called unstable resonators with large diffraction losses; a system of two convex mirrors is a typical representative of this class. In 1969, we already had available a pulsed laser whose radiation was focused directly by a two-mirror unstable resonator (without additional optics) at a specified distance of 50 m, and which produced there apertures of 3 mm to 5 mm diameter in an aluminum plate of 0.5 mm thickness.

The principle of the action of an unstable resonator is illustrated by Fig. 1(b). Part of the radiation which passed

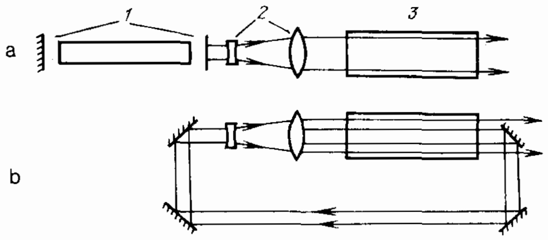

FIG. 1.

through the telescope and active element is fed back into the telescope input, closing the feedback loop, and a part of it leaves the system in the form of a beam of annular cross section, forming a useful signal. Obviously, one can get the same energy characteristics for the radiation by selecting the telescope parameters so that the same fraction of the light beam enters the feedback loop as is reflected from the semitransparent mirror of a plane resonator.

At the same time, the radiation in the unstable resonator passes through the divergence-reducing telescope during each traversal around the closed path; therefore, unlike a plane resonator, the resulting divergence turns out to be close to that which one encounters for a single passage of an originally parallel beam through the active element. Besides, here the radiation enters the peripheral parts of the cross section from its central part, and a definite division of functions exists: the central part serves as a master oscillator, and the peripheral parts as the final amplifier. This creates almost the same possibilities for controlling the radiation as in multistage schemes.

The realization of these advantages of unstable resonators and also work on removing a number of side effects allowed us to be the first ones to suggest and use in practice almost all the schemes by which one now constructs powerful and comparatively simple lasers having small radiation divergence. Thus, large cross section lasers that are controlled by miniature optical elements, single-stage amplifiers with the same enormous amplifications as multistage schemes, lasers with a stable direction for the output beam under conditions of strong vibration of the active elements, etc., have been built.

Towards the middle of the 1970's, only the problem of resonators for wide-aperture lasers using weakly amplifying media remained unsolved: In this case it turns out to be possible to bring only a small fraction of the total radiation flux out of the resonator, and the annulus which is the cross section of the output beam becomes quite narrow. This gives rise to a number of undesirable consequences. A new method of constructing the feedback loop for an unstable resonator, which allows one to obtain a simply-connected compact cross section of the output beam in such cases and, at the same time, to reduce the effect of some forms of inhomogeneities, was suggested by the author in 1975.

All this allowed one to attain, for lasers of the most different designs, such a low divergence as is allowed by the degree of inhomogeneity of the medium. Let us now briefly touch on the struggle to reduce this degree of inhomogeneity. Here the greatest successes have been attained in the matter of reducing the thermal deformations of the resonators of solid-state lasers caused by non-uniform heating over the volume of the medium during its excitation. Often this source of aberrations plays a fundamental role and, in the case of the extensively used glass lasers, it is practically the only source.

Snitzer in 1966 suggested selecting the composition of the glass so that the changes of the index of refraction that are directly caused by the temperature variations and by photoelasticity phenomena (which arise due to thermal stresses) would balance each other off. Two years later the author noticed that the possibility for total compensation appears only after going from a circular to an elongated rectangular cross section for the active elements (similar arguments were expressed in 1970 by Buzhinskiĭ, Dianov, *et al.*), and moreover, by selecting the composition, one can even achieve that the laser radiation is plane-polarized.

Besides formulating these arguments, the author had suggested laser thermooptical constants which had entered into universal practice and which determine the amount of thermal deformations of a resonator both for plane and also for circular cross sections of active elements. All this played its role in the development of Soviet work in creating both "athermal" glasses and also new forms of glass lasers.

The method of reducing thermal deformations that is based on a "zigzag-like" (due to total internal reflection from the side walls) transmission of the light beam through a plane active plate, which was actively promoted at the beginning of the 1970's by Mikaélyan *et al.*, is becoming more and more popular for crystal lasers.

The development of methods capable of eliminating the influence of any optical inhomogeneities of active media independently of their origin has been going on since the middle of the 1960's. In 1971, after realizing the fruitlessness of attempts to build wide-aperture resonators with automatic compensation for inhomogeneities of the medium based on nonlinear effects, the author suggested the scheme of a two-pass laser amplifier with the intermediate operation of wave front reversal, which is the most popular one at present. The method of dynamic holography, which later was named the four-wave interaction, was proposed as one of the possible methods for reversal. Soon the effect of reversal during stimulated back-scattering was discovered by Ragul'skiĭ *et al.*, and work along this line became widespread. Here the author was the originator of some more ideas about the possibilities for using dynamic holography and proposed an original phenomenological model for the stimulated scattering process.

Also the first attempts to use optico-mechanical methods for wavefront correction in laser technology were undertaken by the author with his coworkers. A mirror whose curvature was varied during a laser pulse with a duration of $\sim 10^{-3}$ sec was built in 1970. Models of flexible mirrors with more extensive possibilities for controlling the shapes of their surfaces were produced two to three years afterwards; the high-precision cylindrical mirrors with controllable curvatures that were constructed based on them were used in some large-scale experiments in the mid-1970's. Subsequently, the methods of adaptive optics with the use of flexible mirrors as the main slave mechanisms were developed very extensively.

There exists a number of important problems of laser technology that are still unsolved which require the use of optical elements with surface shapes that differ greatly from spherical (conical, toroidal, etc). This requires the development not only of a suitable manufacturing technology, but also of fundamentally new methods of analysis.

[1] Yu. A. Anan'ev, *Optical Resonators and the Problem of the Divergence of Laser Radiation* [in Russian], Nauka, M. 1979.

[2] Yu. A. Anan'ev, *Optical Resonators and Laser Beams* [in Russian], Nauka, M. 1990.