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Q-switching and mode-locking in a diode-pumped frequency-doubled Nd:YAG laser

V.I. Donin, D.V. Yakovin, A.V. Gribanov

Abstract. **A new method for obtaining *Q*-switching simultaneously with mode-locking using one travelling-wave acousto-optic modulator in a frequency-doubled Nd:YAG laser cavity is described. Further shortening of output laser pulses (from 40 to 3.25 ps) is achieved by forming a Kerr lens in the frequency-doubling crystal. At an average power of ~ 2 W and a *Q*-switching rate of 2 kHz, the peak power of the stably operating reached ~ 50 MW.**

Keywords: *Nd:YAG laser, diode laser, frequency doubling, Q-switching, mode-locking.*

1. Introduction

High-peak-power visible radiation of cw-diode-pumped solid-state lasers is required for a number of applications (precision material processing, nonlinear optics, Raman spectroscopy, medicine, etc.). *Q*-switching allows one to increase the output laser power approximately by a factor of τ_{sp}/τ_{ph} (τ_{sp} is the lifetime of the upper laser level and τ_{ph} is the photon lifetime in the cavity). For a typical Nd:YAG laser, this factor is $10^3 - 10^4$. Peak power can be further increased by mode-locking, but mode-locking in *Q*-switched lasers is more difficult to realise than in cw lasers due to a high gain, hard-to-control nonlinear defects, breakdown of optical laser elements, and so on. Usually, stable operation of *Q*-switched mode-locked (QML) lasers is obtained using two acousto-optic modulators (AOMs) in the cavity, one of them operating in the travelling-wave regime and the other in the standing-acoustic-wave regime (see, for example, [1]). The QML regime can also be realised by introducing absorbing elements into the cavity [2 – 6], but the pulse repetition rate in this case increases with increasing pump power and achievable peak powers are extremely low.

In this paper, we report on a new method of implementing a stable QML regime in a diode-pumped frequency-doubled Nd:YAG laser using only one travelling-wave AOM. In this case, the output laser pulse duration $\Delta\tau$ is further decreased due to formation of a Kerr lens in the frequency-doubling crystal. The inertia of the Kerr lens formation is very low, which, in principle, allows one to decrease $\Delta\tau$ to a value $\sim 1/\Delta\nu$ ($\Delta\nu$ is the spectral width of the laser line).

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2. General scheme of the experiment. Simultaneous *Q*-switching and mode-locking by an AOM operating in the travelling-acoustic-wave regime

The QML regime is realised using a spherical cavity mirror (SM) and a travelling-wave AOM (SMAOM method). The principle of the proposed method [7] and the laser scheme are presented in Fig. 1. The used Nd:YAG laser is designed according to the scheme of efficient frequency doubling [8]. The radii of curvature of mirrors M1, M2, M3, and M4 were 200, – 900, 200, and 150 mm, respectively. The reflection coefficient of mirrors M1 – M4 at λ = 1064 nm was higher than 99.5%. Mirror M4 was dichroic and had a reflectance exceeding 99.5% at λ = 532 nm; the transmittance of mirror M3 at this wavelength was 92%. The optical length L of the cavity was 1.5 m. The AOM was placed near the spherical end mirror M1 at the Bragg angle (θ_B) to the optical axis of the cavity. The distance R_1 between the modulator centre and the reflecting surface of the mirror was equal to the radius of curvature of this mirror. A signal with a frequency f = 50 MHz [which is equal to half the laser intermode distance ($c/2L = 2f$)] applied to the piezoelectric transducer of the modulator forms in the acousto-optic quartz block a travelling wave (short thick arrow in Fig. 1), which undergoes Bragg diffraction. After propagation of a beam with a frequency ν_0 through the AOM from the right to the left, two beams (1 and 2) fall on the mirror. Beam 1 propagates along the cavity axis, is reflected from the mirror, and propagates back along the same path without changing its frequency ν_0. Beam 2, whose

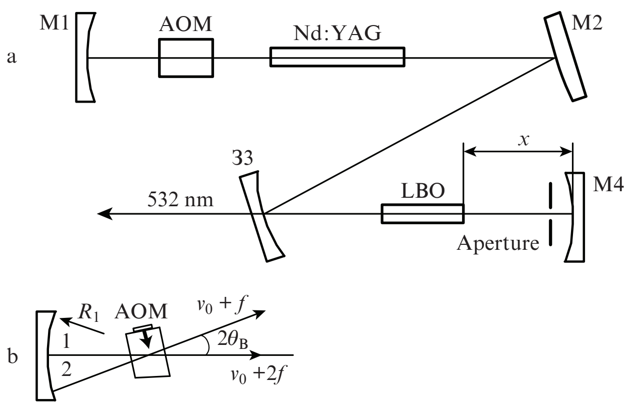

Figure 1. Laser scheme (a) and principle of operation of a SMAOM (b) (M1 – M4 are cavity mirrors).

frequency changes to $v_0 + f$ due to the Bragg diffraction, is reflected by the spherical mirror and returns to the AOM, where it is divided into two beams: a beam with the unchanged frequency $v_0 + f$ propagating out of the cavity in the backward direction at an angle $2\theta_B$ and a beam appearing after repeated diffraction in the acousto-optic block of the modulator. The latter beam with the frequency $v_0 + 2f$ propagates in the backward direction along the cavity axis, thus causing mode-locking. The beam emitted from the cavity at an angle $2\theta_B$ with the frequency $v_0 + f$ is responsible for the losses leading to Q-switching, and the laser operates in the Q-switching regime with a pulse repetition rate determined by the switching frequency of the modulator (1 – 100 kHz). After switching off the driving frequency, the sound wave in the acousto-optic block of the AOM is switched off for the time $t = d_{las}/V_s = 0.2$ cm/(5×10^5 cm s^{-1}) ≈ 0.4 μs, where d_{las} is the laser beam diameter in the acousto-optic fibre and V_s is the speed of sound. The laser pulse duration in the Q-switching regime is ~100 ns, i.e., mode-locking simultaneously occurs in the laser pulse for the time t due to the laser beam with the frequency $v_0 + 2f$ formed as a result of repeated diffraction.

In our experiments, we performed preliminary measurements in the absence of a nonlinear crystal and aperture (without frequency doubling and Kerr lens formation). In this case, mirror M1 was replaced by another mirror with the same radius of curvature but with the transmittance $T = 11\%$ at $\lambda = 1064$ nm. The oscillogram of a Q-switched mode-locked laser pulse is shown in Fig. 2. The average output power was 2 W at a Q-switching rate of 2 kHz. The time resolution of the recording system (a photodiode and an oscilloscope) of 2 ns did not allow us to determine the duration of pulses inside the train, because of which it was determined using an optical correlator and recording second harmonic pulses generated in a KTP crystal (collinear scheme). Thus, the measured duration of synchronised pulses was 40 ps (see Fig. 5a), i.e., the peak power of an individual pulse was ~2 MW.

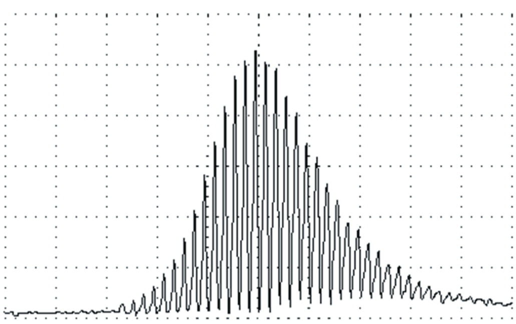

Figure 2. Oscillogram of a laser pulse at the wavelength $\lambda = 1.064$ μm in the QML regime. Scanning rate 50 ns div^{-1}.

3. Kerr lens in a frequency-doubling crystal

A further decrease in the individual-pulse duration and an increase in the peak power was achieved using a Kerr lens formed in the nonlinear crystal generating the second harmonic (LBO crystal, length $d = 20$ mm, type-I second-harmonic generation) and an aperture (i.e., the laser operated at the wavelength $\lambda = 532$ nm according to the scheme in Fig. 1a). The Kerr-lens mode-locking, or self-mode-locking, was studied for the first time in [9]. This process is based on the self-focusing of radiation in a medium, which makes it possible to create in a cavity an effect similar to saturated absorption. Self-focusing occurs because the refractive index of the medium depends on the radiation intensity I ($n = n_0 + n_2 I$). An intense radiation incident on a medium forms in it a lens whose focal power depends on the radiation intensity. This nonlinear lens in combination with an aperture works similar to a saturable absorber. It is also possible to create a scheme without aperture, whose role in this case is played by cavity elements. If self-focusing occurs due to electron polarisation in a solid under action of the electric field of a light wave, it is possible to form an almost inertialess saturable absorber with a recovery time of ~10^{-15} s [10].

The resonator was calculated by the matrix method. To describe the beam propagation through a Kerr element, we used the matrix M proposed in [11]

$$M = \sqrt{1-\gamma}\begin{pmatrix} 1 & d_e \\ -\gamma/[(1-\gamma)d_e] & 1 \end{pmatrix}.$$

Here, $d_e = d/n_0$ is the effective length of the medium at the intracavity radiation power $P = 0$,

$$\gamma = p\left[1 + \frac{1}{4}\left(\frac{2\pi w_c^2}{\lambda d_e} - \frac{\lambda d_e}{2\pi w_0^2}\right)^2\right]^{-1};$$

$p = P/P_{cr}$; $P_{cr} = c\varepsilon_0\lambda^2/(2\pi n_2)$ is the critical self-focusing power, w_c is the beam radius in the medium centre, and w_0 is the beam waist radius calculated at $p = 0$. To ensure saturated absorption, the beam size in the plane of the aperture must decrease with increasing its intensity. This effect is quantitatively characterised by the parameter [12]

$$\delta = \frac{1}{w}\frac{dw}{dp}\bigg|_{p=0},$$

where w is the Gaussian beam radius in a particular plane in the cavity. For efficient pulse shortening, the parameter δ must be negative with the modulus as large as possible. The aperture was placed in a plane close to the end mirror M4 (see Fig. 1a). As a variable parameter in our calculations, we chose the distance x between the end mirror M4 and the nonlinear crystal. The calculated dependence $\delta(x)$ is presented in Fig. 3. It is seen that the parameter δ becomes maximum (in absolute value) at the stability region boundaries. From calculations, we chose $x \approx 14.06$ cm.

Figure 4 shows the cavity stability region in coordinates x–p. One can see that the laser operates at the stability region

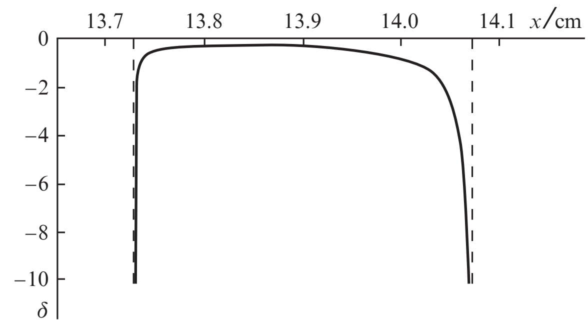

Figure 3. Dependence of the parameter δ on the distance x. Vertical dashed lines denote the stability region boundaries.

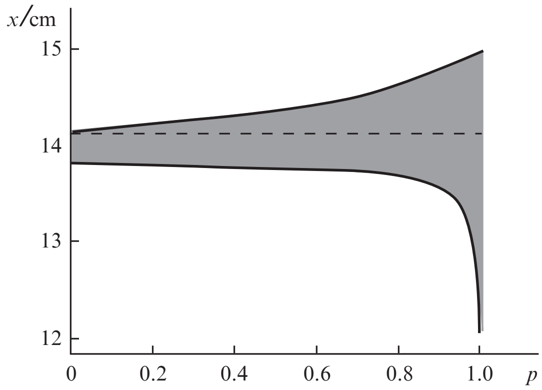

Figure 4. Stability region of the cavity (shown in grey). The horizontal dashed line denotes the distance x used in experiments.

boundary at low powers (in the beginning of a *Q*-switch pulse formation) and passes to a more stable regime with appearance of a Kerr lens and increasing power.

The duration of individual pulses inside the train measured by an optical correlator with recording the two-photon absorption photocurrent in a G1116 (Hamamatsu) GaAsP photodiode was 3.25 ps (Fig. 5b). The average laser power at λ = 532 nm was 1.5 W at a pulse repetition rate of 2 kHz. Using a Foton-2102I acousto-optic monochromator, we measured the spectral widths $\Delta\nu$ of laser lines at λ = 1064 and 532 nm to be ~200 and 400 GHz, respectively (in Figs 5c and 5d, these widths are larger due to the contribution of the instrumental width). Therefore, $\Delta\nu\Delta\tau \approx 0.65$, which, with accuracy up to two, is close to the case of an unchirped pulse whose shape is described by the function sech^2.

The peak power of an individual pulse near the maximum of the envelope of the train of synchronised pulses (see Fig. 2) was ~50 MW. It should be noted that $\Delta\tau$ was measured by the autocorrelation function at λ = 1064 nm. The measurements of $\Delta\tau$ in the *Q*-switched regime showed that the pulse duration at λ = 532 nm is twofold smaller. One can expect that this relation of pulse durations will be approximately the same in the QML regime, i.e., the peak power may reach ~100 MW.

4. Conclusions

Note that the mode-locking regime of a cw laser was previously realised using a travelling-mode AOM in [13–15]. In these papers, it was reported that the mode-locking band was enlarged by a factor of 10 and higher in comparison with the case of a standing-wave AOM. However, in these works, the feedback was obtained using additional mirrors in the laser cavity, which complicated the design, and *Q*-switching regime was not observed. Our SMAOM method, in which a stable QML regime can be obtained using only one AOM, in combination with a Kerr lens, allows one to achieve much higher peak powers. The proposed laser requires no additional conditions for formation of a Kerr lens and has a high short-term and long-term stability of output characteristics without using auto-tuning schemes.

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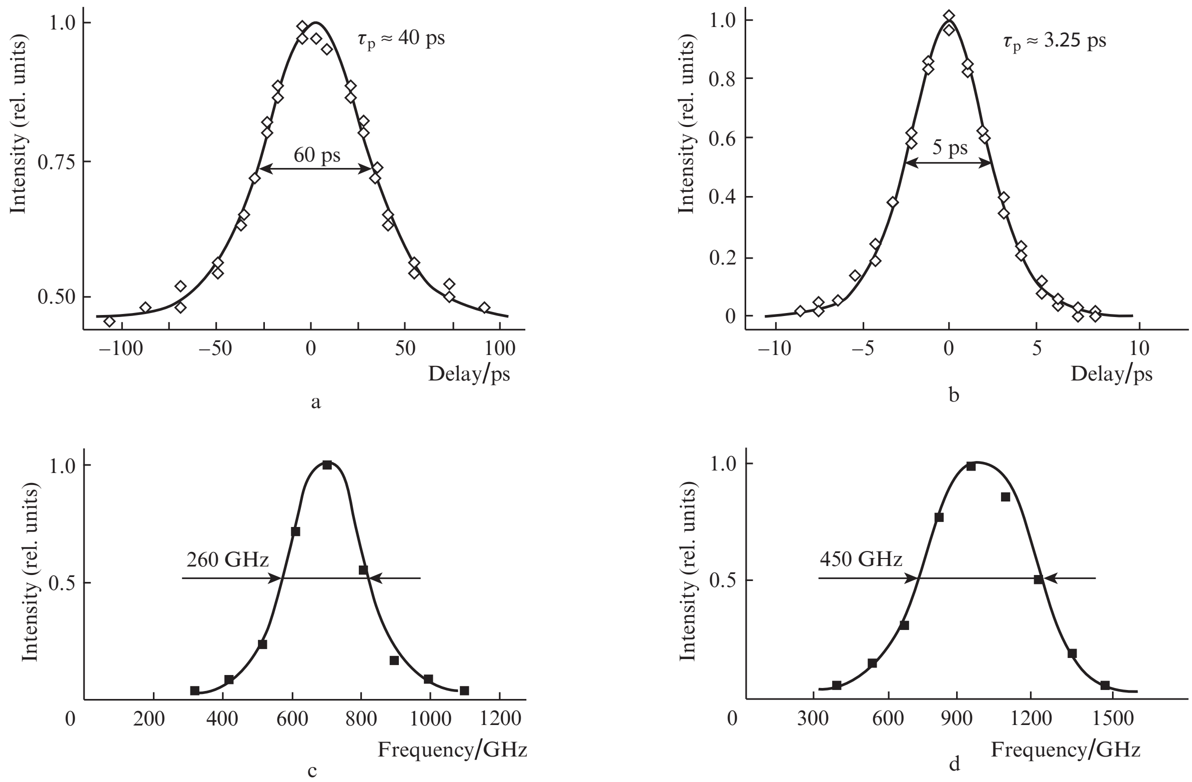

Figure 5. Measured autocorrelation functions of synchronized pulses without (a) and with (b) a Kerr lens (rhombs) and their approximations by functions sech^2 (solid lines) (a, b), as well as measured emission spectra at λ = 1064 (c) and 532 nm (d).

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