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From the Current Literature

"TRAVELING MEDIUM" LASER

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EVEN at the very beginning of the research on solid-state lasers, the physicists have encountered many paradoxical phenomena. First, solid-state lasers generate light waves simultaneously at many close frequencies. Second, the distribution of the intensity over the spectrum of the oscillations generated by the laser has a random form. This is particularly clearly seen in the case of the broad generation spectra of the neodymium-glass lasers. Third, finally, when the active medium is continuously excited (under continuous optical pumping) the intensity of the laser radiation is discrete in time, i.e., has a spiked character. The time intervals between the spikes and also the powers of the spikes vary randomly in magnitude.

These phenomena have given rise to a considerable number of experimental and theoretical investigations during the nine years of the existence of lasers. However, the properties of the spectrum and of the radiation intensity of solid-state lasers, formulated above in the form of the second and third paradoxes, have not yet been explained.

The generation process in lasers comprises self-oscillations of electromagnetic-field oscillators. Such oscillators are the natural oscillations of the electromagnetic field between the resonator mirrors. They have the form of standing waves with a three-dimensional spatial structure. They are customarily called the modes of the resonator.

The frequency of the mode in a resonator made up of flat mirrors is approximately

$$\nu_m \approx \frac{cm}{2L}, \qquad (1)$$

where c is the velocity of light in the medium, L the optical length of the resonator, and m is the longitudinal mode index, which characterizes its spatial inhomogeneity in the direction of the laser axis. Indeed, since $\nu = c/\lambda$, it follows that $L/m = \lambda/2$, i.e., m is the number of half-waves subtended by the resonator length, whereas $\lambda/2$ determines the dimension of the axial inhomogeneity of the mode. In the optical range ($\lambda = 10^{-5}$–10^{-3} cm) at L = 10–100 cm, the longitudinal index is $m = 10^5$–10^7, i.e., it is always of high order.

The two transverse indices p_1 and p_2, which determine the structure of the mode in the transverse directions, cannot assume large values, owing to the very rapid increase of the diffraction losses on the mirrors with increasing mode index. The realistically possible values of these indices range from zero to 10^2. Such a ratio of the longitudinal to the transverse indices ensures a small transverse scatter of the wave vector of the electromagnetic mode of the laser, and consequently hides their activity of the generated radiation. Accordingly, small values of the transverse indices mean that the dimensions of the spatial inhomogeneity of the mode in the transverse direction $\sim d/p$ are comparable with resonator diameter d.

The laser modes whose frequencies lie within the luminescence band of the active centers (Fig. 1) draw their energy in a volume Δv of the active medium in accordance with the law

$$\Delta \dot{N}_m(\mathbf{r}) = D g_m N_m P_m(\mathbf{r})\, n(\mathbf{r})\, \Delta v, \qquad (2)$$

where $\Delta\dot{N}_m(\mathbf{r})$ is the number of photons produced per unit time in a given mode of frequency ν_m in the volume Δv; g_m is the ordinate of the luminescence curve at the frequency ν_m; N_m is the number of photons in the mode; $P_m(\mathbf{r})$ is a function describing the spatial distribution of the mode field in the resonator; $n(\mathbf{r})$ is the density of the inverted population in the volume Δv. The inverted population $n(\mathbf{r})\Delta v$ is equal to

$$n(\mathbf{r})\,\Delta v = [n_2(\mathbf{r}) - n_1(\mathbf{r})]\,\Delta v,$$

where $n_1(\mathbf{r})\Delta v$ and $n_2(\mathbf{r})\Delta v$ are the numbers of active centers in the lower and upper states, respectively, of the quantum transition that the active centers undergo in the volume Δv upon interaction with the photons of the mode. The coefficient D is proportional to the Einstein coefficients for the induced transition between the two aforementioned states.

Since atoms are localized in solids with accuracy to 10^{-8} cm, which is much shorter than the wavelength in the optical band, the active centers in the antinodes of the mode lose their excitation most intensely upon interaction with the photons of the mode, and to the contrary, centers located at the nodes undergo no induced transitions at all in the field of the same mode. However, nodes of a given mode coincide with antinodes of other modes. Therefore the inverted population in the nodes of one mode may serve as a source of energy for other modes. Thus, the source of self-excitation energy in the solid-state lasers feeds the modes in accordance with the distribution of their field in space, and this most unique feature of a laser as a self-oscillating system gives rise to the multimode character of the generation. This is the idea on which the theory of the spectral composition of the radiation of lasers using condensed media is based. It was first formulated only three years after the appearance of lasers[1].

As seen from (1), the frequency difference between two modes whose longitudinal indices differ by unity is

$$\delta\nu = \nu_m - \nu_{m-1} = \frac{c}{2L}.$$

Usually the resonator length is 10–100 cm, so that $\delta\nu \sim 10^8$–10^9 sec^{-1}. Therefore the large number of modes that can potentially generate becomes evident once it is recognized that half the width of the luminescence bands

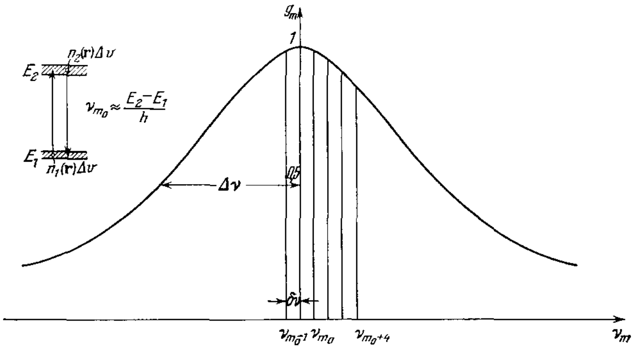

FIG. 1

of the condensed media $2\Delta\nu$ (see Fig. 1) ranges from 10^{10} to 10^{13} sec^{-1}.

With increasing number of generated modes, the number of regions in which the inverted population is retained decreases continuously. The total field of these modes is already more uniformly distributed in space so that for other modes that are potentially capable of generation there is not enough population inversion capable of compensating for their energy loss in the resonator. It can be shown[2] that with increasing pump power the width of the laser emission spectrum reaches a certain limit imposed by the fact that the simultaneous generation of a sufficiently large number of modes ensures such a uniform depletion of the inverted population in space, that further enrichment of the radiation by modes becomes impossible.

The distribution of the radiation in space, which is determined by the set of transverse indices of the modes taking part in the generation, and particularly the existence of a limiting divergence angle, is also connected with the spatial inhomogeneity of the mode field[3].

Thus, the multimode character of the generation of solid-state lasers decreases both the coherence and the directivity. Elimination of the transverse inhomogeneity of the mode field with respect to the active centers should therefore lead to an appreciable narrowing down of the spectrum and to an increase of the directivity of the radiation. In particular, there are several ways of increasing the coherence of solid-state laser radiation.

First, it is possible to change over from standing waves to traveling waves, using a device that ensures unilateral propagation of the electromagnetic waves[4].

Second, one can attempt to develop resonators characterized either by spatially-homogeneous modes[5] or by a high degree of mode degeneracy with respect to frequency, i.e., where the same frequency corresponds to a large number of spatially inhomogeneous modes[6].

Third, the active centers can be shifted from the nodes of the mode during its generation to antinodes rapidly enough to prevent other modes from oscillating as a result of these centers[2,7].

Lasers in which active centers move relative to the standing waves in the direction of the resonator axis will henceforth be called "traveling medium" lasers.

The simplest method of realizing the principle of relative motion of the active centers in standing electromagnetic waves along the laser axis is to move rods of active material mechanically inside the resonator. This was precisely the method used to perform the main experiments on the specific features of "traveling medium" laser emission.

Another group of methods is based on phase-opposition modulation of the refractive index in the resonator in opposite directions of the active rod while keeping the optical length of the resonator constant. In this case the nodes and antinodes of the modes oscillate relative to the active centers. The amplitude and velocity of this motion depend on the depth and frequency of modulation. An electrooptical variant of phase-opposition modulation was realized in 1967 at the Institute of Semiconductor Physics of the Siberian Division of the USSR Academy of Sciences[14].

The main result of the kinetic theory of the "traveling medium" laser with a flat resonator is the existence, for any given pumping, of a velocity $v_{o.g.}$, starting with which one-mode radiation (with respect to the longitudinal index) takes place, with the power equal to the radiation power of a laser with a medium at standstill at the same pumping[2]. This velocity is approximately equal to

$$v_{o.g.} \approx \frac{\lambda}{4}\frac{N}{t_1}M, \tag{3}$$

where t_1 is the average lifetime of the active center in the excited state in the field of one photon ($t_1 = (Dg)^{-1}$; see formula (2)), N is the number of photons in the generated mode, M is the number of different longitudinal indices of the modes whose frequencies fall in half the half-width of the luminescence line of the active medium ($M \sim \Delta\nu/\delta\nu$) (see Fig. 1).

The physical meaning of relation (3) consists in the fact that in order to attain single-mode generation in the "traveling medium" laser, the rate of transport of inverted population in space should increase with increasing distance from the node to the antinode ($\lambda/4$), with increasing rate of "burning out" of the inverted population in the antinode of the generated mode ($\sim N/t_1$), and also with increasing competition on the part of the neighboring mode, a fact taken into account by the factor M. An estimate of the velocity $v_{o.g}$ for ruby lasers at room temperature by means of formula (3) yields, at small pump values, $v_{o.g} \sim 10^2$ cm/sec.

Figure 2 shows a photograph of an experimental

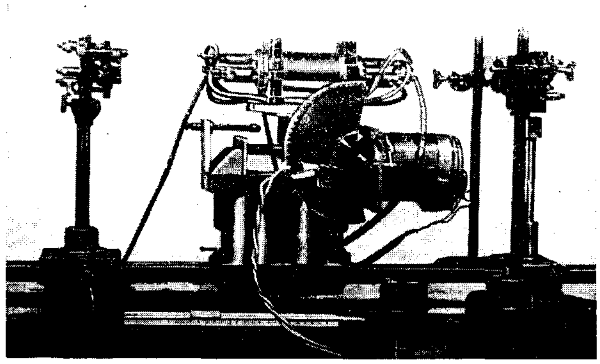

FIG. 2

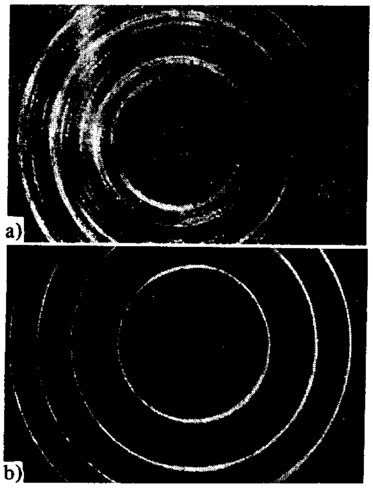

FIG. 3

"traveling medium" laser. It is seen from this photograph that an illuminator placed between the resonator mirrors, together with pump flash lamps and the active rod inside the illuminator, can move along the resonator axis.

In the first papers on "traveling medium" lasers[7,8] it was reported that in ruby, at a velocity 40 cm/sec, the laser radiation spectrum can be narrowed down to a single mode in an interval $(1.0-1.2)W_{thr}$, where W_{thr} is the threshold pump power. In these experiments, the illuminator, together with the ruby crystal, were made to vibrate along the plane-resonator axis, and the pump flash lamp was fired at the instant of maximum velocity.

Figure 3 shows interference patterns of the emission of a laser with a stationary ruby crystal (a) and of one with a crystal moving with velocity 40 cm/sec (b), obtained with a Fabry-Perot interferometer. It is seen from these interference patterns that the multimode generation of the ordinary laser gives way to single-mode generation (with respect to the longitudinal index) of the "traveling medium" laser. This experiment is direct experimental proof of the decisive role played by the spatial mode inhomogeneity in the formation of the laser emission spectrum*.

We now proceed to another feature of the "traveling medium" laser, which casts light on the second paradox of solid-state lasers.

Figure 4 shows the generation spectra of a neodymium-glass laser[9]. In case (a), the glass laser is stationary. The emission spectrum has in this case a random distribution of both the frequencies and the intensities of the individual generation bands. If the rod moves (case b), then the spectrum acquires a regular structure both in frequency and in intensity.

As follows from the theory[1,2], the laser emission intensity at the frequency of a given mode is determined by its gain and by its loss factor. Therefore the emission spectrum depends on the form of the amplification and loss curves as functions of the mode frequency. If these curves are smooth, then the laser-emission spectrum should also have a smooth form. From this it must be concluded, on the basis of the experimental data of Fig. 4, that motion of the active medium relative to the standing waves (modes) of the resonator smooths out both curves, that of the gain as well as that of the loss.

Why do these curves have a random form in ordinary lasers?

In real lasers, the basic internal parameters that determine the radiation characteristics are random functions of the coordinates. The presence of optical inhomogeneities in the active medium can greatly influence the vibrational system of the laser. Just as introduction of a plane-parallel plate into the resonator gives rise to discrimination of certain modes compared with others, namely frequency modulation of the losses takes place with a period

$$\delta'\nu = \frac{c}{2d\mu}$$

(d—thickness of plate and μ—its refractive index), so should the optical inhomogeneity of the medium lead to deformation of the resonator spectrum. In other words, the spatial fluctuations in the absorption and scattering of light by active media (crystals, glasses, liquids) give rise to a random dependence of the loss coefficient on the frequency[9].

Analogous random distributions of the excitations of active centers, determined both by the pumping conditions and by the inhomogeneities inside the active media, lead inevitably to corresponding fluctuations of the gains of the individual modes, since the field of each mode has its own spatial distribution. As a result, random frequencies and intensities are observed in the emission spectrum of the laser, as is most clearly manifest in the case when the generation spectrum width exceeds the characteristic spectral dips that are dictated by the dimensions of the inhomogeneities in the active medium (as is the case in neodymium-glass lasers).

In "traveling medium" lasers at velocities $v \sim 10-100$ cm/sec, there occurs an effective averaging of the gain and loss coefficients of the individual modes[9], and this leads to regularization of the emis-

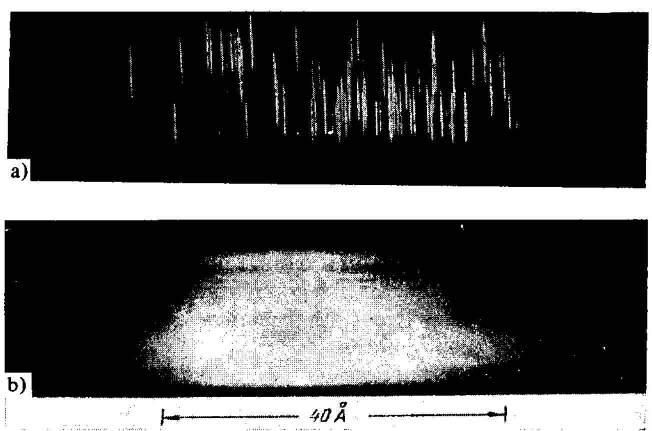

FIG. 4

*The only paper published outside the Soviet Union on "traveling medium" lasers [15] does not contain any significant results, with the exception of some indication of the regularization of the radiation intensity in time.

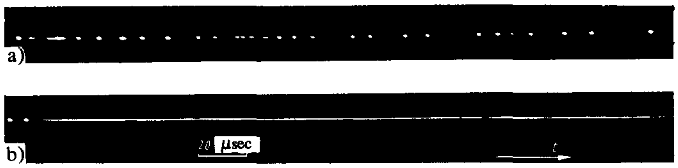

FIG. 5

sion spectra. Smoothing of the gain and loss curves as the active medium moves explains the regularization of the emission of "traveling medium" lasers compared with the emission spectra of ordinary lasers.

One of the unsolved physical problems of quantum electronics is that of spike generation (the third paradox referred to at the start of the article). Here too, investigations of "traveling medium" lasers reveal the decisive role played by inhomogeneities of the active medium.

A record of ruby-laser radiation intensity with the aid of a superhigh speed camera shows that the spiked character of the generation of a laser with a stationary crystal (Fig. 5a) is transformed into continuous generation of a "traveling medium" laser (Fig. 5b). In both cases, a round diaphragm of ~1 mm diameter is placed inside the resonator. This phenomenon, first observed for ruby[10], was subsequently observed also for other media (Nd^{3+} in glass, Nd^{3+} in $CaWO_4$)[11], thus indicating that spike generation in solid-state lasers has a single mechanism. The difference between the conditions under which continuous generation is reached affects only the choice of the diaphragm size.

In the "traveling medium" laser, the influence of inhomogeneities of the medium in the transverse direction, which is connected with the spatial inhomogeneity of the modes in the transverse direction, has not yet been eliminated. Therefore the purpose of introducing into the resonator a diaphragm that limits the cross section of the working part of the medium is to separate a sufficiently homogeneous section of the medium. Experience shows that in order for the radiation to be continuous in time, the diaphragm in the case of ruby should be smaller than 0.7–1 mm, smaller than 1.5 mm in neodymium glass, and smaller than 1.0–1.1 mm in $CaWO_4$ with neodymium.

The motion of the active medium in the direction of the laser axis and the transverse restriction by the diaphragm level out the action of the statistical fluctuations both on the emission spectrum and on the time evolution of the generation. The oscillating system of the laser is stabilized in time both in the longitudinal and in the transverse directions, the inhomogeneities of the pumping over the modes become averaged out, and the generation becomes continuous. The spectral and spatial distributions of the radiation intensity of the laser do not experience fluctuations in time and become regularized[11,12]. Until recently, the attempts at explaining spiked generation were made by using a dynamic model that takes into account the interaction of the laser modes. However, as follows from the foregoing results, the reason for the spike generation is hidden in the statistical fluctuations of the laser-system parameters. This is evidenced also by a recent experiment[13], where it was shown that even single-mode generation (with respect to all indices) of a $CaF_2:Dy^{2+}$ laser has also a spiked character.

These are the main features of the "traveling medium" laser emission. They make it possible to establish the nature and unity of those "paradoxical" phenomena that are inherent in solid-state lasers.

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