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RESEARCH STUDIES ON SHORT OPTICAL PULSE GENERATION
FOR THE LASER FUSION PROGRAM

by

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INTRODUCTION

In recent years, the stability and reliability requirements of an oscillator for laser fusion systems such as Argus and Shiva have gone beyond what can reasonably be expected from a passively mode-locked Nd:YAG laser. It was also realized that the most promising approach to satisfy the short pulse requirements of these systems was an actively mode-locked oscillator.¹

One approach to develop a suitable oscillator was started at Stanford University in 1974 (LLL subcontract 1547503) and was continued at SRI through 1976 (LLL subcontract 5241805). From earlier work at Stanford University,² we knew that a CW mode-locked Nd:YAG laser could provide the necessary range of short pulses required for laser fusion, but pulse energies were too low. Some further work with a simultaneously mode-locked and Q-switched Nd:YAG laser³ showed that considerably more energy was available with this approach, and that under certain operating conditions, short, transform-limited pulses could be obtained. During the development program at Stanford University and SRI we fully investigated this approach.

In September 1976 we completed a prototype laser, and measurements at SRI and LLL showed that the oscillator was very stable and reliable. Hence, it was decided to build this type of oscillator for Shiva and also to assemble one of these oscillators at SRI for Argus. This laser was installed on Argus in January 1977, and was producing successful target shots at the writing of this report.

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TECHNICAL PROGRESS

Technical Considerations

Active mode-locking of the Nd:YAG laser has been investigated in detail,² and under steady state conditions, the pulse width is given by:⁴

$$\tau_p = \frac{(2 \ln 2)^{\frac{1}{2}}}{\pi} \frac{g^{\frac{1}{4}}}{\theta_m^{\frac{1}{2}}} \left(\frac{1}{f_m \cdot \Delta f} \right)^{\frac{1}{2}} \dots \quad (1)$$

where f_m = external modulation frequency

Δf = linewidth

g = round trip amplitude gain

θ_m = depth of modulation .

The steady state pulse width is determined by two processes. On each round trip in the cavity, when the pulse passes through the amplitude modulator, the pulse is shortened a bit, and this contributes the factor $\left(\frac{1}{\theta_m f_m} \right)^{\frac{1}{2}}$ to Equation (1). On each pass through the crystal, due to the linewidth of the active medium, the pulse is lengthened a bit, and this contributes the factor $g^{\frac{1}{4}}/\Delta f^{\frac{1}{2}}$ to Equation (1). For typical operating conditions in a Nd:YAG laser, the shortest pulses available are in the range of 50 to 100 ps, depending mainly on the modulation frequency, and hence on the length of the cavity. For longer pulses, the effective bandwidth of the laser can be narrowed with an etalon, and the pulse width is then given by

$$\tau_p = \frac{(2 \ln 2)^{\frac{1}{2}}}{\pi} \frac{1}{\theta_m^{\frac{1}{2}}} \left(\frac{1}{f_m \cdot \Delta f_e} \right)^{\frac{1}{2}} \quad (2)$$

where Δf_e is the effective bandwidth of the laser. In terms of the reflectivity R , thickness h , and index of refraction n of the etalon, this bandwidth is given by

$$\Delta f_e = \left(\frac{c}{2\pi n h} \right) \frac{1-R}{\sqrt{R}} \quad (3)$$

For an uncoated etalon this becomes

$$\Delta f_e = \left(\frac{2c}{\pi h} \right) \frac{1}{n^2 - 1} \quad (4)$$

The above equations completely predict the width of the pulses in a mode-locked CW Nd:YAG laser, where we have steady state conditions. In such a laser, the energy for single short pulses is in the range of 1 to 10 nJ, and is not sufficient for direct injection into a typical Nd:Glass amplifier for laser fusion.

It is well known that a Nd:YAG laser can easily be Q-switched, and that peak power of 10^4 times the typical CW power or more can be obtained. However, consideration of simultaneous mode-locking and Q-switching of a Nd:YAG laser shows that under almost all operating conditions of the laser, steady state mode-locking conditions are not achieved, and the resulting pulses are long, with a lot of noisy substructure.³ Because build-up time of the Q-switched laser is always too short for the mode-locking process to reach steady state, some method must be devised to allow the mode-locking process to go to steady state before the laser is Q-switched. Such a method is shown in Figure 1.

The laser is pulsed in a quasi-CW way for several milliseconds, and the loss in the Q-switch is adjusted so that the laser goes just above threshold. During this prelude period, the modulator is on all the time, and the mode-locking process can go to steady state. When the laser is Q-switched at the end of the quasi-CW period, the initial conditions in the cavity are transform-limited, stable short pulses, and hence a stable Q-switched train of short pulses is obtained.

FIGURE 1

Principle of operation of the mode-locked and Q-switched laser with prelude period. The long prelude period of several msec allows the mode-locking process to reach steady state, and hence the initial conditions when the laser is Q-switched are stable, short, transform-limited pulses.

To determine how long the prelude period must be to obtain transform-limited pulses, we must consider the transient build-up of the short pulses. When the laser goes above threshold, two processes start in the laser. First, the initial noisy field in the cavity passes through the modulator and this starts to shape the envelope of the short pulses. On repeated passes through the modulator, the pulse envelope gets shorter. Initially, the linewidth has no effect on the pulse envelope. It is only when the pulse width approaches the steady state value that the linewidth takes effect and limits the pulse width to the steady state value given by Equation (1). It can be shown that the pulse envelope is within 5% of steady state value after a number of round trips M given by:

$$M = \frac{0.38}{\sqrt{g} \theta_m} \left(\frac{\Delta f}{f_m} \right) \quad (5)$$

Note the appearance of the ratio of the linewidth to the modulation frequency, $\Delta f/f_m$. This is typically on the order of 10^3 , and hence it takes that many round trips, or more, to reach steady state mode-locking conditions. This condition is easily satisfied during the prelude period.

The second process that starts when the laser goes above threshold is that the spectral width of the field in the laser cavity narrows on each pass through the active medium (or etalon). It is difficult to precisely analyze this narrowing process in the presence of the modulator, but two approximate conditions can be obtained. The bandwidth of the laser field is within a factor of two of that for a perfectly transform-limited pulse after a number of round trips given by:

$$M > \frac{0.5}{\sqrt{g} \theta_m} \left(\frac{\Delta f}{f_m} \right) \quad (6)$$

This is essentially the same as the condition in Equation (5) above; accordingly, when the pulse envelope is within 5% of the steady state

value, the spectral width of the pulse is within a factor of two of the transform limit of the steady state pulse.

A more severe condition for obtaining good transform-limited pulses is essentially the same as requiring single axial mode operation if the modulator is off. This condition is given by:

$$M > \frac{\ln 2}{2g} \left(\frac{\Delta f}{f_{ax}} \right)^2 \quad (7)$$

where f_{ax} is the axial mode spacing of the cavity. For most operating conditions in a typical Nd:YAG laser, it takes a few milliseconds to satisfy this condition.

Finally, the prelude period should also be long enough to let the relaxation oscillations die away after the laser goes above threshold. This usually takes a few upper level lifetimes of the active medium, and hence the prelude period should be at least 0.5 to 1 ms for Nd:YAG. Experimentally, we find that a prelude period of 3 to 5 msec is convenient and satisfies all the above conditions.

A more detailed analysis of this type of Nd:YAG laser was given in an earlier report to LLL.⁴ In this report we calculated the single pulse energy that can be expected from this type of laser, and we discussed the factors limiting the pulse energy. It was shown that single pulse energies in the range of 0.1 to 1 mJ can reasonably be expected from this type of laser, with Nd:YAG as the active medium.

Work Accomplished

The major tasks of this research program were to develop the necessary hardware for a simultaneously mode-locked and Q-switched Nd:YAG laser and to demonstrate the range of pulsewidths available, as well as the single pulse energy range, and the amplitude and pulsewidth stability of these pulses. One design philosophy that was adopted early in the program was

to make all the surfaces in the cavity at Brewster's angle. This had the following advantages:

- There would be no spurious etalon effects, which are probably responsible for most of the poor and anomalous behavior of mode-locked lasers.
- There are no coatings inside the cavity, reducing the risk of optical damage to components.
- Insertion loss of all components is very low.
- The lowest possible noise level between pulses could be obtained by reducing backscatter and multiple reflection between components.

A double ellipse pump cavity was developed for a Brewster angle crystal. To allow uniform cooling, the crystal and lamps had separate flow tubes, and the pump cavity was flooded. It was decided to use an acousto-optic modulator and Q-switch. It is well known that these modulators are acoustically resonant and can be very unstable under high RF drive conditions due to heating of the substrate by heat generated in the transducer. This problem was solved by direct water cooling of the transducer. The main advantage of using acousto-optic devices was that fused quartz could be used as substrate material. This gave good optical-quality substrate and low insertion loss and could easily be made at Brewster's angle. A typical arrangement of such a mode-locked and Q-switched laser is shown in Figure 2.

During the prelude period, the laser is typically about 5% above threshold, and to obtain a stable prelude period it is thus extremely important that all the laser parameters are very stable during this period. In particular, the signal to the Q-switch, the signal to the modulator, and the pump power have to be stable. The latter requirement turned out to be a major problem. Initially, CW pumping was planned for this oscillator, but owing to astigmatism introduced by the Brewster's ends of the rod, thermal focussing in the rod became a severe problem.

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FIGURE 2

Schematic of a typical mode-locked and Q-switched Nd:YAG laser with the essential diagnostics. The modulator and Q-switch are acousto-optic devices, and all components in the cavity are at Brewster's angle.

Because of this astigmatism, the effective thermal focal length in the plane of the Brewster ends is shorter by n^2 , which makes CW pumping of this laser impossible. However, since the maximum repetition rate of this laser has to be about 20 pulses per second, the thermal problem can be solved by pulsing the laser. The conventional L-C discharge type of pulsed pumping was rejected for this laser, because it would be difficult to obtain the required constant pump power during the prelude period, and at best it could probably only be obtained at one particular pump level. Since the required lamp currents are well within the range of available power transistors, a transistor-regulated pulser was constructed. Several problems were encountered. It was found that the risetime of the high-pressure Krypton arc lamps used in these lasers was very slow, usually a few milliseconds, probably because of the slow arc expansion in the lamps. Instabilities of the lamps and the available power supply also caused problems, and eventually a lamp driver was developed that had transistor-regulating circuits for proportional control of both the voltage and the lamp current. A schematic diagram of this lamp controller is shown in Figure 3(a), and Figure 3(b) shows a multiple exposure of various lamp currents. With this circuit, the short- and long-term pump power fluctuations were less than 1%.

The first mode-locked and Q-switched laser that was assembled at SRI had about a 4.5-ns cavity round trip time, or a modulation frequency of 111.17 Hz. The Q-switch was driven at about 50 MHz. The depth of modulation of the modulator was obtained by measuring the single pass transmission of the modulator at 1.06μ . Assuming that the modulator operated in the Bragg diffraction region, we could obtain the depth of modulation, θ_m . We also measured the threshold pump power for a range of output couplers from 0% to 50%, and from this we obtained the laser gain as a function of the pump power. From this, we also learned that the cavity round trip loss was 2.7%, not including the output coupling, indicating

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FIGURE 3

Schematic of the transistor-regulated lamp controller. Regulation of both voltage and current was required to obtain stable, quasi-cw pump power. The multiple exposure of the lamp current characteristics in (b) shows that the quasi-cw operation can be achieved over a wide range of currents. Pulse width can also be adjusted from 1 to 10 msecs.

the very low insertion losses that can be achieved with all the components at Brewster's angle. The laser was usually operated at 20 pps, and we experienced no problems due to thermal focussing in the Nd:YAG crystal.

The pulse widths obtained from this laser were measured with an optical correlator, using Type II SHG to measure the pulses. This type of correlator has been used before,³ but it has been considerably improved and automated for this work. A typical set of pulse width measurements are shown in Figure 4. These measurements were taken for 20-A lamp current. With no etalon, pulses from about 55 to 350 ps were obtained, and with a 1-cm uncoated quartz etalon, pulses from about 250 ps to 1 ns were obtained. This clearly shows that by simply adjusting the RF drive to the modulator and using one, or perhaps a few etalons in the cavity, the pulse width can easily be adjusted over a wide range. The range of pulses that can be obtained as a function of the RF drive for a particular setup is well defined. With strong modulation, where the depth of modulation $\theta_m \gtrsim 1$, the output power from the laser decreases significantly, and the laser can easily go below threshold for very strong modulation. For weak modulation, we find that at a certain level, the mode-locking becomes unstable, a significant noise level exists between the pulses, and the operation of the laser rapidly deteriorates. We find that these two limits are about the same with or without an etalon in the cavity. Between these limits, we always have stable and reliable mode-locking. The experimental results in Figure 4 were compared with the theoretical predictions of Equations (1) and (4). If we assume a linewidth of 175 GHz for Nd:YAG, the theoretical prediction agrees with the experimental results. For the 1-cm etalon, the predictions of Equations (2) and (4) agree well with the measured pulse widths.

Good performance of the laser was obtained with a 33% transmitting output coupler. At pump power levels where output coupling is approximately optimum for this case (~ 24 -A lamp current), we have about 10 short pulses within the Q-switched pulse envelop, allowing selection of a stable pulse

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FIGURE 4

Range of short pulses available for Nd:YAG laser for typical operating conditions. Pulses as short as 60 ps can be obtained in this short laser cavity. The entire range of short pulses can be obtained with only one uncoated quartz etalon.

near the center of the pulse train. We measured the average power from the laser at 20 pps, and also recorded the pulse train with a fast detector. From this we calculated the energy of a single pulse at the peak of the pulse train. These results are shown in Figure 5 for various lamp currents. With this laser, pulse energies up to 400 μ J were obtained. We also noted a rapid decrease in output energy for strong modulation, but the reason for this is currently not well understood.

At this stage of the research effort, the prototype laser was taken to Livermore for further tests, where we obtained more accurate statistical data on the stability of the laser. The output pulse train was recorded on a transient digitizer, and the computer then measured the relative energy of a single pulse with the maximum energy. Figure 6(a) shows a typical pulse train recording. In each data run, we recorded 500 pulse trains. A typical histogram for 500 pulses is shown in Figure 6(b). The width (FWHM) of the histogram is less than 3%, with no spurious pulses outside the $\pm 3\%$ range. We obtained this type of behavior for all pump levels well above threshold and for all depths of modulation where we have good mode-locking as described previously. It was mainly on the basis of these stability measurements that it was decided to use this type of oscillator for Shiva. We also did some streak camera measurements, and in general confirmed the range of pulse widths measured previously at SRI. More important, we found that there was (as expected) no fine structure on the pulses, nor were there any double pulses. The pulse shape was always smooth and symmetrical.

During this research effort, we also found that the prelude method has some other advantages. During the prelude period, the gain in the laser is equal to the Q-switch loss plus other losses, which is constant, and thus the gain is constant. Any fluctuation in pump power causes output power fluctuations, but the gain, and hence the stored energy, remains constant. When the laser is Q-switched, the resulting Q-switched pulse

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FIGURE 5

Energy in a single pulse at the peak of the pulse train for various lamp currents. At strong depths of modulation, pulse energy drops considerably. Pulse energies with the uncoated 1-cm etalon are approximately the same as those without the etalon.

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FIGURE 6

Laser stability measurements. In (a), a pulse train is recorded with a transient digitizer. The computer then records the relative amplitude of a pulse at the peak of the pulse train. The typical energy fluctuations are shown in a histogram for 500 pulses in (b). Typically, no pulses are found outside the $\pm 3\%$ range.

envelope is very stable. This effect contributes considerably to the good stability of the laser reported above. During the prelude period, the excess gain in the laser is very low, about 5% to 10%, and hence transverse mode selection is very easy, and only for high lamp currents is an iris needed to obtain TEM₀₀ mode output.

The actual prelude signal is also a remarkable indication of how well the laser is working. Figure 7 shows some typical prelude signals for various conditions in the laser. These levels were recorded with a slow PIN 10-diode at the high reflector end of the laser as shown in Figure 1. With the modulator off, as shown in Figure 7(a), the relaxation oscillations as the laser goes above threshold are irregular; however, with good mode-locking, these oscillations become very regular. When the cavity length is slightly longer or shorter than that for good mode-locking, the laser goes into driven relaxation oscillations as shown in Figure 7(c). For good mode-locking, the cavity length has to be adjusted to within about 25 μm , and in practice this is done by observing the characteristic prelude levels as shown in Figure 7. All other measurements have shown that this method gives the best performance of the laser. It is rather remarkable and extremely convenient that this laser can be set up correctly with only a slow diode and an oscilloscope. Other laser conditions, such as higher order transverse modes, which come above threshold later, are shown in Figure 7(d).

The prelude signal also indicated other problems in the laser. Small instabilities in the Q-switch driver, which could hardly be observed on an oscilloscope, produced very strong ringing in the prelude level. A signal generator for the modulator with short-term phase fluctuations also produced ringing. However, when a regular, stable prelude level is obtained as shown in Figure 7(b), the laser is running very well.

Tests on the prototype laser were completed during September 1976, and it became clear that this type of laser was needed as soon as possible

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FIGURE 7

Laser prelease conditions. The prelease signal is a very accurate indication of the operation of the mode-locked and Q-switched laser. The prelease signal with no modulation is shown in (a). With modulation, the relaxation oscillations become very stable (b). A slight cavity length change ($\pm 25\mu$) causes driven relaxation oscillations, (c), and conditions such as higher order transverse modes, (d), can be identified. Note that only in (b) does the laser Q-switch at the end of the prelease period. The energy in the Q-switched pulse relative to the above recordings is about 4 V.

for Argus, but the cavity length had to be about 10-ns round trip time to obtain good single pulse selection. At SRI, we had an additional pump cavity, modulator, and Q-switch, and we decided to assemble such a laser for Argus at SRI. The laser was mounted in an invar-stabilized resonator used previously at LLL for the PMO. In this long cavity, the spot size was larger and the laser was much more sensitive to the thermal focussing in the rod. For this reason, the repetition rate of this laser had to be reduced to 5 pps. The control electronics and lamp driver were further improved and redesigned for easier operator control. The modulator and Q-switch were both driven at about 50 MHz, and the Q-switch could be driven by the same RF source as the modulator. The Q-switch also opened at the same phase of the RF signal and, in this setup, the short pulses were synchronized with the opening of the Q-switch, and hence to the envelope of the Q-switched pulse train. Subsequent tests on the laser showed that the laser was now stable enough that a single pulse could be selected by counting a predetermined number of cycles of the RF drive to the modulator from the time the Q-switch is opened. This pulse selection method has not yet been implemented on Argus, but it will be used on the Shiva oscillator. This degree of predictability with which a pulse is available will enable good synchronization of this oscillator with other fast instrumentation on Shiva.

Figure 8 shows the range of measured pulse widths for the Argus oscillator. The modulator has not yet been calibrated to give the depth of modulation, and the pulse width in Figure 9 is given as a function of the RF level setting on the H.P. signal generator. The shortest pulses available from this oscillator are about 110 psec because of the longer cavity used here. We also noted that the range of good mode-locking for this laser is considerably narrower than for the prototype laser. The reason for this is currently not known. Pulse widths were measured without an etalon, and with a 1-cm uncoated etalon. To cover the entire range of

FIGURE 8

Range of measured and predicted pulse widths for the Argus oscillator. For this long cavity ($f_m \approx 50 \text{ MHz}$), the shortest pulses available are about 110 ps.

FIGURE 9

Single pulse energies available from the Argus oscillator.

short pulses available from this laser, from about 120 ps to 3 ns, more etalons were required. The present oscillator on Argus now has three etalons with the predicted pulsewidth range shown in Figure 8. Further measurements should confirm good operation of the laser over this entire range. Figure 9 shows the single pulse energies available from this laser. Single short pulses of 600 μ J are routinely available from the laser, but the decrease of energy for strong modulator drives is even more severe than for the shorter prototype laser. Further work should show the reason for this decrease in pulse energy. This oscillator is now operating successfully in the high-EMI environment of Argus and is producing successful target shots.

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