Q-switched mode-locking with acousto-optic modulator in a diode pumped Nd:YVO$_4$ laser

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Abstract: The Q-Switched Mode Locking (QML) regime provides the generation of relatively high peak power picosecond pulses train with energies of a few μJ each in a simple resonator. The fully modulated efficient QML regime was demonstrated in the diode pumped Nd:YVO$_4$ laser. The acousto-optic cell playing a double role of Q-switch and Mode Locker was located near flat output coupler. The two folding mirrors were mounted on the translation stages for matching the resonance frequency of the cavity to the radio frequency of acousto-optic modulator. The QML pulses with envelope durations of 100-150 ns and near 100% modulation depth were observed for wide range of pump powers and repetition rates. Up to 3 W of output average power, 100 μJ of the envelope energy, having approximately 5-8 mode locked pulses were achieved.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched; (140.4050) Mode-Locked Lasers

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1. Introduction

The ps pulses of μJ energies with dozens kHz pulse repetition frequency (PRF) are demanded in several areas, e.g., micro machining, ophthalmology, dental surgery etc. Their high intensities together with relatively low heat deposition ensure precise removal of material during the short interaction time. The three methods can give pulses satisfying the above requirements: amplification of mode locked pulses in high power fiber amplifiers [1-2], regenerative amplification of mode locked pulses in bulk diode pumped systems [3-4], Q-switched Mode Locking (QML) in bulk diode pumped systems. The last method, well known since the 70'ies of last century, consists in generation of simultaneous Mode Locking and Q-switching in the same cavity. The simple transfer of QML techniques (e.g. liquid dye cells, LiF crystals, color center foils etc.) developed for low PRF lamp pumped lasers is not possible for the laser system operating at several dozens kHz PRF, because of thermal problems. The application of bulk passive crystalline saturable absorbers for such purpose (see e.g. [5–7]) leads as a rule to not fully modulated QML pulses characterized by severe temporal and energetic jitter. However, the perfect QML effect was obtained by means of GaAs wafer with continuously variable transmission [8]. Combination of different mode locking techniques (e.g. nonlinear mirrors [9], specially designed semiconductor saturable absorber elements [10], acousto-optic modulators [11]) with active Q-switches can lead to 100% modulation depth and stabilization of temporal and energetic parameters of QML regime. We have demonstrated in this paper the efficient QML regime enforced by acousto-optic cell. In Part 2, the principle of operation, system description and experiments in free running regime are given. The investigations on QML regime are presented and discussed in Part 3. In the last part, conclusions were drawn and prospects for future work are given.

2. Principle of operation of AO-QML laser

The principle of operation of acousto-optic-Q-switched-mode-locked (AO-QML) laser (see Fig. 1) consists in enforcing in the laser resonator the mode locking on the frequency equal to radio-frequency (RF) of acousto-optic modulator playing the double role of Q-switch and mode locker. We have applied the traveling wave acousto-optic modulator NEOSN33041-10-15 (AOM) operating at 40.67 MHz RF.

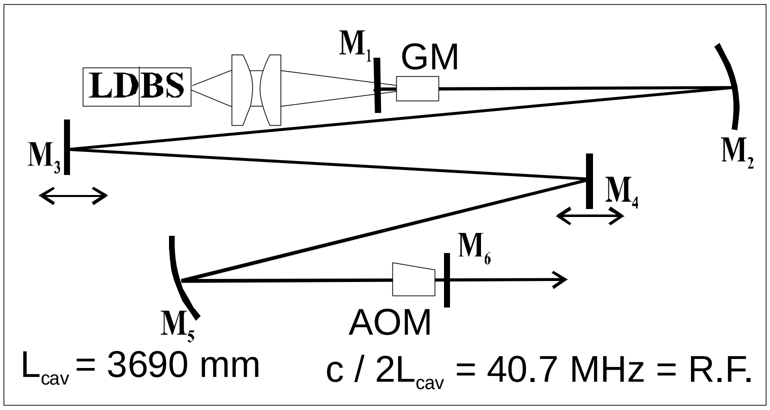

Fig. 1. Schematic of AO-QML laser: LDBS – 20 W laser diode bar with beam shaper made by LIMO, AOM- acousto-optic modulator, M_2, M_5 – folding mirrors of 1-m radii of curvature, GM– 0.3% Nd:YVO$_4$ crystal of 3x3x10 mm^3, M_3,M_4- flat folding mirrors at translation stages, M_6 –flat output coupler (OC), M_1 -rear mirror highly reflective at 1064nm and antireflective at 810 nm.

To characterize dual role of AOM as a mode locker and Q-switch, we measured in far field the signal of 1.06-μm wavelength laser beam after passing through AOM operating in

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“switch on” and “switch off” states. When it was in “switch on” state (i.e. when R.F. signal was supplied) the power in the “zero diffraction mode” decreased to 40% of value measured for “switch off” state. Moreover, we observed the modulation with 15%-depth at 40.7-MHz frequency equal to radio frequency of modulator. We conclude that our AOM has always been modulating the light as a mode locker in “switch on” state. The reason is, in our opinion, the standing wave formed by the weak interference of acoustic waves incident and back reflected at the second edge of modulator. It works as a Q-switch with 60% loss change and Mode Locker (see Fig. 2).

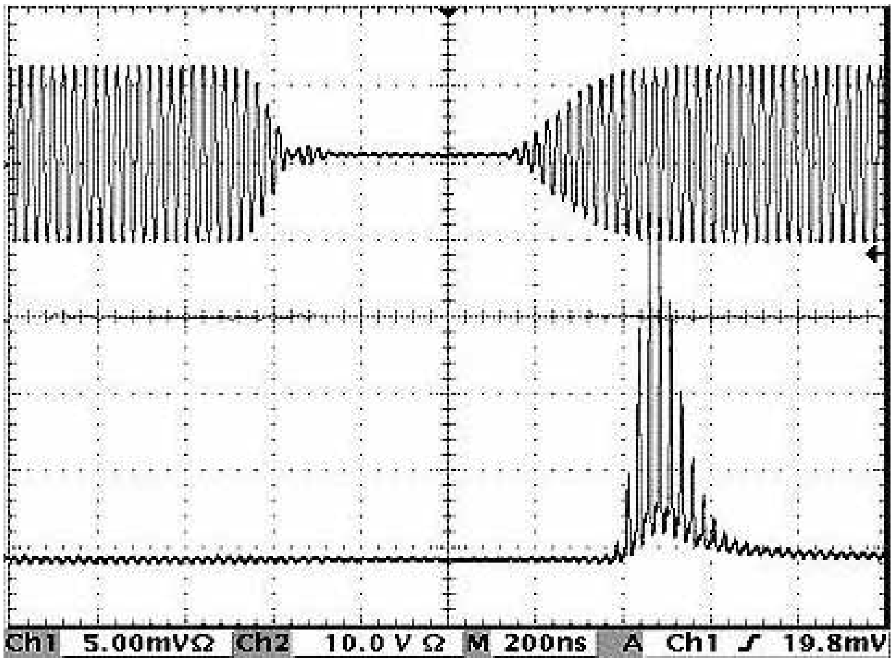

Fig. 2. Oscilloscope traces of RF electric signal at AOM (upper Ch2 trace), optical QML output signal (lower Ch1 trace).

Assuming total resonator length of 3690 mm the dynamically stable layout of Z-type cavity was found analytically and set up in the laboratory. The 0.3%Nd:YVO_4 crystal of 3x3x10mm^3 with facets of 2^o wedge was applied as gain medium. The commercial 30-W laser diode bar with beam shaper HLU32F400-800 made by LIMO was applied as a pump unit. After passing through beam forming optics the pump beam was focused to 0.6-mm width in a gain crystal. Approximately 0.4-mm wide fundamental mode diameter at gain medium was estimated for 1–20 m^{-1} range of dioptric power of thermal lens induced in gain medium, corresponding to pump power range of 1- 20 W. At the output arm of the resonator the divergence half angle was less than 4 mrad for such a dioptric power range. The resonator frequency ($c/2L_{cav}$) was matched to the RF of AOM by means of precise movement of folding mirrors (M_3, M_4) mounted on translation stages. Thus, after “switch off ” gate signal the QML pulse builds up from weak prelasing of mode locked radiation at 40.67-MHz frequency. The mismatching between oscilloscope traces of RF gate and laser pulse shown at Fig. 2. is caused by ~ 1-μs delay of acoustic wave between the transducer and area of laser beam. The maximum pump power corresponding to near stability edge of cavity was approximately 15-17 W. The measurements of energetic characteristics for a wide set of output coupler (OC) transmissions were carried out (see Fig. 3). The optimal OC transmission for free running mode was found to be 30%, resulting in the output power of 3.3 W at a pumping power of 16 W and roundtrip small signal gain of 3.5.

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3. Investigation of QML generation

The investigation of QML effects were carried out in the set up shown in Fig. 1. The fully modulated QML trains were observed for the numerous set of OC transmission. However, for transmission lower than 60%, not negligible laser emission occurred between QML pulses for high excitation levels occurring for pump power above 12 W. It was accompanied by a chaotic background between mode locked pulses inside QML envelope. The two reasons explain this effect namely: increase in mode content of the beam caused by increased thermal distortion as well as high unsaturated gain of Nd:YVO_4 crystal.

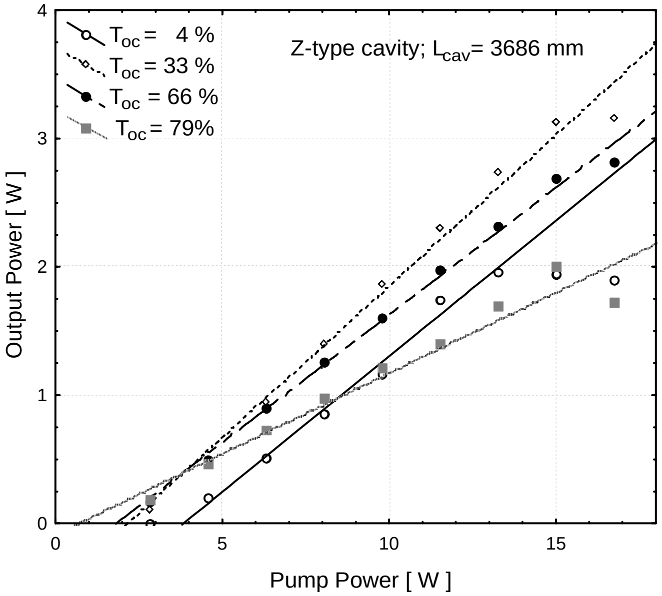

Fig. 3. Output power vs. pump power for several output coupler transmissions; free running regime.

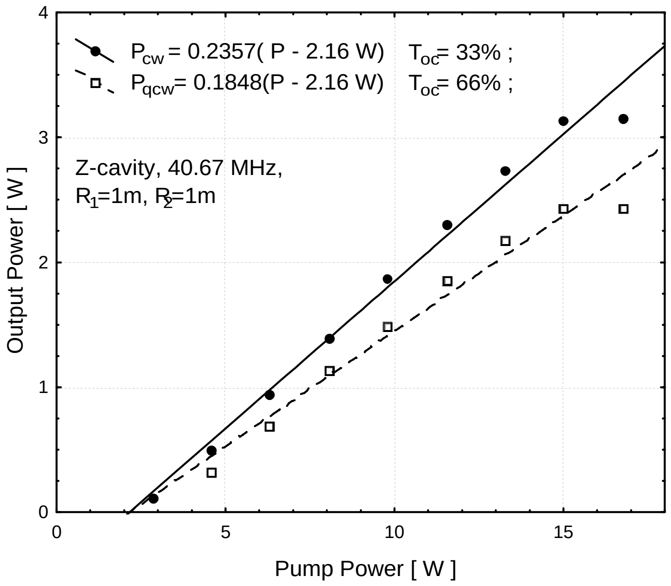

Fig. 4. Output power vs. pump power: diamonds - free running regime, squares - QML regime at 30 kHz repetition rate.

Thus, to obtain clean fully modulated QML pulses with high contrast, OC transmission had to be higher than 60%. The typical energetic characteristic of QML regime in comparison to free running results were presented in Fig. 4. The oscilloscope trace of typical QML train was demonstrated in Fig. 5. Even for uncoated plane parallel plate deployed as an OC mirror, quite reasonable averaged output power of 1.3 W with 50-µJ energy of QML envelope was obtained. With decrease in PRF below 30 kHz, the leakage between QML pulses has appeared for higher pump powers as a results of too small diffraction losses of AOM comparing to the gain. The compromise between QML energy and average power was found for 20–30 kHz of PRF.

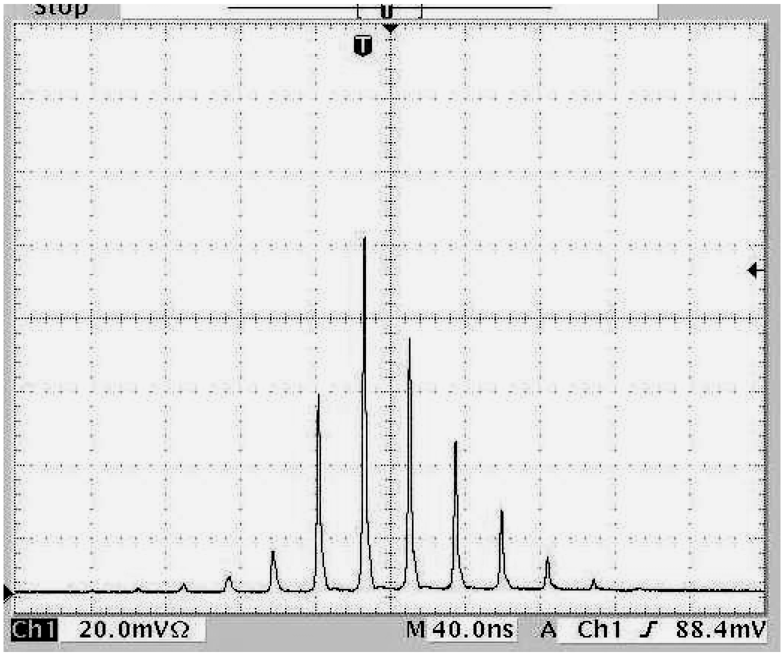

Fig. 5. Oscilloscope trace of fully modulated QML pulse train.

The additional problem was connected with small (6 mrad) of diffraction angles of AOM. The location of AOM at, opposite to the gain medium, end of a cavity, necessary for effective mode locking of single round trip pulse, is not a good solution from the point of laser optics. The M_6 and M_1 mirrors are near to geometrical optic conjugate planes despite high thermal lens induced in gain medium. In effect, the higher orders beam diffracted by AOM could return to gain medium and it will be amplified again. The higher order mode structure in output beam can be observed for high gain and high thermal lensing (pump power > 15 W). Thus, to improve the energetic parameters of QML laser, the additional requirements of low divergence at output arm and possibility of spatial filtering have to be addressed in the cavity design. In the best case we obtained up to 3 W of average power for a pump power of 15 W and 66%-transmission of OC coupler. The maximal QML energy of 130 μJ was achieved with envelope duration of 100 – 120 ns (FWHM). For a roundtrip time of 25 ns, the estimated energy of the highest pulse inside envelope was about 30 μJ. The measurements of mode locked pulse duration gave ambiguity results. Applying electronic technique (1 GHz DSA-601 scope and New Focus 1601 photo receiver of 0.2-ns rise time) we have observed that the pulse is shorter than 1 ns. For comparison we have arranged collinear autocorrelator with the 5-mm II type KTP crystal as a second harmonic conversion element. The pulse duration, averaged over the several QML envelopes, was determined to be not shorter than 0.5 ns. Such a long pulse duration can be caused by relatively big width of frequency spectrum of AOM driver and Fabry-Perot etalon effects occurring in AOM and 3 mirrors of the resonator.

4. Conclusions

The fully modulated, efficient QML regime was demonstrated in AO-QML laser. The acousto-optic modulator playing here a double role of Q-switch and Mode Locker, was located near flat output coupler of Z type resonator. The resonance frequency of the cavity was matched to the radio frequency of acousto-optic modulator by the precise movement of two folding mirrors located at translation stages. The QML pulses with envelope durations of 100-150 ns and 100% modulation depth were observed for wide range of pump powers and

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repetition rates. The best energetic parameters were achieved for 66% of OC transmission and 30 kHz PRF. Up to 3 W of output average power, 130 μJ of the envelope energy, having approximately 5–8 mode locked pulses were achieved. The maximal pulse energy inside the QML train was about 30 μJ. To improve the energetic parameters of QML laser, new cavity design satisfying requirement of the low divergence angle at output arm and possibility of spatial filtering has to be worked out. The estimated pulse duration of 0.5–1 ns was caused mainly by relatively wide width of frequency spectrum of AOM driver and etalon effects occurring in resonator elements.

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