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ELECTRICAL ENGINEERING & COMPUTER SCIENCE

Interim Status Report for NASA Cooperative Agreement NCC5-24, "Dye Laser Traveling Wave Amplifier"

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Report covers the period July 1983 - Dec. 1983

I. Introduction:

The objective of the work done under cooperative agreement NCC5-24 in collaboration with the Electro-optics branch of the Goddard Space Flight Center was to develop a flashlamp-pumped dye laser suitable for use as a single-stage amplifier. The output pulses were to be of nanosecond duration, tunable in center frequency, and of good optical quality. Previous status reports have detailed work done on this project during the period December 1980 – June 1983. As described in the status report dated January 1983, preliminary work was devoted to the actual construction of the laser and the measurement of laser parameters necessary for analysis of the system (i.e. small signal gain, loss and dispersive properties of optical components, etc.). Work during this period also focused on the possibility of operating the system as a laser oscillator. The July 1983 status report detailed the progress made in using the system as a single-stage amplifier. By injecting nanosecond duration, narrowband pulses from a N_2-pumped dye laser we were able to frequency injection-lock the amplifier, allowing amplification of these pulses while retaining their temporal and spectral purity. With the system as shown in Fig. 1 we were able to produce 20-30 mj pulses with linewidths as narrow as .0014 nm over a tuning range of ~10 nm. Nonetheless, as noted in the July 1983 status report there were problems with the system. The temporal profile of the amplified pulse was not as "clean" as desired as a substantial "shoulder" accompanied the cavity-dumped pulse. It was also observed that for output pulse energies of $\geq$30mJ the radiation was sufficiently intense to damage the coatings on the broadband polarizing beamsplitter cubes which limited attempts to extract more energy from the system.

Work performed during the six month period July-Dec. 1983 was devoted to addressing these problems. The polarizing beam-splitter cubes were replaced with thin-film polarizers which have much higher damage thresholds. Substantial effort was then devoted to "cleaning-up" the temporal profile of the amplified pulse by investigating the effects of increasing the polarization and spectral dispersion of the amplifier cavity. Additional investigations into the possibility of spatially enlarging the amplified beam, in the amplifier, in order to extract energy from previously unused dye volume were also performed.

II. Review of Basic Laser Operation

A schematic of the flashlamp-pumped laser amplifier and associated diagnostic equipment as of June 1983 is shown in Fig. 1. The amplifier is in a ring (traveling-wave) configuration as defined by the two broadband polarizing beam-splitter cubes (PBSCs) and the two turning mirrors (one plane and one with a 20 m radius of curvature). It also contains a

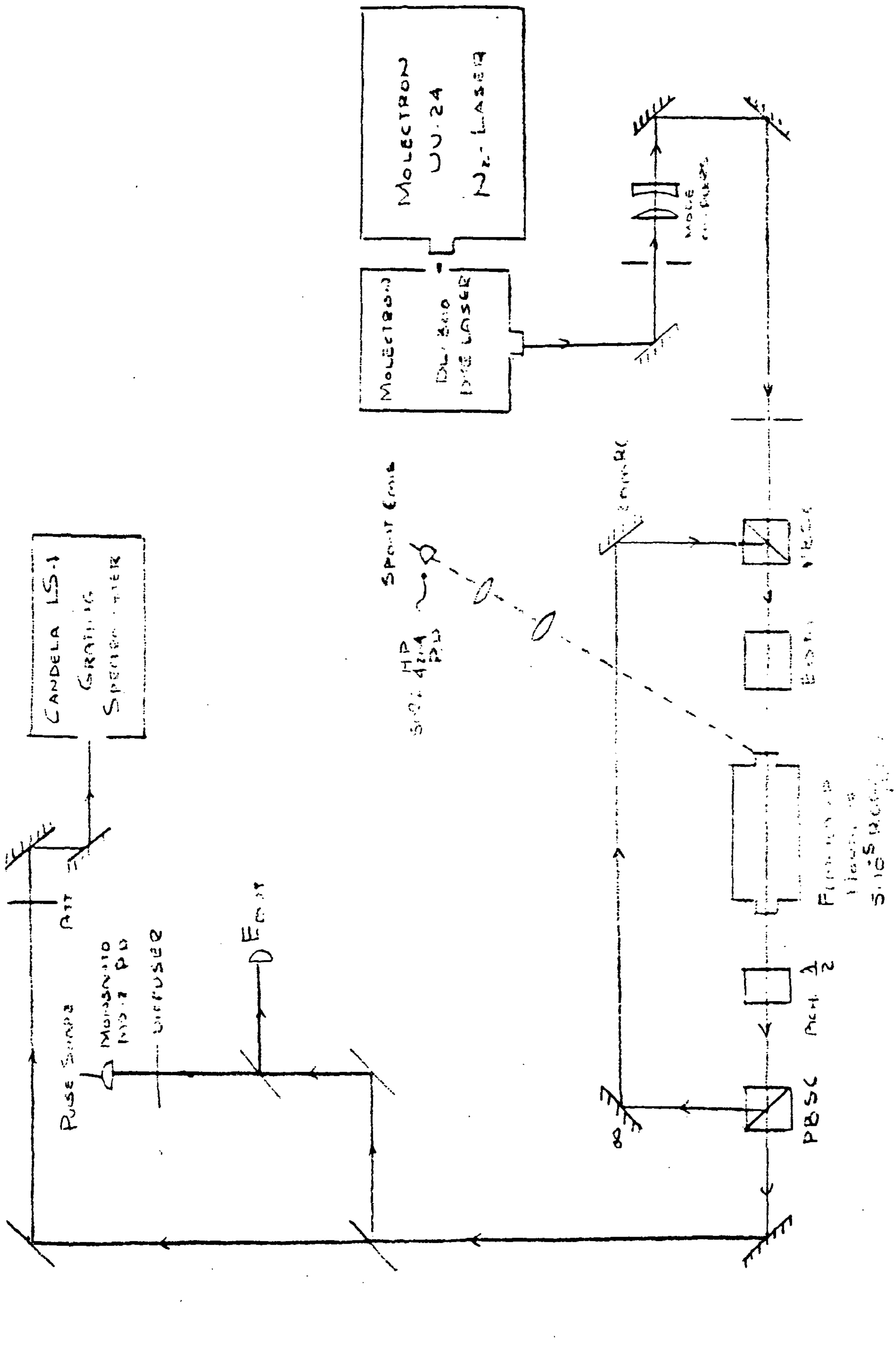

Molectron UV-24 N₂-Laser
Molectron DL-200 Dye Laser
Candela LS-1 Grating Spectrometer
PBSC
Pulse Shape
Diffuser
Att
Spont Emis
Flash Heat

Figure 1

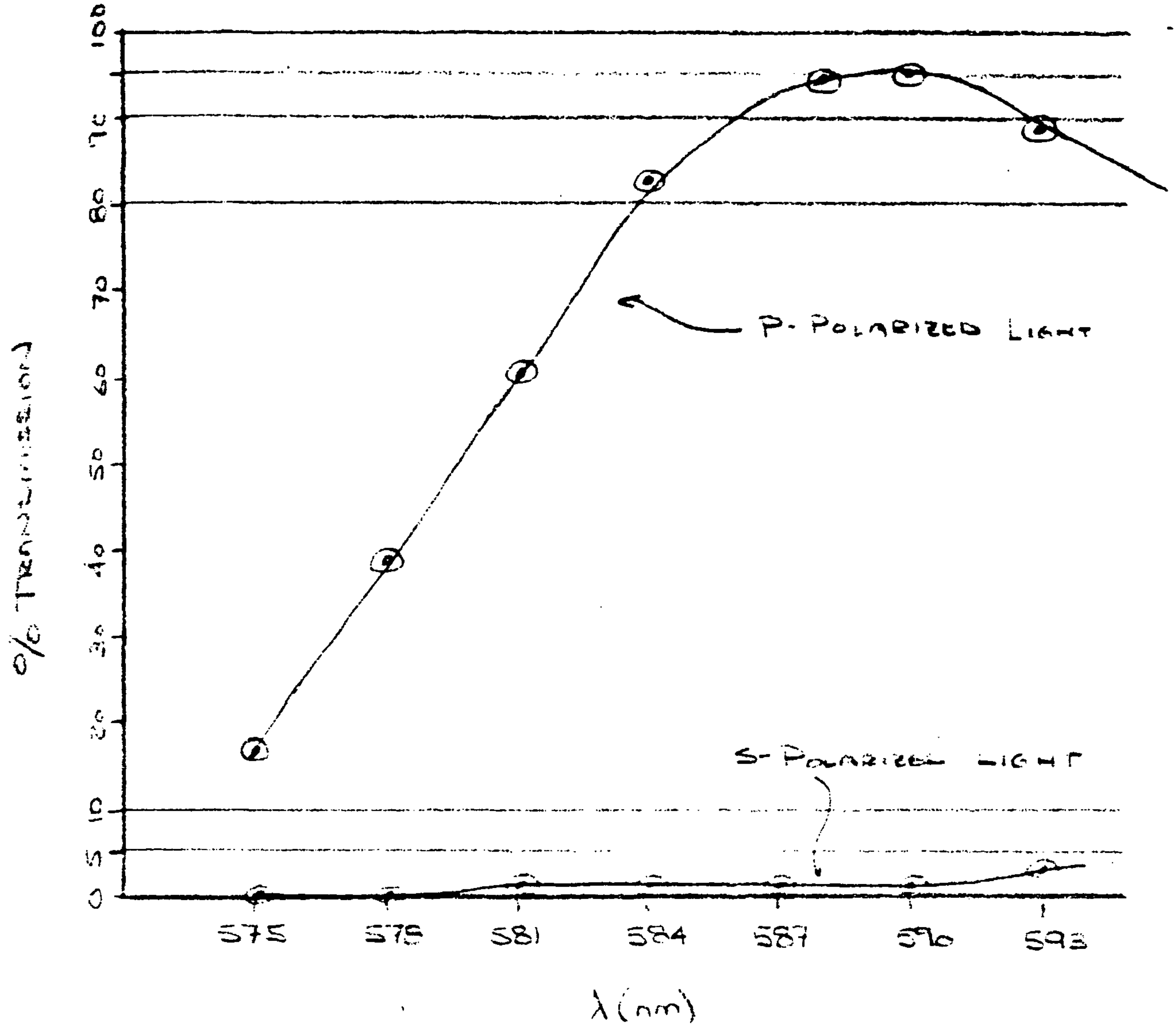
Pockels-cell electro-optic modulator (E.O.M.), an achromatic λ/2 retardation plate, and the dye cell itself. The dye cell consists of a quartz tube mounted inside a 300 J ILC coaxial flashlamp. In the resulting triaxial configuration the dye solution (Rhodamine 6G dissolved in ethanol) was pumped through the quartz tube while distilled water, acting as a coolant, was pumped through the chamber between the quartz tube and the inner wall of the flashlamp. In order to minimize thermal gradients in the dye, the dye solution and the coolant were maintained at nearly equal temperatures through the use of a heat exchanger which was, itself, immersed in a tap-water reservoir so both solutions were kept at near room temperatures. Dye laser pulses of 6 ns duration and energies of 10-40 μJ were produced by a commercial system (Molectron UV-24 N_2-laser pump and Molectron DL-300 dye laser) and injected into the laser amplifier stage. The injected laser light pulse enters the amplifier optical cavity from the right as p-polarized light which is transmitted by the PBSC. Initially, the EOM remains off, effecting no polarization rotation, until the light pulse has passed completely through, at which point it is turned on. The λ/2 plate rotates the polarization of the pulse to s-polarization so that it is reflected by the left-hand PBSC and directed around the cavity in a clockwise manner by the turning mirrors. The EOM, now on, together with the λ/2 plate confines the pulse within the cavity for regenerative amplification. The growth of the pulse during amplification is monitored by observing the spontaneous emission of the dye, as detailed in the last report. When the amplified pulse is observed to be well into the saturation regime, where little additional amplification occurs, the EOM is turned off. The pulse will then exit the cavity as p-polarized light from the left-hand PBSC.

III. Injection-Locking

In order for regenerative amplification of the injected beam to occur without spectral broadening it is necessary to injection-lock the amplifier. In the injection-locking process the presence of an injected laser pulse forces the laser light in the amplifier to build up preferentially at the wavelength and direction of propagation of the injected pulse provided that the injected pulse is of sufficient intensity to override the buildup of radiation in all other possible laser modes. Although the July 1983 report found the injection-locking threshold intensity to be $\sim$ 2-10 kw/cm^2 (corresponding to input pulse energies of 1-5 μJ) it is clear that the arrival time of the injected pulse with respect to the flashlamp-pumping pulse is also a critical parameter (one which, in effect, determines the threshold intensity). If the injected pulse is trapped within the cavity prior to the initiation of the flashlamp-pumping pulse it will be rapidly absorbed by the dye solution and insufficient energy will remain to "lock" the amplifier. On the other hand, if the injected pulse arrives well after the initiation of the flashlamp-pulse it will be of insufficient energy to override already existing laser modes. As the optimal injection time is a strong function of flashlamp-pumping energy, injected wavelength, and overall system jitter, quantitative efforts to determine this parameter were abandoned. In general, however, it was observed that the system performed best for injection times of 200-300 nsec after the beginning of the flashlamp-pulse which corresponds roughly to the point at which unity gain occurs for the amplifier. The optimal extraction time was then found by varying the amount of time the EOM was on and observing the output pulse energies. Output energies were maximized, independent of wavelength and pumping energy, when extraction occurred at the peak of the pumping pulse.

IV. Improvements Over the Period July-December 1983

As concluded in the July 1983 report a limitation on output pulse energy was imposed by the damage threshold of the PBSCs. The PBSCs, which are cemented components, were, thus, replaced with "open-faced" thin-film polarizers (TFPs) which like the PBSCs reflect s-polarized light and transmit p-polarized light, but possess a damage threshold of $\geq 1 \mathrm{Gw/cm}^2$. The TFPs, however, have narrowband coatings so that for a given angle of incidence, p-transmittance will remain near unity for only a small range of wavelengths (±2nm) around the center wavelength, λ_c (s-reflectance is relatively insensitive to wavelength). The dispersion characteristics of the TFPs are shown in Fig. 2. For these measurements the angle of incidence, θ_i, was set to maximize p-transmittance at $\lambda_c = 590$ nm. By altering θ_i, λ_c could be shifted throughout most of the desired tuning range, but for each change in θ_i, a complete realignment of the amplifier would be required; hence, θ_i was fixed for $\lambda_c = 590$ nm. With the optical cavity configurattion identical to that of Fig. 1, with the exception that the PBSCs were now replaced with the TFPs, the amplifier output pulse contained "broad shoulders" both before and after the cavity-dumped pulse. The front "shoulder" (i.e. that which preceeds the cavity-dumped pulse) arises from the feedback and amplification of incorrectly polarized light which, being incorrectly polarized, "leaks" out of the cavity before the E.O.M is switched off. After the E.O.M. is switched off, and the cavity is "dumped", the optical cavity is that of a double-pass oscillator. Since the optimal extraction time of the amplified pulse occurs roughly at the peak of the flashlamp-pumping pulse, enough gain remains in the system for two-pass laser oscillation to occur. It is this radiation which constitutes the "rear shoulder" of the amplified pulse. Spectral analysis of these shoulders indicated that regardless of injected wavelength,



Dispersion Characteristic of

High-Power Thin-Film Polarizers

Figure 2

they were composed of broadband radiation centered at $\lambda \sim 578$ nm. This was predictable, since the p-reflectance of the TFPs at $\lambda = 578$ nm was ~40% (Fig.2) substantial amounts of incorrectly polarized off-color radiation could build up and be emitted before the state of the Pockels cell was changed. Two-pass oscillation at $\lambda = 578$ nm, after cavity-dumping, was also enhanced due to the increased overall feedback at this wavelength.

In view of these results, it became clear that both polarization and spectral purity must be maintained in the amplifier cavity in order to extract as "clean" an output pulse as possible. To achieve this, a 3-element birefringent filter was added to the cavity (Fig.3). The birefringent filter is a low-insertion loss, easily tunable frequency-selective device which has the added advantage of also being polarization-selective, as the 3-elements are placed at Brewster's angle with respect to the incident beam. The presence of a tuning element also aides injection-locking as it reduces the number of modes with which the injected pulse has to compete, thus decreasing the threshold energy for injection-locking. Typical output pulses, with the birefringent filter installed, are shown in Figures 4 and 5. These figures indicate the improvement due to the filter throughout the entire tuning range (582-594 nm). The improvement is due to suppression of the amplification of off-color radiation which

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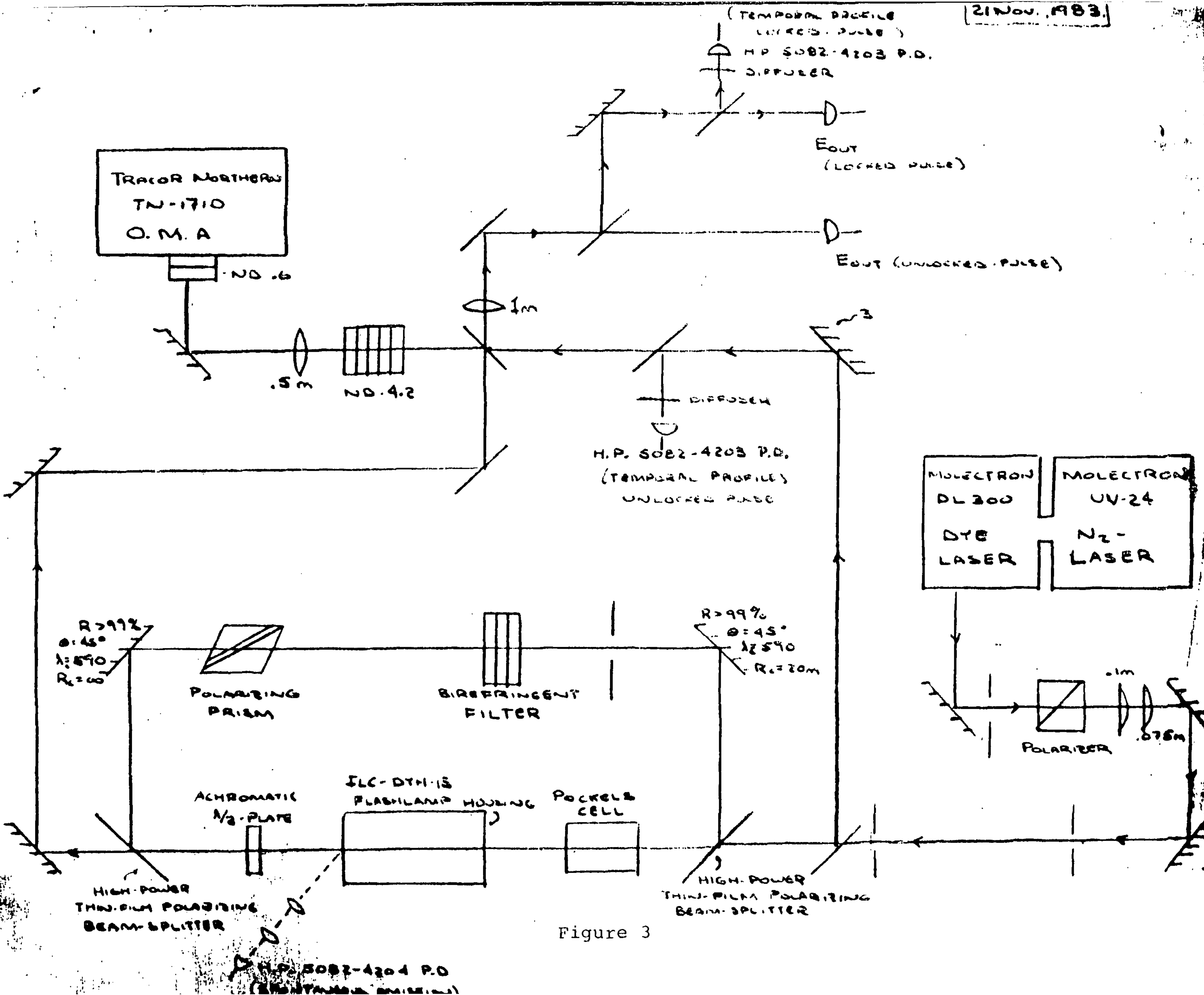
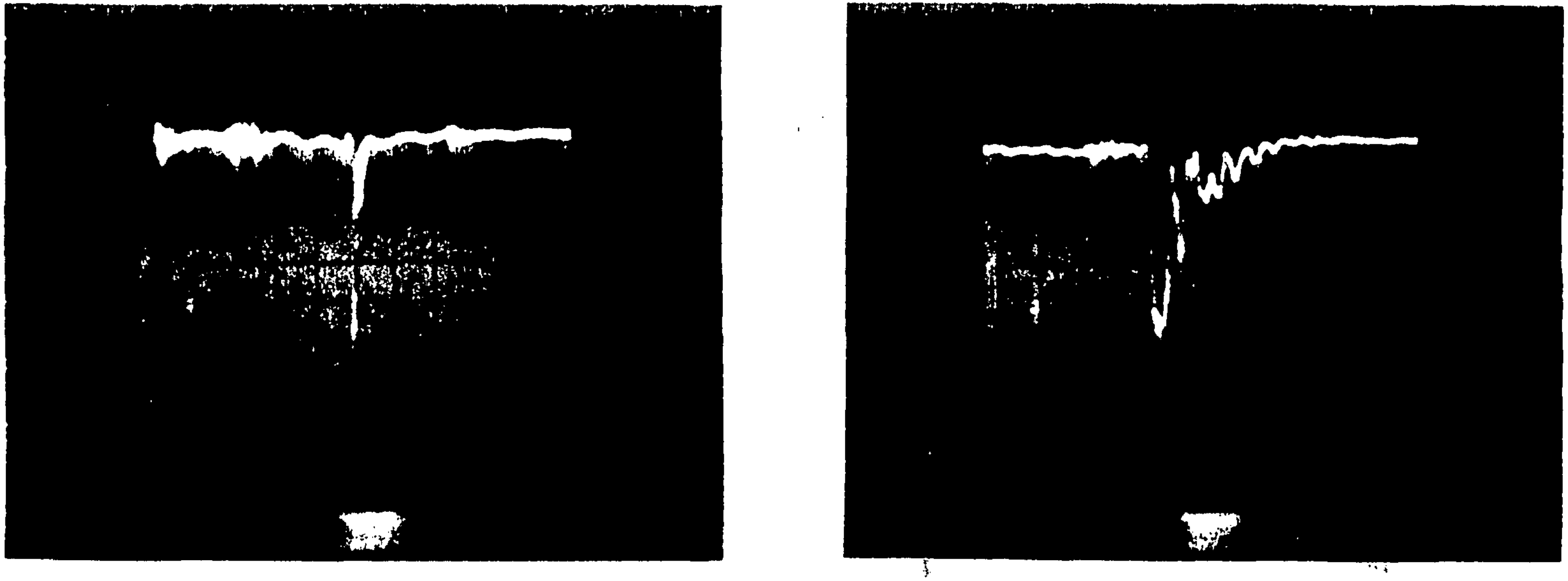


Figure 3



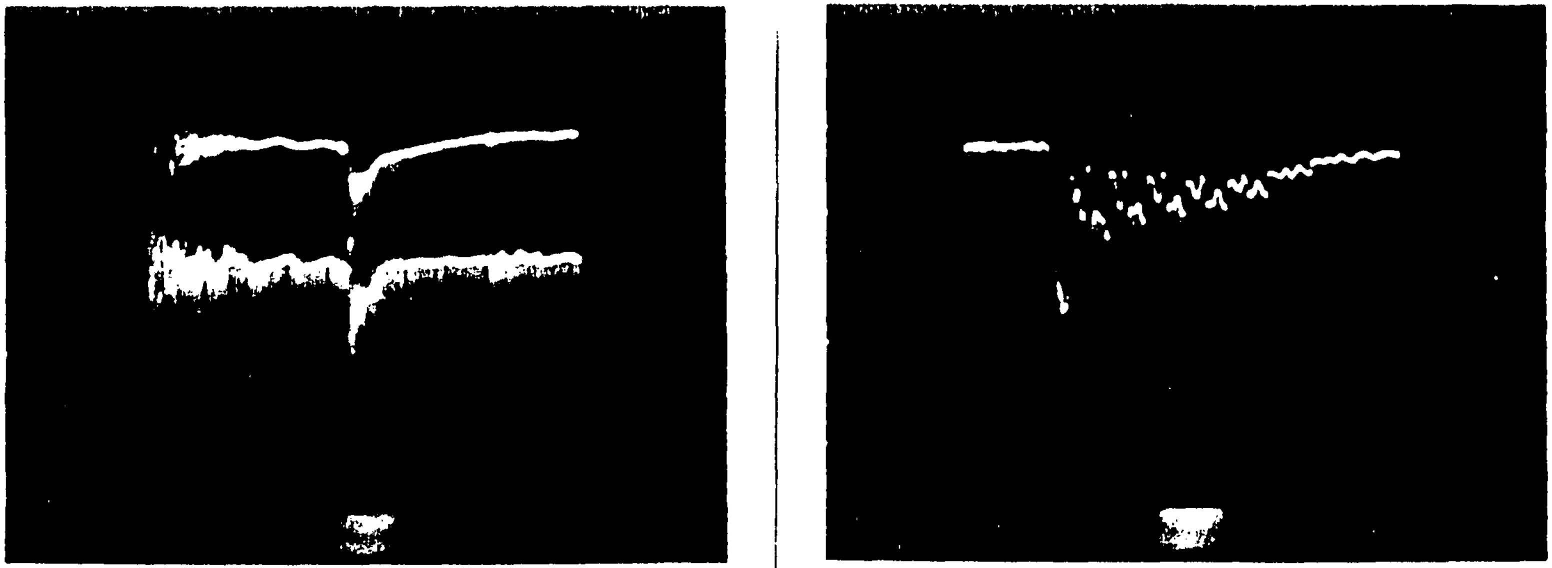
Hor.: 200ns/cm

Hor.: 20ns/cm

Typical Amplified Pulse for 588 nm $\leq \lambda \leq$ 592 nm

E_{out} = 40mj, E_{pump} = 140J, $\Delta\lambda$ [illegible]

Figure 4



Top: Total Pulse at 200ns/cm
Bot: Pulse as seen through a monochromator set at $\lambda = \lambda_{inj}$

Total Pulse at 20 ns/cm

Typical Amplified Pulse for $\lambda <$ 588 nm, $\lambda >$ 592 nm
without prism polarizer

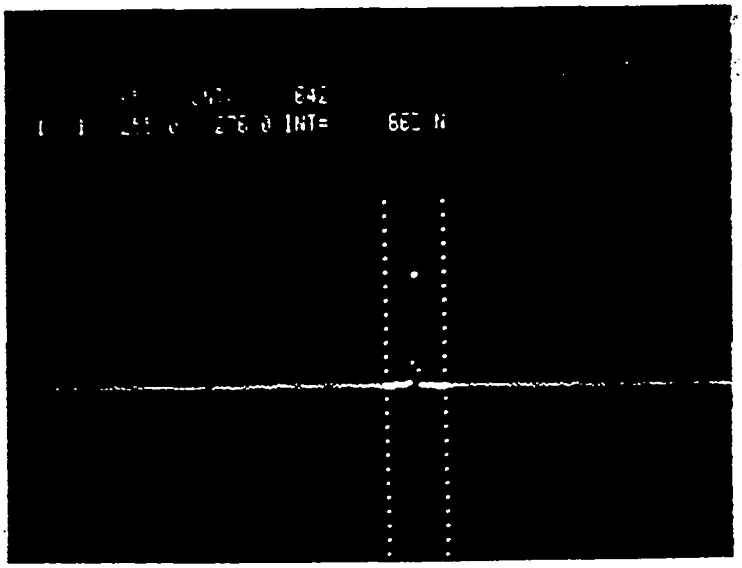
Figure 5

comprised the front shoulder of the amplified pulse. Figure 4 is a typical output pulse in the range 588-592 nm. However, as Fig. 5 indicates, when the laser is operated at a frequency where the p-reflectance of the TFP is high ($\lambda < 588$ nm, $\lambda > 592$ nm) the spectral and polarization dispersion added by the birefringent filter was still insufficient to suppress the off-color laser radiation constituting the "rear shoulder."

The periodic oscillations, following the cavity-dumped pulse in both figures, are due to the non-zero turn-off time of the E.O.M. as light passing through the E.O.M. while it is changing state emerges with a mixed polarization state which results in the feedback of a fraction of the amplified pulse back into the cavity. To further increase polarization dispersion, a high-power air-spaced birefringent prism polarizer was added to the cavity (Fig. 3). This additional dispersion was sufficient to quench most of the "rear shoulder" of the amplified pulse.

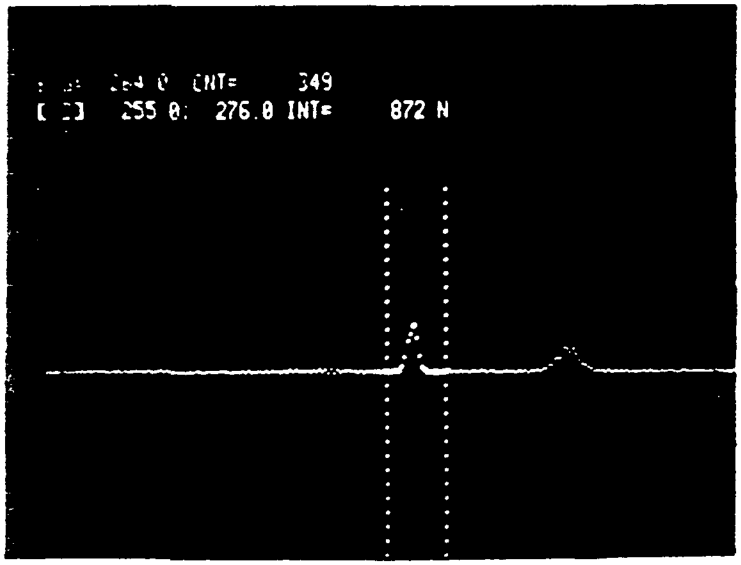
Although the temporal profile of the pulse was as clean as we have achieved and output pulse energies were typically as high as 40-45 mJ for flashlamp pumping energies of 200 J, it was unclear as to what fraction of the measured output pulse energy was actually in the remaining off-color radiation. In an effort to determine this a Tracor Northern TN1710 Optical Multichannel Analyzer (OMA) supplied by NASA was installed. The OMA not only functions as a spectrometer with a 1A/pixel resolution, but it also has an integrating feature which allows the relative energies of various spectral bands to be compared. Figure 6 is an OMA display of the spectral profile of the injected pulse prior to amplification. The vertical bars identify the bounds of the spectral region over which the pixel counts are to be integrated. Subtraction of the counts due to background radiation is automatically performed by the OMA. Figure 7 presents a spectral profile of the output of the system when run as a cavity-dumped oscillator (i.e. no pulse is injected). The integration, here, is being performed on the cavity-dumped pulse whose center frequency ($\lambda = 585$ nm) and relatively narrow linewidth (~0.5 nm) are determined by the passband of the birefringent filter. Note, also, in this figure the off-color radiation whose wavelength is centered at $\lambda \sim 577$ nm . When the laser functions as an injection-locked amplifier, however, (Fig.8) not only is the spectral profile of the amplified pulse identical to that of the injected pulse, but the output energy exiting through the left-hand TFP at the injected wavelength ($\lambda = 585$ nm) (as indicated by the INT (integral) readings in the figures) is almost twice that of the system when no injection occurs. This is definitive evidence that the amplifier is, indeed, injection-locked. As an oscillator, counterpropagating pulses exist in in the ring-cavity, each with equal energy, and when the cavity is dumped each will exit through a different TFP. However,

- OMA DISPLAYS
- Resolution of all figures 1.2A/pixel



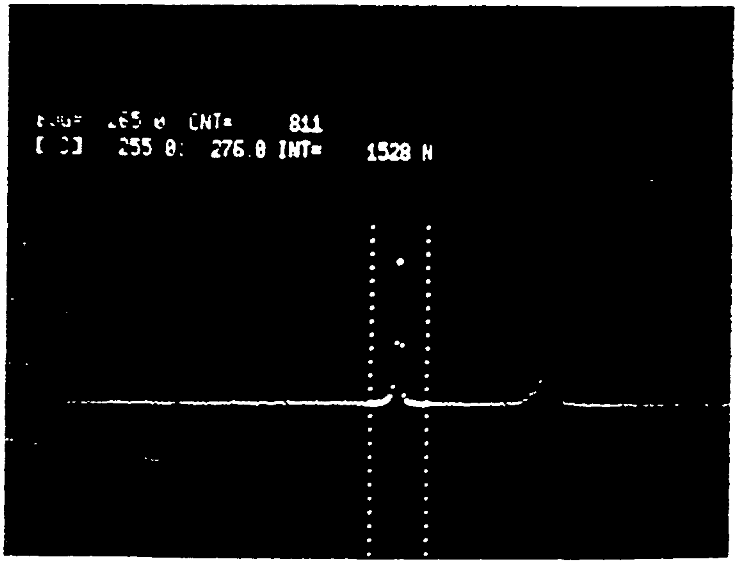
Spectral Profile of Injected Pulse
Prior to Amplification

Figure 6



Unlocked (Oscillator) Output
E_{out} = 22 mJ; E_{pump} = 140 J; λ = 585 nm

Figure 7

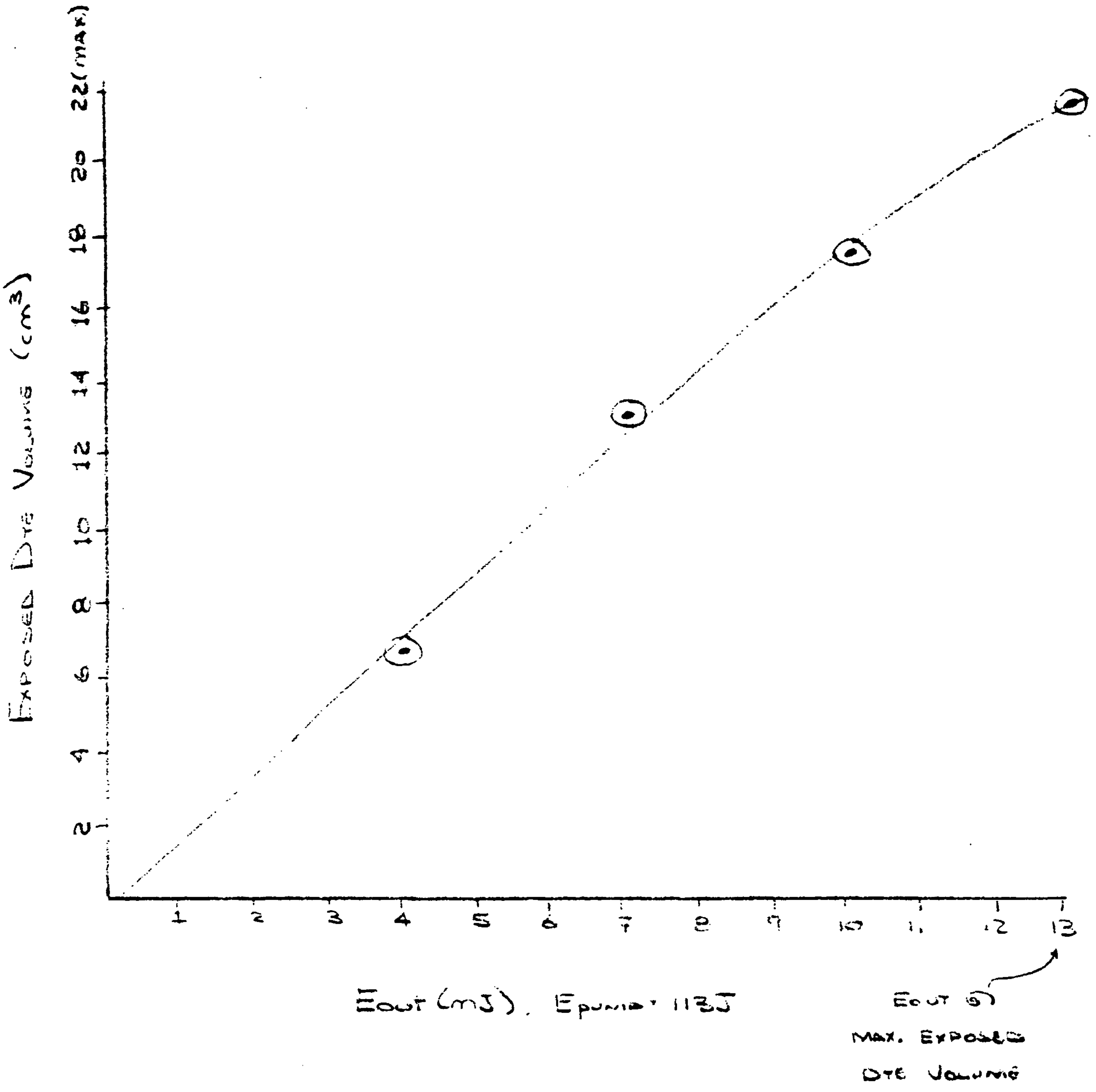


Injection-Locked (Amplifier) Output
E_{out} = 35 mJ; E_{pump} = 140 J; λ = 585 nm

Figure 8

as an injection-locked system the clockwise-traveling pulse will exhibit more rapid growth forcing all of the stored energy to exit through the lefthand TFP so that the measured output energy will be about twice that as when the laser functions as an oscillator. As the OMA display of Fig. 8 indicates, as much as 35% of the total output energy is in the broadband off-color radiation. This is evidence that the cavity is still not spectrally dispersive enough. Preliminary investigations into the possibility of using a linear optical cavity configuration incorporating one or two Littrow prisms, (which are more dispersive than the birefringent filter) have proved successful in totally eliminating all off-color radiation without substantial losses in output pulse energy. Further investigations are presently underway.

During this period an investigation into the spatial profile of the amplified pulse was also performed. According to Gaussian-optics calculations for the optical configuration as shown in Fig.3 the beam diameter at the Gaussian beam waist, $2w_0$ is 1.8 mm while the beam diameter in the dye cell is only slightly larger, $2w_1 = 2.0$ mm . As the dye cell has a diameter of 9mm it appeared that the active dye volume was only a small fraction of that available. Since the only focusing optic in the cavity was a 20mRC mirror little was to be gained by replacing it with a longer focal length mirror. Previous attempts at replacing the 20mRC mirror with a plane mirror proved unsuccessful as output energies decreased due to increased diffraction losses. However, by incorporating a magnifying Galilean telescope into the amplifier cavity the beam diameter could gradually be expanded so that at the extraction time $2w_1 = 9$ mm. By increasing the active dye volume 20 times a dramatic increase in output energy would be expected. In an effort to determine how much could be gained by such a scheme an aperture was placed in the cavity at the output of the dye cell so that by recording output energy as a function of the aperture diameter a spatial profile of the amplified pulse could be obtained. From the spatial profile the active dye volume can be inferred. The data (Fig. 9) show an almost perfectly linear relationship between output pulse energy and exposed dye volume. This indicated that, in fact, the entire dye volume is active and that nothing is to be gained by expanding the beam diameter. This flat spatial profile (spatial broadening) is further evidence of how far into saturation the amplified pulse has taken the amplifier.



SPATIAL PROFILE OF AMPLIFIED BEAM

Figure 9

V. Summary

Work throughout the period covered in this report has focused on attempts to increase output pulse energy and to "clean up" the temporal profile of the injected pulse. Replacement of the PBSCs with high power TFPs allowed the use of higher flashlamp pumping energies (~200J) enabling the system to generate output pulse energies as high as 40-45 mJ. Although investigations into the possibility of increasing output energies by increasing the active dye volume proved unsuccessful, future work devoted to optimizing laser alignment should produce moderate increases in laser output energy. Through the use of various dispersive elements high polarization and spectral purity was maintained in the cavity allowing the amplified pulse to have, currently, an extremely clean temporal profile. Although some off-color radiation still accompanies the cavity-dumped pulse, current experiments involving the use of Littrow prisms in a linear amplifier configuration are expected to totally eliminate all off-color radiation.