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CONTROL OF LASER RADIATION PARAMETERS

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Structure of picosecond pulses of a *Q*-switched and mode-locked diode-pumped Nd : YAG laser

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Abstract. **The pulse duration of a diode-pumped Nd : YAG laser, in which *Q*-switching with mode-locking (QML regime) is achieved using a spherical mirror and a travelling-wave acousto-optic modulator, is directly measured with a streak camera. It is found that the picosecond pulses can have a non-single-pulse structure, which is explained by excitation of several competing transverse modes in the *Q*-switching regime with a pulse repetition rate of 1 kHz. In the case of cw mode-locking (without *Q*-switching), a new (auto-QML) regime is observed, in which the pulse train repetition rate is determined by the frequency of the relaxation oscillations of the laser field while the train contains single picosecond pulses.**

Keywords: *Nd:YAG laser, diode laser, Q-switching, mode-locking, relaxation oscillations.*

1. Introduction

In [1–3], an original method was proposed to obtain *Q*-switching simultaneously with mode-locking in a solid-state laser using a spherical mirror (SM) and a travelling-wave acousto-optic modulator (AOM) (SMAOM method). In this case, as well as in most other studies, the duration of picosecond laser pulses was measured using an optical correlator with recording second harmonic pulses generated in a nonlinear crystal or with recording the two-photon absorption current in a photodiode. As is known (see, for example, [4, 5]), such measurements are indirect and require an assumption on the pulse shape, including its composition.

In the present work, we performed direct measurements of the pulse duration of a diode-pumped *Q*-switched and mode-locked (QML regime) Nd : YAG laser using a streak camera under the conditions of works [1, 2]. A non-single-pulse structure of picosecond pulses is revealed and explained.

2. Measurement scheme and experimental results

The experimental scheme of a laser with a four-mirror *Z*-shaped cavity is shown in Fig. 1. The active Nd : YAG rod 2 mm in diameter with and a length λ = 63 mm was transversely pumped by a diode at a wavelength of 808 nm. The cw pump current was 18.5 A. The radii of curvature of spherical mirrors M1, M2, M3 and M4 were 300, –900, 200 and 150 mm, respectively. The reflection coefficients of mirrors M2–M4 at the laser wavelength λ = 1064 nm exceeded 99.5%. The reflection coefficient of the output mirror M1 at the wavelength λ = 1064 nm was 14%. The optical cavity length L was approximately 151 cm. The AOM was placed close to the output spherical mirror M1 at the Bragg angle (θ_B) to the optical axis of the cavity. The modulator centre was spaced from the reflecting surface of the mirror by a distance equal to the radius of curvature of this mirror. The laser operation in the *Q*-switching regime with simultaneous mode-locking occurred when a signal with the driving frequency f = 49.5 MHz equal to half the intermode distance [$c/(4L) = f$] was applied with a switching rate of 1 kHz to the piezoelectric transducer of the AOM. The output laser radiation was focused by lens L1 into an LBO nonlinear crystal 20 mm long (type I phase matching). Plane mirrors P1 and P2 were highly reflecting at the wavelengths λ = 1064 and 532 nm, while mirror P3 had a high reflection at λ = 1064 nm and a high transmission at λ = 532 nm. Thus, using the system of mirrors P1–P3, the second-harmonic radiation was sent to an Agat-SF3M streak camera and the fundamental-wavelength radiation was directed to an electronic triggering circuit (ETC), which divided the *Q*-switching frequency (i.e., the pulse train repetition rate equal to 1 kHz) by 125 and formed individual pulses. As a result, the Agat camera was triggered by single pulses with a duration of ~2 ns and a repetition rate of 8 Hz. Simultaneously, the radiation passed through the dense mir-

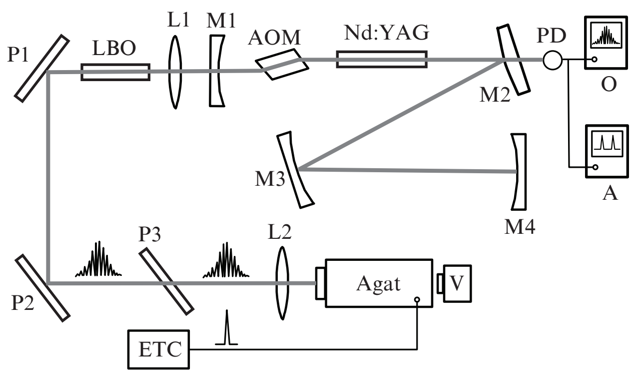

Figure 1. Experimental scheme: (M1)–(M4) cavity mirrors; (LBO) nonlinear crystal; (PD) avalanche photodiode; (O) oscilloscope; (A) spectrum analyser; (L1), (L2) lenses; (P1)–(P3) external plane mirrors; (ETC) electronic triggering circuit of the streak-camera; (V) video camera.

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ror M2 was recorded by an LFD-2 avalanche photodiode PD, whose signal was sent to an oscilloscope and an SF300 spectrum analyser (Rohde & Schwarz).

The image from the camera screen was recorded by a digital video camera, the video shots were processed using the Mathcad software, and the results were used to plot densitograms. The Agat camera was calibrated using a leucosapphire plate 12.2 mm thick, which was placed in front of the camera so that the incident beam was divided into two parts. One part propagated beside the plate and directly entered the camera, while the other part passed through the plate and thus becomes delayed by about 31 ps. This corresponded to an 8-pixel shift on the video shots. Based on this correspondence, we determined the sweep time of the Agat camera.

Figure 2 shows the time sweep of a laser pulse train observed on the screen of the Agat camera (time resolution ~0.7 ns) and the densitogram of pulses. The photograph shows a part of the train (a complete train oscillogram is given in [1–3]).

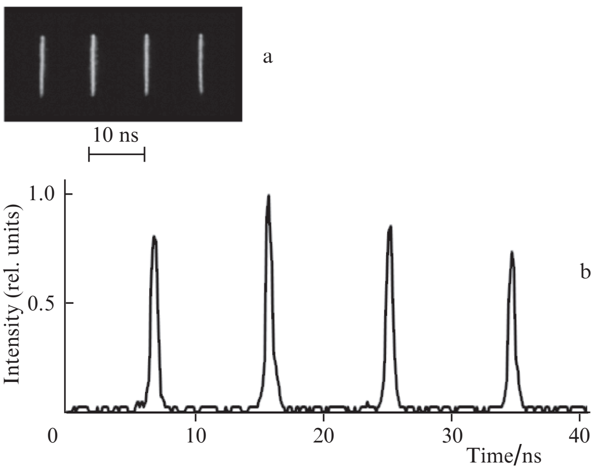

Figure 2. Time sweep of a laser pulse train observed on the screen of the Agat camera (a) and densitogram of pulses (b).

Figure 3 presents the densitograms of laser pulses obtained at a sweep rate of 0.34 ns cm^{-1} (limiting time resolution ~6 ps) at different deviations of the cavity length from the length $L_0 = c/(4f)$, i.e., at different detunings of the longitudinal mode beating frequency from the doubled frequency of the travelling acoustic wave of the modulator. Figures 3a and 3b correspond to the precise tuning of the optical cavity length L = 151.41 cm, while Figs 3c and 3d correspond to a detuning of ±1 mm. The pulse was sometimes split into two in the case of precise tuning and into three and more in the case of detuning. Figure 4 demonstrates the statistics of splitting of single laser pulses into several individual pulses for different cavity detunings. For each detuning, we used about 80 separate shots. As is seen from Fig. 4a, at precise tuning, single pulses dominate (~80%). At a detuning of 0.25 mm (Fig. 4b), triple pulses begin to appear (~9%) and the percentage of single pulses decreases to ~53%. At larger detuning (Figs 4c, 4d), the pulse can split into four and five separate pulses.

Figure 5 presents a typical structure of the laser spectrum near the resonance frequency $c/(2nL)$ = 99 MHz (where n is the average refractive index).

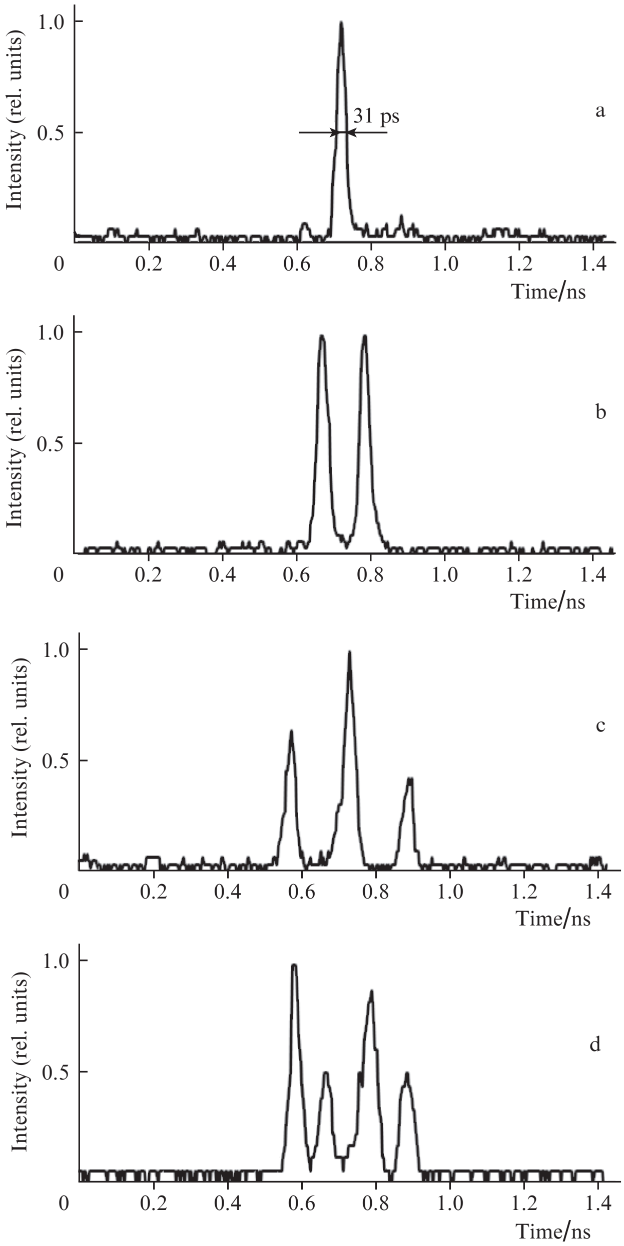

Figure 3. Densitograms of laser pulses at a sweep rate of 0.34 ns cm^{-1} (limiting time resolution 6 ps) at the precise cavity tuning (a, b) and at a detuning of ±1 mm (c, d).

3. Discussion of results

Let us consider the issue of selection of the fundamental TEM_{00} mode. Similar to gas lasers with low concentrations of particles in the active medium [6], the fundamental mode in our case is selected by using a cavity with a long effective length [7] (i.e., with small Fresnel numbers) in the cw regime. The selection is based on the fact that the diffraction losses for the fundamental mode are low with respect to the gain G, while these losses for the other transverse modes are close to G or exceed it.

As was already noted in [1, 2], the gain in the Q-switching regime can increase with respect to the gain in the cw regime by the factor $\tau/\tau_f \approx 10^3 - 10^4$ (at pulse repetition rates no higher than $1/\tau$), where τ is the upper laser level lifetime and τ_f is the

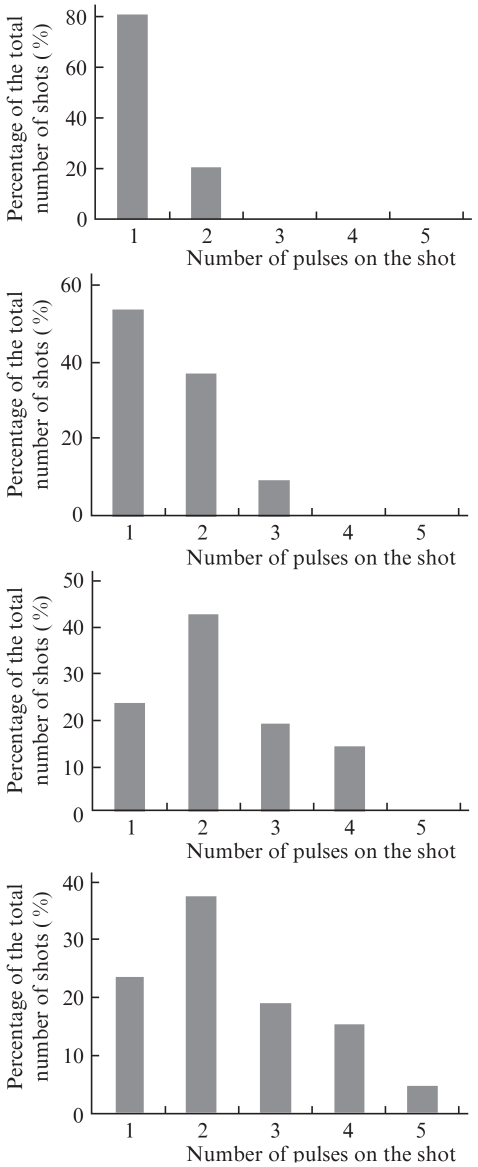

Figure 4. Statistics of splitting of a single laser pulse into several separate pulses at precise cavity tuning (a) and at detunings of (b) ±0.25, (c) ±1 and (d) ±2 mm.

photon lifetime in the cavity. At the same time, the spectrum analyser measurements show that the frequency spectrum contains transverse modes with the intermode distance $\Delta \approx$ 1 MHz. A failed attempt was made to decrease the number of transverse modes by placing an iris diaphragm in the cavity near mirror M4. The diaphragm diameter was continuously decreased up to the violation of the stable mode-locking regime, which caused no change in the transverse-mode pattern, while the streak camera measurements showed no noticeable changes in the pulse statistics. Note that the frequency pulling of transverse modes [8] near the line centre is weak (does not exceed 1 kHz) due to a large linewidth of the laser transition ($\Delta\nu \approx 200$ GHz). The resonance width of a cold (passive) cavity is $\Delta\nu_{res} = c\alpha/(2\pi L) \sim 10$ MHz for the first two transverse modes (α is the total loss per pass equal approximately to 20% and 60% for the TEM_{00} and TEM_{01} modes, respectively). The transverse modes compete with each other, because of which oscillation is chaotic, i.e., mode amplitudes fluctuate chaotically. This chaotic behaviour is

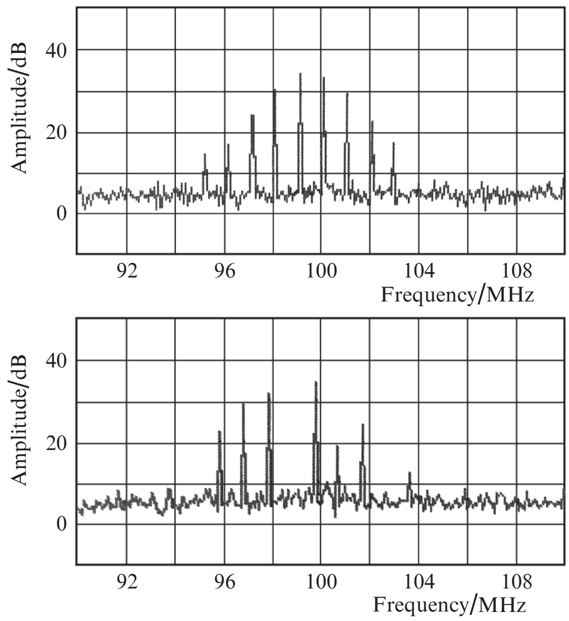

Figure 5. Laser spectrum near the resonance frequency $c/(2nL)$ = 99 MHz at different instants shifted from each other by ~1 s.

illustrated in Fig. 5, which shows two spectra recorded at different instants (the temporal shift is ~1 s, the time of scanning of the spectrum analyser window is 20 ms).

As is known, a standing wave with the frequency $\nu_{m,n,q}$ is formed in a Fabry–Perot cavity when the resonance condition is satisfied. The subscripts *m, n* and *q* correspond to the number of wavelengths of standing waves along two transverse coordinates and one longitudinal coordinate. Therefore, in our case (laser transition linewidth $\Delta\nu \sim 200$ GHz, $L \approx$ 1.5 m), there exists a large number ($\Delta\nu/[c/(2Ln)] \sim 2\times10^3$) of phase-locked longitudinal modes, which determines the maximum possible laser pulse duration; the distance between the laser pulses at the frequencies of transverse modes is $\Delta(2Ln/c)^2$ ~ 100 ps. Here, we should mention early works on the observation of beating and synchronisation of transverse modes in gas and solid-state lasers [9–13], in which attention was paid to the relation between Δ and the minimum time interval between mode-locked pulses, as well as to some specific features of this relation.

The results presented in Figs 3b–3d confirm that the distance between the pulses is approximately 100 ps, but Figs 3c, 3d show rather noticeable (~25%) deviations from this value. Below we discuss the reasons for this deviation.

Let us consider mode pulling in more detail. The frequency pulling of laser modes is determined by the expression $\Delta\nu_{pull} = (\nu_0 - \nu_{res})\Delta\nu_{res}/\Delta\nu$, where ν_0 is the gain peak frequency and ν_{res} is the pulled mode frequency. In our case, $\Delta\nu_{pull}$ lies within the range from 1 kHz (near the line centre) to ~10 MHz (which corresponds to the half maximum of the gain curve). The bandwidth of the 45th picosecond pulse is ~10 GHz, while the typical frequency pulling is approximately 1 MHz (if synchronisation occurs at the gain line centre). Therefore, the pulling is comparable with Δ and can affect the distance between radiation pulses at the frequencies of transverse modes. In addition, double pulses can also appear in the case of locking of only longitudinal modes, if it additionally occurs not at the central part of the gain line. In the latter case, the modes locked not at the line centre will be shifted from the modes at the gain line centre by $\Delta\nu_{\text{pull}}$, which will result in a larger than 100-ps temporal shift between pulses. Obviously, the number of synchronised regions depends on the cavity detuning from the optimal length. It should be noted that sometimes we observed a shallow structure of pulses, which can be caused by the spatial structure of transverse modes [9, 11], as well as by inhomogeneous characteristics of the camera screen.

Let us now study the change in the refractive index n of the active medium due to different contributions from the upper and lower working levels to the medium polarisability. According to the measurements performed in [14], at our optical pump power of ~ 120 W (corresponding power density $\sim 4\times10^3$ W cm^{-2}), this change is $\Delta n \approx 4\times10^{-6}$, which corresponds to $\Delta L = l\Delta n = 0.25$ μm. Taking into account that the difference in the populations of laser levels $N_2 - N_1 = G_{\max} - \alpha = \Delta G$ in the Q-switching regime is formed for the time $\Delta t = 0.5\tau_{\text{f}}$, we find that the cavity length changes with the rate $V = \Delta L/\Delta t = 25\times10^{-6}/(65\times10^{-9}) = 4\times10^2$ cm s^{-1}. The corresponding phase modulation frequency is $F_{\text{ph m}} = V/\lambda \approx 4$ MHz. This effect can be considered as an analogue of the known effect (see [15]), but, in contrast to the latter, it appears without additional special units in the cavity. Since the change $\Delta L = 0.25$ μm is equal to $\lambda/4$ (in this case, the nodes and antinodes of standing waves change places) and the phase modulation frequency exceeds the characteristic lifetime of competing modes (duration of spikes) 0.5 – 1 μs [9], this effect should lead to a considerable filling of holes burned in the amplifying medium. The hole filling together with mode locking facilitates the ordering of relaxation oscillations.

As was noted above, the gain in the case of Q-switching changes from the maximum to the threshold value for $0.5\tau_{\text{f}}$, i.e., after reaching the giant pulse maximum, the gain and, hence, mode pulling effects are absent. Apparently, the disappearance of mode pulling is responsible for a sharp increase in the peak power of individual pulses in the train after reaching the giant pulse maximum, which is observed in the presence of a Kerr element in the cavity [16].

Additional experiments were performed when the driving-frequency (49.5 MHz) signal was applied to the AOM in the cw regime. In this case, the laser operated in the QML regime, but with the pulse train repetition rate equal to the frequency of relaxation oscillations (see, for example, [17]):

$$f_{\text{rv}} = \frac{1}{2\pi}\sqrt{\frac{I}{I_0\tau\tau_{\text{f}}}} \approx 30\,\text{kHz}$$

where I_0 is the saturation parameter. At precise cavity tuning in this auto-QML regime, the pulses of a 2-μs train were stable and their intensities differed by no more than $\Delta I = \pm5\%$, and the train consisted only of picosecond single pulses. The laser radiation spectrum contained only one transverse TEM_{00} mode. At a cavity detuning of ±0.25 mm, relaxation oscillations become chaotic in frequency and intensity, which varied by more than ±50%.

The accuracy of the zero cavity detuning in our case was determined by the modulator driving frequency jitter of ±3 kHz (which corresponds to the cavity detuning of ±0.05 mm). At a lower driving frequency jitter and zero detuning, one can expect operation in the regime of single picosecond pulses.* The measured laser pulse duration at a wavelength of 1064 nm was 45 ± 10 ps for all the cases presented in Fig. 3.

Thus, direct measurements of the duration of pulses of a diode-pumped Nd : YAG laser with Q-switching and mode-locking achieved by the SMAOM method showed that the picosecond pulses can be split, i.e., several pulses can form during the cavity roundtrip. The number of these pulses increases with increasing detuning of the longitudinal mode beating frequency from the doubled frequency of the travelling acoustic wave of the modulator, while the almost single-pulse regime is observed at the precise cavity tuning. The appearance of the non-single-pulse regime is explained by the excitation of several competing transverse modes.

*In a recent experiment, the modulator driving frequency jitter was ±300 Hz. In this case, the percentage of single pulses at a precise cavity tuning reached 95%.

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