KINEMATIC MODULATION OF THE RADIATION INTENSITY FROM A TRAVELING-MEDIUM LASER

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Modulation of radiation due to motion of the active bodies in traveling-medium ruby, neodymium glass, or $CaWO_4:Nd^{3+}$ crystal lasers is investigated experimentally. It is shown that as a rule the output radiation from traveling-medium lasers is modulated at a frequency that is constant for a given velocity. The modulation frequency depends linearly on the velocity of the active medium in the cavity. Some features and causes of modulation of the output radiation from traveling-medium lasers are discussed.

EVEN in the early stage of the investigation of the temporal characteristics of the "traveling medium" laser it was noted that the motion of the active body always leads to a change in the generation kinetics[1]. It was established in[2] that frequently the continuous generation of "traveling-medium" lasers is characterized by strictly periodic oscillations of the intensity with frequency ~1–2 MHz. This becomes manifest, in particular, in the fact that the intensity of the radiation oscillates with a certain frequency that is constant for the given velocity. In this paper we verify the formula proposed in[3] for this frequency.

The experiments were performed with the setup illustrated in Fig. 1. The rods of ruby (8 mm diameter) or KGSS-7 neodymium glass (10 mm diameter) were 12 cm long. The $CaWO_4$ rod, with admixture of ~1 at.% of Nd^{3+} and with compensation with the aid of Na^+ ions, had a length of 60 m and a diameter of 6 mm. The distance between mirrors M_1 and M_2 was 60 cm. The remaining data are shown in the Fig. 1. O_1–O_2–M_3–F comprises an ultrahigh speed photographic camera (SFR-2M). The first lens O_1 (the objective of the camera) projects the image of the surface of mirror M_2, illuminated with the laser light, on the plane where the slit Sl cuts out a narrow band of the image of the illuminated surface of the mirror M_2. The lens O_2 projects the image passing through the slit Sl on to the film F with the aid of rotating mirror M_3. If the rod does not move, then the picture obtained on the film is the time sweep of the radiation-field distribution on the mirror, in the form of individual randomly located spikes having no internal structure (Fig. 2a). On the other hand, if the rod moves with a velocity 55 m/sec, then each spike has an internal structure in the form of equidistant flashes spaced approximately 1 μsec apart.

It is seen in Fig. 2b that these flashes have a complicated structure, as a result of the fact that the active medium is not fully homogeneous, and the laser light passes through the rod, if one can say so, along different channels. In order to cause the light to travel through a single channel, diaphragms D, in the form of round holes having different diameters for the glass and for the ruby, were inserted in the apparatus. The results were striking.

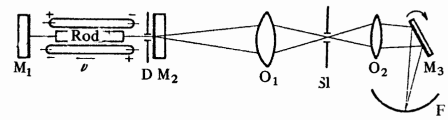

FIG. 1. Experimental setup. The reflection coefficients of mirrors M_1 and M_2 are r_1 = 99.6% and r_2 = 82%, D–diaphragm, the focal lengths of the objectives O_1 and O_2 are f_1 = 21 cm and f_2 = 7.5 cm.

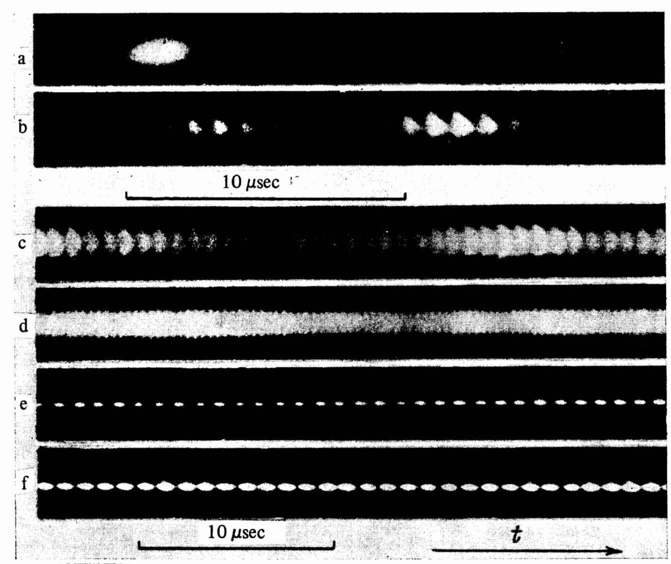

FIG. 2. Time sweeps of the distribution of the "traveling-medium" laser radiation on a mirror: a–neodymium glass without diaphragm, active rod stationary, b–neodymium glass without diaphragm, rod moves with velocity v ~ 55 cm/sec, c–ruby with diaphragm of 0.7 mm diameter, rod moves with velocity v ~ 35 cm/sec, d–ruby with diaphragm of 0.7 mm diameter, rod velocity v ~ 85 cm/sec, e–$CaWO_4:Nd^{3+}$, rod velocity v ~ 55 cm/sec, generation threshold exceeded by a factor 1.5; f–the same as e, but the threshold is exceeded by 10 times, g–laser of Nd^{3+} glass, end faces of rod cut at the Brewster angle.

1. The spikes disappeared and only the fine structure remained (i.e., kinematic modulation). The regularity in the generation regime (i.e., the absence of spikes)[4] makes it possible to observe these oscillations for a prolonged time interval (i.e., from the start of the generation up to the end–approximately 0.5 msec).

2. The fine structure becomes strictly periodic.
3. The periodicity of the structure depends on the wavelength of the generating line and on the rate of motion of the active rod.

Following a suggestion by B. L. Livshitz, the author investigated the dependence of the oscillation frequency (ν) on the velocity (v) of the active body in the resonator. Mukhtarov[3] has shown that the mode loss in the resonator depends on the phases of the modes on the flat boundary (end face) of the active body situated inside the resonator. On this basis, he advanced the hypothesis that when the active body moves inside the resonator, the periodic changes of the phase of the mode on the face causes the losses, and consequently also the intensity of the generated modes, to vary at a frequency

$$\nu = 2v/\lambda. \tag{1}$$

It should be noted that formula (1) is valid only if the condition $\tau_1 \gg \tau_2$ is satisfied, where τ_1 is the characteristic variation time of the resonator parameters ($\tau_1 = \lambda/2v$), and τ_2 is the time of establishment of a standing electromagnetic wave in the resonator, i.e., $\tau_2 \sim L/c$, where L is the resonator length. Thus, formula (1) should take place when the following condition is satisfied

$$v \ll \lambda c/2L. \tag{2}$$

In our experiments, at $\lambda \sim 10^{-4}$ cm and a resonator length $L \sim 100$ cm, the condition (2) yields $v \ll 150$ m/sec; we operated at velocities ~ 1 m/sec, and Eq. (2) was satisfied with a large margin.

Figures 2c and 2d show pictures of the ruby-laser radiation-field distribution on the resonator mirrors as functions of the time. To investigate the nature of the oscillations of the "traveling-medium" laser radiation intensities, it was necessary to regulate the generation regime, so as to observe these oscillations for longer time intervals. This task, as noted above, was solved by introducing inside the "traveling medium" laser resonator a round diaphragm. For ruby the diaphragm diameter was 0.7 mm. In the case shown in Figs. 2c and d, the duration of the laser radiation was ~ 500 μsec. Figure 2c corresponds to the case when the crystal moves with velocity $v \sim 35$ cm/sec, and Fig. 2d—with velocity $v \sim 85$ cm/sec. It is clearly seen here that when the velocity of the active body in the resonator increases, the frequency of the intensity oscillations also increases.

An experiment was performed to verify the influence of the pump on the regime of the observed oscillations.

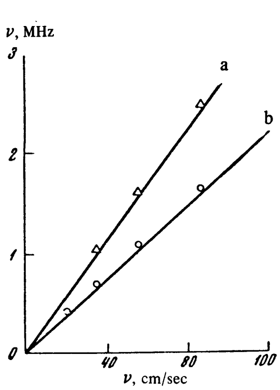

FIG. 3. Dependence of the frequency of the kinematic modulation of the velocity of the active rod: a—for ruby, b—for $CaWO_4:Nd^{3+}$. Experimental points: Δ—ruby, O—$CaWO_4:Nd^{3+}$.

In Figs. 2e and 2f these oscillations correspond to different pumps of the "traveling medium" laser with $CaWO_4:Nd^{3+}$ at a velocity $v \sim 55$ cm/sec. As seen from these photographs, the period of the oscillations is the same at different pump values. In cases e and f the pump energy exceeds the threshold by factors 1.5 and 10, respectively.

Inasmuch as the spike regime has a tendency to go over into the continuous regime when the active body moves[1,2,4], one could expect these oscillations to be of the relaxation type[5-7]. However, the independence of the period of the oscillations of the pumping power (Figs. 2e and 2f) shows that they have a different nature.

We measured the modulation frequencies at different velocities and for different active objects. Figure 3 shows the results of the measurements for ruby and for the $CaWO_4:Nd^{3+}$ crystal. The straight lines a and b were calculated from formula (1) for ruby and $CaWO_4:Nd^{3+}$, respectively.

Thus, experiment shows that, in accordance with formula (1) the period of the oscillations is linearly dependent on the velocity of the active body and is inversely proportional to the wavelength of the radiation, i.e., it depends also on the material of the active rod.

Consequently, the oscillations of the radiation intensity of a "traveling-medium" laser are due to the motion of the active media and the associated modulation of the generated modes. We shall therefore call this kinematic modulation.

In conclusion, notice should be taken of certain features of the phenomenon of kinematic modulation of the radiation of a "traveling-medium" laser.

The investigated active substances can be subdivided into two groups: a) the crystal $CaWO_4:Nd^{3+}$ and neodymium-activated glasses of the type KGSS-7; b) ruby.

In media of group a), the spikes are always modulated at the frequency of the kinematic modulation. For this group, the distribution of the radiation intensity over the mirror was homogeneous. No structures connected with inhomogeneities of the active medium were observed.

We investigated in addition the temporal character of the "traveling-medium" laser emission in the case when the ends of the active rod of LGS-5 were inclined at the Brewster angle to its axis. The velocity of the active rod in the resonator was ~ 80 cm/sec. There was no kinematic modulation.

It should be noted that at low velocities, ~ 10 cm/sec, the phenomenon of kinematic modulation disappears and the usual spiked regime takes place.

The author believes that kinematic modulation in itself does not govern the generation regime, but is only superimposed on the kinetics that is characteristic of the given velocity. At low velocities, the period of the kinematic modulation becomes comparable with or even larger than the duration of the generation spike. Consequently, it is impossible to observe kinematic modulation then.

These experimental data show that the output emission of a "traveling-medium" laser, in the case when the ends and the mirrors are parallel, is always modulated at the frequency of the kinematic modulation. For

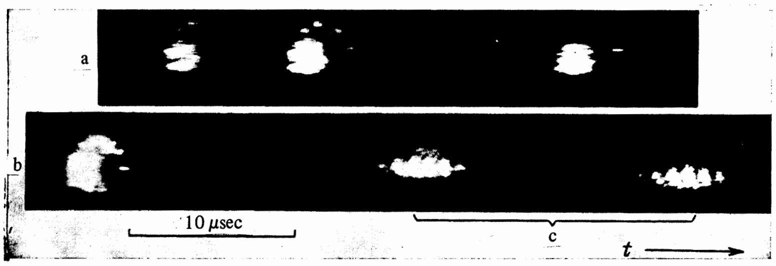

FIG. 4. Time sweeps of the distribution of the "traveling-medium" laser radiation in the absence of the slit (Sl) of the SFR camera (Fig. 1a): a—ruby laser, no diaphragm in the resonator, rod stationary; b, c—ruby rod moves with velocity v ~ 35 cm/sec.

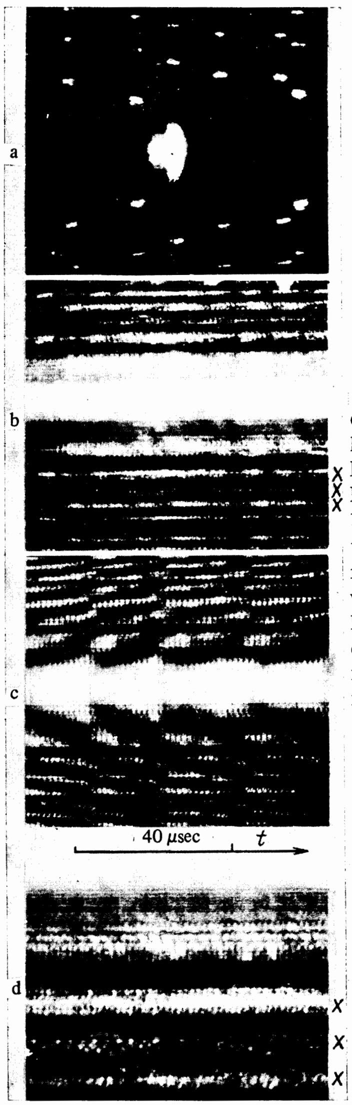

FIG. 5. Time sweep of the emission spectrum of a ruby laser, distance between Fabry-Perot interferometer plates 5 mm. Pump power exceeds threshold by 1.4 times: a—ruby rod stationary, length l = 7.5 cm; b—ruby rod of length l = 7.5 cm, v ~ 30 cm/sec; c—ruby rod of length l = 12 cm, v ~ 30 cm/sec; d—part of photograph b magnified 2X. The corresponding fringes are marked by crosses.

group b), however, there are several super high speed photographs of ruby generation, when there is no kinematic modulation. The point is as follows:

The distribution of the radiation intensity on the "traveling-medium" ruby-laser mirror has a complicated structure. It consists of many generation "channels." This structure is a reflection of the internal inhomogeneity of the crystal. If the spike is of very short duration, i.e., the spike duration is shorter than the period of the kinematic modulation, then the kinematic modulation is not observed. Figure 4a shows the distribution of the intensity over the end face of the crystal when the crystal is at rest; Figs. 4b and c correspond to a crystal moving with velocity ~35 cm/sec. Fig. 4b shows a short-duration spike. We see the extent to which the distribution of the light in Fig. 4b is similar to that in Fig. 4a. Figure 4c shows spikes whose durations are shorter than the period of the kinematic modulation.

As to the superhigh speed photographs of ruby generation in those cases when there is no kinematic modulation, it can be assumed that these photographs with absence of modulation are the consequence of the phase-shifted modulation on different axial modes. To verify this assumption, it is necessary to sweep the ruby generation not only in time but also in frequency, using a Fabry-Perot interferometer. Such experiments were performed. In the other experiments there was observed kinematic modulation. The results are shown in Figs. 5a—c; Fig. 5d is a magnified part of Fig. 5b. Figure 5a shows the generation spectrum with a stationary rod. Each of the spots is a spike corresponding to its own set of wavelengths, sometimes even unresolved by the interferometer. Figure 5b (ruby crystal length l = 7.5 cm) shows the spectrum obtained with the Fabry-Perot interferometer and with the rod moving. This photograph, which contains abundant information, shows how the ruby-laser generation is resolved in wavelength. In the absence of a Fabry-Perot interferometer, owing to the difference in the phase shifts in the kinematic modulation of the different modes, the integral structure may be smeared out. The results obtained with a crystal of 12 cm length are shown in Fig. 5c. We see that in this case, besides kinematic modulation, the results of modulation with a large period. The period of this additional modulation is approximately 25 sec, coinciding in magnitude with the period of the longitudinal elastic oscillations of the crystal[8]. Figure 5c reveals many fine details of the "traveling-medium" laser spectrum.

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235