Reliable passive mode locking with slow Q switching

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An electro-optic modulator (EOM) has been added to a passive mode-locked Nd:glass laser in order to slow Q-switch the cavity. This guarantees that the laser will work near threshold even if the gain of the laser medium or the losses change from shot to shot. The losses at the EOM are used as the output coupling. This new configuration allows more reliable operation of the system.

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As shown theoretically by the fluctuation model,[1–3] it is necessary to pump a laser very near threshold in order to obtain reliable mode locking in solid-state lasers with saturable absorbers. Therefore great effort has to be made to obtain very stable power supplies: adjustment of the dye transmittance has to be critically set, with the additional drawbacks that the dye decomposes and that its transmittance changes with temperature at about 1% per °C; mechanical mountings and alignment must also be carefully set.[4,5]

We describe here a new configuration in which a slow Q switch guarantees that the laser will work near threshold even if any of the previously mentioned parameters changes from shot to shot. Figure 1 shows a schematic diagram of the experimental arrangement. The electro-optic modulator (EOM) is set at an initial voltage that inhibits feedback to the cavity. When it is switched the voltage decreases exponentially very slowly with a time constant τ. In this way the output coupling is varied until at some voltage V_0 the threshold is reached and laser action begins. The voltage keeps on decreasing, and in this way the system is set just above threshold. Any change in such laser parameters as gain, dye transmittance, or any other loss variation will not modify this fact. The degree above threshold at which the system is set can be adjusted with τ. A photodiode was used to measure the fluorescence from the laser rod, and hence the population inversion was determined. The modulator was then triggered at a fixed value of the population inversion as shown in Fig. 2, compensating in this way fluctuations in the pump energy. A Brewster-Brewster cut Owens-Illinois ED-2 Nd:glass $3\times\frac{1}{4}$-in. laser rod was used.

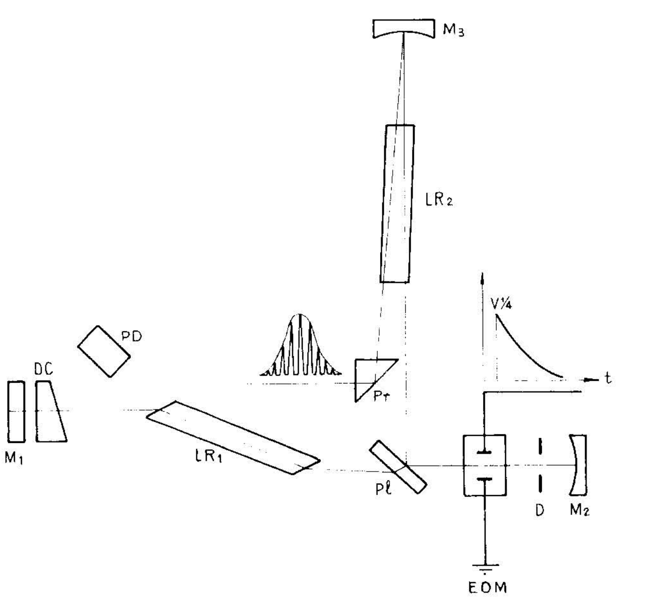

FIG. 1. Experimental setup: M_1 is the 100% reflecting mirror contacted with the dye cell. M_2 and M_3 are the 100% reflecting mirrors $r = 1$ m. DC is the flowing dye cell. PD is the photodiode. LR_1 and LR_2 are the Nd:glass laser rods. EOM is the electro-optic modulator. Pl is the thin-film polarizer. D is the mode selecting diaphragm. Pr is the 90° deflecting prism.

The dye was a solution of Eastman 9860 compound in 1,2 dycloroethane, and flowed through a 0.3-mm-thick cell contacted to the plane mirror. Both mirrors had 100% reflectivity.

Following New,[6] we can compute the gain G_u of the system when the nonlinear process starts by means of the following equations:

$$G = A\,K, \qquad (1a)$$

$$G_u = A\,K_{\rm nl}\,, \qquad (1b)$$

$$G_u = [2A\,\ln(F/NF_0)]^{1/2}, \qquad (2)$$

$$F = \min(F^a, F^b), \qquad (3)$$

$$N = M/\alpha(\pi\,A\,K_{\rm nl})^{1/2}, \qquad (4)$$

$$F^a = 0.02\,G_u^2/(A + G_u)\,\sigma_a\,T_{\rm cav}, \qquad (5)$$

$$F^b = 0.02\,G_u/\rho_{ab}\,\sigma_b\,B_u\,T_{1b}R, \qquad (6)$$

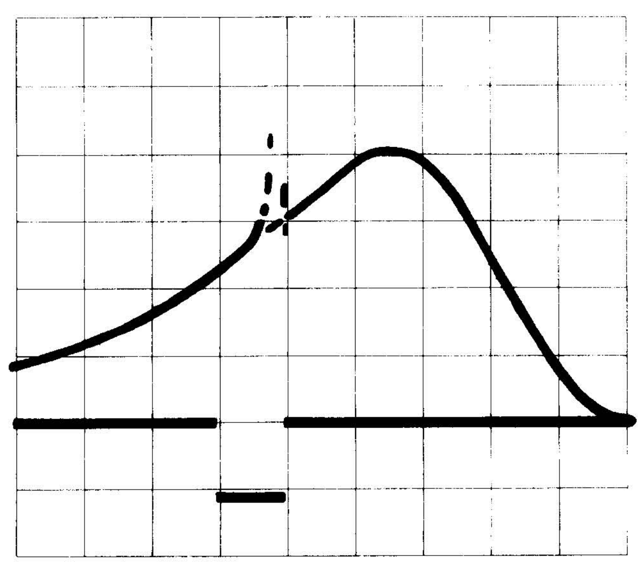

FIG. 2. Lower trace: fluorescence of the laser rod; horizontal 100 μs/div., vertical 200 mV/div. Upper trace: square pulse which shows when the EOM is triggered. Horizontal 100 μs/div., vertical 5 V/div.

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where the first equation means that gain G increases linearly with the number k of transits after the threshold is reached.

In our case this is not due to an increase in the amplification but to a decrease in the loss. M is the number of modes in spectral profile $\alpha = 2(\ln 2)^{1/2}$; N is the number of peaks at $k = k_{nl}$, that is, when the nonlinear stage begins; F_0 is the photon flux per mode at $k = 0$; A is the total linear loss per transit; F is the photon flux at k_{nl}, F^a is the photon flux if the amplifier depletion becomes significant before the onset of absorber nonlinearity, otherwise $F = F^b$; B_u is the small signal loss of the absorber, T_{1b} is its relaxation time, and σ_b its cross section; σ_a is the transition cross section of the amplifier medium, ρ_{ab} is the ratio of the beam area at the amplifier medium and the absorber; R is a statistical parameter; and T_{cav} is the transit time in the cavity.

As the EOM decay time τ was much smaller than the decay time of the population inversion, this was considered as a constant. Hence the transmittance of the EOM-polarizer system is

$$T = \cos^2[\varphi \exp(-KT_{cav}/\tau)], \tag{7}$$

where

$$\varphi = \pi V_0/2V_{1/4} \tag{8}$$

and $V_{1/4}$ is the quarter-wave voltage of the EOM. The linear losses are given by $-\ln T$ and

$$A = (-d\ln T/dk)_{k=0} = 2\varphi tg\varphi\, T_{cav}/\tau. \tag{9}$$

The inversion above threshold is then given by

$$P = 1 + G/A. \tag{10}$$

For our system $A = 1.53$; $\rho_{ab} = 5$; $R = 9$; $\sigma_b = 2\times 10^{-16}\,\text{cm}^2$; $\sigma a = 3\times 10^{-20}\,\text{cm}^2$; $T_{cav} = 5.8$ ns; $T_{1b} = 10$ ps; $M = 10^4$; $B_u = 0.71$, which corresponds to a dye transmittance of 70%; and we measured $\varphi = 0{,}41$.

Solving (1)–(6), we find $G = 6.1\times 10^{-2}$, with $F^b = 5.7\times 10^{21}$ and $F^a = 3.5\times 10^{23}$, $k_{nl} = 446$ and $N = 1736$.

The values of F^b and F^a show that saturation occurs first in the absorber, so we have a class-II operation. With the calculated parameters

$$P = 1.044,$$

that is, 4.4% above threshold.

When tested in the previous setup, very reliable mode locking occurred and satellite pulses did not appear in more than 5% of the shots as was shown on oscilloscope trace. (The detection system had a 0.8-ns rise time.)

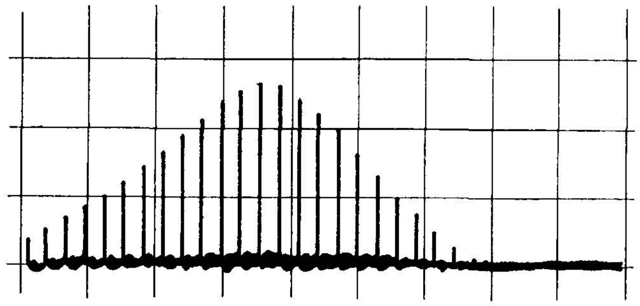

FIG. 3. Typical oscillogram of a mode-locked pulse train. Horizontal 20 ns/div., vertical 500 mV/div. The detector system rise time is 0.8 ns.

A typical pulse trace is shown in Fig. 3. To measure the pulse width by two-photon fluorescence (TPF), it was first amplified by a double pass through a 3 $\times\frac{1}{4}$-in. laser rod, and the pulse-train energy obtained was about 20 mJ.

The TPF pattern showed an average of 13 ps over the whole train with a contrast ratio between 2.8 and 3. The system worked well during a whole month without renewing the dye.

The transmittance changed from 70% to 80% owing to degradation of the solution with no significant deterioration of the reliability of the mode locking. This change in the transmittance would yield

$$\varphi = 0.64,\quad B_u = 0.44,\quad A = 3.68\times 10^{-4},$$
$$G_u = 0.11,\quad P = 1.07,$$

that is, 7% above threshold, which remains a good parameter for the system.

The system was also tested in the usual configuration, with an 80% reflecting mirror. In this case mode locking was never complete, and more than one pulse always appeared in one cavity period, showing very poor reliability. As was remarked before, no effort was made either to stabilize the pump energy or the dye transmittance.

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