Generation of a train of ps-pulses from a diode pumped Nd-laser using electro-optical negative feedback

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ABSTRACT

We present generation of a stable train of picosecond pulses from a diode pumped Neodymium based laser with electro-optical negative feedback. The laser outputs a mode-locked train of picosecond pulses with frequency 115 MHz enveloped by 200 microsecond pump macropulses. The macropulse energy is 4 mJ at a pump repetition rate of 400 Hz. The passive mode locker is a frequency doubling nonlinear mirror with LBO crystal, thermally stabilized at a temperature corresponding to noncritical phase matching for frequency doubling at 1.064 μm. Employing a resonator polarization output detected by a fast photodiode, enabled control on the resonator losses through a Pockels cell, thus creating a negative feedback. Q-switch suppression and stable mode-locking regime have been achieved. Theoretical condition for quasi steady state operation of the laser has been derived. Analysis of the pulse shortening ratio versus the phase difference between the first and second harmonics for different values of the phase mismatch have been made, showing the optimal regime of laser operation.

Key words: nonlinear mirror, mode locking, negative feedback, pulsed Nd:YAG laser

1. INTRODUCTION

The constant need for shorter laser pulses with ever growing energy motivates the research for various mode locking techniques. Due to their inherent advantages, the passive mode locking techniques for diode-pumped solid-state lasers have always attracted great interest. In particular, the nonlinear frequency doubling mirror techniques due to their intrinsic advantages have proven very useful for scaling the output energy. The frequency doubling nonlinear mirror (FDNLM) typically consists of a crystal for second harmonic generation and a dielectric mirror placed at a specific distance from the crystal, in order to achieve a proper phase difference between the reflected fundamental and the second harmonic waves. In the past, FDNM technique have been used for self-mode-locking[1-3] or for pulse shortening[4,5] in both pulse- and CW-pumped lasers. In the results obtained so far for lamp pulse-pumped lasers the FDNLM is usually employed as an amplitude modulator (the so called nonlinear mirror technique[1,2,5]). In this case the nonlinear crystal is tuned to exact phase matching conditions for second-harmonic generation and the dielectric mirror is a dichroic mirror, i.e. having comparatively low reflectivity for the fundamental frequency (~80%) and high reflectivity for the second harmonic. Though the quasi-CW pumping has significant advantages in terms of scaling the energy and less thermal aberrations, in such lasers the fluctuations of both the pulse energy and its duration are a major drawback[1,2,5]. These fluctuations stem from the statistical nature of the light formation in the laser cavity and the effect of simultaneous Q-switching. Thus, since the early days of passive mode locking, the accompanying Q switching has been a major concern[6-8].

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Negative feedback control is a method used for suppressing the Q-switching [9-13] and hence, to permit formation of quasi-stationary pulses whose parameters do not depend on the initial distribution of the field in the resonator. In this work we demonstrate a successful combination of FDNLM mode locking with negative feedback, acting as a mode-locking stabilization in a pulsed pumped Nd:YAG laser. The developed laser benefits from the quasi-CW pumping of the active element without the undesirable instabilities of the mode-locking regime, which are effectively suppressed by the negative feedback.

2. EXPERIMENTAL SETUP

The experimental setup consists of a laser resonator optimized for mode-locking operation (Fig.1) and a negative feedback scheme. The resonator length is 1.3-m with intracavity focusing lens (focal length 100 mm) that compensate for the thermally induced lens in the active element and ensure tight focusing (~ 100 µm) in the nonlinear crystal. The active crystal is a 1 %-doped Nd:YAG with 2 mm diameter and 60 mm length, transversely pumped by fifteen 40-W laser diode bars in three-fold geometry. The diode bars are connected in series and are pulse driven by a home-made diode driver delivering up to 100 A current pulses with adjustable pulse duration and frequency. A ceramic pin-hole aperture is used inside the laser resonator in order to limit the laser operation to TEM_{00} mode. In the FDNM scheme an LBO nonlinear crystal is used with dimensions 20x2x2 mm, thermally stabilized at the temperature of noncritical phase matching (149.0 ± 0.1˚C) for the fundamental wavelength of 1064 nm. The output coupler is a dichroic mirror with high reflectivity for the second harmonic and 80 % reflectivity for the fundamental wave.

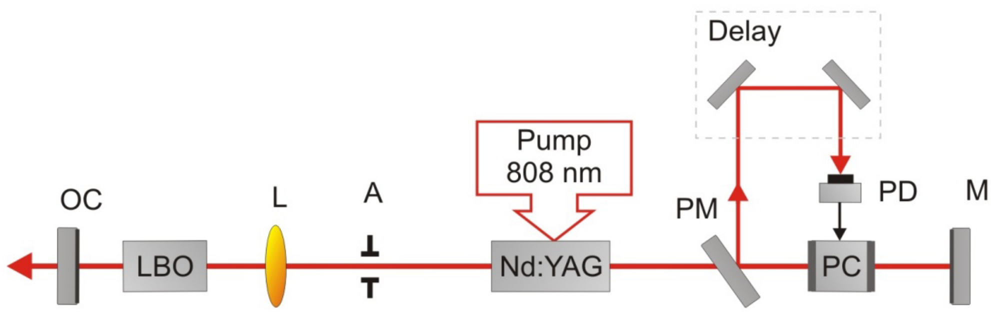

Fig.1 Schematic of the oscillator consisting of: L - 100 mm lens, LBO nonlinear crystal, PC - RTP Pockels cell 4x4x8 mm (Lasertec Inc.), 2 mm diameter Nd:YAG crystal, A - pinhole for single mode operation, PM- polarization mirror, M – high reflectivity mirror for 1064 nm, O.C. - output coupler with 20 % transmission at 1064 nm, PD - fast photodiode.

The negative feedback scheme consists of a polarization mirror in the resonator placed between the Pockels cell and the active element, delay line, fast photodiode and electronic scheme controlling the voltage on the Pockels cell with respect to the voltage on the photodiode. The Pockels cell electrodes are biased with 400 V (close to λ/8 voltage at 1.064µm). The role of this actively coupled negative feedback is to keep the cavity losses at a level allowing the pulse parameters to reach quasi-stationary level. In order to obtain quasi-stationary regime of picosecond pulse generation, the time parameters of the negative feedback should satisfy the following requirements: (i) the voltage applied to the Pockels cell should be proportional to the average round trip intracavity intensity and (ii) the response time of the feedback should be faster than the characteristic time of change of the intracavity intensity. The delay line is employed to synchronize in time the intracavity resonator pulses with the Pockels cell control. Essentially, the delay loop length has to be equal to the length of the resonator (1.3 m), because in this case when the pulse extracted from the polarization mirror is detected by the detector the Pockels cell can influence the next pulse from the train. Briefly the negative feedback operation is as follows: when the intensity of the intracavity pulse is going higher more energy will be decoupled by the polarization output and the signal on the Pockels cell will go higher, triggering a voltage increase on the Pockels cell thus increasing the losses in the resonator. Thus a quasi-stationary level is achieved. The level of the feedback signal and therefore the depth of the feedback can be optimized by controlling the part of the radiation incident on the photodiode with the beam alignment with respect to the clear aperture of the diode.

3. OPERATION OF THE FREQUENCY DOUBLING NONLINEAR MIRROR

The main idea for generating short laser pulses with a FDNLM as a passive mode-locker is based upon its intensity dependent reflectivity. In general, the reflection process in the FDNLM represents a two-way passing of the beam through frequency doubling nonlinear crystal. A basic characteristic of FDNLM is the inherent alteration of the phase interdependence $\Delta\varphi_{in} = 2\varphi_1 - \varphi_2$ between the first and second harmonics on the entrance of the second pass through the nonlinear crystal, compared to the same quantity upon the exit of the crystal on the first pass $\Delta\varphi_{out}$. This change is physically determined by the different phase shifts, acquired by the first and second harmonics during the light propagation from the exit of the nonlinear crystal to the dichroic mirror and back. Its physical reason is the dispersion of the system air - dielectric mirror (DM).

With a type I frequency doubling, the process of energy transfer (either down conversion or up conversion) is determined by the sign of the phase interdependence $\Phi = 2\varphi_1 - \varphi_2 + \Delta kL$, where $\Delta\varphi_{1,2}$ are the phases of the fundamental and second harmonic waves, $\Delta k = k_2 - 2k_1$ the wave vector mismatch, and L is the distance from the entry point of the nonlinear crystal. If $\Phi \in (0, \pi/2]$ the energy is transferred from the fundamental to the second harmonic (up conversion), when $\Phi \in [-\pi/2, 0)$ the energy is transferred backwards to the first harmonic (down conversion). This is illustrated by the equations (1) governing the process of second harmonic generation (SHG). The coupled amplitude and phase equations governing the SHG in a noncentrosymmetric crystal as derived from Maxwell's equations in a slowly varying envelope approximation for the first and second harmonics are:

$$\frac{dE_1}{dz} = -\sigma E_1 E_2 \sin\Phi; \qquad \frac{d\varphi_1}{dz} = -\sigma E_2 \cos\Phi;$$
$$\frac{dE_2}{dz} = \sigma E_1^2 \sin\Phi; \qquad \frac{d\varphi_2}{dz} = -\sigma \frac{E_1^2}{E_2} \cos\Phi; \qquad (1)$$

In the above system of equations E_1, φ_1, E_2 and φ_2 are the amplitudes and phases of the first and second harmonics respectively, and $\sigma = w d_{eff} / c(n_w n_{2w})^{0.5}$, $\Phi = 2\varphi_1 - \varphi_2 + \Delta kL$, where w is the frequency of the fundamental wave, c is the speed of light in vacuum, d_{eff} is the effective nonlinearity of the crystal, and n_w, n_{2w} are the refraction coefficients of the crystal for the first and second harmonics. By introducing dimensionless variables $U = \sigma E L_{cr}$ and $\xi = z / L_{cr}$ in (1) the system of equations becomes:

$$\frac{dU_1}{d\xi} = -U_1 U_2 \sin\Phi; \qquad \frac{d\varphi_1}{d\xi} = -U_2 \cos\Phi;$$
$$\frac{dU_2}{d\xi} = U_1^2 \sin\Phi; \qquad \frac{d\varphi_2}{d\xi} = -\frac{U_1^2}{U_2} \cos\Phi; \qquad (2)$$

By changing $\Delta\varphi = \Delta\varphi_{in} - \Delta\varphi_{out}$ together with ΔkL_{cr} (L_{cr} being the crystal length) we can influence the magnitude and the sign of the FDNLM reflection coefficient. Therefore, the FDNLM reflectivity change will depend upon the magnitude of the input intensity and the optical characteristics of the nonlinear medium as well as on two additional FDNLM's parameters $\Delta\varphi$ and ΔkL_{cr}. Figure 2.a shows the dependence of the normalized reflectivity of the FDNLM (normalization is done to the reflection coefficient of the dichroic mirror R_ω) as function of $\Delta\varphi$ and ΔkL_{cr}.

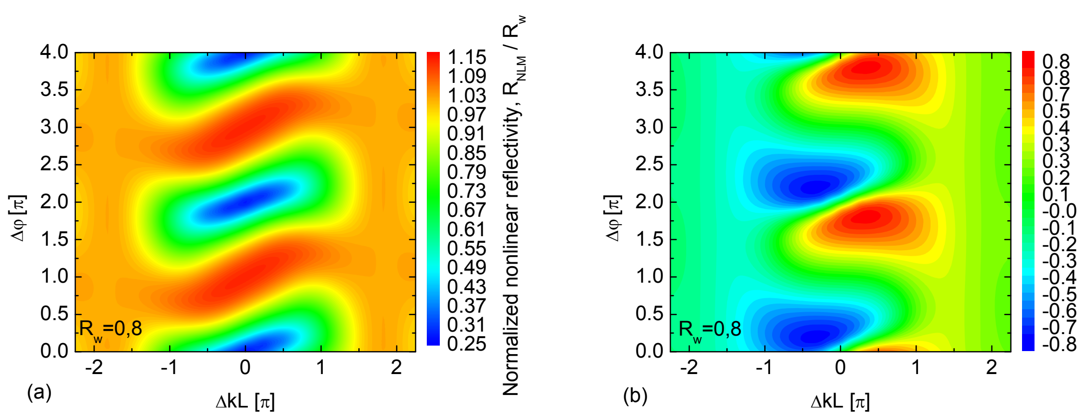

Fig. 2. Normalized amplitude reflection coefficient RNLM/Rω a) and nonlinear phase shift φ1 b) at fundamental wave versus ΔkLcr and Δφ. The calculation is made with values of Rw = 80 % and the normalized input amplitude U01 = 1 (U01 = σal0Lcr), where σ is a nonlinear coefficient, al0 is input amplitude and Lcr is the length of the nonlinear crystal.

For very weak input signals and when the influence of the nonlinear process on the reflection of the nonlinear mirror can be ignored, the value of R_{NLM} goes to R_ω. Therefore, for regions of the value of $\Delta\varphi$ and ΔkL_{cr} where FDNLM's normalized reflection coefficient is greater than 1, the reflection ability of the nonlinear mirror increases with input intensity increase. In this case FDNLM has distinct pulse shortening capability (fig.3). The magnitude of the laser pulse shortening τ_{out}/τ_{in} as well as the actual existence of shortening depend primarily on $\Delta\varphi$ with values of the phase mismatch parameter ΔkL_{cr} smaller than π.

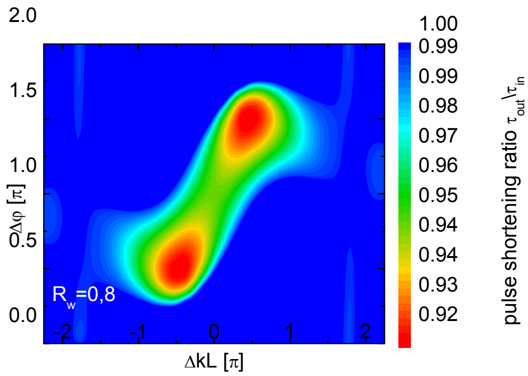

Fig. 3. Calculated pulse shortening ratio $\rho = \tau_{out}/\tau_{in}$, versus ΔkL_{cr} and $\Delta\varphi$

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 (Figure 4).

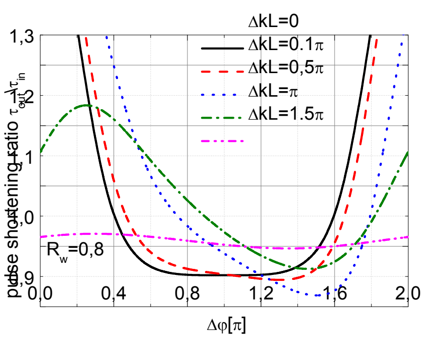

Fig. 4. Pulse shortening ratio $\rho=\tau_{out}/\tau_{in}$ versus $\Delta\varphi$ for different values of phase mismatch parameters ΔkL_{cr}. The calculations are made for a Gaussian temporal pulse shape and for normalized peak amplitude $U_{01} = \sigma a_{10}L_{cr} = 1$.

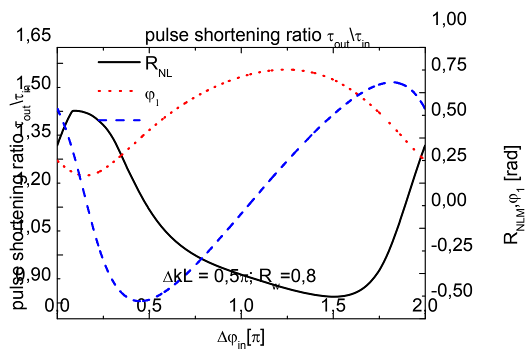

Fig. 5. Calculated pulse shortening ratio $\rho = \tau_{out}/\tau_{in}$ (solid black curve), nonlinear reflection coefficient R_{NLM} (dotted red curve) and a nonlinear phase shift φ_1 (dashed blue curve) at the fundamental wave as a function of $\Delta\varphi$

Together with the nonlinear amplitude reflection, FDNLM, depending on the $\Delta\varphi$ and ΔkL_{cr}, can incur significant nonlinear phase shift of the fundamental wave due to the so called cascaded second order processes via second harmonic generation (Fig. 2b). The value of the phase mismatch parameter (ΔkL_{cr}) for which the acquired via the reflection by FDNLM nonlinear phase shift has a maximum, has a weak dependence of the input intensity value and is about 0.3π.

By changing one of the mirrors of the laser cavity with a phase shifting FDNLM, the latter will act on the laser pulse travelling through the laser cavity as both amplitude and a phase modulator having a periodic transmission with a period of $2L_{cav} / c$. Consequently, by the use of a phase shifting FDNLM a self-mode-locking and a generation of ultra short pulses is possible, due to the nonlinear amplitude reflection and phase modulation. Figure 5 shows the pulse shortening ratio and nonlinear phase shift as a function of the normalized input pulse peak intensity acquired by a single reflection by the FDNLM. The optimal regime of laser operation should be for $\Delta\varphi$ of about 1.5π where the three factors, namely pulse shortening, high cavity Q-factor (i.e. high R_{NL}) and maximal phase modulation effect, are combined.

4. NEGATIVE FEEDBACK LASER: QUASI-STATIONARY OPERATION REGIME

In order to develop a theoretical model for the quasi-stationary operation of passively mode-locked laser with negative feedback we assume that the energy of the (n+1)st impulse depends on the energy of the nth impulse only and is given by the expression:

$$E_{n+1} = R_{NL} g_n^2 T_n E_n \,, \tag{3}$$

where R_{NL} is the nonlinear reflection coefficient for the system of nonlinear crystal and dichroic mirror; $g_n = g_0 / \left(1 + E_n / E_{sa}\right)$ is the gain coefficient for the active element; E_{sa} is the saturation energy; T_n is the transmission coefficient of the system of Pockels cell and polarization mirror. For our case the transmission coefficient of this system depends on the previous pulse energy only: $T_n = T_0 - \beta E_n$, where T_0 is the initial transmission coefficient, and β is the coefficient of the negative feedback. For the nonlinear reflection coefficient in the plane wave approximation without taking into account the walk-off effect one can write[9]:

$$R_{NLM} = A[1 - \tanh^2[\sqrt{A}\,\arctan h(\sqrt{\eta})\cos(\Delta\varphi) + \arctan h(\sqrt{\frac{R_{2w}\eta}{A}})]] \tag{4}$$

where $A = R_{2w}\eta + (1-\eta)R_w$, here R_w, R_{2w} are the reflection coefficients of the dichroic mirror for the first and second harmonic respectively and η is the conversion efficiency for the second harmonic for one pass through the nonlinear crystal assuming a rectangular pulse.

For small η: $tanh(\eta) \approx \eta$, and $arctanh(\eta) \approx \eta$, so expression (4) reduces to:

$$R_{NLM} \approx A[1 - [\sqrt{A\eta}\cos(\Delta\varphi) + \sqrt{\frac{R_{2w}\eta}{A}}]^2] \tag{5}$$

If we take into account that $R_{2w} \approx 1$ then expression (5) becomes: $R_{NLM} \approx R_w[1 - \eta[R\cos^2(\Delta\varphi) + 2\cos(\Delta\varphi) + 1]]$. The conversion efficiency for the second harmonic is $\eta = (\eta_0 sin^2(\Delta kL/2))/(\Delta kL/2)^2$ with $\eta_0 = (8\pi^2 d_{eff}^2 L^2 I_w)/(\varepsilon_0 n_w^2 n_{2w} c\lambda_w^2)$, where L is the length of the nonlinear crystal, ε_0 is dielectric permeability of the vacuum, c is the speed of light, λ_w is the wavelength of the fundamental wave and I_w is the beam intensity. Then $\eta \sim I_w = E_n/(\tau_{pulse} s_{pulse})$ and the above expression becomes:

$$R_{NLM} \approx R_w(1 - \sigma' E_n)\,, \tag{6}$$

with $\sigma' = \sigma / (\tau_{pulse} S_{pulse})$, (7)

where τ_{pulse} and s_{pulse} are the pulse duration and the cross section of the beam in the nonlinear crystal. When we take into account the above equations, the energy of the (n+1)st impulse becomes:

$$E_{n+1} = R_w(1 - \sigma' E_n) g_n^2 (T_0 - \beta E_n) E_n \tag{8}$$

Since we are working in regime where the energy of the impulse is far from the saturation energy of the gain medium, the gain coefficient of the active element can be considered practically constant. At equilibrium: $E_{n+1} = E_n = E_{st}$. If we introduce dimensionless variable $x_n = \beta E_n / T_0$ proportional to the energy, expression (8) becomes:

$$x_{n+1} = r_n(1 - x_n)x_n\,, \tag{9}$$

where $r_n = R_{NL} g_n^2 T_0$. Equation (9) is called a logistic map. At equilibrium: $x_{n+1} = x_n = x_{st}$ and therefore from (6) we derive:

$$x_{st} = 1 - \frac{1}{r_{st}} \tag{10}$$

From equations (9) and (10): $E_{st} = (T_0 R_{NL(st)} g^2 - 1)/(T_0 R_{NL(st)} g^2)$. If we use equations (6) and (7) for R_{NL} then the solution for the equilibrium energy becomes:

$$E_{st} = \frac{1}{2}\left(\frac{T_0}{\beta} + \frac{\tau S}{\sigma}\right) - \sqrt{\frac{1}{4}\left(\frac{T_0}{\beta} - \frac{\tau S}{\sigma}\right)^2 + \frac{\tau S}{R_w g^2 \beta \sigma}} \tag{11}$$

This solution is positive when $R_w g^2 T_0 > 1$. The solution with positive sign in front of the square root is rejected, since it turns out that it is bigger than T_0 / β, and that would make T_n negative. The solution of equation (9) is stable only if $1 < r_{st} < 3$. If $r_{st} > 3$ the solution becomes unstable, and with further increase of r_{st} the system quickly becomes chaotic[14]. The lower limit for r_{st} is obvious, since if it is less than one, then x_{st} becomes negative, and this is not a physical solution (this is the same condition as for the equation (11)). The upper limit is derived from the condition, that in order for the solution of the equation (9) (or any similar series) to be stable, the magnitude of its derivative (at the solution point) should be less than 1, i.e: If $x_{n+1} = f(x_n)$, then $x_{st} = f(x_{st})$, and $|x_{n+1} - x_{st}| = |f'(x_{st})||x_n - x_{st}|$ and in order for the series to converge in x_{st}:

$$|f'(x_{st})| < 1 \tag{12}$$

If we calculate the derivative of (12), and substitute there the solution (10), the condition (11) becomes: $|2 - r_{st}| < 1$, and from there follows that $1 < r_{st} < 3$. Therefore we derive the condition for stable generation for a laser with negative feedback: $1 < R_{NLM(st)} g^2 T_0 < 3$ or for small η (by using equations (6) and (7)):

$$1 < R_w \left(1 - \frac{\sigma E_{st}}{\tau_{pulse} s_{pulse}}\right) g^2 T_0 < 3 \tag{13}$$

5. RESULTS AND DISCUSSION

Without the negative feedback the laser output is a simultaneous q-switching and mode locking regime during the optical pump pulse (~200 µs). Pulse trains enveloped in the pump pulse with significant q-switching instabilities were observed. The application of the negative feedback control led to significant changes in the generation dynamics. A train of stable picosecond pulses was generated (fig.6). The duration of the pulse train depends on the pump duration and energy as well as on the level of the feedback signal. The role of the electro-optical feedback is to keep the cavity losses at such level that allows quasi-stationary operation i.e. the pulse reproduces itself in one round trip. The derived relation (13) in above paragraph includes parameters that have to be adjusted in order to obtain quasi-steady-state operation. For any given nonlinear and active crystals one can adjust the pump power together with the level of the feedback signal and beam waist in the nonlinear crystal in order to fulfil relation (12). The characteristic time parameters of the feedback have to satisfy the following requirements: (i) the voltage applied to the Pockels cell must be proportional to the average value of the round-trip intracavity intensity i.e. the feedback to be inertial and its response time to be higher than the cavity roundtrip time. (ii) The response time of the feedback must be shorter than the characteristic time of the change of the intra-cavity intensity, which in our particular case is in order of microseconds. Adjusting the feedback signal by the attenuation of the light intensity incident on the PIN photodiode we have achieved a stable train of picosecond pulses grouped in the 200 microsecond pump pulse (Fig.5). The amplitude of the pulses is constant, and that is an indication that quasi-stationary regime have been achieved. The output power is 1.5 W at repetition rate of 400 Hz. This corresponds to energy in a macropulse of 3.8 mJ. However, the repetition rate of the picosecond pulses, determined by the 1.3-m length of the resonator is 115 MHz. Therefore, the energy of a single picosecond pulse is around 0.17 µJ which is one to two orders of magnitude higher than the one typically obtainable in CW-pumped mode-locked lasers.

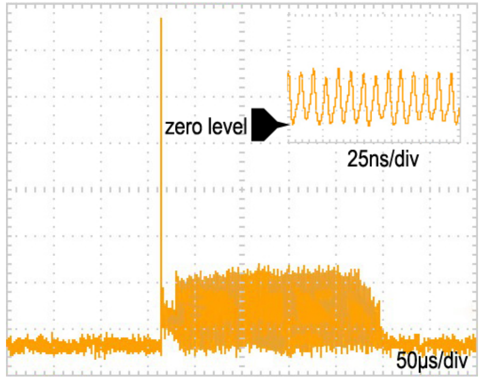

Fig.6. Oscilloscope trace of the output beam.

6. CONCLUSION

By electro-optical feedback the Q-switching instabilities have been suppressed in quasi-CW diode-pumped, passively mode-locked Nd:YAG laser. A condition for quasi-steady state operation has been derived analytically. The expression 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. A stable train of picosecond pulses grouped in 200 µs macropulses has been generated. The repetition rate of the laser system is 400 Hz with 3.8 mJ energy in a macropulse and 0.17 µJ picosecond pulse energy. The work done is in the framework of a project in Sofia University aiming for a picosecond light source at 1 micron with high energy (in the order of 50-100 mJ in a macropulse). Therefore, further development of the current work will be focused on the amplification of the obtained train of picosecond pulses.

7. ACKNOWLEDGMENTS

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