NONSTATIONARY PHENOMENA IN A LASER WITH INTERACTING MODES

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Synchronous generation of modes in a gas laser during self-locking of the modes and during resonator loss modulation at the frequency of intermode beats is investigated experimentally. It is found that in the first case the transient time increases with increase of the laser emission intensity and in the second case it is determined by the magnitude of the modulating potential. A numerical analysis of the process of transition to a self-locking regime is performed.

1. INTRODUCTION

MUCH attention is being paid at present to investigations of lasers with synchronized modes. Interest in this question is motivated by the fact that when the modes are synchronized the laser emission is a sequence of extremely narrow pulses. Their duration is of the order of $2\pi/\Delta\omega$, and their amplitude exceeds by approximately N times the average laser intensity ($\Delta\omega$—width of emission line, N—number of synchronized modes).

There are a number of published articles describing experiments on mode synchronization of a gas laser. The interaction and synchronization of laser modes may be caused by various circumstances. Thus, McClure[1] investigated conditions under which mode synchronization is produced by the nonlinear properties of the amplifying medium. The theory of this effect was presented by Lamb[2]. A correlation method was used in[3] to measure the duration of the pulses generated by a self-synchronized laser. Mode synchronization with modulation of the dielectric constant of the resonator was also investigated[4]. A connection was established between the synchronization region and the magnitude of the modulating voltage[4], and the causes of the shift of the emission spectrum under external synchronous modulation of the phase of the pulse signal were investigated[5]. Mode synchronization with modulation of the resonator loss is the subject, for example, of a paper by Hargrove et al.[6].

All these papers deal with continuous operation of the synchronized lasers. On the other hand, the establishment of a synchronous regime during the onset of laser generation has not been described, in so far as we know. At the same time, investigations were reported in which synchronization of pulsed solid-state lasers was effected with the aid of loss modulation[7] as well as by placing a saturable filter inside the resonator[8]. It is reported, for example, that this yielded pulses of duration 2×10^{-13} sec and power 10^{10} W. In this connection, it becomes important to investigate the establishment of the synchronous regime in a laser during the onset of generation.

A detailed analysis of the processes of establishment of the synchronous regime in a pulsed solid-state laser is as a rule difficult, so that it is of interest to investigate the corresponding processes in gas lasers. In addition, an investigation of the process of establishment of the mode synchronization regime of a gas laser is of interest in itself, since it makes it possible to obtain certain quantitative estimates of the efficiency of the summary interaction of several modes.

In the present study we investigated the following: 1) establishment of the mode self-synchronization regime in a laser using an He-Ne mixture, $\lambda = 0.63\ \mu$; 2) establishment of the forced synchronization regime in the same laser with the resonator loss modulated at a frequency close to the frequency of the intermode beats. We have also integrated numerically the equations describing the establishment of the laser mode self-synchronization regime.

2. ESTABLISHMENT OF LASER MODE SELF-SYNCHRONIZATION REGIME

We have used in the experimental setup a laser with a resonator made up of a spherical mirror (radius 2 m) and a plane mirror, spaced L = 170 cm apart. Only TEM_{00p} modes separated by 85 MHz were excited in the resonator. The intermode beat-frequency signal obtained from a photomultiplier, was observed with a spectrum analyzer. When the laser modes were self-synchronized, this signal increased by 20—30 dB. In addition, this signal was detected and was fed to the input of a two-beam oscilloscope with bandwidth 3 MHz. A signal from a low-frequency photomultiplier, which was used to measure the average laser emission intensity, was fed to the second input of the oscillograph. The laser emission was interrupted by means of a mechanical chopper placed between the mirrors. The minimum lasing interruption time was 1 μsec, and there was no lasing for 30 μsec. Figure 1a shows a typical oscillogram of the establishment of the self-synchronization of the modes. The upper beam characterizes the variation of the laser emission intensity (the left-hand pulse shows the interruption of the emission), and the lower characterizes the amplitude of the intermode beats (the amplitude decreases in the downward direction).

The laser self-synchronization regime was attained either by adjusting one of the mirrors, or by introducing additional losses into the resonator in some manner. It was found that the time of establishment of the mode self-synchronization regime depends strongly on the laser emission intensity. Thus, reducing the emission intensity to one half the maximum value at which self-synchronization is still possible leads to a decrease in the transient time from $\tau = (3-4) \times 10^{-3}$ sec to

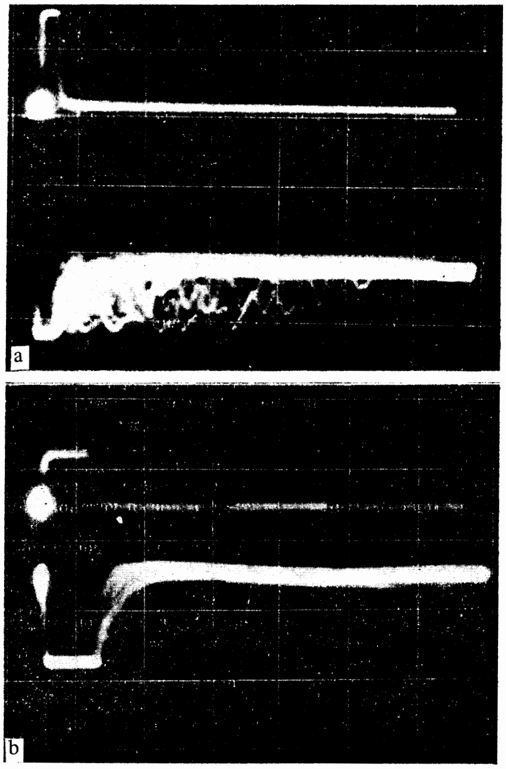

Fig. 1. Establishment of synchronous intermode beats in a laser. Upper trace – emission intensity, pulse on the left – interruption of emission pulse duration – 30 μsec. Lower trace – amplitude of signal at the frequency of the intermode beats. a – mode self synchronization; b – mode synchronization under loss modulation, modulating voltage V_m = 40 V, dc bias voltage 300 V.

$\tau = (1-2) \times 10^{-3}$ sec. It can be assumed that the increase in the transient time with increasing lasing intensity is connected with the fact that this brings into the lasing process the modes that are at the edges of the Doppler line, for which the frequency pulling is larger than for the central modes. It should be noted that the transient time experiences considerable fluctuations (of the same order as τ); these fluctuations decrease with increasing laser emission intensity, and are probably connected with charge fluctuations.

3. ESTABLISHMENT OF THE MODE SYNCHRONIZATION REGIME BY MODULATING THE RESONATOR LOSS

This experiment differed from the preceding one in that an electrooptic KDP crystal was placed inside the laser cavity in such a way that its Z axis coincided with the resonator axis, and one of the axes, X or Y, coincided with the radiation polarization. The electric field was applied to the crystal along the Z axis with the aid of ring electrodes. We applied to the crystal 300 V dc, thereby introducing a constant loss of 1% into the laser cavity, and a modulating signal of a frequency close to the frequencies of the intermode beats. If the modulating signal was $V_m < 10$ V, then competition was observed between two processes, self-synchronization and the synchronization connected with the loss modulation. An increase in the modulating signal causes the synchronization to occur exclusively as a result of the loss modulation. Thus, if the modulating signal is V_m = 20 V, then the time necessary to establish the synchronous regime is ~30 μsec, if V_m = 40 V, this time is ~10 μsec. An oscillogram of the process for the latter case is shown in Fig. 1b.

When the modulating signal is increased, the transient time decreases further, in proportion to V_m^{-1}, and amounts to 1–2 μsec at V_m = 200 V; under such conditions the laser synchronization region is 60 kHz. An increase in the deviation between the frequencies of the modulating signal and the intermode beats, when the detuning still does not exceed the size of the synchronization region, leads to a decrease of the signal at the intermode-beat frequency and to a decrease of the emission intensity. Outside the synchronization region, oscillations are observed of the laser emission intensity and of the signal at the frequency of the intermode beats with the detuning frequency. The laser intensity changes in this case by 5–10%, and the intermode-beat amplitude by 100%.

It is of interest to note that during each triggering of the laser, the oscillations of the emission intensity and of the intermode-beat-frequency signal have the same phase, corresponding to the maximum amplitude of the intermode beats. This is apparently due to the fact that at the start of the lasing, when the mode amplitudes are small, the synchronization region is larger and the relative phases have time to become established. An increase in the laser emission intensity leads to a decrease in the synchronization region and to the occurrence of synchronous oscillations of the relative phases of the different modes, the process beginning each time with the same previously-established phases.

4. ANALYSIS OF THE SYNCHRONOUS REGIME TRANSIENT

The establishment of synchronized oscillations in a three-mode gas laser was investigated theoretically by Lamb[2]. Generalizing the equations derived in his paper to the case of an arbitrary number of modes, we obtain a system of differential equations for the relative phases $\Phi_n = 2\varphi_n - \varphi_{n-1} - \varphi_{n+1}$, in the form

$$\begin{aligned} d\Phi_n/dt = \varkappa_n &+ (2E_{n+1}^2 E_{n+2} E_n^{-1} \eta_{n+1,\,n+2} - E_n E_{n+2} \eta_{n,\,n+2}) \sin\Phi_{n+1} \\ &+ (2E_{n+1} E_{n-1} \eta_{n-1,\,n+1} - E_n^2 E_{n+1} E_{n-1}^{-1} \eta_{n,\,n+1} - E_n^2 E_{n-1} E_{n+1}^{-1} \eta_{n,\,n-1}) \sin\Phi_n \\ &+ (2E_{n-1}^2 E_{n-2} E_n^{-1} \eta_{n-1,\,n-2} - E_{n-2} E_n \eta_{n-2,\,n}) \sin\Phi_{n-1} \\ &- E_{n-2}^2 E_{n-3} E_{n-1}^{-1} \eta_{n-2,\,n-3} \sin\Phi_{n-2} - E_{n+2}^2 E_{n+3} E_{n+1}^{-1} \eta_{n+2,\,n+3} \sin\Phi_{n+2}. \end{aligned} \tag{1}$$

Here E_n is the amplitude of the n-th mode, κ_n characterizes the mode pulling, and the quantities $\eta_{n,n-1}$, $\eta_{n,n+1}$, and $\eta_{n-1,n+1}$ determine the nonlinear interaction. In the case when k modes are excited in the laser, this system contains k – 2 equations.

The system (1) cannot be solved in quadratures, and was therefore numerically integrated with the "Ural" computer in order to investigate the behavior of the relative phases during the self-synchronization process. It was assumed that the gain of the gas mixture at the center of the Doppler line is 10% for a weak signal, and the optical loss in the resonator is 8.5%. Under such conditions, seven longitudinal modes are excited in the laser, if the amplification line width is such that $\Delta\omega L/\pi c$

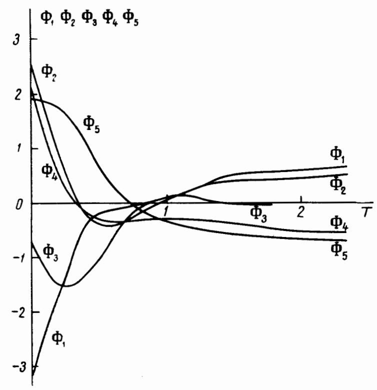

Fig. 2. Establishment of relative phases during the course of laser self synchronization, $T = t\kappa_m$.

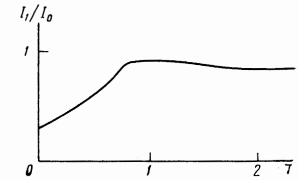

Fig. 3. Establishment of signal at the intermode-beat frequency during the course of laser self synchronization, $T = t\kappa_m$.

= 17. The mode pulling values κ_n were determined from the Kramers-Kronig relations. The coefficients $\eta_{n,n-1}$, $\eta_{n,n+1}$, and $\eta_{n-1,n+1}$, which describe the mutual influence of the modes in the case when the amplifying medium fills the entire resonator, are connected by the relation $\eta_{n,n+1} = \eta_{n,n-1} = -(1/2)\eta_{n-1,n+1}$, but their numerical value is unknown at present. This uncertainty affects the scale of the process and the values of the stationary phases. For numerical integration of the system (1), the values of η were chosen such that $-\eta_{n,n-1}E_0^2\kappa_m^{-1} = 1$, where κ_m determines the maximum generation frequency pulling. Plots showing the variation of the relative phases in time during laser self-synchronization, drawn for one variant of the initial conditions, are shown in Fig. 2. If the laser is synchronized, then its emission field, which is a superposition of the fields of the individual modes, is represented in the form

$$E(t) = e^{i\omega_0 t}\sum_{n=-k}^{n=k} E_n e^{i(n\Omega t+\varphi_n)}. \quad (2)$$

Here ω_0 is the frequency of the center of the emission line. In this case the intensity emitted by the laser is modulated at the frequencies Ω, 2Ω, 3Ω, ..., i.e.,

$$I(t) = E(t)E^*(t) = I_0 + I_1\cos(\Omega t + \psi_1) + I_2\cos'(2\Omega t + \psi_2)\ldots \quad (3)$$

Substituting (2) in (3), we obtain equations for the different spectral components of the emission intensity:

$$I_0 = \sum_{n=-k}^{n=k} E_n^2, \quad I_1 = \Big(\sum_{n=-k}^{n=k-1} E_n^2 E_{n+1}^2 + \sum_{\substack{l=-k\\ l\neq m}}^{l=k-1}\sum_{m=-k}^{m=k-1} E_l E_{l+1} E_m E_{m+1}\cos\sum_{r=l+1}^{r=m}\Phi_r\Big)^{1/2},$$

$$I_2 = \Big[\sum_{n=-k}^{n=k-2} E_k^2 E_{k+2}^2 + \sum_{\substack{l=-k\\ l\neq m}}^{l=k-2}\sum_{m=-k}^{m=k-2} E_l E_{l+2} E_m E_{m+2}\cos\sum_{r=l+1}^{r=m}(\Phi_r + \Phi_{r+1})\Big]^{1/2} \quad (4)$$

It follows therefore that in the case when the modes are equidistant the amplitudes of the intermode beats at the frequencies Ω, 2Ω, etc. depend on the relative phases and vary during the course of the establishment of the synchronous regime. Figure 3 shows the dependence of the mode-beat amplitude at the frequency Ω on the time for the same conditions under which the plots of establishment of the relative phases, shown in Fig. 2, were obtained.

To find the dependence of the relative phases on the time during the establishment of the synchronous laser regime, in the case of resonator-loss modulation, we set up a system of equations of the type (1) and solved it with a computer by means of the same program as for the system (1). We found that in this case the motion of the relative phases has the same character as in self-synchronization, but the scale of the process is determined by the magnitude of the modulated losses or, which is the same, by the modulating voltage.

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