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# Single Picosecond-Pulse Generation in a Mode-Locked Oscillator and Regenerative Amplifier System

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**Abstract.** A mode-locked Nd-glass laser oscillator with intra-cavity pulse selection by a Pockels cell shutter is described. A regenerative amplifier system with a saturable absorber is used to shorten the selected light pulses from the master oscillator. Pulses were shortened from 8 ps to 1 ps.

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In conventional passively mode-locked lasers a train of picosecond light pulses is generated [1–4]. Since many experimental applications require intense single picosecond light pulses, one pulse is separated from the pulse train by a Pockels or Kerr cell shutter. By incorporating the pulse selector into the mode-locked oscillator a single picosecond pulse is directly extracted from the resonator. This technique was invented soon after mode-locking was achieved [5] and has gained recent interest [6].

We studied a mode-locked Nd-glass laser oscillator with an intra-cavity krytron triggered Pockels cell shutter and compared its performance with a conventional mode-locked Nd-glass laser.

A regenerative amplifier [7] (slave oscillator) with saturable absorber for pulse shortening was added to the mode-locking oscillator (master oscillator). In this multiple-pass amplifier the picosecond light pulse durations could be reduced from 8 to 1 ps.

Regenerative amplifiers gained importance as high gain multipass amplifiers for weak injected pulses [7–10]. They are used to obtain a stable output amplitude [8, 9] and to storage the pulse over a certain time [9]. Pulse shapening in a regenerative amplifier with etalons and saturable absorbers was applied to tailor Nd–Yag laser light pulses for plasma diagnostics [11]. Amplitude stabilized trains of picosecond pulses with reduced pulse durations were recently generated by injecting a single picosecond pulse into a ring oscillator [12, 13].

## 1. Single Picosecond-Pulse Generation in Master Oscillator

The experimental setup of the mode-locked oscillator with internal pulse selector is shown in the upper part of Fig. 1. The oscillator consists of a Brewster–Brewster cut Nd-phosphate laser rod AM 1 (Schott type LG 703, length: 13 cm, diameter: 8 mm, concentration: 3 weight % $Nd_2O_3$), two mirrors M 1 (reflectivity $R_1 = 99.8\%$, curvature 3 m) and M 2 ($R_2 = 99.8\%$, plane), a contacted absorber cell AC (thickness: 0.2 mm, dye Eastman A 9860, single pass transmission $T = 0.85$), a Pockels cell PC 1, a thin-film dielectric polarizer TFP1 and an aperture AP (inner diameter: 3 mm). Wedged (1 degree) and antireflection coated mirrors and windows were used to avoid longitudinal mode selection. The Pockels cell was index matched with toluene. A photodetector triggered krytron system [14] generates quarter-wave voltage pulses $V_{\lambda/4} \simeq 5$ kV for complete pulse switching.

Photodetector PD 2 monitors the build-up of the pulse in the oscillator. Figure 2a shows a typical pulse train when no switching voltage is applied to the Pockels cell. The peak pulse energy in the resonator has a value of about 130 µJ. This energy can be completely re-

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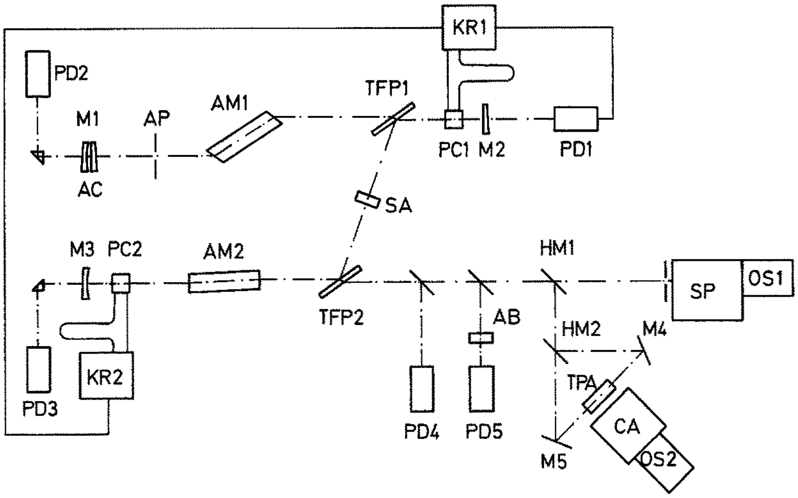


Fig. 1. Experimental setup. M1–M3: laser mirrors; AC: contacted dye cell; AP: aperture; AM 1 and AM 2: Nd-phosphate glass rods; TFP 1 and TFP 2: thin film polarizers; PC 1 and PC 2: Pockels cells; PD 1–PD 5: photodetectors; KR 1 and KR 2; krytron systems; SA: saturable absorber for pulse shortening; AB: saturable dye for intensity detection; HM 1 and HM 2: 50% reflecting mirrors; M 4 and M 5: 100% plane mirrors; TPA: two-photon absorber for pulse duration measurement; CA: camera; SP: 60 cm spectrometer; OS 1 and OS 2: optical spectrum analysers)

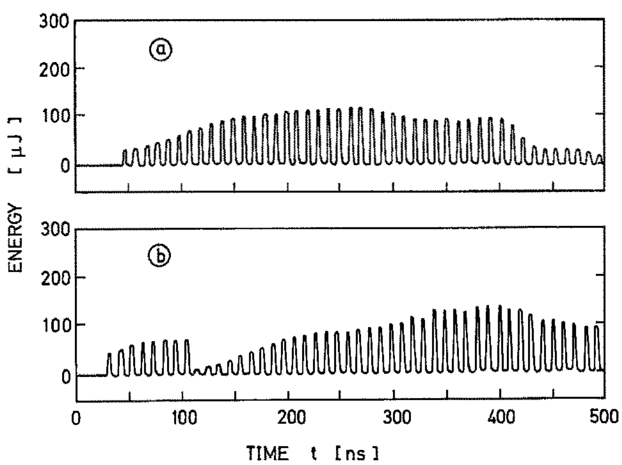


Fig. 2a and b. Pulse build-up in master oscillator. Pulse trains are detected with PD 2. (a) No voltage applied to KR 1. (b) Pockels cell shutter is activated for a period of 10 ns

leased from the resonator. The peak pulse energy inside the resonator of a conventional mode-locked laser with an output mirror of $R_2 = 50\%$ reflectivity is about 50% of the peak pulse energy of the mode-locked laser with intra-cavity pulse selector. Only the fraction of $1 - R_2 (= 50\%$ for $R_2 = 50\%)$ is coupled out in the conventional system.

Figure 2b shows a pulse train when the Pockels cell shutter is activated. A voltage pulse of 10 ns duration is applied to the Pockels cell. At the switching position one pulse of 90% of the circulating energy is extracted. The remaining pulse energy in the oscillator is further amplified by the inverted neodymium medium. This fact limits the tolerable saturable dye concentration for avoiding damage of the optical elements in the resonator. The regrowth of the switched pulse can be prevented when the Pockels cell switch is opened for a longer period.

The intensity of the selected pulse was measured behind polarizer TFP 1 by use of the saturable absorber technique [15]. For the case of Fig. 2b the peak intensity of the selected pulse was $I_{0L} \simeq 5 \times 10^9$ W/cm$^2$. The intensity in the maximum of the train reached a value of $I_{0L} \simeq 10^{10}$ W/cm$^2$.

The duration of the selected pulses was measured by use of the two-photon fluorescence technique [16] (absorber $2.5 \times 10^{-2}$ molar rhodamine 6G in ethanol). The duration was found to be $7 \pm 1$ ps (FWHM) in the early part of the train and increased to $11 \pm 2$ ps towards the middle of the train.

The spectra of the extracted picosecond pulses were measured with a 60 cm spectrometer. Bandwidth limited pulses ($\Delta\nu \simeq 2.5$ cm$^{-1}$, $\Delta\nu\Delta t \simeq 0.5$) were only obtained when the traversing pulse in the oscillator was ejected in the rising part before its energy reached one tenth of the peak value ($I_{0L} \lesssim 10^9$ W/cm$^2$). Towards the train maximum the spectral width broadens to $\Delta\nu \simeq 15$ cm$^{-1}$ due to self-phase modulation [17]. At and beyond the train maximum the spectral shape becomes irregular due to saturation effects.

The mode-locked Nd-glass laser with internal pulse selector shows the same dependence of pulse width and spectrum on the switching position and gives the same absolute values as the system with external pulse selection [18–20].

By intra-cavity pulse selection we obtained a blocking ratio of 100:1, i.e. for every round-trip 1% of the pulse energy is coupled out at TPF 1. This ratio is worse than in case of external pulse selection with a Pockels cell ($\approx 1000$:1) or a Kerr cell ($\approx 10{,}000$:1) and Glan polarizers [21]. If the weak blocking factor is disturbing, various techniques may be used to overcome the problems. For example, a saturable dye may absorb the leakage energy [22], a synchronized second external Pockels cell shutter may be applied, or the detection equipment may be gated [14].

The cavity dumped oscillator needs less electrical threshold pump energy ($\simeq 150$ J) than the conventional oscillator system ($\simeq 230$ J for an output mirror of $R_2 = 0.50$). This fact allows the operation of the intra-cavity selection system at a higher repetition rate than the laser system with external pulse selection, since thermal loading of the neodymium laser rods limits the repetition rate [6, 23].

## 2. Pulse Shortening in Regenerative Amplifier System

The duration of picosecond light pulses may be shortened in multi-pass saturable absorber – amplifier systems [24–26]. The laser oscillator with intra-cavity pulse selector allows a straightforward extension to a master oscillator-regenerative amplifier (slave oscillator) system as shown in Fig. 1. The regenerative amplifier has the polarizer TFP 1, the Pockels cell PC 1 and the mirror M 2 in common with the master oscillator. The additional parts of the regenerative amplifier are the saturable absorber cell SA, the thin film dielectric polarizer TFP 2, the Nd-phosphate laser rod AM 2 (Hoya LHG 7), the Pockels cell PC 2 with krytron system KR 2 and the mirror M 3 (curvature: 3 m). It should be noted that the optical lengths of the master and slave oscillator may be different (no synchronous pumping [1]). In our case the optical length of the master oscillator is 1.5 m while the optical length of the slave oscillator is 2 m. Self-oscillation of the regenerative amplifier is prevented by the saturable absorber SA.

The selected pulse from the master oscillator is transferred to the regenerative amplifier formed by mirrors M 2 and M 3. Its round-trip behaviour is monitored with photodetector PD 3. After a predetermined number of transits the pulse is switched out at polarizer TFP 2 by applying a quarter-wave voltage to Pockels cell PC 2 (Krytron KR 2 is triggered by a synchronization pulse of krytron KR 1).

The energy, intensity, duration and spectral width of ejected pulses from the regenerative amplifier were measured. The energy is detected with photocell PD 4 of Fig. 1. The intensity is determined with PD 4, PD 5 and saturable absorber AB [15]. The pulse duration is derived from the two-photon fluorescence technique [16] and the spectrum is measured with spectrometer SP. Four different saturable dye transmissions were studied ($T = 0.56$, 0.31, 0.1, and 0.012) and the number of round-trips was varied between 1 and 25.

Optimum pulse shortening was obtained when the absorption loss in the saturable absorber was just compensated by the amplifier (double pass amplification $F = 3$ for single pass dye transmission $T = 0.56$, $F = 5$ for $T = 0.31$, $F = 7$ for $T = 0.1$ and $F = 16$ for $T = 0.012$). The energy of the light pulses was kept approximately constant while the peak intensity of the pulses increased with pulse shortening (number of round-trips). Typical input as well as output energies were 30 μJ. The input intensity was held at about $3 \times 10^9$ W/cm$^2$. The output intensity was amplified to about $2 \times 10^{10}$ W/cm$^2$ for pulses shortened to 1 ps.

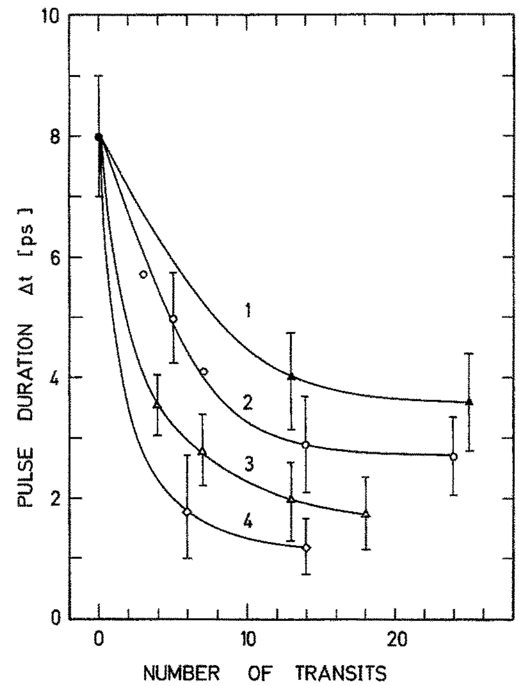


Fig. 3. Pulse shortening in regenerative amplifier. 1(▲), single pass transmission of SA $T = 0.56$ and double pass amplification factor of AM 2 $F = 3$. 2(○), $T = 0.31$ and $F = 5$. 3(△), $T = 0.1$ and $F = 7$. 4(◇), $T = 0.012$ and $F = 16$. Bars indicate standard deviation of single event

The measured dependence of the pulse duration on the number of transits through the regenerative amplifier is shown in Fig. 3 for the dye transmissions and amplification factors cited above. The pulse shortening ratio per transit is largest in the first few passes and reduces for the shortened pulses, since the bleaching becomes more transient ($\Delta t < \tau_D \simeq 6.5$ ps for dye Eastman A 9860 [27, 28], $\tau_D$: recovery time) and the spectral narrowing of the amplifier gains importance [8]). Average pulse durations of $\Delta t = 3.6$ ps for $T = 0.56$, $\Delta t = 2.7$ ps for $T = 0.31$, $\Delta t = 1.7$ ps for $T = 0.1$ and $\Delta t = 1.2$ ps for $T = 0.012$ were obtained. The shortest pulse durations were less than 0.9 ps.

The spectrum of the output pulses depends on the spectral shape of the input pulses, the number of round-trips and the saturable dye transmission. For weak absorber concentrations ($T = 0.56$ and 0.31) the spectra are broadened by self-phase modulation. For absorber transmissions $T \leqq 0.1$ (amplification factors $F \geqq 7$) the spectral narrowing of the amplifier [29] together with the strong absorption of weak signals acts against spectral broadening. In case of $T=0.012$ ($F=16$) nearly bandwidth limited pulses of $\Delta\nu\Delta t \simeq 0.8 \pm 0.3$ were generated with pulse durations down to less than 1 ps (number of round trips $\geqq 6$).

## Conclusions

The described compact mode-locked master-slave Nd-glass oscillator system allows the reliable generation of single picosecond light pulses of 1 ps duration. Application of the new mode-locking dye No. 5 might lead to even shorter pulse durations [30, 31].

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