PHASE SELF-MODULATION AND SELF-FOCUSING OF NEODYMIUM LASER RADIATION WITH MODE LOCKING

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We have observed self-focusing and phase self-modulation of radiation in the active element of a neodymium laser [1, 2] operating in the mode-locking regime, and we show in this paper that these effects greatly influence the character of the generation of this laser.

To estimate the nonlinear changes occurring in the refractive index of the laser active element in the case of self-modulation and self-focusing, let us consider the propagation of a light pulse that varies like

$$E(t) = E_0 \exp\{i\omega_0 t\} \exp\{-(t/\tau_0)^2\}$$

(E_0 is the amplitude, ω_0 the field frequency, and τ_0 the pulse duration), in a medium with a refractive index that depends on the intensity, $n = n_0 + n_2|E|^2$. If n_2 has a short relaxation time compared with the pulse duration, then the phase shift (at small distortions of the envelope) occurring when this pulse propagates in a medium of length L will equal [3]

$$\delta\phi(t) = -\frac{2\pi}{\lambda n_0} L \delta n(t),$$

where $n(t) = n_2|E(t)|^2$ and λ is the radiation wavelength. Then the field emerging from the medium can be represented in the form

$$E_{\text{out}}(t) = E(t)\exp\{i\delta\phi(t)\}.$$

The spectral distribution of the output radiation is determined by a Fourier integral

$$F(\Delta\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E_0 \exp\{i\Delta\omega t + i\alpha\exp[-2(t/\tau_0)^2]\}\exp\{-(t/\tau_0)^2\}dt,$$

where $\Delta\omega = \omega - \omega_0$; $\alpha = 2\pi L n_2 E_0^2/\lambda n_0$. Figure 1 shows the distributions of the spectrum $|F(\Delta\omega)|^2$ obtained by numerical calculation for different values of α. The calculation was carried out only for small values of the parameter α, for in the case of large α it is necessary to take into account the change of the field due to self-focusing. Indeed, it follows from the calculation that noticeable changes of the spectrum should occur at $\alpha \simeq 2$, corresponding to $\delta_n \simeq 1.6 \times 10^{-6}$ (for L = 30 cm and $\lambda = 10^{-4}$ cm). On the other hand, the necessary change of the refractive index of the medium for self-focusing of the radiation over a length L is [4]

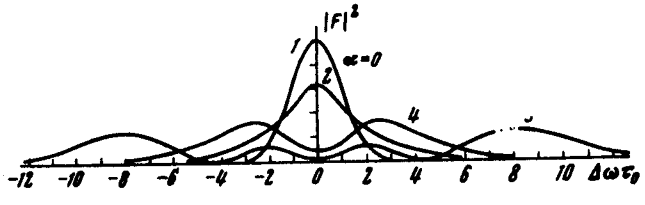

Fig. 1. Computer-calculated densities of the spectrum $|F(\Delta\omega)|^2$ at different values of the phase-modulated parameter α. τ_0 is the duration of the initial light pulse.

$$L = (a/2)\sqrt{n_0/n_2}\,(E_m - E_{\text{cr}})^{-1},$$

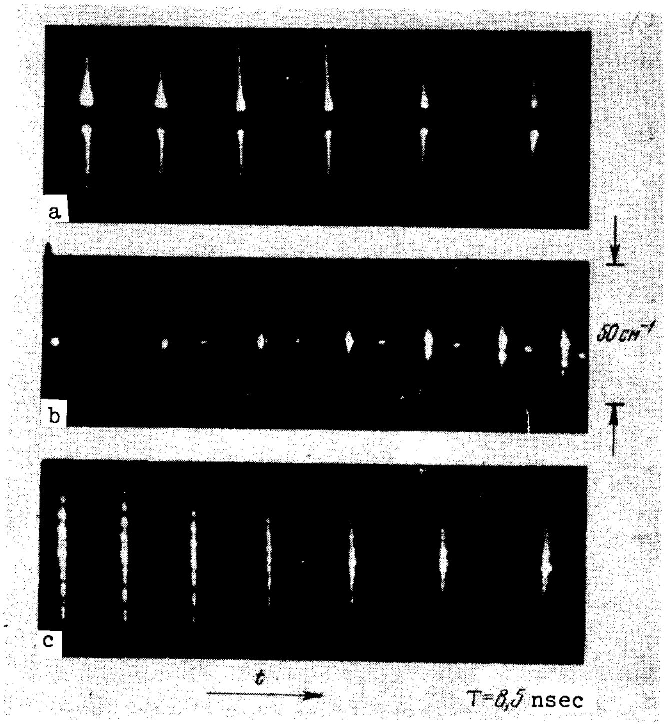

Fig. 2. Time sweeps of the spectrum of the self-synchronization spikes for weak (a) and strong (b and c) light fields.

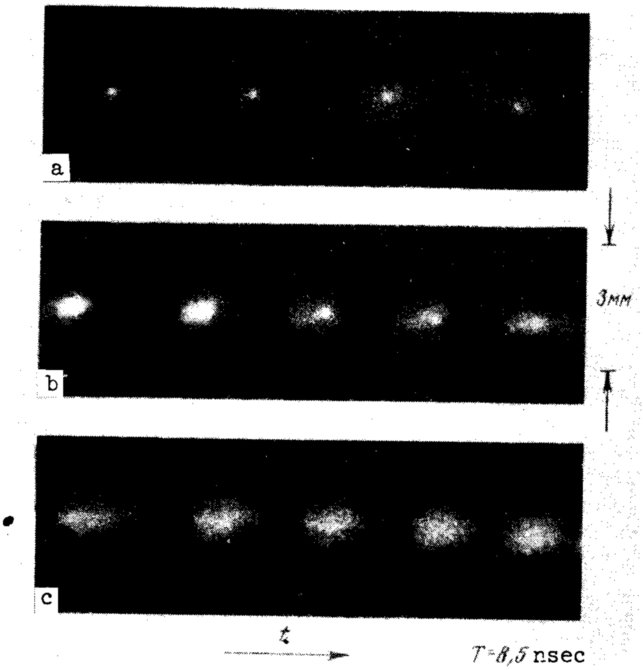

Fig. 3. Distribution of radiation intensity over the diaphragm in the laser resonator for different stages of a giant pulse.

where a is the beam radius, $E_{cr} = \lambda/2\pi a\sqrt{n_2}$ is the critical field intensity, and E_m is the required field intensity, yields

$$\delta n_m = n_2 E_m^2 \approx 5\cdot 10^{-6}$$

(for $a = 10^{-1}$ cm). We note that a change $\delta n \approx 0.5 \times 10^{-6}$ in the refractive index is obtained, for example, at $n_2 \approx 10^{-13}$ cgs esu and at a power ∿1 GW/cm^2.

Thus, both phase self-modulation and self-focusing of the radiation should be observed for $\delta n \simeq 5 \times 10^{-6}$.

We used for the experiment a laser with a ring resonator (T = 8.5 nsec). The length of the active element was 30 cm. The Q-switch was dye No. 3955 dissolved in nitrobenzene in a cell 2 mm thick. The axial modes were separated with a diaphragm of 2.7 mm diameter.

The spectral composition of the radiation and its time variation were investigated, as before [5], with a diffraction spectrograph and an electron-optical camera (EOC) operating in the linear-sweep mode. In the investigations of the field-intensity-distribution changes connected with self-focusing, images of a diaphragm placed in the laser resonator were projected with magnification on the photocathode of the EOC (the distance from the diaphragm to the active element was ∿5 cm). The linear sweep rate and the magnification were chosen such as to prevent the images of the field distribution over the diaphragm for each spike of the self-synchronization from becoming superimposed on the screen of the EOC. Since the spike duration was quite small (∿(2 - 5) $\times 10^{-12}$ sec), there was no smearing of the image and the resolution amounted to about 10 lines/mm.

Figures 2a - 2c show sweeps of the spectra pertaining to different flashes and for different delays in the triggering of the EOC. Figure 2a shows the spectrum for small values of E_0, obtained by increasing the initial transmission of the saturable filter. The central part of the spectrum is covered by the diaphragm, and there is no structure whatever in the wings of the spectrum (accurate to $\sim$0.5 cm^{-1}). Figures 2b and 2c were obtained for larger values of E_0 at the start and the middle of the pulse, respectively. The appearance of the structure of the spectrum can be clearly seen, and the character of its development in Fig. 2b agrees fully with the calculated one (Fig. 1) and corresponds to an increase of α for each succeeding self-synchronization spike.

Figures 3a - 3c show successive pictures of the distribution of the field over the diaphragm in the laser resonator. Since in this case the distance from the laser to the EOC was increased to obtain sufficient spatial resolution, and the time delay of camera operation ($\sim$20 nsec) did not make it possible to photograph the initial stage of generation development, the pictures shown correspond to the time instants 20, 50, and 150 nsec following the operation of the EOC. The pictures demonstrate the appreciable redistribution of the radiation intensity at large values of the field in the resonator. We note that the laser-emission intensity had a uniform distribution in the free-generation regime.

Thus, phase self-modulation explains to a considerable degree the structure of the spectrum of a mode-locked laser [5], and also the discrepancy between the experimental durations of ultrashort pulses obtained by two-photon methods and from the width of the spectrum.

It must be noted that the main contribution to the phase modulation is made by the change of the refractive index of the active element. The change of the refractive index in the nitrobenzene (the solvent of the saturable dye) plays a much smaller role. At a cell thickness of 2 mm, self-focusing in nitrobenzene calls for $\delta n \approx 10^{-1}$, which is much larger than the δn necessary for self-focusing in glass. In addition, the relaxation time of n_2, determined by the Kerr effect for nitrobenzene, is about $(3 - 5) \times 10^{-11}$ sec [6, 7]. On the other hand, when light pulses of duration $\tau_0 \approx 10^{-12}$ sec are used, the mechanism of the nonlinearity of n has apparently an essentially electronic character, and n_2 has the same order of magnitude for glasses as well as for most liquids.

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