MODE LOCKING IN FREE-RUNNING RUBY AND NEODYMIUM GLASS LASERS[1)]

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The degree and period of modulation of the output power in the first spike of a free-running laser are investigated experimentally as functions of the number of excited modes and the position of the active rod in the resonator. Neodymium glass and ruby are used as the active medium. It is shown that a decrease in the number of excited modes from $\sim 10^3$ to ~ 10 increases the degree of modulation from ~ 5 to $\sim 40\%$ and that the modulation period does not depend on the position of the active rod in the resonator. The obtained data are discussed on the assumption of phase independence of the individual modes. It is concluded that mode locking does not occur in the active medium of a free-running laser.

ONE of our papers[1] on the time characteristics of laser emission reported the first observation of a periodic modulation of neodymium glass laser emission intensity in the first free-running spike; the modulation was due to beats between neighboring excited modes. Such an emission intensity modulation was also observed by a number of authors to occur in ruby and neodymium glass lasers, both in free-running and Q-switched operation using various mechano-optical and electro-optical shutters. While studying the behavior of the modulation as a function of a number of factors, some authors concluded that there is a mode-locking mechanism in the active medium itself. It seems to us that these conclusions were reached either on the basis of indirect data or from experiments too incomplete to be convincing.

These studies include the investigation of time characteristics of a single free-running spike from ruby and neodymium glass lasers[2-5].

As to references 2—4, their main fault seems to be the inadequate elimination of parasitic mode selection due to various elements of the resonator and causing a reduction in the number of excited modes. Thus random interference can in some cases make the output signal modulation to be large enough even in the absence of mode locking. Consequently the conclusion as to the presence of mode locking can be made only by a statistical analysis of the results. Furthermore the dependence of the fundamental modulation of the frequency of the output signal on the position of the active rod, constituting one of the principal arguments cited in[3] in favor of the existence of mode-locking mechanism in the active medium, was shown by us earlier[1,6] to be due to mode selection caused by the reflection at the end faces of the active rod. With regard to[5] we must say that according to theoretical research[7,8] the method of recording the expected ultrashort pulses (study of the luminescent track in the liquid under two-photon excitation by colliding pulses) cannot be considered reliable, owing to lack of the requisite photometric accuracy.

The purpose of the present work is to verify the occurrence of mode locking in free-running operation (from now on the discussion concerns the first spike).

A resolution of this problem is important first of all to provide an interpretation of the results of experiments in which free-running lasers are used and peak-power data are needed. Furthermore the problem is of independent interest in connection with the effect of the active medium on the stabilization of phase relations among the excited modes. For this purpose we investigated in detail the degree of modulation of ruby and neodymium glass laser emission intensity as a function of the number of excited modes, and the fundamental period of modulation as a function of the position of the active rod in the resonator for a constant width of the emission spectrum. Under mode-locking conditions we should expect that, given a sufficiently large number of modes, $N \gtrsim 10$, the degree of modulation would be close to 100% and would be almost independent of the number of modes, while the period of modulation would depend on the position of the element responsible for mode locking (the active rod in our case) in the resonator, just as it happens in a laser with a passive shutter[9].

Figure 1 shows the diagram of the experimental setup. The resonator with an optical length $L \approx 150$ cm comprised two mirrors ($R_1 \approx 1.0$ and $R_2 \approx 0.7$) on wedge-shaped substrates to eliminate parasitic selection. The active rod AR (ruby of 15 mm dia and 120 mm length or KGSS-7 glass of 10 mm dia and 130 mm length) had end faces cut at the Brewster angle to the resonator axis for the same reason. Diaphragms D_1 and D_2 (2—3 mm dia) were placed within the resonator to separate the TEM_{00q} modes.

The elimination of parasitic selection in the main resonator enables us to obtain sufficiently broad emission spectra[2)], ≈ 7 cm^{-1} for neodymium glass lasers and

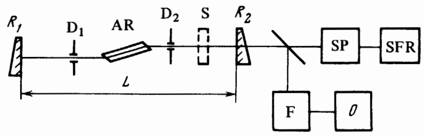

FIG. 1. Diagram of the experimental setup.

[1)] The basic results of this paper were reported to the Fourth All-union Symposium on Nonlinear Optics in Kiev (25-31 October, 1968) and were published in FIAN Preprint No. 3, 1969.

[2)] The spectral width was determined from the intensity distribution curve at the half maximum level.

$\approx 0.25\ cm^{-1}$ for ruby lasers.

The variation in the number of excited modes was achieved by means of various selective elements S installed in the resonator to provide a controlled variation of the width of the generated spectrum. The selective elements were represented by plane-parallel plates of various thicknesses, Fabry-Perot interferometers with various distances between the mirrors and various reflection coefficients, and their combinations. The Fabry-Perot interferometers were placed at an angle to the resonator axis calculated to eliminate the effect of the external plate surfaces on the reflection spectrum[10]. Using the above selectors we were able to measure the spectral width within the limits from $\approx 7\ cm^{-1}$ to $\approx 0.1\ cm^{-1}$ for the neodymium glass laser and from $\approx 0.2\ cm^{-1}$ to $\approx 0.03\ cm^{-1}$ for the ruby laser.

The time characteristics of the first spike emission were recorded with FÉK-09 coaxial photocell F and I2-7 oscilloscope O; the spectral characteristics were recorded with the corresponding SP spectral instrument. Spectra with $\Delta\nu \gtrsim 0.5\ cm^{-1}$ were recorded with a diffraction spectrograph with a dispersion of $d\lambda/dl = 1.1$ Å/mm and resolution of $0.1\ cm^{-1}$; spectra with $\Delta\nu \lesssim 0.5\ cm^{-1}$ were recorded with a Fabry-Perot interferometer with a mirror spacing of $t_{PF} = 1.0$–7.5 cm. When several generation spikes were excited, spectrum of the first spike was brought out with a time-base sweep using an SFR fast photorecorder. It was found that the spectrum of the first spike does not depend on the pumping energy within fairly wide limits.

The number N of the excited modes was determined by photometric analysis of the emission spectra; the intensity distribution curves yielded the values of spectral widths expressed in units of mode spacing of the main resonator (see Fig. 2). We note that the intensity distribution in the generation spectra is close to Gaussian.

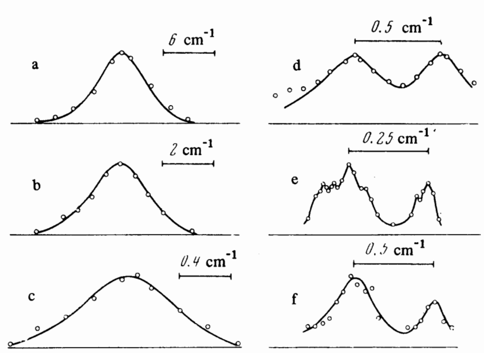

FIG. 2. Typical spectral intensity distributions of the first laser spike emission. Heavy lines – Gaussian distribution for the corresponding values of spectral half-width; circles – experimental data. Neodymium glass laser: a – selector is absent; b – resonator contains Fabry-Perot interferometer of two glass plane-parallel plates (12 mm thick), with plate separation of 0.08 mm, and an angle of inclination of the interferometer to the resonator axis such as to avoid the effect of external plate surfaces on the spectrum; c – resonator contains a Fabry-Perot interferometer with plate separation of 0.24 mm; d – resonator contains a Fabry-Perot interferometer of two mirrors with reflection coefficients of 0.28 and plate separation 0.24 mm; e – resonator contains the same Fabry-Perot interferometer as in (c) and a plane-parallel glass plate 2 mm thick at an angle of 3 - 5° to the axis of the resonator. Ruby laser: f – selector is absent.

In each case of a resonator with a particular selector a series of first spike oscillograms (20–30 pictures) was photographed. The spectral width in a series and consequently the number N of excited modes remained constant with an accuracy of 20–30%.

Since the bandwidth of our recording system (together with the delay line) amounted to about 200 MHz, oscillations with a fundamental frequency $\Omega/2\pi = c/2L \approx 100$ MHz and some neighboring frequencies were separated. Consequently only these frequencies appear in the oscillograms (Fig. 3). On each oscillogram we measured the degree of modulation γ at a frequency Ω equal to the ratio of the maximum modulation amplitude to the signal maximum. The series of γ values was then analyzed for the most probable (most frequent) value of $[\gamma_{prob}]_{exp}$.

As seen from Figs. 2 and 3 (see also the table), a decrease of the number N of excited modes is accompanied by a clear tendency to increase the degree of modulation, i.e., the reverse of the case of mode locking.

We note that the degree of modulation varies within some limits among the oscillograms obtained with the same number of modes. This variation interval and the frequency of deviation from $[\gamma_{prob}]_{exp}$ depend on the

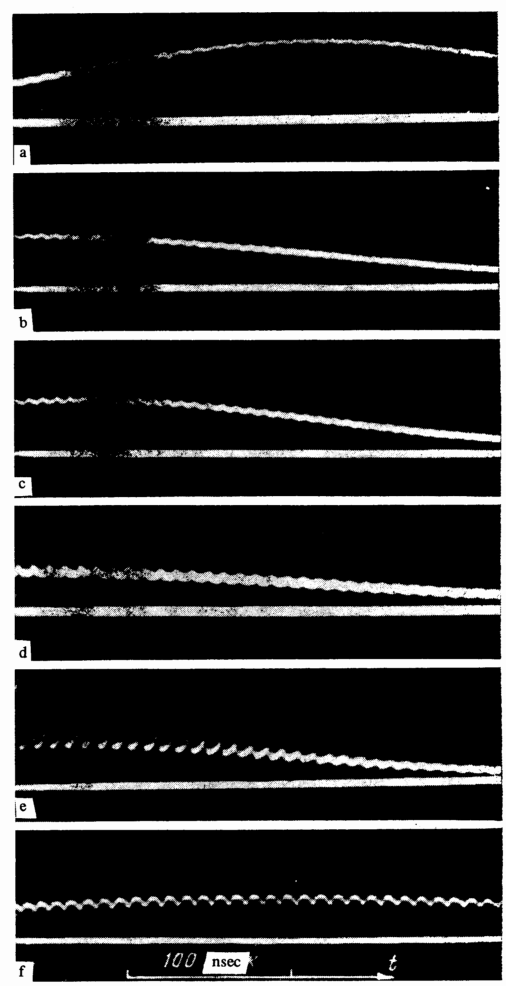

FIG. 3. Typical oscillograms of the first laser spike. Cases a - f correspond to those in Fig. 2.

number of modes in the spectrum, increasing as this number decreases. By way of an example, out of 25 oscillograms for $N \approx 800$ we get $[\gamma_{prob}]_{exp} \approx 10\%$, $\gamma_{max} = 20\%$, $\gamma_{min} = 5\%$; for $N \approx 100$ we get $[\gamma_{prob}]_{exp} \approx 24\%$, $\gamma_{max} = 35\%$, $\gamma_{min} = 10\%$.

As controls we prepared oscillograms and emission spectra of a giant pulse obtained by installing saturable filter cells in the resonator (without affecting its geometry). In this case the spectral width remained almost the same but the nature of its time dependence changed sharply: we regularly observed a series of pulses with a period of 2L/c and a degree of modulation close to 100% that is typical of mode locking (Fig. 4).

We note that the observed relationships (the fundamental modulation frequency and modulation degree) were not affected by the position of the active rod. Oscillograms and spectral widths were obtained for all selectors with the active rod positioned in various regions of the resonator. These results showed that the spectral width, the fundamental modulation frequency, and the degree of modulation do not depend on the position of the rod.

In particular when the active rod was placed in the center of the resonator or near a mirror, the fundamental frequency of modulation was $\Omega = \pi c/L$, while according to[3] a doubled frequency should be observed in such a medium in mode-locked operation when the active rod is in the center of the resonator.

To explain the obtained results we consider the interference of a large number of equidistant modes with random phases and Gaussian distribution of amplitudes entering a square-law receiver. The field in this case has the form

$$E = \sum_{n=-M/2}^{M/2} A_n \cos\left[(\omega_0 + n\Omega)\left(t - \frac{x}{c}\right) + \varphi_n\right], \qquad (1)$$

where

$$A_n = A_0 \exp\left[-\left(\frac{2n}{N}\right)^2 \frac{\ln 2}{2}\right]$$

$\omega_0 + n\Omega$ are the mode frequencies, φ_n are random phases, and M is the total number of modes, while $M > N \gg 1$. The response of the square-law receiver is proportional to

$$\overline{E^2} = B_0 + \sum_{s=1}^{M} B_s \cos\left[s\Omega\left(t - \frac{x}{c}\right) + \psi_s\right], \qquad (2)$$

where

$$B_0 = {}^1/_2 \sum_{n=-M/2}^{M/2} A_n^2$$

is a constant component and

$$\psi_s = \arg\left[\sum_{n=-M/2}^{M/2} A_n A_{n+s} \exp i(\varphi_{n+s} - \varphi_n)\right],$$

$$B_s = \operatorname{mod}\left[\sum_{n=-M/2}^{M/2} A_n A_{n+s} \exp i(\varphi_{n+s} - \varphi_n)\right]$$

are functions of random phases.

In view of the large number of interfering modes ($N \gg 1$) the probability distribution for B_s can be regarded as normal. Furthermore, since we are only interested in modulation at the frequency Ω, we can

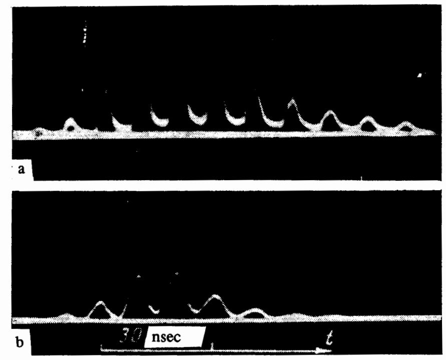

FIG. 4. Oscillograms of a giant pulse obtained by placing a saturable filter cell in the resonator; a – neodymium glass laser, intitial cell transmission 0.55; b – ruby laser, initial cell transmission 0.45.

limit our consideration to B_1 only. In this case the expression for probability density B_1 has the form

$$dp(r < B_1 < r + dr) = 2\pi p(r) r dr, \qquad (3)$$

where

$$p(r) = \frac{\sqrt{2}}{\pi} \frac{1}{A_0^4 N} \exp\left[-\frac{\sqrt{2} r^2}{A_0^4 N}\right].$$

We then find the most probable value of the degree of modulation at the frequency Ω: $\gamma = 2B_1/(B_0 + B_1)$ at which the function $dp(y < \gamma < y + dy)/dy$ reaches a maximum. In the approximation in which $N \gg 1$, this value turns out to be

$$\gamma_{prob} \approx 2 / \sqrt{3 + 0{,}8\,N}. \qquad (4)$$

Consequently in the case of totally unsynchronized modes the most probable value of the degree of modulation at the frequency Ω depends fairly strongly on the total number of excited modes and can become quite a small quantity when the number of modes is large.

At the same time in mode-locked operation the degree of modulation, as noted above, should always be near 100%; this is what we observed (see Fig. 4) when we placed a bleached filter cell in the resonator (without affecting the resonator geometry and with an almost identical spectral width).

The table lists the results of analyzing the experimental data for $[\gamma_{prob}]_{exp}$ against various numbers N of excited modes and the corresponding values of γ_{prob} obtained from (4).

As we can see from the table there is a good agreement between the experimental and theoretical values of γ_{prob}.

We also investigated the case of $N \approx 10$ for a ruby laser (Fig. 5). The measured value of $[\gamma_{prob}]_{exp} \approx 40\%$ differed here from that obtained according to (4): $\gamma_{prob} \approx 60\%$. However the difference was due to the fact that (4) was not applicable to the given spectrum, since the amplitude distribution was not smooth but always contained one or two more intensive modes in the spec-

	Active rod of KGSS-7					Active ruby rod
N	$(2\div3)\cdot10^3$	800±200	270±60	100±20	35±7	70±10
$[\gamma_{prob}]_{exp}$, %	5±3	10±3	16±5	24±5	29±5	25±5
γ_{prob}, %	4.4÷5.6	8±1	14±2	22±2	36±4	27±2

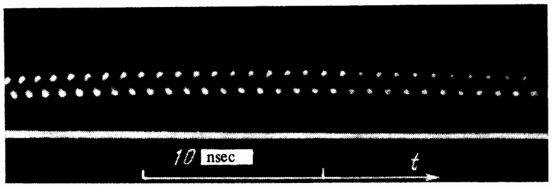

FIG. 5. Typical oscillogram of the first ruby laser spike. Resonator contains a glass plate 1.5 mm thick with a 16% mirror on one side. The spectral width is $\Delta\gamma \approx 10\delta\gamma$, where $\delta\gamma = 1/2L$, and there always are one or two modes in the spectrum whose intensity exceeds the remaining modes 1.5–2.0 times. Time axis scale is 100 nsec.

trum. Similar causes can be held responsible for the difference of $[\gamma_{prob}]_{exp}$ from γ_{prob} in the case of $N \approx 35$ in a neodymium-glass laser (see Fig. 2e).

Therefore all the above facts serve as a foundation for the conclusion that in a solid state free-running laser the mode locking mechanism is either absent or very weak, regardless of the nature of the luminescence line broadening, so that the phases of the individual modes can be considered practically independent in free-running generation[3)].

The independence of phases of individual modes is also indicated by the fact that the degree of modulation of the laser emission intensity does not remain constant at a given spectral width but varies within a certain range whose size increases with decreasing number of modes. Therefore when the number of modes is small we can relatively frequently observe cases of a large degree of modulation that can even approach 100%.

[3)] The same conclusion based on a theoretical examination of processes in a laser with and without a passive shutter is reached by Letokhov [11].

Those may have been the cases that led some authors[2-4] to the conclusion about mode locking in ruby and neodymium glass active media.

In conclusion the authors thank V. A. Babenko for help with the experiment.

[1] V. I. Malyshev and A. S. Markin, Zh. Eksp. Teor. Fiz. 50, 339 (1966) [Sov. Phys.-JETP 23, 225 (1966)].
[2] M. Michon, J. Ernest, and R. Auffret, Phys. Lett. 21, 514 (1966).
[3] H. Statz, G. A. DeMars, and C. L. Tang, J. Appl. Phys. 38, 2212 (1967).
[4] V. V. Korobkin and M. Ya. Shchelev, Zh. Eksp. Teor. Fiz. 53, 1230 (1967) [Sov. Phys.-JETP 26, 721 (1968)].
[5] S. L. Shapiro, M. A. Duguay, and L. B. Kreuzer, Appl. Phys. Lett. 12, 36 (1968).
[6] V. I. Malyshev and A. S. Markin, Zh. Prikl. Spektrosk. 6, 471 (1967).
[7] T. I. Kuznetsova, Preprint FIAN, No. 47, 1968; Zh. Eksp. Teor. Fiz. 55, 1453 (1968) [Sov. Phys.-JETP 28, (1969)].
[8] H. P. Weber, Phys. Lett. **27A**, 321 (1968).
[9] T. I. Kuznetsova, V. I. Malyshev, and A. S. Markin, Zh. Eksp. Teor. Fiz. 52, 438 (1967) [Sov. Phys.-JETP 25, 286 (1967)].
[10] V. I. Malyshev, A. S. Markin, and A. A. Sychev, Zh. Prikl. Spektrosk. 7, 662 (1967).
[11] V. S. Letokhov, Preprint FIAN, No. 106, 1968; Zh. Eksp. Teor. Fiz. 55, 1943 (1968) [Sov. Phys.-JETP 28, 1026 (1969)].

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