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PULSE PROPAGATION IN A ONE-ATMOSPHERE CO_2 LASER AMPLIFIER

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Abstract

The theoretical propagation of short (150-ps) laser pulses in a one-atmosphere CO_2 amplifier is investigated using a fully coherent density-matrix computer code. The influence of coherent effects and of the response times of the amplifying medium on the temporal shape of the output pulse is examined. It is found that short pulses, whose width is approximately equal to the T_2 time of the medium, can be effectively amplified.

Introduction

Although the general coherent density-matrix theory for pulse propagation in a laser gain medium was developed several years ago,[1-4] its formulation is necessarily complex, and it is often difficult to anticipate how the amplifying medium will affect the shape of the pulses transmitted through it. The total output energy of an amplifier is relatively insensitive to the subtle details of the coherent theory; however, the pulse shape, and hence, the peak power do depend on these effects. To date, only a few calculations have been published[3-7] that illustrate the practical implications of the fully coherent theory for short-pulse ($\lesssim$ 1-ns) propagation in real CO_2 amplifier systems. Moreover, only a few experimental studies have been reported[6-10] in which detailed measurements (including temporal puslse shapes) have been compared with theoretical predictions. In this paper the theoretical propagation of short laser pulses in a one-atmosphere CO_2 amplifier is investigated.

This work has been primarily motivated by the results of a recent pulse-propagation experiment,[7] which indicated a factor-of-two discrepancy between the observed and predicted temporal pulse shape. In that experiment a 570-ps pulse was amplified by a 580-torr amplifier with a $gL \simeq 5$. The predicted output pulse width was 370 ps, whereas the experimentally observed width was 880 ps. The pulse actually broadened during amplification instead of narrowing as predicted. Modeling of the experiment was somewhat complicated, however, because the amplifier was triple-passed by a spatially expanding beam. We therefore plan to continue these experiments under more carefully controlled conditions that will allow unambiguous comparisons between theory and experiment. Such an investigation would provide critical tests of the theoretical models that are employed in the design of the high-power CO_2 laser-fusion systems and in the generation of "shaped" pulses for driving inertial-fusion targets. As a prelude to these next experiments a computer code developed by Feldman[4,6] is being used to investigate the predictions of a coherent theory, under a variety of conditions that will elucidate the effects of various properties of the medium on pulse propagation, with an emphasis on those conditions that can be readily tested in the laboratory.

Previous Experimental Tests

Some years ago several experiments were conducted which indicated that the pulse shapes obtained from CO_2 amplifiers were in substantial agreement with those predicted by coherent theoretical models.[8-10] However, all of these measurements were conducted at very low pressures (< 20 torr) with long pulses (> 25 ns). Thus, these tests were made under conditions in which the molecules were inhomogeneously broadened, whereas all practical amplifiers operate in the homogeneously broadened regime. More recently, Volkin[5] found good agreement with theory for the propagation of 1.8-ns pulses in LASL's 1800-torr, 0.5-TW Gemini laser system. However, because the pulse length was much greater than the 23-ps characteristic time constant (see below), of these high-pressure amplifiers, this investigation did not provide a critical test of the coherent aspects of the theory. Modeling the Gemini system was also complicated by a triple-pass geometry with expanding beams. Finally, in all of the earlier experiments (except that of Ref. 7) the laser operated at only a single wavelength [typically, the 10-μm P(20) line], whereas efficient high-power amplifiers operate on multiple wavelengths. Thus, it appears that a definitive test of pulse-propagation theory, as it applies to working high-power CO_2 amplifiers, has not yet been performed.

Theory

The energy levels that are relevant to the lasing process in a CO_2 molecule are shown in Fig. 1. The indicated 10-μm P(20) transition operates between a single rotational sublevel of the upper vibrational state and a single rotational level of the lower vibrational state. Several time constants, which characterize the response of the medium, are shown in the figure. T_2 (the dipole dephasing time) is the one of greatest interest for describing coherent effects. When operating in the pressure-broadened regime ($\gtrsim$ 100 torr), T_2 is a measure of the width of the rotational sublevel. T_1 is the relaxation time of an individual rotational level. T_R is the time constant for repumping a particular rotational level when a reservoir model (in which no ΔJ selection rules apply) is assumed. All of the time constants are inversely proportional to pressure and also depend on the temperature and composition (He:N_2:CO_2) of the amplifier gas mix. Empirically, T_1 has been found to be approximately twice T_2. T_R is equal to T_1 divided by the partition function for the rotational sublevel. For a 580-torr amplifier under conditions[11] that pertained in Ref. 7, T_2 is 83.3 ps, T_1 is 172 ps and T_R is 2.7 ns.

The computer code that has been used in the present work was developed by Feldman and described in detail in Refs. 4 and 6. The following assumptions and approximations were used in the present calculations:

a. the semiclassical theory for the interaction of radiation and the medium,

b. the pulse is an on-resonance plane wave,

c. repumping of the rotational levels is described by the reservoir model,

d. dipole approximation,

e. slowly-varying envelope approximation,

f. the laser pulse is operating on a single line [10-μm P(20)] and has a uniform spatial distribution.

Results

For pedagogical purposes it is useful to first consider how rectangular pulses would propagate through the gain medium, even though such pulses can rarely be observed in practice. Several special cases involving rectangular pulses permit analytic solutions to the fully coherent theory; and, thus, significant insight into the effect of the medium on output pulse shapes may be gained.

The first case considered was that of small-signal propagation (wherein no saturation occurs) for a rectangular pulse. This is shown in Fig. 2 for the conditions described above with $gL=5$. It is seen that the output pulse has relatively long rise and fall times that are approximately equal to gLT_2 and $gLT_2/2$, respectively. Crisp[12] has published a theoretical study of the propagation of step-function signals in which he showed that an analytic solution could be obtained in the small-signal regime. The solid points in Fig. 2 are the predictions of this analytic solution (a straightforward extension of Crisp's work was required to include the falltime domain), and it is seen that they agree well with the computer code.

Figure 3 depicts the output expected for a high-intensity rectangular input pulse that heavily saturates the amplifier. The sinusoidal oscillations typical of optical nutations are seen to develop,[1,3] and at times the output intensity falls below the input intensity, corresponding to the existence of a negative population inversion in the medium. Although the oscillations damp out, their period remains constant, and for the case shown is determined by the Rabi frequency that corresponds to the input intensity. The risetime and width (FWHM) of the first peak are 18 and 52 ps, respectively. Thus, one concludes from this analysis that it should be possible to amplify pulses whose widths are shorter than the T_2 time of the medium! For example, under the conditions of Fig. 3, an input pulse with a duration of ~ 80 ps could have been used effectively.

The conditions of Fig. 3, while instructive, would generally not be of much practical interest because of the high input intensity (1.2 GW/cm^2) and the modest gain-length product ($gL=5$) of the amplifier. A number of cases using larger values of gL and much lower input intensities have also been studied. These exhibit the same general characteristics that appear in Fig. 3, except that the output pulse tends to develop a substantial "tail" after the input is terminated. This phenomenon is related to the decay time shown in the small-signal case (Fig. 2), and the magnitude of the tail is a function of gL. For a 1-MW/cm^2 rectangular input with a gL of 20, a peak output intensity of ~ 1.7 GW/cm^2 is obtained. The risetime and width of the initial output peak are 45 and 61 ps. Thus, significant short-pulse amplification (a factor of 1700 in intensity) should be obtained with a practical one-atmosphere system.

An analytic solution for optical nutations exists for high-intensity rectangular input pulses[3] in the special case in which time scales are much shorter than T_2 and T_1 and in which the output oscillations are a small perturbation on the input. Several such analytic test cases have been compared with the present computer code. In general the outputs of the code are in reasonably good agreement (within 5%) with the analytic predictions over the first optical cycle. The discrepancy increases somewhat on succeeding cycles. The source of this small discrepancy is still under investigation (it may be a real physical effect). Nevertheless, there appear to be no serious numerical problems ("bugs") in the code over the domain of the first peak, which is the region of primary interest in the present work.

The present analysis ignores the existence of magnetic sublevels within each rotational level of the CO_2 molecule. A "single" rotational transition actually represents an average over these many sublevels, and one might expect intuitively that this averaging would wash out the coherent effects illustrated in Fig. 3. In fact, a more complete analysis predicts that this does not occur. For the case shown in Fig. 3, predictions of the present code have been compared with those of a code that includes magnetic sublevels.[13] When magnetic sublevels are included, the intensity of the first peak in Fig. 3 is reduced by ~ 10% and the subsequent peaks damp out more rapidly, but the form of the output pulse is essentially as shown in Fig. 3, and the shape of the output pulse over the first cycle (the domain of primary interest) is quantitatively quite close to that of Fig. 3, in which magnetic levels are ignored. This is in agreement with the conclusions of two other theoretical studies.[2,14] (If circularly polarized light were being used consideration of the magnetic levels would be more important.[14])

Short $\sin^2(t/\tau)$ Input Pulses

To investigate the effects of the medium on propagation in a more practical case, the amplification of very short pulses with a sine-squared temporal shape was studied, using pulses with an 89-ps risetime and a 150-ps width. This pulse shape was selected because it closely approximates those that have been experimentally obtained using fast electrooptic Pockels-cell switches.[15] The amplifier parameters were the same as those listed above. Note that the risetime of the pulse was equal to the T_2 of the medium.

Results for small-signal amplification are shown in Fig. 4. It is seen that both the risetime and width of the output pulse increase significantly (to 129 and 237 ps, respectively). The output peak intensity reaches only 23% of its small-signal value. Thus, the pulse is severely "bandwidth" limited, and initially it does not appear that a one-atmosphere system can amplify such short pulses very effectively.

However, as the medium is driven more heavily into saturation, coherent effects dominate and useful amplification can be achieved. Figure 5 depicts the output predicted for a gL of 30 with a 1-MW/cm^2 $\sin^2(t/\tau)$ input. The risetime and width of the main pulse decrease to 34 and 44 ps, and a peak output power of 3.2 GW/cm^2 is obtained, which represents a power amplification of 3200. A substantial tail (whose magnitude depends on gL) develops, but for many applications this would not be important.

Discussion

The factor-of-two discrepancy between the earlier experiment[7] and theoretical calculation remains unexplained. Further theoretical study will be performed to address this question. Specifically, the sensitivity of output pulse shapes to variations in the values for the T_2 and T_1 time constants must be considered. (Perhaps the experimental values for these parameters are not as accurate as previously thought.) The effects of multiline propagation have not been investigated in this work, although, of course, they were included in the calculations of Ref. 7.

For a limited number of test cases, the predictions of the coherent pulse-propagation code are in essential agreement with those of analytic solutions in the domains of interest. The source of some modest discrepancies is under continued investigation.

It is recommended that a precise experimental test of the coherent theory (including a comparison of temporal pulse shapes) be undertaken. It seems desirable for this to employ a 100-torr amplifier, for which the pressure is sufficiently high so as to be in the homogeneously broadened regime, but low enough so that the interesting coherent temporal effects can be reliably measured with existing detectors (T_2 would be ~ 500 ps). In general, the temporal shape of amplifier output pulses is quite sensitive to the exact shape of the leading edge of the input pulse. Hence, it will be essential to measure the input pulse shape very accurately in experiments whose purpose is to test the theory.

Propagation of pulses through CO_2 amplifiers under a variety of different conditions is being studied and these results will be published elsewhere.

Conclusions

It has been shown theoretically that coherent effects permit the amplification of short CO_2 laser pulses, whose widths are approximately equal to the T_2 time constant of the amplifying medium. Although such amplification is not efficient from an energy standpoint (only a small fraction of the stored energy is extracted), high peak powers and fast risetimes (which are often the parameters of primary interest) can be achieved.

Acknowledgments

The computer code used for these calculations was originally developed by Barry Feldman. John Goldstein aided in this work by studying several additional test cases, using computer codes that he has developed independently. I wish to thank Gottfried Schappert, John Goldstein and Barry Feldman for a number of enlightening discussions on the subtleties of the pulse propagation theory. This work was performed under the auspices of the U. S. Dept. of Energy.

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Figure Captions

Figure 1. Vibrational and rotational energy levels of the CO_2 molecule. The 10-μm P(20) laser transition is indicated.

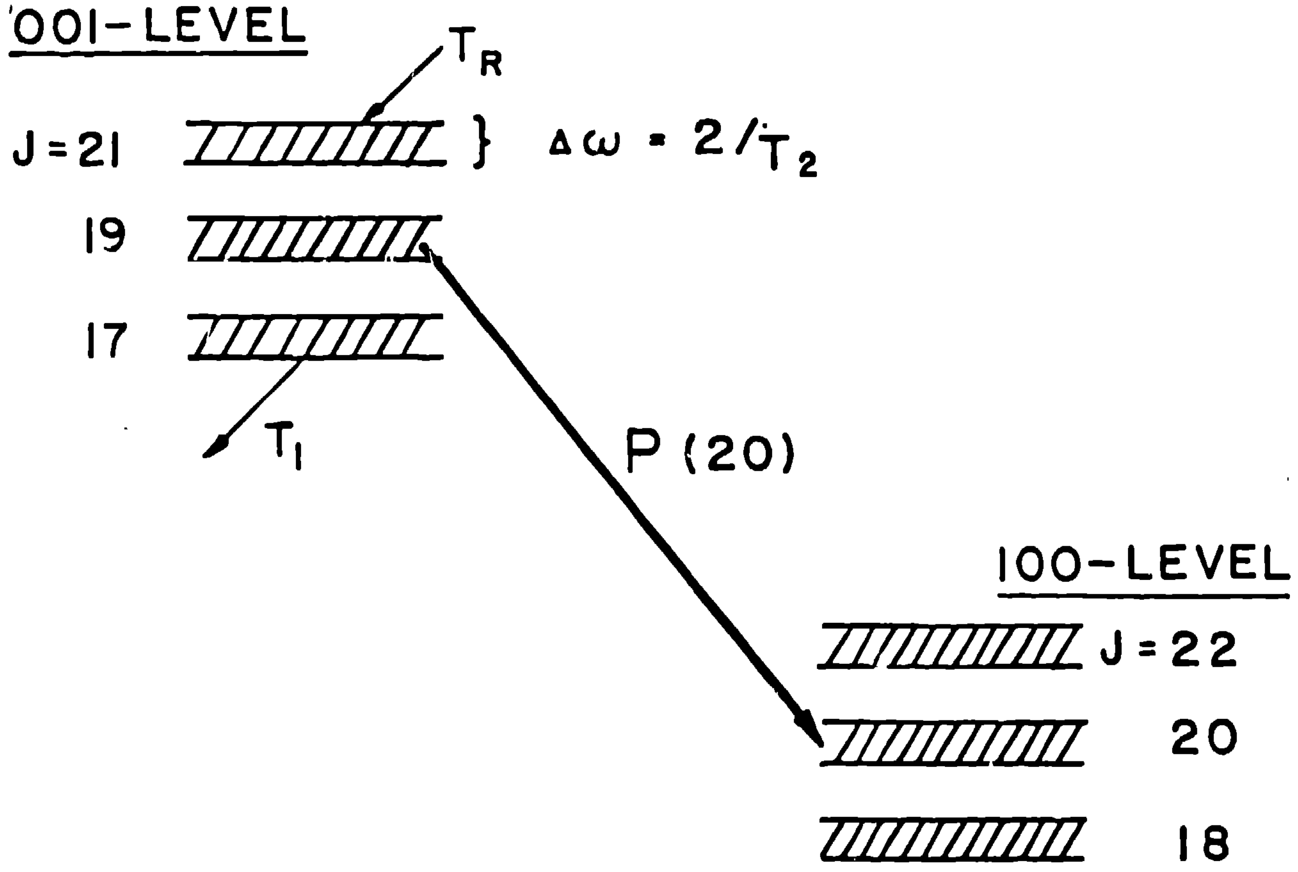
Figure 2. Amplification of small-signal rectangular pulse for $gL=5$. Input intensity is 0.1 W/cm^2; T_2 is 83.3 ps. Dashed line is the input pulse; solid line is the output predicted by the computer code; points are the predictions of an analytic solution to the theory.

Figure 3. Amplification of a large-signal rectangular input pulse. Dashed line is the input pulse.

Figure 4. Small-signal amplification of a short $\sin^2(t/\tau)$ pulse. Input pulse has a width of 150 ps with a peak intensity of 0.1 W/cm^2. Peak output intensity reaches only 23% of the full "small-signal" (e^{gL}) value. Output pulse width is 237 ps. T_2 is 83.3 ps.

Figure 5. High-gain amplification of a short $\sin^2(t/\tau)$ pulse.

CO_2 LASER LEVELS



$$T_2 \propto 1/P$$

$T_1 \approx 2\,T_2$ $T_R \approx 15\,T_1$

FOR: $P = 580$ TORR

$T_2 = 83$ PS

$T_1 = 172$ PS $T_R = 2.7$ NS

Fig. 1

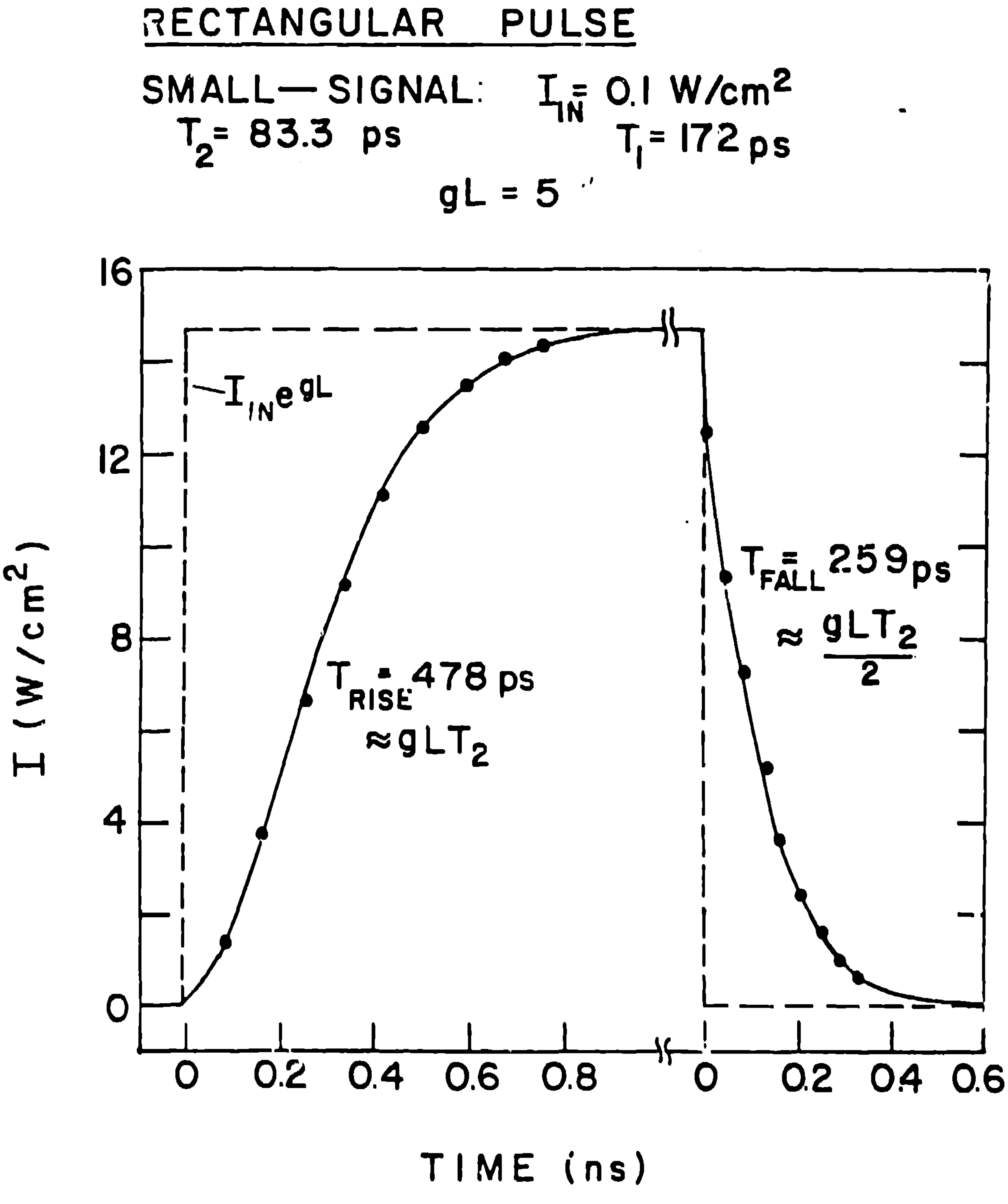

RECTANGULAR PULSE
SMALL—SIGNAL: $I_{IN} = 0.1$ W/cm^2
$T_2 = 83.3$ ps
$T_1 = 172$ ps
$gL = 5$
$I_{IN}e^{gL}$
$T_{RISE} = 478$ ps
$\approx gLT_2$
$T_{FALL} = 259$ ps
$\approx \frac{gLT_2}{2}$
I (W/cm^2)
0
4
8
12
16
TIME (ns)
0
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6

Fig. 2

RECTANGULAR PULSE

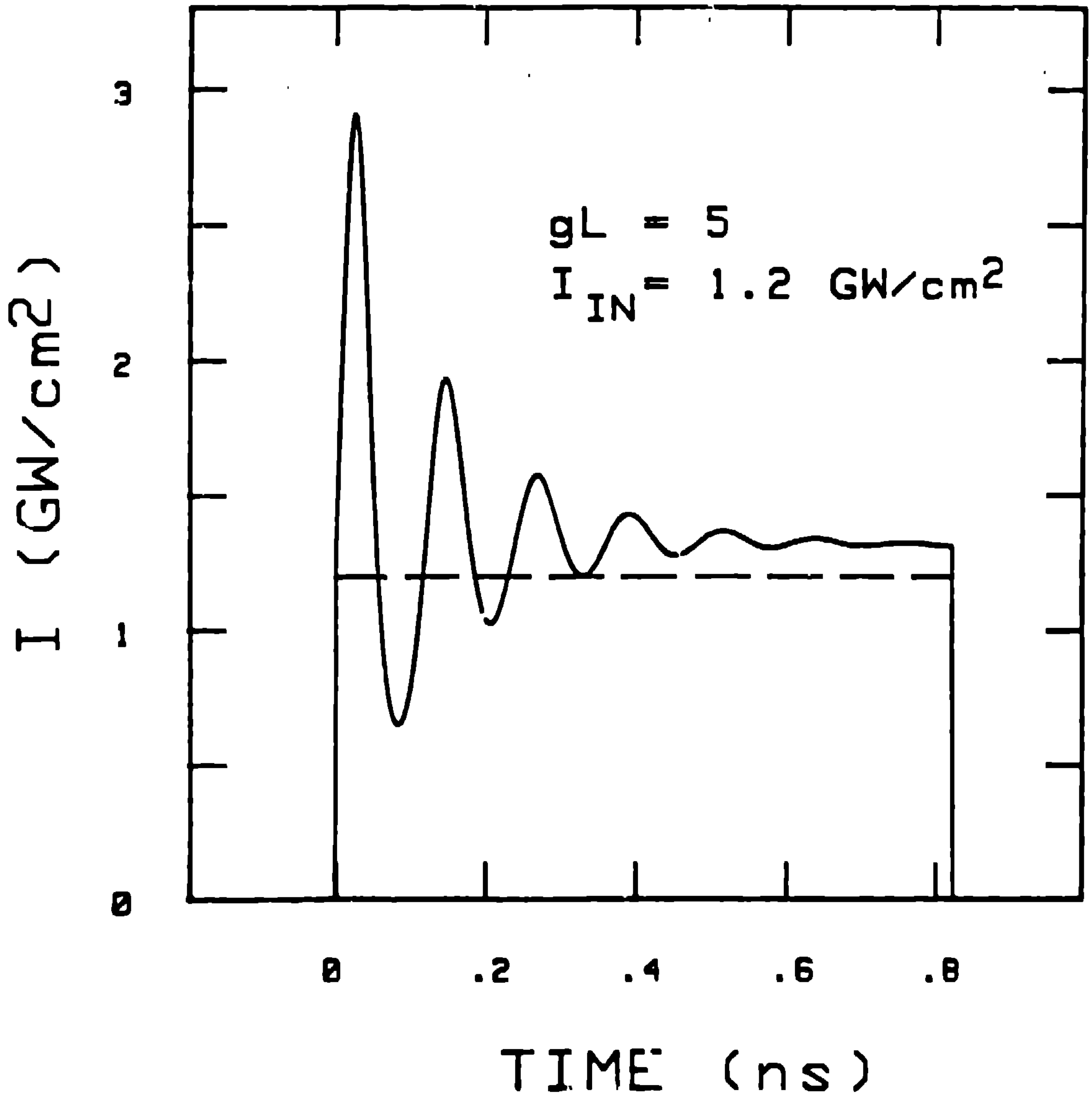
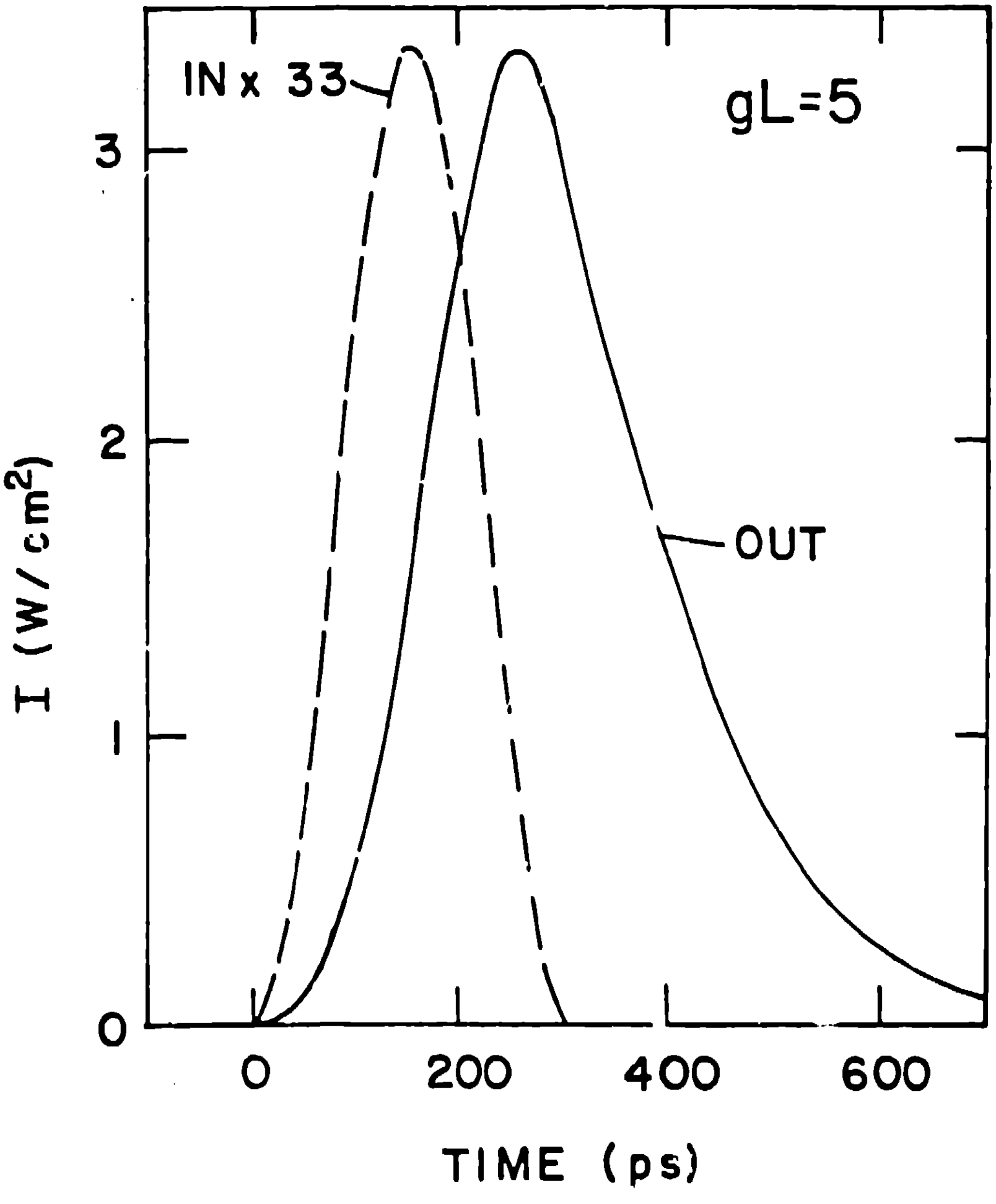


Fig. 3



150-ps SIN$^2(t/\tau)$

SMALL-SIGNAL: $I_{IN} = 0.1 W/cm^2$

$I_{OUT}/I_{IN}e^{gL} = 0.23$

FWHM: $T_{OUT}/T_{IN} = 1.6$

Fig. 4

150-ps SIN^2(t/τ)

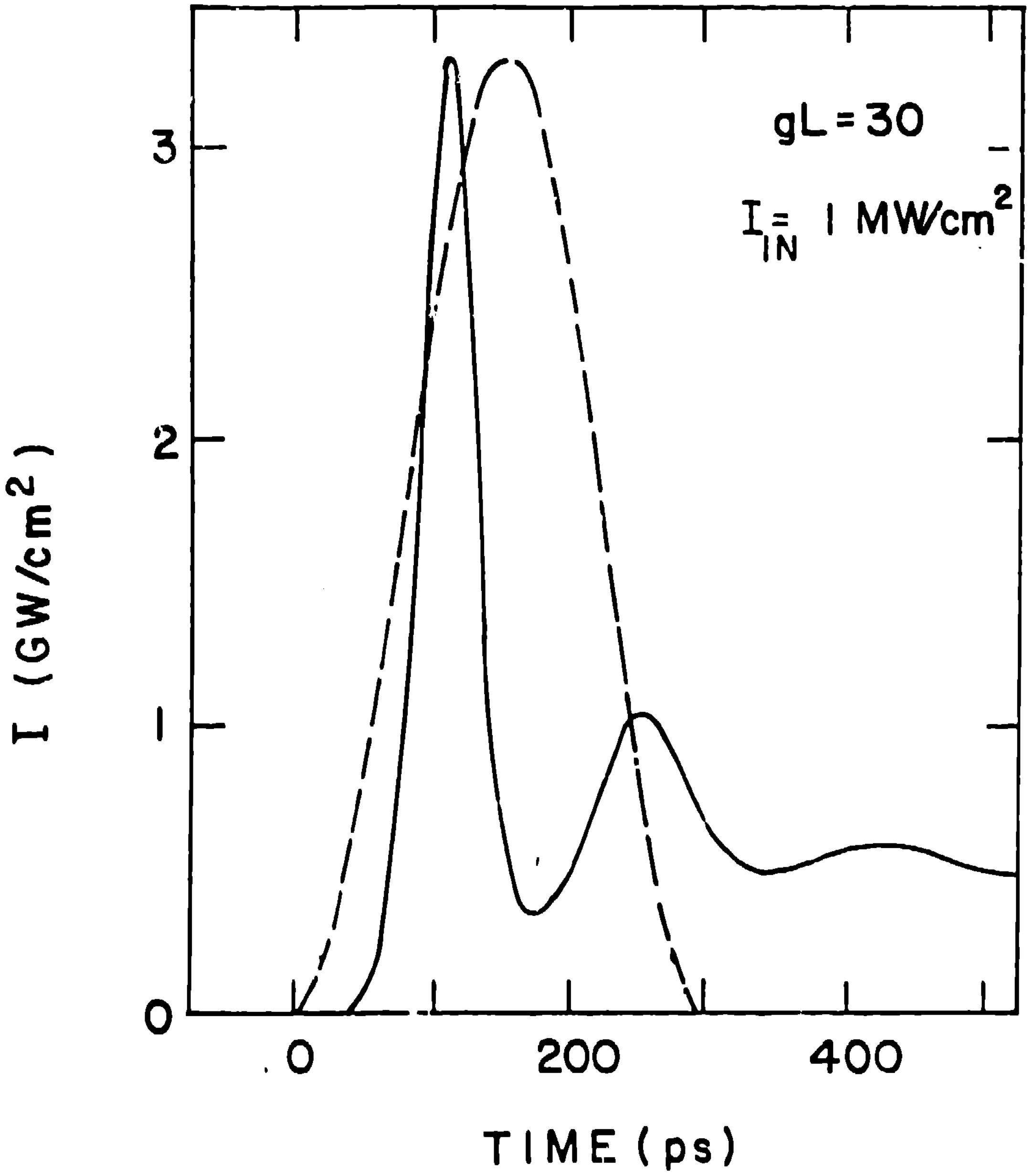


Fig. 5