Quasi-Steady-State Operation of a Pulsed Diode Pumped Passively Mode-Locked Nd:YAG Laser

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Abstract: Generation of a stable train of picosecond pulses with 3.8 mJ energy at 400 Hz repetition rate and 200-µs train envelope from a pulsed diode pumped Nd:YAG laser with electro-optical negative feedback is presented.

OCIS Codes: (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped;

The constant need for utrashort laser pulses with ever growing energy motivates the research for various mode locking techniques. While passively mode-locked CW pumped lasers are the most robust approach for obtaining steady state operation their pulse energy is quite limited (1-10nJ). Pulse pumping has significant advantages in terms of scaling the energy, but in such passively mode locked lasers the fluctuations of both pulse energy and duration, stemming from the statistical nature of the intracavity light formation and the effect of simultaneous Q-switching, are a major drawback [1]. Hence, the quasi-steady-state operation within the pump pulse is problematic, the ultrashort pulse train durations do not exceed several hundred of nanoseconds and the single pulse duration has vast fluctuations. Suppressing the accompanying q-switching in passively mode locked systems through negative feedback control (NFC) has proven effective technique for improving the performance in lamp- and diode-pumped systems, but with low repetition rate (up to tens of Hz) [2,3]. However, the potential of diode pumped passively mode locked lasers seems not to have been exploited effectively, yet. Indeed, in the case of diode pulse-pumped lasers only semiconductor saturable absorber mirrors (SESAM) were used for passive mode locking, but SESAMs low damage threshold and absorption heating pose a limitation on both the pulse energy and the repetition rate (the best achieved value is ~0.5 mJ at ~100 Hz)[3]. Through a successful combination of frequency-doubling nonlinear mirror (FDNLM) mode locking with electro-optical NFC, we demonstrate a mode-locked operation of a pulsed pumped Nd:YAG laser emitting picosecond pulses enveloped in 200 µs pump pulses at 400 Hz repetition rate and 3.8 mJ pulse energy. Additionally, a theoretical analysis of the conditions for quasi steady state operation of the laser system depending on FDNLM and NFC circuit parameters has been done.

The FDNLM used consists of the frequency doubling LBO crystal and the dichroic mirror (DM), highly reflective for the second harmonic and partially reflecting at the fundamental wavelength. The reflection by the FDNLM includes a two-way pass of the beam through the nonlinear crystal (NLC) and it is governed by the back conversion from the second harmonic to the fundamental which depends on the phase difference $\Delta\varphi = \Delta\varphi_{in} - \Delta\varphi_{out}$, where $\Delta\varphi_{\mathrm{in}}$, $\Delta\varphi_{out}$ are the phase relations $2\varphi_1 - \varphi_2$ between the phase of the fundamental (φ_1) and second harmonic wave (φ_2) in the beginning of the second pass through the NLC and at the exit of the NLC on the first pass respectively.

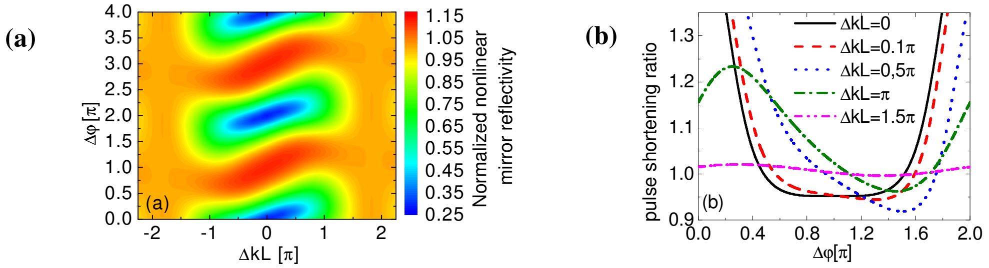

Fig. 1. (a) Normalized amplitude reflection coefficient, (b) pulse shortening ratio versus $\Delta\varphi$ for different values of phase mismatch parameter ΔkL_{cr}. The calculations are made with reflection coefficient of the output dichroic mirror 80 %, normalized input amplitude and Gaussian pulse shape.

Here, $\Delta\varphi$ is determined by the phase mismatched introduced by the NLC - ΔkL_{cr} (L_{cr} being the crystal length, Δk - wave vector mismatch. For some particular values of $\Delta\varphi_{\text{in}}$ and ΔkL_{cr} the value of the FDNLM reflectivity can be higher than the value of the linear reflectivity of the DM mirror (Fig.1a red zones). Therefore, such a setup will have distinct pulse shortening capabilities (see Fig.1b). For values of ΔkL_{cr}=0.5π the value of the pulse shortening is maximal when $\Delta\varphi$ has values between π and 2π, where the exact value in this range depends on the input peak intensity. In particular, for normalized input peak intensity value of 1, $\Delta\varphi$ = 1.56π (Fig.1b). For phase-mismatch exceeding 4.5 rad, the pulse shortening effect of the FDNLM becomes negligible.

Theoretical analysis of the transition from stochastic to dynamic laser operation using logistic map [4], shows that by adjusting the feedback depth together with the beam waist in the nonlinear crystal and the pump power, one can obtain quasi-steady-state operation in pulsed pumped laser. The laser setup is shown on Fig.2a. A 100-mm focusing lens was placed inside the 1.3-m resonator, consisted of high-reflective flat rear mirror and a flat dichroic optical coupler OC (HR @532 nm, T=20% @ 1064 nm). An FDNLM was formed by the OC and a frequency doubling LBO crystal (θ=90, φ=0°) that was kept at the temperature 150 °C corresponding to non-critical phase matching for 1064 nm. The generation of higher transversal modes was suppressed by inserting a pin hole (0.9 mm) right before the Nd:YAG active element. The waist diameter of the resulting TEM00 mode is around 100 µm inside the LBO nonlinear crystal. As an active element, we used a 2x60 mm long 1 %-doped Nd:YAG rod, transversely pumped by fifteen 40-W laser diode bars in three-fold geometry.

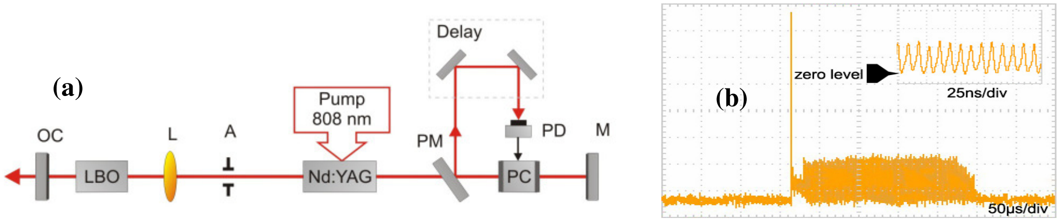

Fig.2 (a) Schematic of the laser consisting of: L - 100 mm lens, LBO nonlinear crystal, PC - RTP Pockels cell 4x4x8 mm, 2 mm diameter Nd:YAG crystal, A - pinhole for single mode operation, PM- polarizer, M – high reflectivity mirror for 1064 nm, O.C. - output coupler with 20 % transmission at 1064 nm, PD - fast photodiode; (b) Oscilloscope trace of the output pulses.

The scheme for optical feedback consists of a thin-film polarizer PM, RTP Pockels cell and a fast high-voltage PIN photodiode for direct control of the Pockels cell. Two high-reflective folding mirrors, forming an optical delay line were used to direct the beam with orthogonal polarization, reflected by PM to the PIN photodiode. Additional high-voltage circuit transforms the signal from the PIN photodiode to voltage driving the Pockels cell.

The 808-nm pump laser bars were operated in QCW mode by a pulsed current driver, delivering rectangular, 40 A, 200 µs current pulses with 400 Hz repetition rate. When the high voltage on the Pockels cell was switched off, we observed a mixed Q-switching and mode locking (QML) regime during the optical pump pulse. The application of the NFC led to significant changes in the generation dynamics. A 200-µs train of stable picosecond pulses was generated (Fig.2b). Through adjusting the depth of the feedback by the adjusting the light intensity incident on the PIN photodiode we have achieved a train of equal pulses with 27-ps FWHM duration grouped in the 200-µs pump pulse. The amplitude of the pulses after the first 30 µs is constant within 3% (Fig.2b inset), indicating that a quasi-stationary regime has been achieved. The output power is 1.5 W at repetition rate of 400 Hz, corresponding to 3.8 mJ energy in each envelope. The repetition rate of the picosecond pulses, determined by the 1.3-m length of the resonator is 115 MHz, with energy of a single picosecond pulse around 0.17 µJ, which is one to two orders of magnitude higher than the one typically obtainable in CW-pumped mode-locked lasers.

In conclusion, by implementation of an electro-optical negative feedback the Q-switching instabilities have been suppressed in a quasi-CW diode-pumped, passively mode-locked Nd:YAG laser. A stable train of 27-picosecond pulses grouped in 200 µs envelopes has been generated. The repetition rate of the laser system is 400 Hz with 3.8 mJ energy of the train and 0.17 µJ single picosecond-pulse energy.

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