GENERATION OF SHORT OPTICAL PULSES

FOR LASER FUSION

by

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M.L. Report No. 2451

June 1975

Final Report

for

Contract LLL 5241805

Prepared for the

University of California

Lawrence Livermore Laboratory

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Stanford, California

ABSTRACT

This report considers some of the problems involved in generating the required short pulses for the laser-fusion program. Short pulses are required to produce the laser fusion, and pulses produced synchronously with this primary pulse are required for plasma diagnostics. The requirements of these pulses are first described. Then we consider several methods to generate pulses at 1.064 μ to drive the Nd:Glass amplifiers to produce laser fusion. Conditions for optimum energy extraction per short pulse for Nd:YAG and Nd:Glass lasers are given. Four methods are then considered to produce these pulses: (1) Using a fast switch to chop the required pulse out of a much longer Q-switched pulse; (2) Active mode locking; (3) Passive mode locking; and (4) A combination of active and passive mode locking. The use of cavity dumping is also considered to increase the energy per short pulse. In each case we evaluate these systems and indicate future research work. We then consider several methods to produce the synchronous pulses for plasma diagnostics.

Finally, we evaluate these short pulse generating techniques from the laser-fusion program point of view, and establish a "roadmap" for future research work.

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INTRODUCTION

The purpose of this report is to present an overview of the state of the art of short optical pulse generation, and then to carefully evaluate these short pulse generation techniques from the point of view of the requirement for laser fusion. There are two main areas where short pulses are required: first, the short pulses to drive the main amplifiers to produce the laser-induced fusion, and secondly, short pulses for plasma diagnostics. The requirements for these pulses, as we understand them now, are discussed in Section I of this report.

To limit the scope of this report somewhat, we will only direct this report at the requirement for laser fusion with the solid state Nd:Glass amplifiers. We will thus not consider short pulse generation in the CO_2 laser.

The final objective of this report will be to draw some conclusions from the evaluation of various short pulse generation techniques, and to establish a "roadmap" for future research efforts on short pulse generation for laser fusion work.

I. SHORT PULSE REQUIREMENTS

We will consider here the two main short pulse requirements for laser fusion, i.e., the primary pulses to drive the Nd:Glass amplifier, and short pulses for plasma diagnostics.

A. PRIMARY PULSES FOR LASER FUSION

Pulse Energy: The pulse energy out of the oscillator should obviously be as high as possible to keep the required gain in the amplifier to a minimum and hence reduce instabilities in the amplifier such as self-focusing. Presently, a reasonable requirement seems to be about 1 mJ in a single short pulse from the oscillator. In a typical 1.06-μm laser, the beam area is about 1.0×10^{-2} cm^2; for a 50-ps (FWHM) pulse, the peak power density in a TEM_{00} beam for the 1-mJ pulse is about 1.9 GW/cm^2, and is larger than this inside the cavity. At these power densities, damage to optical components in the laser can occur. Problems due to self-phase modulation and self-focusing can also occur at these power densities. It thus does not seem very likely that more than about 1 mJ can be expected from the oscillator, unless larger diffraction-limited beams can be maintained in the oscillator, but this is difficult.

The energy repeatability in a single short pulse from the oscillator should be such that the energy fluctuations from pulse to pulse are less than 5%. Since these pulses will pass through many optical components that are close to the damage limit, large pulse-to-pulse fluctuations cannot be tolerated.

Pulse duration and pulse shape: Present requirements for laser fusion call for a pulse duration that is selectable from ≤ 30 ps to ~ 1.5 ns and the repeatability of this pulse duration from pulse to pulse should be better than 5%.

The required pulse shape is a pulse with smooth, monotonic increase to a single peak. Presently, a gaussian pulse shape is acceptable, but later a precisely shaped pulse will be required. There should be no fine structure in the pulse amplitude. As an example of the type of pulse that will eventually be required, present target studies require a pulse with a leading edge that increases smoothly over about 4 orders of magnitude in power during 10 ns. An analytic expression of this pulse shape is

$$I(t) = I(0) \left(1 - \frac{t}{\tau}\right)^{-15/8} \qquad (I.1)$$

for $0 \leq t \leq 9.4$ ns and $\tau = 9.45$ ns. This pulse shape is plotted in Fig. I.1.

Peak to Background Ratio: The power level between the short pulses from the oscillator should be at least 10^4 less than the peak power of the short pulses, and at the target a peak-to-background ratio of > 60 dB is required.

Spectral Characteristics: The pulse should be transform limited, and presently should have no frequency chirp, but later a compressible chirped pulse may be required.

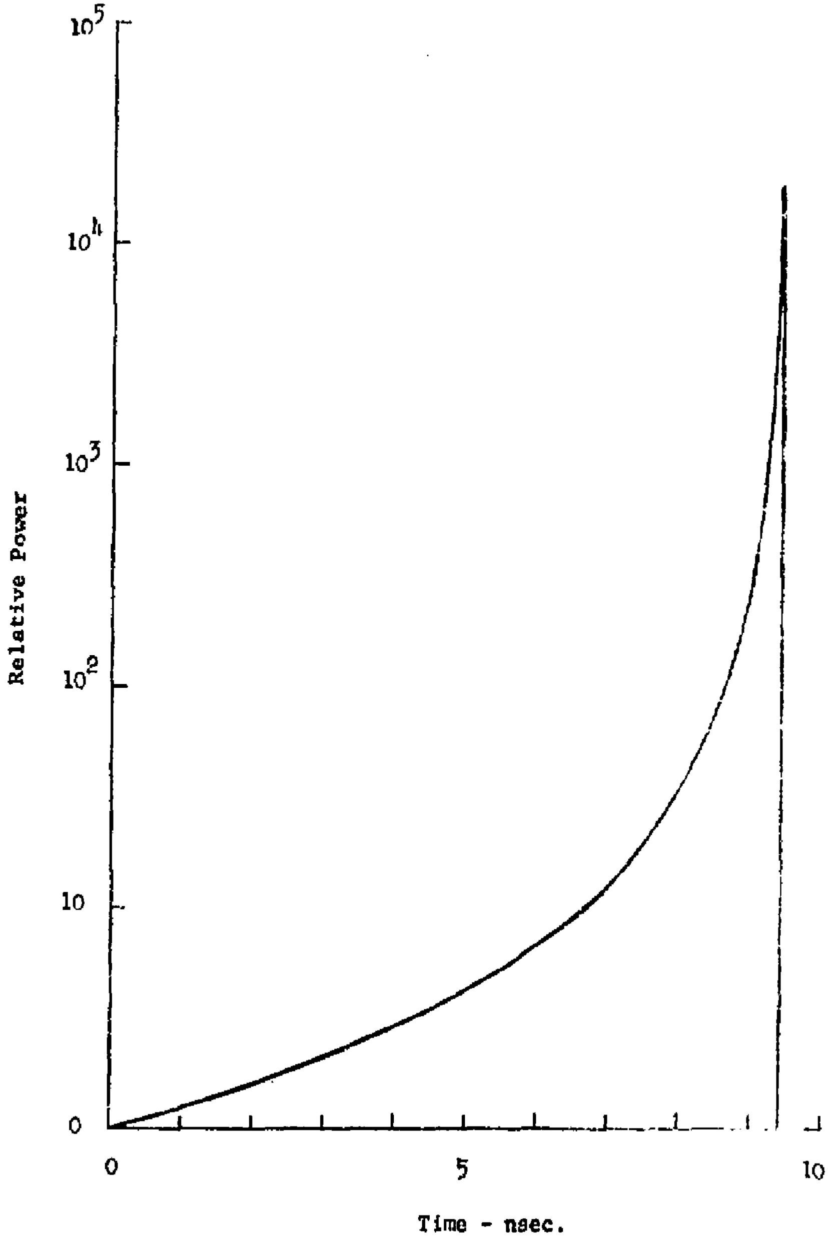

FIG. I.1--Typical shape of pulse required for laser fusion.

Spatial Profile: This should be cylindrically symmetric, with a smooth monotonic decrease from an axial peak. A TEM_{00} mode will be required from the oscillator. This profile will then be apodized to an optimal shape for propagation through the amplifiers.

Positional Stability: This applies to actively mode-locked lasers or lasers where the short pulse generation process is driven by an external source. If this external signal is going to be used to synchronize two or more lasers, the stability of the short pulse with respect to this signal should be better than 10 ps.

Directional Stability: For good shot-to-shot target alignment and interaction, a directional stability of $\leq$ 10 µrad for the oscillator is required.

Selection of a Single Pulse: A given single pulse must be selected reliably and reproducibly from the pulse trains.

B. SYNCHRONIZED PULSES FOR PLASMA DIAGNOSTICS

These pulses should be 10-ps wide or less, and should be synchronized to the primary pulse to better than ± 10 ps. Short wavelengths are desirable, and presently ~ 350 nm seems preferable, but shorter wavelengths will be required later. The pulse energy should be $\gtrsim$ 1 mJ and the pulse energy repeatability requirements are not very stringent.

II. SHORT PULSE GENERATION TECHNIQUES FOR PRIMARY LASER FUSION PULSES

There have recently been a number of review papers on short pulse generation [1-4] and pulse measurements [5], and in this report, we do not merely want to duplicate the material in these papers, but rather evaluate many ideas in these papers from the point of view of laser fusion.

There are basically four methods that are presently being considered to generate these short pulses. These methods are:

(a) A fast switch external to the laser to chop out a small segment of a much longer Q-switched pulse;

(b) Active mode locking;

(c) Passive mode locking;

(d) A combination of active and passive mode locking.

We will consider each of these methods in some detail below.

One thing that all these methods will have in common is that the laser is Q-switched. This obviously is the best way to extract large peak powers from a solid state laser. In this report we will refer to many characteristics of the Q-switched laser. Instead of referring to various publications where these characteristics are discussed, almost all using different notations, it was considered appropriate to include an analysis of Q-switching that mainly emphasizes those points that are relevant to short pulse generation. This is presented in Appendix A and Appendix B. The first important characteristic of the Q-switched solid state laser we want to consider is energy extraction in a single short pulse.

A. ENERGY IN A SINGLE SHORT PULSE

The Q-switching behavior of the Nd:YAG laser can be analyzed very accurately using a rate-equation approach. Usually this laser is considered an ideal four-level system, and this analysis is presented in Appendix A. From this analysis, we obtain an expression for the peak power in the Q-switched pulse under optimum coupling conditions with the laser in the high-gain regime as defined in Appendix A:

$$(P_p)_{opt} = 0.0501 \left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2l}\right) A\alpha^2 \qquad \text{(II.1a)}$$

where

- σ – cross section of the laser transition for small signal amplification
  - = [illegible].0 × 10^{-19} cm^2 for Nd:YAG
  - = 3.0 × 10^{-20} cm^2 for Nd:Glass
- l = cavity length
- A = effective area of beam in cavity
- α = roundtrip power gain coefficient of the active medium at a certain pump level with no saturation

As mentioned above, this expression is valid in the high-gain regime of the laser. This means that the output coupling of the laser is large compared to the other losses in the cavity. Under these conditions, the optimum output coupling is given by:

$$(\delta_t)_{opt} = 0.28\ \alpha \qquad \text{(II.2)}$$

where $\delta_t = \ln (1/R)$ and R is the reflectivity of the output coupler.

The Nd:YAG laser is not really an ideal four-level system, and in Appendix B, we consider the additional complications in the Nd:YAG laser. These are:

(1) The $^4F_{3/2}$ upper level is two-fold degenerate, and the levels are split by 88 cm^{-1}.

(2) The $^4I_{11/2}$ lower level is six-fold degenerate, and these levels are also split, as shown in Fig. B.1.

(3) The lower level has a finite lifetime, and although this lifetime has not been measured accurately, it is thought to be a few nanoseconds long.

We now assume that the levels in both the upper and lower manifolds of the 1.064-μm transition thermalize very rapidly, and that these levels have the same relative distributions, even during the amplification of the short picosecond pulses. Let k_2 and k_1 be the relative population distributions of the upper and lower levels of the 1.064-μm transition. For Nd:YAG we get:

$$k_2 = 0.392$$
$$k_1 = 0.186$$

For Nd:Glass we get:

$$k_2 = 0.317$$
$$k_1 = 0.167$$

As shown in Appendix B, we can obtain analytic solutions for the peak power in the Q-switched pulse for the two extreme conditions where the lower level lifetime is either very fast or very slow.

In the case of very fast relaxation, this peak power under optimum coupling conditions is given by:

$$(P_p)_{opt} = \frac{0.0501}{k_2} \left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right) A\alpha^2 \qquad \text{(II.1b)}$$

We also find that fast relaxation of the lower level means that $\tau_1 < \tau_{c0}/(\bar{N}_e - 1 - \ln \bar{N}_e)$, where τ_1 is the lower level lifetime, τ_{c0} is the cavity lifetime and $\bar{N}_e$ is the number of times the laser is above threshold. For optimum coupling, $\bar{N}_e = 3.57$, and we get $\tau_1 < 0.77\ \tau_{c0}$. It is interesting to note that for the same unsaturated gain, we obtain more output power from the laser due to the split degeneracy of the upper level. This is because the energy that is stored in the second upper level does not contribute to the gain, but due to rapid thermalization, it does add considerably to the output power.

We have also considered slow relaxation from the lower level, and in this case the peak power becomes:

$$(P_p)_{opt} = \frac{0.0501}{k_2 + k_1} \left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right) A\alpha^2 \qquad \text{(II.1c)}$$

In a simple two-level system, slow relaxation of the lower level would reduce the output power by a factor of two, but due to the six-fold degeneracy and low relative distribution of the lower level for the 1.064-μm transition the reduction in output power is much smaller. We also show that slow relaxation of the lower levels means $\tau_1 > \tau_{cQ}$.

In typical Nd:YAG lasers, the cavity lifetime is tens of nanoseconds, and hence this laser is somewhere between the two above extremes. In this report, we will take the somewhat pessimistic approach, and consider that relaxation from the lower level is slow, and use Eq. (II.1c) to predict the peak output power from the Nd:YAG laser. In the Nd:Glass laser where the lower level lifetime is longer and ~ 20 ns, and this approximation is justified.

We can now also consider the generation of the short pulses simultaneous with the Q-switching. This can easily be introduced with a few assumptions. First, we assume that the average power envelope of the Q-switched pulse remains the same with or without short pulse generation. Secondly, we assume that a short pulse appears at the peak of the Q-switched pulse, and that all the energy in the Q-switched envelope within a cavity roundtrip-time, $\tau_\ell = (2\ell/c)$, is concentrated in a single short pulse. If the Q-switched envelope is at least several roundtrips long, the energy in a single short pulse is given by:

$$(E)_{opt} = \frac{0.0501}{k_1 + k_2} \left(\frac{h\nu}{\sigma}\right) A\alpha^2 \qquad \text{(II.3a)}$$

With short pulse generation, the assumption of slow relaxation of the lower level is further justified, because we would now require a lower level lifetime that is fast compared to the short pulse for fast relaxation, and this is not the case. To obtain the Q-switched pulse shape with short pulse generation under these conditions, is quite complicated. This is particularly the case under high-gain conditions, with strong saturation and where only a few pulses appear within the Q-switched envelope. However, the energy per short pulse can never be less than that predicted by Eq. (II.3a), where we assume slow relaxation of the lower level. With this in mind, we will use this equation for short pulse energy calculations in this report. For Nd:YAG, the pulse energy is given by:

$$(E)_{opt} = 0.0867 \left(\frac{h\nu}{\sigma}\right) A\alpha^2 \qquad \text{(II.3b)}$$

With this equation, we can now investigate the conditions in the Nd:YAG laser to obtain a pulse energy of 1 mJ. We recognize the term $(h\nu/\sigma)$ as the saturation energy density of the laser medium, and for the 1.064-μm transition in Nd:YAG, for the given cross section σ, we get:

$$\left(\frac{h\nu}{\sigma}\right) = 0.3 \text{ J/cm}^2$$

We must now assume a reasonable beam area A in the laser. It is easy to put a large area in this equation, and show that tens of mJ energies are possible. However, if we require a stable, TEM_{00} mode in the laser, it is very difficult to get good, large beam areas in the cavity. At high average pump powers, thermal focusing in the rod makes the cavity unstable, but this can be avoided by operating in a low-repetition-rate pulsed mode. With high peak powers in the laser, self-focusing makes large beams unstable. A beam area of 10^{-2} cm^2 is considered a reasonable value for reliable operation of a Nd:YAG laser, and with this estimate, the energy per short pulse is:

$$(E)_{opt} = 0.26\,\alpha^2 \text{ mJ}$$

For 1-mJ output, $\alpha \simeq 2.0$. This value of α clearly puts the Nd:YAG laser in the high-gain regime under these conditions. The optimum output coupling, δ_t , is $0.28\,\alpha$, and hence

$$(\delta_t)_{opt} = 0.56$$

or the output coupling $R = 57\%$. This is large compared to typical additional losses of 5% to 10%, and the initial approximation to use Eq. (II.1) that the Nd:YAG laser is in the high-gain regime, is valid. For these conditions, we can now also calculate the cavity lifetime. From Eq. (A.5) in Appendix A, for $\delta_t \gg \delta_\ell$ and $\delta_t = 0.28\,\alpha$, we get:

$$\tau_{c0} = 7.14\,\ell/\alpha c$$

For $\alpha = 2.0$, the condition to get approximately 1-mJ output, and $\ell = 50$ cm , we get $\tau_{c0} = 6.0$ ns . From Fig. A.3 in Appendix A, we can now get the width, τ_Q , of the Q-switched pulse envelope. For optimum coupling conditions, we get $\tau_Q = 2.3\ \tau_{c0}$, and for $\tau_{c0} = 6.0$ ns , we get $\tau_Q = 13.7$ ns . The Q-switched pulse is thus only a few roundtrips wide. This is a very general conclusion for the Nd:YAG laser. With the large cross section for Nd:YAG, we will find that in general the gain is quite high to get 1-mJ output per short pulse, and consequently, under these conditions, the Q-switched pulse envelope will always be only a few roundtrips long.

We can now also calculate the build-up time for Q-switching. Equation (A.27) in Appendix A gives the build-up time as:

$$\tau_B = 0.388\ \tau_{c0}\ \ln\left[\left(\frac{0.467}{\tau_{c0}}\right)\left(\frac{\ell A}{c\sigma}\right)\right] \tag{II.4}$$

For the above parameters we get $\tau_B = 82$ ns , or about 24 roundtrips. This is a very short build-up time. This is the next very important conclusion we draw here. To get 1 mJ from the laser per short pulse, the Q-switching build-up times are very short, and as we will show in the next section, this build-up time is always much shorter than the time necessary to build up short pulses.

It is also interesting to consider Nd:Glass, say ED-2, where the cross section is 20 times smaller and $(h\nu/\sigma) = 6.0\ \mathrm{J/cm^2}$. To extract 1 mJ, Eq. (II.5) predicts a gain of $\alpha = 0.40$, and for 10% loss in the cavity, the laser is really not in the high-gain regime any more, and one has to do the calculations a little more carefully. The important conclusion, though, is that in glass one can extract the 1-mJ energy at much lower gain, and the Q-switching buildup time and the Q-switched pulse are both about $\sqrt{20}$ longer, i.e., more like 100 roundtrips buildup time and 18 roundtrips Q-switched pulse width. These calculations for glass are oversimplified, and detailed knowledge of the saturation of the more inhomogeneously broadened line is required. However, the general conclusion, that to extract 1 mJ from a Nd:Glass laser the gain of the laser remains quite low, is still valid.

Other materials like Nd:GGG and Nd:SOAP have smaller cross sections and could have interesting properties for mode locking. For all these materials, the maximum energy that can be obtained in a single short pulse may finally only be limited by either damage of the material, or self-focusing and self-phase modulation. Accurate values for n_2 will have to be obtained for each material.

B. SHORT PULSE GENERATION WITH EXTERNAL SWITCHING

Present state of the art fast optical switches operate in the sub-nanosecond regime, and hence chopping a short segment out of a Q-switched laser pulse appears to be a simple way to generate suitable 1.06-μm pulses. Let us compare this method with mode locking from the point of view of producing the same energy in a short pulse.

Considering again the expression for peak power from a Q-switched laser with optimum output coupling, as given in Eq. (II.1), the energy in a chopped-out pulse with pulse width τ_{ext} is

$$E_{ext} = 0.0867 \left(\frac{\tau_{ext}}{\tau_\ell}\right)\left(\frac{h\nu}{\sigma}\right) A\, \alpha^2 \quad , \qquad (II.5)$$

where τ_ℓ is the cavity roundtrip time. For a mode-locked laser, the energy per short pulse is

$$E = 0.0867 \left(\frac{h\nu}{\sigma}\right) A\, \alpha^2 \quad , \qquad (II.6)$$

and we immediately see that we need a gain in this laser that is at least $\sqrt{\tau_\ell/\tau_{ext}}$ larger than the gain in the mode-locked laser. If, for example, we want to get a 100-ps pulse from a laser with a 5-ns roundtrip time, we have to pump this Q-switched laser about 7 times harder, and for YAG, the laser power gain coefficient would be about 14, which is rather high.

Another way of looking at this is that the peak power in the long Q-switched pulse should be the same as in the short mode-locked pulse and the question now becomes what the probability of damage in the laser is for these two pulses. It is a reasonable assumption that the longer-pulse lase: will always be more susceptible to damage at the same peak power, and we will always get more energy per short pulse with mode locking. Thus from this point of view of energy extraction we can conclude that, for pulsewidths of a few nanoseconds or more, one can get the same energy in the chopped-out pulse and in a mode-locked pulse, but for shorter pulses, the chopped-out pulse will have less energy.

However, the fast switch need not be put right after the Q-switched oscillator, but the Q-switched pulse can be amplified right up to the damage limit of the switch and one will certainly be able to get more than 1 mJ in the short pulse. The fast switch acts as an isolator between the initial amplifier and the final amplifier; if a switch with a large enough area can be developed, the total required gain can be divided about equally between the amplifiers before and after the switch. This is an interesting possibility, and certainly warrants the development of fast optical switches, particularly a fast switch that can produce the precisely-shaped pulses for laser fusion as shown in Fig. I.1. For these fast switche one must consider RLC effects, as well as longitudinal and transverse transi time effects.

This method of short pulse generation will easily satisfy almost all the other requirements, except for synchronization with the plasma diagnostic pulse. Let us consider this in more detail. We consider the case where the fast switch is a Pockels cell driven by an appropriate high voltage switch, as are now being developed. It seems unlikely that this same voltage switch or any Pockels cell could produce a 10 ps pulse, and it also seems unlikely that this switch could be synchronized with another electrical signal to better than 10 ps, where this other signal could be a RF signal to an actively mode-locked laser or a signal from a fast photodetector on the laser producing the short diagnostic pulses. Thus it seems that one is limited here to the method of producing a short, synchronized pulse from the primary short pulse. We will consider possible methods to do this later.

In Table I, an evaluation of the external switch method is given, summarizing the ideas presented in this section.

C. ACTIVE MODE LOCKING

The theories of steady-state and transient active mode locking in the Nd:YAG laser have been developed in considerable detail, and have been confirmed by a substantial amount of experimental work [6,7,8]. In this section we will briefly review this theoretical work, and then carefully evaluate this method to generate short pulses for the laser-fusion program.

1. The Steady-State Analysis

In the steady-state analysis of active mode locking, we assume that there is a short pulse traveling around in the cavity. This short pulse, which is assumed to be temporally gaussian, is followed once around the cavity and the effects of the modulator, active medium and losses in the cavity are carefully taken into account. After one roundtrip, a self-consistent solution is required, i.e., the pulse must have exactly the same shape as it had at the start of that roundtrip. In this report we will primarily consider an amplitude modulator, and for either an

TABLE I

Evaluation of Short Pulse Generation With an External Fast Switch

Pulse Properties	Requirements	
Pulse Energy	1 mJ (oscillator)	No
	1 mJ (with amplifier)	Yes
	5% stability	Yes
Pulse Duration	50 ps to 300 ps	?
	300 ps to 1.5 ns	Yes
	5% stability	Yes
	Precisely shaped pulse	?
Peak-to-Background Ratio	$> 10^4$	Yes*
Spectral Characteristics	Transform limited	Yes
Spatial Profile	TEM_{00}	Yes
Synchronizing Signal:		
Optical:	Single short pulse	Yes
	Pulse train	No
Electrical:	Single pulse	Yes
	Short burst	No
	Periodic	No

*Present state-of-art switches can do 30 dB, and 40 dB is marginal.

acousto-optic or electro-optic modulator, the single pass amplitude transmission is given by

$$m(t) = \cos(\theta_\ell \sin \omega_m t) \quad , \qquad \text{(II.7)}$$

where θ_ℓ can be considered the depth of modulation. Since Nd:YAG has a homogeneously broadened line, it is possible to write down what the shape of the line under saturation conditions in the laser is, i.e.,

$$g_a(\omega) = \exp \frac{g_0}{[1 + 2j\ (\omega - \omega_a/\Delta\omega)]} \quad , \qquad \text{(II.8)}$$

where g_0 is the saturated amplitude gain through the active medium at line center (ω_a) for one roundtrip in the cavity.* As explained in detail in reference 6, we can assume that the pulse width is short compared to the cavity roundtrip time, and the pulse spectrum is narrow compared to the linewidth. With these assumptions, the self-consistent analysis gives a pulse width τ_p (FWHM) :

$$\tau_p = \frac{(2 \ln 2)^{1/2}}{\pi} \frac{g_0^{1/4}}{\theta_\ell^{1/2}} \left(\frac{1}{f_m \cdot \Delta f}\right)^{1/2} \quad , \qquad \text{(II.9)}$$

where f_m is the external modulation frequency and Δf is the linewidth, both in Hz. The gain g_0 is related to the cavity losses and output

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* Note that in this analysis we use the roundtrip amplitude gain g, while in the Q-switching analysis in Appendix A we used the power gain coefficient α. They are related by $g = \alpha/2$.

coupling by

$$g_0 = \frac{1}{2} \ln \left[\frac{1}{R(1-L)}\right] \quad , \qquad \text{(II.}$$

For a typical cw Nd:YAG laser we have

$$R = 0.8 \ , \ L = 0.05 \quad \therefore \ g_0 = 0.14$$

$$f_m = 150 \text{ MHz} \quad \text{(cavity length = 50 cm)}$$

$$\Delta f = 120 \text{ GHz} \quad .$$

This gives $\tau_p = 53.7/\theta_\ell^{1/2}$ ps . This expression has been verified experimentally for θ_ℓ over almost two orders of magnitude, and hence Eq. (II.9) is now considered a very accurate description of the active mode-locking process. Practical modulators have a maximum depth of modulation of $\theta_\ell \simeq 1$ to 2 and hence one can generate 50-ps or longer pulses quite easily in the cw Nd:YAG laser, and the pulse width is continuously adjustable by simply changing the drive to the modulator. From this point of view, it looks like an ideal short pulse generator for the present needs of the laser-fusion program. If one, however, considers that a typical cw Nd:YAG has an output power of about 1 to 10 watts, the energy in the short pulse is about 5 nJ to 50 nJ. One must consider Q-switching the laser to approach the desired energy of 1 mJ, and then one has to consider transient mode-locking in a pulsed and Q-switched laser, which we will consider later.

2. Etalon Effects

First, we want to consider some other properties of the steady state mode locking analysis that are pertinent to the laser-fusion program. This analysis has been extended to include the effects of an etalon in the cavity, and the pulse width is now given by

$$\tau_p = \frac{(2 \ln 2)^{1/2}}{\pi} \left(\frac{1}{\theta_\ell}\right)^{1/2} \left(\frac{1}{f_m}\right)^{1/2} \left(\frac{g_0}{\Delta f^2} + \frac{1}{\Delta f_e^2}\right)^{1/4} , \qquad (II.11)$$

where Δf_e is the effective bandwidth of the etalon, and is given by

$$\Delta f_e = \left(\frac{c}{nh\pi}\right) \frac{1 - R}{\sqrt{2R}} , \qquad (II.12)$$

where h is the etalon thickness, n is the etalon index of refraction, and R is the reflection of each surface. This shows that one can conveniently generate longer pulses with the use of an etalon and one generally must use an etalon to generate stable pulses longer than ~ 500 ps. Note that for the active medium one should consider $\Delta f/\sqrt{g}$ as the effective linewidth. This is the term appearing in Eq. (II.11), and it also immediately follows from the expansion of the line shape [Eq. (II.8)] into the gaussian form to give an effective line shape of

$$\exp\left[- 4g\left(\frac{\omega - \omega_a}{\Delta\omega}\right)^2\right] .$$

One can already predict that the higher gain in the pulsed and Q-switched Nd:YAG laser will increase the width of the pulses. We will consider this in detail later.

3. Pulse Synchronization Conditions

There is one more question that one wants to answer with the steady-state analysis and that is, just how well synchronized is the short pulse with the external modulation signal? To be more precise, it is well known that if there is a small change in the modulation frequency, there is a shift in the pulse position. Just to see how this comes about, when there is a small shift in frequency, the short pulse still has the same roundtrip time in the cavity and hence gets out of step with the modulator. As the pulse shifts away from the minimum-loss condition of the modulator, it gets to a portion of the modulation cycle such that there is a change in loss during the pulse, and this effectively shifts the pulse back in the direction of the minimum-loss condition. A steady state is reached with the pulse moved slightly away from the minimum-loss condition, which means there is a relative phase shift between the short pulse and the modulation signal. One can analyze this problem with the circulating-gaussian-pulse model, and if t is the shift in time when we change the modulation frequency f_m , one can show that [6,9],

$$\left.\frac{dt}{df_m}\right|_{f_{mo}} = \frac{\Delta f}{8(f_m)^3 \sqrt{g_0}\ \theta_\ell} \quad , \qquad \text{(II.1}$$

where the parameters have all been defined previously. To consider a specific example, we take the same laser parameters as before to give a 50-ps pulse $(\theta_\ell = 1.15)$ and we get, for $\Delta t = 5$ ps ,

$$\frac{\Delta f}{f_{mo}} \simeq 2 \times 10^{-6} \quad . \qquad \text{(II.1}$$

This frequency stability can easily be obtained with a good crystal-stabilized signal generator. However, the cavity length stability should be the same, i.e., $\Delta l/l = 2 \times 10^{-6}$, and for a 50-cm cavity as considered here, this requires a length stability of 1 μm, which becomes a real problem. In a cw-pumped laser it may be possible to maintain a short term stability of 1 μm, but in a pulsed laser, as we will consider later, this may not be possible. It thus becomes obvious that before one can really say that the short pulse is synchronized with the external signal and use this to synchronize two actively mode-locked lasers, a lot more experimental work in this area is needed.

One can look at this synchronization problem in more general terms. Assume that in some (fictitious, maybe glass) laser, that has a sufficiently wide line, so that for a depth of modulation θ_l, we can generate a pulse width τ_p. Substituting the expression for the pulse width in Eq. (II.13), we can write

$$\left(\frac{df_m}{f_m}\right) = \left(\frac{4\pi^2}{\ln 2}\right) (f_m \tau_p \theta_l)^3 \left(\frac{dt}{\tau_p}\right) \quad . \tag{II.15}$$

Now assume that we want to generate a 10-ps pulse in this laser; for $\theta_l = 1$ and $f_m = 150$ MHz, we get $df/f_m \simeq 10^{-7}$ or $\Delta l = 0.05$ μm ! It becomes obvious that even if there were a laser with this linewidth, the synchronization of such short pulses becomes very difficult. The above equations immediately show the direction one has to go to solve these problems, i.e., shorter cavities, stronger modulation, etc. Going to shorter cavities will help to get shorter pulses and improve synchronization, but will make subsequent pulse selection more difficult. Present pulse selectors require about 5 to 10 ns between pulses. However, looking at the previous equations more carefully, we required higher modulation frequencies for short pulses and good synchronization. The direction to go is to drive the modulator at a multiple of the fundamental mode-locking frequency, but one then has to avoid the problem of having N pulses in the cavity. This will require an additional signal at the fundamental mode-locking frequency to suppress multiple pulses. With this added complication, one will be able to obtain optimum conditions for short pulse generation and single pulse selection. A considerable amount of experimental work is still required here.

4. The Transient Analysis

It became obvious from our previous discussion, that we have to do simultaneous mode locking and Q-switching to increase the energy in the short pulses to a useable value. The question now becomes whether the mode-locking process can approach the steady-state conditions during the buildup of the Q-switched pulse. One can analyze this with basically the same model as for the steady-state conditions. In the transient analysis [8], one allows a small change in the pulse width per roundtrip, and one can eventually obtain an analytic expression that gives the pulse width as a function of the number of roundtrips (M) from the time the mode-locking process starts:

$$\tau = \tau_{po}/[\tanh M/M_o]^{1/2} \quad , \qquad (II.1$$

where

$$M_o \approx \frac{1}{4\sqrt{g}\,\theta_\ell}\left(\frac{\Delta f}{f_m}\right) \quad , \qquad \text{(II.17)}$$

and τ_{po} is the steady-state pulse width. The laser is within 5% of the steady-state conditions when $M = 1.52\, M_o$. It is important to note that the factor $\Delta f/f_m$ appears in the expression for M_o; for a typical Nd:YAG laser, this is on the order of 10^3, and it takes about this number of roundtrip times to reach steady-state conditions. Using the parameters for the typical Nd:YAG laser we considered before, we get $M_o = 470$. Comparing this with Eq. (A.15) in Appendix A, it becomes obvious that for any reasonable conditions where the laser is well above threshold, the mode-locking process does not approach the steady-state conditions during the Q-switching buildup times, particularly in the high-gain regime of the Nd:YAG laser, where the buildup time is only about 24 roundtrips to obtain 1 mJ per short pulse from the laser.

Transient mode locking with an active modulator now naturally divides into two types. The first type, which can be called slow transient mode locking, is where we do not reach steady-state conditions during the Q-switching buildup time and consequently do not get nort pulses. This is usually where we have a sinusoidal type of modulator. The second type, which we shall call fast transient mode locking, is where short pulses are obtained during the Q-switching buildup time. In this case we usually have a very fast modulator that opens for only a very short time and really chops out a short pulse in the first roundtrip, and then narrows this pulse to a steady-state condition in only a few roundtrips. This type of fast transient mode locking has been demonstrated by Johnson at LLL [10] in Nd:YAG, and pulses as short as ~ 250 ps have been generated under conditions where the buildup time was only ~ 20 roundtrips. We shall return to this type of mode locking later, but first we want to consider the slow transient mode locking in more detail.

5. Slow Transient Mode Locking

We have found a way to get around the problem of the slow buildup of the mode locking. The Q-switch loss is adjusted so that it does not hold off the laser completely, but the laser is allowed to oscillate or "prelase" at a low level. During this time the modulator is on and short pulses build up and, if the prelasing time exceeds the transient buildup time given by Eq. (II.17), the steady-state pulse width is reached. When the Q-switch is now opened, the initial conditions for the Q-switching are short pulses, and these short pulses continue through the Q-switched envelop with very little further changes. Saturation and the change in gain during Q-switched regime do not affect the short pulses in any significant way.

If we again consider the expression for steady-state pulses,

$$\tau_p = \frac{(2 \ln 2)^{1/2}}{\pi} \frac{g^{1/4}}{\theta_l^{1/2}} \left(\frac{1}{f_m \cdot \Delta f}\right)^{1/2} , \qquad \text{(II.:}$$

we should remember that g is now the gain in the laser with the Q-switch in the high loss condition; as we showed previously, to get 1 mJ from the laser, the power gain coefficient is 2.0 and hence $g = 1.0$. If we put this in Eq. (II.18), we get

$$\tau_p = \frac{86.3}{g_l^{1/2}} \text{ ps} \quad . \qquad (II.19)$$

This illustrates that under high-gain conditions, it is no longer possible to get 50-ps pulses, because the effective linewidth, $\Delta f/\sqrt{g}$, has decreased considerably. For good active mode locking, it becomes clear that it is much better to have a smaller cross section and wider linewidth and, from this point of view, Nd:Glass looks very attractive for generating reasonably energetic pulses with active mode locking. The best situation seems to be where the linewidth of the active medium is so wide, that an etalon is required to give the desired pulse width. In this case the effective bandwidth of the system becomes independent of the gain, and one can obtain the same pulse width at any pumping level.

The next question one wants to ask is, whether the actively-mode-locked Q-switched laser with prelasing will produce transform-limited pulses. To answer this we have to look at the build-up of mode locking in more detail. As the laser goes above threshold, a large number of axial modes start to build up. These axial modes are randomly phased. As the number of roundtrips increases, the number of axial modes decreases due to repeated passes through the active medium, and hence the total spectral width, B_q , decreases. All these axial modes are essentially independent, and we can view the amplitude modulator as modulating each axial mode independently. Each of these axial modes now gets a set of sidebands; one usually thinks of this as coupling between the axial modes that originally started to build up and that, due to this coupling, all the axial modes are eventually pulled in phase to produce short pulses. This is not the correct view during the transient buildup period. One should rather think in terms of all axial modes except the centermost dying away, and that only this one axial mode with its sidebands survives. When only this one mode with its sidebands is present, the output of the laser is transform-limited. To get an estimate of how long it takes to reach this condition, we can simply consider the Q-switched laser without mode locking. During the buildup the gain g is constant and, after M roundtrips, the envelope of the power spectrum rapidly takes on a gaussian shape, with a spectral width B_q (FWHM) given by

$$B_q = \left(\frac{\ln 2}{8Mg}\right)^{1/2} \Delta f \quad . \qquad \text{(II.2}$$

To obtain a single axial mode, we must satisfy the condition that $B_q < f_{ax}$, where f_{ax} is the axial mode spacing. From this, we get the condition for the number of roundtrips to give a single axial mode,

$$M > \frac{\ln 2}{8\,g}\left(\frac{\Delta f}{f_{ax}}\right)^2 \quad . \qquad \text{(II.2}$$

If this condition is satisfied under mode-locking conditions, very good transform-limited pulses result. Note that the term

$$\left(\frac{\Delta f}{f_{ax}}\right)^2$$

appears, which is on the order of 10^6 for Nd:YAG, and we can immediately conclude that it will take a very large number of roundtrips to satisfy this condition. For example, if we consider the typical cw laser as before, we get $M > 1.0 \times 10^5$ or 0.33 ms. In the higher-gain regime of the pulsed and Q-switched Nd:YAG laser, to obtain a 1-mJ short pulse, $M > 1.3 \times 10^4$, or 42 μs. It generally takes more roundtrips to satisfy the transform-limited condition than it takes for the pulse envelope to reach steady state, and hence the prelasing time should be long enough to satisfy this condition.

The prelasing time should satisfy one more condition, particularly in a pulsed laser. When the laser goes above threshold with the Q-switch in the high-loss condition, spiking occurs and the prelasing time must be long enough for this to die away. The spiking is highly nonlinear, and one cannot easily establish a time for this to die away. The simple linearized theory suggests that this time should be at least equal to the upper-level lifetime of the laser, or about 240 μs for Nd:YAG. If this condition is satisfied, and the modulator is on throughout this prelasing period, one can get very good transform-limited short pulses.

6. Fast Transient Mode Locking

As was mentioned previously, fast transient mode locking is where the laser reaches steady-state short pulse conditions during the buildup of a normally Q-switched laser. In this case, the modulator opens for a very short time ($\lesssim$ 1 nanosecond); a short pulse is formed on the first roundtrip and then narrows very rapidly. To obtain a transform-limited pulse, the bandwidth in the system has to be very narrow; if we consider the analysis in the previous section, which is not quite applicable here, Eq. (II.21) suggests that the bandwidth should only be a few axial modes wide. This is, in fact, what was done experimentally by using a four-element etalon in the cavity to narrow the laser bandwidth sufficiently to get transform-limited short pulses, and pulses as short as ~ 250 ps have been obtained.

7. Amplitude Instabilities

Amplitude instabilities in these mode-locked lasers, in the form of pulse-to-pulse variations, can arise from many causes such as pump supply variations, arc instabilities in lamps, mechanical vibrations, etc. We really do not want to evaluate these extrinsic causes in this report, we do, however, want to consider one intrinsic source of instability that is inherent in the mode-locking and Q-switching system. Under high-gain conditions such as in the Flash-pumped Nd:YAG laser, the Q-switched pulse is only a few roundtrips long, and thus only a few mode-locked pulses appear during the Q-switched envelope. A typical case is shown in Fig. II.1. It now becomes important that the position of the short pulses be stable relativ to the Q-switched pulse envelope. It is reasonable to assume that, as the short pulse position varies underneath the Q-switched pulse envelope, the energy in the short pulses will trace out a stable envelope, given that the pumping conditions remain constant. Figure II.2 now illustrates the two extreme conditions that can exist; one where a short pulse is right at the peak of the Q-switched envelope, and one where there are two equal-amplitude pulses on either side of the peak of the Q-switched envelope. The best that a single-pulse selector can do is to always select a pulse between these

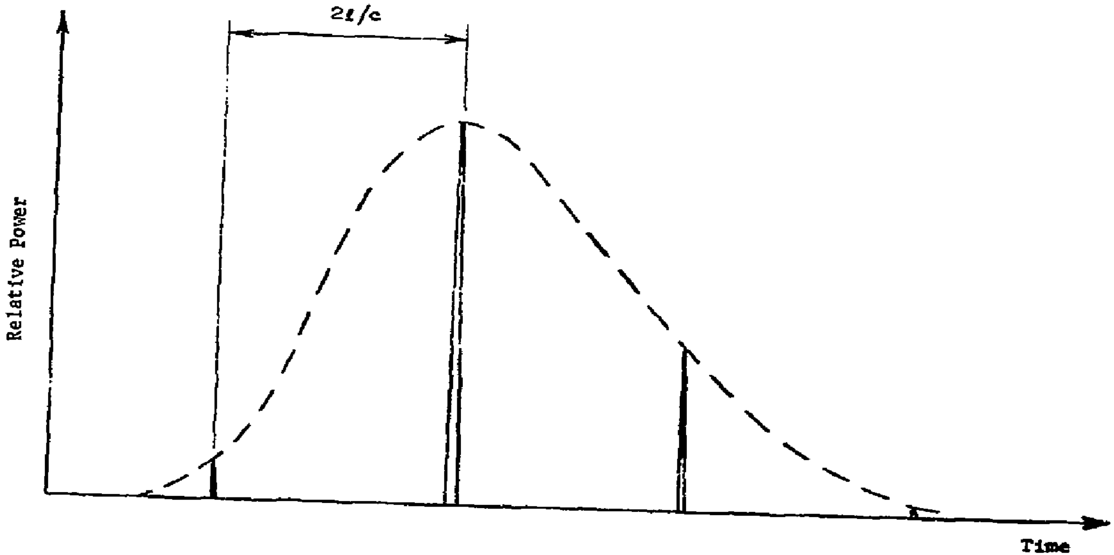


FIG. II.1--Position of short pulses relative to Q-switched pulse envelope.

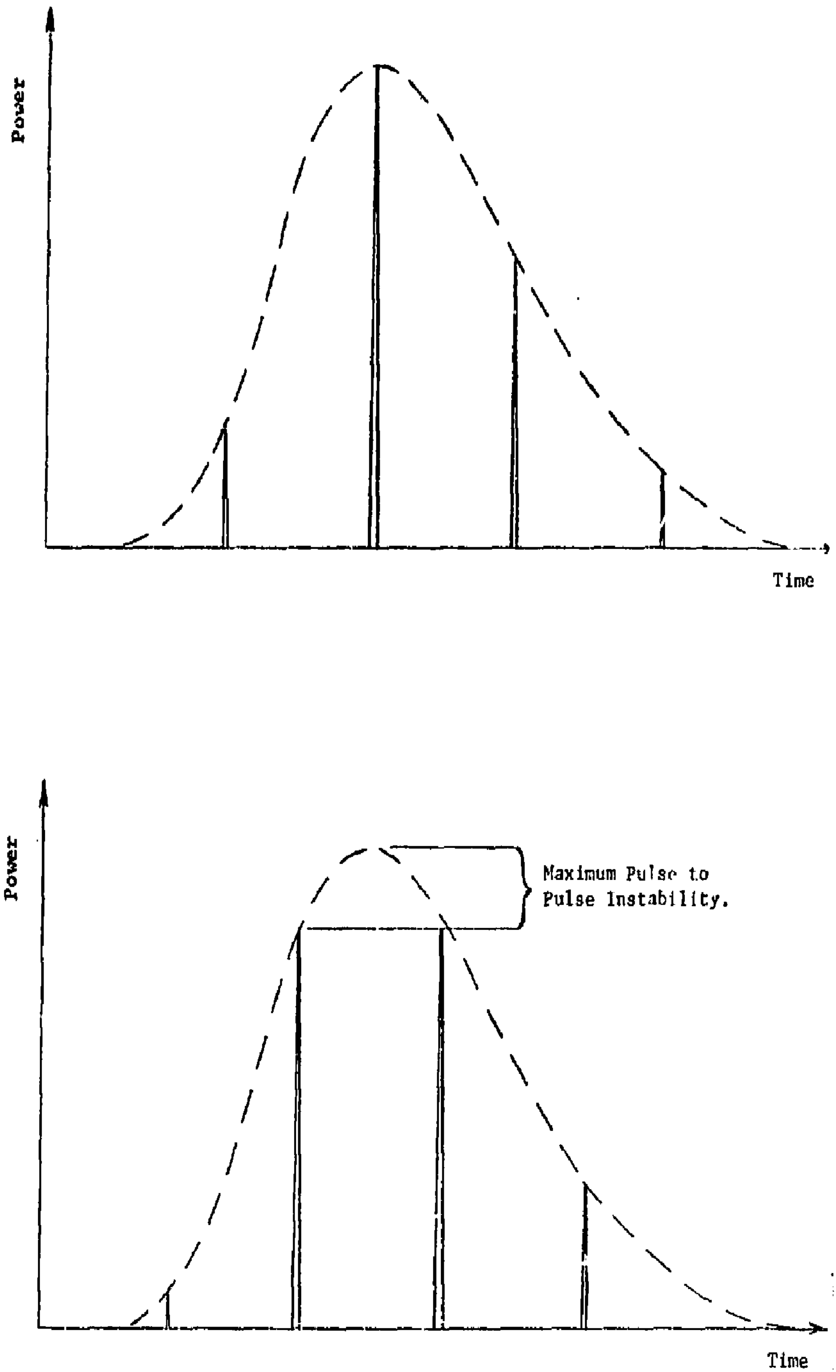


FIG. II.2--Pulse instabilities due to shift of pulse position relative to Q-switched pulse envelope.

extremes, and when the Q-switched envelope becomes short, it is obvious that we can get considerable pulse-to-pulse instability, even under ideal pumping conditions. To eliminate this problem, the Q-switched envelope has to be synchronized with the position of the short pulses.

In general, three conditions have to be satisfied to achieve this synchronization:

(1) Constant Gain: The gain has to be sufficiently constant from shot to shot that the variation in the total Q-switching buildup time is much less than one cavity roundtrip time.

(2) Constant Initial Conditions: The fluctuations of conditions when the Q-switch opens have to be much less than the roundtrip excess gain during the Q-switching buildup.

(3) The opening of the Q-switch has to be synchronized with the mode-locking modulator.

We can now review the various short-pulse generation techniques from this point of view. First, we consider slow transient mode locking with prelasing. Due to the prelasing, the gain in the active medium will be determined exactly by the loss in the Q-switch if the prelasing period is sufficiently long that steady-state conditions are reached. From shot to shot, it will be possible to stabilize the loss in the Q-switch sufficiently to stabilize the gain. The initial energy in the short pulses at the time the Q-switch is opened is determined by the excess gain during prelasing, and this excess gain will have to be stabilized to within a few percent, say less than 10%, to give sufficiently stable initial conditions. This will generally mean that the total gain, and hence the pump power, will have to be stabilized to within a fraction of one percent to satisfy these conditions. It will have to be determined experimentally how constant the pump power can be maintained from shot to shot for this type of laser. Finally, the synchronization of the Q-switch opening to the mode-locking modulator is well within the state of the art of fast switching circuits, and should pose no problems.

We next consider fast transient mode locking [10]. Even if the gain is sufficiently stabilized, there is simply no way in this type of setup to stabilize the initial conditions. When the fast modulator is opened the first time, the initial condition in the cavity is random noise, and hence the energy in a single selected pulse from this system can be expected, at least to some extent, to show random variation between the two extremes depicted in Fig. II.2. It will be interesting to evaluate the pulse-to-pulse stability in this system from this point of view.

The main conclusion that we can draw here is that, by allowing a long enough period of prelasing, we can eliminate the noisy initial conditions, and only then does it become possible to eliminate the short pulse fluctuations in a situation where the Q-switched envelope is only a few roundtrips long. We can also conclude that in a laser material with a cross section considerably smaller than Nd:YAG, the Q-switched envelope will be much longer, and therefore this problem will disappear.

8. Evaluation of the State of the Art of Active Mode Locking

Table II below presents an evaluation of active mode locking and summarizes some of the ideas presented in this section, and makes some reasonable predictions.

TABLE II

State of the Art of Active Mode Locking

Pulse Properties	Requirements	CW Nd:YAG		Pulsed Nd:YAG	
		Mode Locked	Mode Locked Q-Switched	Slow Mode Locked	Fast Mode Locked
Pulse Energy:	1 mJ	No	No	Yes*	Yes
	5% Stability	Yes	Yes	Yes*	Yes(?)
Pulse Duration:	50 to 300 ps	Yes	Yes	Yes(?)	No
	300 ps to 1.5 ns	Yes	Yes	Yes	Yes
	5% Stability	Yes	Yes	Yes	?
Peak-to-Background Ratio	$> 10^4$	Yes	Yes	Yes*	Yes(?)
Spectral Characteristics	Transform Limited	Yes	Yes	Yes	Yes
Spatial Profile	TEM_{00}	Yes	Yes	Yes	Yes
Synchronizing Signal:					
Optical:	Single Short Pulse	--	Yes	Yes	Yes
	Pulse Train	--	Yes	Yes	Yes
Electrical:	Single Pulse	--	No	No	No
	Short Burst	--	No	No	Yes
	Periodic	Yes	Yes	Yes	No

*Predictions.

9. Future Directions of Active Mode Locking

Most of the experimental work in active mode locking has been done in cw lasers, at low power levels, and only more recently have pulse energies of more than 10 μJ been obtained in the mode-locked and Q-switched Nd:YAG laser with cw pumping. In all these experiments, the power levels have been low enough to avoid a large number of problems. Damage in laser components and self-focusing in the laser material have not been problems, and self-phase modulation and subsequent changes in the pulse shape due to dispersion in the cavity have also not been experienced. In the experimental work now in progress with mode-locking and Q-switching the pulsed Nd:YAG laser, some or all of these problems will occur, and they will eventually limit the amount of energy that can be obtained in a single short pulse from the Nd:YAG laser. It presently seems reasonable to expect about 1 mJ from such a system that will satisfy the requirements for the laser-fusion program. Future experiments will establish the maximum energy per short pulse that can be obtained from this laser, but it seems highly unlikely that it will exceed 1 mJ by even an order of magnitude.

Some of the problems with Nd:YAG have become quite obvious from the past discussion, particularly the large gains one needs to extract the maximum energy from the Nd:YAG laser. Future research should be done on materials with smaller cross sections, and Nd:Glass is probably one of the first that should be investigated. Very few, if any, experiments have been done in Nd:Glass using an active modulator to get short pulses. Nd:Glass will bring along its own particular problems, such as the extremely wide linewidth, which will have to be effectively narrowed down to get 50-ps or longer pulses for the primary pulses, but the wide linewidth may also make it possible to generate considerably shorter pulses. Theory indicates that this will be possible, but active mode locking in any laser has not produced pulses much shorter than 40 to 50 ps, and trying to generate shorter pulses is an almost unexplored area. Active mode locking in the cw dye laser has been notoriously unsuccessful in getting to the 1- to 10-ps range, and active mode locking in Nd:Glass to get to these short pulses will add much to the understanding of mode locking in this pulse width range. The extremely long buildup times and consequently the long pulsed pumping of Nd:Glass can already be seen as one problem.

Other materials with intermediate cross sections will also be of interest. One interesting possibility is to operate Nd:YAG at higher temperatures. In going from $300^{\circ}K$ to $400^{\circ}K$, the linewidth doubles and the gain will be about half, but the relative distribution in the upper and lower levels will also change, as discussed in Appendix B.

In all of the active-mode-locking work in Nd:YAG, very good gaussian-shaped pulses have been obtained. In the future one might like to change this in order to generate pulse shapes more suitable for laser fusion. This is an area that is totally new and quite unpredictable, and at present some good ideas and experiments are needed.

We can now attempt to set up a "roadmap" for future research work in active mode locking for the laser-fusion program, and some reasons why it should be done.

(1) Nd:YAG: CW pumped, mode locked with or without Q-switching.

Reasons: (a) Repeat earlier work with better modulators to obtain shorter pulses.

(b) Measure transform-limited properties of pulses.

(c) Measure peak-to-valley ratios.

(d) Test several single-short-pulse selection schemes under well controlled pulse generation conditions.

(e) Investigate synchronization of short pulses with respect to the modulation signal.

(2) Nd:YAG: Pulse pumped, mode locking and Q-switching with pre-lasing.

Reasons: (a) More energy per pulse.

(b) All of (b) through (e) in Section (1) above to see how much the laser properties deteriorate under the higher-gain conditions.

(c) Establish maximum energy per short pulse available due to limitations of damage, self-phase-modulation and self-focusing.

(d) Measure shot-to-shot stability.

(3) Nd:YAG: Pulse pumped with fast transient mode locking.

Reasons: (a) Attempt to get pulses as short as 50 ps.

(b) Evaluate pulse-to-pulse stability from the point of view discussed earlier in this section, i.e., relative short pulse and Q-switched envelope stability.

(4) Nd:Glass and other materials.

Reasons: (a) Extend active-mode-locking experience gained from Nd:YAG lasers to Nd:Glass.

(b) Generate shorter pulses.

(c) Possibly more energy per short pulse.

(d) Study self-phase modulation, and possibly generate chirped pulses.

(e) The ability to select any glass for laser-fusion work, and not be limited to those that can be driven by Nd:YAG.

(5) Pulse shaping in actively mode-locked lasers, starting from cw pumped and mode-locked lasers, and once some pulse shaping techniques have been developed, progress with these techniques through the Q-switched lasers, and then pulsed and Q-switched. The final aim is then to obtain a mode-locked Nd:Glass laser with a precisely shaped pulse.

D. PASSIVE MODE LOCKING

Passive mode locking was first observed by DeMaria, et al. [11] and, since then, an enormous amount of work has been done in this area. In this report, we shall not attempt to review all of this work. A recent paper by Laubereau and Kaiser [2] gives a good review, and a paper by Duguay, et al. [12] gives a good treatment of the Nd:Glass laser and a particularly good reference list.

In the past years, considerable theoretical understanding of passively-mode-locked systems has been developed, and two distinct theoretical models are now accepted. The first is the so-called "Fluctuation Model" first proposed by Letokhov [13,14] and further developed by Kryukov and Letokhov [15], Kuznetsova [16], Fleck [17,18], and Hausherr, Mathieu and

Weber [19]. This model mainly considers the selection of a single noise spike, and the growth of this noise spike into the mode-locked output of the laser. The most recent works on this model by Glenn [20] and Zherikhin, et al. [21] have presented considerable progress in this area, and both papers treat the passively mode-locked Nd:YAG laser that is now being used in the laser-fusion program. The discussion in this section will largely be based on these two papers.

The other theoretical approach that has developed is the so-called "Quasi-continuous" theory, as presented by New [22]. This theory mainly considers the shaping of short pulses by the saturable absorbers and the laser media, and is most useful for dye lasers.

Both of these theoretical approaches will be needed to understand the short pulse generation problems associated with the laser fusion program. The fluctuation model is now well established as explaining the behavior of the Nd:Glass and Nd:YAG lasers. The quasi-continuous theory will help in the development of short-pulse dye lasers that may be useful for plasma diagnostics.

In this section, we want to consider passive mode locking of the Nd:YAG and Nd:Glass lasers. First, a qualitative review of the "fluctuation model" will be presented, and we will attempt to draw some conclusions on the behavior of the passively mode-locked Nd:YAG and Nd:Glass lasers, and compare them with the short pulse requirements for the laser fusion program.

A simple model of the behavior of the laser and bleachable dye will be used, and we will follow the model and notation used by Glenn. The dye cell is treated as an inertialess absorber and thus saturates instantaneously with the intensity in the laser cavity. The transmission coefficient is given by

$$K = \frac{K_0}{1 + I/I_s} \quad , \tag{II.22}$$

where K_0 is the unbleached absorption coefficient. I_s is the saturation intensity, and is about 50 MW/cm^2 for the common bleachable dyes at 1.064 μm. The laser medium has a very long upper-level lifetime compared to the Q-switching times considered here, and thus saturates on the total energy extracted from the laser medium.

There are four very distinct regions in the operation of the passively mode-locked Nd:YAG laser:

Region I: The pump power is turned on, but the laser is below threshold. The intensity in the laser cavity is dominated by spontaneous emission.

Region II: The laser is above threshold, and the intensity grows until it reaches the saturation intensity of the dye.

Region III: Saturation of the dye occurs, and a single pulse is selected, if and only if the laser medium saturates at the same time, as pointed out by Glenn.

Region IV: The laser Q-switches, and the stored energy is extracted by a single short pulse.

We will now consider each of these regions in more detail.

Region I. The pump is turned on at time $t = 0$, and spontaneous emission in the cavity is amplified. At the start of this region, the field in the cavity is pure white noise, and by the end of this period, it has more bandwidth-limited properties.

<u>Region II</u>. As the laser goes above threshold, the spontaneous emission is amplified, and after just a few roundtrips, it becomes bandwidth-limited noise, and after more passes, the bandwidth is <u>further narrowed</u>. If there is an etalon or other bandwidth-limiting element in the cavity, this can dominate the bandwidth-narrowing process. In the time domain, the cavity field consists of a large number of noise spikes, with random amplitudes and widths. As this noise is amplified in region II, the finite bandwidth of the system lengthens each pulse; the width of these noise pulses at the end of region II is largely determined by the bandwidth of the system, and the number of roundtrips in the cavity, but it also depends on the statistical properties of these noise spikes at the start of region II Consider a simple model here of a single temporally-gaussian pulse with pulsewidth τ_0 at the beginning of region II. After M roundtrips in the cavity with an effective linewidth Δf_e [see Eq. (II.12) and discussion there], the pulse width becomes:

$$\tau_N = \left\{ (\tau_0)^2 + \frac{4 \ln 2}{\pi^2} \frac{M}{(\Delta f_e)^2} \right\}^{1/2} \quad . \qquad \text{(II.23)}$$

τ_0 now has all the statistical properties of the initial noisy pulse. There is further no reason to believe that there is any correlation between the amplitude and width of the noise spikes, and hence the largest amplitude pulse that will finally be selected by the dye, can have a random variation in pulsewidth. At the beginning of region II, the mean pulsewidth will be approximately equal to the inverse of the effective linewidth, with a standard deviation of the same order of magnitude. To reduce the statistical fluctuations in the final pulse, we must have the second term in (II.23) much larger than the initial pulsewidth, and this requires a large number of roundtrips. We can now draw our first important conclusion. To reduce the statistical fluctuations of the pulsewidth, the laser must be brought slowly above threshold so that we can make many roundtrips in the cavity during the linear amplification region of the build-up. The pulse that we will obtain at the end of this region will be much wider than the inverse of the bandwidth, and will approximately be given by $\tau_N \simeq M/\Delta f_e$, with $M \gg 1$. At the end of region II, the laser will have an excess gain of $\Delta\alpha$.

Region III. In this region, a single pulse must be selected from the large number of noise pulses in the laser at the end of Region II. In the early discussion of the fluctuation model by Letokhov and others, only the nonlinearity of the dye was considered responsible for single-pulse selection. Glenn argues that the dye alone can never select a single pulse with good probability and that, if only the dye acts as the single-pulse selector, a single pulse can be obtained only 36.8% of the time. "This is contrary to experimental observation" [Glenn]. He then continues to show that the saturation of the active medium must be considered for single-pulse selection, and he supports this argument by very good numerical solutions of a typical system. The argument is best presented by quoting Glenn's paper:

"In more physical terms, it is necessary to invoke some mechanism by means of which one pulse can capture the stored energy of the laser at the expense of the other pulses. Only in this way can an output consisting of a single large pulse be obtained consistently. In terms of the statistics, the joint probability distribution must be such that the presence of a large-intensity pulse implies that the intensities of the other pulses are low. There are a number of mechanisms that could cause this. Perhaps the simplest is gain saturation. The net gain experienced by a pulse is a function of its intensity. The effective gain coefficient is

$$\alpha_{net} = \alpha - \gamma - K_0/(1 + I_{ki}) \quad .$$

At the start of region III, this quantity is positive for all pulses, although it may be quite small. Only a minute amount of saturation is necessary, however, before this quantity can become negative for pulses of very low intensity while remaining positive for pulses of higher intensity. The higher intensity pulses continue to grow while the lower intensity pulses decay. This provides a powerful discriminant. It is convenient to think of a critical intensity I_c for which

$$\alpha - \gamma - K_0/(1 + I_c) = 0$$

$$I_c = \frac{K_0}{\alpha - \gamma} - 1 = \frac{K_0}{K_0 + \Delta\alpha} - 1 \quad .$$

At the start of region III, $I_c < 0$, i.e., all pulses have gain. As the gain becomes depleted, $\Delta\alpha = \alpha - \gamma - K_0$ goes to zero and becomes negative, and $I_c > 0$. Only pulses with greater intensity than this continue to grow. Clearly, the presence of a very large pulse will deplete the gain faster and will cause I_c to rise more rapidly. This results in more effective elimination of the smaller pulses. To achieve good mode locking, one wants to have the intensity of only the largest pulse 'outrun' the rising value of I_c. This picture is borne out in detail in the results to be described below."

There is another way of looking at this, and this is essentially the approach presented by Zherikhin, et al. [21]. As the laser goes above threshold at the beginning of region III, the laser will gain-switch. Consider first the case where there is no dye in the cavity, or the intensity in the cavity never reaches the dye saturation intensity. As the intensity in the cavity increases during region III, it will reach the saturation density of the active medium. If the excess gain at that stage is $\Delta\alpha$, the laser will Q-switch subject to this initial condition. Since the active medium will be saturated by the average energy in the cavity. there will essentially be no change in the distribution of the noise pulses. With high loss in the cavity due to the dye, the excess gain $\Delta\alpha$ will be small, the laser will be just above threshold, and we extract very little energy from the laser. This low-level pulse will have all the noisy characteristics of the cavity field at the end of region II.

We can now consider the other extreme, where the dye saturation intensity is low and is reached before the active medium saturates. The field in the cavity rapidly grows through the level where the dye is nonlinear, and there is only partial selection of a single pulse. Poor mode locking results.

Now we consider conditions when everything is just right. The laser starts to gain-switch as described above. The active medium is saturated by the average energy in the cavity, and the net gain goes to zero. However, the strongest noise spike saturates the dye most, and if conditions are right, this noise pulse has net gain and grows, but is still close to threshold. A competing pulse with a little lower amplitude is much closer to threshold, and almost all the other pulses are below threshold. It is this difference in net gain that acts as a very strong pulse selector, and the strongest pulse grows rapidly, saturates the active medium and keeps all the other pulses below threshold and suppresses them completely.

Glenn has simulated this process on the computer and shows that three to five orders of magnitude peak-to-background can be obtained. The simulations also show that an outstanding characteristic of the optimum pulse selection condition is a distinct pre-pulse in the average intensity out of the laser. In the paper by Zherikhin et al. [21], this pre-pulse is clearly observed under conditions where very good peak-to-background ratios are obtained. They find that to get these conditions, the beam area in the dye has to be twice as big as in the Nd:YAG crystal. For smaller area ratios, they get poorer mode locking, and for larger ratios, the pump power is too high to get saturation of the dye and good Q-switching. One can thus conclude that there are certain conditions that have to be satisfied to get good pulse selection in region III.

During region III, the single pulse that is finally selected makes many passes through the dye with an intensity that is comparable to the saturation intensity of the dye. One can expect that during this time, the nonlinear behavior of the dye will tend to make this pulse shorter. This pulse shaping now has to be treated using the approach taken by New [22]. Both Letokhov and Glenn consider this a secondary effect in the pulsewidth determining process, and claim that the action of the finite bandwidth in region II is most important. However, to do a complete analysis, the approach by New in this region must be considered to obtain accurate results. Some of the work presently done by New is apparently going in this direction.

Region IV. Once the dye has been saturated, the single pulse that has now been selected sees a large excess gain and the laser Q-switches. The peak of the Q-switched pulse envelope under good conditions is one to two orders of magnitude above the peak of the pre-pulse. Under good conditions, it is reasonable to expect that the envelope of the Q-switched pulse will be quite independent of the position of the pulse relative to the peak of the envelope, and hence variations in peak pulse energy should only be limited by the fact that the pulse positions are random w.r.t. the peak of the pulse envelope, as shown in Fig. II.2.

During this Q-switching region, other effects and problems can occur. The intensities in a typical laser now can get high enough that the nonlinear index of the laser medium and other components in the cavity become important. Self-focusing and subsequent damage of components can occur, and self-phase-modulation can occur. It appears that Nd:Glass laser is more susceptible to these effects than Nd:YAG. This is stated very strongly by Zherikhin [21], and is supported by the work of Carmen, et al. [23]. Yet the results by Owyoung [24] clearly show that the n_2 coefficient for Nd:YAG is considerably larger than for Nd:Glass. One must conclude that the smaller cross section for glass is mainly responsible. As pointed out in the previous section on energy extraction, for a given change in loss with a Q-switch in the cavity, the glass laser will give considerably higher peak powers, and the Q-switched pulse envelope for glass will also be much longer One can simply store that much more energy in glass. Thus in the long pulse trains that are generally obtained for glass, the pulse makes many more passes through the glass. The nonlinear effects such as self-phase-modulation are cumulative, and the trailing pulses can display large effects due to n_2 . An enormous body of literature with associated TPF patterns exist to support this.

At this stage, no simple rules have been developed for optimum pulse selection, and suppression of the initial statistical properties of the mode-locked pulse, and it is not certain that all these conditions can be optimized at the same time.

The research direction for these systems for the laser-fusion program is now fairly obvious. The analytical model for passively mode-locked systems has to be developed further, to the point where general rules for optimum behavior are obtained. We can then evaluate the trade-offs in operating conditions to get the output characteristics of the laser as close to the requirements for the laser-fusion program as possible. This work then has to be closely supported by experimental work to carefully measure the properties of the laser under given conditions. Measurement of the statistical properties will be particularly important. From this work, one has to answer whether the following three conditions can be met simultaneously:

(1) 5% pulse energy stability

(2) 5% pulsewidth stability

(3) 10^4 peak-to-background ratio.

It presently seems unlikely that a purely passively mode-locked system can satisfy these conditions, but if this approach is going to be useful, one must find how close we can get to these requirements under reasonable operating conditions.

Table III presents the state of the art for passive mode locking. Note that the appearance of the mode-locked pulse will always be completely random within the roundtrip time of the cavity, and this will make synchronization with other short-pulse lasers difficult and in most cases impossible. This is a very serious shortcoming of the passively mode-locked laser.

E. A COMBINATION OF ACTIVE AND PASSIVE MODE LOCKING

Combining active and passive mode locking is an attempt to get all the best properties of both methods in one system. Each method has the following unique properties:

Active Mode Locking:

(1) The process can be completely determined and there are no statistical properties left in the final short pulses.

(2) The pulses are synchronized to an external signal.

Passive Mode Locking:

(1) The pulses are generally shorter than for active mode locking in the same laser.

Two very distinct approaches are apparent.

(I). An active modulator is used to give a much narrower window within which a single pulse can be selected by the bleachable dye. We now only have

TABLE III

State of the Art of Passive Mode Locking

Pulse Properties	Requirements	Nd:YAG	Nd·Glass
Pulse Energy:	1 mJ	Yes	Yes
	5% Stability	No	No
Pulse Duration:	30 to 300 ps	Yes	Yes (?)
	300 ps to 1.5 ns	Yes	Yes (?)
	5% Stability	No	No
Peak-to-Background Ratio:	$> 10^4$	Yes (?)*	Yes (?)*
Spectral Characteristics:	Transform Limited	Yes	Yes**
Spatial Profile:	TEM_{00}	Yes	Yes
Synchronizing Signal:			
Optical:	Single Short Pulse	Yes	Yes
	Pulse Train	Yes (Short)	Yes (Long)
Electrical:	Single Pulse	No	No
	Short Burst	No	No
	Periodic	No	No

*Peak-to-background ratio in the range of 30 dB to 50 dB are observed for good mode-locking conditions in the laser.

**Transform limited pulses are usually only observed early in the pulse train.

to consider the statistical properties of the noise pulses within this window, and in general the probability of obtaining spurious pulses is reduced by the ratio of the cavity roundtrip time to the modulator window. This can be a considerable improvement.

(II). An active modulator takes the mode-locking process to completion at a low level in the laser and, after a Q-switch is then opened, the saturation intensity of the dye is reached, and thus will shape the pulse and make it shorter. This method can be viewed as a use of the active modulator to eliminate the initial noisy conditions of spontaneous emission and replace it by well-determined short pulses. However, the function of the dye now also changes completely, from a selecting and discrimination process to a pulse shaping process, and with this, we have to switch from the "Fluctuation Model" to the "Quasi-Continuous Model" by New [22].

A system following the first approach has been demonstrated by B. Johnson at LLL with a fast modulator in a Nd:YAG laser and a saturable absorber, and very good results have been obtained. The same approach with a slow, sinusoidal modulator has not been demonstrated, but in general the same results can be expected, except that the effective window will be considerably wider.

The second method, to use an active modulator to change the initial conditions, has not yet been demonstrated. However, one can show that pulse narrowing due to the dye will not be very large, and only a factor of 2 or 3 can be expected. In some cases, such as in the Nd:YAG laser, this can be very significant.

The question that now arises is, just how well are the pulses synchronized to the external signal in these two approaches? In the first method, the dye can still select a short pulse anywhere within the window of the modulator, and hence the short pulse is at best synchronized with external signal to within the width of the window. This will almost certainly not be within ± 10 ps, and hence the method will still not satisfy the stringent synchronization requirements for the laser fusion program. In the second method, the synchronization will be the same as that of the actively mode-locked system without the dye.

Future research should be aimed at improving the first method where the modulator just acts as a narrow window to improve the statistical properties of the pulses from a passively mode-locked laser. The other method, where the dye is used to further shorten the pulses from an actively mode-locked laser should be demonstrated and evaluated.

Table IV presents the state of the art and predictions for combined active and passive mode locking.

TABLE IV

State of the Art and Predictions for Combined Active and Passive Mode Locking

Pulse Properties	Requirements	Method I Active Modulator as Window	Method II Active Modulator for Initial Conditions
Pulse Energy:	1 mJ	Yes	Yes*
	5% Stability	?	Yes (?)*
Pulse Duration:	30 to 300 ps	Yes	Yes*
	300 ps to 1.5 ns	Yes	Yes
	5% Stability	?	Yes*
Peak-to-Background Ratio:	$> 10^4$	Yes	Yes*
Spectral Characteristics:	Transform Limited	Yes	Yes
Spatial Profile:	TEM_{00}	Yes	Yes
Synchronizing Signal:			
Optical:	Single Short Pulse	Yes	Yes
	Pulse Train	? (Very Short)	Yes
Electrical:	Single Pulse	Yes	No
	Short Burst	Yes	No
	Periodic	No	Yes

*Predictions.

F. CAVITY DUMPING

We will not consider cavity dumping as a technique for generating short pulses, but together with either active or passive mode locking, this can be a useful method to obtain high energy pulses. We will consider ideal cavity dumping here, i.e., we have a cavity with high reflectors, and somewhere near the peak of the Q-switched pulse train, a single pulse is completely dumped out of the cavity. Cavity dumping has some obvious advantages:

(1) Short pulses can be obtained with peak powers equal to the limits in the laser due to component damage or self-phase-modulation.

(2) With low losses in the cavity, the required pump power to get the same energy in the pulses as with conventional output coupling, is much lower.

To consider these advantages in more detail, we can obtain an expression for the peak power of a Q-switched pulse inside the laser cavity. If P_{ext} is the peak power external to the cavity, then the internal power traveling towards the output coupler is given by $P_{int} = \frac{P_{ext}}{(1-R)}$, where R is the output coupler reflection. From Eq. (A.22) in Appendix A, with the additions due to the finite life-time of the lower level and thermalization within the upper and lower manifolds, we get for the internal peak power of the Q-switched pulse:

$$P_{int} = \frac{1}{(k_2+k_1)}\left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right)\frac{A}{2}\cdot\alpha\left(\frac{\delta_t}{1-R}\right)\left\{1-\left(\frac{\delta_t+\delta_\ell}{\alpha}\right)\left[1-\ln\left(\frac{\delta_t+\delta_L}{\alpha}\right)\right]\right\} \tag{II.24}$$

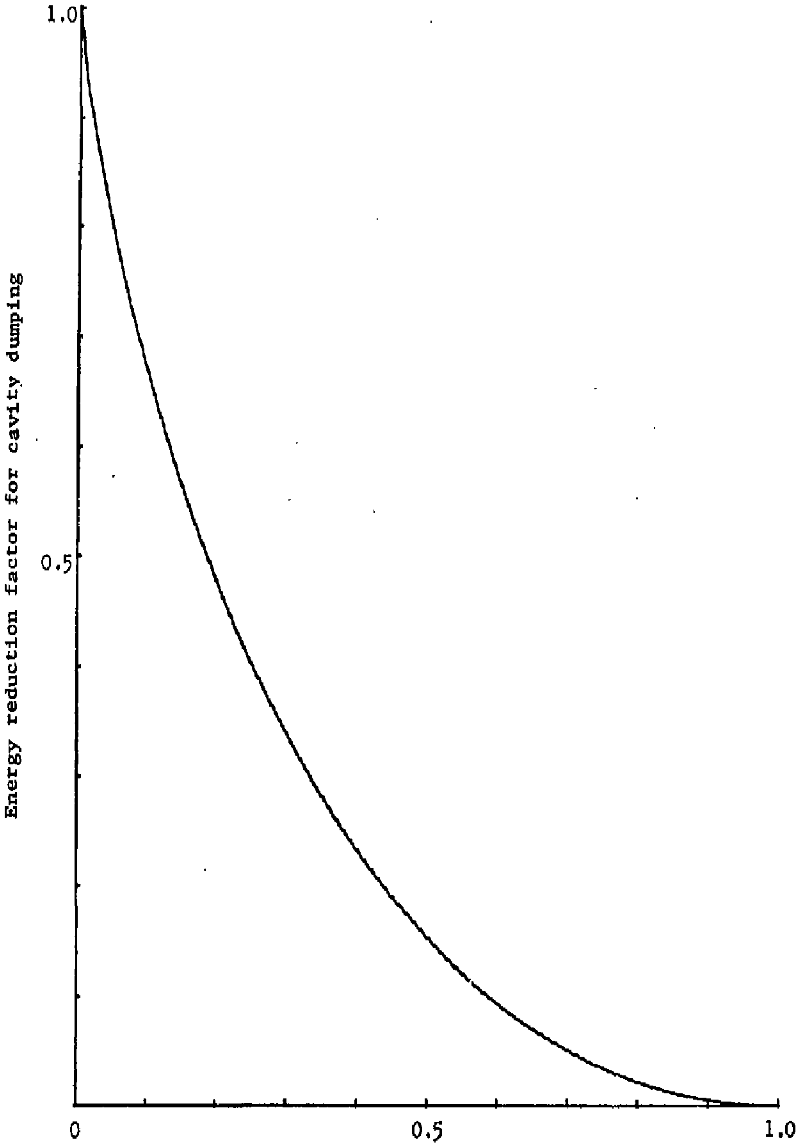
All these parameters are defined in Appendices A and B. We can now let the output coupling go to zero, i.e., $R \to 1$ and $\delta_t \to 0$. We can also show that in this limit, $\delta_t/(1-R) \to 1$. In a low loss cavity, the internal peak power now becomes:

$$P_{int} = \frac{1}{(k_2+k_1)}\left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right)\frac{A}{2}\,\alpha\left\{1-\frac{\delta_\ell}{\alpha}+\frac{\delta_\ell}{\alpha}\ln\left(\frac{\delta_\ell}{\alpha}\right)\right\}, \qquad (II.25)$$

and finally, the energy per short pulse inside the low loss cavity is:

$$E_{int} = \frac{1}{(k_2+k_1)}\left(\frac{h\nu}{\sigma}\right)\frac{A}{2}\alpha\left\{1-\frac{\delta_\ell}{\alpha}+\frac{\delta_\ell}{\alpha}\ln\left(\frac{\delta_\ell}{\alpha}\right)\right\}. \qquad (II.26)$$

This equation has an interesting interpretation: α is the roundtrip power gain coefficient of the laser, and we can write this as $\alpha = 2\sigma N_e \ell$, where N_e is the upper level population when the Q-switch is opened. The collection of terms $\left(\frac{h\nu}{\sigma}\right)\frac{A}{2}\alpha$ now become $N_e(h\nu)\cdot A\cdot \ell$, and this we recognize as the total energy stored in the upper level. Thus, in an ideal two-level laser with zero cavity losses (i.e., $\delta_\ell = 0$), all the energy that is in the upper level prior to the Q-switch opening, is transferred to the single short pulse at the peak of the Q-switched pulse. Equation (II.26) does indeed obey conservation of energy! The factor $\frac{1}{(k_2+k_1)}$ accounts for the thermalization in the upper and lower levels, and the quantity in brackets must be considered an energy reduction factor due to losses in the cavity. We plot this factor in Fig. II.3 as a function of (δ_ℓ/α), and we note that the available short pulse energy is reduced very rapidly as the losses increase.



$\frac{\delta_l}{\alpha} = \frac{\text{Losses in laser cavity per roundtrip}}{\text{Laser roundtrip power gain}}$

Fig. II.3--Reduction of pulse energy with cavity dumping due to losses in cavity.

From Eq. (II.26), we can now obtain the conditions to get 1 mJ in a single short pulse. Using the same parameters as in Section A, i.e., $(h\nu/\sigma) \approx 0.3\ J/cm^2$, $A = 10^{-2}\ cm^2$ and $k_2 = 0.392$, $k_1 = 0.186$, we get

$$E_{int} = 2 \cdot 60\, \alpha \left\{ 1 - \frac{\delta_l}{\alpha} + \frac{\delta_l}{\alpha} \ln\left(\frac{\delta_l}{\alpha}\right) \right\} \text{ mJ} \quad . \qquad (II.27)$$

For an extremely low loss cavity, $\delta_l = 0$, the required gain to obtain 1 mJ is 0.39, which we can compare with a required gain of 2.0 for an external pulse of 1 mJ with optimum output coupling. The required pump power has been reduced by more than a factor of 5! Assuming zero losses in the cavity is not realistic, and to get an idea of the effect of cavity losses, Fig. II.4 gives the required laser roundtrip gain to give a 1 mJ short pulse, as a function of the cavity losses. We note that the required gain does not increase very rapidly, and even for 10% losses in the cavity $(\delta_l \simeq 0.1)$, the required gain is ~ 0.7. This is still a factor of three less than for a laser with optimum output coupling. It should be noted that for the Nd:YAG laser, roundtrip gains in the range of 0.4 to 0.7 are available in a cw pumped laser.

The required pump power is, of course, proportional to α, and with cavity dumping, the pump power is reduced considerably. However, efficiency of the oscillator is not an important consideration for laser fusion, but the reduced pump power could help to make the oscillator more stable.

However, the reduced gain has an important effect on short pulse generation. The equation (II.18) in Section II.C shows that for active mode locking, the short pulse width is proportional to $(g)^{1/4}$, where g is

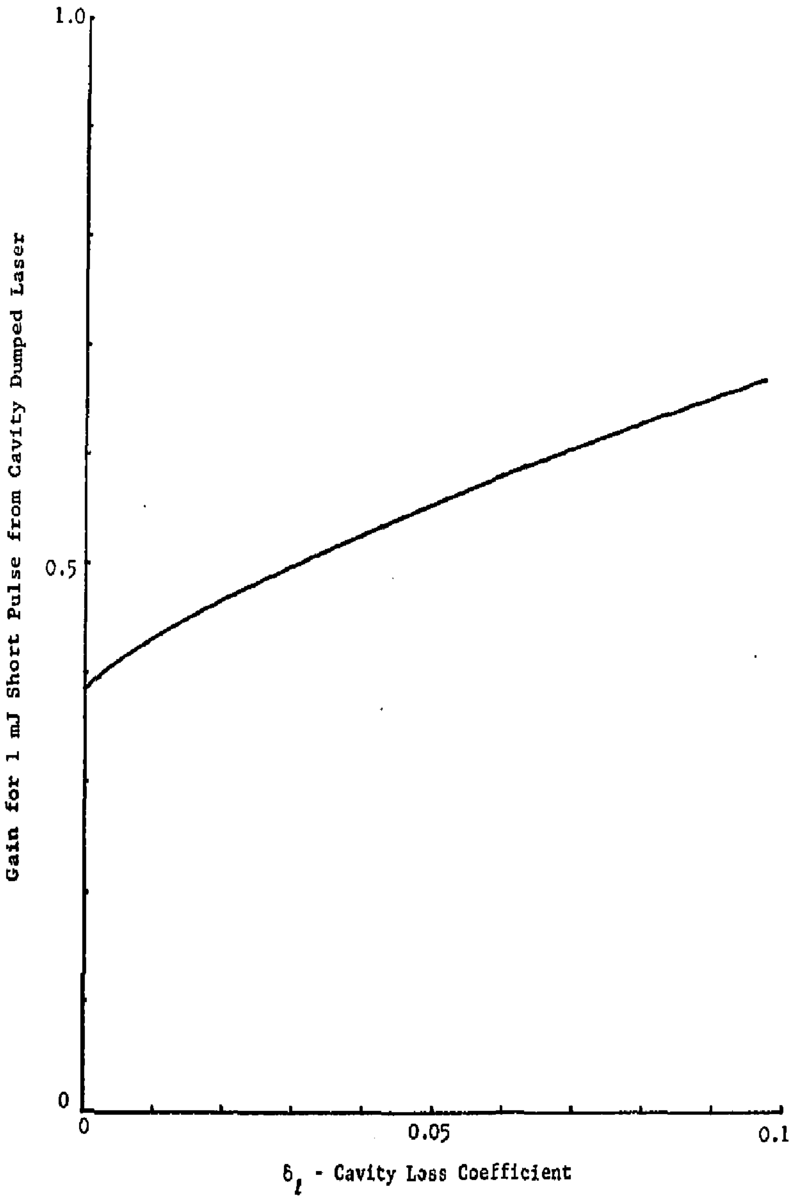


FIG. II.4--Required roundtrip gain for 1 mJ pulse from cavity dumped Nd:YAG laser as a function of cavity losses.

the roundtrip amplitude gain. Since $\alpha = 2g$, we also have that $\tau_p \propto (\alpha)^{1/4}$, and with the reduced gain for cavity dumping, we can now generate considerably shorter pulses. From Eq. (II.18), for a depth of modulation $\theta_l = 1$ and modulation frequency $f_m = 150$ MHz , we get that the pulse width is given by:

$$\tau_p = 74.3\ (\alpha)^{1/4}\ \text{ps} \qquad \text{(II.28)}$$

With cavity dumping we can now generate pulses in the range of about 60 ps to 68 ps, while for a laser with optimum output coupling, for the same parameters, we get a pulse width of 88 ps. Cavity dumping thus has a considerable advantage with the lower gain to generate shorter pulses.

Cavity dumping has one further advantage. With a low loss cavity, the fall time of the Q-switched pulse is very slow, and this will help considerably to reduce the pulse-to-pulse instabilities as shown in Fig. II.2.

We see that cavity dumping has some very important advantages, and this technique should be investigated for the laser-fusion program. This will require development of a suitable cavity dumper. The acousto-optic cavity dumpers that are presently available, cannot be used in this case. To get the fast switching time in the acousto-optic cavity dumper, the laser beam has to be focused very tightly into the acousto-optic substrate of the switch, and this will then damage at very low pulse energies. An electro-optic switch is required and presently KDP[#] looks like a good choice for this switch. Obtaining low insertion loss for this switch is important and should receive careful attention. The other problem will be to get the appropriate high voltage drive pulse that is properly synchronized with the short pulses. It should be noted that the complexity of the cavity dumper is about the same as an appropriate single pulse selector for a laser with normal output coupling, and this should further encourage the development of a cavity dumper.

III. PULSES FOR PLASMA DIAGNOSTICS

The requirements for these pulses have been mentioned in Section I, and can briefly be stated as follows:

(1) Pulse width: $\lesssim$ 10 ps .

(2) Synchronization with primary fusion pulse: ± 10 ps .

(3) Wavelength: ~ 350 nm or shorter.

(4) Pulse energy: ~ 1 mJ .

We shall not concern ourselves too much with the wavelength requirement here. If these short pulses with the required synchronization can be generated anywhere in the visible or near infrared, one can probably use nonlinear methods to shift these pulses to the desired wavelength range. Preserving the very short pulse width may become a problem with these techniques due to group velocity dispersion.

The two major problems for the plasma diagnostic pulses we want to consider here, are the very short pulse width and the synchronization requirements. Let us first consider the pulse width requirements. There are very few lasers that are capable of producing pulses 10-ps wide. The best known systems that can do this are:

(1) Passively mode-locked Nd:Glass, usually close to threshold, with carefully controlled conditions [25].

(2) Flashlamp-pumped dye laser with saturable absorber, such as Rhodamine 6G laser with DODCI saturable dye [3].

(3) Dye laser pumped synchronously by a train of short pulses, with the roundtrip time of the dye laser the same as the time between the short pulses. The best known systems here are the R6G dye laser pumped with the second harmonic from a passively mode-locked Nd:Glass [26] or Nd:YAG [27] laser, and a passively mode-locked ruby laser pumping a dye such as DTNCT [28].

(4) CW dye laser with saturable absorber [29].

(5) CW dye laser pumped synchronously with mode-locked argon laser [3(

There are other systems that have been proposed but not demonstrated:

(6) Parametric oscillator pumped by a mode-locked laser [31].

(7) A very thin dye cell, ~ 10-μm thick, pumped by a single picoseconc pulse.

In an attempt to evaluate these systems, we can classify them as follow First there are those that must be considered unsynchronizable. The passive mode-locked Nd:Glass and flashlamp-pumped dye lasers must be considered in t class. It is particularly unfortunate that the flashlamp-pumped dye laser must be classified as unsynchronizable, since it is a well developed and reasonably reliable source of short pulses.

The next class of short-pulse lasers are those pumped by a short train of pulses from a mode-locked laser. This must be considered the most promising class of short-pulse lasers to produce the synchronized pulses for plasm diagnostics. The main advantage is that they can be pumped by either passive or actively mode-locked lasers. The R6G dye laser pumped with either a doub Nd:Glass [26] or Nd:YAG [27] laser has recently been investigated in conside detail at NRL. The following properties of these systems become apparent fr this work:

(1) Synchronization between the pump laser and dye laser is extremely good, and well within the ± 5 ps required for plasma diagnostics.

(2) The pulse width from the dye laser is somewhat wider than the pump pulse. Close to threshold for the dye laser, the pulse widths are almost the same, but further above threshold, the dye pulses were about 50% wider than the pump pulse. Thus to get 10 ps pulses from the dye laser, the pump pulses must be less than 7 ps wide!

(3) Matching of the cavity lengths to within a small fraction of a millimeter is very important to obtain good operation of these systems.

More research work on these systems is required to investigate the following:

(1) How long a pulse train is required to pump this system to get good pulses? This is particularly important because, as we showed in Section II.A, that to get high energies per short pulse out of the Nd:YAG laser, the pulse train becomes quite short, with just a few pulses, and this will probably not be enough pulses to synchronously pump a dye laser.

(2) How much energy per short pulse can be obtained out of the dye laser? One can easily visualize amplifying the Nd:YAG output to get the energy in the pulse train up to a fraction of a Joule or more, and it seems that the energy conversion limitation will be how much energy can be stored in the dye. The important parameter here is how large an area in the dye can be used.

(3) Can the pulses in the dye laser be shortened by a saturable absorber? This is very important, because if a pump source with a pulse width less than 10 ps is required, one really does not need the dye laser

at all to generate synchronized pulses, except if one needs tunable short pulses. With a saturable absorber, it may be possible to obtain the 10-ps pulses from the dye laser, when we pump it with a train of 50-ps pulses from the mode-locked Nd:YAG laser.

The next class of lasers that can generate these short pulses is the cw dye laser, either with a saturable absorber or pumped by a mode-locked argo laser. This laser can easily produce the 10-ps pulses, and the cw dye laser with a saturable absorber has operated in the sub-picosecond region. One problem with this type of laser is the very small energy per pulse, typicall about 1 nJ [29] or less for present systems, requiring amplification of thes pulses by 60 dB. Before one considers amplifying these pulses, the problem of synchronizing these pulses with a mode-locked Nd:YAG (or Nd:Glass) laser should be considered. This laser can only be synchronized with an actively mode-locked laser. With a fast detector, the repetition rate of the cw dye laser can be obtained, and after amplification, this signal can then drive the actively mode-locked Nd:YAG laser. Synchronization of these two systems can then be studied. The synchronization problems associated with the Nd:YA laser have been discussed in Section II.B, and this will probably be the weakest link in this synchronization problem. If this synchronization is successful, amplification of the dye laser should be attempted.

The final class of lasers that must be considered, comprises those pump a single short pulse. One possibility is to make a very short laser with a sub-picosecond cavity lifetime. A theoretical analysis of a 10-μm thick dye laser, filled with high concentration of R6G, shows that this will oscillate pumped with a 50-ps pulse. The energy per short pulse from this system is very small ($\ll$ 1 nJ). However, it will be useful to demonstrate this type of laser. Another system that falls in this last class involves compressing a "chirped" pulse to 10 ps; this seems very difficult to do.

The discussion in this section has largely been based on well known and state-of-the-art systems, and it does not attempt to cover all the possibilities now being considered by many other workers in this field. Many other ideas are presently being proposed, and as new developments come along, they may offer new and possibly better approaches to the synchronization problem. However, based on these state-of-the-art systems, we can establish a reasonable "roadmap" for the research program for plasma diagnostic pulses in the near future. There are presently only two approaches that should be considered, i.e., the dye laser pumped synchronously with a train of short pulses, and the cw dye laser system. The following should be investigated in each system:

Synchronously pumped dye laser:

(1) Generation of pulses much shorter than the pump pulse with the use of saturable absorbers.

(2) Obtaining more energy per short pulse in an attempt to get 1 mJ per short pulse from the oscillator. This may not be possible, and thus amplification of these pulses must be investigated.

CW dye laser:

(1) Synchronize with actively mode-locked Nd:YAG laser.

(2) Obtain more energy per pulse from cw dye laser.

(3) Amplify these pulses to 1 mJ.

Once these pulses have been obtained, well synchronized and with sufficient energy, nonlinear processes can be investigated to generate the desired wavelength for plasma diagnostics.

IV. SUMMARY AND CONCLUSIONS

In this report we have investigated the various methods for short pulse generation, and in each section we have made some recommendation for further research work to improve the state-of-the-art of short pulse generation. Some of these recommendations are very important to obtain the required pulses for laser-fusion, but some other recommendations can be considered as interesting research work, but not really vital to the laser-fusion effort. In this section we will attempt to draw this distinction and then make recommendations for a systematic research program on short pulse development for the laser-fusion program.

Let us first view the present state of affairs. The present short pulse oscillator is a passively mode-locked Nd:YAG laser. This is, in principle, a simple system to obtain short pulses. This system has been well engineered, and is probably as reliable as such a system can reasonably be. However, the pulse-to-pulse stability is far from the desired 5%, and the appearance of low level pre-pulses have been troublesome in target interaction experiments. An intense research effort on this system will probably not improve the situation very much. The basic problem in the passively mode-locked laser is that the initial conditions for short pulse generation are noise spikes, and the statistical properties of these noise spikes are still evident in the single short pulse that is finally selected. In Section II.D this problem is discussed in some detail, and we must conclude that the passively mode-locked system has inherent deficiencies. One recent improvement in this system is the use of a fast modulator to reduce the "window" within which a short pulse can appear, as discussed in Section II.E. This approach can best be considered an interim improvement of the passively mode-locked system, but will probably not produce the desired short pulse source.

The passively mode-locked laser has one further problem. It will be very difficult, if not impossible, to produce synchronized short pulses for plasma diagnostics. This problem is discussed in detail in Section III. The only reasonable method to obtain these synchronous pulses with a passively mode-locked oscillator, is to use the entire pulse-train from the laser, generate the second harmonic, and then synchronously pump a dye laser, i.e., the dye laser has the same pulse roundtrip time as the Nd:YAG oscillator. This method has been demonstrated and can produce the plasma diagnostic pulses. However, there is an inherent contradiction here in the operation of the Nd:YAG laser. To obtain about 1-mJ energy in a single pulse, the entire pulse train will only consist of a few pulses, and there will not be enough pulses to drive a dye laser as described above. A longer pulse train can only be obtained with lower gain in the laser and this will reduce the energy per short pulse to a level too low to drive the main amplifiers for laser fusion. This problem comes from the large cross section for the 1.064 μm transition in Nd:YAG, as explained in Section II.A. Even if this problem can be solved in materials with smaller cross sections, it still seems unlikely that this approach can be developed into a stable oscillator for laser fusion.

The first major recommendation then is not to do further development work on the passively mode-locked Nd:YAG laser.

The main emphasis to develop a reliable short pulse oscillator should be on active mode locking. This approach has produced very stable pulses as short as 50 ps in the Nd:YAG laser, but pulse energies in present mode-locked and Q-switched Nd:YAG lasers are still more than an order of magnitude less than the desired 1 mJ. However, there are clearly two methods to increase the energy per short pulse. The first is simply to pulse pump the laser, then Q-switch, and simultaneously mode lock this laser. The analysis in Section II.B shows that quite a high gain is required in the Nd:YAG laser, and that there are only a few pulses in the train of pulses from this laser under these conditions. The shortest pulse widths will be in the range of 80 ps to 100 ps. We conclude in Section II.C that the main source of pulse-to-pulse instability will be due to the fact that there will only be a few pulses in the pulse train, and if the pulse envelope shifts relative to the pulses, this will lead to pulse-to-pulse instabilities. Figure II.2 illustrates this effect. However, this system should be able to satisfy all the requirements for a good short pulse source for laser fusion.

The second approach with active mode-locking is to use a cavity dumper in addition to the Q-switching and mode-locking. The analysis in Section II.F shows that the required pump power to get 1 mJ per short pulse is reduced by a factor of 3 to 5, depending on how low the cavity losses can be made. These gains can now be obtained in a good cw pumped Nd:YAG laser, or in a low duty cycle quasi-cw pumped laser. The lower gain allows shorter pulses in the range of 60 ps to 70 ps, and the lower pump power will probably also help make the laser more stable. However, what will really help pulse-to-pulse stability, is that in this low gain and low loss cavity, there will be a large number of pulses underneath the Q-switched envelope if we do not dump a pulse. The pulses near the peak of the Q-switched envelope will all have about the same energy, and hence we can dump any one of these pulses, and still get good pulse-to-pulse stability.

The next major recommendation for the laser-fusion program is that both these methods with active mode-locking and either normal output coupling or cavity dumping should be very thoroughly investigated. Both look like very good methods to generate the required pulses, and both will most probably be very useful in this program. Where a train of pulses is required, normal output coupling will of course be used, but it seems that when only a single pulse is required, cavity dumping has some potential advantages.

This approach of active mode-locking should also be extended to other materials, such as Nd:Glass. As discussed in Section II.A, the smaller cross section will make it easier to obtain 1 mJ pulses. In addition, if Nd:Glass can be actively mode-locked, this will allow the use of new types of glasses.

Once it has been demonstrated that active mode-locking can indeed produce the desired pulses, synchronizing of these lasers with plasma diagnostic pulses can now be considered. As discussed in Section III, the two most promising systems to produce these pulses are the synchronously pumped dye laser, and the cw dye laser with passive mode-locking. The synchronously pumped dye laser will require the synchronization of two actively mode-locked Nd lasers, either Nd:YAG or

Nd:Glass or one of each. One laser will produce a single short pulse for the laser-driven fusion, and the other will produce a long pulse train with pulses as short as possible, to pump the dye laser (after SHG). The first laser will probably be a cavity dumped Nd:YAG or Nd:Glass laser, and the second will probably be a Nd:Glass laser to give short pulses in the range of 10 ps to 50 ps.

The passively mode-locked cw dye laser should also be considered. It can produce sub-picosecond pulses. This laser will now have to be synchronized with the actively mode-locked Nd laser. This is discussed in Section III, and it seems possible to do this. Amplification of these short pulses to about 1 mJ or more will now be the main problem.

For the laser-fusion program we strongly recommend that both these methods for plasma diagnostic pulse are thoroughly investigated. We further recommend that future proposals in this area should be encouraged and that the merits of each scheme are given careful consideration.

The remaining topic that has to be considered is that of shaping the pulse for the laser-driven fusion. No specific recommendations will be attempted here, except to say that investigators in this field should be encouraged to think about this problem, and each proposal should be given careful attention.

From the previous comments, we can now briefly outline the "roadmap" for this research program:

(1) Investigate active mode-locking of the Nd:YAG laser to produce the pulses for laser-driven fusion. The laser should be simultaneously mode-locked and Q-switched. Both conventional output coupling and cavity dumping of a single pulse should be considered.

(2) A major effort to improve the passively mode-locked laser should not be pursued, unless major problems are experienced with the active mode-locking. (This seems highly unlikely.)

(3) Investigate active mode-locking of the Nd:Glass laser.

(4) Attempt to synchronize two actively mode-locked Nd:YAG lasers to ± 5 ps.

(5) Investigate both the synchronously pumped dye laser, and the passively mode-locked cw dye laser for generation of plasma diagnostic pulses.

(6) Encourage new ideas on pulse shaping and carefully evaluate all proposals.

APPENDIX A

Q-SWITCHING OF AN IDEAL FOUR-LEVEL LASER

This appendix presents a detailed analysis of active Q-switching that is particularly useful for the Nd:YAG laser, but applies to any four-level laser with a fast lower laser level relaxation time. We start off with the basic rate equations given by:

$$\dot{n} = K(n+1)N - n/\tau_c \tag{A.1}$$

$$\dot{N} = -KnN - N/\tau_a + R_p \quad , \tag{A.2}$$

where

K = constant (see below)

n = total photon number in cavity

$N = N_2$ = total population inversion in cavity

τ_a = upper level lifetime

τ_c = cavity lifetime

R_p = pumping rate

and

$\tau_c = 2\ell/c\delta$, ℓ = cavity length, δ = total roundtrip loss coefficient.

It is useful to split τ_c up in its components due to output coupling, other losses in the cavity and additional losses due to the Q-switch. We can write

$$\frac{1}{\tau_c} = \frac{1}{\tau_{ct}} + \frac{1}{\tau_{c\ell}} + \frac{1}{\tau_{cq}} \quad , \tag{A.3}$$

where

$$\frac{1}{\tau_{ct}} = \frac{c\delta_t}{2\ell} \quad \text{and} \quad \delta_t = \ln(1/R) \quad ,$$

$$\frac{1}{\tau_{c\ell}} = \frac{c\delta_L}{2\ell} \quad \text{and} \quad \delta_L = \ln\left(1/(1-L)\right) ,$$

$$\frac{1}{\tau_{cq}} = \frac{c\delta_q}{2\ell} \quad \text{and} \quad \delta_q = \ln(1/T_q) \quad ,$$

where

R = output mirror reflectivity

L = other losses in cavity

T_q = Q-switch transmission.

For a slowly opening Q-switch, the correct time dependence of T_q must be included. We will here consider only a fast, ideal Q-switch. We define the cavity lifetime, τ_{c0} , with the Q-switch in the low loss condition.

We can rewrite these equations in terms of the laser output power. The rate of loss of photons to output coupling is n/τ_{ct}, and thus the output power P is

$$P = \left(\frac{h\nu}{\tau_{ct}}\right) n \quad . \tag{A.4}$$

Considering steady conditions, $\dot{n} = \dot{N} = 0$, $n \gg 1$ and the Q-switch in the low loss condition, from Eq. (A.1) we get

$$N = 1/K\tau_{c0} \quad . \tag{A.5}$$

We recognize this as the laser threshold inversion, N_{th}, in a low-loss cavity. Note that

$$\tau_{c0} = \frac{2\ell}{c(\delta_t + \delta_L)} \quad ,$$

which is the cavity lifetime with no losses in the cavity due to the Q-switch. Equation (A.2) in the steady state gives

$$n = \frac{1}{K\tau_a}\left(\frac{\tau_a}{N_{th}} R_p - 1\right) \quad . \tag{A.6}$$

We recognize N_{th}/τ_a as the threshold pump power $R_{P_{th}}$, and we define the normalized pump power as $r = R_p/R_{P_{th}}$. Rewriting (A.6) in terms of output power, we get

$$P = P_1(r - 1) \quad , \tag{A.7}$$

where

$$P_1 = \frac{h\nu}{K\tau_a\tau_{ct}} \quad . \tag{A.8}$$

We recognize P_1 as the output power of the laser when we pump it with twice the threshold pump power. For a typical cw YAG laser, this is usually about one watt. We can relate K to the laser medium parameters, i.e.,

$$K = \frac{c\sigma}{\ell A} \quad , \tag{A.9}$$

where

σ = cross-section of transition

ℓ = cavity length

A = effective beam area.

We can then write P_1 as

$$P_1 = \left(\frac{h\nu}{\sigma\tau_a}\right) \cdot \frac{A}{2} \cdot \delta_t \quad , \tag{A.10}$$

and we recognize the terms in brackets as the saturation power density, I_{sat}. For Nd:YAG, $h\nu = 1.887 \times 10^{-19}$ joules, $\sigma \simeq 6.0 \times 10^{-19}$ cm^2, $\tau_a = 240$ μs and for a typical laser we can have $A \simeq 1.0 \times 10^{-2}$ cm^2, $\delta = 0.8$, we get $P_1 \simeq 1.4$ watts, as expected.

We can now rewrite the rate equations in terms of the output power and population inversion normalized to the low-loss steady-state conditions in the cavity, i.e., $\bar{P} = P/P_1$ and $\bar{N} = N/N_{th}$. We get

$$\dot{\bar{P}} = \left\{ \left(\bar{P} + \frac{c\sigma\tau_a}{\ell A} \right) \bar{N} - \bar{P} - \frac{\delta_q}{\delta_t + \delta_L} \bar{P} \right\} \Bigg/ \tau_{c0} \qquad \text{(A.11)}$$

$$\dot{\bar{N}} = \left\{ - \bar{P}\,\bar{N} - \bar{N} + r \right\} \Bigg/ \tau_a \quad . \qquad \text{(A.12)}$$

The term $c\sigma\tau_a/\ell A$ originates from the additional photon due to spontaneous emission and is retained to give the proper initial conditions. For a typical Nd:YAG laser, with $\ell = 50$ cm and $A = 10^{-2}$ cm^2 , we get $c\sigma\tau_a/\ell A = 0.9 \times 10^{-11}$. Equations (A.11) and (A.12) now give a good description of the Q-switching behavior of the Nd:YAG laser. The term $\delta_q/(\delta_t + \delta_L)$ accounts for the action of the Q-switch. For an ideal Q-switch, the loss term δ_q changes from its high loss value to zero stantaneously. For a Q-switch with a finite opening time, or a deliberately programmed Q-switch, the correct time dependence can be included in the term δ_q , and numerical solutions of Eqs. (A.11) and (A.12) then give the correct behavior of the laser.

We will now use these equations to investigate two types of Q-switching. The first is "pure" Q-switching where the initial losses in the Q-switch are sufficient to hold the laser well below threshold. The other is Q-switching with prelasing, where the laser is slightly above threshold with the Q-switch in the high-loss condition. In both these cases, we are interested in the Q-switching build-up time, the peak power in the Q-switched pulse, and the width of the Q-switched pulse.

Let us first consider the steady-state solution of Eqs. (A.11) and (A.12). If we set $\dot{\bar{P}} = 0$ and $\dot{\bar{N}} = 0$, we can solve the equations exactly for $\bar{P}$, the output power. We get

$$\bar{P} = \left(\frac{r' - 1}{2}\right) + \sqrt{\left(\frac{r' - 1}{2}\right)^2 + r' \left(\frac{c\sigma\tau_a}{\ell A}\right)} \quad , \qquad \text{(A.13)}$$

where

$$r' = \left(\frac{\delta_t + \delta_L}{\delta_t + \delta_L + \delta_q}\right) r \quad .$$

Careful investigation of this equation shows the well known threshold behavior of the laser. The term r' indicates how far the laser is below or above threshold with the Q-switch in the high-loss condition, and r indicates how far the laser is above threshold with the Q-switch in the low-loss condition.

1. Pure Q-Switching

For pure Q-switching, as defined above, the laser is well below threshold with the Q-switch on, i.e., $r' \ll 1$. Under these conditions, the approximate (but very good) solution to Eq. (A.13) is

$$\bar{P}_{in} = \left(\frac{r'}{1 - r'}\right) \left(\frac{c\sigma\tau_a}{\ell A}\right) \quad .$$

This gives the correct initial conditions for Q-switching. If one simply takes the "extra" photon due to spontaneous emission as the initial condition, the term $r'/(1 - r')$ does not appear. This term accounts for how far the laser is below threshold. The exact value of $r'/(1 - r')$ is usually not significant, and only slightly effects the build-up time of the laser.

We now consider an ideal Q-switch. After the Q-switch has opened, $\delta_q =$ and the inversion $\bar{N}$ is equal to r, the amount by which the laser is above threshold with the Q-switch in the low loss condition. We can now solve Eq. (A.11), subject to the initial conditions $\bar{N} = \bar{N}_e = r$, and $\bar{P}_{in} = [r'/(1 - r')]\,(c\sigma\tau_a/\ell A)$. During the build-up, $\bar{N}$ is constant, and we get the exact solution of Eq. (A.11) under these conditions, given by:

$$\bar{P} = \left(\frac{c\sigma\tau_a}{\ell A}\right)\left[\left\{\left(\frac{r'}{1 - r'}\right) + \left(\frac{r}{r - 1}\right)\right\} e^{(\bar{N}_e - 1)t/\tau_{c0}} - \left(\frac{r}{r - 1}\right)\right] \quad . \quad \text{(A.1}$$

We can neglect the second term, $r/(r-1)$ in the square brackets, because after just a few roundtrips it is small compared to the first term. To get some idea what Eq. (A.14) means, we consider a laser well below threshold with the Q-switch on, i.e., $r' \ll 1$, and well above threshold with the Q-switch off, i.e., $r > 1$. We can then write (A.14) approximately as

$$\bar{P} \simeq \left(\frac{c\sigma\tau_a}{\ell A}\right) e^{(\bar{N}_e - 1)t/\tau_{c0}} \quad ,$$

and if we take the build-up time, τ_B, as the time for the laser to reach

$\bar{P} = 1$ where saturation starts, we get

$$\tau_B = \left(\frac{\tau_{c0}}{\bar{N}_e - 1}\right) \ell n \left(\frac{\ell A}{c\sigma\tau_a}\right) \quad . \tag{A.15}$$

During this time the laser is in the linear amplification region. For a typical Nd:YAG laser,

$$\tau_B \simeq 25 \left(\frac{\tau_{c0}}{\bar{N}_e - 1}\right) \quad .$$

It is also possible to calculate the peak power during the Q-switched pulse. If we make the approximation that pumping is negligible once the Q-switch has been opened and further neglect the spontaneous-emission term in Eq. (A.11), we get

$$\dot{\bar{P}} = \left\{\bar{P}\,\bar{N} - \bar{P}\right\}/\tau_{c0} \quad , \tag{A.16}$$

$$\dot{\bar{N}} = \left\{- \bar{P}\,\bar{N} - \bar{N}\right\}/\tau_a \quad . \tag{A.17}$$

We can eliminate time in these equations by dividing out these two equations, and then rearrange them to give

$$\left(1 + \frac{1}{\bar{P}}\right) d\bar{P} = - \left(\frac{\tau_a}{\tau_{c0}}\right) \left(1 - \frac{1}{\bar{N}}\right) d\bar{N} \quad . \tag{A.18}$$

Integrating this equation, for the initial conditions $\bar{P}_{in}$ and $\bar{N}_e$

we get

$$(\overline{P} - \overline{P}_{in}) + \ln\left(\frac{\overline{P}}{\overline{P}_{in}}\right) = \left(\frac{\tau_a}{\tau_{c0}}\right)\left\{(\overline{N}_e - \overline{N}) - \ln\left(\frac{\overline{N}_e}{\overline{N}}\right)\right\} \quad . \qquad (A.19)$$

Since $\tau_a \gg \tau_{c0}$, we will always have $\overline{P} \gg \overline{P}_{in}$ and $\overline{P} \gg \ln\,(\overline{P}/\overline{P}_{in})$ during the actual Q-switched pulse, and hence

$$\overline{P} = \left(\frac{\tau_a}{\tau_{c0}}\right)\left\{(\overline{N}_e - \overline{N}) - \ln\left(\frac{\overline{N}_e}{\overline{N}}\right)\right\} \quad . \qquad (A.20)$$

At the peak of the pulse, $d\overline{P}/d\overline{N} = 0$ and this occurs when $\overline{N} = 1$; thus the peak power is given by

$$\overline{P}_p = \left(\frac{\tau_a}{\tau_{c0}}\right)\left\{(\overline{N}_e - 1) - \ln\,\overline{N}_e\right\} \quad . \qquad (A.21)$$

Figure A.1 shows a plot of $\overline{P}_p/(\tau_a/\tau_{c0})$ as a function of $\overline{N}_e$.

From the above expression for $\overline{P}_p$, we can now find out what the laser output coupling should be to optimize the peak power. To do this, we have to rewrite (A.21) in terms of the unnormalized parameters, since the normalizing parameters all depend on the output coupling. We note that

$$\overline{N}_e \quad N_e K\tau_{c0} = \left(\frac{2N_e\sigma}{A}\right)\left(\frac{1}{\delta_t + \delta_L}\right) \quad .$$

The first collection of terms we recognize as the total, unsaturated laser roundtrip gain, α . With this substitution, and also using the expression

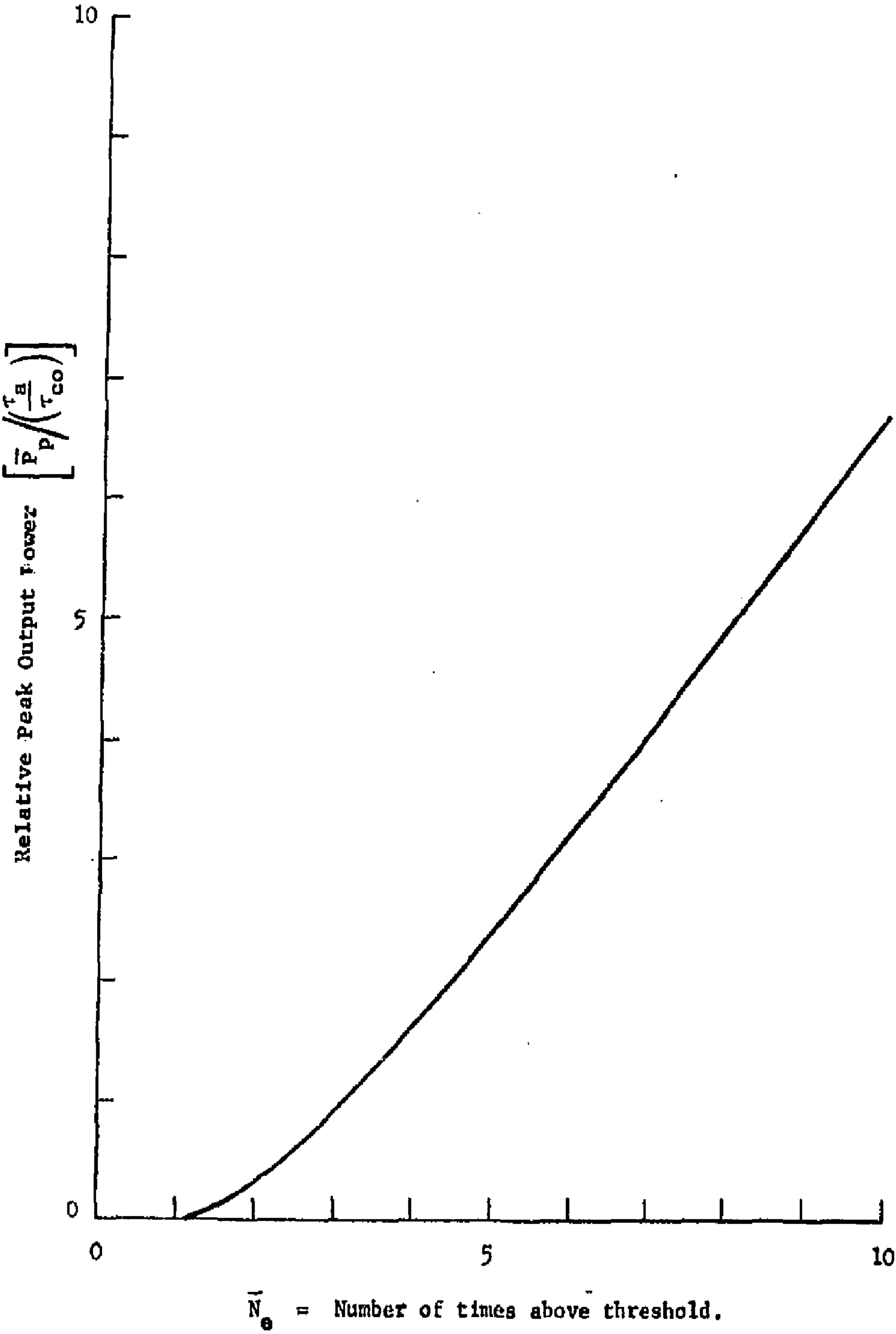


FIG. A.1--Relative peak power of a Q-switched Nd:YAG laser as a function of pump power.

for P_1 given by Eq. (A.10), we can write the output power as

$$P_p = \left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2l}\right) A \frac{\alpha}{2} \delta_t \left\{1 - \left(\frac{\delta_t + \delta_L}{\alpha}\right)\left[1 - \ln\left(\frac{\delta_t + \delta_L}{\alpha}\right)\right]\right\} \quad . \qquad (A.22)$$

To obtain the optimum peak power, we set $(dP/d\delta_t) = 0$. From this condition we get

$$1 - \left(\frac{\delta_t + \delta_L}{\alpha}\right) + \left(\frac{2\delta_t + \delta_L}{\alpha}\right) \ln\left(\frac{\delta_t + \delta_L}{\alpha}\right) = 0 \quad . \qquad (A.23)$$

We can obtain a solution to this equation by putting in a certain value for $(\delta_t + \delta_L)/\alpha$ and then solving for δ_t/α and hence δ_L/α . In Fig. A.2 we plot

$$\frac{(\delta_t)_{opt}}{\alpha}$$

as a function of α/δ_L . The most important result from this figure is that for high gain in the laser, i.e., where the gain exceeds the losses in the cavity (without output coupling) by 10 or more, the ratio of optimum coupling to roundtrip gain coefficient approaches a constant value of 0.28. If one compares this with optimum coupling for cw operation, which in the notation used here is given by

$$\frac{\delta_t}{\alpha} = \sqrt{\frac{\delta_L}{\alpha}} - \frac{\delta_L}{\alpha} \quad , \qquad (A.24)$$

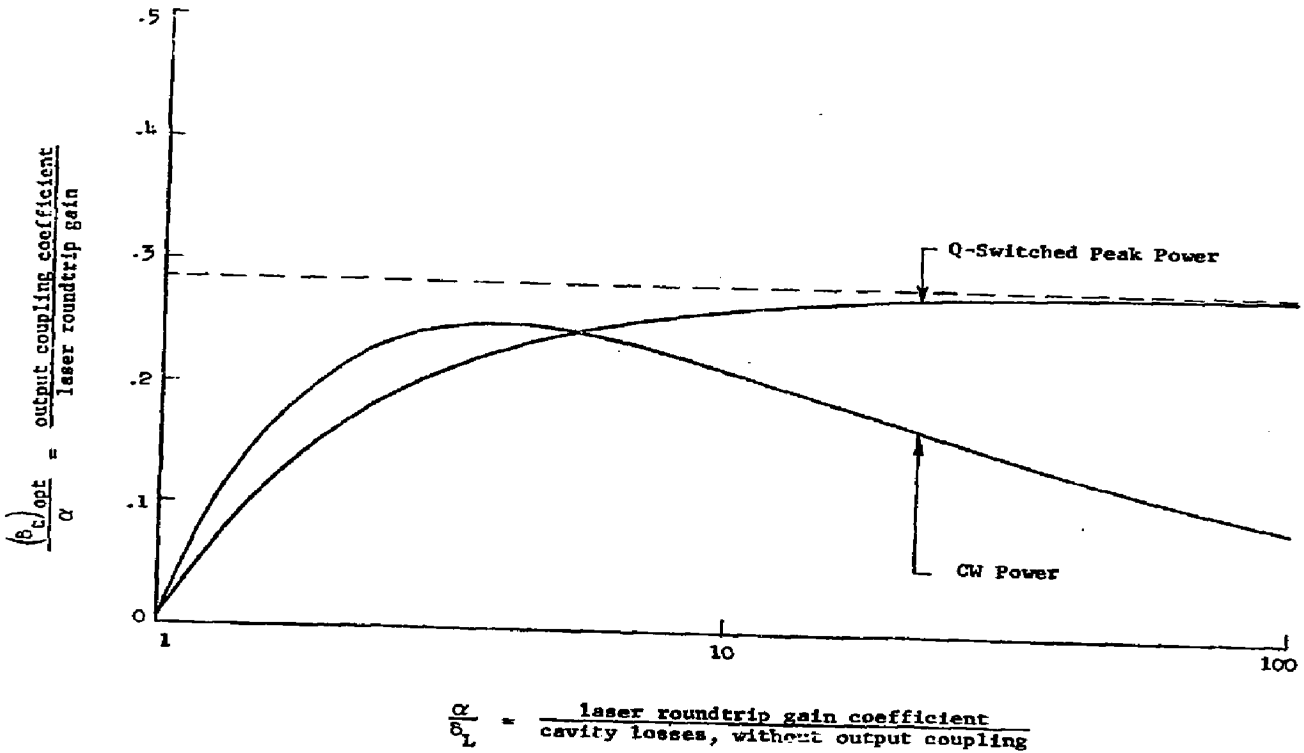


FIG. A.2--Optimum output coupling for peak power in a Q-switched laser, and comparison with optimum coupling for a cw laser.

one obtains the curve also shown in Fig. A.2. It is very obvious that in the high-gain regime, optimum coupling for maximum peak power in the Q-switched pulse requires much more output coupling than for optimum cw operation. From detailed plots of the output power as a function of output coupling using Eq. (A.22), one finds that these curves are quite sharply peaked, and one thus wants to operate close to optimum output coupling. This is particularly true in the high-gain regime, and if one overcouples, the peak power drops rapidly.

In the high-gain regime, $\delta_t \gg \delta_L$ and for optimum coupling,

$$\frac{\delta_t}{\alpha} \simeq \frac{(\delta_t + \delta_L)}{\alpha} = 0.28 \quad .$$

Substituting this in Eq. (A.22), the optimum peak output power is given by

$$(P_p)_{opt} \simeq 0.0501 \left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right) A\,\alpha^2 \quad . \qquad (A.25)$$

The last characteristic of the Q-switched laser we want to investigate is the Q-switched pulse width. It is not possible to obtain an analytical solution for the pulse width and one has to solve the rate equations numerically. Wagner and Lengyel have done this; in Fig. A.3 we plot Q-switched pulse width (τ_Q) normalized with respect to τ_{c0} as a function of $1/\bar{N}_e$. We also plot the risetime from the half-peak intensity to the peak of the pulse (τ_R), to indicate the asymmetry of the pulse. The risetime of the pulse is always faster than the fall time.

We can now also define the build-up time of the Q-switching more accurately. We define the build-up time as the time to reach half the peak

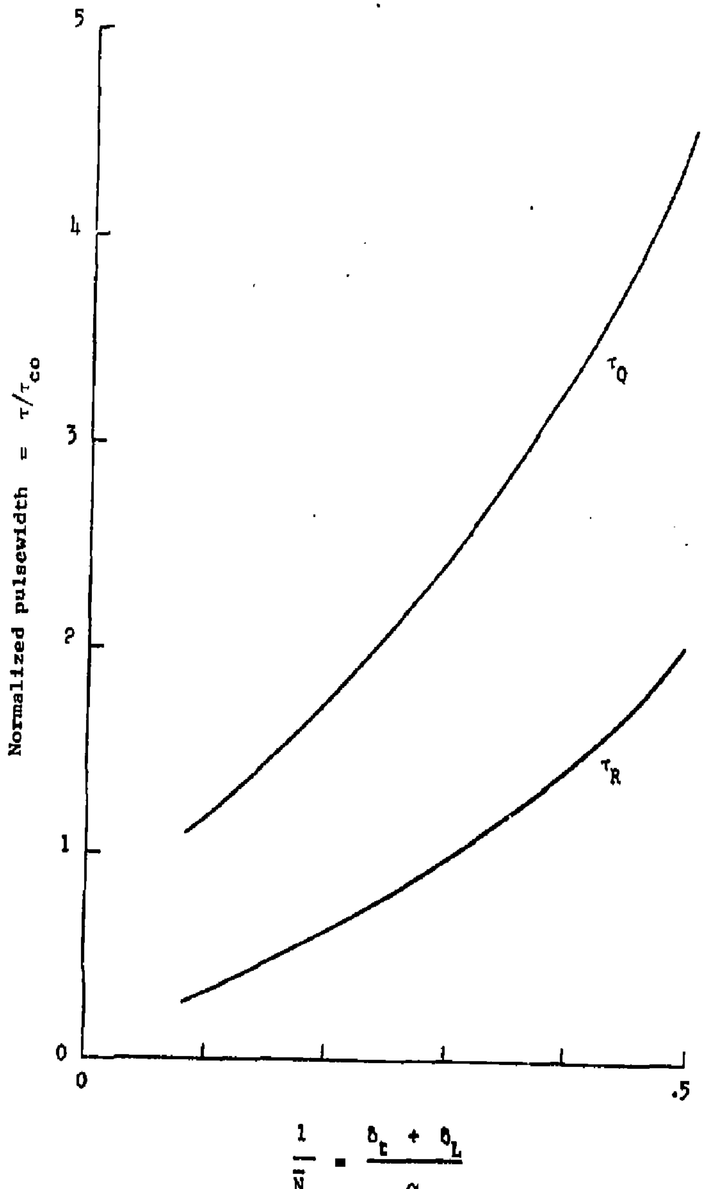


FIG. A.3--Pulse width (τ_Q) in a Q-switched laser as a function of pump power, and risetime (τ_R) of the Q-switched pulse.

power of the Q-switched pulse. We recognize that under these conditions, the inversion $\bar{N}$ does not remain constant, as assumed for the derivation of Eq. (A.14), but we will use this equation, knowing that the actual build-up is somewhat longer. The finite opening time of a real Q-switch will further increase the build-up time, and the expression we get here is a lower limit for the Q-switching build-up time.

From the peak power given in Eq. (A.21), and Eq. (A.14), we get

$$\tau_B = \left(\frac{\tau_{c0}}{\bar{N}_e - 1}\right) \ell n \left\{ \frac{1}{2\tau_{c0}} \left(\frac{\ell A}{c\sigma}\right) \left(\frac{\bar{N}_e - 1 - \ell n\, \bar{N}_e}{\bar{N}_e / (\bar{N}_e - 1)} \right) \right\} \quad . \qquad (A.26)$$

We have assumed that the laser is well below threshold in the high loss condition, and hence $r'/(1 - r') \simeq 0$. With optimum coupling, $\bar{N}_e \simeq 3.57$, and we get:

$$\tau_B = 0.388\, \tau_{c0}\, \ell n \left\{ \left(\frac{0.467}{\tau_{c0}}\right) \left(\frac{\ell A}{c\sigma}\right) \right\} \quad . \qquad (A.27)$$

This will give a somewhat longer build-up time than obtained previously.

2. Q-Switching With Prelasing

With prelasing, the laser is slightly above threshold with the Q-switch in the high loss condition. From Eq. (A.13) this means that the output power during prelasing is $\bar{P} = (r' - 1)$ where

$$r' = \left(\frac{\delta_t + \delta_L}{\delta_t + \delta_L + \delta_q}\right) r \quad ,$$

and r is the number of times the laser is above threshold in the low loss condition. The initial condition for Q-switching is now $\bar{P}_{in} = (r' - 1)$, and the initial inversion is such that the laser gain is exactly equal to the roundtrip losses with the Q-switch in the high loss condition, i.e., $\alpha = \delta_q + \delta_t + \delta_\ell$ and $\bar{N}_e = \alpha/(\delta_t + \delta_\ell)$. Defining the build-up time again as the time to reach half the peak power, we get from Eq. (A.21)

$$\tau_B = \left(\frac{\tau_{c0}}{\bar{N}_e - 1}\right) \ell n \left\{\left(\frac{1}{r' - 1}\right)\left(\frac{\tau_a}{2\tau_{c0}}\right)(\bar{N}_e - 1 - \ell n\, \bar{N}_e)\right\} \qquad (A.28)$$

and with opti- coupling

$$\tau_B = 0.388\, \tau_{c0}\, \ell n \left\{\left(\frac{0.650}{r' - 1}\right)\left(\frac{\tau_a}{\tau_{c0}}\right)\right\} \quad . \qquad (A.29)$$

This build-up time is always much shorter than for pure Q-switching.

The rest of the characteristics of the Q-switched laser with prelasing are similar to the pure Q-switched results if we put $\alpha = \delta_q + \delta_t + \delta_L$ and $\bar{N}_e = \alpha/(\delta_t + \delta_L)$. Optimum output coupling conditions are the same.

APPENDIX B

Q-SWITCHING OF THE Nd:YAG LASER

In Appendix A we considered the Q-switching behavior of an ideal four-level laser. This analysis is usually applied to the Nd:YAG laser. However, the Nd:YAG laser is not really a simple four-level system. The following complications have to be considered:

(1) The $^4F_{3/2}$ upper level is two-fold degenerate, and these levels are split by 88 cm^{-1}.

(2) The $^4I_{11/2}$ lower level is six-fold degenerate, and these levels are also split. The energy level diagram for Nd:YAG is shown in Fig. B.1. (Data for this figure were obtained from an LLL memo by W. F. Krupke, with additions for Nd:YAG by W. D. Fountain).

(3) The lower level has a finite lifetime τ_1. For Nd:YAG this lifetime has not been measured accurately, but it is thought to be roughly a few nanoseconds. For Nd:Glass it can be as long as 20 ns. It is now accepted that for amplification of short pulses, the lower level in Nd:YAG and Nd:Glass are essentially frozen.

We assume that thermalization between the two upper levels, as well as the six lower levels is very rapid, and that the relative distributions as given in Fig. B.1 are maintained, even during the amplification of picosecond pulses.

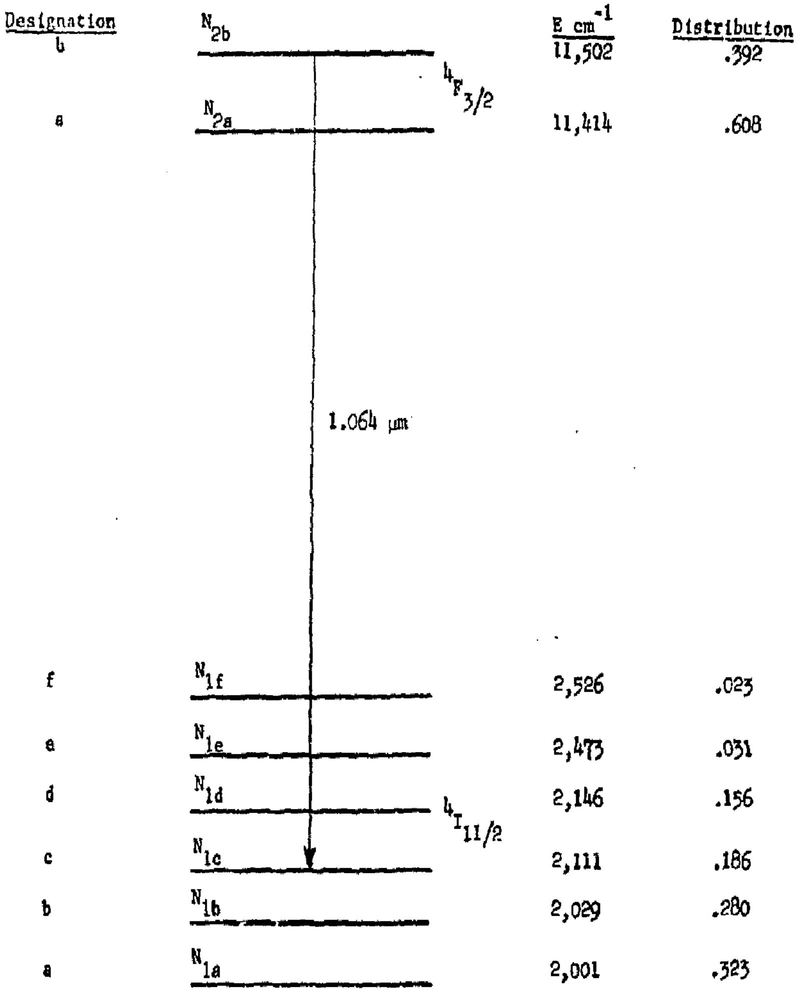


FIG. B.1--Energy levels of Nd:YAG and population distributions at 300° K.

We now want to estimate how the above complications effect the energy extraction from a Q-switched Nd:YAG laser. In general, let N_2 and N_1 be the populations of the upper and lower levels, each with relative distributions k_2 and k_1. For Nd:YAG in particular, these populations would be N_{2b} and N_{1c} for the 1.064-μm transition, with distributions 0.392 and 0.186 as indicated in Fig. B.1. The photon rate equation becomes:

$$\dot{n} = Kn\,(N_2 - N_1) - n/\tau_c \tag{B.1}$$

We have left out the additional photon due to spontaneous emission. We only need this to give the correct initial conditions for Q-switching, but under these conditions, the lower level is empty and the analysis in Appendix A is correct.

The rate equation for the upper level is given by:

$$\dot{N}_2 = -k_2Kn\,(N_2 - N_1) - N_2/\tau_a + k_2R_p \tag{B.2}$$

For this equation we have assumed that the thermalization between the two upper levels is very fast, and hence for energy transitions from the upper laser level, effectively only k_2(0.392 for Nd:YAG) of the energy comes from this level, and this accounts for this factor in the first term. We also add this factor of k_2 to the pumping term. Here R_p is the total pumping rate into both the upper levels, and accounts for all the energy stored in the upper levels, but rapid thermalization reduces the effective pumping rate to the upper level for the 1.064-μm transition by k_2.

The rate equation for the lower level becomes:

$$\dot{N}_1 = k_1 Kn (N_2 - N_1) + \beta N_2/\tau_a - N_1/\tau_1 \qquad (B.3)$$

The factor k_1 appears because of rapid thermalization in the lower levels, as explained above. τ_1 is the lower level lifetime. The term $\beta N_2/\tau_a$ is included to account for that part of the fluorescence decay from the upper levels that end up in the lower laser level. The total fluorescence efficiency from the $^4F_{3/2}$ level to the $^4I_{11/2}$ level is 0.60 [32,33], and assuming rapid thermalization, $\beta = 0.60\ k_1/k_2$. For the 1.064-μm line in Nd:YAG this is 0.29.

If we now define N as the population inversion, i.e., $N = N_2 - N_1$, Eq. (B.1) becomes:

$$\dot{n} = KnN - n/\tau_c \qquad (B.4)$$

Combining Eqs. (B.2) and (B.3), we get

$$\dot{N} = -(k_1 + k_2) KnN - (1 + \beta) N_2/\tau_a + N_1/\tau_1 + k_2 R_p \qquad (B.5)$$

We can again normalize these equations with respect to the steady state and threshold conditions, as in Appendix A.

From Eq. (B.4) for $\dot{n} = 0$, we get

$$N = N_{th} = 1/K\tau_{c0} \qquad (B.6)$$

and N_{th} is again the threshold inversion with the Q-switch in the low-loss condition.

From Eqs. (B.2) and (B.3) for $\dot{N}_2 = \dot{N}_1 = 0$, we can solve for the output power P of the laser under steady state conditions. As in Appendix A, this can again be written in the form

$$P = P_1(r - 1) \tag{B.7}$$

and we now get that P_1 is given by:

$$P_1 = \left(\frac{h\nu}{\sigma\tau_a}\right) \cdot \frac{A}{2} \cdot \delta_t \cdot \frac{1}{\left(k_2 - \frac{\tau_1}{\tau_a}\beta k_2 - \frac{\tau_1}{\tau_a}k_1\right)} \tag{B.8}$$

The normalized pump power $r = R/R_{th}$ and the threshold pump power is now given by

$$R_{th} = \frac{N_{th}}{\tau_a k_2\left(1 - \frac{\tau_1}{\tau_a}\beta\right)} \tag{B.9}$$

With these definitions, the normalized rate equation can now be obtained. The photon rate equation is the same as before in Appendix A, and is given by:

$$\dot{\bar{P}} = \left\{\bar{P} \cdot \bar{N} - \bar{P} - \left(\frac{\delta_q}{\delta_t + \delta_L}\right)\bar{P}\right\}\Big/\tau_{c0} \tag{B.10}$$

Equation (B.5) can be written as:

$$\dot{\bar{N}} = \left\{ \frac{-(k_1 + k_2)}{\left(k_2 - \frac{\tau_1}{\tau_a}\beta k_2 - \frac{\tau_1}{\tau_a}k_1\right)} \bar{P}\cdot\bar{N} - (1 + \beta)\,\bar{N} \right.$$

$$\left. + \bar{N}_1 \left(\frac{\tau_a}{\tau_1}\right)\left(1 - \beta\frac{\tau_1}{\tau_a} - \frac{\tau_1}{\tau_a}\right) + \frac{r}{\left(1 - \beta\frac{\tau_1}{\tau_a}\right)} \right\} \Big/ \tau_a \qquad \text{(B.11)}$$

As the third independent equation, we can best take Eq. (B.3) for $\dot{N}_1$, and this becomes:

$$\dot{\bar{N}}_1 = \left\{ \frac{k_1}{\left(k_2 - \frac{\tau_1}{\tau_a}\beta k_2 - \frac{\tau_1}{\tau_a}k_1\right)} \bar{P}\cdot\bar{N} + \beta\bar{N} - \bar{N}_1\left(\frac{\tau_a}{\tau_1}\right)\left(1 - \beta\frac{\tau_1}{\tau_a}\right) \right\} \Big/ \tau_a \qquad \text{(B.12)}$$

These last three equations can now be used to obtain the behavior of the Q-switched Nd:YAG laser very accurately. In general numerical methods must be used to solve these equations exactly. However, we can make some approximations to obtain reasonable analytic solutions. These equations appear somewhat complicated due to the fact that β and τ_1 have been retained without any approximations. However, for the Nd:YAG laser we always have $\tau_a \gg \tau_1$ and $\beta \lesssim 1$, and (B.11) and (B.12) take the simpler forms:

$$\dot{\bar{N}} = \left\{ -\left(1 + \frac{k_1}{k_2}\right)\bar{P}\cdot\bar{N} - (1 + \beta)\,\bar{N} + \left(\frac{\tau_a}{\tau_1}\right)\bar{N}_1 + r \right\} \Big/ \tau_a \qquad \text{(B.13)}$$

and

$$\dot{\bar{N}}_1 = \left\{ \frac{k_1}{k_2} \bar{P} \cdot \bar{N} + \beta\bar{N} - \left(\frac{\tau_a}{\tau_1}\right)\bar{N}_1 \right\} / \tau_a \tag{B.14}$$

With these equations we can now proceed to analyze the Q-switching behavior of the laser. During the build-up of the Q-switching, before saturation becomes significant, we have steady state conditions for $\bar{N}$ and $\bar{N}_1$, and $\bar{P} \simeq 0$. From (B.13) and (B.14) we get $\bar{N} = \bar{N}_e = r$ and $\bar{N}_1 = \beta(\tau_1/\tau_a)r$ and these are now the initial conditions for Q-switching. To obtain the Q-switching behavior, we can make further approximations to (B.13) and (B.14). During the Q-switched pulse, we can neglect pumping. The upper level life-time, τ_a, is also very long compared to the Q-switched pulse, and hence we can neglect the terms $(1 + \beta)\,\bar{N}/\tau_a$ and $\beta\bar{N}/\tau_a$. This is equivalent to neglecting fluorescence from the upper level during the Q-switched pulse, an accurate approximation since τ_a is 240 μs and we are considering Q-switched pulses on the order of tens of nanoseconds. This simplifies the equations to

$$\dot{\bar{N}} = \left\{ -\left(1 + \frac{k_1}{k_2}\right) \bar{P} \cdot \bar{N} + \left(\frac{\tau_a}{\tau_1}\right) \bar{N}_1 \right\} \Big/ \tau_a \tag{B.15}$$

and

$$\dot{\bar{N}}_1 = \left\{ \frac{k_1}{k_2} \bar{P} \cdot \bar{N} - \left(\frac{\tau_a}{\tau_1}\right) \bar{N}_1 \right\} \Big/ \tau_a \tag{B.16}$$

Together with Eq. (B.10) for $\bar{P}$, these three equations give a good description of the Q-switching of the Nd:YAG laser. However, the term $\bar{N}_1/\tau_1$ still makes it impossible to obtain accurate analytical solutions. However, from the above equations, we can decide when the effects of τ_1 can be correctly included in this analysis. The first case we consider is where τ_1 *is long enough such that*

$$\left(\frac{\tau_a}{\tau_1}\right) \bar{N}_1 \ll \frac{k_1}{k_2} \bar{P} \cdot \bar{N} \qquad \text{(B.17)}$$

during the Q-switched pulse. Equation (B.15) then becomes:

$$\dot{\bar{N}} = \left\{ - \left(1 + \frac{k_1}{k_2}\right) \bar{P} \cdot \bar{N} \right\} \Big/ \tau_a \qquad \text{(B.18)}$$

With this equation we can obtain an analytic solution for the peak power in the Q-switched pulse as was done in Appendix A. The second case we want to consider is where the relaxation of the lower level is fast enough such that $\bar{N}_1$ remains small. However, the ratio $\bar{N}_1/\tau_1$ can remain significant in Eq. (B.15), and we cannot simply neglect the second term. However, adding Eqs. (B.15) and (B.16) we get the rate equation for $\bar{N}_2$, given by:

$$\dot{\bar{N}}_2 = - \bar{P} \cdot \bar{N}/\tau_a \qquad \text{(B.19)}$$

For $\bar{N}_1$ small, we now have

$$\bar{N} \simeq \bar{N}_2$$

or (B.20)

$$\bar{N}_1 \ll \bar{N}_2$$

This is now the condition for fast relaxation of the lower level.

Using the same method as in Appendix A, we can solve the equations:

$$\dot{\bar{P}} = \{\bar{P} \cdot \bar{N} - \bar{P}\}/\tau_{c0} \tag{B.21}$$

and

$$\dot{\bar{N}} = -C\bar{P} \cdot \bar{N}/\tau_a \tag{B.22}$$

where $C = 1$ or $[1 + (k_1/k_2)]$. We get

$$\frac{d\bar{P}}{d\bar{N}} = \frac{1}{C}\left(\frac{\tau_a}{\tau_{c0}}\right)\left\{-1 + \frac{1}{\bar{N}}\right\} \tag{B.23}$$

Subject to the initial condition $\bar{N} = \bar{N}_e = r$, we get

$$\bar{P} = \frac{1}{C}\left(\frac{\tau_a}{\tau_{c0}}\right)\left\{(\bar{N}_e - \bar{N}) - \ln\left(\frac{\bar{N}_e}{\bar{N}}\right)\right\} \tag{B.24}$$

As in Appendix A, we can now obtain the peak power in the Q-switched pulse under optimum coupling conditions. Using Eq. (B.8) to give P_I , we get

$$(P_p)_{opt} \simeq \frac{0.0501}{k_2 C}\left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right) A\alpha^2 \tag{B.25}$$

Thus with "slow" relaxation from the lower level we get:

$$(P_p)_{opt} \simeq \frac{0.0501}{(k_1 + k_2)}\left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2\ell}\right) A\alpha^2 \tag{B.26}$$

and for "fast" relaxation we get

$$(P_p)_{opt} \simeq \frac{0.0501}{k_2}\left(\frac{h\nu}{\sigma}\right)\left(\frac{c}{2l}\right) A\alpha^2 \qquad (B.27)$$

We can now also define the conditions for "slow" and "fast" relaxation more precisely. Consider first the "slow" relaxation. From the condition given by Eq. (B.17), we get

$$\tau_1 \gg \frac{\bar{N}_1 \tau_a}{(\bar{P}\cdot\bar{N})_{max}} \cdot \frac{k_2}{k_1} \qquad (B.28)$$

Since $\bar{N}$ is a slowly varying function, the maximum value of $\bar{P}\cdot\bar{N}$ occurs approximately when $\bar{P}$ is a maximum, and from (B.23), this occurs when $\bar{N} = 1$, and from (B.24), we get

$$(\bar{P}\cdot\bar{N})_{max} \simeq \frac{1}{\left(1 + \frac{k_1}{k_2}\right)}\left(\frac{\tau_a}{\tau_{c0}}\right)\left\{(\bar{N}_e - 1) - \ln \bar{N}_e\right\}$$

From (B.15) and (B.16) for "slow" relaxation we can get:

$$\frac{d\bar{N}}{d\bar{N}_1} = -\left(\frac{k_2}{k_1} + 1\right) \qquad (B.29)$$

and this we can solve to give

$$\bar{N}_1 = \left(\frac{k_2}{k_1} + 1\right)(\bar{N}_e - \bar{N}) \qquad (B.30)$$

Substituting this in (B.28) for $\bar{N} \simeq 1$, when $(\bar{P} \cdot \bar{N})$ is a maximum, we get that:

$$\tau_1 \gg \tau_{c0} \left\{ \frac{\bar{N}_e - 1}{\bar{N}_e - 1 - \ln \bar{N}_e} \right\} \tag{B.31}$$

and this is essentially $\tau_1 \gg \tau_{c0}$. Thus the lifetime of the lower level *must be long compared* to the cavity lifetime for the lower level to fill up.

For "fast" relaxation, we have to satisfy the condition $\bar{N}_1 \ll \bar{N}_2$, and this follows when $\dot{\bar{N}}_1 \lesssim 0$. For this condition, from Eq. (B.16) we get:

$$\left(\frac{\tau_a}{\tau_1}\right) \bar{N}_1 \gtrsim \frac{k_1}{k_2} \bar{P} \cdot \bar{N}_2 \tag{B.32}$$

This must be satisfied when $\bar{P}$ is a maximum, and substituting for maximum value of P from (B.24) when $\bar{N}_2 = 1$, we get:

$$\left(\frac{\tau_a}{\tau_1}\right) \bar{N}_1 \gtrsim \frac{k_1}{k_2} \left(\frac{\tau_a}{\tau_{c0}}\right) \left\{ (\bar{N}_e - 1) - \ln \bar{N}_e \right\} \tag{B.33}$$

We must also have that $\bar{N}_1 \ll \bar{N}_2$, or in this case $\bar{N}_1 \ll 1$. From (B.33) it then follows that we must have

$$\tau_1 \ll \frac{\tau_{c0}}{\bar{N}_e - 1 - \ln \bar{N}_e} \tag{B.34}$$

Equations (B.31) and (B.34) now clearly establish the limits for slow and fast relaxation of the l .er level.

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