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Interim Status Report for NASA Cooperative Agreement NCC 5-24, "Dye Laser Traveling Wave Amplifier"

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I. Introduction

The objective of the work done under cooperative agreement NCC 5-24 in collaboration with the electro-optics branch of the Goddard Space Flight Center was to develop a flash lamp pumped dye laser suitable for use as an amplifier stage. The desired output laser pulses were to be of nanosecond duration, tunable in center frequency, and of good optical quality. After some preliminary experiments with the laser, it became apparent that it was also useful as a laser oscillator. Much of the subsequent work has focussed on that application, since it would constitute a compact, relatively efficient source of tunable dye laser light. Other types of dye lasers require auxillary lasers (e.g. Nitrogen, YAG, or Argon-Ion) as optical pumping devices necessary to achieve laser action. The work described in the following covers the period from the inception of the award, December 1980, through December 31, 1982.

II. Design of the Laser Amplifier

The basic design chosen for the dye laser amplifier consisted of a traveling wave configuration shown in Figure 1 below.

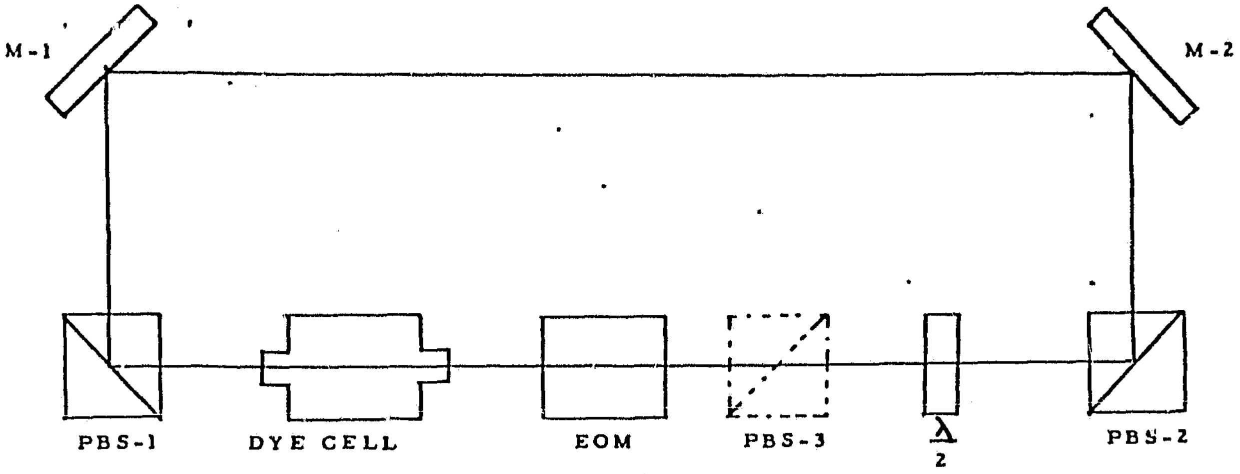


Figure 1: Block Diagram of Dye Laser Oscillator/Amplifier.

The dye cell and flash lamp pump consisted of a commercial unit, ILC Model DYH-15. It consists of a 40 cm long, 1 cm diameter flowing dye cell mounted coaxially with a 300 J coaxial flash lamp, ILC Model L-2600. The flash lamp was driven by a capacitor discharge and pulse forming network contained in a base on which the flash lamp and dye cell were mounted.

Since the flash lamp energy absorbed by the dye solution (R6G in ethanol) rapidly heats the dye cell, the fluid must be exchanged with a resevoir as rapidly as possible. To accomplish this, a stainless steel pumping system was constructed that was capable of changing the entire volume of dye contained in the cell about ten times per second. In addition, the dye was cooled before being returned to the pump resevoir container.

The optical component configuration for the laser amplifier shown in Figure 1 was not commercially available and had to be constructed from individual components and mounts. The components labeled PBS-1, PBS-2 are broad band polarizing beam splitter cubes obtained from CVI-Laser Corporation. These components transmit p-polarized light (T=98%) and reflect s-polarized light (R=99%) over a spectral range of 450-700 nm. Mirror M-1 is a flat broad band totally reflecting mirror for s-polarized light at a 45° angle of incidence. M-2 is a similar mirror, except that it has a 20m radius of curvature. The round trip optical path length of the cavity is approximately 240 cms. The polarizing beam splitter cubes reflect upwards about 1-2% of the p-polarized light which strikes them, and are otherwise anti-reflection coated.

If the optical cavity shown in Figure 1 did not contain the half wave retardation plate (component labeled λ/2), the electro optic modulator (labeled EOM) and the third beam splitter cube (shown in dotted lines), the following would occur. Light emitted spontaneously by the dye cell would exit the cavity if p-polarized, and would be retained totally within the cavity if s- polarized. The s-polarized light confined by the optical cavity would be further amplified each time it passed through the active dye cell. Consequently two contra propagating laser beams (one traveling clockwise, the other counter clockwise) would form in the cavity for the duration of the flash lamp output optical pump pulse. After that, they would both rapidly decay, due to absorption losses caused by the dye cell and non-zero transmittance of the optical components.

In order to obtain laser energy from the cavity, two more components need to be added. The first is a half wave retardation plate, labeled $\lambda/2$. In the first version of the laser, this consisted of a 15th order $\lambda/2$ plate centered at $\lambda = 589$ nm . Its function is to rotate the plane of polarization of all 589 nm light present in the cavity by $\pi/2$. Other wavelengths will experience a plane of polarization rotation also, as shown by the graph of Figure 2. Consequently, any s- polarized laser light at 589 nm that strikes the $\lambda/2$ plate is changed to p- polarized light, and exits the cavity as soon as it encounters either polarizing beam splitter cube. The optical resonator is then "lossiest" at $\lambda = 589$ nm , and is less lossy at wavelengths on either side of 589 nm . Since the polarization rotation at these other wavelengths is not exactly $\pi/2$, some light is retained in the cavity, and some exits on each round trip. The result is an output laser light pulse containing many frequencies and of rather long temporal duration (examples will be given later).

In order to retain light at 589 nm , an electro-optic modulator consisting of a Laser Metrics Model 5016 Pockels Cell

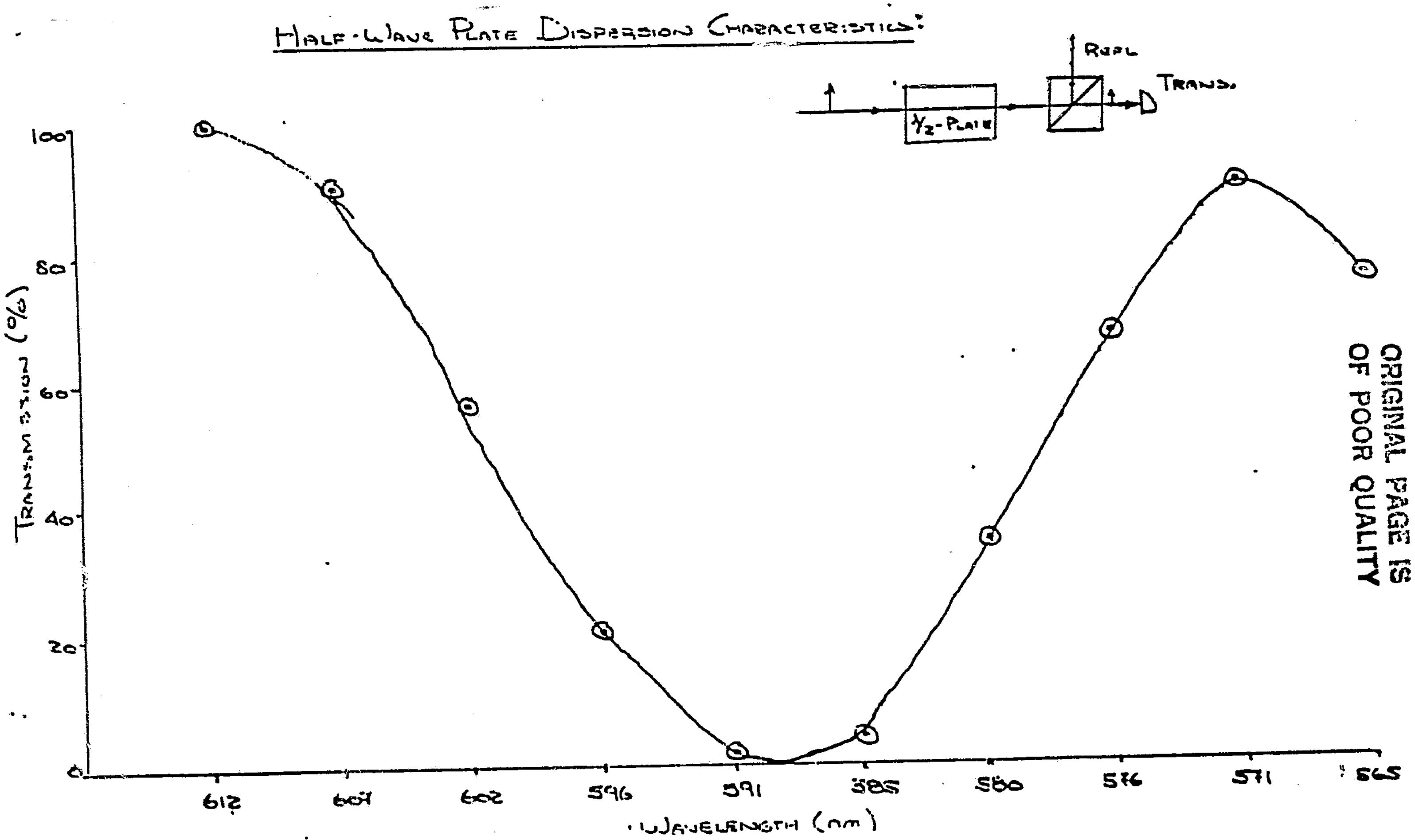


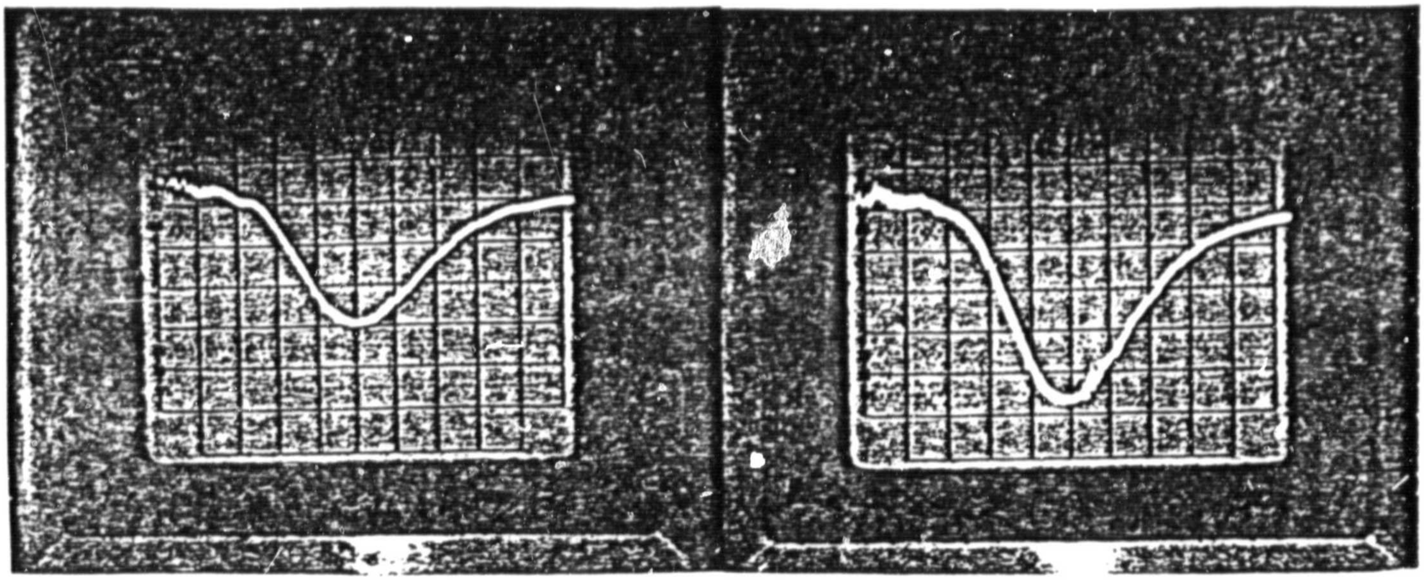
Figure 2: Rotation characteristics of the 15th order half-wave retardation plate.

was introduced. The EOM can be used either to retain 589 nm laser light originating from spontaneous emission (oscillator configuration) or from an initially injected laser light pulse at 589 nm (amplifier configuration) within the cavity for a desired length of time. The high voltage applied to the cell causes the plane of polarization of incident light to be rotated by an amount dependent on wavelength. In order to retain 589 nm light, a voltage that causes an additional rotation of $\pi/2$ is used. Consequently, any s-polarized 589 nm light reflected by either beam splitter encounters a net rotation of π radians after passing through both the EOM and $\lambda/2$ plate and is hence retained in the optical cavity. Light at 589 nm is extracted by removing the high voltage applied to the EOM so that the retained s-polarized light will exit the cavity on the next pass through the no longer active EOM. Consequently laser light at some particular wavelength determined by the $\lambda/2$ plate – EOM combination will be either generated or amplified. The function of the remaining polarizing beam splitter cube, PBS-3 shown in dotted lines will be discussed later.

III. Performance as an Oscillator

In order to characterize the performance of the laser system, a detailed series of measurements of the small signal gain of the dye cell were made. This involved first removing all optical components from the cavity except for the dye cell itself. Light from a c-w ring dye jet laser was then passed through the cell and then detected by a fast Montsanto photodiode. The laser flash lamp was then discharged and the resultant output pulse shapes measured with and without the c-w injected laser light by photographing the output signal from the photodiode as recorded by a fast storage oscilloscope. The difference in pulse shapes then gives a direct measurement of the gain experienced by the injected dye laser light. Since the intensity of the c-w dye laser light was in the 10-100 milliwatt range, which is far below the saturation intensity of the R6G dye, small signal gain is directly measured. Since the spontaneous emission time for the upper laser level in Rhodamine is a few nanoseconds, and the lower state lifetime is much less, the output gain pulse follows the flash lamp excitation pulse, which is of about 1 microsecond duration, extremely closely.

Typical small signal gain pulses are shown in Figure 3a and 3b. Figure 3a is due to the flash lamp alone, and 3b shows the increased output energy when c-w dye laser light is present when the flash lamp is discharged.



3(a) 3(b)

Figure 3. Output light from flash lamp pumped dye cell without (3a) and with (3b) injected c-w dye laser light. Flash lamp input energy was 140 J, horiz. scale = 200 ns/div, vertical scale = 0.2v/div., $\lambda = 590$ nm.

The small signal gain is determined by the relationship of output to input laser intensity as

$$I_0 = I_{in} e^{g_0 \ell} \qquad (1)$$

Here ℓ is the length of the active laser medium and g_0 is given by

$$g_0 = \frac{\Delta N_0 \lambda^2}{4\pi^2 n^2 t_{sp} \Delta\nu_H} = \sigma_{em} \Delta N_0 \qquad (2)$$

ΔN_0 is the zero field population inversion density, t_{sp} the spontaneous lifetime of the upper laser state, and $\Delta\nu_H$ the homogeneously broadened linewidth of the transition. σ_{em} is the stimulated emission cross section. The quantity

$g_0\ell = \ell n(I_0/I_{in})$ is here defined as the small signal gain. It was determined from the peak values of the photodetector output signals as represented in Figures 3a and 3b.

The results obtained as a function of wavelength, dye concentration, and input flash lamp electrical energy are shown in Figures 4-7. Best results were obtained for dye concentrations of between 0.5×10^{-4} Molar and 1.0×10^{-4} Molar. From the data of Figures 4-7, it appears that at 200 J input energy, a value of $g_0\ell = 4$ can be expected at 590 nm. Using the published value of $\sigma_{em}(\lambda = 590\text{ nm}) \approx 0.5 \times 10^{-16}$ cm^2 gives a value of $\Delta N_0 = 2 \times 10^{15}$ atoms/cm^3. At a concentration of 0.5×10^{-4} M, there are 3×10^{16} molecules of rhodamine/cm^3, so about 6 to 7 percent of the active dye atoms are excited to the upper laser state at the time of peak laser gain. g_0 itself is about 0.1 cm^{-1} or $10\%\text{ cm}^{-1}$, which is a quite respectable value for any laser system.

Next, the performance of the system as an oscillator was measured. The dye concentration used was 0.5×10^{-4} M. The output of the laser with the EOM always off is shown in Figure 8. The output pulse is very long (500 ns) and follows the overall shape of the flash lamp pumping pulse. The spectral content of the pulse is very broad, due to the dispersion characteristics of the multiple order $\lambda/2$ plate. The output pulse energies were on the 10-100 millijoule range.

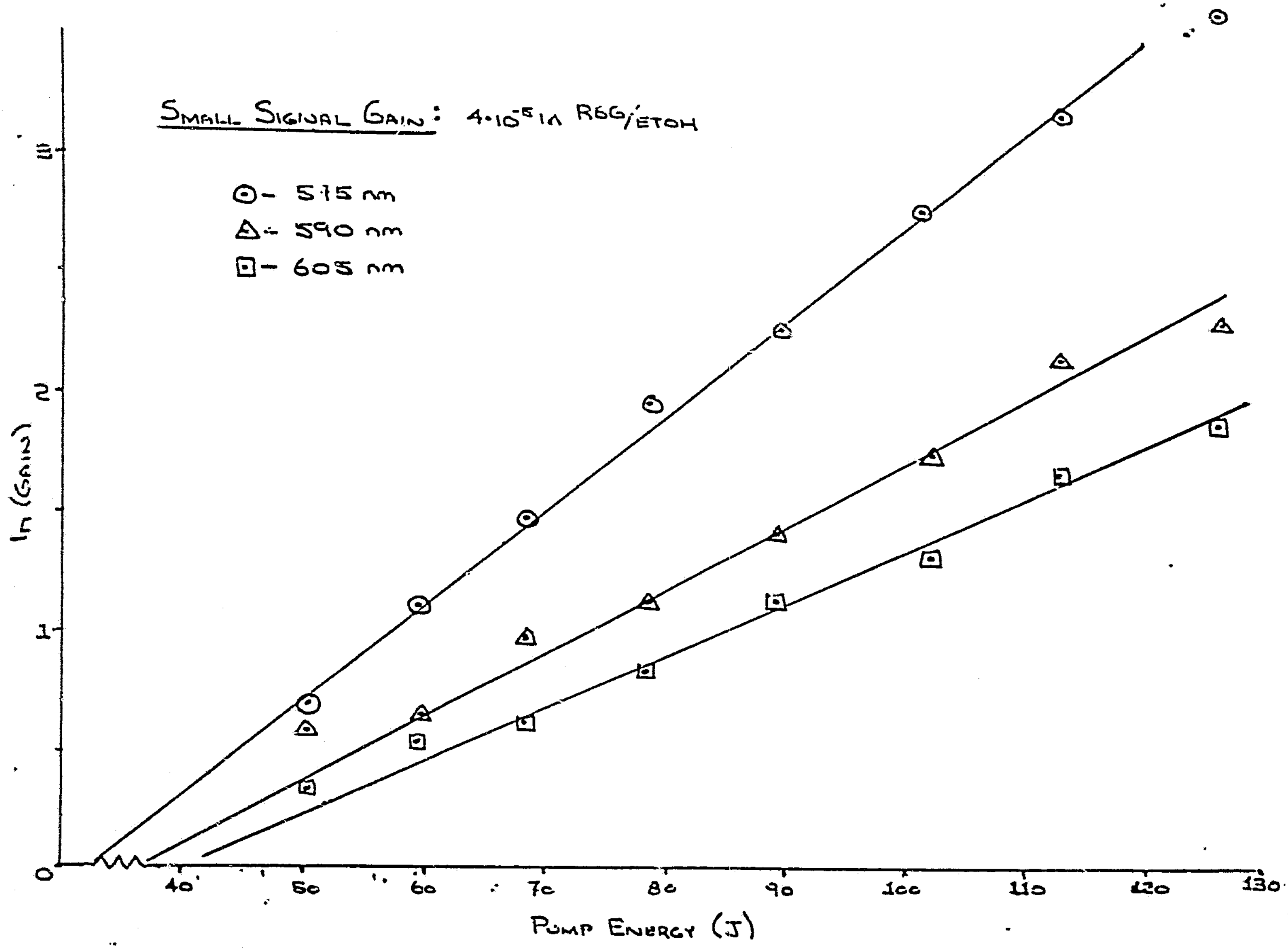


Figure 4. Small signal gain as a function of input electrical energy to the flash lamp.

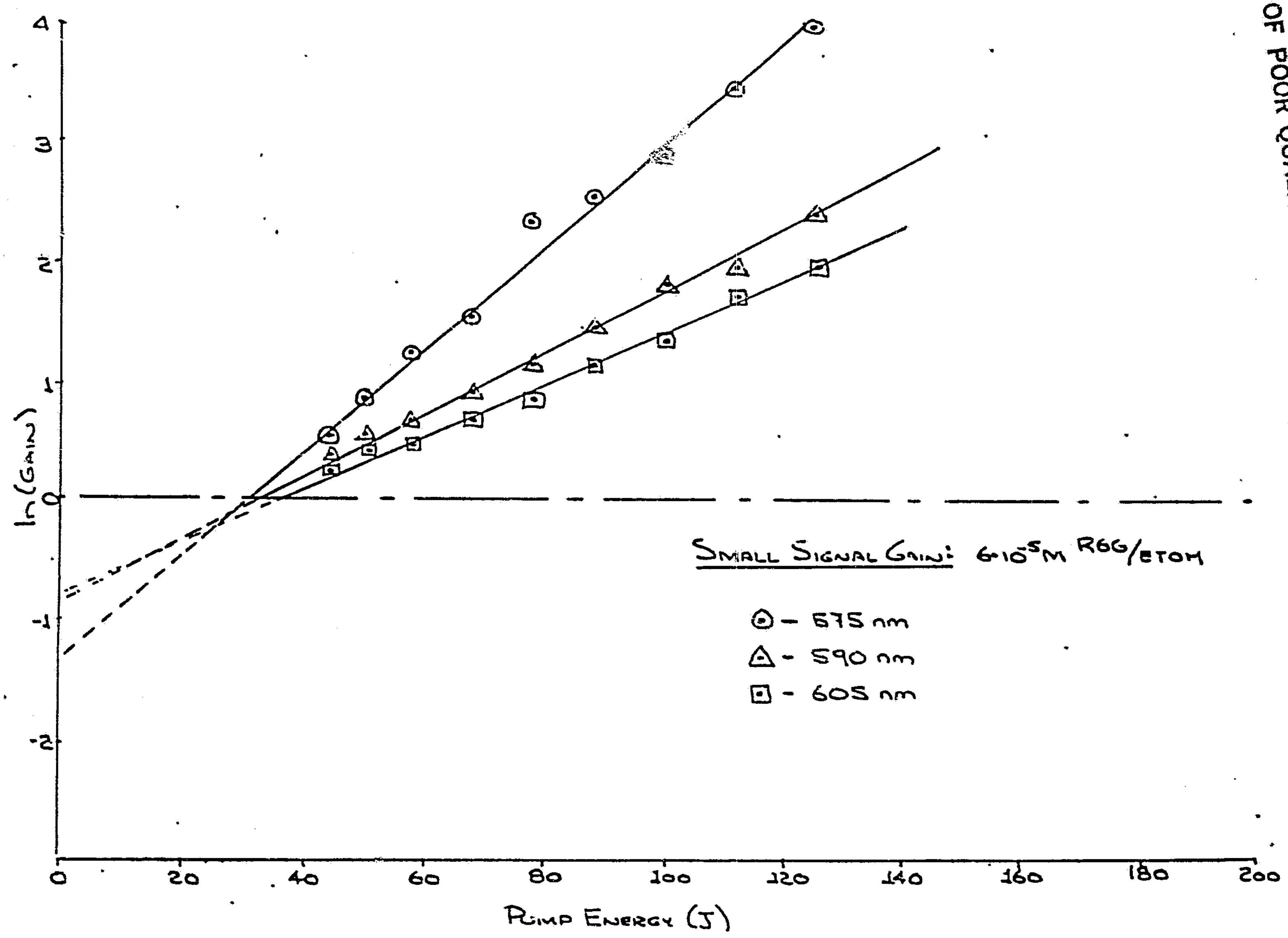


Figure 5. Small signal gain as a function of input electrical energy to the flash lamp.

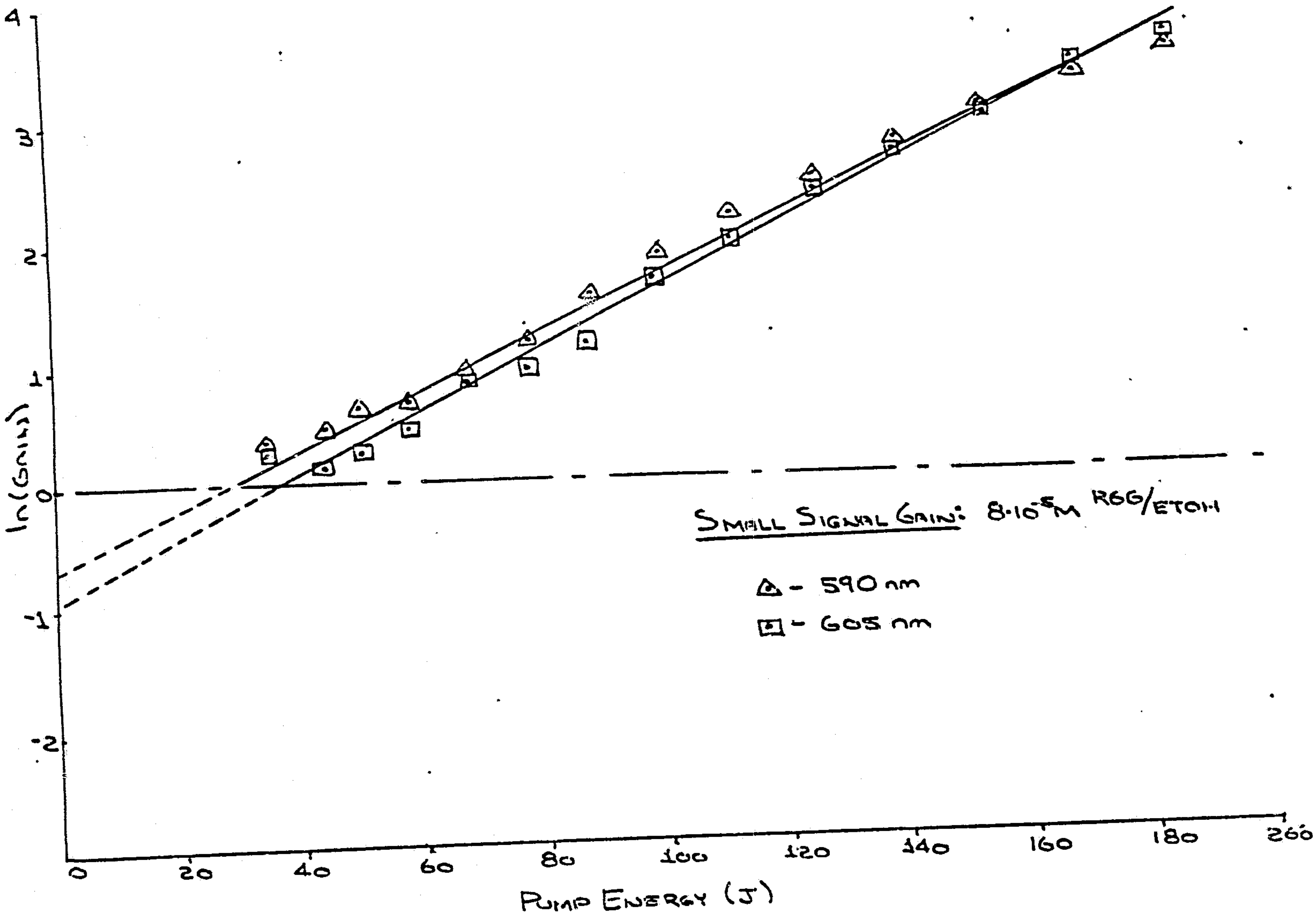


Figure 6. Small signal gain as a function of input electrical energy to the flash lamp.

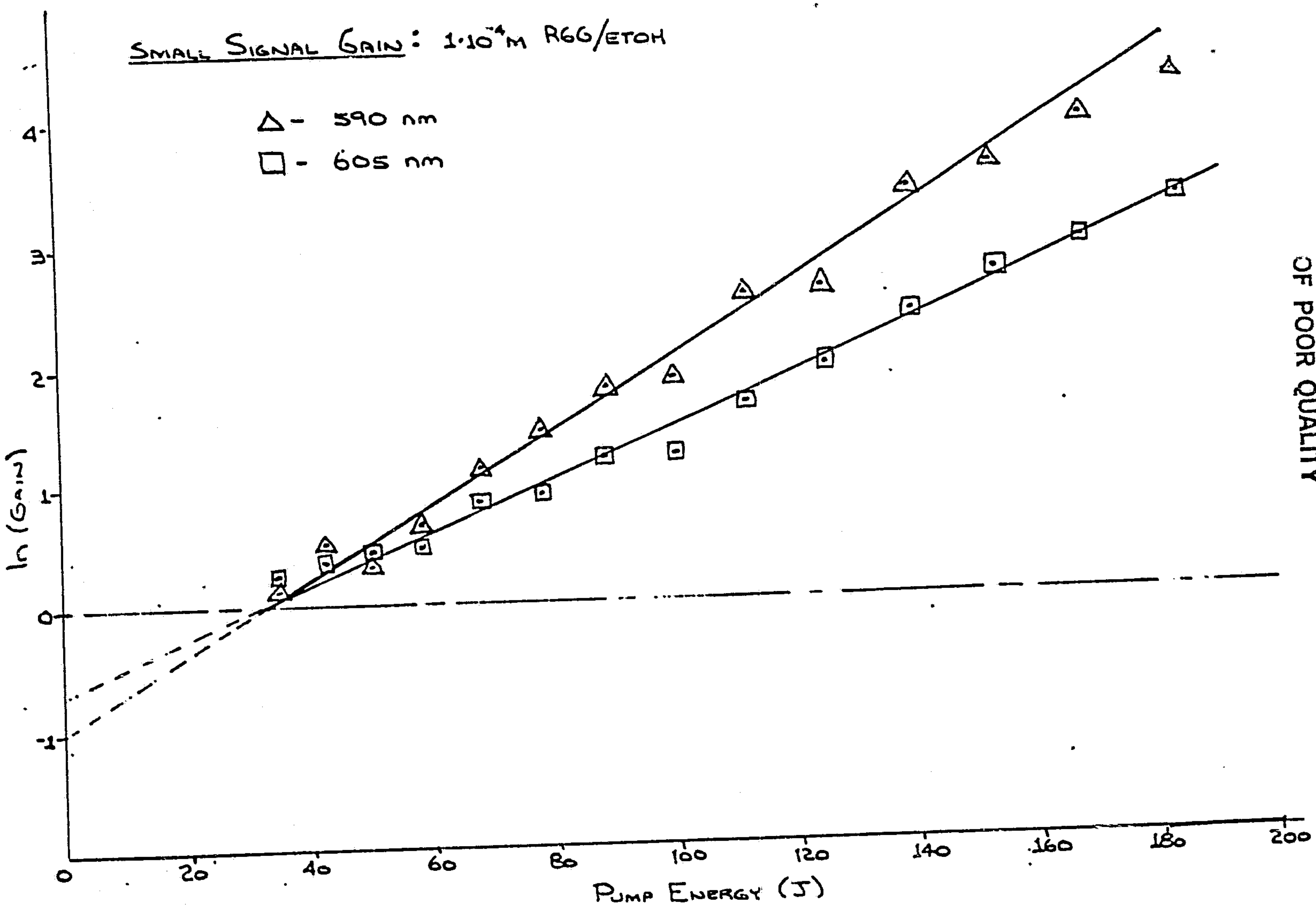


Figure 7. Small signal gain as a function of input electrical energy to the flash lamp.

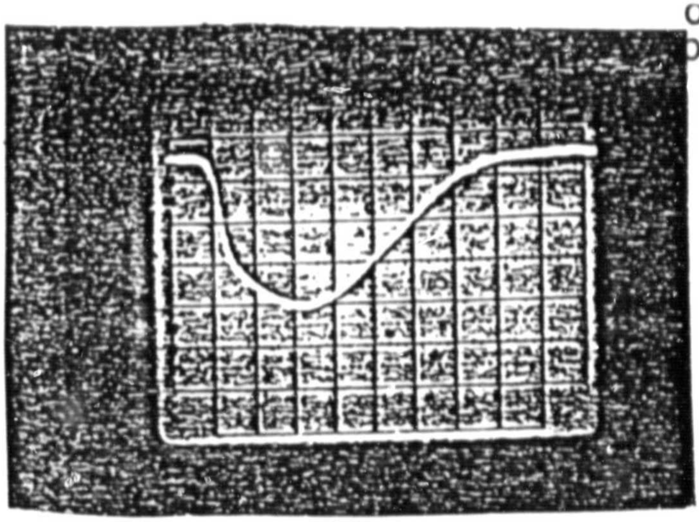


Figure 8. Typical dye laser output pulse with no cavity dumping. Horizontal scale = 100 ns/div. , vertical scale = 0.5 v/div. Flash lamp input energy was 140 J . EOM remained off, dye concentration of 3×10^{-5} M .

Considerably improved performance is of cource obtained with the use of the EOM as originally intended. The EOM is turned on as soon as the flash lamp is fired, and remained on for 100 to 750 ns , as set by a control on the power supply unit for the EOM. The EOM traps mostly 589 nm laser light in the cavity, but some light of nearby wavelengths as well. A variety of output pulse shapes can be obtained, as shown in Figures 9-12, depending on how long the EOM remains on and active.

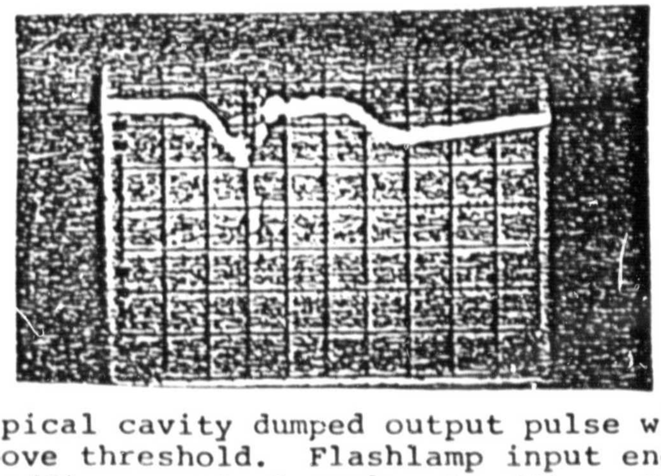


Figure 9. Typical cavity dumped output pulse with laser pumped slightly above threshold. Flashlamp input energy = 113 J , horizontal scale = 50 ns/div, vertical scale = 1 v/div. Output laser spike occurs at $\lambda \cong 589$ nm, dye concentration = 5×10^{-5} M, total output pulse energy = 9 millijoules. EOM voltage turned on as soon as flash lamp fires, and was turned off about 500 ns later, producing sharp laser output pulse.

The output pulse shape shown in Figure 9 is due to the following. The initial part of the pulse is due to laser action at wavelengths other than 589 nm. The sharp output spike approximately 50 ns after lasing begins is due to the EOM being turned off and the cavity emptied or "dumped" of all $\lambda = 589$ nm laser radiation. This stops all laser action for another 150 ns. After that time, the flash lamp pulse, which is still present again generates laser action at wavelengths other than 589 nm. Finally all laser action ceases as the flash lamp output ceases. The wavelength of the emitted radiation could only be determined crudely with a monochromator, and later by a spectrograph. The duration of the sharp laser output is about 10 ns.

At higher input flash lamp energies, the laser output is broadened in spectral composition. Figure 10 gives typical results obtained with the EOM operated as in Figure 9. Once the cavity is emptied of $\lambda \approx 589$ nm light, it recovers and begins to lase at the longer wavelengths. Once the EOM is off, the cavity is extremely lossy for $\lambda = 589$ nm light. From the $\lambda/2$ plate characteristics shown in Figure 2, longer wavelength radiation is retained in the cavity for more than two round trips, and hence laser light builds up over the 570-610 nm spectral region. At still higher input flash lamp energies, shorter wavelength light also builds up after the cavity is "dumped" by the EOM.

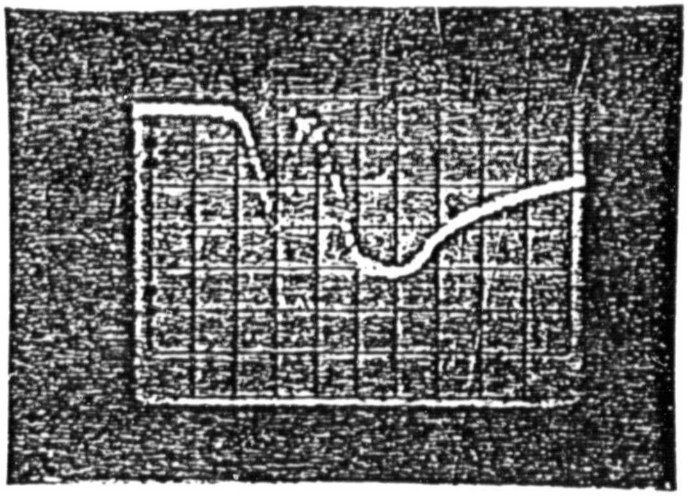


Figure 10. Typical cavity dumped laser output pulse at higher pumping levels. Laser output spike occurs at $\lambda \approx 589$ nm , but extends from 585 nm to 590 nm. Second "hump" is composed of 570 and 610 radiation. Flash lamp input energy = 177 J , horizontal scale = 50 ns/div, vertical scale = 1 v/div. Total pulse energy = 36 millijoules, dye concentration = 5×10^{-5} M .

Another interesting phenomenon occurs if the cavity is dumped after laser oscillation at other wavelengths is well under way, as shown in Figure 11.

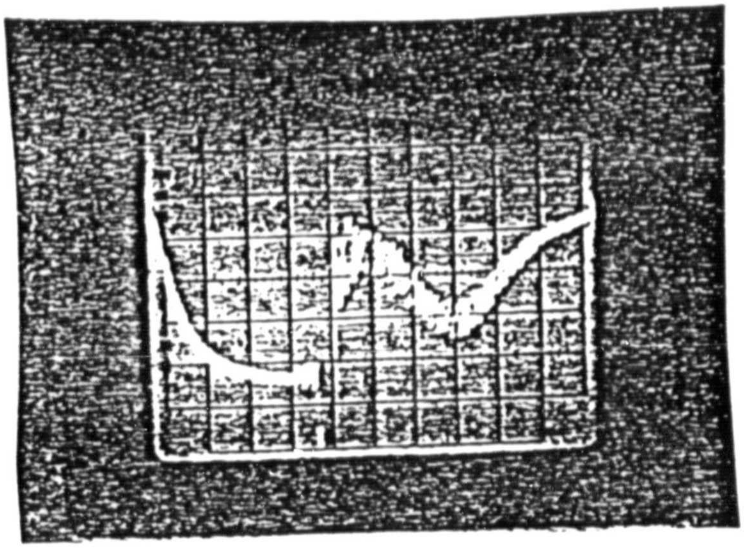


Figure 11. Typical self mode-locked output pulse train. Laser begins to lase as shown by hump on left side, then is cavity dumped, as shown by sharp spike. EOM voltage adjusted for half wave retardation at shorter wave lengths (λ < 589 nm). Output radiation is substantial over wave length range 570-610 nm. Input flash lamp energy = 113 J, horizontal scale = 50 ns/div, vertical scale = 0.5 v/div. Total output pulse energy = 22 millijoules, dye concentration = 5×10^{-5} M. Conditions are same as for Figure 9, except EOM voltage and time duration were adjusted to produce mode locking.

Here the laser appears to self mode lock. Apparently the perturbation caused by the sudden removal of laser light at a certain frequency introduces propagation of short intense light pulses within the cavity. The pulse train is shown on an expanded time scale in Figure 12. At present, we do not have the necessary diagnostic equipment to determine the spectral content of the pulse train.

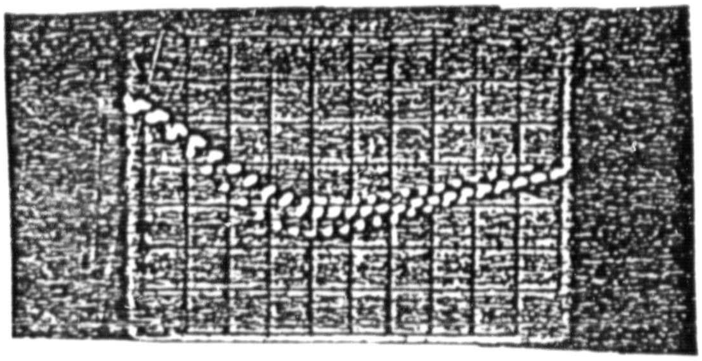


Figure 12. Conditions similar to Figure 11, except displayed on faster time scale, horizontal scale = 20 ns/div. Periodicity of pulse train ≈ 8 ns, the optical cavity round trip time.

In order to eliminate the unwanted spectral components of the output laser light, an additional polarizing beam splitter cube, PBS-3, was inserted between the $\lambda/2$ plate and the EOM. At that point, all 589 nm light present has p- polarization and is transmitted nearly without loss by PBS-3. Light at other wavelengths has both p- and s- polarization components due to the properties of the $\lambda/2$ plate. The cube PBS-3 eliminates all s-polarized light from the cavity at that point. Consequently, the optical cavity is much more lossy at wavelengths other than $\lambda = 589$ nm . This greatly reduces the spectral width of the laser output pulse, which now has as its strongest component light at 589 nm .

The addition of PBS-3 resulted in a very short output laser light pulse of 1 to 10 millijoule energy. A typical output pulse is shown in Figure 13. The full width at half maximum is 6 ns . This configuration of the laser has produced the highest peak power and shortest pulse length of any flash lamp pumped, non mode-locked R6G dye laser of which we are aware.

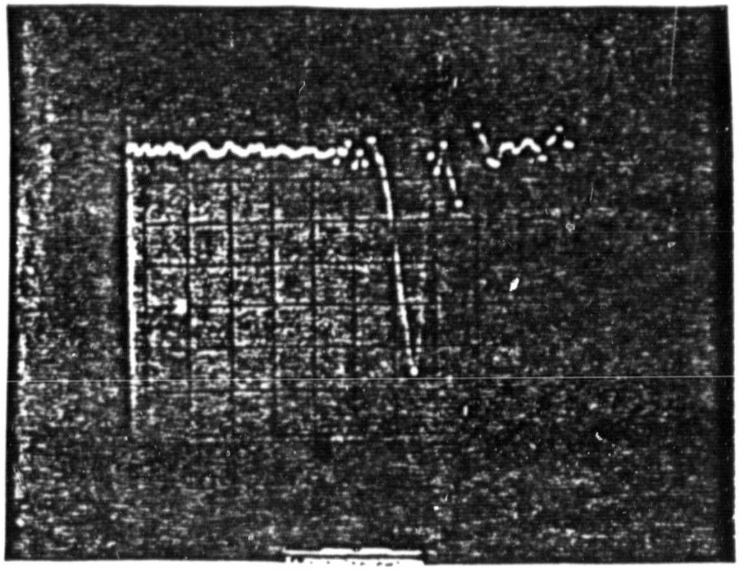


Figure 13. Fast laser output pulse. Input electrical energy to flash lamp was 150 joules. Output pulse energy was 3.5 m joules. Horiz. scale = 10 ns/div, vert. scale = 0.5v/div. Noise on trailing edge is due to EOM being turned off and is not due to laser light.

At present, the dye laser, as an oscillator, is not easily tunable; the center wavelength of the $\lambda/2$ plate would have to be changed in order to change the output laser pulse wavelength. The EOM itself is not sufficiently dispersive to significantly tune the laser oscillator. It also is rather lossy as only about 90% of the incident light is transmitted through the device. Experiments are under way with a much less lossy EOM (1-2%), which should significantly increase the output pulse energy. During subsequent work, a linear cavity configuration will also be investigated with a low loss littrow prism as a tuning element. Some work has been done with a constant deviation prism located between M-1 and M-2. This element was so lossy (15%) that the laser output, although tunable, was greatly reduced in output energy, and hence viewed as unsatisfactory.

IV. Performance as an Amplifier

The laser as shown in Figure 1 can also be used as an optical pulse amplifier, at least in principle. The 15th order $\lambda/2$ plate must be replaced by an achromatic $\lambda/2$ plate (all wavelengths have their plane of polarization rotated by $\pi/2$ radians), and PBS-3 is removed. The injected light pulse consists of p- polarized light that enters the optical cavity through PBS-2. It is converted to s-polarized light after passage through the $\lambda/2$ plate. The pulse then passes through the EOM which remains in the off or inactive state. As soon as the pulse has passed through the EOM, it is turned on. The light pulse then enters the active gain region of the dye cell, which has begun to be pumped by the flash lamp whose discharge cycle must already be in progress prior to the arrival of the light pulse. The s-polarized light pulse is amplified, reflected around the cavity by PBS-1, M-1, M-2, and PBS-2. Passage through the $\lambda/2$ plate and the now active EOM results in no net change in the polarization state of the light pulse, which is again amplified on passage through the dye cell. This process continues until the EOM is turned off. The s-polarized light pulse, on the last pass through the cavity is left as p-polarized light after passage through the $\lambda/2$ plate and is ejected from the cavity by PBS-1.

The actual operation of the laser as an amplifier has proved more difficult than anticipated. The injected dye laser light pulse must be less than 8 ns in duration, and sufficiently intense to force the flash lamp pumped dye cell to produce laser amplification at the same wavelength, rather than some other wavelength that spontaneously builds up in the optical cavity. In order to obtain such pulses, a Molectron Nitrogen Laser and Molectron Nitrogen pumped dye laser were supplied by the Goddard Space Flight Center. We experienced some difficulty in obtaining satisfactory operation from this system, but were finally successful. The net result was that 6 ns tunable dye laser light pulses were finally obtained from that system.

In order for the amplifier to function as intended, the flash lamp discharge, and the application of the high voltage pulse to the EOM must be closely synchronized with the arrival of the injected light pulse from the Nitrogen pumped dye laser system. This required the construction of elaborate timing electronics, which are now operational. It consists of a stable pulse generator operating at 2^{16} times the desired repetition rate of the dye laser amplifier stage. TTL logic is used to decode the occurrence of the 2^{16} th and immediately preceeding pulses (($2^{16}-1$)st pulse). The 2^{16} th pulse is used to externally trigger the Nitrogen laser. This laser is operated with a very stable thyratron discharge system, which is almost jitter free. The Molectron dye laser produces an output pulse almost exactly 750 ns later. The immediately preceeding pulse is delayed and then used to trigger the spark gap that discharges the flash lamp in the amplifier stage. Spark gap discharge circuits have considerably more pulse jitter than thyratron circuits. To date we have been unable to stabilize the exact discharge time of the flash lamp to better than a few microseconds, which is totally inadequate. We are in the process of improving the stability of the operation of the spark gap, and hope to obtain pulse amplification shortly. It may, however, be necessary to construct a thyratron firing circuit for the flash lamp discharge of the amplifier stage.