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Pulse evolution in CO_2 lasers

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Pulse evolution in CO_2 lasers *

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Explicit formulas are examined for the development of optical pulses in gain-switched or Q-switched laser oscillators and for the distortion of such pulses in succeeding stages of laser amplification. The results are compared to data obtained with a TEA CO_2 oscillator-amplifier system.

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For many laser oscillators and amplifiers operated in a pulsed mode, nonlinear effects produced by the varying optical gain can dominate the pulse evolution and effect large amounts of distortion. In a recent analysis of gain-switched lasers it was shown that under some conditions the resulting giant pulses from the oscillator can be well approximated by simple explicit formulas.[1] Here we examine the conditions under which these approximate formulas can be expected to reasonably represent the exact solutions and then compare them to experimental data obtained from a specific lasing system: the TEA CO_2 laser. As an illustrative example, we show how the analysis and formulas may be used to predict the effect of the distortion produced by propagation in a saturated CO_2 laser amplifier.

In the case that pumping and spontaneous relaxation can be ignored for the duration of the pulse, the oscillator intensity is given by the solution of[1]

$$\frac{dI(t)}{dt} = g_c[I(t) + I_0]\exp\left[-2s\int_0^t I(t')\,dt'\right] - \gamma_c I(t), \qquad (1)$$

where g_c is the initial cavity gain, s is a saturation parameter, γ_c is the total cavity loss coefficient, and I_0 represents the contribution of spontaneous emission. The parameters appearing in Eq. (1) can be calculated or measured for a particular lasing system and for present purposes we regard them as known quantities. Equation (1) cannot in general be solved explicitly although the peak intensity of the exact solution can be shown to be

$$I_p = \frac{\gamma_c}{2s}\left[\frac{g_c}{\gamma_c} - \ln\left(\frac{g_c}{\gamma_c}\right) - 1\right] \qquad (2)$$

with the peak intensity occurring at a time given approximately by

$$t_p \approx (g_c - \gamma_c)^{-1}\ln\left\{(g_c - \gamma_c)\left[\frac{g_c}{\gamma_c} - \ln\left(\frac{g_c}{\gamma_c}\right) - 1\right](2sI_0)^{-1}\right\}. \qquad (3)$$

We wish to consider as an approximate solution to Eq. (1) the exponential function

$$I(t) = \frac{I_p g_c \exp[-\gamma_c(t - t_p)]}{\gamma_c\{\exp[-g_c(t - t_p)] + (g_c/\gamma_c) - 1\}} \qquad (4)$$

with I_p and t_p as given above. This particular choice suffers from the disadvantage of being apparently integrable only for the special case $g_c/\gamma_c = 2$. In a practical situation where an integrable approximation is required one might consider in turn approximating Eq. (4) numerically by a curve-fitting technique to the family of (symmetric) pulses

$$I_p\{\mathrm{sech}[g_c(t - t_p)/2n]\}^n$$

or the family of (asymmetric) pulses

$$I_p\left(1 + \frac{t - t_p}{nt_0}\right)^n \exp\left(\frac{-(t - t_p)}{t_0}\right)$$

for values of $t > t_p - nt_0$. Both of these families of curves are integrable exactly.[2,3]

To make a general comparison of the approximate solutions in Eq. (4) to the exact solutions of Eq. (1) it is convenient to introduce a normalized time $T = \gamma_c t$, intensity $J = 2sI/\gamma_c$, and threshold parameter $r = g_c/\gamma_c$. Then Eqs. (1)–(4) reduce to

$$\frac{dJ(T)}{dt} = r[J(T) + J_0]\exp\left(-\int_0^T J(T')dT'\right) - J(T), \qquad (5)$$

$$J_p = r - \ln r - 1, \qquad (6)$$

$$T_p = (r - 1)^{-1}\ln\left(\frac{(r - 1)(r - \ln r - 1)}{J_0}\right), \qquad (7)$$

$$J = \frac{rJ_p \exp[-(T - T_p)]}{\exp[-r(t - T_p)] + r - 1}. \qquad (8)$$

Some typical approximate pulse shapes from Eq. (8) are shown in Fig. 1 and numerical solutions corresponding to Eq. (5) have been given previously.[4] Significant discrepancies between the exact and approximate solutions occur only for small values of the threshold parameter r. These results are summarized in Fig. 2 where the errors in the pulse widths and peak times of the approximate solutions are plotted as functions of r. For values of the threshold parameter greater than about

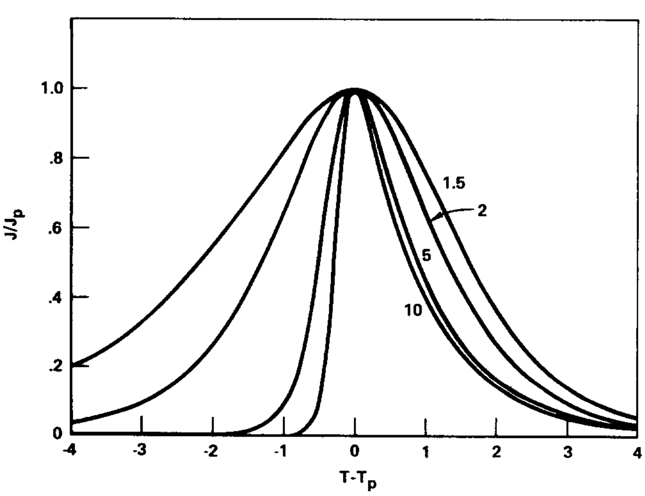

FIG. 1. Laser pulse shapes for various values of the threshold parameter r. The pulses are symmetric for $r = 2$.

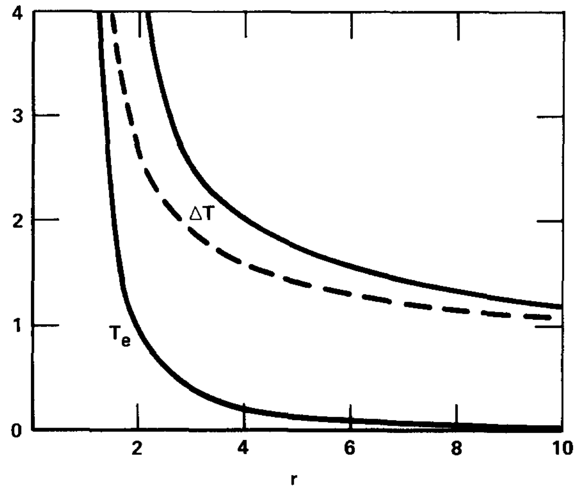

FIG. 2. Dependence on r of the pulse width ΔT for the exact (solid line) and approximate (dashed line) pulse shapes and the extra delay T_e of the exact pulse shape in comparison with the approximation. For r greater than about 2 the differences may be neglected compared to the total pulse width and delay.

$r=2$, the exact and approximate solutions are in excellent agreement with respect to pulse shape and total pulse delay. Most gain-switched and Q-switched lasers operate with large values of the threshold parameter, and it is difficult to imagine situations where the approximate formula would not be appropriate.

The specific problem that we have investigated experimentally concerns the propagation of optical pulses through prepumped laser amplifiers. The relationship between input and output pulses for this case can be written[5–8]

$$I(\zeta,\tau)=\frac{I(0,\tau)\exp[s\int_{-\infty}^{\tau}I(0,\tau')\,d\tau']}{\exp[s\int_{-\infty}^{\tau}I(0,\tau')\,d\tau']+\exp(-g_0\zeta)-1}, \tag{9}$$

where g_0 is the initial (small-signal) gain, and the coordinates τ and ζ are related to the time and space coordinates by

$$\tau=t-z/v_g, \quad \zeta=z. \tag{10}$$

The intensity integrals in Eq. (9) are an example of a situation where the analysis is greatly simplified if the intensity distribution can be integrated analytically over time.

The basic experimental apparatus consists of a Lumonics Model 103-1F TEA CO_2 laser oscillator with a stable resonator configuration followed by a series of three homemade corona-preionized CO_2 laser amplifiers. The amplifiers were developed by Marhic and are similar to those described in Ref. 9. The amplifier discharge precedes the oscillator discharge by 4 μsec so that an initially uniform gain distribution is obtained in the amplifiers with a measured value of $g_0=2$ m^{-1} and a 2.74-m active length. The laser pulses are monitored by calibrated photon drag detectors before and after passage through the amplifiers and displayed on a dual-beam oscilloscope.

Typical experimental results are shown as solid lines in Fig. 3. The oscillator pulse intensity is shown in the upper solid curve and has a peak intensity of about

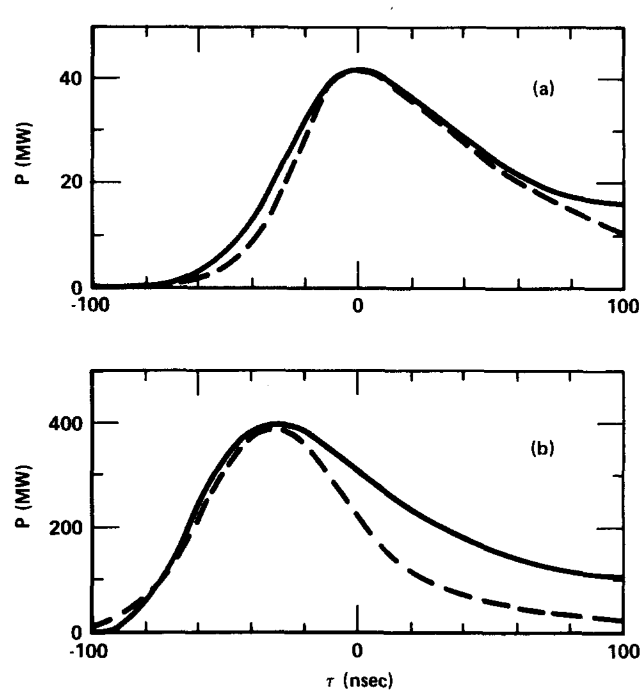

FIG. 3. Experimental (solid lines) and theoretical (dashed lines) pulse shapes at (a) the input to the laser amplifiers and (b) the output of the laser amplifiers.

3.7×10^{10} W/m^2 for this example. The time scale has been adjusted so that $t=0$ occurs at the peak of the pulse (the input pulse to the amplifier). The dashed curve is a plot of the approximate pulse given by Eq. (4) with assumed values of $g_c=10^8$ sec^{-1} and $\gamma_c=1.5\times10^7$ sec^{-1}. The solid lower curve is the same pulse observed after transmission through the amplifier. The time delays in the two detector channels had been previously adjusted so that the two traces are matched in time with the laser amplifiers turned off. Here the amplified pulse exhibits the pulse advance characteristic of propagation through saturated media. The dashed lower curve is a plot of the output pulse as predicted by Eq. (9) and Eq. (4) with an assumed value in the amplifier of $s=2\times10^{-4}$ m^2/J.

The good agreement of the experimental and theoretical results confirms the basic validity of these analytical models. The numerical constants used in the comparisons are typical values for lasers of this type, and the general form of the power curves is not especially sensitive to the precise values used. The most significant feature of the data is that the output pulse is advanced in time by about 30 nsec due to saturation in the amplifier. This advance is accurately predicted by the analysis and completely dominates the slight retardation that is expected due to dispersion in unsaturated amplifiers.[10] The main discrepancy between the experimental and theoretical results involves the tail of the laser pulse. In CO_2 lasers one expects continued pumping by nitrogen atoms and a limited decay of the lower laser level.[11] Both of these effects tend to augment the pulse tail. Agreement will be still better in pulsed lasers having simpler energy level structures. As a practical matter we have found the above measurements and analysis useful for the measurement of the various laser parameters and subsequent diagnosis and optimization of laser operation.

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