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# Nonlinear doubling mode-locking of feedback controlled pulsed Nd:YAG laser

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**Abstract**

We present the first investigation of a passively mode-locked Nd:YAG laser by nonlinear doubling mirror with dynamically electro-optical negative feedback control. The laser was operated in two modes: *long train mode* with relatively low peak power of the pulses and *short train mode* with high peak power of the pulses.

## 1. Introduction

The process of passive mode-locking by a saturable absorber is described in detail in Refs. [1–4]. The investigations, as pointed out in these papers, show undoubtedly that the statistical nature of the light formation in the cavity and the effect of $Q$-switching lead to substantial shot to shot variations of the energy and pulse duration. Ultra short pulse train duration does not exceed several hundred of nanoseconds and individual pulse duration is generally above the spectral transform limit. Negative feedback control [5–7] is a method used to suppress the $Q$-switching behaviour. This feedback permits the formation of quasi-stationary pulses whose parameters do not depend on the initial distribution of the field in the resonator [6–8]. In the references it is observed that negative feedback control results in the amplitude of the generated ultra short pulses to remain nearly constant for time intervals in the range of 1 to 50 μs.

A conventional passive mode-locking system based on saturable dy absorbers has a variety of disadvantages: (i) photochemical instability; (ii) relatively long decay times ( ~ 10 ps) which are the main limiting factor for the shortest possible pulse width in lasers with broad band spectral amplifications curves; (iii) lower allowed pulse density in comparison with the solid-state elements.

A new mode-locking device that does not have these disadvantages is the "frequency doubling nonlinear mirror" (FDNLM) [9–11]. It consists of a nonlinear crystal for second harmonic generation (SHG) and dichroic mirror separated by a proper distance in order to adjust the phase difference between the reflected fundamental and SH waves. The reflectivity of FDNLM at the fundamental wavelength depends on the efficiency of the SHG process and on the phase shift $\Delta\varphi_{in}$ between the fundamental and SH waves, falling on the second surface of the nonlinear crystal after reflection from the mirror. If this shift $\Delta\varphi_{in}$ differs by $\pm\ \pi$ from the phase shift $\Delta\varphi_{out}$ between the fundamental and SH waves coming out of the same surface, the reflectivity of the FDNLM at the fundamental wavelength increases with increasing of the input intensity. In this case the FDNLM is equivalent of a passive positive feedback and acts as a mode locker [10,11].

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Passive mode-locking of a Nd:YAG laser (at 1064 nm [10,11], 1320 nm [14]) and a Nd:YLF laser [13] has been obtained with such a nonlinear mirror. Shot to shot variation of pulse parameters of lasers mode locked by FDNLM is quite large [10,11]. The same type of nonlinear mirror was used by us for additional shortening and stabilisation of the pulses [15] and for obtaining extremely long trains of ultra short pulses [16] in an actively mode-locked Nd:YAG laser.

The main goal of this work is to design a passively mode-locked pulsed Nd:YAG laser in which are combined the advantages of the frequency doubling mode-locking technique and the stabilisation features of the active negative feedback.

## 2. Experimental set-up

The experimental set-up is shown on Fig. 1. The frequency doubling nonlinear mirror (FDNLM) consists of a KTP crystal for second harmonic generation and a dichroic mirror (M) situated at 19 mm from the closest KTP face. The KTP crystal (8×8×13 mm) has antireflection coatings; the dichroic mirror has 15% reflectivity at 1064 nm and 99.7% reflectivity at 532 nm. The harmonic splitter M2 reflects totally second harmonic wave and transmits fundamental wave and serves as second harmonic output. The diameter of the Nd:YAG active element is 6.35 mm and it is 65 mm long. At a distance of 1100 mm from the dichroic mirror (M) is situated and AR coated lens (L) with focal length of 1200 mm. This lens is used for reduction of the spot size in the KTP crystal. The two electrodes of the Pockels cell (PC) are biased with a voltage difference of approximately 1800 V (close to $\lambda/8$ voltage at $\lambda = 1.064$ μm). The Pockels cell and the thin film polarisation mirror (P) are elements of the negative feedback. The laser resonator is 1500 mm long. The power supply is able to provide 300 μs long pump pulses at frequencies up to 15 Hz.

The role of this actively controlled negative feedback is to keep the cavity losses at such a level, that allows the pulse parameters to reach quasi-stationary level. In order to obtain the quasi-stationary regime of ultra short pulse generation, the time parameters of the negative feedback should satisfy the following requirements: (a) the voltage applied to the PC must be proportional to the average round-trip intracavity intensity and (b) the response time of the feedback must be shorter than the characteristic time of the change of the intracavity intensity. The time constant of the p-i-n photodiode (PD2) used in the feedback control unit is 800 ps. The minimal delay time in the broad band amplifier (A) achieved by us is 3.5 ns. The level of the feedback signal can be optimised by the attenuation of the light intensity in front of the p-i-n photodiode (PD2) by neutral density filters.

## 3. Results and discussion

Without negative feedback the laser output was a single train of picosecond pulses. Pulse trains with duration in the range of 210–250 ns (fwhm) had asymmetry typical for the passively mode-locked systems without feedback [14]. The application of the negative feedback control unit led to significant changes in the generation dynamics. A train with low energy picosecond pulses was generated. At this low level of the pulse energy rate of the pumping compensates the reduction of the gain coefficient. The duration of the pulse train depends on the pump duration and energy, and on the level of the negative feedback signal. With our set-up we were able to generate pulse trains 30–50 μs long.

On Fig. 2a is shown part of the train 10 μs after the beginning. It is seen that the amplitude of the pulses is constant indicating that quasi-stationary pulse parameters of the pulses are being achieved. Mean power of the pulses at this moment is 0.8–1.0 kW. The typical value for the energy of the 30 μs long train is 30 mJ in the case where the feedback is on during the pulse train generation (long train mode). The amplitude of the pulses can be varied by the depth of the feedback. The range of change of the amplitude of the generated pulses in this quasi-stationary regime is a factor of 1.5–2.5 for our system. When negative feedback was used we also observed the well known two-threshold behaviour for passive mode-locked systems [3,8]. We observed that the mode-locking threshold occurred at a pump energy 15% greater than the free running mode threshold. It was noticed that the pump energy difference between the two thresholds was decreasing with increasing the intensity inside the nonlinear doubling crystal by changing the lens position.

The individual pulse energy at this long train mode is about 10 μJ. This energy can be increased by reduc-

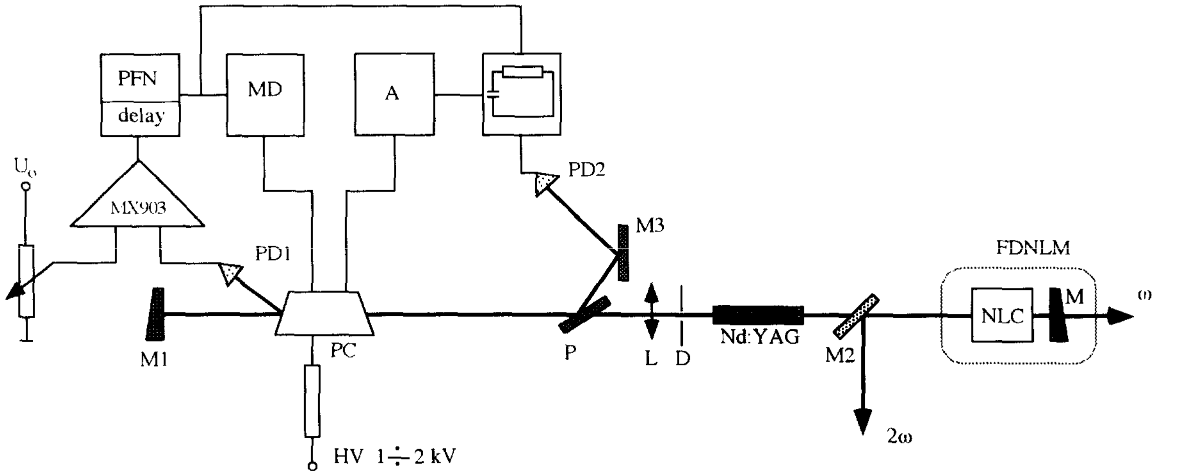


Fig. 1. Experimental set-up: M: dichroic output mirror, M1: rear mirror with maximum reflection at 1064 nm, M2: $1\omega/2\omega$ separator, M3: declining mirror, PC: Pockel's cell, P: thin film dielectric polarizer, L: antireflection coated lens, D: diaphragm, FDNM: frequency doubling nonlinear mirror, NLC crystal for second harmonic generation, PD1, PD2: p-i-n photodiods, MD: electronic unit for control of Pockel's cell, PFN: pulse forming electronic unit, A: broad band amplifier.

ing the losses in the cavity at the moment when picosecond pulses reach its quasi-stationary parameters. This can be done by dropping the applied voltage on PC to zero. The light pulse undergoes fast amplification and the stored energy inside the active media is emitted as a short than of picosecond pulses. On Figs. 2b and

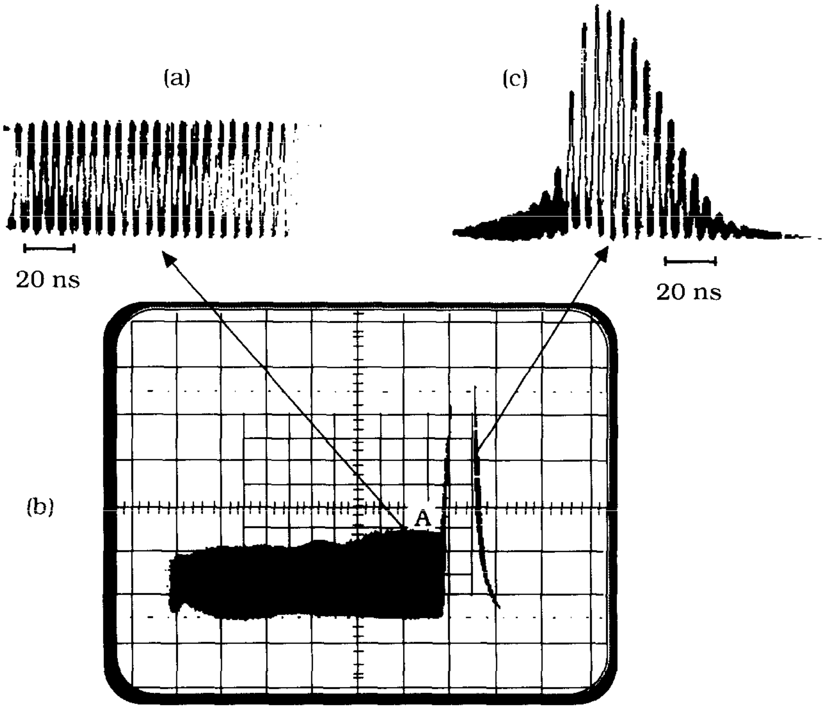


Fig. 2. Oscillograms of the laser output: (a) part of the train 10 μs after the beginning; (b) output of the laser in short train mode of operation (scale 1 ms/small div.); (c) only high-energy picosecond pulse part of the train.

2c are shown the oscillatograms of the laser output for this short train mode of operation of the negative feedback control. The left part of the oscilogram (Fig. 2b) is showing the initial period of establishing the quasi-stationary parameters of the pulses. Reducing the PC voltage at pont A results in a short train high energy picosecond pulses as shown on Fig. 2c. We measured that the energy of the short train is highly reproducible – 95% of the shots were inside the margin of 10%. The duration of the individual pulses was determined by the use of the autocorrelation technique. Assuming a hyperbolic secant shape for the pulses we derived duration equal to 35 ps (fwhm) for the short train mode of operation. This value was independently confirmed by measuring the duration with streak camera AGAT-SF1. The limiting factor for the obtained pulse duration we explain with the fact that output pulses are longer in duration with respect to the intracavity pulses [17] and with the spectral narrowing, result of the action of the nonlinear crystal as Liot filter [11]. The output energy of the train in this short train mode of the laser operation was 5.1 mJ at "1064 nm" output of the laser and 1.45 mJ at "532 nm" output of the laser. These parameters remained almost the same for all repetition rates up to 15 Hz.

## 4. Conclusion

In conclusion here we report on pulsed passively mode-locked Nd:YAG laser with high degree of pulse reproducibility. The system uses frequency doubling mirror as a passive mode-locker and also a negative feedback loop. The main advantages of this type mode locking in comparison with the conventional saturable dye absorbers are:

(i) availability of the output at second harmonic of the lasing frequency;

(ii) capability to work in any lasers emitting in the spectral range where nonlinear crystals for phase matched second harmonic generation are available;

(iii) the respond time can be an order of magnitude less than the respond time of conventional saturable absorbers with proper choice of the nonlinear crystal and its length;

(iv) no limitation on the pulse repetition rate;

(v) no need of dye pumps.

The main drawback of this type of mode-locking device is its relatively higher threshold.

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