AMPLITUDE-STABILIZED PULSED LASER

Contract No. N00014-70-C-0342

ANNUAL REPORT

covering the period 29 June 1970 to 29 January 1971

Wm. D. Fountain and R. L. Hansen

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Electro-Optics Organization
GTE Sylvania Inc.
Electronic Systems Group
Western Division
P.O. Box 188
Mountain View, California 94040

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Project Engineer/Principal Investigator: Wm. D. Fountain
(415) 966-2261

26 February 1971

Prepared by

Wm. D. Fountain
Electro-Optics Research and
Development Department
Optically-Pumped Lasers Section

R. L. Hansen
Electro-Optics Research and
Development Department,
Optically-Pumped Lasers Section

Approved by

L. M. Osterink
L. M. Osterink, Manager
Electro-Optics Research and
Development Department

Electro-Optics Organization
GTE Sylvania Inc.
Electronic Systems Group
Western Division
P.O. Box 188
Mountain View, California 94040

FOREWORD

This Annual Report on "Amplitude-Stabilized Pulsed Laser", summarizing work performed during the period 29 June 1970 to 29 Jan. 1971, was prepared by the Electro-Optics Organization of the Western Division of the Electronic Systems Group of GTE Sylvania, Inc., under Contract N00014-70-C-0342. Wm. D. Fountain and R. L. Hansen are the principal investigators under this program; C. B. Hitz, Dr. G. A. Massey, Dr. L. M. Osterink, J. E. Raffarin, and P. Joesi have also contributed materially to this program, and we acknowledge helpful discussions with Prof. S. E. Schwarz of the University of California at Berkeley.

All work under this program is being administered by the Director, Physics Programs, Physical Sciences Div., Office of Naval Research (ONR), Department of the Navy, Arlington, Virginia, under funding from the Advanced Research Projects Agency (ARPA).

ABSTRACT

This report summarizes the results during the reporting period of a program whose goal is the development of a flash-pumped, Q-switched, mode-locked, cavity-dumped, amplitude-stabilized laser operating at approximately 1.06 μm in the fundamental transverse (TEM_{00}) mode. System design is presented, and also test results for those parts of the system which have been completed and tested.

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1. INTRODUCTION

The goal of this program is to design and develop a 1.06 μ laser, operating reliably for long periods of time without damage, with the following specifications:

pulse rate:	10 to 30 pps
pulse duration:	≤ 100 ps
pulse energy:	≥ 50 mJ @ 10 pps
amplitude fluctuation:	≤ 4% of peak (goal: ≤ 2% of peak)
integrated leakage:	≤ 10% of pulse energy
beam quality:	TEM_{00} mode

It is worth noting that at the minimum specified performance (10 pps, 100 ps, 50 mJ) this laser must deliver an average power of 500 mW and a peak power of 500 MW.

These specifications imply that the laser material must have properties comparable to those of $Nd:Y_3A\ell_5O_{12}$ (hereafter, referred to as YAG); otherwise the thermally-induced stresses, focusing, and birefringence present formidable problems. The specifications also imply that the laser must be flash-pumped and Q-switched (to obtain the pulse energy), mode-locked (to obtain the pulse duration), and cavity-dumped (to obtain the pulse-to-pulse stability). Our design approach is presented in Section 2, and the design itself is presented in Sections 3 and 4.

Section 5 is devoted to the current status of this program; it includes experimental verification of our design for those parts of the system which have been tested. Section 6 contains our recommendations for additional work relevant to potential ultimate uses of this laser, and is followed by a list of references and a glossary of abbreviations.

2. DESIGN APPROACH

There are a number of well-known techniques for the intentional mode locking of lasers; they may generally be divided into loss modulation, phase modulation (including schemes which modulate the eigenfrequencies of the resonant cavity), self-injection, and direct injection. One criterion for choosing a technique is the effective modulation depth required, which is directly related to the time required for the laser pulse to build up from noise ($P_n \sim 10^{-13}$ W) to its peak ($P_{pk} \sim 500$ MW). The number of round trips required is approximately given by

$$G^m = P_{pk}/P_n, \qquad (2\text{-}1)$$

where G is the round-trip gain and m is the number of round trips. For this system, $G \gtrsim 10$ and therefore $\lesssim 22$ round trips are required. This implies a very large effective modulation depth, and thus eliminates all mode-locking techniques except electro-optic loss modulation, loss modulation using a bleachable dye, and direct injection.

Electro-optic loss modulation is marginal from the standpoint of modulation depth, and is eliminated by materials considerations. This is so because only $LiNbO_3$ and KDP, of the commonly available quality electro-optic materials, have low RF dissipation factors, but $LiNbO_3$ has a low threshold for laser damage and KDP has a small electro-optic coefficient. Bleachable dyes are inefficient for use in this type of system, since a significant fraction of the laser energy is expended in bleaching the dye; also, the dye must be protected from blue and higher-energy light.

Direct injection mode locking utilizes a subsidiary low-power oscillator, mode-locked by any practical technique, pulses from which are injected into the power oscillator. The peak power of the injected pulse is $P_{inj} \sim 100$W, so the number of round trips required for buildup is approximately

$$G^{m'} = P_{pk}/P_{inj} \qquad (2\text{-}2)$$

which, for this system, yields $m' \lesssim 7$. During this time the noise builds up to a background of approximately

$$P_b = P_n G^{m'} \quad , \qquad (2\text{-}3)$$

so that $P_b \lesssim 500$ nW. Actually, we have significantly overestimated P_b by using the approximation of constant small-signal gain, since the rod inversion is severely depleted during the last few passes of the built-up injected pulse. This method of mode locking has an additional advantage over other techniques in that the subsidiary oscillator can be operated in the TEM_{00} mode with little effort, and the output of this oscillator can then be expanded to fill the effective available aperture of the power oscillator. Our penultimate embodiment of this design approach is shown in Fig. 2.1 (the ultimate embodiment uses Cr,Nd:$YAlO_3$, hereafter referred to as YALO, rather than YAG). The rhomboidal structures in the figure are low-loss four-port polarizers, the design of which is proprietary to GTE Sylvania.

The output amplitude of this system will be actively stabilized. In addition, several aspects of the design promote passive stability. Refer to Figures 2.1, 2.2, and 2.3. The smaller laser rod (~0.150" x 70 mm) is pumped continuously by two tungsten-iodine lamps. The Brewster's-angle c-axis $LiNbO_3$ mode-locking crystal (ML) and the aperture constrain the rod to oscillate quasi-continuously in a polarized, mode-locked, Gaussian beam. Generally, this optical signal can be available outside the laser for timing and/or diagnostic purposes. The larger laser rod (~0.250" x 3") is flash-pumped by two Kr or Xe lamps. This rod is inverted at the end of the lamp pulse since the "Q-switch" (QS) and "rotator" (rot.) crystals are both at $V_{\lambda/4}$ while the "cavity-dump" (CD) crystal is at zero. At this time, "switch No. 1" is switched and a mode-locked pulse is coupled into the larger rod. This pulse has its polarization rotated so that it can build up, after which time the "rotator" is switched to zero. Meanwhile, the "Q-switch" has been switched to zero to allow the pulse to build up, and then "switch No. 2" is switched to provide protective isolation (so that any energy cross-coupled into the "wrong" polarization in the large rod does not disturb the

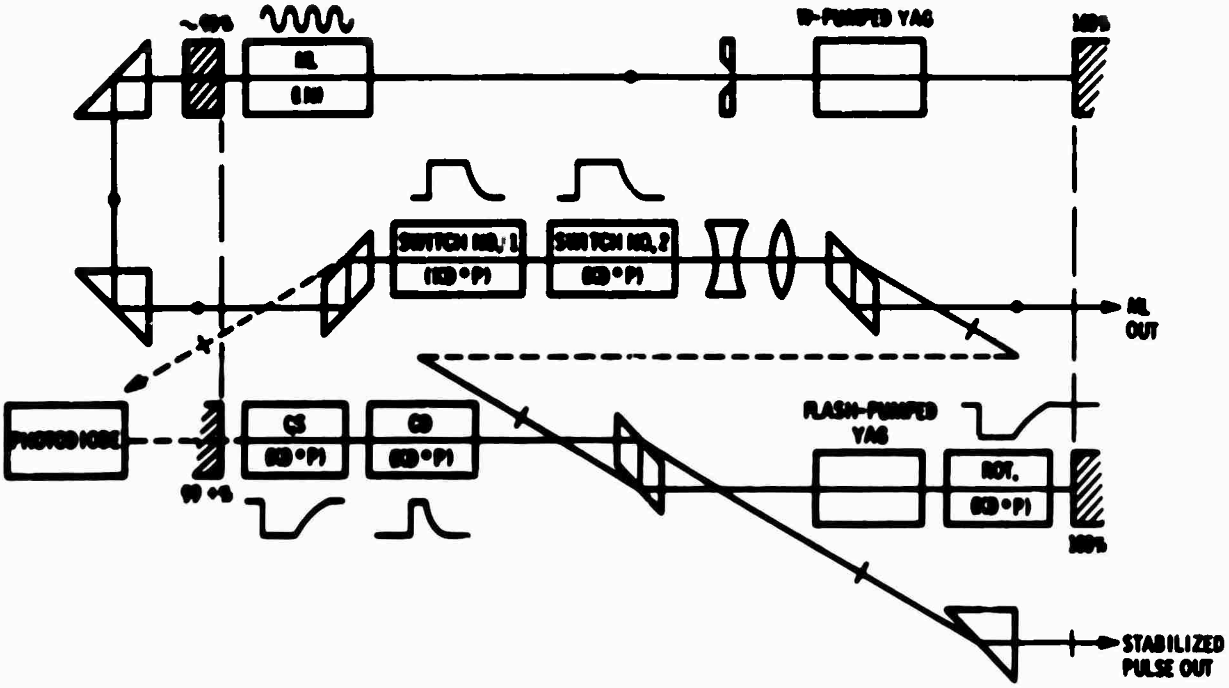

Fig. 2.1 Optical Block Diagram

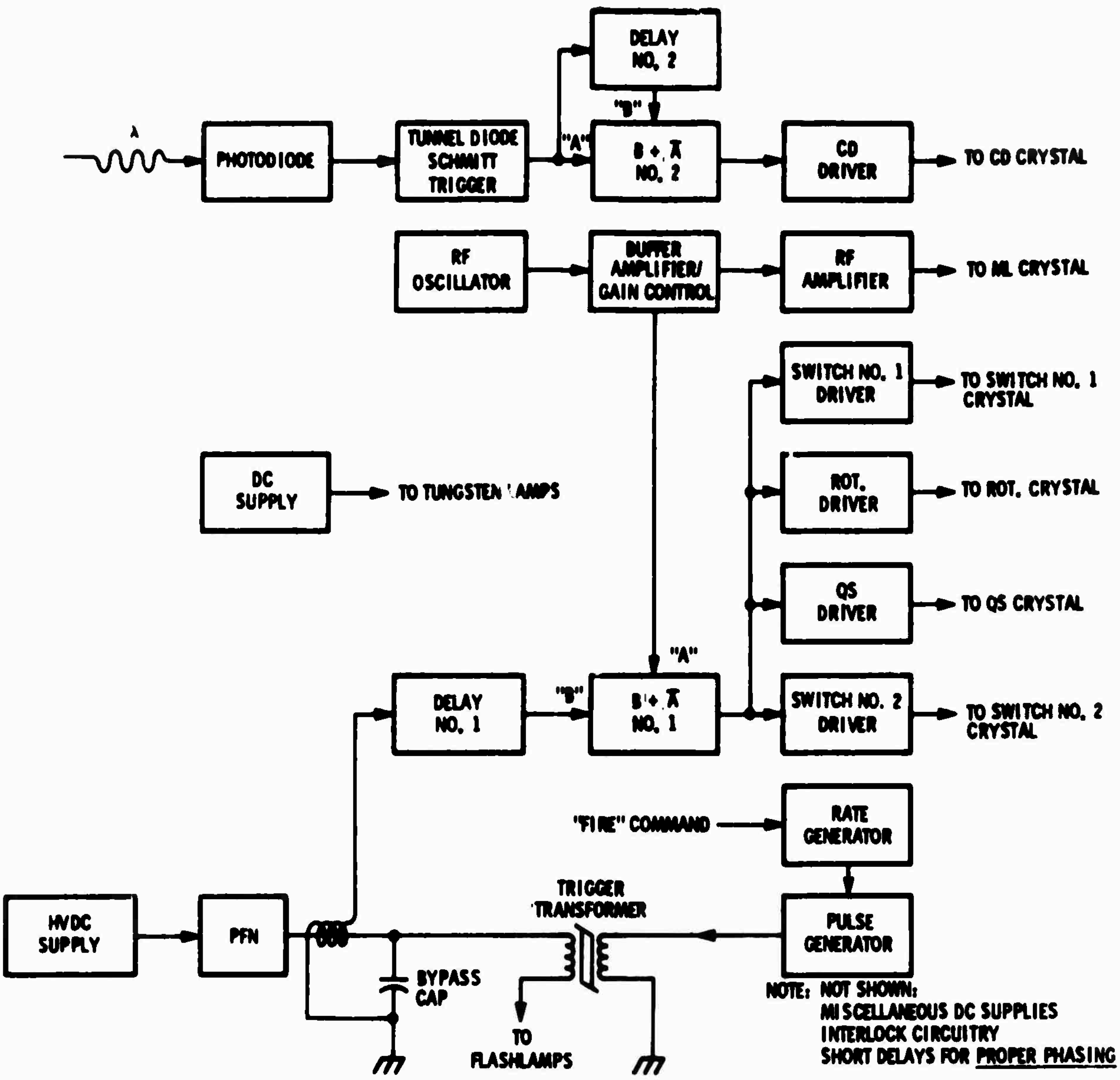

Fig. 2.2 Electronic Block Diagram

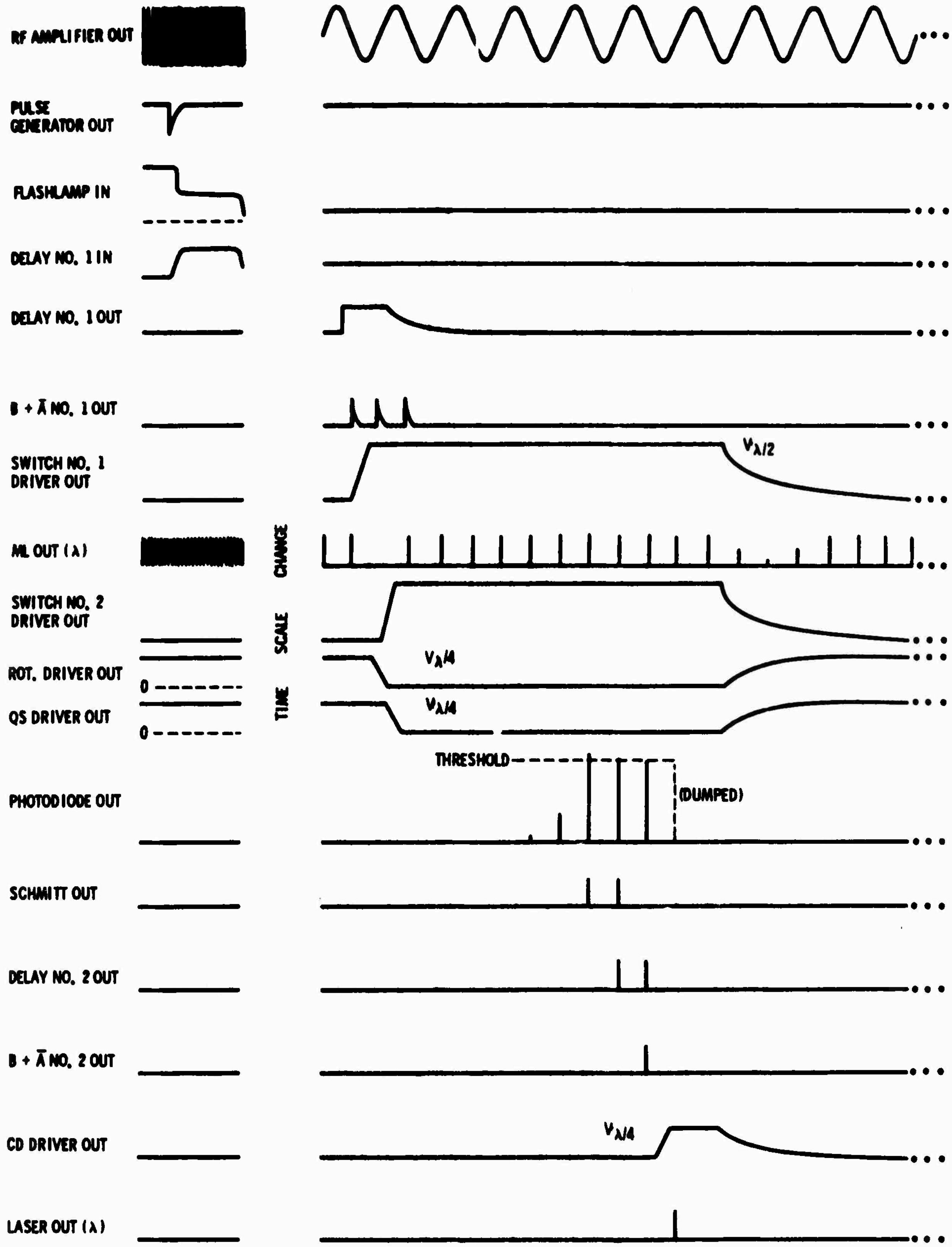

Fig. 2.3 Timing Diagram

mode-locking or cause the $LiNbO_3$ to be damaged). When the intensity of the pulse, as monitored by the photodiode, crosses and recrosses the electronic circuitry's threshold, the pulse is dumped. Since the pulse is dumped during its decay, its amplitude is selectable in steps which differ by the inherent cavity round-trip loss (scattering, absorption, mirror leakage) less the residual round-trip gain. The latter is variable simply by varying delay no. 1 such that switching occurs during the appropriate portion of the end of the flashlamp pulse; hence, the net loss can be minimized, and therefore also the difference between amplitude steps.

We have elected to use YALO rather than YAG as the laser material, because YALO has about twice the energy storage capability of YAG (Ref. 1) and, more important, does not suffer polarization loss due to thermally-induced birefringence (Ref. 2). Thermal focusing effects are similar in the two materials, and optical quality is comparable. GTE Sylvania has accumulated considerable operating experience with this material under in-house programs.

3. OPTIMECHANICAL DESIGN

3.1 SUBSIDIARY OSCILLATOR

The power level obtained from the subsidiary oscillator is not critical; hence we have chosen to use tungsten-iodine-quartz pump lamps for long life and low cost. The lamps are air-cooled (using a built-in blower), but the rod and pump cavity are water-cooled. Mirror and rod-end curvatures are selected to approximately maximize the TEM_{oo} mode volume in the rod, and an aperture constrains oscillation to this mode.

The resonant cavity end plates (which are shared by the power oscillator) are supported on isolation-mounted Invar rods. The resonant cavity is passively stabilized against ambient temperature variations by locating each mirror at a point within its mirror mount such that thermal effects on the mirror mounts, the Invar supports, the mode-locking crystal, and the air path are mutually compensating (the laser rod temperature will be as stable as the city water supply temperature, which normally does not vary by more than a few ^{o}C). Output stability is further enhanced by the modelocking technique, which provides a high effective modulation depth.

The c/2L frequency of the resonant cavity is about 150 MHz. The Brewster-cut c-axis $LiNbO_3$ loss modulator is driven by a 75 MHz sinusoidal voltage (with no dc offset, so that the zero-loss times, which are identical with the voltage zero-crossings, are separated by identical intervals and occur at a 150 MHz rate). Since the zero-loss times occur at the voltage zero-crossings, this technique provides high effective modulation with relatively simple and inexpensive components. This technique does not provide the lowest modulator insertion loss, but maximized output power is not required for this application.

3.2 POWER OSCILLATOR

Optomechanical design of the power oscillator is relatively simple, since beam geometry can be primarily determined by the subsidiary oscillator and the beam-expanding optics, and since passive stabilization of the resonant cavity is not particularly important. The power oscillator, as it is operated in this system, is essentially a regenerative amplifier.

The laser rod, pump cavity, and flashlamps are all water-cooled. The lamps of either oscillator may be changed easily and rapidly without disturbing the optical alignment of any part of the system. During development of this system we will determine whether xenon or krypton lamps are preferred for flash-pumping YALO at these energy levels (Ref. 3); see also Section 4.1.

3.3 MODULATOR AND SWITCHES

The Brewster-cut c-axis $LiNbO_3$ mode-locking crystal is operated with voltage applied to the "a" faces, to obviate acoustic standing waves by forcing all strains to be pure shears (Ref. 4), and is held in a structure (of design proprietary to GTE Sylvania) that provides a high degree of damping for acoustic energy. This damping structure is quite satisfactory except when the applied electrical signal corresponds exactly to a crystal mechanical resonance; however, since the length of the laser resonant cavity may be varied by over 2%, this failing presents no problem. See also Section 4.2.

The optical switches all use 45° z-cut KD*P transverse-field Pockels cells, with Fresnel reflections from the KD*P suppressed by an index-matching liquid. The sw. #1 and sw. #2 crystals comprise one matched pair, the QS and CD crystals comprise another, and the rot. crystals are a third matched pair. It is conceivable that, at the power densities to be encountered in the power oscillator, the index-matching liquid may exhibit power-dependent losses (e.g. Raman scattering); in this event the Pockels cells can be operated without index-matching liquid, if necessary. The Pockels cells and their drivers are assembled in structures with aluminum outer shells for RFI suppression. See also Section 4.4.

3.4 THE LASER CHASSIS

The mounts for all of the optical components except the mirrors are attached to a single baseplate. This baseplate is stiffened transversely by three rectangular bars (to which the adjustable mounting feet are attached) and by the chassis endplates,and longitudinally by two lengths of channel stock. The Invar rods that support the resonant cavity end plates are isolation-mounted to the channels, and the rigid dust-cover is mounted to the channels and the chassis endplates. Most of the plumbing (water, air, and electrical) is confined to the under side of the baseplate, for esthetic reasons.

The high-current components (see Section 4.1) are mounted in a separate enclosure that mates with the laser assembly. This permits a simpler, lighter cable assembly to be used between the control console and the rest of the system (see Figure 4.1), and eases the task of RFI suppression.

4. ELECTRONIC DESIGN

This section will concisely discuss the electronic circuitry developed to perform the functions indicated on the block and timing diagrams in Fig. 2.2. The laser excitation is covered in 4.1, with important aspects of the rf circuitry being presented in 4.2. Sections 4.3 and 4.4 discuss the logic electronics and Pockels cell drive circuitry performance, respectively. Section 4.5 covers the system's control and protection features.

The lamp power supplies, Pockels cell power supply, control and interlock circuitry, and some of the RF circuitry are contained in the control console, shown in Fig. 4.1. The high current electronics are located in the enclosure associated with the laser chassis, and the remaining electronics are attached to the laser chassis.

4.1 LASER EXCITATION

The tungsten lamps are driven in parallel by a constant-voltage/current-limiting DC power supply. The lamps may be driven to about 1.2 kW each with this supply; since they are rated at 1.5 kW each, long lamp life is assured. The proper lamp envelope temperature is maintained by a built-in air-cooling system.

The flashlamps are driven in series by a double-mesh pulse-forming network (pfn) of critically-damped design (Ref. 5). The lamps are triggered by a series trigger transformer in order to ensure maximum triggering reliability and to provide additional protection against underdamped operation. The polarities of the power supply and trigger pulse are those recommended by the lamp manufacturer for maximized triggering reliability and lamp life (Ref. 6). Lamp life should exceed 10^6 shots with negligible output degradation at the design maximum of 20 J per lamp.

The pfn capacitors are pulse-charged by the charging power supply. This technique, based on a 1600 Hz inverter, allows voltage regulation to $\leq$ 2.5%. A built-in recharge delay allows time for lamp deionization, thus obviating lamp "hang-up" (or, "hold-on").

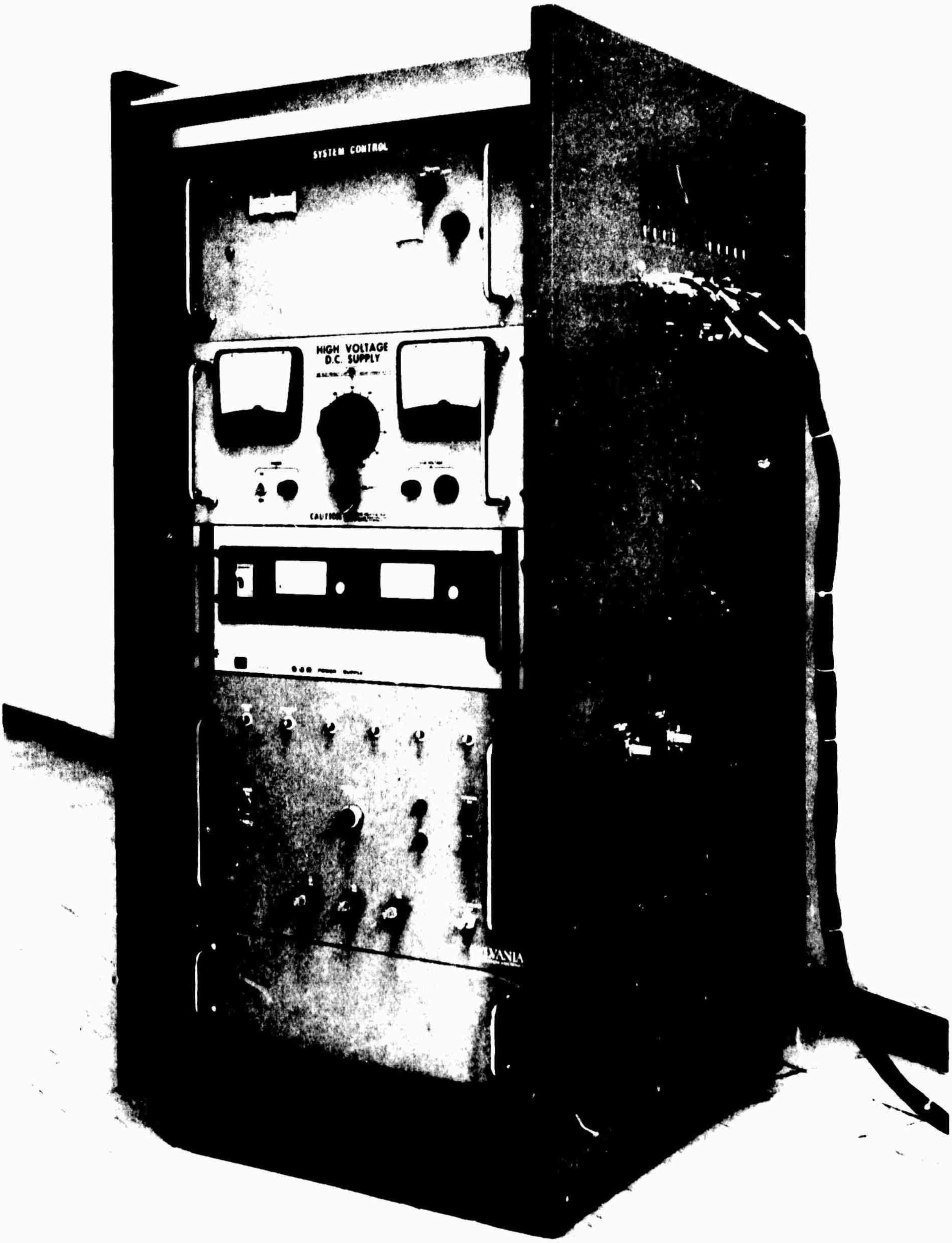

Fig. 4.1 Control Console

4.2 R.F. CIRCUITRY

An amplitude-and frequency-stable r.f. signal is used for two purposes in the system: 1) to drive the $LiNbO_3$ mode-locking crystal, and 2) to provide timing information for the logic circuitry. The signal is generated by an internal 75 MHz solid state oscillator (for determination of the oscillator frequency, see Section 3.1). This unit is mechanically tunable from 60 - 84 MHz at a power output of +15 dbm, constant to 0.5 db from $-30^{\circ}C$ to $+70^{\circ}C$. Its frequency stability is $0.005\%/C^{\circ}$. DC power for the oscillator is +28 Vdc at 20 mA.

One portion of the oscillator output is amplified to a nominal 2 watt (+33 dbm) level by a solid state Sylvania-built r.f. amplifier. The schematic (furnished with the operation manual) utilizes a 2N4072 as a preamplifier and a 2N3961 as the power amplifier stage. Both the r.f. oscillator and its associated amplifier are physically contained in the System Control portion of the control chassis. Since the amplifier is a narrow-band design, the output stage must be re-tuned whenever the oscillator frequency is changed by more than 2 MHz. The DC power required is +28V at 300 mA.

The output of the r.f. amplifier is fed to the crystal matching network, located on the laser chassis. This network, Fig. 4.2, transforms the lossy, capacitive load presented by the $LiNbO_3$ mode-locking crystal to a resistive 50Ω load acceptable to the r.f. amplifier. The network is contained within an aluminum shell to minimize RFI and is mounted on an annular circuit board, similar to those of the Pockels cell drivers (see Fig. 4.4).

4.3 LOGIC AND TIMING CIRCUITRY

The system's logic and timing circuitry are all contained within either the Delay 1 and Logic subassembly located on the System Control chassis, or in the Delay 2 subassembly located on the laser chassis.

The Delay 1 and Logic unit is activated by a signal received from a current monitor which senses the flash lamp current in the power oscillator. After a (nominal) 150 μs adjustable delay, a CA3028A connected as an AND opens and waits for a positive-going, voltage-zero-crossing from the rf oscillator. This condition, of course is satisfied once every rf

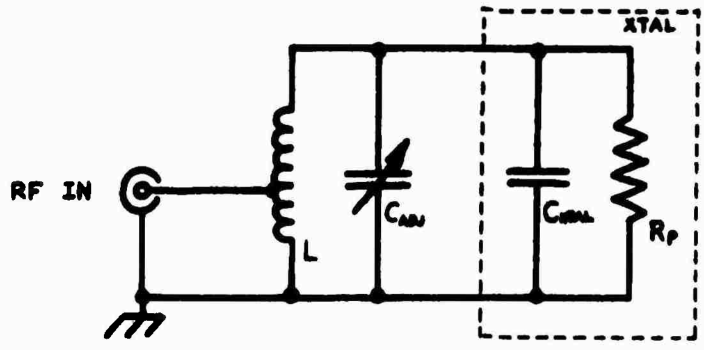

Fig. 4.2 Crystal Matching Network

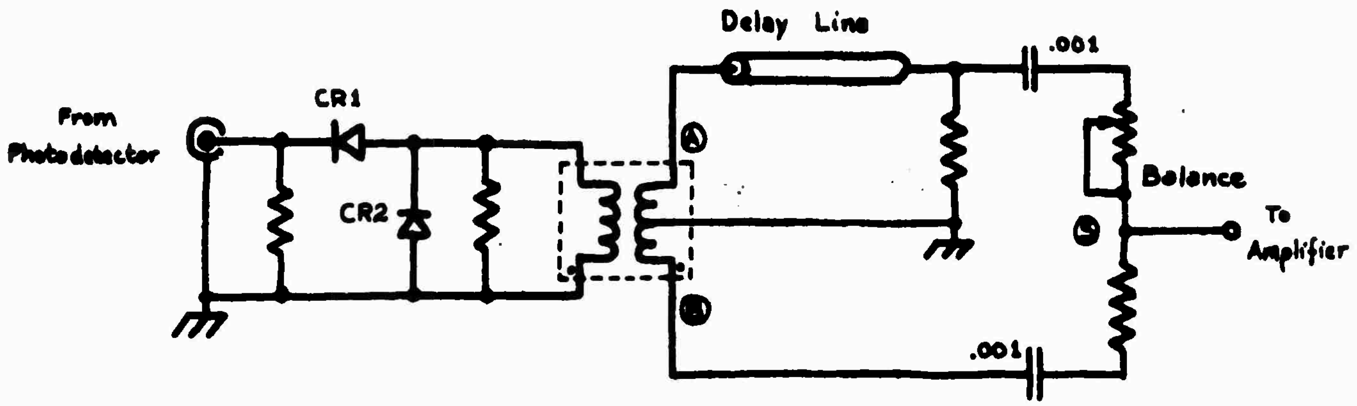

Fig. 4.3 Delay 2

cycle (at 75 MHz). At the coincidence of both input conditions, i.e., the first positive-going zero crossing of the 75 MHz rf, 150 μs after the start of current flow through the power amplifier laser flashlamp, the Delay 1 and Logic unit generates a 5V pulse which is delivered to the Pockels cell drivers associated with Switch No. 1, Switch No. 2, Q-S, and Rot. (see block diagram, Fig. 2.2). The coaxial cable lengths are such that: sw. #1 switches from zero to $V_{\lambda/2}$ just before the selected pulse traverses it; sw. #2 switches from zero to $V_{\lambda/2}$ just after the pulse traverses it; rot. switches from $V_{\lambda/4}$ to zero just after the pulse traverses it (twice - once in each direction); and QS switches from $V_{\lambda/4}$ to zero just before the pulse traverses it.

The Cavity Dump driver is controlled by a command generated in the Delay 2 unit, the heart of which is shown in Fig. 4.3. The unit is completely enclosed in a 1.7" x 2.6" x 4.3" aluminum box, for RFI protection, and is mounted on the laser chassis.

End mirror leakage from the power amplifier cavity is directed via a fiber optic assembly to the active area of a Coherent Optics Model 32 avalanche photodetector. Its output is a negative voltage proportional to the input radiation pulse power. Since the pulse power in the cavity first increases rapidly and then decays, the photodetector output is a group of pulses, the first part of which increase in amplitude rapidly with the remainder decaying at a somewhat slower rate. Referring to Fig. 4.3, the input pulses from the photodetector are clipped to a constant height with CR2. By adjusting a symmetrical π attenuator between the photodetector and the CR1-CR2 diode input, the proper cavity peak power threshold may be selected. This, however, will have to be done with the complete laser package operating.

The constant height photodetector pulses spaced 6.7 ns apart (the cavity round trip time) are fed into a balanced transformer. The CR1-CR2 diode combination assures that the beginning and end of the pulse train correspond to crossing the threshold positively and negatively, respectively. Output (A) (equal in magnitude but opposite in polarity to that at (B)) is delayed by 4.18 ft. of miniature coaxial cable - a delay of 6.7 ns. The cable output and output (B) are summed at (S). The net output at (S) is a pulse coincident with the positive crossing through threshold, and a pulse of opposite polarity occuring 6.7 ns after the negative crossing through threshold. This second pulse is amplified and delivered to the Cavity Dump driver through an appropriate length of cable.

These Sylvania-built circuits, the Delay 1 and Logic unit- and the Delay 2 unit, both require DC power of +28V, at 85 mA and 25 mA respectively.

4.4 POCKELS CELL DRIVE CIRCUITRY

A standard Pockels cell driver, Fig. 4.4, is used as the driver for Switch No. 1, Switch No. 2, Q-S, Cavity Dump, and Rot. (ref to Fig. 2.2). It is a proprietary design that will switch KD*P through 2 kV in 2-3 ns. The electro-optic crystal mounts in the center of the driver assembly with the optical axis coincident with the assembly centerline. The unit is driven with a +4 V logic pulse; it also has the capability to apply a 0 - 2000 Vdc bias to the crystal as required. The complete driver circuit schematic will be included in the operation manual.

4.5 SYSTEM CONTROL AND PROTECTION CIRCUITRY

The PRF for the system is generated by the Rate Generator located in the System Control Console. It produces a continuously variable PRF from 0.5 to 35 pps, and has a manual "single shot" capability. The generator incorporates a unijunction transistor in a relaxation oscillator circuit. The controls for selecting the operating mode (Standby, Manual, Continuous), for controlling the PRF, and the single-shot push button, are all located on the Control Console front panel. Required dc power is +28 V at 30 mA.

Output from the Rate Generator is channelled to the Pulse Generator unit, located near the pulse forming network for the power oscillator flashlamps. This assembly essentially amplifies the 6V pulse from the rate generator to a 600V pulse to drive the flashlamp trigger transformer. The

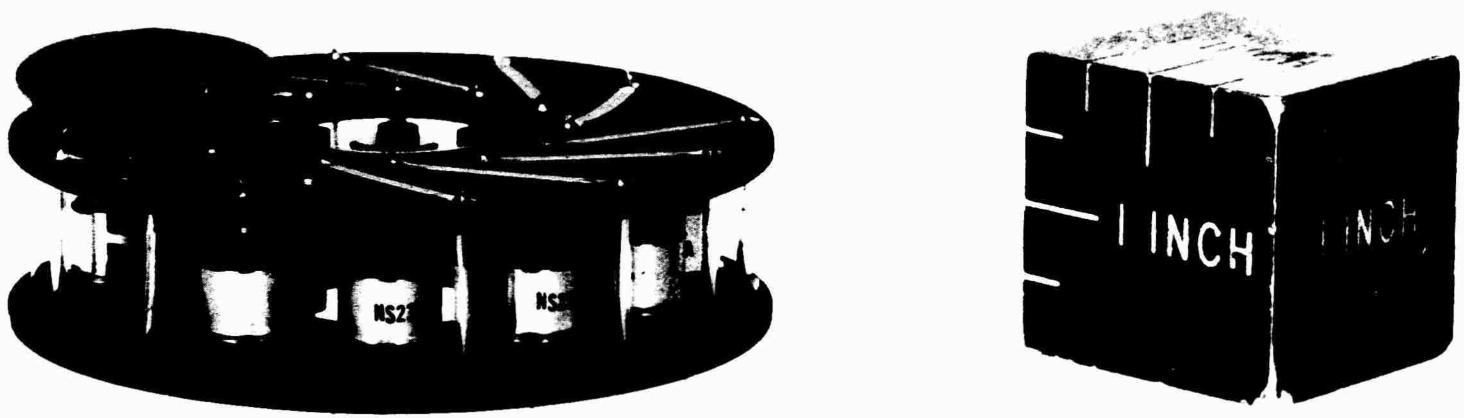

Figure 4-4. GTE Sylvania Pockels Cell Driver

technique is straightforward : discharge a capacitor, via an SCR, through the trigger transformer primary. Further explanation of the pulse forming network is given in Section 4.1.

DC power for the subsidiary laser oscillator, the Pockels cell drivers, and the power laser oscillator is provided by three separate commercially available supplies, an EMI SCR-120-20, a Del 2.5 RHPT-50-1, and an ILC PS1500, respectively. The system voltage (+28 Vdc) is provided by a Powermate UNI-88.

Prime power required for the entire Amplitude-Stabilized Pulsed Laser system is 3Ø, 60 Hz, 120V/208V, "WYE"connected. Total system input power will be approximately 4.7 KVA at about 13 amps per leg. The only other required system input is tapwater for cooling at nominal rate of 2.5 gpm.

The system is interlocked for both equipment and personnel protection and will cease operation if the console rear door is opened, or if the laser cover is removed or if the pulse-forming network cover is removed. (These interlocks may be overridden if it is mandatory that the system operate with a cover off or the door open.) In addition, if coolant water pressure is lost, or if a fault occurs within the cooling system (flow tube breakage, for example) the system will immediately shut down to avoid damage to other critical system components. The operator can, of course, stop the system at any time by merely opening the main power switch on the System Control front panel.

All of the above indicated methods of stopping system operation remove ac power from all but one component, that being the fan which provides cooling to the pump lamps in the subsidiary laser oscillator. (It runs for approximately 15 seconds after the system has been shut off.)

The Laser Chassis and the System Control Console may be operated up to 10 feet apart and an electrical cable assembly is provided as are the interconnecting coolant hoses.

5. PROGRAM STATUS

Upon finalization of the system design approach, detailed optical and electronic design began. The start of electronic fabrication soon followed, with the result that electronic assembly and preliminary testing has been completed. The rf amplifier output was measured at 1.9 watts over an 8-hour period. Both logic units have operated normally for an 8-hour period with any further testing and time delay adjusting to be done when the laser is in operation. The prime power DC supplies have been tested (with the exception of the ILC PS1500) with equivalent resistive loads. The control and interlock circuitry has been tested and calibrated. All parts of the System Control Console have been installed with its interunit cabling completed and checked. The 10-foot Laser-Console cable assembly is completed. Final timing adjusting, voltage level setting, and adjustment of rf power levels will be completed when the lasers are turned on and the KD*P crystals used. All major electronic parts and sub assembles are complete and tested.

Optomechanical procurement and assembly have lagged somewhat behind the electronic system units, with the result that the laser chassis portion of the system is about 50% assembled. Both laser rods, pump lamps and associated laser head hardware (except pump cavity inserts) are in house and partially assembled with the subsidiary oscillator turn-on expected during the week of 1 March 1971. The power oscillator turn-on should follow in about 1.5 weeks. The KD*P Pockels cell crystals are not in house at this time, hence completion of the crystal assembles is pending. Mechanical parts (mirror mounts, coolant assemblies, crystal holders, etc.) have been completed by our shop and will be mounted on the laser chassis shortly.

6. RECOMMENDATIONS

For a number of potential applications of systems of the sort described above, higher pulse energy is very desirable. The most efficient and straightforward approach to this goal is to combine an oscillator such as this one with a chain of saturated amplifiers. The use of saturated amplifiers not only enhances the efficiency of the system, but it also improves the pulse-to-pulse amplitude stability available from the oscillator and negates the possibilities of significant after-pulsing and amplified target reflection.

The key to saturated amplifier design is the parameter $\beta E_{in}/A$, where β is the specific gain of the material ($\beta = \sigma/h\nu$, where σ is the laser ion cross section for stimulated emission and $h\nu$ is the energy of a laser photon), E_{in} is the energy of the radiation pulse to be amplified, and A is the effective amplifier cross-sectional area. If $E_{in}/A \geq \beta^{-1}$, the stored energy remaining in the amplifier after passage of the pulse will be less than 1/e of the stored energy just prior to passage of the pulse. We find that for YAG, $\beta^{-1} \doteq 210$ mJ/cm^2 @ 1.0641µm (Ref. 7); for YALO, $\beta^{-1} \doteq 400$ mJ/cm^2 @ 1.065µm (References 1 and 7); and for Owens-Illinois ED-2 laser glass, $\beta^{-1} \doteq 6.2$ J/cm^2 @ 1.0623µm (from manufacturer's data).

For moderate amplified-pulse energies, YALO is the amplifier material of choice: for example, we calculate that three saturated YALO amplifier stages will provide an output energy of approximately 4 J/pulse. To obtain much higher energies, additional amplifier stages utilizing Nd:glass can be used.

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8. GLOSSARY

ARPA	Advanced Research Projects Agency
CD	cavity-dump
KDP	KH_2PO_4
KD*P	KD_2PO_4
ML	mode-locking
ONR	Office of Naval Research
QS	Q switch
rot.	rotator
sw.	switch
YAG	here, $Nd:Y_3A\ell_5O_{12}$
YALO	here, $Cr,Nd:YA\ell O_3$