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Negative Feedback Using a Nonlinear Mirror for the Generation of a Long Train of Short Light Pulses

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Abstract. A nonlinear mirror is used to provide a passive negative feedback in an actively mode-locked pulsed Nd:YAG laser. Trains of 250 ps pulses with a total length of up to 50 microseconds were generated. The train duration is limited only by the flashlamp pump pulse length.

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During the last few years, negative feedback (NFB) in pulsed mode-locked lasers has emerged as a promising technique for the generation of highly reproducible picosecond pulses [1–9]. The long pulse trains thus obtained are an ideal pump source for synchronously pumped dye lasers and parametric oscillators. The stability of the generated pulses is similar to that of the cw actively mode-locked lasers, having at the same time an order of magnitude higher intensity and quasi-cw power.

There are generally two techniques – active and passive – for the realization of negative feedback. The first one is based on an external electronic circuit consisting of a fast photodetector, an amplifier and a Pockels cell. In some implementations the photodetector and the amplifier are combined in a single high-current photomultiplier [5, 6]. It is required that the time response of the system is of the order of the round-trip time of the laser cavity. This is not a trivial task and thus makes the system quite complex.

The first demonstration of the active NFB technique in a mode-locked laser is probably due to Keller [1]. In his experiment, the pulse train of a passively mode-locked Nd:glass laser was extended approximately twice with improved satellite suppression. The superiority of negative feedback for generating reproducible pulses of extremely short duration has been demonstrated in [4] by obtaining 500–600 fs pulses from a passively mode-locked Nd:glass laser. In another experiment with a Nd:YAG laser, up to 5000 pulses each with 20 ps duration have been reliably generated [6]. High performance NFB picosecond neodymium-doped crystal lasers were described in [7].

A passive negative feedback based on two-photon absorption in GaAs has been also described in the literature. The introduction of NFB has in this case reduced the pulse duration from 40 ps to 4.5 ps in a Nd:YA1$0_3$ laser [8]. In a Nd:YAG laser, 10-ps pulses have been generated with high reproducibility [9].

In this paper we report on a new technique of passive negative feedback based on the nonlinear mirror, which was originally used for passive mode-locking [10, 11]. Although it yields longer pulses than other NFB techniques, it offers some advantages with respect to versatility and simplicity.

1. Nonlinear Mirror with Decreasing Reflectivity

The combination of a frequency-doubling crystal and a dichroic mirror has, under certain phase conditions, a reflectivity which increases with increasing light intensity. The principle of operation is based on second harmonic generation in the first pass through the crystal and reconversion of the second harmonic back into the fundamental in the second pass after reflection by the mirror. This is provided by the phase condition for the two light waves before reentering the crystal, which is stated as $\Delta\phi = 2\phi_1 - \phi_2 = \pi/2 \pm (2m+1)\pi$, $(m = 0, 1, 2...)$, where $\Delta\phi$ is the phase difference between the phases ϕ_1 and ϕ_2 of the fundamental and second harmonic waves. The nonlinear dependence of the reflectivity of this device provides positive feedback as in the case of a saturable absorber and can be used to mode-lock a laser [11].

It has already been pointed out [12] that the action of the nonlinear mirror can be reversed so that the reflectivity decreases with increasing light intensity, which in other words is negative feedback. The phase condition

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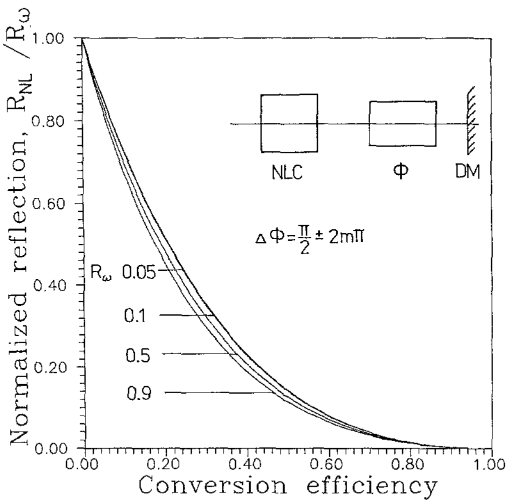

Fig. 1. Normalized nonlinear reflection for the case of negative feedback as a function of the conversion efficiency and for various reflectivities R_ω of the dichroic mirror at the fundamental wavelength. Second harmonic reflectivity is 100%. In the schematic presentation of the nonlinear mirror NLC denotes a nonlinear crystal, Φ is a phase-difference adjusting device and DM is a dichroic mirror

for this is $\Delta\phi = \pi/2 \pm 2m\pi$. We recall that the phase difference can easily be controlled by simply translating the nonlinear crystal with respect to the mirror, by using the dispersion in air, by tilting a glass plate positioned between the nonlinear crystal and the mirror or by an electro-optic (acousto-optic) device. Thus the action of the nonlinear mirror can be reversed to provide either positive or negative feedback.

The expression for the nonlinear reflection in case of negative feedback can be derived following [10]. The new phase condition changes the sign of the term: arctanh $\{(\eta R_{2\omega})^{1/2}/[\eta R_{2\omega} + (1-\eta)R_\omega]^{1/2}\}$ in [Ref. 10, Eq. (13)] from negative to positive. Thus, with a mirror totally reflecting at the second harmonic, the nonlinear reflection coefficient R_{NL} is:

$$R_{NL} = B\left\{1 - \tanh^2\left[\sqrt{B}\,\mathrm{arctanh}\sqrt{\eta} + \mathrm{arctanh}\left(\sqrt{\eta/B}\right)\right]\right\}, \qquad (1)$$

where $B = \eta + (1-\eta)R_\omega$ and η is the conversion efficiency in a single transit through the nonlinear crystal; R_ω is the reflection of the dichroic mirror at the fundamental wavelength.

The variation of the normalized reflection coefficient R_{NL}/R_ω as a function of the conversion efficiency and various fundamental reflectivities is depicted in Fig. 1. Compared to the positive feedback, the dependence of the nonlinear reflectivity on R_ω is much weaker. This allows implementation in lasers with quite differing amplifications and correspondingly, with different output mirror reflectivities.

2. Experiment

The experimental setup is based on a laboratory-built actively mode-locked Nd:YAG laser as shown in Fig. 2. The acousto-optic mode-locker ML (Intra Action Model ML-70B) was situated close to the total reflector, mirror M1. The latter was mounted on a translation stage allowing precise matching of the cavity length to the driving radio frequency. The Nd:YAG crystal was 60 mm long, 6 mm diameter, with antireflection coating on both faces. An internal telescope T and a proper aperture restricted the operation to a single transversal mode.

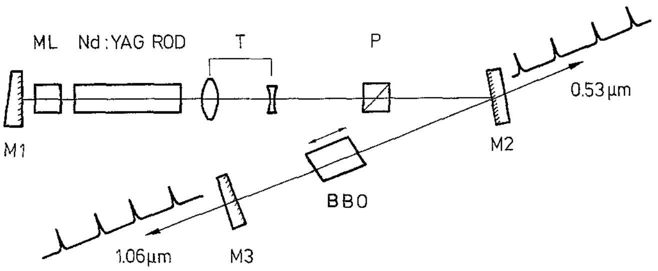

Fig. 2. Experimental set-up for the actively mode-locked pulsed Nd:YAG laser with a nonlinear mirror in negative-feedback mode: M1 – total reflector; ML – acousto-optic mode-locker; T – telescope; P – polarizer; M2 – harmonic splitter; BBO – nonlinear crystal; M3 – dichroic mirror

The 8-mm long BBO frequency-doubling crystal was cut for oo-e type interaction and when tilted for phase matching had an effective length of 8.2 mm. It was fixed on a translation stage to allow adjustment of the phase difference $\Delta\phi$ by using the dispersion of the index of refraction of the air.

The dichroic mirror M3 was totally reflecting at the second harmonic and had 25% reflectivity at the fundamental wavelength. An additional harmonic splitter enabled extraction of the second harmonic from the laser cavity.

The measuring equipment was the same as used in other experiments [11] and included a fast photodiode and an oscilloscope, a streak camera and an energy meter. All measurements of the individual pulse duration with the streak camera were performed by converting the laser radiation externally into second harmonic and by slicing a part of the train after a certain delay by means of a Pockels cell.

The laser was operated with a repetition rate of up to 10 Hz. When the BBO crystal was detuned from the exact phase-matching angle with precise adjustment of the cavity length and with pumping well above threshold, the laser output consisted of regularly decaying pulse trains as shown in Fig. 3a. Each pulse train was about 150 ns long as in Fig. 3b. With 2 W of rf driving power applied to the acousto-optic mode-locker, the individual pulse duration was 110 ps (second harmonic). Under these conditions, the total energy amounted to about 9 mJ.

The adjustment of the BBO crystal for phase-matching had a dramatic influence on the operation of the laser. First, when the crystal-to-mirror distance was adjusted for positive feedback, the laser operated in the active-passive mode-locking regime. Due to the Q-switching action of the nonlinear mirror, the whole energy of the laser generation was concentrated in a single pulse train of 150 ns duration with a somewhat steeper leading edge. By translating the nonlinear crystal approximately 3.5 cm (which corresponds to a change of the phase difference by π due

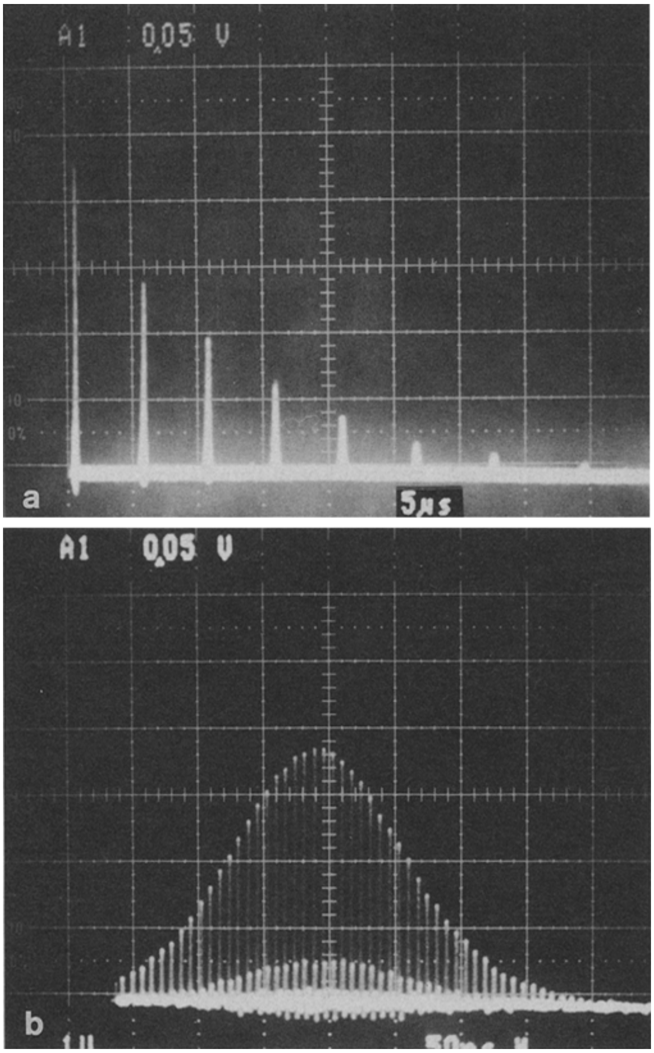

Fig. 3 a, b. Operation of the laser in a purely active mode-locking mode: **a** pulse train sequence, 5 µs/div; **b** pulse form of a single pulse train, 50 ns/div

to dispersion in the air), all pulse trains of the pure active mode-locking had merged into a single long train with a duration approximately equal to that of the pulse train sequence of the pure active mode-locking. This mode of operation generated the typical pulse form of a mode-locked laser with negative feedback: a well-pronounced overshoot at the beginning of the pulse train followed by a plateau, as shown in Fig. 4a. When the pump energy was varied, the pulse train duration followed that of the flash lamp pump pulse. Hence the pulse train duration is limited only by the pump pulse duration.

Different sweep rates of the oscilloscope revealed a steady-state pulse generation (Fig. 4b) and a pulse sequence free of satellites as shown in Fig. 4c.

Streak-camera measurements of the individual pulse durations were performed along the pulse train. The results are illustrated in Fig. 5. In the middle of the initial overshoot, pulses of about 500 ps with a well-pronounced substructure were observed (Fig. 5a). However, along the pulse train progressive pulse shortening was observed, Fig. 5b. After 20 µs the pulse duration had reached an almost steady-state value of about 230 ps and a smooth pulse form was observed.

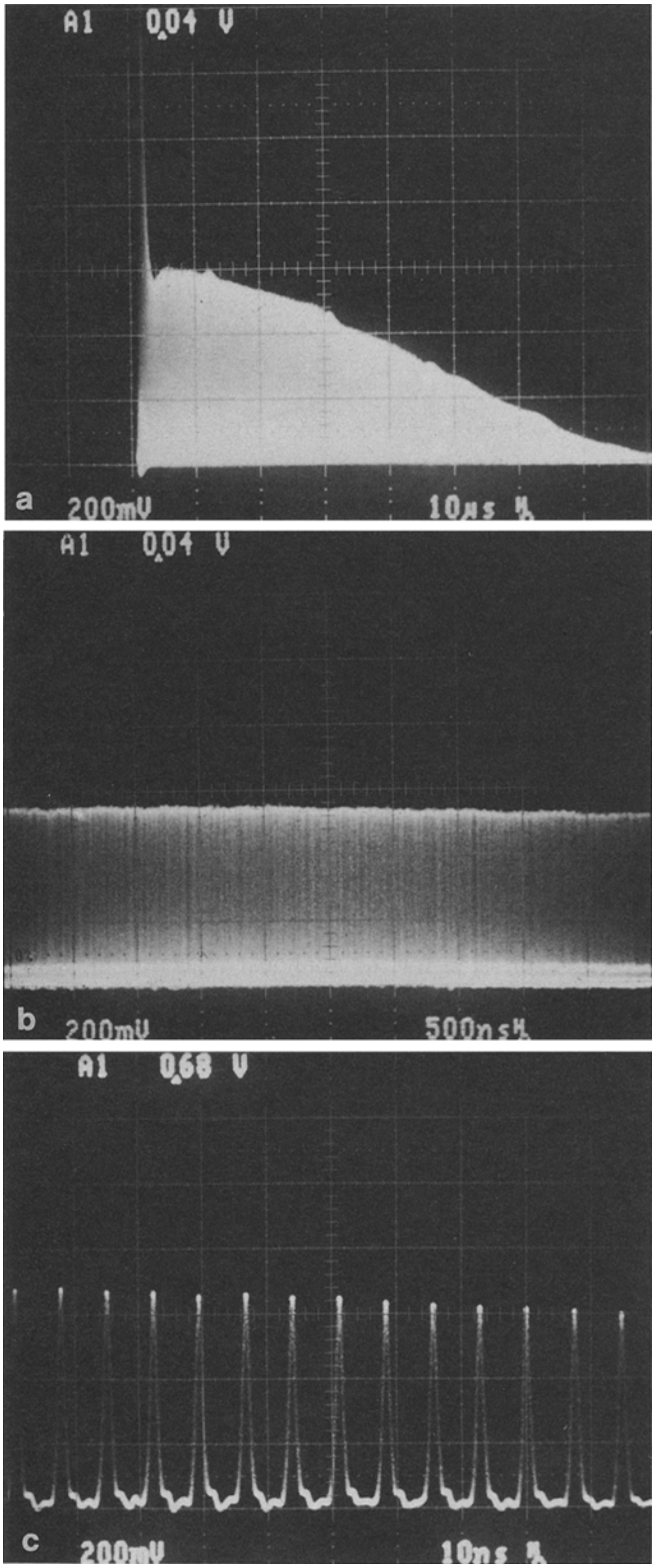

Fig. 4 a–c. Pulse train form for the negative-feedback mode at different sweep rates; **a** 10 µs/div; **b** 500 ns/div; **c** 10 ns/div

We have noticed a strong dependence of this steady-state individual duration on the rf driving power applied to the acousto-optic mode-locker. For example, 1 W power yielded 280 ps pulses whereas with 2 W power the pulse duration was 180 ps. This is due to a bal-

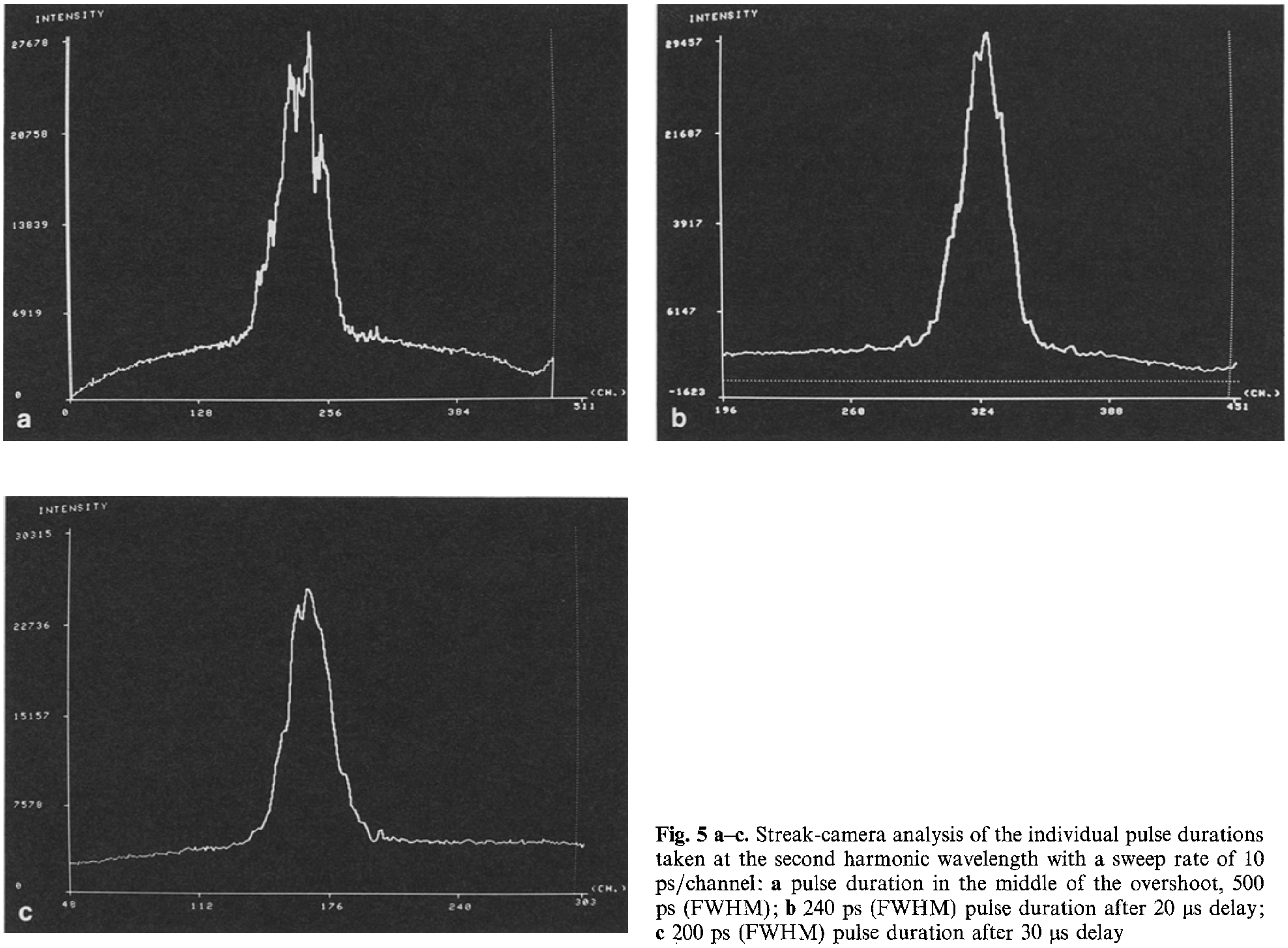

Fig. 5 a–c. Streak-camera analysis of the individual pulse durations taken at the second harmonic wavelength with a sweep rate of 10 ps/channel: **a** pulse duration in the middle of the overshoot, 500 ps (FWHM); **b** 240 ps (FWHM) pulse duration after 20 μs delay; **c** 200 ps (FWHM) pulse duration after 30 μs delay

ance between the pulse-shortening action of the active mode-locker and the pulse lengthening due to the negative feedback [13]. The relatively long individual pulse duration is a result of the fast response of the nonlinear mirror. The negative feedback tends to stretch the pulse in this case. When used to synchronously pump a dye laser, this shortcoming will be compensated by the increased number of pump pulses and the high peak power as compared to a cw pump laser. The individual pulse energy was calculated to be approximately 1.26 μJ with a peak power of 5 kW (taking into account that the fundamental wavelength pulse duration is approximately $\sqrt{2}$ longer than the measured second harmonic pulse length and amounts to 250 ps). The quasi-cw power of the laser was 180 W. As compared to other NFB mode-locked lasers, this laser exceeds either the quasi-cw power [4–6], or the total pulse train duration [7–9] by an order of magnitude. For synchronously pumped dye lasers, both quasi-cw power and pulse train duration are important for the generation of very short pulses.

It is easy to convert the operating mode of the laser from the active-passive mode-locking, which provides high peak power and short pulses, to negative feedback active mode-locking which yields long pulse trains. This is achieved simply by translating the nonlinear crystal. By inserting an electro-optic crystal between the mirror and the nonlinear crystal, the type of feedback (negative or positive) can be effectively controlled.

With a negative feedback a small amount of green power which is less than 1% of the infrared output is available from the harmonic splitter M2 in Fig. 2. It is interesting to compare this value in the case of positive feedback (active-passive mode-locking with nonlinear mirror), where the energy of the second harmonic amounts to 50% of the infrared output (3 mJ green and 6 mJ infrared). In all modes of operation (pure active, active-passive, and NFB active mode-locking), the total output energy was essentially the same.

3. Conclusion

We have demonstrated the generation of long trains of short light pulses from an actively mode-locked Nd:YAG laser by using a nonlinear mirror in a negative-feedback mode. The pulse train duration is limited only by the flash lamp pump pulse length. The nonlinear mirror allows different modes of operation thus making the laser a versatile source of short light pulses.

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Note added in proof. Using this technique, pulse trains up to 1.5 ms long were recently obtained [14]. We believe that these are the longest pulse trains generated from a pulsed laser so far.

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