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PULSE STRETCHING AND SHAPE CONTROL BY COMPOUND FEEDBACK IN A Q-SWITCHED RUBY LASER

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PULSE STRETCHING AND SHAPE CONTROL BY COMPOUND FEEDBACK IN A Q-SWITCHED RUBY LASER

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Abstract

Feedback control is employed to stabilize the output of a Q-switched ruby laser. A computational model of the rate equations plus feedback terms is used to examine pulse shapes with changing feedback parameters. It is shown that a lengthened flat-top pulse cannot be obtained with negative feedback alone, a compound feedback arrangement is suggested to facilitate this. A practical laser system is constructed with an associated feedback loop, good agreement is found between theory and experiment. Pulses flat to within ± 5% are obtained with durations up to 600 ns and are amplified with no apparent saturation. Output powers of 15 MWatt are achieved for hundreds of nanoseconds with a divergence of 7 milliradians and a spectrum consisting of transform limited lines separated by the axial mode spacing.

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Introduction

Ultra high frequency drift waves in a plasma are expected to scatter laser light by acting as a diffraction grating. A preliminary study[1] showed the need for a rectangular pulse of light lasting about 200 nanoseconds. Long pulses have been obtained from Q-switched lasers by introducing non-linear materials into the cavity[2,3,4,5], lengthening the cavity[1] or by use of a feedback loop to control the switching of an electro-optic shutter[6,7,8]. The first two methods produce light pulses whose time variation is either approximately Gaussian or asymmetric with a fast rise and a decay time of several hundred microseconds. The feedback technique with a Kerr cell has converted the random relaxation oscillations of a ruby laser to a steady flux which decays exponentially in several hundred microseconds[6], but the resulting output power is low (< 100 kW) and high frequency oscillations occur[7].

The laser pulse for the proposed scattering experiment is required to have a power of at least 10 MW, a duration of about 200 ns, and rise and decay times less than 20 ns. Any ripple in the power should be less than 5% of the peak value and should occur at a frequency of less than 10 MHz.

The laser which produced the pulse is represented in Fig.1 and contains a feedback loop consisting of a pellicle beam-splitter and a photodiode which applies a negative feedback potential to a Pockels cell shutter. Initially, the Pockels cell is biased for zero transmission by applying the quarter wave voltage. As soon as this voltage is reduced the optical transmission rises and laser action begins. Five percent of the intercavity photon flux is used in the feedback loop.

After some preliminary experiments, a numerical analysis was carried out to determine which were the significant terms in the control equations governing the feedback system. A number of modifications were made to the system, based on the results of this computation.

Numerical analysis

Previous calculations[4,7] had shown that lengthened pulses could be generated by a Q-switched laser with the disadvantage that high frequency oscillations occurred for an appreciable part of the pulse. The present analysis makes use of the rational extrapolation method of R Burlisch and J Stoer[9] through a software facility (ORDIFFS) for solving up to ten coupled first order differential equations with teletype printout.

Elementary feedback system

The laser rate equations of Wagner and Lengyel[10] are used to describe the growth of photon flux which results from gain in the ruby and losses within the laser cavity. The rate of growth of photon density is given by:-

$$\frac{d\phi}{dt} = \frac{1}{t_1}(\alpha_o nL - \gamma)\phi \qquad (1)$$

and the rate of decay of the population inversion in the ruby is

$$\frac{dn}{dt} = -\frac{2\alpha_o L}{t_1} \cdot n\phi \qquad (2)$$

where $\phi = \Phi/N_o$ is the normalised photon density, Φ the total photon density (photons cm^{-3}) and N_o is the chromium ion density (Cr^{+++} cm^{-3}) in the ruby. The time taken for a photon to traverse the cavity is t_1, and the fraction of photons lost per traverse is γ. The fractional population inversion is $n = (N_2 - N_1)/N_o$. The absorption coefficient of the unexcited ruby is α_o which becomes a gain parameter when n is greater than zero. L is the length of the ruby rod, N_2 the density of chromium ions excited to the upper level and N_1 the density in the ground state.

These rate equations have been solved and yield giant pulses. However in the present application γ is not constant but is made explicitly dependent upon ϕ by the feedback loop, i.e.

$$\gamma = \gamma_c + \gamma(\phi) \qquad (3)$$

where γ_c is the constant loss term, which is mainly attributable to the output mirror transmission T_1 and may be written $\gamma_c = -\ln(1-T_1) = -\ln R_1$, whilst $\gamma(\phi)$ includes the transfer function of the feedback loop and shutter characteristics. It is assumed that the photodetector output current i is directly proportional to the input light flux so that $i = M\phi$. Then a voltage V may be produced by the load resistance R of Figure 2 with

$$V = i R = M R \phi .$$

The transmission of the Pockels cell is

$$T = \cos^2 \left(\frac{\pi}{2} \frac{V}{V_o}\right)$$

where V_o is the quarter wave bias-voltage.

Then

$$\gamma(\phi) = - \ln \left[\cos^2 \left(\frac{\pi}{2} \frac{V}{V_o}\right)\right] . \tag{4}$$

Before inserting equations (4) and (3) into (1) for solution terms must be added to account for the stray series-inductance and shunt-capacitance of the feedback circuit. Since the photodiode is a pure current generator the voltage at its output is determined by the impedance of the circuit connected to it; with capacitance C_1 in shunt to earth, V cannot rise to the level iR until C_1 is charged in a time of the order $C_1 V/i$. Thus a time lag is introduced into the loop. It will be seen that values of C_1 of a few picofarads can produce de-stabilising delays, whereas typical amounts of series wiring inductance do not seem significant.

The effect of shunt capacitance requires that the V in equation (4) be the solution of the circuit equation:

$$C_1 \frac{dV}{dt} = M\phi - \frac{V}{R} . \tag{5}$$

<u>Computations</u>

Equations (1), (2), (4) and (5) were integrated by the ORDIFFS routine which is capable of handling up to ten coupled first order ordinary differential equations. No algebraic expressions may be used in addition to the differential equations so that parameters must be treated as time dependent variables. The normalised photon density in the Pockels cell was assumed to be 10^{-4} at the instant of switching with $t_1 = 4$ ns, $L = 10$ cm and $\alpha_o = 0.4$ cm^{-1}. The value of the load resistor R was chosen as 200 ohms after some experience; larger values produced instability because C_1 could not be less than a few picofarad, but smaller values required more current than the available photodiode could supply.

An initial computation was carried out with $M = 0$, corresponding to zero feedback and resulting in a conventional Q-switched pulse having a peak flux 400 times the initial value as shown in Figure 3a.

When negative feedback is introduced with $M = 10^3$ and the stray capacitance C_1 in parallel with the 200 ohm load resistor is 20 pF, the pulse shown in Figure 3b is obtained. A small initial overshoot occurs as the capacitor charges making the feedback momentarily ineffective. Subsequently the output falls almost exponentially with a decay time of 80 ns which is determined by C_1/M.

Compound feedback

The purpose of introducing the feedback mechanism was to generate a rectangular pulse, but the circuit of Figure 2 will always give a monotonic decay even with RC_1 made small enough to reduce the initial spike. To make the pulse rectangular the feedback must be reduced as time progresses. This is accompanied by adding an auxiliary positive-feedback loop consisting of an inductance L_1 in series with capacitor C_2 having a time constant comparable with $\frac{C_1}{M}$.

The resulting feedback circuit is shown in Figure 4. It is assumed that C_2 is initially uncharged but at a time approximately RC_1 after the laser pulse begins, a voltage appears on the Pockels cell and partially closes it. At the same time this voltage produces a current i_2 rising at a rate V/L_1, which charges the capacitor C_2 and reduces the net bias on the Pockels cell, tending to re-open it. For a constant input voltage the series circuit L_1 C_2 produces a potential V_2 on C_2 which increases as $(1 - \cos 2\pi t)/(L_1 C_2)^{1/2}$ so that the shutter re-opening does not become very rapid until about a quarter period after the pulse onset.

From Figure 4 it is seen that the single circuit equation (5) must be replaced by a set of three new equations given below, and that V in equation (4) must be replaced by $V_1 - V_2$.

$$C_1 \frac{dV_1}{dt} = i_1 = i_0 - i_2 - i_3$$

$$= M\phi - \frac{V_1}{R} - i_3$$

$$C_2 \frac{dV_2}{dt} = i_3$$

$$L_1 \frac{di_3}{dt} = V_1 - V_2 \ .$$

Pulse shapes computed from these equations combined with equations (1), (2), (3) and (4) are given in Figures 3c, d, e, f. A value of 0.5 was assumed for the population inversion ratio, 20 μH for the inductor L_1 and 200 pF for C_1, the combined capacitances of the Pockels cell (6 pF), photodiode (6 pF) and circuit stray capacitance. This last value is slightly larger than the realizable minimum and results in a giant spike at the beginning of the output as shown in Figure 3c. This spike takes a large part of the available ruby energy from the rest of the pulse but is reduced if the pumping energy is lowered. The laser gain is then reduced, resulting in a lower pulse rise rate and a voltage rise on C_1 which follows the photon pulse more closely. In Figure 3d the ruby is pumped to $n = 0.3$ which is more realistic than 0.5, and C_1 is made equal to 20 pF. The pulse overshoot is now seen to be negligible.

An increase in the pulse length must result in a decrease in pulse amplitude so that a longer pulse should be attained by increasing the feedback loop gain M. In Figure 3e the gain M is increased from 10^3 to 3.10^3 resulting in a decrease in the initial pulse level but the amplitude rises steadily until its sudden collapse after about 150 ns. To recover a flat-topped pulse, the L_1C_2 product of the positive-feedback loop must be increased. In Figure 3f, L_1 has been increased to 120 μH and the resulting pulse is slightly longer than 200 ns but over 150 ns the amplitude varies by less than 5%.

The abrupt turnoff of the pulses in Figure 3 is obtained because the voltage V_2 rises quite rapidly in the later stages, exceeding V_1, causing momentary complete opening of the shutter. This sustains a high output, but V_2 continues to swing upwards and re-closes the shutter. V_1 then drops, further increasing the value V_1-V_2, and causes the final shutter closure to be very rapid. Some part of the population inversion remains and must be included in the final optimization of the system.

By solving the Frantz and Nodvik[11] equation for the gain of a laser amplifier it was shown that amplification of the laser pulse (Figure 3f) causes a departure, from the flat-topped structure, of not greater than 10% when the pulse power at the amplifier input is as much as 15 MW.

A Q-switched long pulse laser

A laser was constructed with a cavity 100 cm long and an output mirror of 50% reflectivity. The feedback loop consisted of an ITT FW114A photodiode and a KD*P Pockels cell, with the photodiode mounted so close to the Pockels cell that connections between terminals were only a few cm in length to minimise the stray capacitance. A 200 ohm load resistor R was employed as shown in Figure 4. The Pockels cell was switched on initially by means of a Krytron switch type KN6B. The cavity flux was polarized with a Glan-Thompson prism and about 5% was diverted by a pellicle beam splitter into the feedback loop. All other optical surfaces were anti-reflection coated.

To operate the system the Pockels cell was initially biased to its quarter wave voltage thereby preventing laser action. On firing the Krytron tube the Pockels cell bias falls to zero and light amplification begins. The switching time of about 1 ns determined by the load resistor and the Pockels cell capacitance, is insignificant compared with the pulse build up time of about 200 ns. The megohm isolation resistor prevents C_2 charging from the power supply during the laser pulse duration but is low enough to keep the Krytron conducting.

It was shown that a conventional Q-switched pulse of 40 ns duration, as seen in Figure 5a, could be obtained by making the optical attenuator of Figure 1 completely opaque to laser light and thereby eliminating all feedback. With simple feedback omitting inductor L_i, the laser pulse and feedback voltage shown in Figure 5b were obtained. It is apparent that control of the kind observed by Marshall and Roberts(6) has been effected since the fast rise and long decay is the same as the computed shape of Figure 3b. Compound feedback was achieved with the addition of a random-wound inductor of 75 μH together with a capacitor of 240 pF. An early result employing both positive and negative feedback is shown in Figure 5c, where the shunt capacitance to earth was high. The difference in shape between the feedback voltage and the laser pulse is due to ringing in the LC circuit. The initial spike and following hump of the laser pulse is the same as the computed shape of Figure 3c. On reducing the shunt capacitance the flat-topped pulse of 160 ns duration shown in Figure 5d was obtained. When the feedback loop gain M was increased without increasing the inductance, the laser pulse rose with time as in Figure 5e until the surge in the positive feedback voltage reduced it to zero. This figure compares with the computational shape of Figure 3e. Finally, in Figure 5f we show the pulse shape obtained when the inductance was increased to 160 μH, the flat top in the computed curve of Figure 3f is reproduced with a deviation from flatness of ± 5% for 130 ns of the total pulse duration of 240 ns.

Measurements of the output pulse made with a cone calorimeter showed that between 80 and 90% of the energy of the Q-spoiled pulse is retained in the extended pulse.

The spectrum of the laser pulse was determined in a photomixing experiment. An attenuated pulse was allowed to fall on a biplanar photodiode (I.T.L. HCB2) with a 125 ohm load. The output voltage was analysed up to 30 MHz with a Heathkit RG52 communications receiver and up to 870 MHz with an Eddystone 990S U.H.F. receiver. The spectrum was found to consist of lines having a transform limited half width of 2.5 MHz with subsidary satellites, separated by the axial mode spacing of 125 MHz.

Conclusions

It has been shown that the shape of a ruby laser pulse can be controlled by the use of a Pockels cell whose transmission is governed by the intensity of light in the laser cavity. The latter is related to the potential difference across the Pockels cell by the use of a photodiode and a combination of negative and positive feedback.

Using the Wagner and Lengyels giant pulse equations coupled with the equations of the electric circuit, pulse shapes have been computed which bear a close resemblence to those actually measured in the laboratory.

A correct choice of feedback parameters permits the generation of approximately rectangular laser pulses whose length can be varied at will between 120 and 600 ns, and which, moreover, are free from high frequency oscillations. 15 MW reactangular pulses have been amplified without distortion.

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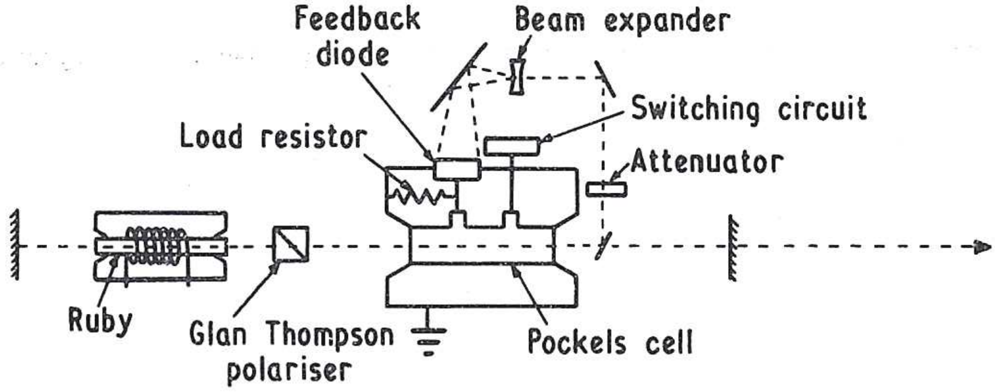

Fig.1 Laser cavity with feedback elements.

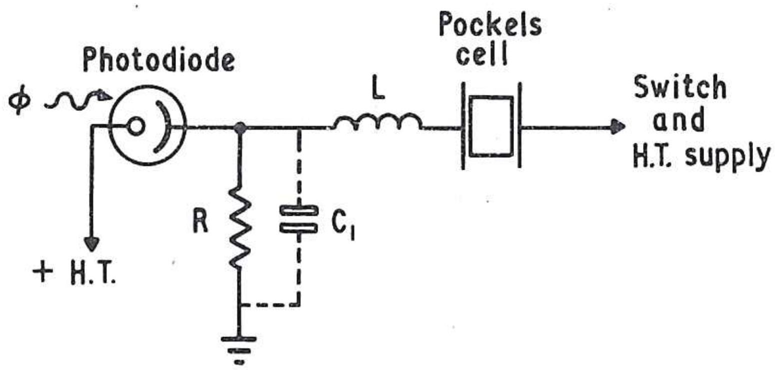

Fig.2 Feedback control circuit with parasitic inductance and shunt capacitance.

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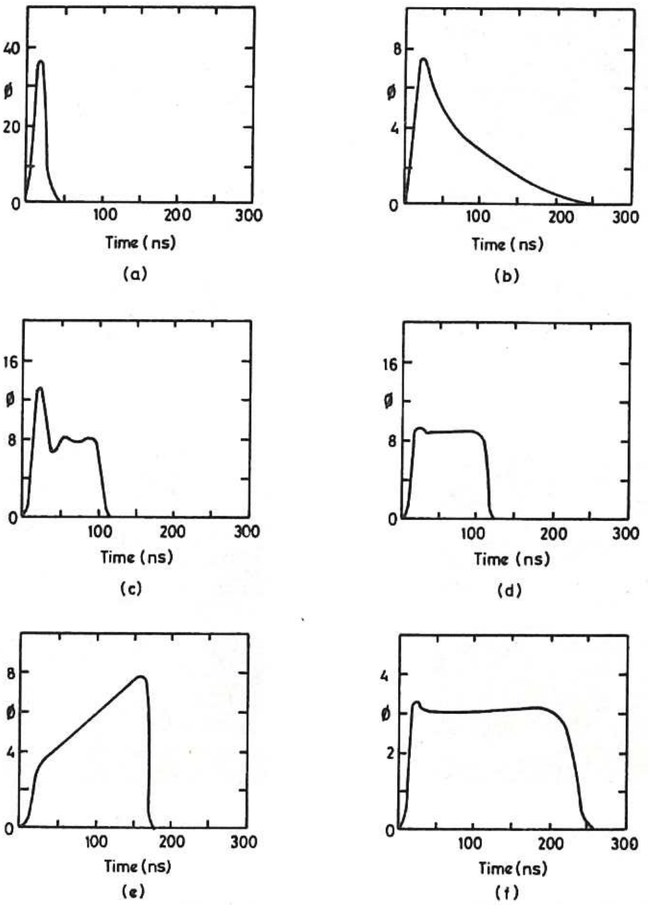


Fig.3 Computed output for a controlled laser in units of 10^{-3} photons cm^{-3}/chromium ion density.

(a) No feedback
(b) Negative feedback only
(c) Compound feedback with n = 0.5
(d) Compound feedback with n = 0.3
(e) Increased feedback loop gain, L_1 = 20 μH
(f) Increased feedback loop gain, L_1 = 120 μH.

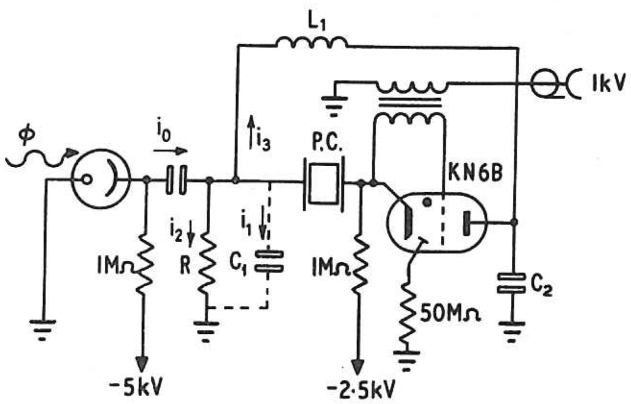
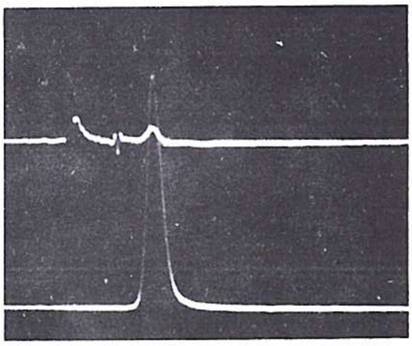
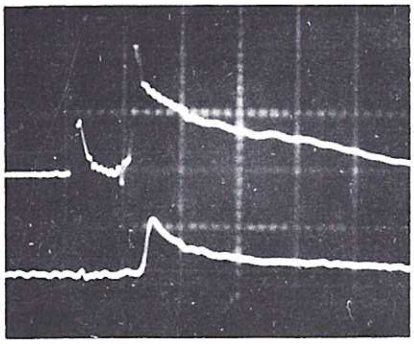


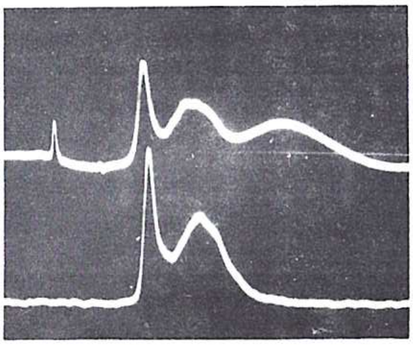
Fig.4 Compound feedback circuit, with a Krytron switch.



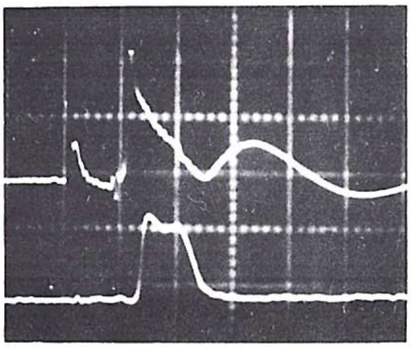
(a)



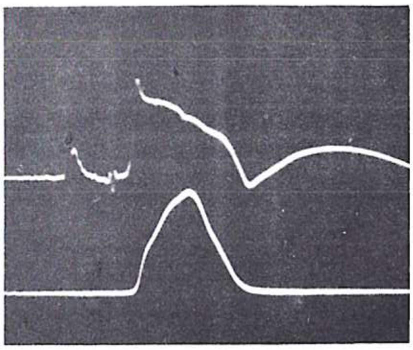
(b)



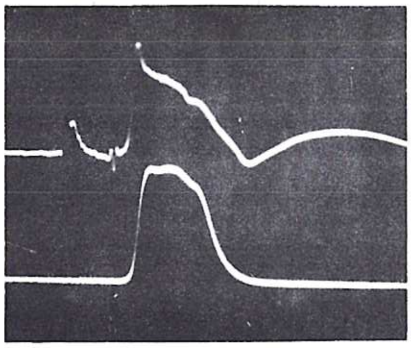
(c)



(d)



(e)



(f)

Fig.5 The upper trace is the feedback voltage and the lower trace the laser pulse. 200 ns per major division.
(a) No feedback
(b) Negative feedback only
(c) Compound feedback large shunt capacitance
(d) Compound feedback low shunt capacitance
(e) Increased feedback loop gain, inductance 75 μH
(f) Increased feedback loop gain, inductance increased to 160 μH.