Feedback Stabilized Actively Mode-Locked Nd:Phosphate Glass Laser

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Abstract—**An electrooptic, actively mode-locked Nd:phosphate glass laser system is described employing a novel single-step feedback system to stabilize the pulse buildup time. Single output pulses of ~100 ps duration with energies of up to 1 mJ could be reliably generated with a standard deviation in the ~3.2 μs pulse buildup time of ±40 ns allowing synchronization with pulses from laser systems at other wavelengths. Evidence of pulse broading due to self-phase modulation was observed together with wide tunability of the output wavelength from 1.054 to 1.068 μm.**

I. Introduction

In the past number of years the use of picosecond laser pulses has expanded in many fields [1], [2] such as nonlinear optics, plasma physics, and ultrafast kinetic studies in biological and chemical systems. Different types of laser systems have been developed to produce ultrashort light pulses for use in such studies [2], [3] each satisfying various requirements of pulse intensity, duration, wavelength, and stability. Many such applications require the use of intense pulses from solid-state laser systems which, to date, have mainly been generated by passive mode-locking techniques. It is well known in theory and in practice [4]-[6] that successful mode locking in such systems occurs in only ~80 percent of the laser shots taken due to the statistical nature of the pulse generation mechanism. Intense short pulses may be produced more reliably using a combination of Q-switching and active mode-locking techniques [7]-[11] but with a limitation on the pulse durations to values $\gtrsim 40$ ps. In some applications it is also desirable to synchronize an ultrashort laser pulse either with another laser pulse or an external event. Such applications rule out the use of passive mode-locking techniques for solid-state lasers due to the large jitter in pulse output time inherent in the slow buildup and statistical nature of this mode-locking process. However, in the case of active mode-locking of an Nd:glass laser system such synchronization is possible [10], [11] through the utilization of special Q-control techniques.

In the present paper we describe a Q-controlled, feedback stabilized, actively mode-locked Nd:phosphate glass laser system capable of producing pulses of ~100 ps duration and ~1 mJ energy at a wavelength of 1.054 μm. The use of a novel single step feedback system to control the buildup time allows the reliable synchronization of the single output pulse with any external event which is fixed in time.

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II. Theory

The theory of active mode locking has been derived both for the case of CW laser operation [12], [13] and the case of transient buildup and shortening of a laser pulse after Q-switching [7], [13], [14]. Consider the case of an electrooptic modulator located at one end of a linear laser cavity driven by a sinusoidal electrical signal at a frequency f_m. The frequency f_m is thus one half of the resonator roundtrip frequency. The intensity transmission function of such a modulator is given by

$$T = \cos^2 \left[\theta_m \sin (2\pi f_m t)\right] \tag{1}$$

where the depth of modulation parameter θ_m is defined by

$$\theta_m = \frac{\pi}{2} \frac{V_p}{V_{\lambda/4}} \tag{2}$$

and where V_p is the peak applied modulation voltage and $V_{\lambda/4}$ is the quarter-wave voltage. By assuming a Gaussian pulse shape in time and using Gaussian approximations to the spectral line shape of the laser medium and to the transmission peak of the modulation function, the limiting value for the mode-locked pulse duration is given by [13]

$$\tau_{p0} = \frac{\sqrt{2 \ln 2}}{\pi} \left(\frac{g^{1/2}}{\theta_m f_m \Delta f}\right)^{1/2} \tag{3}$$

where g is the natural logarithm of the roundtrip intensity gain and Δf is the laser bandwidth.

In the case of a Q-switched laser for which the pulse duration decreases with each transit through the resonator, the pulse duration after M roundtrips is given by [13]

$$\tau_p = \tau_{p0} \left[\tanh (M/M_0)\right]^{-1/2} \tag{4}$$

where

$$M_0 = \frac{\Delta f}{2\sqrt{g}\ \theta_m f_m}. \tag{5}$$

Normally in Q-switched systems the buildup time is so short that $M \ll M_0$, in which case the output pulse duration is given by

$$\tau_p = \frac{\sqrt{\ln 2}}{\pi \theta_m f_m \sqrt{M}}. \tag{6}$$

It can be seen that the production of short pulses requires both a large depth of modulation and a large number of roundtrips.

The requirement of a long buildup time is limited by the desire to have a low jitter in the pulse appearance time so as to

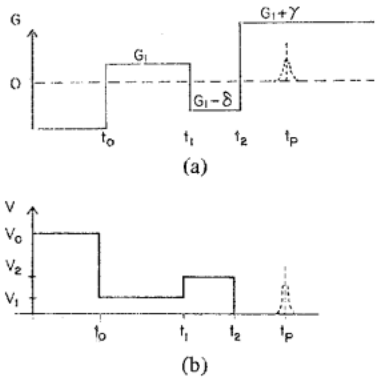


Fig. 1. (a) Roundtrip resonator gain as a function of time for the Q-control circuit. (b) Q-control voltage as a function of time.

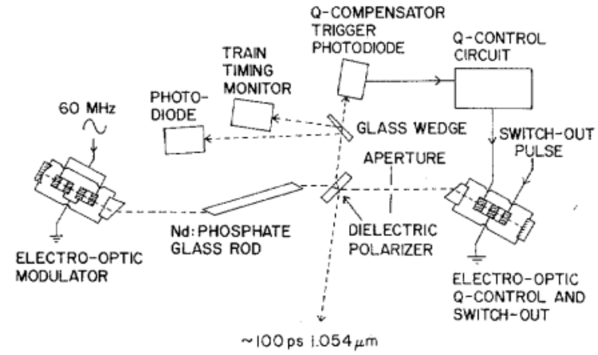


Fig. 2. Schematic diagram of the actively mode-locked, Q-controlled, Nd:phosphate glass laser system.

allow synchronization of the output pulse with other events. In the present system, a relatively long buildup time, ~400 roundtrips, was employed while the jitter in the pulse appearance time was controlled by a novel single step feedback system which formed part of the Q-control system. Simple two-step Q-control voltages have been used by previous authors [15], [8], [10] in order to stretch the pulse buildup time while direct feedback control has been used by other authors for pulse shaping or stretching [16]-[18]. In the system described here, a two-step Q-control was used to stretch the buildup time together with a feedback Q-compensation system used to stabilize the buildup time.

The Q-compensation is accomplished by detecting the time interval after the original Q-switch that is required for the laser radiation in the cavity to reach a predetermined low intensity level. On a particular laser shot when the gain is slightly higher than normal, this time would be less than normal and additional loss is then introduced in the cavity to compensate for the higher gain. Similarly, for shots when the gain is low, the buildup time to the trigger intensity is longer after which the cavity loss is reduced to compensate for the difference in gain. In practice this is accomplished by controlling the cavity gain G as shown in Fig. 1(a). The gain is defined such that the intensity of the laser pulse increases by the factor e^G after one roundtrip. The initial Q-step at the time t_0 increases the gain to a value G_1 which is slightly above threshold to allow slow buildup of the laser pulse from a starting intensity of I_0. At time t_1, a photodiode detector senses that the intensity in the cavity has reached the preset value I_1 and triggers a decrease in gain to the value $G_1 - \delta$. Finally, at the prefixed time t_2, the laser cavity is fully opened with a gain of $G_1 + \gamma$ to allow the quick development of an intense laser pulse reaching an intensity I_p at the time t_p. If the saturation of the gain medium and change in pulse duration are ignored, then a simple analysis of the feedback control system is possible. If the buildup times are expressed in units of the resonator roundtrip time, then the following equation must be satisfied:

$$\frac{I_p}{I_0} = \exp\{G_1(t_1 - t_0) + (G_1 - \delta)(t_2 - t_1) + (G_1 + \gamma)(t_p - t_2)\}. \tag{7}$$

Consider the case where the gain fluctuates by an amount α around the mean value of G_0 so that

$$G_1 = G_0 + \alpha. \tag{8}$$

Then the variation in the time t_1 with α is given by

$$\frac{dt_1}{d\alpha} = -\frac{\ln(I_1/I_0)}{G_0^2}. \tag{9}$$

When t_2, t_p, δ, γ, and G_0 are held fixed, then the variation in intensity at the time t_p is given by

$$\left.\frac{d(\ln I)}{d\alpha}\right|_{t_p} = \delta\frac{dt_1}{d\alpha} + (t_p - t_0). \tag{10}$$

Therefore, using (9) and (10) the variation of intensity at the time t_p due to fluctuations in gain can be made zero to first order if δ is chosen such that

$$\delta = \frac{(t_p - t_0)G_0^2}{\ln(I_1/I_0)}. \tag{11}$$

The implementation of such a scheme can be accomplished using the voltage function shown in Fig. 1(b) applied to an electrooptic crystal within the laser resonator. In the actual laser system the situation is more complex, involving gain saturation, shortening of the pulse duration throughout the buildup time, slow time response of the Q-compensation step, and the ringing response function of the electrooptic Q-control crystal.

III. System Description

The actively mode-locked laser system employed a linear resonator with an optical path length of 1.25 m as shown in Fig. 2. The cavity was bounded by a planar and a 10 m radius, totally reflecting, mirror mounted at the ends of liquid filled Pockels cell holders. The gain medium was a 6 mm diameter, 150 mm long, Brewster angled, Nd:phosphate glass rod made from Kigre Q-88 laser glass and mounted in a double elliptical cavity. The laser medium was pumped by two linear flashlamps powered by 40-100 J of energy from a power supply with a capacitance of 60 μF and inductance of 96 μH. During initial cavity alignment, much higher pump energies up to 1 kJ were necessary in order to obtain lasing since precise alignment with an HeNe laser was not possible due to the different dispersion within the resonator at the different wavelengths. An adjustable aperture of ~2.5 mm diameter was employed to control the cavity mode structure while a dielectric polarizer was used to maintain the radiation polarization. Normal operation consisted of firing the laser at fixed intervals of 30 s to 2 min. Operation at faster repetition rates did not allow sufficient time for cavity elements to thermalize and led to erratic results.

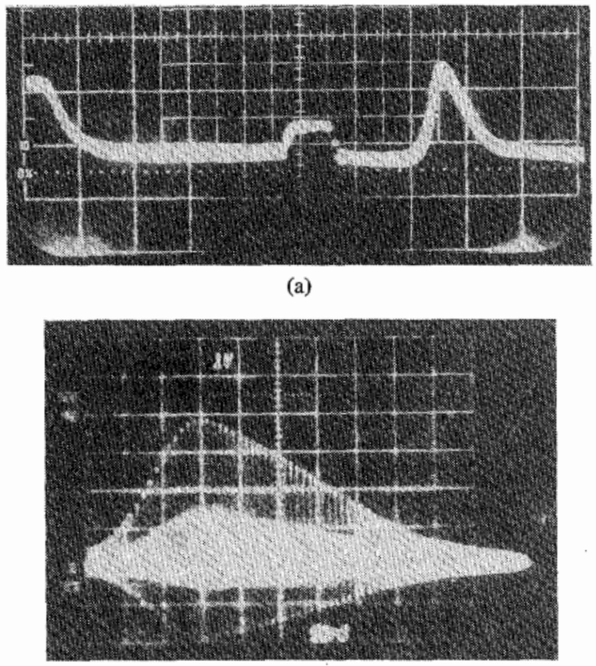
An electrooptic cell employing two KD*P crystals located at one end of the cavity was used as an active loss modulator. The 10 mm diameter, 20 mm long crystals were plated with cylindrical gold electrodes and immersed in an index matching fluid of Cumene in a holder enclosed by a cavity mirror and a Brewster angled window. The longitudinal Pockels effect crystals were oriented such that, with the center electrodes grounded and a voltage applied to both end electrodes, the optical phase shift was additive giving an effective quarter-wave voltage of ~1.7 kV at 1.054 μm. A special driver circuit employing an RCA 4860 coaxial transmission tube, as described in [11], was capable of driving the modulator with a 200 μs pulse of 60 MHz signal at ~5 kV peak to peak. This gave an effective depth of modulation of $\theta_m = 2.3$ per roundtrip. A fixed dc bias voltage in the range of ±150 V was also applied to the modulator to compensate for birefringence in the crystal and distortion in the RF signal.

At the opposite end of the laser resonator, a 12 mm diameter, 40 mm long KD*P crystal mounted in a similar holder was employed for Q-control and cavity pumping. The crystal was coated with three cylindrical gold electrodes such that with the center electrode grounded, separate control voltages could be applied to each half of the crystal. On one end of the crystal a Q-control voltage as shown in Fig. 1(b) was applied. The voltage steps were generated using Krytron circuits while a sensitive photodiode-avalanche-transistor circuit was used to trigger the compensation step when the intensity in the cavity reached a fixed value of ~10–100 kW. The photodiode-avalanche-transistor circuit was triggered by leakage radiation reflected from the dielectric polarizer due to induced and natural birefringence in the resonator elements. In addition, part of this leakage radiation was reflected from a glass wedge and used to monitor the development of the pulse in the cavity and also to trigger a second photodiode-avalanche-transistor circuit used as a synchronization timing monitor. Typical voltages and times employed in the Q-control circuit were $V_0 = 2.3$ kV, $V_1 = 0.25$ kV, $V_2 = 1$ kV, $t_2 - t_0 = 2.4$ μs, and the total buildup time $t_p - t_0 \simeq 3.2$ μs. The electronic circuits used to generate these voltage steps can be found in [19].

The laser pulse could be switched out of the cavity by applying a fast rise time quarter-wave voltage pulse, generated by a laser triggered spark gap, to the second half of the KD*P crystal. The cavity could also be dumped by applying a Krytron generated voltage pulse to the Q-control side of the crystal but the slower rise time of this voltage step led to the production of two output pulses. The latter method proved useful for aligning optics along the output beam path.

IV. Laser Performance

The buildup of the laser pulse was monitored on every shot by displaying the Q-control voltage and signal from the monitor photodiode on a single oscilloscope trace as shown in Fig. 3(a). The monitor photodiode observed the pulse train coupled out of the laser cavity by reflection from the dielectric polarizer due to induced and natural birefringence in the cavity elements. When monitored with an underdamped fast biplanar photodiode-oscilloscope system, Fig. 3(b), the leakage train had a duration of ~300 ns (FWHM) and consisted of resolution limited pulses <600 ps duration. The single switched out 1.054 μm pulse had an energy of up to 1 mJ while the background leakage radiation had an energy of ~0.3 mJ. This background leakage radiation could be reduced by the insertion of the electrooptic gate, driven by the same signal as the switch-out gate, in the path of the output pulse.



(a)

(b)

Fig. 3. (a) Combined Q-control voltage monitor and photodiode monitor signals (0.5 μs/div). (b) Output leakage train as measured by a fast underdamped photodiode and fast oscilloscope (50 ns/div).

The duration of the output pulse was measured using a streak camera with an S1 photocathode and a theoretical resolution of 15 ps. In general, the duration of the output pulse depended on the time of switch-out with the shortest pulses early in the train and longer pulses in the middle and end of the train. When well adjusted, the average pulsewidth during the rising edge of the pulse train buildup was 77 ps with a standard deviation from shot to shot of ±19 ps. At the peak of the train the average pulsewidth was 126 ps with a standard deviation of ±25 ps from shot to shot. Typical streak pictures of the output pulse early in the train and in the middle of the train are shown in Fig. 4. Spectral measurements were made of the upconverted second harmonic of the output radiation and indicated a spectral width of ~2 Å when the laser was only Q-switched without active modulation and a bandwidth of ~6 Å with active modulation. The pulse broadening throughout the duration of the pulse train together with the increased spectral width during mode locking can be explained by the onset of self phase modulation [20] due to the nonlinear refractive index of the laser medium and other optical components within the cavity. The peak intensities in the present system were ~250 MW · cm^{-2}, above the threshold of ~150 MW · cm^{-2} for the onset of self phase modulation observed in

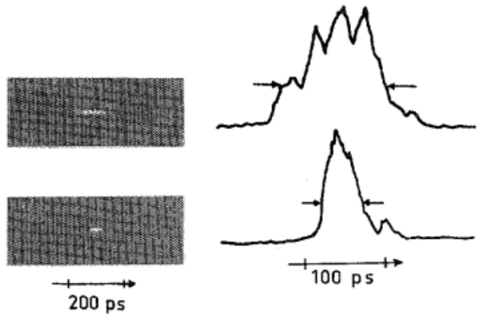


Fig. 4. Streak pictures and corresponding densitograms of single 1.054 μm pulses switched out near peak intensity of (a), and well before peak intensity (b). The half intensity points are indicated by the arrows.

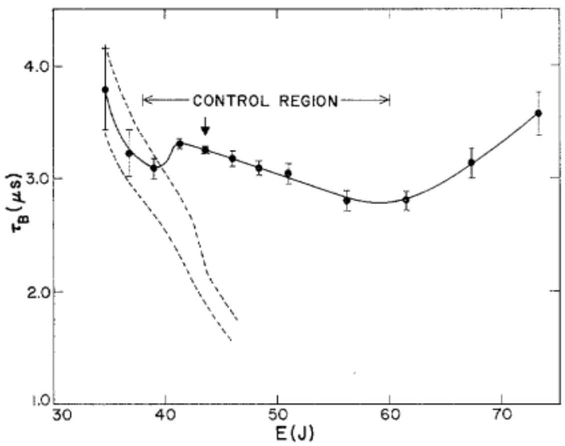


Fig. 5. Buildup time from the first Q-step to peak intensity as a function of flashlamp-pump energy. The dashed lines represent the range of buildup times without the Q-compensation while the solid line represents the times with Q-compensation. The optimum operating point is indicated by the arrow.

passively mode-locked Nd:phosphate glass lasers [21]. From (6) for the conditions of the present laser system, $M = 400$, $\theta_m = 2.3$, $f_m = 60$ MHz, a pulsewidth of 96 ps is predicted, in good agreement with the observed pulsewidths.

The effectiveness of the Q-compensation system was determined by measuring the buildup time to peak intensity as a function of flashlamp-pump energy, as shown in Fig. 5. Using a two-step Q-switch together with a triggered compensation step as shown in Fig. 1(b) the region of effective feedback control extended from ~38 to ~60 J of pump energy as indicated in Fig. 5. At lower pump energies the Q-compensation step never triggered, while at much higher energies the pulse growth was so rapid that substantial lasing and gain saturation occurred before or during the time of application of the compensation step. At each measured point the error bars represent the standard deviation in buildup time for five or more shots. The point of zero variation in buildup time with gain occurs at 41.5 J, but in fact more stable operation was obtained at 43.5 J pump energy at the point indicated by the arrow. In this region the shot-to-shot standard deviation in the buildup time was ±40 ns. Such a low jitter in buildup time allowed good synchronization with other external events.

It was also discovered that it was possible to obtain good laser operation over a wide range of wavelengths up to a wavelength of 1068 nm. This broad-band tuning was accomplished by adjusting the angle of the dielectric polarizer and was used to optimize the transmission of second-harmonic radiation through interference filters used in the optical diagnosis of laser produced plasmas.

V. Conclusions

The results presented here show that by means of active mode-locking alone single 1.054 μm laser pulses with energies of up to 1 mJ and durations of ~100 ps can be reliably produced from a Nd:phosphate glass laser system. By means of a single step Q-control feedback system it is possible to stabilize the jitter in the ~3.2 μs pulse buildup time to ±40 ns. Such a system then allows reliable synchronization of this laser pulse to another laser pulse or external event.

One area where such systems are of great importance is in the study of laser produced plasmas particularly when long irradiating laser pulses, $\gtrsim 1$ ns, are employed. The present system has proven particularly useful in this area as a source of optical probe pulses to study the plasmas produced by high intensity 1 ns CO_2 laser pulses [22]. The method used to synchronize the probe pulse and the CO_2 laser pulse to within ±200 ps is similar to that described in [11]. Successful synchronization of the 1.054 μm pulse and the 10.6 μm laser pulse was obtained in 77 percent of all the shots taken.

Such actively mode-locked laser systems with stabilized buildup times should also prove useful in many other applications requiring the reliable production of intense ultrashort light pulses synchronous with laser pulses at other wavelengths or synchronous with other triggered events in various experimental systems.

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