Diode-pumped green Nd:YAG laser with *Q*-switch and mode locking

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We propose a new method for achieving simultaneous operation of laser mode locking and the *Q*-switch technique using only a single acousto-optic modulator (AOM) with a traveling wave; this AOM was placed inside the cavity of a green-emission Nd:YAG laser. The further shortening of the lasing pulse duration from 40 ps to less than 3.25 ps was obtained by the formation of a Kerr lens in a doubling-frequency crystal. At average output power of 1.5 W and pulse repetition rate of the *Q*-switch equal to 2 kHz, the peak power in a steady-operating laser exceeded 50 MW.

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Some applications (high-precision material processing, nonlinear optics, and Raman spectroscopy) require a high peak power of visible-range emission from a solid-state laser with continuous diode pumping. The technique of modulation for the laser cavity Q factor (Q-switch) offers amplification of the laser peak power approximately as $\tau_{\mathrm{sp}}/\tau_{\mathrm{ph}}$ (where τ_{sp} is the upper laser level lifetime and τ_{ph} is the photon lifetime in the cavity). This estimate for a typical Nd:YAG laser gives peak amplification of about $10^3 - 10^4$ times. The further gain in peak power can be achieved through methods of laser mode locking (ML). However, realization of ML together with the Q-switch (unlike the case of the continuous operation mode) is a technically challenging task: we face a high amplification, almost uncontrollable nonlinear effects, and damage of optical elements in the laser. In prior art, the steady mode of generation for the Q-switch coupled with ML (so called QML) is accomplished by use of two acousto-optic modulators (AOMs) in a cavity; one modulator operates in the traveling acoustic wave mode, and the other modulator has the standing-wave mode (see, e.g., [1]). In this Letter we give for the first time to our knowledge the performance of a steady QML mode in a diode-pumped green-emission Nd:YAG laser using only one AOM operating in the traveling wave mode. Meanwhile, the further shortening of laser pulse duration $\Delta\tau$ is achieved through formation of a Kerr lens in a frequency doubling (nonlinear) crystal. Because the process of the formation of a Kerr lens has very low inertia, this approach allows the pulse shortening $\Delta\tau$ down to the level $\approx 1/\Delta\nu$ (where $\Delta\nu$ is the spectral width for the generation line).

The developed new method [2] for achievement of the QML mode requires two main elements: a spherical mirror (SM) of the cavity and a traveling wave AOM (the symbols taken together create the abbreviation SMAOM). The operation principle for the SMAOM method and laser diagram is illustrated in Fig. 1. A green-emission Nd:YAG laser is engineered according to the effective frequency-doubling scheme [3]. The cavity optic length was $L = 1.5$ m. The AOM was oriented under the Bragg angle (θ_B) to the optic axis of the cavity near the end-SM M1. The modulator's center is distanced from the mirror's reflection surface by distance R1, equal to the curvature radius of this mirror.

When the driving frequency $f = 50$ MHz (half of the intermode interval $c/2L = 2f$ of the laser) is supplied to the AOM's piezoelectric transducer, this creates a traveling ultrasonic wave in the quartz block (this is shown in Fig. 1(b) with a small "bold" arrow), and this wave creates Bragg diffraction of the laser emission. When a light beam (with frequency ν_0) passes the AOM from right to the left, this makes two beams to the mirror (1 and 2). Beam 1 goes along the cavity axis and is reflected from the mirror backward through the same path without any change of the laser frequency ν_0. Beam 2—after Bragg diffraction—incidents the mirror with the frequency $(\nu_0 + f)$ and after reflection from the spherical surface of the mirror goes back to the AOM, where it is split into a beam with the same frequency $(\nu_0 + f)$ exiting the cavity in the back direction under the angle $2\theta_B$ and a beam after repeated diffraction in the quartz block of the modulator. The latter kind of beam with the frequency of $(\nu_0 + 2f)$ goes in the backward direction along the cavity axis. It is this beam that produces the effect of ML. The

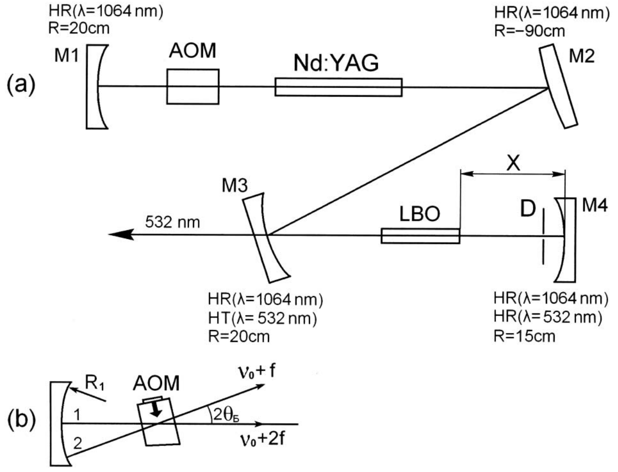

Fig. 1. (a) Laser scheme: M1–M4, cavity mirrors; AOM, acoustic-optic modulator; Nd: YAG, active element of laser; LBO, nonlinear crystal; D, diaphragm. (b) Operation principle for SMAOM.

beam with frequency $(\nu_0 + f)$ exiting the cavity at angle $2\theta_B$ ensures the losses that modulate the Q factor, and the laser can operate with the Q-switch at the pulse repetition rate assigned by the modulator switch frequency (~1 ÷ 100 kHz). Moreover, when the driving frequency is off, the sonic wave in the AOM's region of acousto-optic interaction disappears within the interval $t = d_b/V_s = 0.2\ \text{cm}/5.10^5\ \text{cm/s} \approx 0.4\ \mu\text{s}$ (where d_b is the diameter of the laser beam in the light-acoustic duct and V_s is the sound velocity). The duration of the lasing pulse in the Q-switch mode is about ~100 ns, i.e., during time t due to the passing of repeatedly diffracted beam with the frequency $(\nu_0 + 2f)$ within the lasing pulse, ML occurs as well.

On the first stage, we performed measurements without the nonlinear crystal and diaphragm (this means no frequency doubling and no Kerr lens formation). In this case we replaced mirror M1 with another one with similar curvature radius, but possessing the transparency of $T = 11\%$ at $\lambda = 1064$ nm. The oscillogram of a Q-switched pulse with ML is depicted in Fig. 2. The average power of the laser was 2 W (at the Q-switch frequency equal to 2 kHz). The registration system resolution time (photodiode and oscillograph) of ≈2 ns did not allow us to determine the actual duration of pulses inside a "train," so this task required assembling an optical correlator for pulse registration on the second harmonic in the KTP crystal (collinear scheme). This optical correlator gave the pulse duration for ML generation about 40 ps [see Fig. 5(a)]; i.e., a single peak power was ~3 MW.

The further shortening of an individual pulse and growth in the peak power was achieved with a Kerr lens being formed within a nonlinear crystal for harmonics generation (phase-matched type I LBO with the length of $d = 20$ mm) and a diaphragm [that is, lasing at the wavelength $\lambda = 532$ nm by a scheme depicted in Fig. 1(a)]. The cavity parameters were calculated with a matrix technique. The beam passing via the Kerr element was described by a matrix offered in [4]:

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

where $d_e = d/n_0$ is the effective length of the medium at the power inside the cavity $P = 0$, and here

$$\gamma = p\left[1+\frac{1}{4}\left(\frac{2\pi\omega_c^2}{\lambda d_e}-\frac{\lambda d_e}{2\pi\omega_0^2}\right)^2\right]^{-1}, \qquad (2)$$

where $p = P/P_c$, $P_c = c\varepsilon_0\lambda^2/(2\pi n_2)$ is the critical power for self-focusing), ω_c is the beam size in the middle of the medium, and ω_0 is the beam size in the waist place, calculated for $p = 0$. To obtain the phenomena of "saturating absorption" we need a decline in the beam size while an increase in intensity in the place of a diaphragm. This phenomenon can be described by the following parameter [5]:

$$\delta = \frac{1}{\omega}\frac{d\omega}{dp}\bigg|_{p=0}, \qquad (3)$$

where ω is the Gaussian beam radius in a specific plane within the cavity. For efficient shortening of a pulse, parameter δ should be negative and big in modulus. The diaphragm was installed in a plane at the end mirror M4 [see Fig. 1(a)]. The variation parameter in our calculations was the distance between the end mirror M4 and the nonlinear crystal; this distance is marked as X in our diagrams. The calculated parameter δ is plotted in Fig. 3. As one can see from this figure, parameter δ takes a maximum value at the boundary of stability zone. Therefore we picked up the value $X \approx 14.06$ cm.

Figure 4 shows the stability zone for the cavity in coordinates $X - p$. One can see that at low power (at the beginning of the formation of the Q-switched pulse), the laser operates almost at the margin of the stability zone, but when the Kerr lens exists and high power is generated, operation occurs in a stable mode.

When the optical correlator for pulse registration on the two-photon-induced photocurrent in a GaAsP photodiode (type-G1116, Hamamatsu) was applied for measurements, the duration of a single pulse from the Nd:YAG laser was 3.25 ps; this was at the average output power 1.5 W and the pulse repetition rate of Q-switch equal to 2 kHz. Figure 5(b) demonstrates the measured autocorrelation function for a pulse. The measured spectral bandwidth of generation is $\Delta\nu \approx 200$ GHz. Therefore, $\Delta\nu \cdot \Delta\tau \approx 0.65$, which is close (within the accuracy of 2) to the case of the unchirped sech^2-shaped pulses.

The peak power of a single pulse taken near the maximum of the Q-switch envelope (see Fig. 2) was ≈50 MW. In this connection, it should be noted that $\Delta\tau$

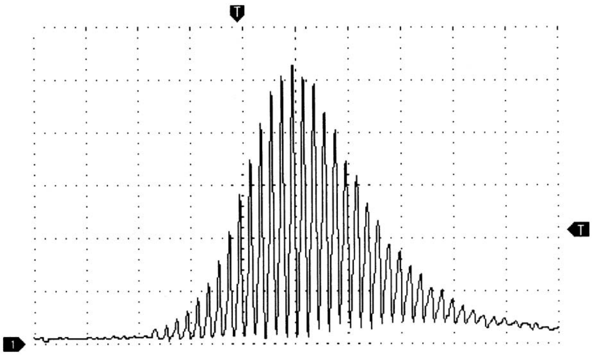

Fig. 2. Oscillogram of the generated pulse at the wavelength $\lambda = 1064$ nm produced in the QML mode. The division value for the abscissa axis is 50 ns.

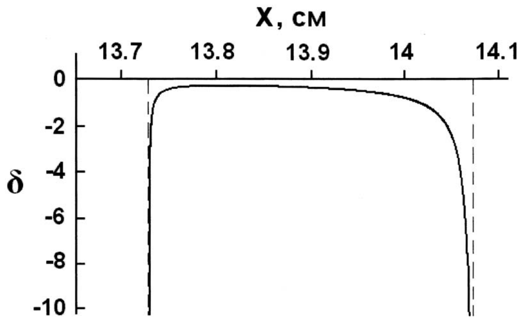

Fig. 3. Dependence for parameter δ versus distance X. The vertical dashed lines indicate the boundaries of the stability region.

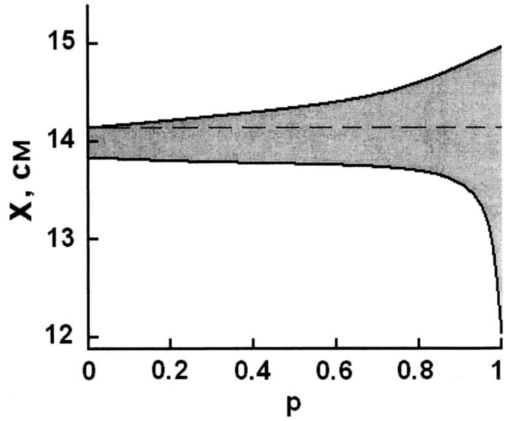

Fig. 4. Stability zone for a cavity (depicted by gray shading). The horizontal dashed line shows the operative distance X.

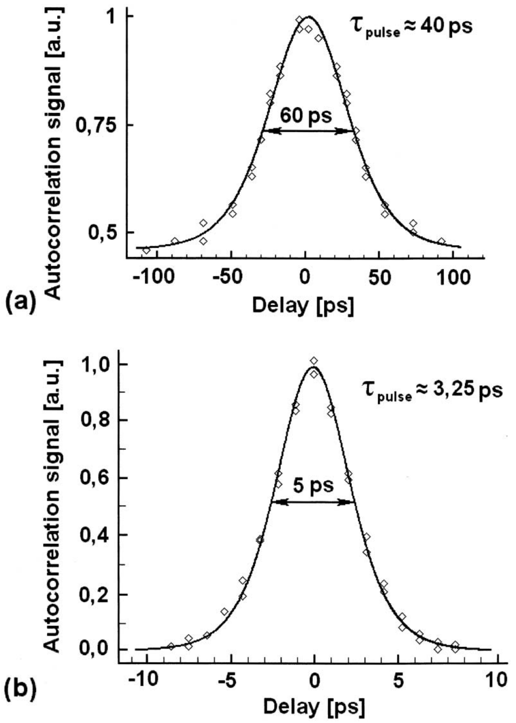

Fig. 5. Measured autocorrelation traces for ML pulses and their sech^2 fits.

was measured from the autocorrelation function at wavelength $\lambda = 1064$ nm. When we made measurements of $\Delta\tau$ for the Q-switch mode, it was shown that at $\lambda = 532$ nm the pulse duration was approximately twice shorter. One might expect that this proportion in the pulse lengths will be almost the same for operating in the QML mode, so the actual peak power of the lasing may be about ≈100 MW.

In conclusion, we should note that previously the ML generation regime for a continuous laser using a traveling wave AOM was achieved in [6–8]. The authors emphasized that the ML band had increased by a factor of ≥10 times in comparison with the case of a standing-wave AOM. However, in these researches, feedback was provided through additional mirrors installed in the laser cavity; this makes the entire design more complicated, and there was no Q-switch mode. In [9] the QML mode was observed with AOM near a flat mirror and at some additional conditions (output coupler transmissions must be >60% and pulse repetition rate >20 kHz). In previous experiments, we also used the flat mirror near the AOM, but the steady QML mode was not observed. Our technical solution, SMAOM, when one AOM is enough to gain the steady QML, in combination with a Kerr lens, ensures appreciably higher levels of peak power. The developed design of laser does not require any additional "start-up" conditions for the Kerr lens and offers high (both short- and long-run) stability of output parameters without using any kind of autoadjustment schemes.

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