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# Nd:YAG LASER DEVELOPMENT FOR SPACEBORNE LASER RANGING SYSTEM 

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15. Supplementary Notes

This report sumarizes the results of the development of a unigue modelocked laser device to be utilized in future NASA space-based, ultraprecision laser ranging systems. The engineerting breadboara constructed proved the feasibility of the pump-pulsed, actively modelocked, Fm Q-switched $N d: Y A G$ laser concept for the generation of sumamosecond pulses
 double-pass Nd:YAG amplifier and provision for a pype II KD*P frequency doubler. The specific technical accomplishment was the generation of single 150 psed, 20 mm pulses at 10 pps at a wevelength of 1.064 gicicrometers wing 25 dA sappression of pre-and post-pulses.

The significant hardware implementations within the engineering breadboard were the rugged, crossed mir prism, integral Invar optical bed subboard were the rugged, crossed PIR prism, integral Invar optical bed sub-
system; the pulsed eiectro-optical $\mathrm{KD*F}$ modelocker; and the pre-Iase and system the pulsed eiectro-optical kD* modelocker; and the pre-Iase and
switching synchronization controi electronic dircuits. The success of these subsystems establishes the engineering breadboard as the actual foundation for the planned engineering prototype development.

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## Section I

## INTRODUCTION

GENERAL - In 1975, ILS was. Iunded by the Instrument Electro-Optics Group of NASA Goddard to engage in the development of a state-of-the-art laser transmitter that could serve as one element of a visible, precision optical rangefinder. The scope of the current contract (NAS5-22916) includes a detailed design analysis of the system and development and test of an operational breadboard that would have the potential for spaceborne qualification. NASA's interest in pursuing a development of this nature stems basically from the recognized need to satisfy geophysical measurement requirements generated by the NASA Earth and Ocean Physics Applications Program (EOPAP). One such application centers upon the use of a spaceborne laser terminal which can range to $2-\mathrm{cm}$ accuracy against ground based retroreflectors. The laser system developed to meet these requirements consisted of a Nd:YAG, subnanosecond pulse oscillator, a double-pass Nd:YAG amplifier, and a Type II KD*P frequency doubler. As originally conceived, the program called for completion of preliminary system tests of the engineering model in 1978 followed by an initial space flight demonstration aboard Spacelab in the 1980-81 time frame.

This report describes the results of the design and analysis efforts undertaken to develop the Spaceborne transmitter design and includes details of the constructed hardware. Breadboard performance is also reviewed covering evaluation testing that has been performed to date. A brief overview of the program technical objectives highlighting key physical/functional features of the assembled hardware is given below.
A. PROGRAM OBJECTIVES

The contract statement of work and performance specification are summarized in NASA RFP Solicitation 5-28413/227. The principal elements of the program call for the development and test of the laser transmitter in two phases: The Phase I activity centering primarily on the detailed design, analyses and preliminary evaluation of breadboard performance whereas the. Phase II activity (as originally scoped) related to an advanced development leading to the delivery of an engineering prototype suitable for integration into NASA's precision rangefinder engineering model. . For background,
it is work noting that early in the program the decision was made to modify the program objectives to reflect construction of the optical bed engineering prototype as part of the Phase I effort. The unanticipated complexity of this optical bed resulted in schedule delays and cost increases in completing the originally forecasted Phase I milestones. However, it is felt the decision to go directly to an optical bed prototype design'in the initial program phase could result in savings both with regard to total program cost and hardware delivery schedule. The optical bed design is definitely suited for implementation in Phase II. Table l-l summarizes details of the program objectives as they are presently defined.

## B. HARDWARE DESIGN OVERVIEW

Based upon rationale to be presented in subsequent sections of this report, a flashlamp-pumped, Q-switched, actively modelocked, and cavity-dumped laser oscillator optical configuration is found to have the highest potential for achieving the level of performance specified for the Spaceborne laser transmitter subsystem. These performance specifications are outlined in Table l-2. The requirement to generate very narrow optical pulses at reasonably high output pulse energies at a wavelength of 532 nm necessitates implementing an oscillator-amplifier optical configuration with the oscillator operating in what is commonly referred to as pulse transmission mode (PTM) operation. A view of the overall optical system layout is depicted in Figure 1-1. The layout basically reflects implementation of an oscillator-amplifier configuration with provisions incorporated for output frequency doubling. In the oscillator section, two Pockels cells are used to accommodate both modelocking and simultaneous $\Omega$-switching operation with single-pulse selection. The oscillator derived output is amplified and frequency doubled to produce the desired pulse output. The optical system is part of the transmitter assembly; remaining portions of the system include:

- A power supply (specially designed for operation from 28. V-dc prime power);
- A liquid-to-air, closed-loop cooling system; and
- "An ultrastable RF signal generator module used to actively modelock the system.

A view of the assembled hardware subassemblies is shown in Figure 1-2.

Table 1-1. Spaceborne Program Objectives

| Phase | Objectives |
| :---: | :---: |
| I | 1. Analyze laser subsystem and system concepts. |
|  | 2. Design and fabricate experimental breadboard incorporating PTM Q-switching and active modelocking. <br> 3. Characterize system performance with principal emphasis on oscillator evaluation. |
| II | I. Generate detailed technical/program plan. |
|  | 2. Complete experimental breadboard evaluation including SHG testing. <br> 3. Redesign breadboard to reconfiqure for deliverable hardware. <br> 4. Test and qualify deliverable prototype. |

Table l-2. Spaceborne Laser Specifications

| Characteristic | Specification |
| :---: | :---: |
| Output Energy | $0.025 \mathrm{~J} / \mathrm{pulse}$ |
| Pulse Rate | 10 pps |
| Pulsewidth (10\% PTS) | 200 psec |
| Wavelength | 532 nm |
| Beam Divergence | $\leq 2 \mathrm{X}$ diffraction limit |
| Transverse Mode | TEM ${ }_{\text {O }}$ |
| Polarization | Linear |
| Pulse Amplitude Stability | $\begin{aligned} & \pm 5 \% \text { short-term (min) } \\ & \pm 15 \% \text { long-term (days) } \end{aligned}$ |
| Prime Power | 50 to 75 W |
| Lifetime (50\% OUTPUT) | $10^{8}$ pulses |
| Volume | $1.5 \mathrm{ft}^{3}\left(0.023 \mathrm{~m}^{3}\right)$ |
| Weight | 35 lb ( 15.9 kg ) |
| System Thermal Sink | $20^{\circ} \mathrm{C}$ |
|  | . |

## FOLDOUT FRAME $\mid$



P2780

Figure l-1. Optical System Layout


Figure 1-2. Hardware Subassemblies

The Spaceborne laser system developed on the program represents an advancement in the state-of-the-art of neodymium-doped, yttrium-aluminum-garnet (Nd:YAG) laser devices. Several of the fundamental design concepts implemented in this system previously have been experimentally confirmed. However, to the knowledge of ILS they have not been synthesized in one laser device prior to this program. Additionally, the spaceborne laser implements this synthesis of concepts in a hardware design that ILS believes to be space-qualifiable. The system incorporates many unique design and operational control features which are summarized in Table l-3. As configured, the system requires a maximum prime power input on the order of 300 W and weighs approximately 150 lb .

## C. STATUS SUMMARY

As of the submittal of this report, essentially all Phase I task objectives have been met with the singular exception of experimentally demonstrating frequency-doubled operation. The performance achieved for the modelocked oscillator for optimum operation is summarized in Table $1-4$. The $1.0 \mathrm{~mJ} /$ pulse energy is a limit for reliable operation imposed by laser damage constraints. The maximum picosecond pulse energy generated by the oscillator was 3.0 mJ . The maximum pulse energy generated by the oscillator and double-pass amplifier when modelocking was 28 mJ with an aporoximate pulsewidth of 300 psec with operation at lo pps. The preand post-pulse suppression following the amplifier was 25 db .

Table l-3. Spaceborne Breadboard Design Features

| Component | Feature |
| :---: | :---: |
| Transmitter |  |
| Optical Construction | Crosseत̧ TIR prism, common-mirror resonator. |
|  | Double-pass amplifier utilizing phase retarder/mirror Porro prism. |
|  | Dual Pockels cells for PTM Q-switching and modelocking. |
| Electronic Control | PTM synchronization circuit. |
|  | Prelase radiation control loop. |
| Mechanical Design | Integral Invar optical bed. |
| Power Supply | Flyback design. |
|  | Flashlamp simmer mode. |
| Cooling Supply | Closed-loop liquid cooling. |

Table.l-4. Oscillator Pexformance

| Parameter | Value |
| :--- | :--- |
| Pulse Energy | 1.0 mJ |
| Efficiency | $0.05 \%$ |
| Pulsewidth | 150 psec (FWHM) |
| Beam Divergence | 0.98 mr |
| Mode Diameter (3w) | 1.92 mm |
| Pulse Rate | 10 pps |
| Pre- and Post-Pulse Suppression | 30 dB |
| Pulse Amplitude Stability | $\pm 10 \%$ |

## Section II

## THEORY

A. CONCEPT ANALYSIS

The system concept implemented in the Spaceborne Laser is a flashlamp-pumped, actively modelocked, PTM Q-switched Nd: YAG laser oscillator utilizing prelase and a double-pass Nd:YAG laser amplifier. The laser oscillator concept will be explained in detail in the following paragraphs. Following this explanation will be an overview of the synthesis of theories which provides a mathematical description of the Spaceborne Laser System.

An optical diagram indicating the essential elements necessary to implement the Spaceborne Laser oscillator is given in Figure 2-l. The diagram shows maximum reflectance mirrors terminating the oscillator, a Nd:YAG laser rod, a kickout polarizer, a modelocking modulator, and a $\varrho$-switch modulator. Figure $2-2$ is a diagram illustrating the operational event sequence for the flashlamp-pumped, actively modelocked, PTM Q-switched laser oscillator. (The time scale for each event is compressed or expanded to simplify illustration of the actual event sequence.) The dynamics of the Spaceborne Laser can be divided naturally into three temporal intervals as indicated in Figure 2-2. Flashlamp and modelocking modulator turn-on simultaneously initiate interval $I$. This interval is terminated when prelase radiation begins near the time at which the energy stored in the laser rod is maximum.

The dynamics of interval II involve the most fundamental idea of the Spaceborne Laser concept. During this interval prelase radiation is compressed to a subnanosecond pulse via repeated passes through a modulator whose frequency is synchronized to the photon round-trip frequency of the laser resonator. Given fixed laser and modelocking modulator parameters, the pulsewidth at the end of the prelase interval depends on the number of round-trip passes through the modelocking modulator, i.e., the length of the prelase interval.


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Figure 2-1. Simplified Oscillator Optical Diagram


Figure 2-2. Spaceborne Laser Event Sequence

The buildup time ( $\sim 3 \mu s e c$ ) of the first normal mode pulse emitted by the laser is the prelase interval for the present laser device. Radiation feedback control of the $\Omega$-switch transmission was initially attempted to extend and stabilize the prelase radiation duration. This approach was unsuccessful as implemented by two different experimental circuit designs. The details of these designs and the results achieved are given in a later section of this report.

Interval III of the Spaceborne Laser event sequence is initiated by Q-switching - that is, the Pockels cell transmission is maximized. The subnanosecond pulse is thus trapped between two maximum reflectance mirrors and is regeneratively amplified by the oscillator laser rod. During this amplification period, the pulsewidth of the seed pulse does not change significantly as will be shown in a following section. When the subnanosecond pulse has achieved maximum amplitude, the Q-switch is closed and the pulse is dumped from the resonator. Synchronization of the dump switching time with the propagation of the subnanosecond pulse is achieved electronically by monitoring the pulse amplitude and the modelocking modulator drive signal. The output of the actively modelocked, PTM, Q-switched, Nd:YAG laser is thus a single subnanosecond pulse.

The overall objective of the theory development on this program is to develop a mathematical description of the spaceborne Laser System concept which provides information on energy output, pulsewidth, energy output stability, and pulsewidth stability as a function of energy input to the oscillator and amplifier rods, modelocker modulation depth and frequency, resonator and amplifier losses, and prelase temporal interval. The desired mathematical description of the system concept can be synthesized from laser Q-switching, active modelocking, and amplifier theory plus the use of empirically determined ralationships between the gains of the oscillator and amplifier and their respective input energies. The details of the above theories together with a discussion of the prelase radiation concept are the topics of the remainder of the theory sections of this report. The following paragraphs discuss the synthesis of these theories.

Figure $2-3$ is a block diagram illustrating the inputs required and the outputs obtainable from each of the three theories and how these input/output parameters interrelate. This diagram is essentially self-explanatory with regard to these interrelationships. However, the diagram also illustrates that calcu-


Figure 2-3. Theory Synthesis Diagram
lations using this synthesis of models can proceed in several ways. The constraint on laser output energy imposed by laser material damage limitations indicates the calculational path chosen for use on this program.

Laser damage constraints on the Spaceborne Laser performance are evaluated in a design section of this report. . An important conclusion of this evaluation is that the laser oscillator output energy is limited to low levels. Laser amplifiers, of course, perform most efficiently when the input energy is high level. Thus system efficiency will be maximized for the Spaceborne Laser by operating the oscillator at its highest energy output level within the optical damage constraints. Defining this maximum energy output level is the primary input to calculations using the laser system model.

Most of the input parameters to the Spaceborne Laser System model can be and have been selected via design studies presented in this report. The experimental relationships between the gains and pump energies of the oscillator and amplifier.can be determined. Also, the oscillator and amplifier losses can be determined experimentally. Finally, the one remaining parameter, the prelase interval, can be known experimentally. Thus all the information necessary to use the system model is accessible. Parametric calculations using the system model are presented in the theory sections of this report. These calculations indicate the range of overall system performance that can reasonably be expected. The sensitive parameters for energy output and pulsewidth stability are also determined.

## B. Q-SWITCHED LASER MODEL

The laser model selected to describe the PTM Q-switched Nd:YAG laser is the rate equation model ${ }^{1}$. The Nd:YAG energy levels and energy transfer dynamics are first presented to determine the particular formulation of the rate equations for the Q-switched Nd:YAG laser. Solutions of these equations are then presented which are employed to give characteristic performance of the PTM Q-switched Nd:YAG laser. Finally, energy output and pulse envelope stability are investigated analytically via the laser model.

The energy level structure of Nd:YAG and the energy transfer processes relevant to $Q$-switching are shown in Figure 2-4.


Figure 2-4. Energy Levels and Energy Transfers in Nd:YAG Relevant to Q-switching ${ }^{2}$

The laser transition from the upper sublevel of the ${ }^{4} \mathrm{~F}_{3} / 2$ level to the third sublevel of the ${ }^{4} I_{11 / 2}$ energy level is indicated in this figure via the thick arrow. The remainder of the arrows indicate energy transfers between the sublevels of the ${ }^{4} \mathrm{~F}_{3} / 2$ and ${ }^{4} I_{11} /{ }_{2}$ energy levels, respectively. These energy transfers between sublevels occur as a result of the neodymium-ion and yAG crystal interactions (phonon-ion interactions). The numbers in parentheses to the right of the energy sublevels of Figure 2-4 are the percentages of the total energy in each energy level that is stored in a particular energy sublevel. These percentages were calculated by assuming a Boltzman ion population distribution within each energy level. This assumption is valid if the energy transfers between sublevels of each energy level are much faster than any other energy transfer processes involving the ${ }^{4} F_{3} / 2$ and ${ }^{4} I_{11} / 2$ energy levels. This hypothesis will be shown to be true for all processes except stimulated emission in the following paragraph. It will also be shown that energy transfer processes other than the phonon-ion interactions and stimulated emission are much slower than the Q-switching process.

A phenomenological theory of the phonon-ion interaction yields the following equation ${ }^{3}$ for the rates of these processes:

$$
\begin{equation*}
W_{\mathbb{N}}(T)=\operatorname{Bexp}(A \Delta E)[1-\exp (-h \nu / k T)]^{-N} \tag{2-1}
\end{equation*}
$$

where $T=$ temperature in Kelvin degrees,

$$
\text { hv }=\text { phonon energy, }
$$

$\mathrm{N}=$ number of phonons in interaction,
$\Delta E=$ energy gap of transition,
and $B$ and $A$ are phenomenological parameters unique to the particular ion host crystal. Although the above equation is for multi-phonon interactions, its extrapolation to the single phonon energy transfer processes between the sublevels of the upper and lower Nd:YAG laser level is assumed to be valid. It is to be noted that phonons of the proper energy to bridge the gap between the sublevels do exist in YAG ${ }^{4}$. The calculations of the sublevel energy transfer times.are admittedly an estimate since the extrapolation discussed above may lack accuracy. However, an estimate of the sublevel energy transfer times is necessary since to the knowledge of İंS - these parameters have not been determined experimentally.

For YAG, $B=2.24 \times 10^{8} \mathrm{sec}{ }^{-1}$ and $A=3.5 \times 10^{-3} \mathrm{~cm}^{3}$. Table 2-1 presents the energy transfer times calculated via the above equation for interactions within the sublevels of the ${ }^{4} \mathrm{~F}_{3} /{ }^{2}$ and ${ }^{4} I_{11} / 2$ energy levels. The time constant calculated for interaction between the ${ }^{4} I_{11} / 2$ and ${ }^{4} I_{9} /{ }^{2}$ ground level is 600 nsec . The fluorescence lifetime of the ${ }^{4} \mathrm{~F}_{3}$ / 2 energy level is $240 \mu \mathrm{sec}$ and optical pumping of this level typically extends over 100-200 usec. Clearly, all three of the latter energy transfer processes are slow compared to the typical time interval of the Q-switching process of $100-200 \mathrm{nsec}$. Thus, only the stimulated emission and the crystal-ion interactions need to be taken into account in the formulation of the rate equations for the Q-switching of the Nd:YAG laser. It is also obvious that the phonon-ion interactions between sublevels are much faster than any energy transfer processes other than stimulated emission. Thus, the energy distribution among the energy sublevels of the ${ }^{4}{ }^{2}{ }_{3} /{ }^{2}$ and ${ }^{4} I_{11} / 2$ levels are as shown in Figure $2-4$ prior to laser emission.

From the above discussion, a proper formulation of the rate equation for Q-switching of the Nd:YAG laser is indicated which involves equations describing the ion population dynamics of each of the sublevels of the ${ }^{4} F_{3} / 2$ and ${ }^{4} I_{11} / 2$ energy levels plus an equation describing the photon density dynamics. These equations could not be soluble analytically. Thus, an approximate formulation of these equations utilizing an empirical parameter is made. This empirical parameter is the time-averaged decrease in population inversion between the upper and lower laser levels per photon emission from the upper level. This parameter, denoted as $\alpha$, can be estimated from the calculated time constants of the interactions between energy sublevels or can be determined empirically. (Note that $\alpha=1$ for an ideal four-level laser and $\alpha=2$ for an ideal three-level laser.) A comparison of the results of the rate equation theory to be presented and a numerical iterative approach developed at ILS indicates that $\alpha$ is between 0.7 and 0.8 .

An estimate of $\alpha$, the decrease in population inversion per photon emitted, is made by time-averaging the laser dynamics over a single round-trip through the laser resonator. From Table 2-1, the time constant for repopulation of the upper laser sublevel of the ${ }^{4} \mathrm{~F}_{3}{ }^{2}$ energy level by the lower sublevel is 6 nsec . The time constant for decay of the lower laser sublevel of the ${ }^{4} I_{11} /{ }^{2}$ energy level to the remaining ${ }^{4} I_{1}{ }_{1} /{ }^{2}$ sublevels is 1.6 nsec. The round-trip time of a photon within the Spaceborne resonator is 9.48 nsec . When a single photon is emitted by a neodymium ion, the actual population of the upper laser sublevel

Table 2-1. Energy Transfer Times

| Transition | Transfer Time <br> (Nanoseconds) |
| :---: | :---: |
| ${ }^{4} \mathrm{~F}_{3} / 2 \mathrm{I}_{2} \rightarrow 2$ |  |
| ${ }^{4} \mathrm{I}_{11} / 23 \rightarrow 1$ | 6 |
| $3 \rightarrow 2$ | 18 |
| $3 \rightarrow 4$ | 15 |
| $3 \rightarrow 5$ | 5 |
| $3 \rightarrow 6$ | 6.5 |
| $3 \rightarrow \Sigma$ | 1.6 |

decreases by 00.4 units and the population of the lower laser sublevel increases by $0: 2$ units if given time to equilibrate afer emission of a single photon. The net population inversion decrease is thus 0.6 units per photon emission if equilibration is allowed time to occur. The 9.48 nsec round-trip time of the laser resonator does not permit this to occur. A calculation of the equilibration of the ${ }^{4} F_{3} / 2$ and ${ }^{4} I_{11 / 2}$ levels over the resonator round-trip time after emission of a photon yields a decrease in net population inversion of 20.8 units (exponential equilibration processes are assumed). This value of 0.8 for $\alpha$ will be used in the rate equation model.

The rate equations ${ }^{1}$ for 0 -switching of the $N d: Y A G$ laser which takes into account, in an approximate manner, the sublevel dynamics of the ${ }^{4} \mathrm{~F}_{3} /{ }^{2}$ and ${ }^{4} \mathrm{I}_{11 / 2}$ energy levels are:

$$
\begin{aligned}
& \frac{d \phi}{d t}=\left(\frac{\sigma N \ell}{T_{r}}\right) \phi-\left(\frac{\gamma}{T_{r}}\right) \phi \\
& \frac{d N}{d t}=-\alpha\left(\frac{\sigma N \ell}{T_{r}}\right) \phi
\end{aligned}
$$

where

```
\sigma = Stimulated emission cross section,
\phi = Photons/unit volume (referenceत to rod volume)
N = N N - N N = active ion inversion/unit volume,
\ell = Laser rod length,
\gamma = - 咅ln(RT ( }\mp@subsup{}{\ell}{}\mp@subsup{}{}{2})=\mathrm{ total losses per single pass in
        resonator,
Tr = I/c = single-pass resonator transit time,
L = Resonator length,
c = Velocity of Iight,
R = Reflectivity of output mirror,
TQ = Single pass transmission of resonator,
\alpha = Decrease in inversion per photon emission.
```

The term ( $\sigma N / T_{n}$ ) $\phi$ in the first equation is the increase in the number of photons per unit volume on a single pass through the resonator due to stimulated emission. By the definition of the parameter, $\alpha$, the term in the second equation is clearly the decrease in the net population inversion during a single resonator transit. The term - $\left(\gamma / T_{r}\right) \phi$ in the first equation is the decrease in the number of photons on a single resonator transit due to losses and output coupling.

The above rate equations are analytically soluble and explicit equations are obtained for the energy output for the case of PTM Q-switching. A fast Q-switch is assumed as is the case for the Spaceborne Laser. An analytical expression for the - switched pulsewidth is not obtainable from the above equations. This must be obtained numerically. However, an approximate analytical treatment of the pulse dynamics yields an explicit equation for the pulsewidth which is accurate within a few percent. The equation for the energy output ${ }^{1}$ and the pulsewidth ${ }^{5}$ of the internal radiation intensity of a PTM $Q$-switched Nd:YAG laser are:

$$
\begin{align*}
& \mathrm{E}_{\text {out }}=\left(\frac{h \nu}{\sigma}\right) \frac{A g}{\alpha}\left\{1-\frac{1}{\beta}+\frac{1}{\beta} \ln \frac{1}{\beta}\right\},  \tag{2-4}\\
& E_{\text {out }}=\frac{E_{\text {stored }}}{\alpha}\left|1-\frac{1}{\beta}+\frac{1}{\beta} \ln \frac{1}{\beta}\right|,  \tag{2-5}\\
& \tau(\text { FWHM })=\frac{2.4929 T}{\sqrt{\frac{\beta}{\alpha}\left(1-\frac{1}{\beta}+\frac{1}{\beta} \ln \frac{1}{\beta}\right)}} \text {, and }  \tag{2-6}\\
& \tau(\text { FWHM })=\frac{2.4929 \mathrm{~T}}{\sqrt{\beta_{\text {(E }} \text { out }} / \mathrm{E}_{\text {stored }}} \text { ) } \\
& \text { A = Laser rod cross-section area, } \\
& g=\sigma N \ell=\text { Single pass gain coefficient, } \\
& B=\frac{g}{\gamma}=\text { (pump energy)/(threshold energy), } \\
& T=(2 L / C) / \ln \left(1 / R T_{\ell}{ }^{2}\right)=L / C \gamma .
\end{align*}
$$

where

The above equations are utilized to generate characteristic performance curves for the Spaceborne Laser. Figure $2-5$ is a graph depicting energy input/output curves versus resonator loss. An empirical relationship between pump energy and energy stored in the laser rod is utilized. Figure $2-6$ is a graph showing the pulsewidth of the internal radiation intensity of the PTM $Q$-switched laser as a function of resonator loss for a fixed output energy of $5.0 \mathrm{~mJ} /$ pulse. Figure $2-7$ is a graph of the internal radiation intensity envelope as it would appear if the dump switching did not occur in the PTM Q-switching operation. The envelope curve was obtained numerically. Superimposed on this envelope are the modelocked pulses with a pulse centered at the peak of the envelope. The purpose of this graph is to indicate that energy output variation will occur due to jitter between the radiation intensity envelope and modelocked pulse temporal position. This jitter is probably unavoidable and the graph in Figure $2-7$ predicts approximately a $5 \%$ amplitude jitter in energy output due to this phenomena alone for the case of a $25 \%$ resonator loss/pass. From Figure 2-6, it is clear that higher resonator losses result in shorter pulse envelopes. Thus, the energy instability due to the modelocked pulse and envelope positions will increase with increased resonator loss.

This phenomena described above is clearly dominant in importance over other sources of energy output instability such as gain or loss variation from shot-to-shot. The latter parameters can be controlled more carefully, but the envelope-pulse position jitter is apparently unavoidable. Clearly, a low resonator loss to stretch the pulse envelope is the desirable solution to this problem. However, if this is not feasible in practice, operation of the oscillator at lower output energy levels in order to stretch the pulse envelope may resolve the problem.


Figure 2-5. PTM Q-switched Energy Input/Output
Curves vs Resonator Losses


Figure 2-6. Envelope Pulseridth vs Resonator Losses


## C. TRANSIENT MODELOCKING

The mathematical treatment of transient and steady-state active modelocking by Kuizenga and Siegman 6,7 has been proven experimentally to be a viable description of the active modelocking process in Nd:YAG. The basic approach of their treatment is to approximate the laser material gain function, the modulator temporal function, and the initial pulse shape of the intracavity radiation as gaussian curves. Via this approach, the initially gaussian pulse remains gaussian after transmission through the laser material and modulator.

In the steady-state analysis, the changes in the gaussian parameter of the intracavity radiation pulse caused by the modulator and the laser material on one round-trip through the laser interferometer are equated. From this equation, the steady-state value for the gaussian parameter and thus the pulsewidth of the modelocked pulse are determined as a function of the laser material and modulator parameters.

The analysis of active modelocking in the transient regime is initiated by setting up a differential equation in time for the gaussian parameter of the intracavity radiation pulse. The changes in the latter parameter caused by the modulator and the laser material on each round trip through the laser interferometer divided by the round trip transit time are the rate terms in the above mentioned differential equation. This equation is easily solved to yield the modelocked pulsewidth in the transient modelocking temporal regime.

The modulator gaussian parameter derived via the gaussian approximation to the modulator transmission function depends solely on the temporal duration of the modulator gate. Similarly, the- laser gain bandwidth determines the gaussian parameter derived from a gaussian fit to the gain curve. The curvature of the gain function at its peak dictates the effective bandwidth of the laser material for the modelocking process since only axial modes near the peak participate in laser action.

The effects of the modulator and the laser rod on the temporal and spectral character of the laser output are competing ones. The gain function of the laser rods acts to decrease the spectral content of the laser radiation and consequently also acts to increase the temporal duration of this radiation. The modulator acts to decrease the temporal duration of the laser
radiation and thus acts to increase the spectral content via the generation of frequency sidebands of the initially oscillating axial modes.

At least two distinct stages of transient modelocking can be identified prior to the achievement of steady-state modelocking on the basis of the relative magnitude of the effects of the modulator and laser rod. For moderate duration modulator time gates, the increase in the spectral width resulting from the application of this gate to the intracavity laser radiation is at first, negligible compared to the frequency bandwidth of the laser material gain. Thus, in the first stage of transient modelocking the modulator essentially governs the temporal and spectral characteri.stics of the laser radiation. As an example, consider the case where the duration (FWHM) of the time gate is $\simeq 3.5 \mathrm{nsec}$. This corresponds to a sinusoidal modulation at 75 MHz with a modulation depth of 1.0 from the equation for the modulation function $M(t)=$ $\cos [\theta \sin (\omega t)]$. This temporal width corresponds to a spectral width of $140^{\mathrm{m}} \mathrm{MHz}$ or $\simeq 0.005 \mathrm{~cm}^{-1}$ according to the Fourier relationship between time and frequency. Figure 2-8 clearly shows that this spectral width is negligibly small compared to the Nd:YAG gain curve shown as a function of frequency.

Thus, in the initial stage of transient modelocking the modulator characteristics determine the pulse duration of the modelocked pulse. Kuizenga and Siegman derived the following equation for the modelocked pulsewidth for the first stage of transient modelocking,

$$
\begin{equation*}
\tau_{p}=\sqrt{\frac{\ln 2}{2}} \frac{1}{\pi \theta_{m} f_{m} \sqrt{M}} \tag{2-7}
\end{equation*}
$$

where

$$
\begin{aligned}
\theta_{\mathrm{m}} & =\text { modulation depth } \\
\mathrm{f}_{\mathrm{m}} & =\text { modulation frequency } \\
M & =\text { number of passes through modulator. }
\end{aligned}
$$

To quote Reference 7, "From a physical viewpoint, equation (2-7)
——_GAIN COEFFICIENT $g$

-     - GAIN FOR $g=0.65$


Figure 2-8. Nd: XAG Gain vs Frequency
remains valid so long as the pulses' spectral width is narrow enough so that it is not affected by the atomic linewidth".

Stage 2 of the transient approach to steady-state modelocking begins when equation (1) ceases to be valid. In this stage the pulsewidth of the modelocked pulse begins to be comparable to the steady-state pulsewidth. Equivalently, in this stage the spectral width of the laser radiation has been increased by the action of the modulator to the point where the frequency dependence of the gain function becomes significant (see Figure 2-8). In this temporal regime of the active modelocking process, the laser rod reduces the effectiveness of the modulator to decrease the pulsewidth via gain discrimination. Kuizenga's and Siegman's derivation 7 for the modelocked pulsewidth in stage 2 of the transient approach to steady-state modelocking yielded:

$$
\begin{equation*}
\tau_{p}=\frac{\tau_{o}}{\sqrt{\tanh \left(M / M_{o}\right)}} \tag{2-8}
\end{equation*}
$$

where

$$
\begin{aligned}
\tau_{0} & =\text { steady-state modelocked pulsewidth, } \\
M & =\text { number of passes through modulator, } \\
M_{0} & =\frac{1}{4 \theta \sqrt{g}} \cdot \frac{\Delta f}{f_{m}} \\
\Delta f & =\text { laser line bandwidth }, \\
g_{0} & =\text { unsaturated laser gain. }
\end{aligned}
$$

The steady state pulsewidth is given by

$$
\begin{equation*}
\tau_{0}=\frac{\sqrt{2 \ln 2}}{\pi}\left(\frac{\sqrt{g}}{\theta_{m} \mathrm{~F}_{\mathrm{m}} \Delta \mathrm{~F}}\right)^{\frac{1}{2}} \tag{2-9}
\end{equation*}
$$

A basic assumption made in all analyses presented previously is the following. It is assumed that the modelocked pulse formed during the prelase or Q-switch buildup time is essentially unchanged during the period of high intracavity radiation intensity just prior to ejection of the pulse from the resonator. The analysis below shows that this assumption is valid.

The change in the temporal gaussian pulse parameter caused by passage through the rod and modulator are given by Reference 6 to be:
and

$$
\begin{equation*}
\Delta \xi_{\text {rod }}=-\frac{4 g \xi^{2}}{\pi^{2}(\Delta f)^{2}} \tag{2-10}
\end{equation*}
$$

$$
\begin{equation*}
\Delta \xi \text { modulator }=4 \pi^{2} \Theta_{\mathrm{m}}^{2} \mathrm{~m}^{2} \tag{2-11}
\end{equation*}
$$

where $g=$ the saturated gain,

$$
\Delta f=f l u o r e s c e n c e ~ b a n d w i d t h \text { of laser line, }
$$

$$
\theta_{\mathrm{m}}=\text { modulation depth }
$$

$$
f_{\mathrm{m}}=\text { modulation frequency }
$$

and

$$
\begin{aligned}
\xi= & \text { gaussian pulse parameter of modelocked pulse } \\
& \text { just prior to entering high intracavity } \\
& \text { radiation regime. }
\end{aligned}
$$

( $\xi$ is defined by $f(t)=e^{-\xi t^{2}} \cdot$ )
The number of round trip passes made by the pulse in the high intracavity radiation regime prior to extraction of the pulse from the resonator was shown by previous ILS analysis to be $\simeq 10$ for intracavity losses of $36 \%$ per round-trip. The net change in the gaussian pulse parameter is calculated for 10 passes to be

$$
\begin{equation*}
\Delta \xi_{\text {net }}=10\left(\Delta \xi_{\text {rod }}+\Delta \xi_{\text {modulator }}\right)=+15 \times 10^{18} \tag{2-12}
\end{equation*}
$$

where $\theta_{\mathrm{m}}=1.5 ; \mathrm{f}_{\mathrm{m}}=75 \mathrm{Mhz} ; \mathrm{g}=0.96 \mathrm{~g}_{\mathrm{o}}=0.624$; and $\Delta f=160 \mathrm{Ghz}$. The gaussian pulse parameter corresponding to an initial 200 psec ( $10 \%$ pts) pulsewidth is $2.3 \times 10^{20}$. The gaussian pulse parameter following the 10 passes through the interferometer prior to pulse extraction is $\xi+\Delta \xi=2.45 \times 10^{20}$. This value of the gaussian pulse parameter corresponds to a pulse duration of 194 psec ( $10 \%$ pts). Thus it is seen that the change in pulse duration during the period in which significant energy
is extracted from the rod is negligible and in fact a desirable shortening of the pulse. This could have been predicted from Equations (2-10) and (2-ll) which show that the only changes in these equations from the low intensity case is the replacement of $g_{0}$ (the unsaturated gain) with $g$ (the saturated gain). Since g is less than $g_{0}$, the laser rod contributes to pulse lengthening less in the high radiation intensity temporal regime than in the low intensity regime (the pre-lase period).

Figure 2-9 presents the pulsewidth versus prelase time for two resonator loss parameters and a gain value which in each case yields a $5.0 \mathrm{~mJ} /$ pulse output energy.


Figure 2－9．Pulsewidth vs Prelase Time

## D. PRELASE CONCEPTS

The calculations presented in the previous section show that the desired pulsewidth ( 200 psec @ $10 \%$ points) for the Spaceborne laser can only be obtained by several hundred resom nator round-trip transistions. This corresponds to several usec, a time much longer than typical 0-switch buildup times (~ $100-200 \mathrm{nsec}$ ). The generation of low level radiation. (prelase radiation) for the necessary temporal duration permits the attainment of the desired laser pulsewidth.

The duration of prelase radiation should be precisely controlled in order to obtain shot-to-shot pulsewidth stability. Also, the level of the prelase radiation should be precisely controlled in order to prevent depletion of the energy stored in the laser rod. In this manner, laser efficiency can be maintained at the level obtained in the absence of prelase radiation. One manner in which precise control of both the duration and level of the prelase radiation can be obtained in a pulsed laser is via an active radiation feedback control loop.

A feedback control loop was implemented in the Spaceborne laser by detection of the leakage radiation from the resonator and control of the 0 -switch loss via an applied variable, voltage. The detector is the input to an electronic circuit which increases or decreases the differential voltage across the 0 wwitch cell when radiation within the resonator increases or decreases respectively. Thus, the loss of the cell increases/decreases when the prelase radiation increases/decreases. The two experimental circuits designed to perform the feedback control on prelase radiation were unsuccessful as described elsewhere in this report. The problems encountered were difficult and the prelase approach described in the following paragraph was employed.

Prelase radiation is generated in the present laser device by setting the Q-switch bias voltage slightly below the lase holdoff voltage. In this manner, a low energy normal mode pulse is generated when the maximum gain of the laser rod occurs. The buildup time for this normal mode pulse of $\sim 3.0 \mu s e c$ is the prelase duration. Q-switching is dynamically synchronized to occur near the peak of the normal mode pulse. The synchronization is accomplished by direct lase detection via a circuit which initiates 0 -switching when prelase radiation exceeds a preset level. The preset threshold level can be varied experimentally to adjust prelase radiation
intensity. The disadvantage of the above-described prelase technique is that the prelase interval fluctuates from pulse to pulse. This occurs because of normal mode pulse amplitude fluctuations induced by small net laser gain fluctuations which in turn result from flashlamp-rod coupling variations from pulse to pulse.

Experimentation is planned with the pulsed, quasi-CW flashlamp pumping mode used in the Lawrence Livermore SHIVA modelocked oscillator. This pumping mode with the Q-switch bias voltage set to allow low level lasing results in quasi-CW operation prior to Q-switching. The duration of this lase period is set by the CW pumping duration to allow damping of normal mode spiking prior to Q-switching. The above prelase technique will provide prelase durations of $\sim 150 \mu \mathrm{sec}$ and thus ensure the generation of steady-state modelocked pulses with insignificant variations in pulse profile or pulsewidth from pulse to pulse. The disadvantage of this prelase technique relative to the one presently used is an increase in oscillator flashlamp power from 25 to 75 Watts.
E. AMPLIFIER MODEL

The theoretical model which describes the characteristics of amplifier action for modelocked pulses is developed with consideration given to equilibration times of the energy transfer processes. For subnanosecond pulses with double pass transit times of less than 2 nsec through the amplifying medium, one may assume that equilibration effects between levels are negligible. With reference to the description of energy transfer processes as developed in the section on Q-switching dynamics, the value of $\underline{\alpha}$, the time-averaged decrease in population inversion, may then be established. By neglecting equilibration times, the decrease in the upper laser level population per photon emitted is just equal to the increase in the population of the lower laser level. Thus, $\alpha=2$ represents the change in the population inversion per photon emitted for amplification of modelocked pulses using Nd: YAG.

The rate equations 8 which describe the amplifier dynamics with consideration given to the sublevel dynamics of the laser medium are:

$$
\begin{align*}
& \frac{\partial \phi(X, t)}{\partial t}+c \frac{\partial \phi(X, t)}{\partial t}=\sigma \mathrm{cn}(X, t) \phi(X, t)  \tag{2-13}\\
& \frac{\partial n(X, t)}{\partial t}=-\alpha \sigma \operatorname{cn}(X, t) \phi(X, t) \tag{2-14}
\end{align*}
$$

where

$$
\begin{aligned}
\phi(X, t) & =\text { Photon/Unit Volume, } \\
n(X, t) & =\text { Inversion/Unit Volume, } \\
\sigma & =\text { Simulated emission cross section, } \\
c & =\text { Velocity of Iight, } \\
\dot{\alpha} & =\text { Decrease in inversion per photon emitted. }
\end{aligned}
$$

The rate of change of the photon density is proportional to the product of the functions of the photon density and inversion density with the stimulated emission cross section for the particular laser level under consjderation. The rate of change of the inversion density is just the negative of the rate of the photon density multiplied by the factor $\alpha$. These equations may be solved analytically to yield:

$$
\begin{equation*}
\phi(X, t)=\frac{\dot{\varphi}_{i}(t-X / c)}{1-\left(1-e^{-\sigma n_{0} X}\right) \exp \left\{-\alpha \sigma c \int_{0}^{\tau} \dot{\varphi}_{i}\left(\tau^{\prime}\right) d \tau\right\}} \tag{2-15}
\end{equation*}
$$

Where

$$
\begin{aligned}
& \dot{n}_{o}=\text { Uniform inversion/unit volume, } \\
& \dot{\Phi}_{i}=\text { Input photon density. }
\end{aligned}
$$

Application of a square pulse input given by:

$$
\begin{aligned}
\phi_{i}(t)=\phi_{0} \quad & 0 \leq t \leq T, \text { and } \\
& 0 \text { otherwise; }
\end{aligned}
$$

yield an accurate approximation to the solution of the energy gain equation. The energy gain equation 8 for the square input pulse is:

$$
G_{E}=\frac{1}{\alpha \sigma \phi} \quad \ln \left\{1+e^{\sigma n_{o}}\left(e^{\alpha \sigma \phi}-1\right)\right\}
$$

Where

$$
\begin{aligned}
& \phi=\text { Input photons/unit area, } \\
& \alpha=\text { Decrease in inversion per photon emitted, } \\
& \sigma=\text { Stimulated emission cross section, } \\
& \ell=\text { Laser rod Iength, } \\
& n_{0}=\text { Initial uniform inversion/unit volume. }
\end{aligned}
$$

The energy gain equation expressed in terms of the energy stored in the upper laser level and the amplifier input energy is:

$$
G_{\dot{E}}=\frac{h \nu / \sigma \alpha}{E_{I N} / A} \ln \left\{I+\exp \left(\frac{E_{\text {stored/A }}}{h \nu / \sigma}\right)\left[\exp \left(\frac{E_{I N} / A}{h \nu / \sigma \alpha}\right)-I\right]\right\}(2-17)
$$

$$
\begin{aligned}
& \mathrm{E}_{\text {IN }} \\
& \mathrm{E}_{\text {stored }} \\
& \text { Amplifier input energy, } \\
& \\
& \\
& \\
& \\
& \\
& \frac{h \nu}{\sigma}
\end{aligned}
$$

Employing this expression for the energy gain equation one. may determine the output energy for a given set of input and energy storage conditions. Given initially an energy storage of 179 mJ (corresponding empirically with a 9.0 Joule pump energy) with a .2827 cm rod area exposed to an input energy of $5 \mathrm{~mJ} /$ pulse one may calculate the expected output energy for a doublepass amplifier system. On the first pass:

$$
\begin{aligned}
G_{E} & =\frac{.200}{.0177} \ln \left\{1+e^{(.619 / .4)}\left[e^{(.0177 / .2)}-1\right]\right\} \\
& =4.08
\end{aligned}
$$

which multiplied by the input energy yields an output energy of $20.4 \mathrm{~mJ} / \mathrm{pulse}$. The beam is then folded back on itself with an assumed loss of $5 \%$ which makes the input energy on the second pass equal to $19.0 \mathrm{~mJ} /$ pulse.

The energy storage in the rod has dropped to $149 \mathrm{~mJ} /$ pulse as a result of the energy extracted on the first pass. For the second pass

$$
G_{E}=2.88
$$

which yields a final output energy of $54.6 \mathrm{~mJ} /$ pulse for the double pass amplifier.

Using the equation for the energy gain with $\alpha=0.8$, values were computed for the relative extracted energy per unit amplifier cross sectional area as a function of oscillator input energy. This value of $\alpha$ corresponds to $\sim 20 \mathrm{nsec}$ input pulses. These results are shown in Figure $2-10$ with experimental data also presented. A close correspondence can be seen between the theoretical curve and the experimental data. Thus a theoretical model is available which accurately predicts amplifier performance characteristics.


Figure 2-10. Amplifier Energy Extraction as Function of Oscillator Energy Density

DESIGN
A. SYSTEM OVERVIEW

1. Hardware Description

The Spaceborne Laser System consists of four units: the laser transmitter, power supply, cooling system and modelocker driver. Figure 3-1 is a photograph of these units and Figure 3-2 is a system block diagram.

The laser transmitter housing is hermetically sealed and consists of a cover and a baseplate mounted on four steel rods terminating in Gaertner magnetic bases. All electronic and coolant connections are made through the baseplate. The transmitter contains the optical bed and interferometer, the radiation and synchronization control electronic packages, the o-switch driver package and miscellaneous minor electronic components. The transmitter derives its electronic inputs from the power supply via a single primary cable and several BNC cables. A single BNC cable connects with the cooling system via inlet and outlet coolant hoses. The output of the transmitter will be a single subnanosecond pulse.

The Spaceborne Laser System power supply subsystem is mounted on a standard 19-in. enclosed chassis that is rackmountable. The power supply contains the flashlamp power module, the pulse-forming networks (PFNs), pulse rate generator, prelase and Q-switch delay logic, Q-switch bias and driver voltage sources, and miscellaneous minor electronic components.


Figure 3-1. Hardware Subassemblies


Figure 3-2. System Block Diagram

All power supply connections are made through the front panel. The prime power input of $24-v$ dc to the system is made via the power supply. The power supply provides a logic input to the modelocker driver via a single BNC cable. All other power supply connections are with the laser transmitter. Essentially all the controls of the Spaceborne Laser System are accessible via the power supply front panel. These controls -- described in detail in the power supply design section -- are flexible and complex because of the experimental nature of this hardware.

The modelocker driver electronics are packaged in the housing of an Electronic Navigation Industries Model 3l0L RF amplifier. This housing contains, in addition to the RF amplifier, a precision crystal-oscillator frequency source and a frequency synthesizer. The power input required for this unit is 120 v , 60 Hz ac. The two BNC cables from this unit to the power supply and the transmitter connect to the front panel. The controls for this unit also are on the front panel. The prime power input will be modified to 28 V -dc in Phase II of this program.

The cooling system for the Spaceborne Laser System is housed in a chassis and case. The system is a closed-cycle unit containing a fan, coolant pump, ion-exchange filter and liquid-to-air heat exchanger. The $24-v$ dc power required for this unit is obtained via a cable splitting from the main transmitter power supply cable. Quick-disconnect coolant fittings are provided for the inlet and outlet coolant hoses at both the transmitter and cooling system ends. All connections to this unit are made via the front panel. The cooling system will use a liquid-liquid heat exchanger in Phase II.

## 2. Mechanical Configuration

The mechanical design effort on the Spaceborne Laser System program was essentially the design of the laser transmitter. Existing packaging designs were used with minor modifications for the power supply and cooling system. The modelocker driver packaging was a minor modification to a purchased unit. The mechanical design of the Spaceborne Laser System transmitter is almost entirely new. This design effort involved designs of the optical bed, modulator housing and optical mounting, laser pump cavity, passive optics mounts, and the transmitter packaging.

A major function of the mechanical design task involved the conception, analysis and design of the optical bed. The mechanical and thermal stability of this bed was an important parameter since the Spaceborne Laser System involves active modelocking. Modelocking of this type reguires stringent control of the optical length of the laser resonator which depends substantially on optical bed dimensional stability.

Figure $3-3$ is a sketch of the optical bed conceived on this program. The material used for this optical bed was Invar, a low thermal expansion material. A thermal and mechanical stress analysis was performed on this optical bed which indicated a dimensional and distortion stability approaching that of the Invar material. This optical bed concept is considered by ILS to be a near optimum one for the implementation of the Spaceborne Laser System concept. Appendix $C$ gives the details of the optical bed analysis.

## 3. Electronic System Overview

The electronic system, as considered in the most elementary form, is depicted in Figure 3-2. Four component blocks comprise the system. These blocks are:

- The power supply unit;
- The laser head unit, or transmitter unit;
- The modelocker driver unit; and
- The cooling system unit.


Figure 3-3. Optical Bed Sketch

Figure 3-4 elaborates upon the major system circuit block to depict the subunits contained within.

The power supply unit contains:

- The flashlamp power modules (two each);
- The pulse-forming networks (two each);
- The Q-switch voltage sources (two each);
- The prelase and Q-switch control logic;
- The pulse repetition rate/frequency (PRF) generator;
- The logic voltage source or power supply; and
- The simmer supplies (two each).

The prime power input is 24 to 28 V dc.
The transmitter unit contains:

- The O-switch drivers and Pockels cell;
- The synchronization electronics;
- The prelase control electronics;
- The flashlamps and ignition transformers;
- The active modelock modulator; and
- Ancillary low-voltage power supplies.


All laser transmitter power is routed from the power unit, the exception being the modelock drive which originates from the modelocker driver unit. Figure 3-5 depicts the transmitter unit electrical system.

The remaining unit, the modelocker driver unit, contains:

- An ultrastable crystal. controlled oscillator;
- A frequency synthesizer;
- A radio frequency (RF) amplifier; and
- A power pulser.

Power for the modelocker driver is currently from the 117 V ac mains; however, the unit lends to modification for 24$V$ dc operation. Because the modelocker driver is only a breadboard, this modification was not considered necessary.

## 4. Optical Concepts

The primary optical concepts developed on the spaceborne Laser System program are the common-mirror, crossed TIR prism resonator and the double-pass amplifier utilizing a Porro prism as both mirror and half-wave phase plate. Analysis involving these two concepts plus modulator, pump cavity and laser damage studies were the topics of the optical design performed on this program.

The common-mirror, crossed TIR prism resonator is the most important optical concept developed on this program. Figure $3-6$ shows the optical elements of this resonator as employed in the Spaceborne Laser System. The importance of this concept stems from its relative insensitivity to misalignment with respect to small motions of the common mirror and TIR prisms and the compactness (low volume) provided by the four folds. Both of these properties are very important for laser hardware, the end goal of this development program. The design studies performed related to the Spaceborne Laser System resonator 'included resonator mirror design, resonator length and alignment sensitivity analysis, and the specific optical design of each resonator element. The goal of the latter design task was to avoid etalon effects within the resonator.


Figure 3-5. Transmitter Flectronic System


Figure 3-6. Spacehorne Oscillator Optical Configuration

The optical elements of the amplifier system are depicted in Figure 3-7. The optical designs of these elements were simple because etalon effects were not important as in the resonator system. The concept of using a Porro prism as Max $R$ reflector and as a half-wave phase retarder was generated to avoid the use of crystalline quartz, a low damage threshold optical material. The roof line of the Porro prism actually is $45^{\circ}$ to the polarization plane. It is shown vertical for ease of illustration.

All of the optical materials used in the Spaceborne Laser System were evaluated with respect to laser damage threshold via the published literature and discussions with vendors. The effects of nonlinear self-focusing also were evaluated. The latter phenomena was shown to be the primary limiting factor on the energy output of the Spaceborne Laser System.

The modulator study determined the electronic drive requirements for the cylindrical ring electrode (CRE) KD*P crystals used as the Q-switch and modelocker modulators. The transmission uniformity, the quarter-wave voltage and the capacitance of the CRE KD*P crystals were reviewed. Also, the loss tangent reported for $K D * P$ was utilized to analyze heating effects in the modelocker modulator.

The pump cavity design study involved a review of the literature on pump cavity design and consultation with ILS experts in this area. The design generated combined several ideas from the literature and ILS personnel in an attempt to improve pumping efficiency and uniformity.

## B. OPTICAL DESIGN

1. Laser Damage Evaluation

Nonlinear self-focusing effects limit the attainable power density and thus the energy output of the Spaceborne Laser System. These effects limit the power density in two ways. Localized self-focusing induced by spatial intensity fluctuations of the laser beam can result in laser damage. Whole-beam self-focusing can limit the TEM Oo -mode volume. The $^{\text {- }}$ laser damage thresholds of the optical materials and dielectric thin films utilized in the Spaceborne Laser system are substantially higher than the limits imposed by self-focusing.


The electric field intensity of a high-peak-power laser beam modulates the refractive index of optical materials through nonlinear effects. The variation of the index as a function of the electric field is given by:

$$
\begin{equation*}
\mathrm{n}=\mathrm{n}_{0}+\mathrm{n}_{2}|E|^{2} \tag{3-1}
\end{equation*}
$$

where $\quad n_{0}=$ the refractive index of the optical material; and $|\mathrm{E}|^{n_{2}}=$ the nonlinear index of refraction; and $|E|^{2}=$ the instantaneous value of the electric field squared.

The relationship between the latter parameter and the beam intensity, denoted by $I$, is:

$$
\begin{equation*}
I=\frac{n_{0}|E|^{2}}{2 n_{0}} \tag{3-2}
\end{equation*}
$$

where $\eta_{0}=$ the characteristic impedance of free space.
The index of refraction of a material irradiated by a gaussian beam of intensity,

$$
\begin{equation*}
I=I_{p}\left(-2 r^{2} / w^{2}\right) \tag{3-3}
\end{equation*}
$$

is thus given by

$$
\begin{equation*}
n(r)=n_{0}+2\left(n_{2} n_{0} / n_{0}\right) I_{p} \exp \left(-2 r^{2} / w^{2}\right) \tag{3-4}
\end{equation*}
$$

Clearly, the index of refraction is greatest at the center of the gaussian beam and falls gradually to $n_{o}$ as one moves from beam center. Thus, the beam propagates slower at the center of the beam than elsewhere and optical focusing results.

The effects of whole-beam self-focusing on the $\mathrm{TEM}_{\mathrm{OO}}$ mode diameter in Nd:Glass lasers has been analyzed by Eckhardt ${ }^{9}$. A critical parameter in this analysis was the temporal regime in which the pulse has a high intensity. The degree of whole-beam self-focusing is inversely proportional to the duration of this temporal regime. The higher gain of Nd:YAG relative to Nd:Glass significantly reduces the extent of the temporal regime in which the power density is significant. A power density limit of $\sim 1.0 \mathrm{GW} / \mathrm{cm}^{2}$ was extrapolated from the results of Eckhardt's analysis for the Spaceborne Laser System resonator.

An optical beam with an intensity greater than the critical power of its propagation medium is unstable with respect to localized self-focusing. The critical power ${ }^{10}$. of an optical medium is defined by

$$
\begin{equation*}
P_{c}=3.77 \frac{\varepsilon_{0} c \lambda_{0}^{2}}{8 \pi n_{2}} \tag{3-5}
\end{equation*}
$$

Table 3-1 gives the critical power of several optical materials used in the Spaceborne Laser System.

Table 3-1 Critical Power of Selected Optical Media 11,12

| Material | $\mathrm{n}_{2}$ | $\mathrm{P}_{\mathrm{C}}$ |
| :--- | :---: | :---: |
|  | $\left(\mathrm{X.10}^{-22} \mathrm{~m}^{2} / \mathrm{V}^{2}\right)$ | $(\mathrm{X} \mathrm{10} \mathrm{W})$ |
|  |  |  |
| YAG | 4.5 | 10.01 |
| @UARTZ | 1.1 | 40.96 |
| KDP | 1.1 | 40.96 |
| ED-4 | 2.1 | 21.46 |

Transverse spatial fluctuations in an optical beam of greater intensity than the critical intensity will, in general, grow exponentially and might eventually result in laser damage. Clearly, localized self-focusing can be controlled by obtaining a smooth spatial profile. However, inevitable optical defects will generate spatial fluctuations. It is difficult to obtain analytic power density limits for which localized self-focusing is not a problem. However, the literature does report operation of modelocked Nd:YAG laser oscillators at or slightly above $1.0 \mathrm{GW} / \mathrm{cm}^{2}$ without incurring laser damage as the result of localized self-focusing. ${ }^{13,14}$

Tables 3-2 and 3-3 present the damage threshold at $1,064 \mathrm{~nm}$ of the optical materials and dielectric thin-films selected for use on the Spaceborne Laser System. Clearly, these power densities exceed considerably the limits set by self-focusing effects.

Table 3-2 TEM ${ }_{O O}$ Mode Laser Damage Thresholds ${ }^{15,16}$

| Material | Damage Threshold |
| :--- | ---: |
| KD*P | $22 \mathrm{GW} / \mathrm{cm}^{2} *$ |
| ED-4 | $108 \mathrm{GW} / \mathrm{cm}^{2} *$ |
| Nd:YAG | $>12 \mathrm{GW} / \mathrm{cm}^{2}$ |
| Quartz | $>100 \mathrm{GW} / \mathrm{cm}^{2}$ |
|  | *Pulsewidth $=125 \pm 25 \mathrm{psec}$ |

Table 3-3 TEM $\quad$ Mode Laser Damage Threshold ${ }^{15}$
of Dielectric Coatings

| Coating | Substrate | Average <br> Damage Threshold |
| :--- | :---: | :---: |
| Antí-reflection $\%$ | EY-I | $3.7 \mathrm{~J} / \mathrm{CM}^{2}\left(29.6 \mathrm{GW} / \mathrm{CM}^{2}\right)$ |
| Dielectric Polarizer | $\mathrm{BK}-7$ | $3.6 \mathrm{~J} / \mathrm{CM}^{2}\left(28.8 \mathrm{GW} / \mathrm{CM}^{2}\right)$ |
| Maximum Reflection | -- | $3.3 \mathrm{~J} / \mathrm{CM}^{2}\left(26.4 \mathrm{GW} / \mathrm{CM}^{2}\right)$ |
| pulsewidth $=\cdot 125 \pm$ psec |  | Spot Diameter $=0 . \dot{25} \mathrm{~cm}$ |

## 2. Resonator Design

The design of the resonator mirrors for the Spaceborne Laser System took into consideration spot size sensitivity to thermal lensing and alignment sensitivity of the common-mirror resonator. A concave-convex resonator was chosen for implementation because of the absence of a beam waist within the resonator as well as other properties cited in the literature.

The spot size, w, of a gaussian $T_{O M}$ laser beam is defined by the equation:

$$
\begin{equation*}
I(r)=I_{p} \exp \left[-2(r / w)^{2}\right] \tag{3-6}
\end{equation*}
$$

where $I_{p}=$ peak beam intensity and

$$
r=\text { distance from center of beam. }
$$

The spot sizes ${ }^{16}$ on the mirrors of a resonator with a thin internal lens are given by

$$
\begin{equation*}
w_{2,1}=\left(\frac{\lambda B}{\pi}\right)^{\frac{1}{2}}\left[\frac{g_{1,2 / g_{2,1}}}{1-g_{1} g_{2}}\right]^{\frac{1}{4}} \tag{3-7}
\end{equation*}
$$

where

$$
\begin{aligned}
& B=d_{1}+d_{2}-\frac{d_{1} d_{2}}{f}, \\
& g_{1}=1-\frac{d_{2}}{f}-\frac{B}{R_{1}}, \\
& g_{2}=1-\frac{d_{1}}{f}-\frac{B}{R_{2}}: \\
& f \quad=\text { lens focal length, } \\
& R_{1,2}=\text { mirror radii of curvature, and } \\
& d_{1,2}=\text { distance from mirror } 1,2 \text { to lens center. }
\end{aligned}
$$

In practice, the laser rod can be treated as a thin lens if the rod thermal focal length is long. "This condition will be shown to be the case for the Spaceborne Laser System.

The sensitivity of the TEM -mode volume in the laser rod to fluctuations in thermal lensina can be expressed analytically. The derivative of the spot size on the mirror nearest to the laser rod with respect to the focal length of the rod can be derived as follows:

$$
\begin{align*}
& \left.\frac{d w_{2}}{d f}=\frac{w_{2}}{4 f^{2}\left(1-g_{1} g_{2}\right)} \right\rvert\, \frac{2 d_{1} d_{2}\left(1-g_{1} g_{2}\right)}{B}+\frac{d_{2}}{g_{1}}\left(1-\frac{d_{1}}{R_{1}}\right)+\frac{d_{1}\left(2 g_{1} g_{2}-1\right)}{g_{2}} \\
& \left.\left(1-\frac{d_{2}}{R_{2}}\right) \right\rvert\, \tag{3-8}
\end{align*}
$$

This derivative can be calculated numerically given the mirror radii, mirror-rod optical distances and rod focal length.

The sensitivity of the common mirror resonator to misalignment can be determined analytically. The partial derivatives ${ }^{17}$ of the beam displacements on the laser mirrors with respect to mirror angular tilt, $\theta$, are

$$
\begin{equation*}
\frac{\Delta d_{1}}{\Delta \theta}=\frac{R_{1} R_{2}\left(1-g_{2}\right)}{X} \text { and } \frac{\Delta d_{2}}{\Delta \theta}=\frac{R_{1} R_{2}\left(g_{1}-1\right)}{X} \tag{3-9}
\end{equation*}
$$

where $\quad X=g_{1} R_{1}+R_{2}+R_{1} R_{2} \cdot \frac{f}{d_{2}} \frac{\partial g_{1}}{\partial f}$.
$\Delta d_{1}$ and $\Delta d_{2}$ are the lateral displacements of the beam center on mirrors 1 and 2 , respectively, and $\Delta \theta$ is the mirror tilt.

The thermal focal length of a solid-state laser rod that is uniformly pumped and symmetrically cooled is given by the equation: ${ }^{18}$

$$
\begin{equation*}
f=\frac{K \pi r^{2}}{H\left[(1 / 2) \mathrm{dn} / \mathrm{dT}+\mathrm{Can}_{0}^{3}\right]}=\frac{\mathrm{K}}{\mathrm{H}} \tag{3-10}
\end{equation*}
$$

where

$$
\begin{aligned}
f & =\text { focal length of laser rod thermal lens, } \\
K & =\text { thermal conductivity of laser material, } \\
r & =\text { laser rod radius, } \\
\mathrm{dn} / \mathrm{dT} & =\text { refractive index thermal coefficient, } \\
n_{0} & =\text { refractive index at lasing wavelength, }
\end{aligned}
$$

$\alpha=$ coefficient of linear expansion
$C=$ stress optic coefficient,
$H=$ heat per unit time absorbed by laser rod.

Typical thermal lensing of Nd:YAG laser rods is shown in Figure 3-8. The pump level of the Spaceborne Laser system ranges betwet 3 to 5J. Thus, a focal length of $\sim 25 \mathrm{~m}$ is used in the calculations given below for the $5 \times 101.6 \mathrm{~mm}$ oscillator laser rod.

The equations given above permit calculation of the spot sizes on the laser mirrors as a function of rod focal length, the alignment sensitivity and the sensitivity to thermal lensing. Figure 3-9 gives these quantities for a laser resonator with parameters near those of the spaceborne Laser System resonator.
3. Oscillator Optical Design

The optical design of the Spaceborne Laser System resonator shown in Figure 3-10 was generated with the paramount consideration of avoiding etalon effects. These effects would limit the spectral width of the laser radiation and then make the achievement of the desired puisewidth difficult, if not impossible. Every element of the laser resonator was designed as a wedge except the laser mirror. Also, every optical surface was set $0.20^{\circ}$ to $0.25^{\circ}$ off every other optical surface. The one exception was two sets of optical surfaces of the TIR prisms. These surfaces however were tilted sufficientily and far enough apart to eliminate the interference effects of the established etalon. In practice, the establishment of this etalon was improbable because of the optical tolerance of intervening optical components.

The laser rod leg of the resonator was designed to include a quartz wedge which essentially compensated for the deviation and lateral offset introduced by the wedged laser rod. The KD*P Q-switch and modelock cells were designed to be identical and were mounted such that the deviation and lateral offset of one cell was compensated for by the other cell. The dielectric polarizer internal to the resonator also was designed as a wedge. The two quartz Risley wedges were designed to compensate for both the offset and deviation of the polarizer. These Risley wedges also were designed to have a range of deviation and offset sufficient to compensate for the cumulative fabrication tolerance of the optical elements. The quartz TIR prisms were designed with a pyramidal error so


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Figure 3-8. Dependence of Laser Rod Focal Length on Pump Level.


Figure 3-9. Spaceborne Resonator Spot Size Characteristics


Figure 3-1.0. Spaceborne Oscillator Optical Configuration
that the entrance and exit faces were not parallel internal to the TIR prisms. The detailed description of all of the optical components is presented in the appendix containing the optical design drawings.
4.

Modulator Analysis
The nonlinear crystal. KD*P was used as the modelocking and Q-switching modulators. The cylindrical ring electrode (CRE) Configuration for $K D * P$ is employed. The transmission uniformity, the $\lambda / 4$ voltage and the modulator capacitance are significant for both the modelocking and Q-switch KD*P cells. In addition, the loss tangent is significant for the modelocking modulator. Table 3-4 summarizes the properties of KD*P crystals.

The $\lambda / 4$ voltage for a CRE KD*P Pockels cell given by Lasermetrics literature is 3200 v . The $\lambda / 4$ voltage is related to the nonlinear electro-optic coefficient $r_{63}$ by

$$
\begin{equation*}
v_{1 / 4}=\left(\lambda / 4 n_{0}\right)^{3} r_{63} \tag{3-11}
\end{equation*}
$$

where $n_{0}$ is the ordinary index of refraction of $K D * P$. This index is reported by Harshaw to be $1.47 .^{19}$ However, a close comparison of the ordinary index of refraction of $K D * P$ and KDP reveals that $n_{0}$ is probably closer to 1.49 .

The electro-optic coefficfent for $90 \%$ deuterated KD*P at high frequencies is $24.0 \times 10^{-12} \mathrm{~m} / \mathrm{V}$ at 500 nm for room temperature. Assuming $r_{63}$ to be wavelengih-independent, $V_{\lambda / 4}$ at $1,064 \mathrm{~nm}$ for high-frequency modulation is calculated to ${ }^{\lambda / 4}$ be 3350 v . The corresponding static $\lambda / 4$ voltage is $\sim 3200 \mathrm{v}$.

Table 3-4 Properties of $K D * P^{20}$
Thermal Conductivity $18 \frac{\mathrm{~mW}}{\mathrm{~cm}^{\circ} \mathrm{K}}$ @ $300^{\circ} \mathrm{K}$
Electrical Conductivity
$10^{-10}(\mathrm{Ohm}-\mathrm{cm})^{-1}$

Resistance
$1000 \mathrm{M} \Omega$
$\frac{\text { Maximum Safe Operating }}{\text { Temperature }}$
$100^{\circ} \mathrm{C}$

Surface Resistivity
$1.3 \times 10^{11} \mathrm{ohm} / \mathrm{cm}^{2}$

| Dielectric Strength | $\sim 70,000 \mathrm{~V} / \mathrm{cm}$ |
| :---: | :---: |
| Dielectric Constant ( $\varepsilon_{C}$ ) | 45 @ $30^{\circ} \mathrm{C}$ @ 9.2 GHz $50 @ 24^{\circ} \mathrm{C}$ @ 1000 Fz |
| $\begin{aligned} & \text { Piezoelectric Constants } \\ & \text { @ } 30^{\circ} \mathrm{C} \end{aligned}$ | $\begin{aligned} & \mathrm{a}_{36}=52 \times 10^{-12} \mathrm{C} / \mathrm{N} \\ & \mathrm{~d}_{14}=3.3 \times 10^{-12 \mathrm{C} / \mathrm{N}} \\ & \mathrm{~g}_{36}=0.13 \mathrm{~m}^{2} / \mathrm{C} @ 60 \mathrm{MHz} \end{aligned}$ |
| Loss Tangent @ $24^{\circ} \mathrm{C}$ | $\begin{array}{llrl} 0.0012 & 100 & \mathrm{MHz} \\ 0.0072 & @ \\ 1000 & \mathrm{MHZ} \end{array}$ |
| Dielectric Constant a $24^{\circ} \mathrm{C}$ | $\begin{aligned} & 39.3 @ 100 \mathrm{MHz} \\ & 41.3 @ 1000 \mathrm{MHz} \end{aligned}$ |
| $\begin{aligned} & \text { Electro-Optic Coefficient } \\ & \underline{\text { @ } 30^{\circ} \mathrm{C}} \end{aligned}$ | $\begin{aligned} & r_{63}^{t}=25.6 \times 10^{-12} \mathrm{~m} / \mathrm{V} \\ & r_{63}^{S}=24.0 \times 10^{-12} \mathrm{~m} / \mathrm{V} \end{aligned}$ |
| Refractive Index | $\begin{aligned} & \mathrm{n}_{\circ}=1.47 @=1.0 \mu \\ & (\mathrm{E} 1 \text { to } \mathrm{C} \text { axis) } \end{aligned}$ |

The capacitance of a CRE KD*P Pockels cell is given according to Steinmetz ${ }^{21}$ by the equation

$$
\begin{equation*}
C=\left(\pi R^{2} \varepsilon_{z} \varepsilon_{0} / 2\right)(I-W) \tag{3-12}
\end{equation*}
$$

where $R=$ the crystal radius;

$$
\begin{aligned}
\varepsilon_{z} \varepsilon_{0}= & \text { the electrical permittivity of the crystal } \\
& \text { in the } z \text { direction; } \\
2 \mathbb{L}= & \text { the length of the crystal; and } \\
W= & \text { the electrode width. }
\end{aligned}
$$

The CRE configuration identifien by Steinmetz as near optimum with respect to transmission uniformity for a 0.25 -in. diameter beam had $L=12 \mathrm{~mm}, \mathrm{~W}=8 \mathrm{~mm}$, and $\mathrm{R}=6 \mathrm{~mm}$. This configuration will be used in the Spaceborne Laser System. and has a calculated capacitance of 6.4 pF . Measured capacitance of 7 to 10 pF for CRE cells of these dimensions are regularly obtained by Lasermetrics.

According to a McDonnell Douglas report ${ }^{22}$ the loss tangent of $\mathrm{KD} * \mathrm{P}$ is 0.0012 at 100 MHz . Other sources (Cleveland Crystals ${ }^{23}$ and the Handbook of Linear Electro-optic Materials ${ }^{20}$ ) confirm that this value is fairly accurate. The loss tangent is almost certainly no greater than. 0.002 for the driving frequency of $\simeq 60 \mathrm{MHz}$. These values are for $30^{\circ} \mathrm{C}$. Data in the handbook mentioned above indicate that the loss tangent decreases with increasing temperature. However, the data is not definitive for the proposed driving frequency.

The KD*p modelocking modulator is driven via a series resonant circuit. The voltage source for this series resonant circuit is a temperature stabilized crystal oscillator ( $\geq 1 / 10^{6}$ stability) amplified to 3 V peak-to-peak by a commercial $\overline{\mathrm{RF}}$ amplifier system.

The differential equation for a RLC circuit driven by a sinusoidal source is

$$
\begin{equation*}
I \frac{d^{2} i}{d t^{2}}+R \frac{d i}{d t}+\frac{i}{C}=V_{m} \omega \cos (\omega t) \tag{3-13}
\end{equation*}
$$

where $\quad v=V_{m} \sin (\omega t)$ is the driving voltage.
The steady-state solution to this equation is

$$
\begin{equation*}
i=\frac{V_{m}}{\sqrt{R^{2}+(1 / \omega C-\omega L)^{2}}} \sin \left[\omega t+\tan ^{-1}\left(\frac{1 / \omega C-\omega L}{R}\right)\right] \tag{3-14}
\end{equation*}
$$

At the series resonant condition,

$$
\begin{align*}
& \frac{1}{\omega C}=\omega L \text { and } \\
& i=\frac{V_{m}}{R} \sin (\omega t) . \tag{3-16}
\end{align*}
$$

The literature ${ }^{22}$ gives a value of 0.0012 for the loss tangent of $\mathrm{KD} * \mathrm{P}$ at 100 MHz -that is, $\omega C R=0.0012$. The capacitance of a typical cylindrical-ring-electrode (CRE) KD*P cell is no greater than 10 pF . The modelocking frequency that has been selected is 60 MHz . Assuming that the loss tangent for 60 MHz is approximately that at $100 \mathrm{MHz}--$ say $0.002--$ the effective resistance of the cell is $R \cong 0.53 \Omega$.

The resonant frequency of a series resonant circuit is given by

$$
\begin{equation*}
\mathrm{f}=\frac{1}{2 \pi} \frac{1}{\sqrt{I C}} \tag{3-17}
\end{equation*}
$$

Thus, the ideal inductor required to produce series resonance in series with a KD*P cell with $w$ lopi of capacitance at a frequency of 60 MHz is $\mathrm{L} \simeq 0.7 \mu \mathrm{~h}$. Recall that the current at series resonance is given by $i=\left(V_{m} / R\right) \sin (\omega t)$. Thus, the voltage across the KD*P cell is given by

$$
\begin{equation*}
V_{C}=\frac{i}{\omega C}=\frac{V_{m}}{\omega C R} \sin (\omega t) \tag{3-18}
\end{equation*}
$$

Recalling that $v=V_{m} \sin (\omega t)$, it is clear that the voltage multiplication factor is given by

$$
\begin{equation*}
V_{C} / v=\frac{1}{\omega C R} \simeq 500 \tag{3-19}
\end{equation*}
$$

for $f=60 \mathrm{MHz}, \mathrm{C}=10 \mathrm{pf}$, and $\mathrm{R}=0.53 \Omega$. Thus for a voltage input of 6 v peak-to-peak, it should be possible to obtain a voltage of 3000 v peak-to-peak across the KD*P cell.

The equation for the average power dissipated in the RIC circuit at series resonance is

$$
\begin{equation*}
P=\frac{V_{m} I_{m}}{2}=\frac{V_{m}^{2}}{2 R} \simeq 34 \mathrm{~W} \tag{3-20}
\end{equation*}
$$

for $V_{m}=6 \mathrm{v}$ and $\mathrm{R}=0.53 \Omega$. For a ruty cycle of 1000 of $I$ the average power input to the modulator is 37 mW . Thus, crystal heating problems should not be encounterer.

## 5. Pump Cavity Design

The pump cavity designs for the Spaceborne Laser System were guided by information obtained from a literature review and previous ILS experience. International Laser Systems has personnel who have been involved in pump cavity design and experimentation for the past 15 years. The emphasis in the studies performed has always been on increasing laser efficiency. As a result, ILS pump cavities now represent the state-of-the-art with regard to pumping efficiency.

Pumping and cooling uniformity also were goals of the final designs of the Spaceborne Laser System pump cavity. These latter two parameters are important for the efficient operation of a TEM -mode laser. The designs developed for the Spaceborne Laser System pump cavity were plural because an experimental approach was indicated by the reviews of pump cavity theory. At present, this theory analytically speaking is fragmented and only provides design guidelines.


Figure 3-11. Typical ILS Pump Cavity

Figure 3-11 shows two typical ILS pump cavity cross sections on a two-to-one scale. The cavity reflectors are silver-plated for optimum reflectivity. Degradation of chese reflectors is avoided by use of ultra-clean coolant and ionexchange filters. The reflectors are approximately four times longer than the average cross-sectional dimension. Both of the pump cavities shown are nonfocal--that is, the flashlamp and
rod are not at the focal points or a precise focal point is not definer.

A color filter is indicated between the rod and lamp in Figure 3-11. These filters are essentially opaque below 3500 A and thus reduce heating of the laser rod due to UV absorption. Shaping the filter into a wedge as shown in Figure $3-13$ results in better laser efficiency in some cavity geometries.

A typical feature of ILS pump cavities not shown in Figure 3-11 is the use of silver baffles to direct coolant flow uniformly around the rod. This feature results in essentially uniform cooling and, as a consequence, uniform thermal lensing of the laser rod. Symmetrical thermal lensing is essential to the achievement of efficient TEM -mode operation. The flashlamp diameter for $6.35-\mathrm{mm}(0.25-1 \mathrm{~m}$.$) -diameter laser rods$ that is near optimum for laser efficiency is 5 mm . The actual bore diameter is 3 mm because the quartz envelope is typically 1 mm thick.

The pump cavity design guidelines given in the literature ${ }^{24,25,26,27}$ essentially mirror the present ILS designs. From severa] references the following guidelines have been establisher:。

- A single elliptical cavity is more efficient than multiple - ellipses;
- Long elliptical cavities are more efficient than short ones;
- Nonfocal pump cavities can be more efficient in small elliptical cavities because of enhanced multiple reflections through the laser rod; and
- The flashlamp should be the same diameter or smaller than the laser rod diameter.

All of the above guidelines are followed by present ILS pump cavity designs to the extent that is practically possible. Additionally, ILS has determined particular optimization of some of the above guidelines via experimentation as mentioned previously.

Information, not mentioned in the literature but discovered experimentally by ILS personnel, is that the pumping
enclosure need not be elliptical. Also, the effects of filters between the laser rod and flashlamp are not mentioned as a potential enhancement of efficiency. Thus, the major conclusion of the internal ILS experimentation and the literature review is that the two factors remaining to be investigater in pump cavity design are the shape of the pump cavity and the effects of an intra-cavity filter. A limited experimental effort was initiated on the Spaceborne Laser System program to investigate these two parameters. The pump cavity shapes shown in Figure 3-11 together with various filter shapes were chosen for investigation based on previous ILS experience. Experimentation with a diffuse filter also was planned in an attempt to improve pumping uniformity as described by Lewinberger and Herziger ${ }^{28}$. The specific design details of the pump cavities are given in the mechanical design section of this report.
6.

## Amplifier Optical System

The Spaceborne Laser System double-pass amplifier optical system is shown in Figure 3-12. The elements of this system are a beam-expanding telescope, two dielectric polarizers, a Na:YAG laser rod, and a Porro prism which functions as a mirror and a half-wave phase retarder. The design of this optical system was performe with two quidelines. First, to eliminate or reduce spurious reflections back into the oscillator and, second, to avoid damage-prone components. The first guideline resulted in the NA:YAG laser rod and the TIR prism being wedged. The second quideline resulted in the use of a qlass porro prism as a phase retarder instead of a crystalline quartz phase plate.

The operation of the amplifier system is described with reference to Figure 3-12. Initially, the oscillator beam is vertically polarized with reference to the shown dielectric polarizers, expanded by the telescope and directed by the two dielectric polarizers through the TIR prism. When the beam has been amplified by the laser rod, it enters the anti-reflectioncoated half of the Porro prism. Two reflections off the Porro prism TIR surfaces direct the beam to the maximum reflectancecoated half of the Porro prism. Proper alignment of this element directs the beam back on itself and two more TIR reflections are made. The four TIR reflections result in a half-wave phase retardation. The resultant horizontally polarized beam is amplified again, once more traverses the TIR prism and is transmitted by the second folding dielectric polarizer. The transmitted beam is the output of the Spaceborne Laser System.

The lenses are of quartz and were anti-reflection (AR) coated by Valtech. The telescope is designed to diverge any reflections from the lens surfaces to eliminate the danger of a reflection focus resulting in laser damage. Two sets of negative lenses were made. One gives a madnification of 1.499 and the other gives 1.587. These magnifications permit a beam diameter near 5 mm


Figure 3-12. Spaceborne Amplifiex Optical Configuration
with the oscillator beam diameter ranging from 3.0 to 3.5 mm .
The folding polarizers and the TIR prism were both fabricated of quartz. The polarizers were coater by Optical Coating Laboratory, Inc. (OCII) and the prism was coated by Valtech. The TIR prism was fabricated with a pyramidal error which eliminates spurious reflection from the prism outer surfaces back into the oscillator.

The amplifier laser rod is a $1 / 4$-in. by 4 -in. Nd:YAG crystal. The rod is wedged on both ends in the same direction to eliminate reflections into the oscillator. The laser rod ends were AR-coated by Lambda-Airtron.

The Porro prism is the one special optical piece in the amplifier system. This element performs as both maximum reflectance mirror and phase retarder. The operation of the element as a mirror is clear. The beam enters the AR-coated side of the prism, reflects from the TIR surfaces and is returned on the same optical path by the Max R-coated side of the prism. Thus, the beam makes four TIR reflections on one pass through the prism. The fact that the two polarizations perpendicular and parallel to the TIR surfaces have different phase retardations after a TIR reflection is used to make the porro prism a phase retarder. The following paragraoh describes in detail how this was accomplished.

Define $I_{0}$ as the beam intensity incident on the Porro prism, $I_{1}$ as the beam intensity polarized vertically, and $I_{\|}$ as the intensity polarizen horizontally. Before entering the Porro prism, the beam polarization is defined by $I_{0}=I_{1}$. If the roof line of the Porro prism is placed $45^{\circ}$ to the incident polarization, the beam reflected out of the porro prism is defined in a polarization sense by

$$
\begin{equation*}
I_{\mid} / I_{0}=\sin ^{2}(\theta / 2) \tag{3-21}
\end{equation*}
$$

$\theta$ is the total phase retardation (after four reflections) between the polarization components parallel and perpendicular to the plane of incidence of the TIR reflections. This relationship is expressed by

$$
\begin{equation*}
\theta=8 \tan \sqrt[-1]{1-2 / n^{2}} \tag{3-22}
\end{equation*}
$$

Thus,

$$
\begin{equation*}
I_{\mid} \mid / I_{0}=\sin ^{2}\left[4 \tan ^{\left.-1 \sqrt{1-2 / n^{2}}\right]}\right. \tag{3-23}
\end{equation*}
$$

defines the polarization state for the beam reflected from the Porro prism. If BAK-4 or ED-4 glass ( $n \simeq 1.55$ ) is useत for this prism, $I \| / I_{0} \simeq I$ - that is - the polarization has been rotated $90^{\circ}$ as desired.

## C. ELECTRONIC DESIGN

This section of the report deals with the specific design concepts as dictated from the requirements established within the section devoted to the system overview. Specifically, the elecEronic design must provide the flashlamp excitations and the overall timing and control as constrained from and by the lase energy sequence and the lase command sequence. The reader is. referred to Figure $3-13$ and Figure $3-14$ so he can acquire a concise view of the design requirement.

Slight departures from the depiction of Figure 3-14 will occur to provide ease of discussion of the various hardware groups. Three specific groupings are discussed, namely:

- The modelocker electronics;
- The switching and control electronics; and
- The power supply.

1. Modelocker Electronics

The modelocker electronics must generate a sinusoidal voltage across the modelocker pockels cell to provide a variable transmission within the optical resonator at a rate synchronized to the optical resonator roundtrip transit time. The end result of this modulation is the compression of the resonator energy into a photon packet whose half-power pulsewidth is in the region of 200 psec duration. The compression is to occur prior to the Q-switch time.
a. Modelocker Subsystem

The modelocker subsystem consists of: the modulation Pockels cell and drive circuitry for impedance match, which is referred to as the helical resonator assembly; a precise crystal. controlled oscillator as a frequency reference; a frequency synthesizer; and a radio frequency (RF) power amplifier unit. The basic subsystem circuitry is depicted in Figure 3-15.
b. Frequency Source

The precision frequency source oscillator is a Vectron Model C0276 series unit, having an integral proportional tempera-ture-stabilization oven. The frequency stability, as specified by Vectron, is $\pm 0.0001 \%$ over temperatures from $-40^{\circ}$ to $50^{\circ} \mathrm{C}$, following a stabilization period of 15 to 30 min . from turn-on.


P4733

Figure 3-13. Spaceborne Laser Command Sequence and Lase Energy Sequence



Figure 3-15. Modelocker Electronics

The RF amplifier selected is an Electronic Navigation Industries Model $310 L$ broadband unit. This unit is specified to produce an output power of 10 W at a distortion level of $7 \%$; however, useful higher powers are available when this unit is operated in conjunction with a helical resonator load. This becomes true because of the inherent high Q-factor of the resonator. Powers in excess of 20 W are readily available as useful outputs. The high Q-factor of the helical resonator also results in the suppression of frequencies other than the resonant frequency. Thus, the harmonic distortion of the RF signal at the modelocker terminals should be less than 0.1\%.

Figure 3-16 illustrates, in block form, the configuration of the amplifier. (Schematics are included in the appendices of this report.) It is to be noted that four power amplifier modules are driven through power splitters from a common preamplifier module. The outputs from the power modules are then combined to form the RF output. The final combining network also contains a directional coupler. This directional coupler feature is most valuable, since it renders the amplifier able to operate into any load without damage.

From examination of the supplied schematics, it should be noted that the basic power for the amplifier modules is 224 V dc. Thus, the unit would easily operate from the prime power source of $24 / 28 \mathrm{~V}$ dc with little modification. Presently, the power source is from the 117 V ac power mains, however the modification to $24 / 28 \mathrm{~V}$ dc prime power will be made in Phase II.
d. Frequency Synthesizer

The necessity for the frequency synthesizer arises from the inability to precisely determine the roundtrip time within the optical resonator with sufficient accuracy to utilize a crystalcontrolled oscillator alone. The design concept allows frecruency adjustment increments of 10 kHz within the range of 50.000 to 69.990 MHz . The basic design is depicted in Figure 3-17. A vol-taqe-controlled oscillator is compared to a precision oscillator through a phase detector. The phase detector is of the type one class which achieves lock with zero phase error. Schematics and circuit description are provided within the appendices. Experimental results of frequency stability of the combined frequency synthesizer and the reference oscillator are provided in Section IV.


Figure 3-16. RF Amplifier Block Diagram


Figure 3-17. Frequency Synthesizer Diagram

The paramount function of the helical resonator assembly is the voltage transformation from the RF amplifier to the CRE Steinmetz cell. The basic design approach is the series-resonantcircuit $Q$ multiplier which serves to increase the voltage amplitude In this circuit configuration, the high impedance point is the junction of the resonating inductor and the resonating capacitor. The high-impedance point also is the point of greatest voltage. Thus, if the resonating capacitor were predominantly the Pockels cell the cell would experience the maximum voltage. Resonant circuits of this nature tend to become excessively lossy when conventional lumped constant inductors are utilized. The losses stem from various sources such as direct radiation, surface or skin, resistance, driving source impedance and the like. The mechanism implemented utilizes a helical resonator which is foreshortened to accomodate a high-end capacitive load which, in actuality, is the Pockels cell.

Figure 3-18 shows the construction of the modelocker RF cavity while Figure 3-19 depicts the circuit in schematic form. The mechanical construction is exceedingly critical to proper performance of the voltage multiplication action. The RF cavity wall must be of unitized construction. No mating mechanical interfaces are permissible because they tend to increase the resistivity of the cavity and because the circulating current in the cavity wall is reduced. Placement of the helix within the cavity also is critical. The low-voltage terminal of the helix must contact the inner wall of the cavity at a point placed from the cavity end by not less than the cavity diameter divided by four. Additionally, the helix must be reasonably well centered within the cavity and the turns spaced such that the high-voltage terminal is not closer to the cavity end than the cavity diameter divided by four. With these design criteria ${ }^{29}$, the cavity ends may be open with little or no radiation loss.

The cavity is constructed of brass which is nickel plated, silver plated, nickel flashed (to prevent migration) and finaliy hard gold plated. This process assures high $Q$ for an extended time because the plating enhances electrical conduction and prevents surface contamination. Typically, helical resonators of this nature and size exhibit $Q_{\mu}$ factors (unloaded quality factor) in the realm of 800 to 1,000 . However, the introduction of the Pockels cell, with its inherent loss factor, reduces the circuit $Q$ to $Q_{\mu} \sim 125$.



P2781

Figure 3-18. Modelocker RF Cavity Construction


P2688

Figure 3-19. RF Cavity Circuit

The electrical configuration includes a small trimmer capacitor, in parallel with the cell, which is utilized to bring the cell into resonance at the desired frequency. Drive to the helix occurs at the $50-\Omega$ impedance point. A small probe is introduced into the cavity to extract a RF signal for use in the PTM command generation circuitry. This energy loss is of miniscule magnitude. Experimental data relating to the performance of the helical resonator modulator cell is supplied within section IV.
a. O-switch/Dump Subsystem

The o-switch and dump subsystem is depicted graphically as a portion of Figure 3-20. The subsystem consists of:

- The Pockels cell;
- The Pockels cell electronic interface;
- The O-switch driver;
- The PTM or dump driver;
- The radiation control circuit; and
- The PTM/dump synchronizing circuit.

The most stringent requirement within the area of switching and control was to assure adequate switching speed. This requirement stems from the fact that most transitions must be completed before expiration of one round trip time interval within the optical resonator. This constraint dictates that the interval be not greater than 9.5 nsec .

The second stringent requirement was the implementation of the Pockels cell interface electronic circuitry to accommodate the O-switch drive, the PTM drive and the radiation control drive without mutual interaction. Basically, this problem area was solved by implementing the circuit depicted in Figure 3-21. Voltage/drive input was at the point and in the sequence illustrater. Certain specific embellishments were incorporated to lessen mutual interaction. These will become apparent in the specific discussion to follow.
b. Q-switch/Dump Electronic Interface

Because of the multiplicity of drive reçuirements needed to satisfy the control event sequence, it became necessary to employ differential drive techniques for the Pockels cell. Furthermore, because the Pockels cell is essentially a capacitor when considered electrically, it became necessary to provide small capacitive loading to each side of the cell to achieve adequate voltage drop across the cell. Figure 3-22 depicts this basic differential drive circuit where capacitors $C_{A}$ and $C_{B}$ are the loading capacitors. Depending upon which side is driven, the cell capacity and either $C_{A}$ or $C_{B}$ form a voltage divider, which increases the driver voltage requirements and increases the switching time. Additionally, the remaining capacitor is shunted across the driver and serves only to reduce the switching time.


Figure 3-20. Transmitter Electronic System


Figure 3-21. Simplified Q-switch Interface


A trade off now becomes evident. The shunted capacitance can be made small which requires a much higher drive voltage, or the capacitance can be of moderate value which requires little additional drive voltage. The latter was selected in view of the need for introduction of the radiation control drive signal and the consideration of reliability when the driver voltage is increased significantly. Figure 3-23 illustrates the transform to determine the effective capacitance the driver is requiren to discharge when $C_{A}$ and $C_{B}$ are selected to be 100 pF . This arrangement results in a discharge current through the driver of approximately 77 A , which is well within the driver capability.

Figure 3-24 depicts in schematic form the actual interface circuit. Driver bias voltage is established to be 3.6 kV which affords $100 \mu \mathrm{~A}$ dc quiescent current to each driver. The cell bias voltage could range from 1 kV dc to a maximum of 3.6 kV तc. Resistor $R 3$ and the prelase radiation control establish a voltage of near +300 V dc at terminal B . of the Pockels cell. Resistors R4 and R6 develop a potential of near +400 V dc at the cathode of diode CR3. The O-switch driver is diode coupled to terminal A of the Pockels cell. The PTM driver is capacitively coupled to the cathode of diode CR3 and thence to terminal $B$ of the Pockels cell. The operating sequence places the cell bias voltage below holdoff value, which is generally about $+2,700 \mathrm{~V}$ dc. The radiation control electronics forces the terminal $B$ of the Pockels cell to be in the region of +300 V dc, at the $Q$-switch event time.

When the 0 -switch event occurs, the $Q$ terminal voltage of the Pockels cell is discharged to near ground by the forward conduction of diodes CR1 and CR2. Simultaneously, the B terminal voltage of the Pockels cell is reduced to near ground potential by the voltage divider action of the cell capacitance and 100 pF capacitor C5. The cell differential voltage now is zero and HI O is assured within the resonator.

A brief time later the PTM or dump event is commanded. The PTM voltage excursion is 3.4 kV ; thus, the cathode voltage of CR3 excursion is from +400 to -300 V dc. The diode CR3 did not become forward biaser until the cathode potential reached 0 V . The cell voltage becomes -3.0 kV dc. An interesting and aiding phenomenon occurs at the A terminal of the Pockels cell. Diodes CRI, and CR2 exhibit long minority carrier storage time (in the region of 2 to $3 \mu \mathrm{sec}$ ) following the 0-switch current surge. This effectively clamps the A terminal of the Pockels cell to the avalanche driver. The avalanche driver also is exhibiting a similar minority storage phenomena which effectively clamps the A terminal of the Pockels cell to ground. Thus, no voltage divider action occurs at the A terminal and the full PTM voltage is applied across the cell. Capacitor C 4 cannot be omitted because it is the discharge current that this capacitor


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Figure 3-24. Q-switch Interface Schematic
produces which induces the storage effect. Diodes CR4 to CR7 isolate the radiation control electronics from the PTM drive voltage.

Construction techniques are important for effective operation of the interface. The interface housing is nickel plated, silver plated, nickel flashed, and hard-gold flashed to achieve adequate surface conduction and, thereby, preserve switching speed. Aतditionally, this surface preparation assures. reliable operation for extended time periods because surface contamination is unlikely. Interconnections are as direct as possible, heavy leads or straps are used to minimize stray inductance. Noninductive, high-voltage resistors are used throughout. Monolithic chip-type capacitors are employed whereever possible to minimize coupling loss and/or stray inductance. A specific circuit description and schematic of the interface circuit is included in the appendices of this report.
c. High-Voltage Avalanche Driver

The avalanche driver design is rather straight forward. The transistors utilized are selected 2N3019 devices. These devices are coaxially packaged end-to-end within a tubular shield enclosure. The packaging technique ensures low switching impedance, prevents false triggering from ambient noise, and prevents interaction by radiation from the driver at transition. Each transistor is selected for an avalanche holding voltage of $>250 \mathrm{~V}$ dc at $100 \mu \mathrm{~A}$ holding current. Thus, 14 devices will withstand $3,500 \mathrm{~V}$ dc and will provide a transition voltage of nearly $3,250 \mathrm{~V}$. Ouiescent power dissipation within each transistor string is equal to approximately 0.35 . .

Typical voltage transition time with a l0-pF load is 2 nsec. With additional capacitance, the switching time is degraded. Subsystem experimental data contained in section IV illustrates the switching speed obtained. A specific circuit description and schematic of the driver are included in section VI which contains the appendices of this report.
d. PTM/Dump Synchronization

The paramount function performed by the PTM synchronizer is the determination of the proper time to effect pulse emission from the resonator. This determination is accomplished by sensing the optical resonator energy level referenced to a predetermined threshold value. Whenever the threshold is exceeded, the PTM initiate command is generated. Additionally, a determination of the photon packet placement within the resonator is accomplished so that the PTM driver transition occurs before the energy pulse encounters the Pockels cell. This synchronization is accomplished by sampling the morelocker cavity signal and through signal conditioning of the sample.

The sinusoidal $R F$ signal sample is squared at the centroid, or zero, level by a thresholr voltage comparator. This signal then is used as a "clock" to initiate the PTM command whenever the PTM threshold is exceeded. Two staqes of phase shift circuitry precede the squaring comparator which permit empirical adjustment to assure that pulse "slicing" of the photon packet is avoided. The phase adjustment range is $\pm 170^{\circ}$. The ECL logic family is utilized in all high-speed stages to assure speed and to minimize component count.

The PTM threshold circuit is windowed to the laser PRF command to assure that the PTM driver is not discharged prior to the event time. A detailed schematic and circuit description are provided in section VI which contains the appendices of this report.

## e. Radiation Control Loop

The purpose of the radiation control loop is to energy stabilize and pulse stretch the oscillator optical resonator energy during the prelase interval prior to Q-switching. Basically, the system consists of an optical detector, and an amplifier which controls the Pockels cell transmission. This system operates as a servo mechanism to effect a low-level radiation density within the oscillator optical resonator.

The photo detector is chosen to exhibit some integration for narrow-pulse inputs; thus, the average power within the oscillator resonator is maintained rather than the peak power. For very narrow lase pulses - approaching the 200 -psec region this integration action is necessary in view of the limited amplifier high-frequency limit.

The bandwidth of the preamplifier is establisher to be $\simeq 360 \mathrm{MHz}$, that is

$$
\begin{align*}
& \text { Observed } t_{r}=1.5 \mathrm{nsec}  \tag{3-24}\\
& \text { Oscilloscope } \tau=0.8 \mathrm{nsec} \\
& \text { Ampl } t_{r}=\sqrt{1.5^{2}-.8^{2}}=1.26 \mathrm{nsec} \\
& f=\frac{1}{2.2 t_{r}} \simeq 360 \mathrm{MHz}
\end{align*}
$$

The preamplifier low-end response is quite good, showing a droop of less than 1 dB over a pulsewidth of 3 usec. Maintaining proper amplifier bandwidth is essential for the prelase control to effectively stretch the normal-mode pulse to a usable value.

A high-voltage driver stage follows the preamplifier and must handle voltages in the region of 400 V . Additionally, the voltage is predominately discharging; therefore, it is meaningful to consider slew times or attack time rather than bandwidth. Voltage slew time from the $400-\mathrm{V}$ level to near 0 V is $\sim 50 \mathrm{nsec}$ or $8 \mathrm{kV} / \mu \mathrm{sec}$. Because of the nature of the normal mode buildup, this slew rate is adequate to effect control.

Irradiance sensitivity is $\leq 100_{\mu} W$ total illumination to the detector to achieve the total control voltage range. This apparent over-design was purposeful in that neutral-density filters easily reduce the gain of the servo loop.

A detailed circuit description together with a schematic are provided within Section VI, which contains the appendices of this report.

## 3. Power Supply

The power supply consists of various subunit circuit blocks which effect power input conversion or mode control for the spaceborne laser. Figure 3-25 depicts the interface between the power supply unit and the remainder of the laser system. Additionally the subunit circuits are listed within the power supply block depiction. These subunits are designated:

- The flashlamp power modules;
- The pulse forming networks;
- The Q-switch driver voltage sources;
- The prelase and Q-switch control logic;
- The pulse repetition frequency (PRF) rate generator; and
- The logic voltage power supply.

Because the laser system design encompasses an oscillator and an amplifier, some of the subunits appear in duplicate. Specifically, this applies to the flashlamp power modules and the pulse-forming networks. In the case of the power modules, no differences exist relating to power output or charge time; however, the different power requirements between the oscillator and the amplifier necessitate a variation in voltage regulation level. This level change is accomplished by the front panel controls. Functionally, the pulseforming networks are identical. The component values are optimized for the requirements of oscillator and/or amplifier pump.

Additionally, two simmer circuit subunits are required. Each circuit is identical and is of the full simmer type. The simmer current is adjusted for approximately 120 mA dc. Flashlamp ignition is automatic whenever the lamp current falls below a preset sense level in order that lamp ionization is maintained.


The choice of high-voltage, avalanche-type drivers for the 0-switch and PTM switch functions, necessitates two highvoltage supplies. One supply is utilized for quiescent avalanche holding current for the avalanche drivers, while the sole purpose of the second supply is the generation of the hold-off bias voltage for the pockels cell. The two supplies are inentical in regard to the output voltage and the output current capabilities. Design of these supplies employs the closed-loop voltage sense technique which ensures excellent stability with time and load. Voltage adjust of these supplies is accomplished from panel mounted controls.

A single logic card contains both the pulse repetition frequency'(PRF) generator and the prelase and o-switch control logic. These functions are derived from a l0-MFz crystal clock oscillator through digital counter technology. This assures excellent long-term as well as short-term stability. The timing resolution is limited to one clock pulse period which equates to 100 nsec . Operator control is accomplished as an enablement of the logic circuitry, rather than a direct-line switch function. Thus, timing accuracy is unimpaired and noise pickup is prevented. A single logic voltage power supply is incorporated to convert the prime power to an isolated 5 NV level for operation of the logic circuitry.

Interface connections for the power supply unit are depicted in Figure 3-26. Figure 3-27 shows the overall laser system in pictorial format and serves to depict the front panel controls for the power unit. Prior to specific subunit circuit discussion, a brief description of controls, indicators, and connectors is provided.

Prime power enters the power supply unit via high-current jacks which are located on the left-rear corner of the panel. Polarity must be observed in this connection. The prime power source is 24 to 28 V dc. The prime power interrupt (circuit breaker) is located on the left side and immediately above the prime power input jacks. This switch engages the power source and arms the control circuit. An incandescent indlcator mmediately over the switch is illuminated for power engaged conditions. An armed/standby switch - located to the right side and about midway up the panel - controls power to the flashlamp charging circuits, the simmer circuits and the high-voltage driver circuits. The system is armed when the switch is in the elevated position. An incandescent indicator - located immediately above the switch is illuminated when the power supply unit is armed. It is to be noted that the simmer circuits automatically ignite the flashlamps when the system is armed. However, the lamps are unable to discharge the PFN until each flash command is engaged by the operator. This characteristic will become evident from the following discussion.



Figure 3-27. Hardware Subassemblies

The laser head/transmitter unit power is interfaced via the large MS type connector adjacent to the prime power input jacks. All power functions, with the exception of the driver high voltages and the modelock drive signal are transmitted through this connector to the transmitter unit. Typical power inputs are the cooling system 24 Vdc power, the oscillator flashlamp power, and the amplifier flashlamp power.

The analog meter and the associated selector switch are used to determine the voltage level of the PFNs. Either the oscillator PFN or the amplifier PFN can be monitored. Adjustment of the charge voltage for either the oscillator or the amplifier can be accomplished at the front panel. Adjustment of the knob potentiometers accomplishes the voltage change. These controls are located below the panel meter to either side of the meter select switch.

An electro-mechanical totalizer is located near the center top of the panel. Each .ten flashes of the oscillator flashlamp results in the totalizer advancing one least-significant count. A mechanical reset is possible for the totalizer through an access port to the left side of the totalizer.

The high-voltage adjustments and enable switches are grouped together to the right top of the panel. Each high-voltage supply is independently adjustable in voltage via the potentiometer knob. Each high-voltage supply can be enabled (turned on) independently by the control switch located above each knob. The high-voltage output is scaled to equal approximately $50 \%$ of the dial reading times ten.

The pulse repetition frequency (PRF) is accomplished by. the position of the rotary switch at the top right of the panel. The PRF may be operator selected as, 1, 5, 10, or 20 pulses per second (pps).

Two thumbwheel switch arrays allow operator programmed delays for the prelase initiation and the Q-switch initiation. The thumbwheel entry is in the decimal format. The least significant digital resolution is 100 nsec . The maximum delay entry value is $399.9 \mu \mathrm{sec}$ which is established by mechanical limitation to the most-significant digit thumbwheel. These controls allow precise delay for the appropriate function. Typical indicated jitter at the command lines, referenced to the flashlamp command, is equal to or less than $\pm 2 \mathrm{nsec}$.

Two high-voltage connectors appear near the bottom center of the panel. These connectors interface to the laser head to supply bias to the drivers and the Pockels cell. They are labeled 0 -switch driver and 0-switch bias respectively.

Five BNC type connectors are utilized for various command outputs. These are:

- The oscillator flash command;
- The amplifier flash command;
- The prelase command;
- The O-switch command; and
- The modelock command.

These outputs are essentially self-explanatory. The prelase command and the o-switch command are routed to the laser transmitter unit for initiation of their respective functions. The modelock command is routed to the modelock driver unit to initiate the modelock pulse burst. The oscillator and amplifier flash commands are available as convenient reference synchonization signals for use with auxiliary instrumentation such as oscilloscopes. Each command function is controlled by an operatorselectable mode switch. These five selection switches appear at the lower right of the control panel. Each switch is designated for the control function. These functions are identical to the BNC outputs previously enumerated.

The remaining indicators pertain to over-temperature conditions within the laser system transmitter. Separate indication is provided for the laser oscillator and the laser amplifier. Direct control of these incandescent lamps is from snap action thermostats located upon each respective optical pump housing assembly within the laser transmitter.
a. Power Supply Subsystem

Organization of the power supply unit subsystem is illustrated in Figure 3-28. Figure 3-29 enumerates the subsystem circuits which comprise the power supply unit. This report section deals generally with the components and the component interface. A detailed description and associated circuit schematic material for each subsystem is provided within the appendices.

Flashlamp power is provided by two circuit groupings. Each circuit grouping consists of: a pulse-forming network (PFN), consisting of an inductor and an energy storage capacitor; a voltage-charging power module assembly; a simmer supply; and a discharge switch, consisting of a silicon-controlled rectifier (SCR) .



Figure 3-29. Electronic System Block Diagram

The simmer supply voltage initially rises to the kilovolt level when the laser system is armed and the automatic flashlamp ignition circuit - located within the simmer supply circuitry energizes the lamp ignition transformer. The lamp ignites and draws current from the simmer supply. The output voltage of the simmer supply reduces to a level which maintains a current $\simeq 100 \mathrm{~mA}$ dc through the flashlamp. The automatic ignition circuit is disabled so long as the simmer current is maintained. The simmer supply design is essentially a constant-current type; thus, no problem arises when the terminal voltage varies. Flashlamp arc wander and minute variations within the flashlamp plasma result in rapid voltage fluctuations at the flashlamp terminals. For this reason, inductive ballasting is provided.

Simultaneously, beginning at laser system arm time, the PFN capacitor charging power modules produce a voltage across the PFN capacitor. These modules are of the inductive "fly-back" type which perform as constant-current-charging generators. When the voltage of the PFN capacitor reaches a predetermined level, the charging current is removed. The charging circuitry is designed to maintain the voltage level within $\pm 0.5 \%$ of the preset value.

The flashlamp is ignited and simmered, and the PFN now is charged. An output from the pulse-repetition-frequency (PRF) generator commands the SCR to dump the PFN through the flashlamp. Transformer isolation allows the SCR to be placed in series with the flashlamp and the PrN. A quench circuit senses the flashlamp current pulse and inhibits the charging circuit for a time $\simeq 2$ msec. Interaction between the charging circuit, the dump circuit and the simmer circuit is avoided by diode isolation to the simmer power modules.

The arming circuit is enabled by closure of two case interlock switches and by the temperature monitors of each optical pump cavity assembly. Interruption of any one circuit results in disarming, and both the simmer current and the PFN voltage axe removed. One case switch is located within the transmitter unit, while the other switch is within the power unit.

The PRF generator outputs the delayed commands at the appropriate delayed time(s). These commands, with the exception of the flash commands, are utilized within the laser transmitter unit and the modelock unit.

The operation of the remaining power supply submodules is completely straight forward. Each power supply is a standalone assembly. Only the logic power unit - the $5-\mathrm{V}$ de supply is powered external to the interlocked arm/standby control.
b.

## Flashlamp High-Voltage Supplies

Two completely independent power supplies are required. One supply charges the oscillator PFN capacitor, while the other supply charges the amplifier PFN capacitor. The charging supplies are of the fly-back type which produce constant-current charging of the capacitors. In the interest of predictable operation, these units are configured as driving mechanisms.

A modular approach has been applied to the implementation of the supplies. The basic power capability of a single power module is $\simeq 250 \mathrm{~W}$. Two power modules are slaved for each charging circuit to achieve the necessary output charging capability. Module slaving is at $180^{\circ}$ phasing to minimize power current peaking and electrical noise. Operating efficiency is in the $80 \%$ region; thus, heat sinking and convection cooling are more than adequate to maintain the component temperatures below $60^{\circ} \mathrm{C}$. Voltage regulation is equal to or better than $0.5 \%$ as the result of the voltage regulation implementation chosen.
c. Flashlamp Simmer Supplies

The paramount requirements for the flashlamp simmer supplies are:

- The commanding of the trigger transformer to achieve lamp ignition; and
- Supplying a small keep-alive current, referred to as simmer current, within the lamp to stabilize the arc and to maintain ionization.

Flashlamps with varying lengths, varying arc bore diameters and varying fill pressures exhibit widely diverse requirements from the standpoint of simmer voltage and/or simmer current. Ideally, the supply should furnish constant current to the lamp and should possess excellent voltage tracking with the lamp.

The present implementation is considered adequate even through the circuit is of the constant-energy type, which produces a nominal simmer current of 125 mA dc. Voltage tracking speed is enhanced by the use of an inductive ballast. Complete circuit schematics and circuit operation descriptions appear within the appendices.

A separate simmer supply is required for each flashlamp. For this reason, two identical supplies are incorporated into the Spaceborne Laser System. One supply serves to ignite and simmer the oscillator flashlamp, while the second supply performs for the amplifier flashlamp.
d.

Flashlamp PFN
The current density near optimum for krypton flashlamps is near $3,500 \mathrm{~A} / \mathrm{cm}^{2}$. This current density results in a good spectral match between the krypton emission lines and the Nd:YAG absorption lines. ${ }^{30}$ The following calculation determines the inductor and capacitor resulting in critical damping for the oscillator and amplifier pulse-forming networks (PFN) to generate a current density near the optimum at the necessary pump energy levels.

The flashlamp selected for use in the Spaceborne Laser System is a 3 -mm bore, $3.375-i n$. arc length krypton flashlamp manufactured by IIC, Inc. The gas pressure was 450 Torr. The damping parameter for flashlamp discharges is given by ${ }^{30}$

$$
\begin{equation*}
\mathrm{X}=\frac{\mathrm{Ko}}{\sqrt{\mathrm{VO}_{\mathrm{O}} \sqrt{\mathrm{~L} / \mathrm{C}}}} \tag{3-25}
\end{equation*}
$$

where

$$
\begin{aligned}
\mathrm{V}_{0} & =\text { voltage across capacitor, } \\
\mathrm{I}_{1} & =\text { PFN inductor value, } \\
\mathrm{C} & =\text { PFN capacitor value, } \\
\text { and } \mathrm{K}_{\mathrm{O}} & =\text { flashlamp parameter } .
\end{aligned}
$$

Ko is 33 for the particular flashlamp selected. For critical damping, $x$ should be approximately $0.8 .0^{\circ}$

The equation relating the pump energy, the PFN capacitor and PFN voltage is

$$
\begin{equation*}
E=(I / 2) C V^{2} \tag{3-26}
\end{equation*}
$$

This equation and the equation resulting from setting $X=0.8$ can be used to calculate the remainder of the PFN.characteristics given the pump energies. The average pump energy for the Spaceborne Laser System oscillator is $4 J / p u l s e ~ a n d ~ t h a t ~ f o r ~ t h e ~ a m p l i-~$ fier is $8 \mathrm{~J} /$ pulse. Table $3-5$ gives the results of the PFN calculations.

| Characteristic | Oscillator | Amplifier |
| :---: | :---: | :---: |
| Pump Energy (J/pulse) | 4 | 8 |
| Voltage (V) | 886 | 948 |
| Capacitance ( $\mu \mathrm{F}$ ) | 10.2 | 17.8 |
| Inductance ( $\mu \mathrm{H}$ ) | 37.6 | 5.7 .0 |
| Pulsewidth (usec) | 69 | 111 |
| Current Density ( $\mathrm{A} / \mathrm{cm}^{2}$ ) | 3268 | 3746 |

e. $\quad P R F$ and Delay Generator

The PRF and delay generator circuitry establishes the laser emission rate and provides precise, delayed initiate commands for activation of the 0 -switch driver and the prelase control. Various enable gating circuits are provided for ease of laser control. These are:

- Q-switch enablement;
- Prelase enablement;
- Mode lock enablement;
- Oscillator lamp flash; and
- Amplifier lamp flash.

The PRF can be operator selected for $1,5,10$ and 20 pps . Additionally, a divide-by-10 scaler is incorporated to drive the flash shots counter.

The Q-switch delay and the prelase delay are entered from thumb wheel switch arrays. The maximum delay is 399.9 usec, while the minimum delay is $\pm 0 \mu \mathrm{sec}$. The minimum program increment of delay is 100 nsec . The entry format is decimal. Highspeed TTL logic is utilized in the interest of timing accuracy. A detailed circuit description and circuit schematic are provided in Section VI, of this report which contains the appendices.
f. High-Voltage, Low-Current Supplies

Two high-voltage power units are provided. One supply is utilized to establish the Pockels cell hold-off bias voltage. The other power supply supplies the bias voltage for the ava-. lanche drivers.

Design care was exercised to assure good regulation, minimum ripple voltage and ease of adjustment. Each supply is capable of producing voltage output within the range of +800 V to +4.0 kV dc. Each supply is capable of furnishing current in excess of 500 mA dc. A concise circuit description and schematic are provided in section VI of this report which contains the appendices.
D. MECHANICAL DESIGN

1. Transmitter Packaging

Figures 3-30 and 3-31 show the transmitter mechanical assembly. The optical bed is mounted to an aluminum base plate by a three-point kinematic suspension. One point of this suspension is shown in Figure $3-30$ as item 20. The kinematic suspension of the bed allows free relative thermal expansion between the Invar bed and aluminum base plate without inducing mechanical stress in the optical bed. Each point of the suspension consists of a ball spring-loaded into a conical-like aperture with belleville washers. Two of these apertures are elongated to permit motion in orthogonal directions and one is a perfect cone which constrains that point in all three dimensions.

The electrical and cooling hose interfaces of the transmitter with the other three modules of the laser system are made through the aluminum base plate from below. The base plate is suspended. on four steel rods terminated by Gaertner magnetic bases to permit space for these interface connections. The transmitter subsystem is sealed by an aluminum cover which fastens to the base plate via a hermetic o-ring seal. This cover has a dry-gas fill port, a pressure relief valve, and a sealed beam output window.

The major subsystems within the transmitter are the optical bed assembly, the Q-switch driver assembly, the Q-switch and PTM dump synchronization electronic assemblies, and minor electronic components. The following descriptions of the mechanical design center on the optical bed and its component optical mounts.



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Following the discussion of the optical bed design, the subajssemblies attached to the bed will be discussed in the following order:

- Beam-folding TIR prisms;
- KD*P Q-switch;
- KD*P modelocker;
- Pump cavities;
- Resonator mirror;
- Double polarizer;
- Risley prisms;
- Folding polarizers;
- Porro prism reflector;
- Expanding telescope;
- Compensating wedge;
- Aperture assembly; and
- Q-switch drivers.

Three optical bed subassemblies are shown in Figure 3-30 which were not implemented in Phase I of this program. These are the frequency doubler, dichroic mirror, and a diffuser and are existing ILS designs.

## 2. Optical Bed

The stability of the optical path length of the laser resonator is of paramount criticality to keep the optical transit time matched to modelocker frequency. Accordingly, early consideration was given to environmentally induced distortions of the optical bed during operation. A goal of $0.001 \%$ bed length stability was established with temperature control to $\pm 5^{\circ} \mathrm{F}$ and in a one " g " ground checkout conđition. Bed length control methods considered were:

- Use of materials of differing and offsetting thermal expansion. While feasible, certain problem areas were recognized. Accurate knowledge of both steady-state and transient temperature gradients throughout the bed would be required. These probably could not be adequately determined until a prototype system was fabricated and tested. Additionally, with a bed structure of discrete parts bolted together, minute positional shifting of parts with respect to each other during temperature cycling was considered a detrimental possibility;
- Control of modelocker frequency to compensate for bed length changes caused by temperature variations. Temperature sensing would be required with attendant uncertain effects of steadystate and transient temperature gradients throughout the bed which would have to be compensated. Modelocker frequency control, while feasible, would require additional electronic circuitry complexity;
- Use of stable, low-expansion alloy such as Invar. Thermal and stress analysis showed thermal effects to exceed gravity distortion by $\simeq 10: 1$. Therefore, use of Invar (Temperature expansion coefficient $0.9 \times 10^{6} /{ }^{\circ} \mathrm{F}$ ) would approach the above goal - (0.001\% stability). This was selected as a direct, practical approach.

The configuration selected for the Invar optical bed is an integral structure as shown in Figure 3-30. The bed thickness is 0.5 -inch and the walls are 0.1875 -inch thick by 1.25 -inches high. The optical mounts fasten to the sides of the bed such that the beam height off the bed is 0.75 inch. Three TIR prisms are mounted to the ends of the bed to fold the beam along the desired paths through the optical components.

The bed was fabricated from a block of free-machining Invar 36 . The substantial machining required to fabricate the bed dictated stress-relief heat treatments. Two in-process, stressrelief treatments were performed prior to the final machining of the bed. The Invar block was first machined to 0.06 -inch oversize in its major dimensions, then heat-treated for one hour at $1200^{\circ} \mathrm{F}$ and cooled slowly. Machining of the bed to 0.03 -inch oversize in the major dimensions was performed next followed by heat treatment as above. The bed was then machined to its final dimensions with the inclusion of all detail machining. A final heat treatment was as described above but at a temperature of $600^{\circ} \mathrm{F}$. An acid treatment of the bed was performed to remove oxidation elements resulting from the final heat treatment. The bed was then nickel-plated to prevent future oxidation. The bed fabrication procedure described above was developed in consultation with a metallurgist at Carpenter Technology, the Invar vendor.

The three beam-folding TIR prisms attach to the bed via metal clamps with rubber pads between the clamp and prism as shown in Figure 3-30. The prisms are held against Invar pads attached to the bed. These pads are located to avoid mechanically-induced stress in the prisms at the beam paths through them. The purpose of the Invar pads is to align the prisms in their sensitive plane. The machining of these pads was a two-stage precision process. The result desired and achieved was a non-adjustable optically precise mounting of the TIR prisms.

The TIR prisms were designed to have a $1.5^{\circ}$ pyramidal error to avoid etalon effects. Thus, it was necessary to tilt the entrance surface of the prism $2.175^{\circ}$ to the required optical paths in order to achieve alignment. This implies a requirement that the Invar pads be fabricated as wedges with an angle of $2.175^{\circ}$ with the assumption that the bed ends are perpendicular to the required optical paths. In practice, fabrication errors of both the prisms and the optical bed dictated a slightly different angle that could be determined only through an optical measurement to be described in the laser alignment section of this report. An optical polish of both sides of the Invar pads and the optical bed ends to $\lambda / \Delta$ flatness using sodium light was performed to ensure the accuracy of the above-outlined alignment technique. It is implied above that a second machining operation is required for the Invar pads. This machining and subsequent repolishing was achieved to an accuracy of better than 10 arc-seconds.

- Proper location of the TIR prisms relative to the optical axes was also necessary. This was also achieved via a precision mechanical reference surface. Each prism was mounted with one side flush against an Invar bar attached to the optical bed. These metal bars were mounted to the bed and then the reference surface was machined to be either parallel or perpendicular to the optical bed surface on which the remaining optical mounts were attached. The particular beam-folding direction of each prism dictated the correct reference plane. Slippage of the prisms parallel to the pads mounting surfaces was constrained by Noryl blocks attached to the bed.

A KD*P crystal, 0.5 -in. in diameter and l-in. long is mounted in a sealed cell with quartz end windows and partly filled with a refractive-index-matching fluid ( $\mathrm{FC}-77$ ) . Both the crystal and windows were fabricated with small, carefully selected, precise wedge angles to avoid etalon effects. Fluid thickness between the crystal and windows was kept thin ( 0.040 in. Max) by Teflon spacers which also provide some resilience at assembly. The indexmatching fluid was selected for high surface tension to inhibit formation of small air bubbles which might occur between the crystal and windows. A bubble-trap is provided to collect larger air bubbles out of the optical path. A second purpose of the bubble trap is to provide a built-in air volume to compress and accommodate liquid thermal expansion. A high-voltage drive (3,250 V) applied to each end of the crystal accomplishes Q-switching. Thus, an electrically insulating cell body with conductive end caps isolated from ground to serve as crystal electrodes was indicated. The cell end caps also serve as window retainers. The cell body is made of Macor, a machinable ceramic, and the end electrodes of gold-plated brass with flexible fingers about the periphery of the crystal. The cell is supported by a three-ball kinematic mount which allows $2^{\circ}$ adjustment of the cell axis in pitch and yaw attitude. Full $360^{\circ}$ rotational adjustment and locking of the cell is provided by set screws riding in an annular v-groove in the Macor cell body:

## 5. Modelocker Cell and RF Cavity

The crystal cell is internally the same as the o-switch (KD*P crystal, index-matching fluid, quartz windows). External parts were modified for modelocker application where only one end of the crystal is driven by high voltage, the other end being at ground potential. The metal end caps serving as crystal electrodes were modified as follows:

- A screw attachment is provided for an electrical lead to the high-voltage electrode; and
- The ground electrode is modified to provide the annular v-groove for rotational adjustment of the cell, thus providing a ground electrical contact.

Again a three-ball kinematic mount supports the cell on the modelocker RF cavity. The range of adjustment of cell position are:

- Pitch and Yaw $\pm 1.50^{\circ}$
- Rotation $\pm 0.50^{\circ}$

The cell is oriented so that its optical axis nominally is on the centerline of the RF cavity. Layout studies were made of methods to mount the cell transverse to the RF cavity, but none promised as compact an assembly as the coaxial configuration.

The RF cavity provides a high-efficiency, RF, LC circuit
 a coil, a capacitor, and a ground tube with electrical connections to excite and monitor the circuit. The coil consists of 10 turns of 0.1-in. diameter wire wound to a 1.0 -in. ID with a pitch of 0.15 in. One end of the coil is attached to the external ground tube of the cavity. The other end is connected to an adjustable piston capacitor mounted in the ground tube wall and to the highvoltage electrode of the KD*P crystal. The cround tube has a 2.0 in. ID, and a 0.1-in. wall thickness and is 3.35 in. long. As the result of high circulating currents, both the coil and ground tube are gold plated and minimum interruptions of material are allowed in approximately 2.5 in . of the tube spanning the coil. The ground tube provides attachments for:

- A coil ground connection;
- A piston capacitor;
- A coil excitation connector;
- A voltage sensing connector (no electrical connection to the coil is required);
- A support for the cell kinematic mount;
- Three-ball adjustable kinematic attachment to the optical bed.


## 6. Pump Cavity

An important system objective was to optimize optical coupling between the flashlamp and the laser rod. The oump cavity was designed to allow acquistion of comparative test data on the following configuration variables:

- Elliptical versus intersecting-circle cavity cross sections (two sizes of each);
- Optical filters between the lamp and rod with five different wedge angles.

It was considered that by trial of these variables, optical coupling from the lamp to the laser rod could be optimized.

The cavities are water/glycol cooled and contain the Nd:YAG rod and krypton flashlamp. Coolant is circulated first through the rod side of the cavity and then through the flashlamp side to optimize rod cooling. The coolant path is haffled to enhance turbulant flow for more uniform cooling. Cavities were designed to accept $0.25-i n$. x 4 -in. and $5-\mathrm{mm} \mathrm{x} 101.6-\mathrm{mm}$ rods. Cavities are of brass with all internal surfaces highly polished and silver plated. Rod ends were fabricated at wedge angles to avoid etalon effects.

## 7. Passive Optical Mounts

a. Concave/Convex Resonator Terminating Mirror

A single double-faced concave/convex mirror is used to terminate both ends of the resonator optical path. It is a $0.5-i n$. diameter $x$ 0.312-in. thick glass mirror with high reflectivity coatings. The mirror is bonded into a stainless steel holder which is in turn clamped into an adjustable mount. This arrangement was provided to facilitate changing mirrors during Phase I testing. six mirrors of differing face radii were provided. The adjustable mount has a three-ball kinematic support providing a pitch and yaw range of 10 mr with $0.4-\mathrm{mr}$ resolution.
b. Double Polarizer Assembly

The function of this component is to direct the resonator beam either into the resonator path or, with a parallel offset ( $0.8-\mathrm{mr}$ limit to deviation from parallel) out to the amplifier path depending upon the direction of polarization of the beam). Two matched polarizers are cut from the same dielectric-coated glass blank so that the optimum angle of incidence of both will be the same. These are bonded to a special holder which, in turn, is supported on a special adaptation of standard ILS polarizer mounts with screw adjustment for tilt and rotation.
c. Wedge Risley Prisms

These components provide beam corrections either angularly or laterally offset. They consist of two prisms 0.5 -in. in diameter
x 0.25-in. thick with faces polished at wedge angles. The prisms are bonded into holders in which one roller only can be rolled or both rollers can be rolled in unison. The mount is an adaptation of standard ILS designs with a screw adjustment on the optical axis for pitch and yaw. Roll adjustment and locking of the prism holders is achieved through set screws riding in annular V-grooves.
d. Folding Polarizers

The function of these two items is to provide a lateral offset of the output beam from the telescope to the laser amplifier via a folcing prism. Two matched polarizers are cut from the same dielectric-coated glass blank so that the optimum angle of incidence of both will be the same. Each is bonded to identical special holders with rotational and tilt capability. The pivot-points for rotation of the holders is selected so that regardless of the angle of incidence of the beam on the polarizers (within $46^{\circ}$ ), the beam lateral offset remains constant. It is required, however, that both polarizers have the same optimum incidence angle.
e. Porro Prism Subassembly

This is a conventional Porro prism with half of the front face coated so that the incident beam can be reflected back exactly on the same path. A three-ball kinematic suspension is provided so that the prism axis can be directed precisely into the incident beam. The prism is bonded into a sleeve which, by virtue of three set screws riding in an annular slot, can be rotated and locked.

## f. Expanding Telescope

A 1.5x telescope is provided to expand the output beam diameter. Although redesigned for this application as the result of space limitations, it is a direct adaptation of a standard IIS design.
g. Compensating Wedge

This component provides beam path angular and lateral offset correction. The glass, with a $2^{\circ} I^{\prime}$ wedge angle is bonded to a standard ILS polarizer mount. The base of the mount is attached to the bed by a shoulder screw and belleville washer to allow mount rotation. The holder is shaft mounted to the base with screw adjustment for tilt.

## h. Aperture Assembly

Beam diameter can be controlled by this item. It consists of an adjustable holder into which varied sizes of aperture can be inserted. Screw adjustment of aperture position in both transverse directions for aperture diameters of $0.118,0.138$ and . 158 in. was provided.
i. Avalanche Driver

Two units of an existing ILS design are used to drive the Q-switch high-voltage electrodes. Particular attention was paid to mounting these in proximity to the Q-switch with low-impedance circuitry.

The test configuration for this measurement is illustrated in Figure 4-1.

The helical resonator is intolerant to either capacitance. loading or energy radiation loading; therefore, direct measurement of cell voltage becomes a problem. Attachment of a probe to the voltage side of the helix adds capacitance to the circuit and conducts energy from the circuit to effectively reduce the circuit $Q$. Adjustment of the resonant circuit to compensate for the additional capacitance does nothing to restore the circuit $Q$; thus, it is apparent that any probe technique is unacceptable and an alternate approach must be attempted.

Meaningful measurements require that the actual Pockels cell be part of the resonant circuit. It is to be noted that one terminal of the pockels cell is at ground reference in the normal configuration. Now consider the insertion of a series capacitor of large value between the cell terminal and the ground reference to form a capacitance type of voltage divider. This is the technique used to accomplish cell voltage measurement and is an indirect method. It also is to be noted that the series capacitor value must be in the order of 10,000 to 20,000 times the cell capacitance to prevent excessive energy loss from the cavity assembly and the resultant degradation of the circuit $Q$. Additionally, the series capacitor must possess low-lead inductance; thus, "chip"-type (leadless) capacitors were selected.

The assembled cell was measured to exhibit a total capacitance of 9.9 pF . The series capacitor was chosen to be 200 nF ( $200,000 \mathrm{pF}$ ) approximately 20,000 times greater than the cell capacitance. Multiple capacitors were distributed around the low side terminal of the cell assembly to ground. These capacitors were trimmed to provide a measured value of $199,000 \mathrm{pF}$. The additional capacitance of the cable from the test capacitor to the oscilloscope attached is ~ 120 pF .

The frequency synthesizer/amplifier was adjusted to operate in a gated or burst mode and to furnish a peak power output of nearly

TEKTRÓNICS MODEL
7904 OSCILLOSCOPE
7AI9 VERTICAL AMPLIFIER
(200,000 pf) $0.2 \mu \mathrm{f}$ CHIP CAPACITOR


Figure 4-l. Modelock Cell Voltage Measurement Setup

30 W during the pulse. The pulse repetition rate was 10 pulses per second. The RF output was adjusted to $69,860 \mathrm{MHz}$. The cell was connected and peaked to proper resonance. Figure 4-2 presents scope traces of voltage waveforms obtained to assess modelock cell performance.

Oscilloscope photo no. I in Figure 4-2 illustrates the voltage available across the cell at resonance. It is to be noted that approximately 4.8 divisions of the vertical range are distended by the peak-to-peak excursions of the sine wave. For a given sensitivity of $50 \mathrm{mV} /$ division, this relationship equates to a peak-to-peak voltage of 24 mV . The capacitive voltage divider ratio is approximately equal to $20,000 \mathrm{x} 24 \mathrm{mV}$ or $4,800 \mathrm{~V}$ peak-to-peak. This figure equates to a peak cell voltage deviation of $2,400 \mathrm{~V}$ from 0 V , which corresponds to $75 \%$ of the quarter-wave voltage of the Pockels cell and a modulation depth of 1.178.

The measurements were deliberately taken at the maximum expected operating frequency expected to illustrate the worstcase conditions. The worst-case condition arises from the fact that the helical resonator is foreshortened by capacitive loading (the pockels cell capacitance). Obviously, the higher the frequency the more severe the capacitance loading becomes for a fixed helix length.

The approximate RF frequency the Spaceborne Laser System will operate at is 60 MHz . The resonant cavity $Q$ is a function of frequency; lower frequencies yield higher $Q$ and, thus, higher voltage amplitude. The extrapolated voltage amplitude excursion from 0 V at 60 MHz is $\sim 2,600 \mathrm{~V}$.

## 1. RF Burst Envelope

The RF burst envelope is obtained with the test configuration depicted in Figure 4-1. Oscilloscope photograph no. 2 serves to illustrate the burst. It is to be noted that a slight envelope "over-shoot" occurs at the leading edge. Apparently, this characteristic is produced by the Pockels cell material response to the pulse because it is not present whenever a highquality capacitor is substituted for the cell. In addition, photograph no. 2 illustrates the overall flatness of the pulse for the pulse interval, which is approximately 110 usec. oscilloscope photograph no. 3 shows the pulse burst leading edge which illustrate the pulse burst envelope build-up time of $22.5 \mu \mathrm{sec}$. Oscilloscope photograph no. 4 shows the pulse burst trailing edge decay time. The time trailing edges of the pulse burst are indicative of the high $Q$ of the resonant cavity.


OSCILLOSCOPE PHOTO NO. 3


OSCILLOSCOPE PHOTO NO. 4

Figure 4-2. Modelock Cell Voltage Waveforms

Clearly, the pulse burst amplitude envelope is temporarily sufficiently long and reaches stability rapidly enough to provide the desired modulation and, thus, the pulse compression required in the prelase period ( $\sim 3 \mu \mathrm{sec}$ ) of the Spaceborne Laser System device.

## 2. Frequency Synthesizer Stability Measurement

The test configuration of this measurement is illustrated in Figure 4-3. Test data are tabulated and attached.

It is to be noted that the modelocker cell could not be utilized in this test because the output signal of the synthesizer must be of the continuous-wave (CW) mode. Under CW excitation, the crystal would be required to dissipate excessive heat and crystal damage would probably occur. The modelocker cell was replaced with a $50-\Omega$ resistive load and the amplifier was operated at the maximum power output to simulate the worst-case thermal loading of the ENI RF power amplifier. It is to be noted that replacement of the cell with the load resistor in no way affects the frequency stability measurement accuracy because the unidirectional signal isolation afforded by the RF amplifier circuitry provides excellent isolation of the frequency synthesizer from the load. Test conditions are tabulated with the test data.

The frequency synthesizer/amplifier assembly was tested from a cold start--that is, the test is begun with the reference crystal oven at ambient temperature. The test data show that the reference crystal frequency drifted sufficiently during the first 20 min . of the test to create an output frequency change equating to ~ 6,155 Hz . This drift is not serious since the manufacturer of the reference crystal specifies the oven stabilization time to be approximately 15 to 30 min . Therefore, the stability data occurs following crystal oven stabilization. The initial data are included only to illustrate that the reference crystal oscillator exhibits no wild frequency excursion during the stabilization time.

At an elapsed time of 60 min . into the test, the synthesizer output frequency is $60,000,024 \mathrm{~Hz}$. The test data show that a gradual increase in frequency of 68 Hz has occurred from the data taken at an elapsed test time of 25 min . Thus, the drift during this period is equal to approximately one part per million. An additionai 7 Hz of drift occurs to an elapsed test time of 90 min . The test data indicates a total drift during the second hour of the test interval to be $\sim 16 \mathrm{~Hz}$, which equates to a sta-


Figure 4-3. Frequèncy Synthesizer Stability Measurement Setup

REFERENCE:

TEST EQUIPMENT:

Figure 4-3 for Test Configuration
HP Model 5327A
Frequency Counter S. No. 1248A-00321
Calibration Date 6/13/77

TEST CONDUCTED BY:
SPECIAI CONDITIONS:

1. Model 5327A Counter in operation 1 hr minimum prior to test start.
2. Ambient temperature $\sim 25^{\circ} \mathrm{C}$.
3. Device under test. (frequency synthesizer) measured from cold-start to illustrate stabilization time.
4. Test frequency 60 MHz .

## TEST DATA:

ELAPSED TTME
(MIN)
0
5
10
15
20
.25
30
35
40
45
50
55
60
65
70
75
80
85
95

FREQUENCY (Hz)
$60,006,1077$ 60,002,589 60,000,340 60,000,002 59,999,952]
59,999,956
59,999,962
59,999,979 69,999,980 59,999,999
60,000,003
60,000,017
60,000,024]
60,000,026
60,000,028
60,000,029
60,000,032
60,000,031
60,000,032

COMMENTS

Synthesizer and crystal oscillator oven warm-up

TEST DATA: (continued)

| $\begin{aligned} & \text { ELAPSED TIME } \\ & \text { (MIN) } \\ & \hline \end{aligned}$ | FREQUENCY ( Hz ) |
| :---: | :---: |
| 96 | 60,000,031.8 |
| 97 | 60,000,032.3 |
| 98 | 60,000,032.3 |
| 99 | 60,000,032.8 |
| 100 | 60,000,033.0 |
| 101 | 60,000,033.7 |
| 102 | 60,000,033.9 |
| 103 | 60,000,034.0 |
| 104 | 60,000,034.5 |
| 105 | 60,000,034.5 |
| 106 | 60,000,034.7 |
| 107 | 60,000,035.0 |
| 108 | 60,000,035.4 |
| 109 | 60,000,035.6 |
| 110 | 60,000,035.8 |
| 111 | 60,000,035.8 |
| 112 | 60,000,036.6 |
| 113 | 60,000,037.0 |
| 114 | 60,000,036.9 |
| 115 | 60,000,037.5 |
| 116 | 60,000,037.6 |
| 117 | 60,000,037.9 |
| 118 | 60,000,037.9 |
| -119 | 60,000,038.3 |
| 120 | 60,000,038.9 |
| 121 | 60,000,039.1 |
| 122 | 60,000,039.9 |
| 123 | 60,000,040.1 |
| 124 | 60,000,040.9 |
| 125 | 60,000,040.5 |
| 126 | 60,000,040.0 |
| 127 | 60,000,040.1 |
| 128 | 60,000,039.5 |
| 129 | 60,000,039.5 |
| 130 | 60,000,039.2 |
| 131 | 60,000,039.2 |
| 132 | 60,000,039.0 |
| 133 | 60,000,039.0 |

Data taken each minute
to illustrate settletime of frequency output
$F=16 \mathrm{~Hz}$ over second hr period ( 2.6 parts in $10^{7}$ stability)

Thermal roll-over point
bility of 2.6 parts in $10^{7}$. The test data indicates further that the frequency drift/temperature roll-over occurs at 123 min . into the test. The required drive signal stability for satisfactory modelocking is 1 part in $10^{5}$. The ILS modelocker driver system exhibits a stability exceeding this level after stabilization of the crystal oscillator.

Operation of the ILS modelocker driver system in a pulsed mode will result in a frequency stability equal to that exhibited in the CW mode. The crystal oscillator is operated continuously in either the pulsed or $C W$ mode and pulsing of the modelockex driver system is achieved by pulsing the RF amplifier. Because the frequency stability is dependent primarily on the crystal oscillator as illustrated in the reported experiment, the required or better frequency stability can be achieved in the pulsed•mode by allowing 30 min . of warming time prior to system operation.
3. Q-Switch/Dump Switch Waveform Measurements

The Q-switch/dump switch measurement configuration is depicted, in simplified form, in Figure 4-4. It is to be noted that the cell is excited in the differential drive configuration. Prior to discussion and presentation of voltage waveforms of the cell drives, a brief discussion of the basic circuit configuration is appropriate.

The pockels cell voltage conditions will be defined for each phase of the laser performance so that a systematic description of the required driver performance can be presented. Initially, the driver and pockels cell are required to develop a very low $Q$ within the optical resonator. This condition, or hold-off, allows energy storage to the laser rod for a determined time in- . terval. The input, termed the $V$ bias ( $+H V$ ), establishes a voltage potential across the cell effecting the low $Q$ condition. When the energy storage is accomplished, it becomes necessary to effect a rapid increase in the $Q$ of the optical resonator to achieve lase action. The block in Figure 4-4, termed Q-switch avalanche, effects this change by reducing the applied voltage of the cell to near zero potential. It is to be noted that the greatest " $Q$ " is obtained within the optical resonator when no potential is impressed upon the cell. The output voltage from the " $Q$ " switch avalanche driver is conducted to the cell through the action of capacitor $C_{A}$. The high " $Q$ " condition causes rapid lase action to occur.


Figure 4-4. Simplified Pockels Cell Drive Configuration

In actuality, the low "Q", or hold-off state of the laser, is altered by varying the cell bias voltage in such a manner as to produce coherent radiation, slightly above laser threshold, just prior to the Q-switch time. The simple depiction of Figure 4-4 does not provide for this detail.

Energy rise within the opti.cal resonator following Q-switching occurs rather slowly as referenced to the modelocked pulse interval because many reflections within the resonator are required to deplete the stored energy within the rod. This point is significant as it dictates the required interval for the removal of voltage from the cell. A voltage fall time of approximately 15 nsec is quite adequate for this $Q$-switching operation.

As energy is depleted from the rod, the active resonator energy increases. When the energy reaches a critical magnitude, it is necessary to direct the energy from the optical resonator. This process -- that is, the cavity dumping of the modelocked pulse must occur very rapidly. Thus, the necessity for the dump avalanche driver. The requirement for this driver is the generation of a differential cell voltage of 3200 V . It is to be noted that the dump voltage is not equivalent to the initial bias voltage, but is a greater voltage. Furthermore, the dump avalanche drive circuitry must successfully apply the cell voltage within. one roundtrip time of the optical resonator. This condition dictates the switching speed required which is a total elapsed time of approximately 9 nsec . Additionally, the initiation of this action must be synchronous to the modelocked pulse within the resonator. Thus, synchronization jitter must be maintained at the lowest possible level. A jitter of +1 nsec is achievable which dictates a maximum dump switching time of 6 nsec . The action of the dump avalanche switch is conducted to the cell by the action of capacitor $C_{B}$. Dumping of the modelocked pulse from the optical resonator completes the voltage switching sequence.

As pointed out earlier, the drive to the Pockels cell is of the differential mode which creates some problem in achieving the required performance. Thus, the need for capacitors $C_{A}$ and $C_{B}$ is realized. Application of a very abrupt voltage step to either point $A$ or point $B$, with the shunt capacitors omitted, would result in virtually no voltage impressed across the cell because basically the cell appears as a capacitor. Any impressed voltage would be caused by stray capacitive coupling to the cell terminal not being excited directly. The addition of capacitors $C_{A}$ and $C_{B}$, forms a
capacitance voltage divider, regardless of exitation from source A or $B$. Obviously, the greater the capacitance value used for capacitors $C_{A}$ and $C_{B}$, the greater the percentage of the applied voltage which will be impressed upon the cell. The remainder of the impressed voltage will be impressed on either $C_{A}$ or $C_{B}$ as dictated from the excitation source. It is to be noted that the capacitors $C_{A}$ and $C_{B}$ appear in parallel with the avalanche drivers. Each driver must either charge or discharge its appropriate capacitor simultaneously with driving the cell. For this reason, it becomes quite apparent that capacitors $C_{A}$ and $C_{B}$ must be of the minimum capacitance value possible to achieve adequately rapid cell excitation. Previous experience has dictated a ratio of one to ten between the cell capacitance and the shunt capacitance. This relationship assures that roughly $90 \%$ of the applied voltage is impressed upon the cell, while the remaining voltage appears across the shunt capacitor.

Figure 4-5 lends some clarification of the voltage sharing across the various capacitors involved. Cell capacitance, cell holder capacitance, and stray wiring capacitance total in the order of 10 pF . Thus, the shunt capacitors are selected to exhibit 100 pF of capacitance. Figure 4-5 additionally illustrates the effective capacitance load to either avalanche driver, which simplifies to a value of 109.09 pF , the total effective capacitance load. Optimum switching action occurs for an impressed voltage of 3200 $V$ across the cell. This voltage represents $90 \%$ of the input voltage; thus, 355 V appears across the shunt capacitor, and the applied voltage must be $3,555 \mathrm{~V}$.

To allow some small time margin in the dump switching operation, the required cell voltage risetime will be reduced to 5 nsec as measured from the 10 to $90 \%$ points. This condition allows the avalanche pulse current to be calculated as follows:

$$
\begin{equation*}
I=\frac{C V}{t} \tag{3-26}
\end{equation*}
$$

where

$$
\begin{aligned}
& C=109.09 \times 10^{-12} \mathrm{~F} \\
& \mathrm{~V}=3,555 \mathrm{~V} \\
& t=5 \times 10^{-9} \mathrm{sec} \\
& I=\frac{\left(109.09 \times 10^{-12}\right)(3,555)}{5 \times 10^{-9}} \\
& I=77.56 \mathrm{~A}
\end{aligned}
$$



EQUIVALENT CAPACITANCE LOAD FOR DRIVER， SHOWING INDEPENDENT CAPACITORS


EQUIVALENT CAPACITANCE

Figure 4－5．Effective Capacitance Load for Avalanche Driver

This value of pulse current is quite acceptable from a standpoint of reliable avalanche driver operation. Additionally. this current peak is required only for the dump driver. The Q-switch driver is required to discharge only the bias voltage upon the cell, which is lower than the $3,555 \mathrm{~V}$ seen at the dump driver, and the fall time requirements also are less stringent for the Q-switch driver.

Conclusions which are drawn to this point are: Initially, the 100 pF shunt capacitor is acceptable from a standpoint of voltage risetime and avalanche current; the differential drive technique is acceptable; and, finally, good avalanche driver isolation can be maintained, with regard to false triggering.

Now that the description of the basic Pockels cell interface is complete together with the definition of the required sequence of operation, the actual hardware operation will be presented. Variation from the elementary configuration will be noted, and reasoning for the departure in technique will be presented.

The schematic shown in Figure 4-6 details the actual hardware from which the exhibit oscilloscope trace photographs were recorded. Inspection of Figure 4-6 immediately reveals, the departure in the coupling circuitry for the Q-switch driver input. A series diode string $\left(C R_{1}\right.$ and $\left.C R_{2}\right)$ is used for this coupling. This coupling technique is used because: Excellent isolation is achieved between the driver output and the cell bias voltage; the driver is required only to reduce the differential cell voltage to near zero potential; and the diode string assists in maintaining the appropriate differential cell voltage for the Q-switch function whenever the cell bias voltage is adjusted. It is to be noted that were capacitive coupling used only one value of bias voltage would be possible to achieve the optimum Q-switch condition of zero cell voltage. This bias voltage would be essentially the Q-switch hold-off voltage. Were a lower bias voltage utilized, the differential cell voltage would be driven below zero volts. Conversely, a higher voltage would result in a lack of achieving zero volts.

Further inspection of Figure 4-6, reveals that the dump driver is capacitively coupled and also diode isolated. This technique is necessary so that the prelase radiation control can be effected. Resistor R5 is the bias resistor for the dump avalanche driver. Capacitor $C 6$ is the output coupling capacitor.


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Figure 4-6. Q-switch Interface Schematic

Resistors R 4 and R6 form a voltage divider to achieve a position potential of approximately 460 V at the cathode of diode CR3. Obviously, the output from the dump driver is referenced to this voltage as a start potential when coupled through capacitor C6. Resistor $R 3$ provides current to the prelase radiation control circuitry through diodes CR4, CR5, and CR6 by way of connector J6.

The voltage of the radiation control circuitry is limited to a maximum positive value of 400 V whenever an absence of radiation exists to the control circuitry optical detector. Normally, the bias voltage is adjusted to allow a "leakage" which affords a lase action in the region of 1 to $3 \%$ above threshold during the prelase interval. The prelase control electronics removes voltage from the dump side of the cell (point B) and increases the differential cell voltage which increases optical hold-off to achieve control.

It is to be noted that diode CR3 is reverse biased for all conditions other than the dump function. It is to be further noted that the prelase electronics always reduces the point $B$ cell voltage prior to the Q-switch interval, and that the Q-switch function additionally reduces the point $B$ voltage resulting from the capacitor C5. Cell bias voltage input of 1.5 kV , results in a voltage division to reduce the C 5 voltage by 177 V . This voltage together with the reduction afforded by the prelase radiation control electronics, results in a point $B$ voltage which is approximately $\pm 100 \mathrm{~V}$, as referenced to ground, at the completion of the Q-switch action, and the cell voltage is, indeed, near zero differential voltage. Initiation of the dump driver, produces a voltage transition of approximately 3.4 kV . Diode CR3 conducts when the $\nabla o l t a g e ~ e x c u r s i o n ~ h a s ~ r e a c h e d ~ t h e ~ 460 ~ V ~ p o i n t, ~ a n d ~ c a p a-~$ citor C5 is charged to roughly 3.0 kV .

An interesting phenomenon occurs when the delay from Q-. switch to PTM switch is less than 100 nsec . The Q-switch avalanche driver is still in the high-current-conducting state. Diodes CRl and CR2 also are unable to recover because of the large minority carrier concentration resulting from Q-switch discharge current. Thus, the dump driver voltage is impressed almost in its entirety across the cell because the point $A$ side of the cell is clamped to ground. It is to be noted that the differential cell voltage is $3.0 \mathrm{kV} \pm 100 \mathrm{~V}$ when the dump driver output occurs.

At the occurrence of the dump event, diodes CR4, CR5, and CRE are reverse biased, and the prelase radiation control electronics is effectively removed from the circuit. The remainder of the discussion and presentation deals specifically with the measurements taken of the actual hardware.

Figure 4-6 depicts the actual circuitry which comprises the Q-switch/dump-switch/radiation-control interface. For these tests the radiation control voltage was fixed at a value of +400 V . The Q-switch was driven directly from the pulse repetition frequency (PRF) generator at a 10 pps rate. A delay generator was utilized to dxive the dump avalanche switch. Voltage waveforms highlighting switching response in the Q-switch and PTM dump modes are illustrated in Figure 4-7. The delay time was adjusted initia Iy to roughly 40 nsec : however, clarity was somewhat impaired in the scope photographs obtained, and the delay time was increased to 100 nsec to obtain better trace clarity.

It is to be noted that all photographs are realtime exposures with no superposition of either graticle or scope nomenclature. A Tektronix model 7904 oscilloscope with a model 7 Al6 vertical amplifier was used in conjunction with a type 96016 highvoltage probe to acquire the oscilloscope trace photographs.

Oscilloscope trace photograph (OTP) no. 6 is presented to illustrate the $Q$-switch voltage magnitude. The probe attachment was at point $A$ and measurement was made of the switch recovery waveform: Cell bias voltage was adjusted to 3.2 kvdc . It is to be noted that the full 3.2 kVdc is switched. OTP no. 7 illustrates the leading edge fall time of the Q-switch. Note that some slight ringing occurs at the transition time which is inevitable when a lead/probe attachment is provided. It also is to be noted that the indicated response always is slower than the actual circuit response. This condition is caused by: first, the probe posesses an input capacitance of roughly 18 pF ; and, second, the probe response time is finite because of probe inductance. Thus, the probe causes degradation of pulse rise/fall presentations which are 1 to 5 nsec greater than reality when the oscilloscope sweep speed is 5 nsec/division.

OTP no. 8 depicts the voltage at point $B$, the dump drive. This trace is taken with a vertical sensitivity of $1,000 \mathrm{~V} / \mathrm{divi}-$ sion. Once again, measurement is made of the switch recovery waveform to show the voltage excursion and the recovery characteristics. OTP no. 9 shows the leading edge with the 300 m step


OSCILLOSCOPE PHOTO NO. 6


OSCILLOSCOPE PHOTO NO. 8


OSCILLOSCOPE PHOTO NO. 10


OSCILLOSCOPE PHOTO NO. 7


OSCILLOSCOPE PHOTO NO. 9


OSCILLOSCOPE PHOTO NO. 11


OSCILLOSCOPE PHOTO NO. 12
which is induced by the Q-switch excitation. The Q-switch activation time is 40 nsec prior to the dump output. The ringing is induced from the probe attachment. The OTP no. 10 is a repeat of the previous photograph with the exception that the PTM switch time has been extended 100 nsec from the $Q$-switch time.

OTP no. 11 shows the fall time of the dump avalanche drive. In reality, this is the rise time of the cell voltage for the dump action. Probe attachment is at point B. Again, the ringing is because of the probe attachment. It is to be noted that the risetime, as indicated on OTP no. ll, is considerably more than 5 nsec. Thus, OTP no. 12 is provided in an attempt to depict a more realistic presentation of the true risetime of the dump drive pulse. These photo data depart from that produced from the previous test configuration. A capacitance probe is provided by placing a VHF $x 10$ probe in proximity to the driven electrode of the cell. Thus, the response degradation of the type P6015 probe is avoided. As indicated, the response of dump drive to the cell occurs well before 4 nsec of elapsed time.

## B. SYSTEM OPTICAL ALIGNMENT

## 1. Alignment Overview

The alignment of the Spaceborne laser oscillator is a complex task because of the use of wedged optical elements to avoid etalon effects on pulsewidth. The basic problem is that the correct optical path through the resonator lacks an optical reference normal to this path prior to alignment of the laser mirror. The precision machining of the optical bed allows the use of the mechanical centers of the beam exit holes to establish correct reference optical paths. The alignment of the optical components to these reference paths achieves the resonator mirror alignment and oscillator alignment to an accuracy which permits lasing. Dynamic tweaking of particular optical elements while operating the laser then achieves optimum laser alignment.

The amplifier subsystem alignment is a simple and straightforward procedure since the optical components are not wedged. Therefore, this procedure will not be discussed. The description of the detailed alignment procedures for the oscillator subsystem are given in the following paragraphs of this report section. Figures 4-8 and 4-9 show the oscillator optical diagram and an optical bed sketch as references for understanding of the oscillator alignment procedure. The steps in this procedure are:



Figure 4-9. Optical Bed Sketch

- TIR prism alignment;
- Rod-wedge leg alignment;
- KD*P cell leg alignment;
- Mirror-rod alignment;
- Risley prism-polarizer alignment; and
- Dynamic laser alignment.

A He-Ne beam was used in all the following alignment techniques. The alignmenterror introduced by the difference in optical indices of the oscillator components was calculated and proved in practice to be negligible.

## 2. TIR Prism Alignment

Each of the three TIR prisms is designed to have a pyramidal error of $1.5^{\circ}$. One of these is illustrated in Figure 4-10. The pyramidal error results in the entrance and exit faces of the prism to be non-parallel. Thereby, etalon effects are avoided. The $1.5^{\circ}$ pyramidal error of the prisms dictates, via Snell's Law, that they be tilted $2.175^{\circ}$ to the required optical paths so that the entrance and exit beams be parallel. The orientation of the TIR prisms is governed by the Invar pads that they are clamped to, as discussed in the mechanical design section. Perfect fabrication of the Invar bed and pads and the TIR prism would result in correct prism alignment simply by attachment to the bed. However, in practice, fabrication to better than 10 arc-seconds, as required, is not achievable. Thus, the precision mounting of the TIR prisms to the bed is a two-stage process involving a second machining of the Invar pads. A description of this process follows which is identical for each TIR prism.

First, the prism is clamped to the Invar pads attached to the optical bed. A He-Ne beam is then aligned through the center of the appropriate beam exit holes using mechanical apertures with 0.04 inch holes. In general, the He-Ne exit beam is not parallel to the beam entering the prism. A measurement of the angle between the entrance and exit He-Ne beams is then made. By elementary optics, the orientation of the prism is defined then to be in error by half the measured angle. The TIR prism is then removed along with the Invar pad. The Invar pad is then remachined and optically polished to a new wedge whose angle differs from the initial fabrication angle by the angular error (either positive or negative) of the initial prism orientation. This was proved to be achievabie to an accuracy of better than 10 arc-seconds. Following the above procedure, the prism was

remounted to the optical bed and the optical alignment remeasured for verification. With correct measurements, the above-described procedure resulted in the alignment of all three TIR prisms to within 10 arc-seconds of the correct optical paths of both the oscillator and amplifier subsystems.

## 3. Rod-Wedge Leg Alignment

The optical drawings of the oscillator laser rod anc the compensating wedge are shown in Figure 4-11 and 4-12. The compensating wedge corrects for both the angular and lateral displacements from the correct optical path produced by the wedged oscillator rod. As before, the first step in the alignment is to direct a He-Ne beam through the centers of the beam exit holes using mechanical apertures in order to establish the correct reference optical path. The second step is to mount and orient the laser rod so that its deflection is parallel to the optical bed. The laser rod is also positioned by moving the pump cavity mounting so that the He-Ne beam enters and exits the laser rod at the center of the rod ends. The final step is to mount and orient the compensating wedge so that the He-Ne traverses the same path after exit as it did before mounting the laser rod and compensating wedge. Figure 4-13 illustrates the He-Ne beam propagation through the rod-wedge leg after alignment completion. The angles are exaggerated for clarity of illustration.

## 4. KD*P Cell-Mirror Leg Alignment

The KD*P modelocker cell, the common laser mirror, and the KD*P Q-switch are the specific optical elements of this oscillator leg. The modelocker and Q-switch cells are designed identically. Figures 4-14, 4-15 and 4-16 are optical drawings of the KD*P crystal, the cell windows, and the laser mirror respectively. Figure 4-17 is an optical diagram of this oscillator leg when correctly aligned to the illustrated reference optical path. The modelocker and $Q$-switch cells are aligned to give equal ana opposite angular deviations and a net lateral displacement of 0.002 inches. The cells must actually be individually aligned as well, so the the He-Ne beam propagates along the KD*P optical axes. Rotation of the cells so that the $X$ or $Y$ axes of the crystals are parallel to the optical bed - the oscillator polarizer transmission plane - is also necessary. This rotation is necessary to achieve maximum phase retardation by the KD*P cells when voltage is applied.

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'Figure 4-11. Oscillator Laser Rod





Figure 4-13. Rod-Wedge Leg Alignment

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Figure 4－i4：KD＊P Crystal

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Figure 4-17. KD*P Cell-Mirror Leg Alignment (Angles Exaggerated for Clarity)

The initial step in this complex alignment procedure is to verify the achievement of the optical specifications of the KD*P cells. The angular deviations of the cell windows and KD*P crystals are first measured. The cells are then assembled and their net angular deviations are measured. The latter measurement setup is illustrated in Figure 4-18. The planned cell deviation was achieved to within 30 arc-seconds for each cell.

The precision alignments of the KD*P crystal axes as discussed above was accomplished using a mechanically referenced He-Ne beam as before. A brief discussion of the electrooptical properties of KD*P crystals is necessary before describing the alignment technique. The application of voltage along the $Z$-axis or optical axis of $K D * P$ results in the originally uniaxial crystal becoming biaxial. The birefringent axes of the crystal as viewed along the optical axis are $45^{\circ}$ to the $X$ - and $Y$ - axes of the crystal. A He-Ne beam polarized parallel to one of these birefringent axes will traverse the KD*P crystal with its polarization unchanged. These observations form the basis of the technique for correctly aligning the optical axes of the KD*P crystals to the reference He-Ne beam.

After establishing the $H e-N e$ beam reference path, a calcite polarizer mechanically referenced to the optical bed is mounted to transmit the polarization plane parallel to the optical bed. The purpose is to.establish a reference polarization plane parallel to the oscillator polarizer transmission plane. Two film polarizers mounted in precision rotation assemblies are then placed external to each end of the bed in a sequence that results in these polarizers being crossed with one transmitting the same polarization plane as the reference polarizer. One of these polarizers is then rotated $45^{\circ}$ and the other is rotated to null the He-Ne beam. The point of this procedure is that the correct mounting of the KD*P modelocker and Q-switch cells between these polarizers will now introduce zero phase retardation with voltage on or off the crystals. To elaborate, the He-Ne beam remains nulled by the crossed polarizers when the KD*P cells - with voltage applied - are aligned such that one birefringent axis is parallel to a polarization plane $45^{\circ}$ to the optical bed plane and the optical axis of the crystals are aligned to the He-Ne reference beam. This corresponds to the correct alignment of the KD*P cells as discussed earlier in this section.


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Figure 4-18. KD*P Cell Deviation Measurement

The specific procedure to align the KD * P cells is now apparent. The mechanical apertures in the optical bed beam exit holes are removed and each cell is sequentially mounted to the optical bed with no voltage applied. A rough alignment of the optical axis of each KD*P crystal is then performed after mounting each cell by placing a lens tissue between the $\mathrm{He}-\mathrm{Ne}$ beam and cell and centering the resulting isogyre pattern. This pattern is observed by placing a white card behind each cell. The second nulling polarizer is not used in these observations. Following these procedures, each KD*p cell is fine-tweaked to null the He-Ne beam. This results in the alignment of the KD*P crystals optical axes to the reference He-Ne beam. Voltage is then applied in sequence to each crystal which is rotated to once more achieve nulling of the $\mathrm{He}-\mathrm{Ne}$ beam by the crossed polarizers. These procedures result in the alignment. of one of the birefringent axes of each crystal to the polarization plane of the $H e-N e$ beam. Thus, the X- or Y-axis of each crystal is aligned parallel to the optical bed plane as required. A verification of the cancellation of the angular and lateral deviations of the $K D * P$ cells is then made by re-installing the mechanical apertures in the beam exit holes of the optical bed. A positive result of this verification is achieved in practice, but is essentially assured via the verification of the correct fabrication and assembly of each cell discussed earlier. This completes the description of the alignment of the KD*P cells.

The final step of the alignment of the KD*P cell-mirror oscillator leg is to mount the laser mirror bed to the optical bed and to align the mirror so that its He-Ne reflection falls on the He-Ne laser exit aperture. To recapitulate, the abovedescribed procedures resulted in the alignment of the KD*P crystal axes and the laser mirror normal axis precisely referenced to both the optical bed plane and to a He-Ne beam correctly referenced to the planned optical path for this oscillator leg.

## 5. Mirror-Rod Alignment

The alignment of the laser rod axis and the laser mirror axis should be achieved by simply mounting the TIR prism adjacent to the quartz wedge (See Figure 4-8). This is the result in practice if the TIR prism, rod-wedge leg, and KD*P cell-mirror leg alignments are correctly performed. However, a verification of this result is necessary.

The verification procedure consists of installing the above-mentioned TIR prism; mounting a partially reflective laser mirror external to the bed which is aligned to the oscillator mirror; and establish lasing. The achievement of a round beam pattern for the normal mode radiation generated by tweaking only the external mirror verifies correct mirrorrod alignment. Figure $4-19$ illustrates the experimental arrangement for the alignment of the external mirror via a He-Ne laser.
6. Risley Prism-Polarizer Alignment

The rod-wedge and $\mathrm{KD} * \mathrm{p}$ cell-mirror leg alignments are necessarily performed with the oscillator TIR prisms removed from the bed. The risley prism-polarizer alignment involves two oscillator legs as illustrated in Figure 4-8. The TIR prism adjacent to the compensating wedge remains on the bed to establish the risley prism - polarizer alignment. Figures 4-20 and 4-21 are optical drawings of the polarizer and one risley prism. The two risley prisms are identical and are initially set to yield zero angular optical deviation via an experiment using a He-Ne beam which is performed external to the optical bed. The plane-parallel polarizer produces only a lateral deviation and the pair of prisms are tilted to compensate for this deviation which occurs in a plane parallel to the optical bed.

Figure 4-22 illustrates the risley prism-polarizer alignment. The first step in this alignment after establishing the He-Ne reference path is to mount and orient the dielectric polarizer. The criteria for the proper orientation are that the angle of incidence of the He-Ne beam must be $56 \pm 2^{\circ}$ and that the polarizer be perpendicular to the optical bed. This orientation is performed by simply adjusting the polarizer so that the He-Ne beam reflection from the polarizer is incident on the inner wall of the optical bed at a pre-calculated point. Adjustment of the risley prism tilt to yield parallism of the entrance and exit He-Ne beams through the bed completes this alignment.

## 7. Dynamic Laser Alignment

The preceding alignment procedures result in the alignment of all four legs of the oscillator. The next step is to mount


Figure 4-19. Mirror-Rod Alignment Verification




Figure 4-22. Risley Prism-Polarizer Alignment (IIR Fold shown in orthogonal plane to actual case for clarity)
the second oscillator TIR prism on the optical bed. The laser is then operated with the modelocker and Q-switch being passive. Slight rotational and/or tilt tweaks of the risley prisms results in low-level lasing which is detected using an infrared viewer. An $\lambda / 8$ voltage bias is then applied to the $Q$-switch so that a laser output is obtained via the polarizer. Further tweaking of the risley prisms leads to energy output optimization via monitoring of the laser output. The following report section covers further dynamic tweaking of the laser to optimize PTM Q-switching and active modelocking.

Appendix E gives all optical drawings for the amplifier subsystem except the KD*P doublex.

## C. LASER PERFORMANCE EVALUATION

1. Introduction

The experimental evaluation of the Spaceborne laser system has shown the basic soundness of its concept and design. Extensive testing has been performed on the oscillator subsystem and essential tests have been performed on the amplifier subsystem. The results of the tests show essential agreement with the theoretical predictions given in Section II of this report. The following paragraphs report the results of:

- Normal mode testing;
- PTM Q-switch testing;
- Modelocking tests;
- Amplifier testing

The parameters evaluated in these tests, where appropriate, are pulse energy, beam divergence, laser efficiency, TEM size, pulse amplitude stability, pulsewidth or lase femporal profile, and pre-and post-pulse suppression.

## 2. Normal Mode Testing

Normal mode testing of the Spaceborne oscillator was performed to verify good pump cavity efficiency and the achievement of optimum oscillator alignment. Figure $4-23$ is an input/output curve illustrating the best normal mode performance achieved. Laser output was obtained by placing a dc voltage bias on the 0 switch. This voltage was set to optimize the output coupling to achieve maximum lase energy at the $10-15 \mathrm{~mJ}$ level. The low pump threshold of 1.3 Joules and the slope efficiency of $1.25 \%$ indicate a high effective reflectivity in the $70-80 \% \mathrm{R}$ range. Correlation of the normal mode performance observed with previous ILS parametric studies on input/output curves versus reflectivity demonstrate a pump cavity efficiency equivalent to the best results previously obtained at ILS. The normal mode beam patterns obtained were uniform and round which verifies optimum oscillator alignment.

## 3. PTM Q-switch Testing

PTM Q-switch testing was performed in two operational modes. One of these was to utilize electronically-based timing for both


Figure 4-23. Normal Mode Performance Curve
the Q-switch and dump switching operations. This test provided information concerning the sensitivity of the dump synchronization with respect to the time at which the internal resonator radiation achieves its peak. Figure 4-24 illustrates this synchronization sensitivity via a graph of the PTM pulse energy output versus the delay time between the Q-switch and dump events. The energy input/ output performance curve for this PTM Q-switching mode is shown in Figure 4-25. This curve shows lower efficiency than the normal mode performance curve due to a non-optimum oscillator alignment.

The second operational mode for PTM Q-switching utilized pre-lase and active synchronization of the Q-switch and dump events via direct lase detection. The specific techniques used to implement these concepts were previously described in the design section of this report. Figure 4-26 shows the energy input/output curves for this operational mode both with and without the 3 millimeter aperture used to achieve TEM lated well with the theoretical curve shown in Figure $2-5$ for a loss/pass value of $50 \%$. This curve was generated previous to the achievement of an optimum oscillator alignment. Later normal mode data (Figure 4-23) indicates a $25 \%$ loss/pass value. Figure 4-27 is a photograph of the pulse profile of a typical PTM Q-switched laser pulse.

TEM ${ }_{O O}$ mode operation in the PTM Q-switched mode using prelase was verified in two ways. The beam divergence and spot size of the beam was measured and shown to correlate, within experimental error, via the gaussian beam equation. Film burn patterns were also generated which indicate $\mathrm{TEM}_{O O}$ mode operation. These burn patterns were made at distances ranging from directly adjacent to the laser to the limit at which the film would burn. The burn patterns increased in diameter and decreased in intensity monotonically with increasing distance from the laser. The patterns also exhibited greatest intensity in the center with a smooth burn intensity decrease with increasing radius. This latter result strongly indicates TEM ${ }_{00}$ mode operation. Together with the previous correlation of beam divergence and beam spot size, $\mathrm{TEM}_{O O}$ mode operation is verified. The above results are summarized in Figure 4-28.

Initial problems were encountered in the achievement of the $T E M_{0 O}$ mode. An annular film burn pattern was observed with the initial -lom, +11.35m radii common laser mirror. A second mirror with radii of -7 m and +5 m was installed and successful $T E M O 0$ mode operation was achieved. The measured oscillator spot size of 2 mm ( $3 \omega$ diameter) did not correspond with a theoretical prediction of 3 mm . This phenomena is probably explained by pre-lase effects and a possible radial variation in the oscillator rod optical gain.


Figure 4-24. PTM Timing Synchronization


Figure 4-25. PTM Q-Switched Performance Curves (Electronic Timing)


Figure 4-26. PTM Q-Switched Performance Curve (Pre-lase and Active Timing)


TIME SCALE - 10 NSEC/DIVISION
P4867

Figure 4-27. Typical PTM Q-Switched Pulse


$$
\begin{aligned}
& \text { BEAM DIVERGENCE }(90 \text { POINTS })=0.98 \mathrm{mr} \\
& \text { SP.OT SIZE }\left(W_{0}\right)=0.64 \mathrm{~mm} \\
& \sigma=\frac{2 \lambda}{\pi W_{0}}=\frac{2\left(1.064 \times 10^{-9} \mathrm{~mm}\right)}{\pi(0.64 \mathrm{~mm})}=1.06 \mathrm{mr} \\
& \text { GAUSSIAN BEAM EQUATION CORRELATION }
\end{aligned}
$$

## 4. Modelocking Tests

The objective of the initial modelocking tests was to establish the correct RF modelocking frequency. These tests were performed via normal mode lasing with the modelocker active and a voltage bias applied to the o-switch to generate a laser output via the polarizer. Initial testing failed to establish stable $100 \%$ modulation of the normal mode pulse profile. The problem was traced to an insufficient RF voltage level and was solved by adding an RF amplifier stage to the modelocker RF drive electronics. The design and operation of this RF amplifier is described in Appendix $D$. Modelocking of the normal mode pulse was then achieved and a photo of the oscilloscope trace of the pulse profile is shown in Figure 4-29. Figure $4-30$ is a photo of an expanded trace of this profile. The modelocking RF frequency determined to be near optimum was 52.63 Mhz .

Extensive testing of the Spaceborne laser oscillator was performed for the actively modelocked, PTM Q-switched operational mode using pre-lase. The initial attempts to establish operation in this mode failed due to the unsuccessful attempts to achieve active feedback control of the pre-lase radiation. These efforts are described in the following report section. The actual prelase technique successfully implemented is fully described in a previous report section.

Figures 4-31 through 4-34 illustrate some essential results of the modelocking tests performed at ILS. Figure 4-31 is a photo of the oscilloscope trace of the intra-cavity radiation while simultaneously modelocking and PTM Q-switching. This photo indicates optimum single modelocked pulse selection via PTM Q-switching by the complete truncation of the intra-cavity Q-switch pulse profile. Figure 4-32 illustrates a typical oscilloscope trace of the single picosecond pulse emitted from the oscillator. The indicated pulsewidth is 800 picoseconds. However, the response time of the pulse detection equipment utilized was only 0.7 nanoseconds so that the actual pulsewidth is near 400 psec. Figure $4-33$ indicates the pre- and post-pulse suppression achieved via the PTM Q-switch pulse selection. Expansion of the amplitude scale of the oscilloscope display showed a pre- and post-pulse suppression of 30 dB . Figure 4-34 illustrates the occurrance of both pre- and


Figure 4-29. Modelocked Normal Mode Pulse


Figure 4-30. Normal Mode Modelocked Pulses


Figure 4-31. Intracavity Radiation for PTM Q-Switched, Modelocked Operation


TIME SCALE - 1 NSEC/DIVISION

Figure 4-32. Typical Picosecond Pulse (Temporal Resolution - 700 psec )

$\begin{aligned} \text { Figure 4-33. } & \text { Picosecond Pulse Showing } \\ & \text { Pre- and Post-pulse Suppression }\end{aligned}$


TIME SCALE - 5 NSEC/DIVISION
$\begin{array}{ll}\text { Figure 4-34. } & \text { Picosecond Pulse Showing } \\ & \text { Pre- and Post-Pulses }\end{array}$
post-pulses approximately 9.5 nsec from the primary pulse. These resulted primarily from non-optimum dump switch phasing. TEMOO mode verification of the modelocked oscillator output was performed as described previously with nearly identical results.

The pulse energies generated via the PTM Q-switched, modelocked operation of the oscillator were in the 0.5 to $5.0 \mathrm{milli}-$ joule range. Laser damage to the oscillator laser rod and one KD*P crystal eventually occurred at approximately the 5.0 mJ level. Testing was resumed following the replacement of these elements and operation was subsequently maintained below 1.0 mJ . other problems that occurred during experimentation were chronic leakage of the fluid-filled KD*P cells and KD*P modelocker crystal damage due to excessive contact resistance at the crystal electrodes. The first problem necessitated several cycles of refilling and realigning the $\mathrm{KD} * \mathrm{P}$ cells. Careful attention to the $0-r i n g$ seals at the cell windows and seal port essentially solved this problem. The second problem was solved by a new KD*p crystal electrode which used indium, an extremely malleable metal, to achieve low electrode contact resistance.

Modelocking experimentation at ILS was performed using instrumentation which locked the response time to clearly define modelocking performance. The instrumentation employed consisted of a bi-planar photo-diode, a Tektronix Model 7912 Transient Digitizer, and a Tektronix Model 605 Oscilloscope. This pulse detection system had a temporal response time of 700 psec. Definition of the pulsewidth and pulse profile of the modelocked pulse was essential to determine the efficacy of these pulsesfor ultraprecision ranging. Thus, a computer-controlled streak camera instrument developed within the Electro-Optics Branch of the NASA Goddard space Flight Center was employed. The temporal resolution of this instrument was 10 psec.

Following the transfer of the Spaceborne breadboard to NASA, extensive modelocking experimentation was pexformed. The pulse profile characteristics were observed as a function of the critical theoretical parameters of pre-lase duration, pulse energy, RF modelocker drive amplitude, and pe frequency variations. Figure 4-35 shows four typical pulse profiles obtained for the optimum modelocking achieved. The pulse profile varied from shot-to-shot with $75 \%$ single pulses for optimum operation. The optimum modelocking was achieved for minimum pre-lase normal mode amplitude


$$
\begin{array}{ll}
\text { Figure 4-35. Typical Pulse Profiles for } \\
& \text { Optimum Modelocking } \\
& \text { (Time Base: } 200=1 \mathrm{nsec} \text { ) }
\end{array}
$$

(maximum pre-lase duration) and maximum $R F$ modelocked drive at a RF frequency of 52.676 Mhz . The maximum frequency detuning of the RF drive while maintaining optimum performance was observed to be 500 Hz . Theory predicts and the experimentation confirmed that the modelocked pulse increases in width with decreasing pre-lase duration on RF drive amplitude. The pulse energy level was observed to have little effect on pulsewidth as expected via theoretical analysis presented in this report. Table $4-1$. summarizes the experimental results for the Spaceborne modelocked oscillator. The variation of the pulse profiles observed from pulse-to-pulse was impossible to eliminate in the experimentation performed. The cause of these fluctuations is explained theoretically via the variation of modelocked pulsewidth with pre-lase duration and the statistical characteristics of the initial intra-cavity radiation. ${ }^{31}$ The pre-lase duration (the normal mode pulse buildup time) fluctuates from pulse-to-pulse due to fluctuations in the normal mode pre-lase pulse amplitude. The latter fluctuations are caused by very small flashlamp-rod coupling efficiency variations from pulse-to-pulse. The above observations demonstrate that the spaceborne laser operates as theoretically planned.
Table 4-1.

OSCILLATOR PERFORMANCE

| Parameter | Value |
| :--- | :--- |
| Pulse Energy | 1.0 mJ |
| Efficiency | $0.05 \%$ |
| Pulsewidth | 150 psec (FWHM) |
| Beam Divergence | 0.98 mr |
| Mode Diameter (3 $\omega$ ) | 1.92 mm |
| Pulse Rate | 10 pps |
| Pre- and Post-Pulse Suppression | 30 dB |
| Pulse Amplitude Stability | $\pm 10 \%$ |

However, the pulse profiles fluctuations caused by the statistics of the initial intra-cavity radiation was not foreseen. A computer evaluation of the suitability of the present pulses generated by the Spaceborne breadboard is in progress. However, an approach to eliminating pulsewidth and pulse profile fluctuations is planned. This approach, defined in the Theory section of this report, is to utilize a quasi-CW, pulsed flashlamp power supply to extend the pre-lase duration to $150 \mu s e c$. Normal moding of the pre-lase radiation will damp out with this pre-lase duration and the achievement of stable pulse profiles from pulse-to-pulse should be achieved. The feasibility of this pre-lase technique has been demonstrated with the SHIVA modelocked oscillator at Lawrence Livermore Laboratories. 32

## 5. Amplifier Testing

The amplifier subsystem testing established the pulse energy output levels possible with the double-pass Nd:YAG amplifier for both PTM Q-switched and modelocked pulse inputs. Figure 4-36 illustrates the optimum performance achieved. All amplifier testing was performed at ILS. The maximum modelocked pulse energy achieved was $28-\mathrm{mJ}$ with an approximate pulsewidth of 300 psec. Pre- and post-pulse suppression following the amplifier was measured to be 25 dB . The beam divergence measured for the optimized oscillator/amplifier system was 1.0 mr .


DOUBEE-PASS AMPLIFIER PERFORMANCE

Figure 4-36. Oscillator/Amplifier Performance

$$
\mathrm{C}-3
$$

## D. RADIATION CONTROL EVALUATION

This report section describes the attempts to achieve a feedback control of the normal mode pre-lase energy as discussed earlier. The basic approach was an energy control servo mechanism utilized to increase the Pockels cell. voltage toward the holdoff value as the cavity energy rises. This negative feedback system was chosen to be linear, in order that the maximum energy stability might be achieved. Negative feedback affects the normal mode output pulse width by reducing the pulse amplitude and increasing the pulse width. It is reasonable to expect that a reduced detection threshold, or increased sensitivity, will result in a greater temporal stretching of the pulse. The pulse stretching technique has been successfully employed in the past 33,34 .

Investigations have shown that low values of reflectivity, and therefore low cavity gain, normal mode spiking occurs as a relatively broad pulse which tends to have rather poor temporal stability and poor amplitude stability. Normal mode spike separation was in the region of 2 to $6 \mu \mathrm{sec}$.

Figure 4-37 illustrates Oscilloscope Trace Photographs (OTP) which were taken from normal mode output. Three series of OTPs are presented. The first OTPs show the laser action when the $K D * P$ Pockels cell voltage was adjusted 340 V below the holdoff value of $3,250 \mathrm{~V}$ or a bias voltage of $2,910 \mathrm{~V}$. The second set of OTPs illustrate the output when the bias voltage was adjusted to $2,850 \mathrm{~V}$, a departure of 400 V below holdoff. The thirत set of OTPs illustrate the output when the bias voltage was adjusted to $2,800 \mathrm{~V}$, a departure of 450 V below holdoff.

It is significant to note that these sets of oTPs were. taken while using the external synchronization feature of the oscilloscope; therefore, the temporal jitter characteristics are excluded, in the interest of clarity of the photographs. Additionally, the combined.energy of ali normal mode spikes groupen was equivalent to the microjoule regime.


Series 1


Series 2


Series 3


F804-4

Fiaure 4-37. Normal More Sinale Pulse Profile

The OTPs disclose several pertinent characteristics:

- The average normal mode spike half power pulse width is $\simeq 400 \mathrm{nsec}$.
- The average normal mode spike pulse rise time is $\simeq 400 \mathrm{nsec}$, as measured from the $10 \%$ to $90 \%$ points; and
- The pulse is essentially gaussian in shape.

Several conclusions concerning the energy control servo requirements may be drawn from these characteristics.

- The prelase may be obtained when the Pockels cell voltage is reduce less than 400 V ; thus, a $400-\mathrm{V}$ control range is adequate to achieve holdoff and cause laser action to cease;
- The laser action initial buildup is quite slow (i.e., the energy increase per unit time exhibits a low-slope near the leading edge). Therefore, provided that adequate sensitivity is achieved within the energy control servo, the pockels cell voltage slew rate need never become excessive; and
- The energy control servo must exhibit good low-frequency response - ideally the response should be near dc, since the initial pulse width of $\sim 400 \mathrm{nsec}$ indicates a stretched pulse width of well into the microseconds is to be achieved.

These conclusions led to the hardware implementation depicted in Figure 4-38 and Figure 4-39, the Pockels cell interface, and the energy (i.e. radiation) control electronics respectively. The hardware was constructed and testeत as a subsystem. The performance was considered to be satisfactory. The prime characteristics observed were:

- The frequency response of the detector and preamplifier was observed to be flat from $200 \mathrm{KH}_{2}$ to $\sim 400 \mathrm{MFz}$;
- The attack time of the $400-\mathrm{V}$ output driver was observed to require $\sim 50 \mathrm{nsec}$ when loaded into the Pockels cell interface;
- The output-driver voltage-level was observed to be linear relative to input irradiance;
- The output-driver voltage-level was observed to track pulsating input to the preamplifier, to achieve a mean-level as required, when the mode structure input change over occurs; and
- The output-driver voltage slew of 400 V was observed to occur for irrariance input of less than $10 \mu^{\mathrm{W}}$.


D1018736

Figure 4-38. Q-switch Interface Schematic


D1018738

Figure 4-39. Radiation Control Schematic

Based upon the subsystem tests, the energy control electronics assembly was integrater to the laser system. The pockels cell voltage was reduced to $2,950 \mathrm{~V}$ to achieve prelase action. Little or no observable change occurred to the prelase normal mode spike. Careful investigation revealed that:

- The threshold is quite high - in other words the lase action is well developed before the control electronics responds;
- The driver output-voltage essentially follows the response curve of the prelase pulse; however, at this high radiation level within the resonator, insufficient control voltage range is available to the Pockels cell. Thus, the control driver saturates; and
- The control-driver output lags the energy-input change by some 55 to 60 nsec during the control trial period. This tends to indicate that about 20 nsec of response time is inherent within the control loop.

Of the observed integration performance, the most significant shortcoming is the lack of sensitivity. The through-put or response time is considered to be the second significant problem area.

The first problem was attacked by reducing the losses of the interfaces of the fiber optical bundle which transmits lase energy leaked through the oscillator polarizer to the detector circuit. Experimentation with the radiation control electronics revealed that the majority of the through-put delay occurs within the post amplifier or the driver portion of this circuit. This circuit was revised and fabricated as shown in Figure 4-40. Both bipolar transistors and VMOS devices are utilized within the circuit design.

Experimentation with the revised radiation control unit integrated to the laser system gave results that were unsuccessful as described for the initial design. The essential problems identified were insufficient input radiation to the control circuit and a too slow recovery time for the electronic post-amplifier. Experimentation with this concept was terminated and the pre-lase technique described earlier in this report was employed.


Figure 4-40. Radiation Control Schematic - Revised

## CONCLUSIONS AND RECOMMENDATIONS

The Nd:YAG laser system developed by ILS for the Spaceborne Laser Ranging System has been shown to satisfy the essential objectives of Contract NAS5-22916. The engineering breadboard constructed proved the feasibility of the pulsed, actively modelocked, PTM Qswitched Nd:YAG laser concept for the generation of subnanosecond pulses suitable for ultra-precision ranging. The specific technical accomplishment was the generation of single $150 \mathrm{psec}, 20 \sim \mathrm{~mJ}$ pulses at 10 pps at a wavelength of 1.064 micrometers with 25 dB suppression of pre- and post-pulses.

The significant hardware implementations within the engineering breadboard were the rugged crossed TIR prism, Invar optical bed subsystem, the pulsed electro-optical KD*P modelocker, and the prelase and switching synchronization control circuits. The success of these subsystems establishes the engineering breadboard as the actual foundation for the planned engineering prototype development.

The reconfiguration and improvement of the existing breadboard into a prototype unit suitable for its planned use on the Spacelab Geodynamics Ranging System consists of the following tasks:

- Repackaging of the system into the following subsystems: control unit, power suppy, laser transmitter, and cooling system;
- Implementation of a Quasi-CW power supply to stabilize and extend pre-lase and thus achieve stable pulse profiles;
- Temperature control of the transmitter to eliminate all operational temperature sensitivity;
- Reconfiguration of the cooling system to use liquid-toliquid heat exchanger;
- Reconfiguration of all electronics for 28 V -dc prime power; and
- Extension of experimentation to identify and correct any existing problems related to overall system long-term stability and to perform frequency-doubling.

The engineering prototype developed in accordance with the above outlined tasks will be a reliable, rugged, compact, subnanosecond pulse laser system with extensive applications for spacebased ultra-precision laser ranging systems.

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Appendix A

SPACEBORNE ELECTRONIC DESCRIPTIONS

Each flashlamp high-voltage supply is composed of four circuit assemblies. These assemblies are:

- The low voltage regulator and driver;
- The power converter module;
- The high voltage assembly module: and
- The high voltage regulator circuitry.

Drawings, numbers Cl008876 through Cl008879, depict the circuitry in schematic form. These drawings will be the reference for the detailed circuit operation description which follows.

Basically, the power conversion mechanism is in the form of a driven fly-back capacitor charging transformer. Energy is stored within a transformer, and is then transferred to the capacitive load. The energy imparted is a function of the allowed storage time and the transfer rate. Many charge cycles or steps are necessary to establish the desired capacitor terminal voltage. This method of charging imparts a precise energy pulse to the capacitor each time the fly-back action occurs, regardless of the instantaneous capacitor voltage, and given that a uniform energy storage is accomplished for each charge cycle. Thus the capacitor voltage increases in stair-step fashion.

In order that the charging action occurs in a systematic fashion, the power switching to/from the fly-back transformer is commanded by preliminary circuitry. This circuitry is the low voltage regulator and driver assembly, which is illustrated on drawing Cl008876. The circuitry consists of a voltage regulator (low voltage $\simeq 16 \mathrm{Vdc}$ ), and an oscillator. Transistors $\Omega 3,04$, and Q5 form the voltage control circuitry, with D3 and D4 providing the reference voltage. Transistors $Q 1$ and 02 interface the interlock circuitry to the voltage requlator. Regulated voltage appears at the emitter of $Q 4$ when the interlock circuit is intact. Interruption of the interlock removes base drive to $Q l$, the collector voltage of Q1 rises and 02 saturates. Q2 effectively shorts D3 and D4 to ground. Thus the reference voltage is now zero and the regulator performs to produce zero output voltage.

Under normal operation the input voltage is nominally 28 Vdc , which is regulated to 16 V .




## NOTES:

1. UNLESS OTHERWISE SPECBRED;

ALL RESISTANCE IS IN ONHS, $1 / 4 W, ~ 55 \%$ ALL CADACITANCE IS IN MICPORMRDDS (uF).



The oscillator is of the square-loop saturated transistor inverter type, which produces a square wave output. Q6, Q7 and Tl form the oscillator. Oscillator start-up is assured by P. 8 and the inherent imbalance in beta ( $B$ ) of the drive transistors. Base drive is taken from the feedback windings on Tl. The feedback phase is positive. R7 and R19 limit base drive current.

This oscillator exhibits good frequency stability, since the power input is regulated. Thus, the predominant freduency determining mechanism is the core saturation time.

Two output windings are evident on Tl. The bridge rectified output, marked +300 v , is of no concern since it is unused within the Spaceborne laser system. The remaining output, termed power module 1 and power module 2 , are of interest. This output is the synchronization command for the power fly-back circuit.

It is to be noted that this output is center-tapped to the 28 V ground, which splits the phase of the output and generates two command signals of 180 degree phase relation. This alternate output signal allows use of two power modules to effectively double the capacitor charge slope, since the charge current is doubled.

The remaining circuitry, of the low voltac̣e regulator and driver assembly, is the quench signal generator. This signal is required, during and for a brief time following the pFN discharge, to prevent $C W$ excitation of the flashlamp from continued operation of the power charging circuit. Thus, this signal is an inhibit command to the power module. The inhibit duration is on the order of $2-3 \mathrm{msec}$.

Q8 and Q9 form a monostable multivibrator (MSMV). Olo is an output driver. The flashlamp current pulse is sensed and appears at the base of $09 . \quad \mathrm{C} 2$ provides the necessary signal interjection path. The input signal is negative going, which removes. base drive from Q9. The collector voltace of 09 rises, Q8 is driven to saturation, and base drive to 09 via Rl2 is removed. Capacitor charging occurs over a period of time for c3, which establishes the output pulse duration. When c3 is charged, Q8 is base current starved and can no longer maintain saturation. The collector voltage of 08 rises. Current flows in Rl2 to the base of 09 . 09 quickly saturates terminating the quench signal pulse. Qlo faithfully outputs the quench signal by operating as a current sink to external circuitry.

Schematic Cl008879 depicts the circuitry of the power converter module. Input power to this circuitry is non-regulated, but filtered, 28 Vdc. $Q 2$ and 94 are the power switching transistors. Q1 and Q5 are current and voltage actuated turn-off mechanisms to the power switches.

In normal operation, the drive command, the synchronization command from the driver circuitry, appears at input point C. This signal is transformer coupled, via $T 2$, into the base circuit of Q2 and Q4. Q2 and Q4 conduct, the collector voltage falls to produce a current in the primary of $T 1$ and to produce positive feedback through $T 2$ to the base of 02 and Q4. Current rises linearly in time in the primary of $T l$ and in the feedback winding of $T 2$. After a precise time interval, $T 2$ saturates, base drive is abruptly removed from $Q 2$ and $Q 4$, and the $f l y$-back action is initiated. The secondary of $T 1$ is loaded into the capacitive load via CR8, and the stored energy is transferred to the capacitor.

Transformer T3 terminates the base drive of $Q 2$ and Q4 when fault conditions occur in the output circuitry. This occurs by forward biasing the base of 05 which initiates turn on $O f S C R$, Q1. Q1 shorts one winding of $T 2$; thus, no drive can reach Q2 or 04 , and any drive which was present was removed.

When the capacitor voltage is increased to the desired level, the regulator circuit outputs a positive pulse to input terminal A. Again $Q 5$ activates $Q 1$, drive to $Q 2$ and $Q 4$ is removed, and no additional charge is imparted to the capacitor.

Each power converter module is conservatively rated at $250 \mathrm{~W} ;$ thus, it is generally necessary to operate two or more modules, slaved to a single driver, to charge a reasonably sized PFN capacitor. A maximum of 4 modules usually suffices for the most stringent requirements. Two modules, slaved at 180 degree phasing, are utilized in the Spaceborne laser system, one group each, for both the oscillator and the amplifier PFNS. The 180 degree phasing is essential to limit current peaking from the $28-V$ power source.

The high-voltage assembly monitors the output of the PFM capacitor, which is really the output of the power converter modules, to provide;

- The voltage regulation sense;
- The generator of the quench signal; and
- The power down discharging of the PFN capacitor in the interest of safety.

Kl is the discharge relay. $28-\mathrm{V}$ excitation of the relay positions the armature to open the normally closed contacts. Interruption of the interlock circuit allows contact closure and the capacitor is discharged through R4, R5; R6 and R7.

The PFN discharge is sensed through the network comprised of CI, R9, RI0, RI R3 and CRI-4. Discharge of the PFN creates a steep voltage decline at the capacitor. This voltage step is capacitively coupled to forward bias CRl-3. CR4 is also forward biased to produce a negative pulse output at the quench sense, terminal $S$. This pulse activates the MSMV of the low voltage regulator and driver board, to produce the timed quench signal output.

R22, a high voltage 22 MS resistor, senses the output voltage. The voltage drop across the resistor equates to nearly the capacitor charge voltage. This voltage drop results in a current flow which is sensed within the final circuit group which comprises the power supply subassembly.

The high-voltage regulator is illustrated in schematic drawing cl008877. This circuit consists of:

- A voltage reference mechanism;
- A voltage comparator mechanism; and
- An error signal amplifier.

The paramount function of this circuitry is to disable the power converter module at the time the capacitor voltage is at a preset magnituade.

CRI is the voltage reference diode. R7 maintains the zener current at the minimum drift magnitude.

Q1 and Q2 are the voltage comparator. $Q 2$ is taped across the reference voltage by the voltage divider produced by $R 5$ and $R 6$.

Q3, Q4, 05 and 06 comprise the error signal amplifier. The individual power modules are disabled via CR4 and CR5.

The high-voltage sense, from the high-voltage assembly, is applied to the input terminal 5. Generally a high-voltage adjustment potentiometer is connected from terminal $T$ to ground, terminal $v$. Thus, the current from the hioh-voltage sense produces a voltage drop across the high voltage adjustment potentiometer. When the sensed voltage slightly exceeds the reference voltage, Q6 saturates and the charge current for the PFN capacitor is removed.

Voltage regulation is assured, since gradual voltage decay at the capacitor results in deactivation of 06 which reinitiates charging to the capacitor until the voltage aoain is at the preset/controlled value.

Voltage regulation accuracy for this system is better than $0.5 \%$. Control is therefore not limited to the granularity afforded by the driver oscillator..
2. High Voltage Low Current Supply

Drawing, ILS Blo082l0-S, Revision $B$, details the specific circuitry which comprises the power unit.

A power pass transistor pair, Q1 and Q2 serve to energize Z1, a tracking dc to dc converter unit. The power pass stages are controlled by a gain stage $22 . \quad C R 1$ is a voltage reference unit. Resistive divider, R9, Rl0, Rll. and Rl2 sample the highvoltage output to compare to the voltage reference. The input voltage to Zl , is served to achieve equality between the reference. voltage and the feedback voltage. The 5 K external potentiometer is utilized to vary the effective voltage reference and consequently: the high voltage output. Capacitor $C 2$ and resistor $R 5$ stabilize the loop response.

Input power is 24 to 28 Vdc . Input current at full load is $\leq 400 \mathrm{~mA}$ dc.
3. Flashlamp Simmer Supply

The flashlamp simmer supply is schematically depicted in ILS drawing DI013775. The primary subsystems. which comprise the . supply are;

- A high rate clock or oscillator;
- An energy output sense mechanism;


## NOT SUPPIIED

B1008210-S RB

EOLDOUT Frame 1
FOLDOUT FRAME 2


NOTES: LNLESS OTHERWISE SPECIFIED
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- A dc to dc converter; and
- A flashlamp ignition circuit.

The high rate oscillator is configured by VI and the associated circuit components. The frequency of oscillation is 20 KHz .

One half of U2; together with LI, and associated circuitry shape the oscillator output signal to drive Q2. The drive signal is transformer coupled to the base of 04.

Tl, T2 and Q4 comprise the SC to SC converter. This implementation is of the inductive fly-back type in order to accommodate widely varying lamp voltage excursions and to afford good conversion effeciency.

Drive to the base of $Q 4$ causes a reduction in collector voltage, to produce a voltage drop across the primary of $T 2$ and the feedback winding of Tl. Q4 rapidly reaches saturation, due to the positive feedback through Tl. Rl6 senses the base drive to Q4. Resistors RI3-15 couple the base drive sample to comparator V2, causes the comparator to react, and $Q 2$ and Q1 are activated. Ql clamps a winding of $T 1$ and effectively removes drive from 04.

RI4 is the energy control adjustment. The voltage at pin 4 of V 2 is a ramp type signal; thus, adjustment of Rl4 determines the on time $Q 4$ and determines the energy stored in $T 2$. Abrupt removal of base drive from 04 results in a swift fly-back response in T2.

CR10 and CRII are forward biased so that charging current is supplied to C9 and Cll. Initially, no simmer current flows in the flashlamp, as the lamp is deionized. Voltage rise on C9 is quite high - in the KVdc region. CRIl and CR12 serve a dual purpose. For one thing they provide a portion of the over voltage fly-back transient snubber. Additionally, they provide a voltage depletion region which prevents activation of the ignition circuitry when normal simmer exists since no charge exists on Cl0 and Cll during this operation. Cll is charged through CRI2. When the voltage rises sufficiently on Cll, Cl0 charges through CR13 and R17. At a charge voltage, in the area of 15 to 20 V upon Clo, CRI4 enter conduction to activate the gate of SCR, 03 . 03 discharges abruptly the stores charge of Cll through the primary of the ignition transformer, to ionize the flashlamp.

C9 is charged quite high. and aids in intial lamp ignition. c9 discharges to a nomininal holding voltage equating to the average lamp simmer voltage. Durina PFN discharge, the inductive ballast prevents activation of the ignition circuit.

In the event "simmer" is lost, due to deionization, a reignition sequence is"intiated.
4.

PRF and Delay Generator
The PRF and delay generator circuitry establishes the laser emission rate and provides precisely delayed initiate output commands for Q -switch and prelase control.

Additionally, a divide-by-l0 prescaler is incorporated to drive the shots counter.

Various enablement features are incorporated for laser mode control.

The circuit is depicted in schematic format in ILS drawing number Dl018733. The counter chain comprised of U9-15 establishes the laser emission PRF and serves also to provide the precise timing delay function. The system clock, Ul6, is selected to be 10 MHz in order to afford a minimum timing interval of 100 nsec .

At initial power-up the counter chain is active at a random count. The counters accumulate content synchronously at the 10 MHz rate. When the counter content is equivalent to the programmed period, the $J$ input of $U 4$ pin 3 is enabled. The next sequential clock transition causes U4 to toggle. Pin 5 becomes a logic high state to enable to U4 pin 11 and the delay comparators U20-22 and U28-30. Simultaneously US-II are disahled by the $\bar{\Omega}$ output of U4 pin 6. U9-ll are: preset to zero content, while Ull is preset to a content of one, which equates to a time of 1 msec .

It is significant to note that counters Ul2-15 are naturally at a count content of zero because of the detection implementation technique for the PRF generation.

The delay comparators are programmed from digital decimal thumb wheel switches.

For a program delay input of zero to the delay comparator/ comparators the $J$ input/inputs to U3 are now also enabled. For programmed delay $\geq I$ the $J$ inputs of $U 3$ are held at a logic low level.


The next sequential clock pulse toggles U4 pin 9 to generate the basic $\ddagger l a s h ~ c o m m a n d . ~ T h e ~ c o u n t e r s ~ c o n t i n u e ~ t o ~ a c c u m m u l a t e ~ c o n-~$ tent. As the content agrees with the programmed delay content U3 is enabled and toggles at the appropriate time, to produce the prelase command and the Q-switch command. When counters Ul2-15 reach a content of 999.9 usec, the $K$ input of $U 4$ pin 2 is enabled. U4 toggles at the elapsed time of $1,000.0 \mu \mathrm{sec}$. The preset strobe is removed from counter U9-ll and the enable is. removed from the digital comparitors. All output commands are removed.

It is significant to note that counters U12-15 are now naturally at a content of zero, counter U9 and Ul0 are preset to zero, and counter Ull is at a content of 1 which equates to $1,000.0 \mathrm{sec}$, which is the proper count sequence state.

The counter content accumulation continues until again the selected PRF decodes the content to re-initiate the sequence.

To this point in the discussion no output commands have actually been generated. U1, U2, U23 and U24 comprise output drivers. Ul7, and Ul8 serve as gated signal sources to generate and control the various outputs as commanded from operator adjustable front panel control switches.

The remaining area for discussion is the shots counter scaler U7. Transistors Q1 and Q2 comprise an input signal conditioner for U7. Transistors @l-3 comprise a driver circuit to allow U7 to drive the shats counter. The scale factor of UT is division by 10.

## 5. Frequency Systhesizer Circuit Description

- The following circuit description details the signal flow in step by step fashion within the frequency synthesizer.

Previous discussion from Section 3 of this report, has outlined the basic circuit concept and operation.

Schematic, ILS DIO18735 shows the circuit in schematic format.

Signal output from the precision reference oscillator is 65 MHz and is in the emitter coupled logic (ECL) format. This signal enters the frequency synthesizer board at pin number 3.


Resistor, R18, provides the proper termination for the input signal.

Transistor Q3 and associated circuitry comprise an ECL to TTL level shift function, to generate the signal referenced CP 2.

Ul6 reduces the signal frequency by a factor of 10 such that the output of pin 12 is 6.5 MHz .

U8 reduces this signal frequency by a factor of 10 to produce an output at pin 12 of 650 kEz .

U3, U4, U6 and U7 operate in concert to reduce the 650 kHz signal to a frequency of 10 kHz , which appears at pin 6 of U3. This signal, of negative attitude, is the reference signal to the phase detector/comparator U2. This signal pulsewidth is 1,538. 4 nsec.

The voltage controlled oscillator, Ul0 is of the ECL family. The output, pin 3, drives Ull. The output of Ull, pin 3 drives Ull pins 11,12 and 13 . Additionally, this signal drives Q1. Ql and associated circuitry perform an ECI to TTL voltage translation, which drives pins 4 and 5 of U 22 . The output signal from pin 6 to $U 22$ is designated $C P I$ and is the modulo prescaler clock signal.

U4, U5, U13, U14, U18, U20, U21, U23 comprise the modulo prescaler. Initially, the prescaler is preset with the 9 complement of the desired output frequency. This preset is generated from thumbwheel switches which are operator programmable. The switch input range is limited to values which fall within the range of 50.000 MHz to 69.990 MHz through mechanical stops installed ot the most significant digit thumbwheel. The least significant digit is the 10 kHz thumbwheel.

Once the counters are loaded the counters may accumulate content at the CPI rate, which is the VCO rate. When the least significant digit counter, U23, has reached a content of 3 and all other counter contents are equal to 9 , coincidence detection occurs and the $J$ input, pin 3 , of $U 5$ is enabled. The next sequential transition of CP 1 toggles U 5 and pin 5 becomes a logic high level. Pins 1 and 2 of $U 22$ are both a high level, and pin 3 of U22 becomes a logic low level to again load the counters. Simultaneously, pins 11 and 12 of u5 are enabled, and the clock to the counter string is disabled. The second clock
pulse following coincidence toggles u5. Pin 9 becomes a logic high level to enable Ul5 pins 2 and 3 . Pin 7 becomes a logic low level to remove the counter preset command. The third and fourth clock pulses, following coincidence detection, toggle U15 to preset the $K$ input, pin 2 of U5. The fifth clock pulse returns U5 to the original state and removes the clock inhibit command from the counter string. The sequence may now repeat.

The phase locked PRF pulsewidth is the CPI $P_{W} \times 4$; thus, adequate pulsewidth is available to drive U 2 .

It is to be noted that the unusual coincidence detection deviation from true 9 complement logic is necessary to achieve adequate clear time through the coincidence detector, UA, Ul3 and U14.

U2 is the phase comparator. The comparator is connected to form a type 1 phase detector to provide an in-phase lock.

Assume that the VCO frequency is above the reference frequency for the sake of circuit explanation. 42 pin 5 becomes a logic high-level which drives pin 8 of U 2 to a more negative value. This reduces the bias voltage upon the varactor diodes CR2 and CR3 to increase the effective capacitance to the VCO tank circuit, and the frequency is reduced. This action continues until lock is obtained. When lock is obtained, no current flows from or into U2 and varactor voltage stabilizes, as does the VCO frequency.

For conditions where the VCO frequency is less than the reference frequency the reverse occurs. U2 pin 10 becomes a logic low-level, the varactor voltage and the VCO frequency increase until lock is again achieved.

R7 and C2 are the predominant loop filter components. R9 and C4 form a additional filter for high frequencies in order to improve the spectral line of the VCO.

RIO decouples and VCO radio frequency energy from the control loop.

Ull is the output buffer amplifier. The output occurs at pin 60 of the frequency synthesizer.

Ul9 is a monostable multivibrator (MSMV). This circuit conditions the PRF input command signal to a precise pulse duration, in order to establish the emission burst duration. Gate, U22,
pin 12 is controlled to effect either the pulsed emission or continuous wave (CW) emission.
6. PTM Synchronizer

The PTM synchronizer determines the appropriate time to initiate the laser emission. This determination is accomplished in the following sequence:

- The laser PRF command (flash) enables the sensor with a window aperture of approximately 200 microseconds duration.
- The optical resonator energy level is monitored against a reference level comparator.
- The laser energy packet position is determined by sampling of the modelocker drive voltage through a squaring circuit.
- The PTM/Dump command is generated whenever the laser energy exceeds threshold and the modelock voltage squarer provides a transition. Drawing ILS DI018737 depicts the circuit in Schematic format.

The PRF (flask) command is utilized to activate monistable multivibrator (MSMV) V6, at input pin 2. Triggering occurs at the low to high transition. The MSMV output occurs at pin 4 . This output exists for a period of $200 \mu \mathrm{sec}$ following the leading edge of the PRF signal. . During this time, the circuitry is active to accomplish the determination.

Photo detector CR2 senses the optical resonator energy. Energy pick-off is from the polarizer. Circuit $V 2$ is the comparator. The photo detector converts the optical energy output into a corresponding current flow. This current flow pxoduces a voltage drop across resistior R19.

The resistive voltage divider comprised of R17. R20 and R2l establish the reference for the threshold comparator. Resistor R20 allows adjustment of the threshold magnitude, Circuit v2 is operated as comparator only, the output of pin 2 is utilized to clock V3, a storage "D" flop. Whenever the enexgy level within the optical resonator excees threshold, the output at pin 2 of V3 latches in the logic high-state. The D input of $V 4$ is now enabled.


FOLBOUT ERAME 2


Transistor Ql and associated circuitry form the first phase shifter for the sampled modelocker R.F. signal. Resistor R5 allows phasing adjustment.

Transistor $Q 2$ and associated circuitry form the second phase shifter. Resistor $R 6$ allows phasing adjustment.

Circuit VI is the signal squarer. It is to be noted that the reference for this comparator is at ground potential; therefore the sine wave signal input is sliced at the centroid of the excursion or at ground.

The low to high transition of the output of VI at pin 2 clocks V4. The 0 output of V4 becomes a logic-one level, and the $\bar{Q}$ output of $V 4$ becomes a logic zero level whenever the $D$ input of V4 is a logic high level. This action forward biases the base/ emitter junction of transistor Q3, the collector voltage of 03 falls, and the output of $V 5$ at pin 6 is generated. This sional is the PTM/Dump initiate command.

At the expiration of the timing interval of MSMV V6, the direct set inputs of V3 and V4 are activated and the PTM initiate command is terminated.

The sequence repeats at the next PRF command input.

## 7. "Radiation Control Loop

The radiation control loop has only one function to perform for the laser system, the stabilization of the oscillator optical resonator energy during the prelase interval. Roughly 600 to 800 round trip intervals are required within the resonator to achieve active modelocking. This equates to an elapsed time of ${ }^{*} 6 \mathrm{usec}$ that the loop must remain active. The control function must effect a pulse stretching for this 6 usec interval.

During the interval the active modelocker is compressing the resonator energy into a shorter pulse, so that the control system must respond at a reasonable rate to the decreasing pulse width.

A control tradeoff is effected whereby the response is good to a specifič frequency or pulse width for peak energy control. The loop then effects a reduced performance whereby the average resonator energy is controlled. By the time the average
energy control is in effect the pulse shapina is well under way and the energy stabilization is quite effective. The photo detector affords the integration for average control.

The complete circuit is depicted in ILS drawing D1018738. Diode CR3 is the photo detector. Transistors Q1-3 and associated circuitry form a transimpedance preamplifier, to convert the diode current into an analog voltage. Resistors R24 and R25 form the transresistance.

Transistors $Q 407$ and associated circuitry comprise a post amplifier. The output of the post amplifier is positive in attitude, and saturates at 600 to 800 mV .

Transistors $Q 8-10$, and associated circuitry comprise the final voltage amplifier to drive the pockels cell.

Resistor R15 provides some control of the energy threshold, by determining the point of voltage drive where the final voltage amplifier becomes active.
8. Revised Energy Control Output Driver

The discussion specifically details the revised/re-engineered output-driver for the energy control loop for the Spaceborne Laser System.

Schematic 1018738A depicts the revised energy control driver in schematic form. Basically, the circuitry is a veryvery fast operational amplifier of the inverting confirguration. Because of the need for proportionality, within the control loop, some means for loop gain adjustment is desired. Additionally, since the control loop is closed through the optical paths, all the classical problems of closed loop servos must be considered. Usually, a lag or lead/lag stabilization network must be provided. An operational amplifier concept lends ease for the loop stabilization network insertion. For this discussion, the network will be omitted other than to illustrate the awareness for the inclusion of the circuitry.

Specific Circuit Description
The circuit is a closed-loop operation amplifier. As implemented, only the inverting input terminal is utilized. True current mode summation is employed in the design.




FOLDOLT FRAME 2



The design emphasis was placed upon:

- The circuit must possess a 400 v output voltage excursion range;
- The circuit must be of the linear type;
- The through-put time delay must be minimized at all costs;
- The output slew rate must be in the order of $\simeq 10 \mathrm{kV} / \mathrm{sec}$; and
- The circuit must not possess instability when capacitively loaded.

Using this criterion the circuit depicted in Schematic 1018738A evolved. Transistors Ql and Q2 form a differential amplifier. The base of Q 2 is referenced to an interval reference, while the input signal is applied to the base of ol. Transistors Q3, Q4 and Q10 furnish the excess gain needed in addition to the gain afforded by the differential pair.

Transistors Q5-9 furnish no gain, rather they operate as voltage range extenders, to enable an output voltage swing of 400 V. Power for the output stage is derived from the Pockels cell bias supply, which is depicted as RL. The capacitive load is denoted as CL.

Resistive-divider network R14, R15, R18, R20, and R21, determines the quiescent dc voltage which appears at output jack, J2, by virtue of the fact that the summation mode (the base of Ql) is connected to the divider. Network weighting of the feedback network shapes the desired ac response.

Considerable care was exercised in the device selection. Bipolar transistors were chosen for the differential pair, and the predriver ( 3 and Q4) because good gain bandwidth product ( $F_{t}$ ) devices are readily available, which operate at the necessarily low current. The $F_{t}$ of the differential amplifier devices, at $I_{C}=15 \mathrm{ma} d c$, is specified to bl $\geq 1,600 \mathrm{MHz}$. The $F t$ of the predriver devices, at $I_{C}=30 \mathrm{ma}$ dc, is specified to b2 $\geq 5,000 \mathrm{MHz}$. Thus, the response and delay time of this circuitry is $\leq 4 \mathrm{nsec}$.

The capacitive load, plus the necessity to swing 400 V , places quite a limitation on device selection for the output drivers.

In the interest of determination of the current required to discharge a capacitive load of 120 pF in 20 nsec , the following calculation is included.

$$
\begin{aligned}
& I=\frac{C V}{t} \\
& I=\frac{\left(120 \times 10^{-12}\right)(400)}{20 \times 10^{-9}} \quad=2.4 \mathrm{~A}
\end{aligned}
$$

Obviously, this current requirement precludes any small geometry devices not already excluded on the basis of low collector/ emitter voltage ratings.

Additionally, in the interest of circuit efficiency, bipolar transistors are not desirable from the inordinately high base drive current requirements necessary to achieve collector currents of 2.5 A at the needed response speed.

A recent development within the field effect transistor (FET) family of devices has yielded the power FET, or the VMOS. This device is of the enhancement gate drive variety, which requires virtually no gate drive current. Excellent current capabilities, coupled with extreme speed, make this device attractive. Typical switching speed at the drain current level of 2 A, is 4 nsec. This time includes both delay and fall time. Obviously, the device is much faster than present bipolar selections.

At present the device voltage rating, the source to drain sustaining voltage, is $90-\mathrm{V}$ maximum. This is not a serious problem. The devices permit an ease of series operation, since the gate drive current is miniscule.

VMOS devices are used for Q5-10. The gate voltage source is clamped to +15 Vdc for devices $05-9$ in order to preserve good low end voltage response. The bipolar driver actuates the gate of Q10. The preamplifier/detector unit, positive attitude output, voltage drives the base of Q l toward cutoff. The ol collector current reduces and the collector voltage moves toward ground potential. The base current of 04 is reduced, causing the collector voltage of 04 to advance toward the $15-V$ source. Diode, CRI, is reverse biased and the base of $Q 3$ is $\overline{\text { driven positively. Emitter }}$ current flows in $Q 3$ to charge the gate capacitance of 010 . The gate voltage of Q10 becomes positive.

The voltage divider string of R1-6, and Cl-6, establishes a fixed distributed gate potential of Q5-9.

The drain current increases in 010 , which causes the drain voltage to decrease. This decrease produces gate drive to Q9 since the source voltage of 09 becomes less than the gate voltage.

This ripple process continues up the string, until 05 is energized. The drain voltage of 05 falls toward ground potential.

It is to be noted that the capacitor and resistor divider string are driven from the drain terminal of 05 . As the applied voltage of the 05-10 amplifier string is reduced, the individual gate voltage potential of 05-9 are proportionately reduced, and each device shares the instantaneous remaining applied voltage.

As the drain voltage falls, less current flows through R15 and R18. When the reduction current is equivalent to the injected current through $R 20$, the differential pair is again brought into balance, and drive voltage is reduced to $Q 10$, and the output voltage stabilizes.

Capacitors, Clo-11, and R13 afford current pullup when the input pulse is no longer present, since energy was stored in the capacitors.

The performance of this circuit is well illustrated from the oscilloscope trace photographs of Figure A-1 and Figure A-2. Figure A-l illustrates complete stability with the capacitive load. Figure A-2 was taken with only the resistive load and illustrates the lack of stability in the loop response. This is no great problem since normal operation includes the capacitive load.

The present loop gain of the driver is $\simeq 2,000$. Tests indicate that this value may be altered, in order to adjust the overall control loop servo gain, with no great problems arising.

## 9. Avalanche Transistor Pockels Cell Driver

a. Introduction

Prior to the discussion of specific Pockels cell driver circuitry, it is necessary to characterize the avalanche action of the transistor. The discussion is concerned with the external properties of avalanche transistor switches, such as bias current and bias voltage, and is intended to illustrate usage of the device rathex than design of the transistor junction.

$6 乙-$ だ

－F80 $\mathbf{A}_{4}^{2}$
Figure $A-1$ ．Revised Driver Output Wave Forms $C_{L}$ Terminated



P804-3

Figure A-2. Revised Driver Output Wave Forms output Terminated $R_{r}$ Only

Because avalanche transistors operate in breakdown, a brief description of breakdown characteristics is in order. Figure A-3 depicts the avalanche transistor collector breakdown characteristics. BVCER is the collector-emitter breakdown voltage for a specified external resistance from base to emitter of the transistor. Increasing the voltage across the transistor above the breakdown potential causes the collector current to increase until it reaches the level termed $I_{H O R}$, or the hold-off current. After $I_{H O R}$ is reached, the transistor appears as a negative resistance element -- that is, for voltages between the value of $B V_{C E R}$ and $B V_{C E O}-$-and the breakdown avalanches to a value near $B V_{\text {CEO }}$. If the collector current is further increased beyond $I_{H E O}$, the open-base breakdown characteristics will further drop the collector voltage to a low-voltage level equivalent to $\mathrm{V}_{\mathrm{CF}}$ (sat).

The first avalanche -- that is, from $\mathrm{BV}_{\mathrm{CER}}$ to $\mathrm{BV}_{\mathrm{CEO}}$-- is termed low-current-mode avalanche. If the collector current supplied by the low-current-mode avalanche is sufficient to overcome IHEO, the device enters the high-current-avalanche state. When $I_{\text {HFO }}$ is small, only the high-current avalanche is detectable.

Figure A-4 illustrates the relationships of $B \dot{V}_{C E R}$ and the base emitter resistance $\mathrm{R}_{\mathrm{BE}}$. It should be noted that the choice of $R_{B E}$ is limited to reasonable low values to maintain the maximum voltage differential between $\mathrm{BV}_{\mathrm{CFO}}$ and $\mathrm{BV}_{\mathrm{CFS}}$. If $R_{\mathrm{BF}}$ is chosen too large in value, the difference between $B V_{C F R}$ and $B V_{C E O}$ will be too small to generate sufficient collector current to exceed $I_{\text {FFo }}$ and the high-current-mode-avalanche state will not occur.

Hold-off current versus $R_{B F}$ obeys a curve similar to that shown in Figure A-5. As can be seen, hold-off current can be changed merely by alteration of the external $R_{B E}$ resistance value.

Two types of collector bias arrancements are used in avalanche transistor circuits -- current biasing and voltage biasing. Each has advantages and disadvantages.

A device is current-biases. if $V_{C C}$ is oreater than $B V_{C E R}$. The quiescent collector current is limited by Rl and must be less than $I_{H O R}$. In a voltage-biased circuit, $V_{C C}$ is slightly less than $\mathrm{BV}_{\text {CER }}$, but sufficiently greater than $\mathrm{BV}_{\mathrm{CE}}$ o to ensure high-current-mode-avalanche operation.


Figure A-3. Avalanche Transistor Collector Breakdown Characteristics


Figure $A-4 . \quad B V_{C E R}$ versus $R_{B E}$


Figure A-5. $I_{\text {HOR }}$ versus $R_{B E}$ (typical)

Generally, the voltage-bias technique is used where the power budget and/or dissipation limits preclude current biasina: obviously, the voltage-biasing technique imposes a moderate voltage stability requirement, whereas the current-biasing technique removes the stability requirement to the extent that the quiescent Rl current must not exceed the $I_{H o R}$ value. The current-biasing technique generally provides shorter delays and risetimes associated with increased voltage and current outputs.
c. Typical Avalanche Transistor Circuit

A typical avalanche transistor circuit is depicted in Figure A-6. A discussion of the circuit operation will clarify some of the previous voltage and current related parameters.

Assume that the circuit is biased in the quiescent-current mode. In the off or holding state, load capacitor C2 is charged through resistor RI. The voltage charge on capacitor C2 is equal to $B V_{C E R}$ because the transistor diverts charging current for values of current less than $I_{H O R}$. It is assumed that the $V_{C C}$ level is adjusted to produce a quiescent collector current through RI which is less than IHOR.

When a short positive pulse is apolied to the base of the transistor $Q 1$, the collector current and $Q I$ exceeds $I_{H O R}$ and the transistor avalanches to $\mathrm{V}_{\mathrm{CE}}$ (sat) to present a low impedance to the discharge loop. Capacitor C 2 is unable to discharge immediately because of the impedance of RI; therefore, most of the voltage charge of C 2 is impressed across RL.

Because RI, is generally a very low value, the capacitor discharges rapidly. When the discharge loop current falls to a value below $\mathrm{I}_{\mathrm{HOR}}$, the avalanche transistor impedance aqain becomes high and the capacitor again charges to $B V_{C F R}$ through RI. The cycle can now repeat.

It is significant to note that once avalanche action is initiated, the base drive pulse provides no control and the cycle is irreversible.

Avalanche transistors can be successfully operated over a wide temperature range. When a wide temperature range is to be encountered, the prime parameter to consider is the $I_{H O R}$. Figure A-7 depicts the $I_{\text {HOR }}$ change with temperature.


Figure A-6. Typical Avalanche Transistor Circuit


P3009

Figure A-7. $I_{\text {HOR }}$ versus Temperature (typical)

A device with a $2.5-$ to $3.0-\mathrm{mA}$ dc $\mathrm{I}_{\mathrm{HOR}}$ at $25^{\circ} \mathrm{C}$ can be expected to exhibit about $1.0-\mathrm{mA}$ de $I_{\mathrm{HOR}}$ at $150^{\circ} \mathrm{C}$ and a 5 - to $7-\mathrm{mA}$ do $I_{H O R}$ at a temperature of $-55^{\circ} \mathrm{C}$. Surprisingly, the $\mathrm{V}_{\mathrm{CER}}$ voltage value changes very little with changes in temperature. The change results in a $\Delta_{V}$ slope which can be either positive or negative and generally exhibits a change $\leq \pm 200 \mathrm{PPM} /{ }^{\circ} \mathrm{C}$. Therefore, when the worst case drift is considered, a collector voltage stability of $\pm 1 \%$ is achievable over a temperature excursion of $+50^{\circ} \mathrm{C}$. This stability factor is of significance because the output voltage is dependent primarily upon the BVCER level.
d. Recovery Recharge Time

The remaining discussion of the preliminary characteristics of avalanche transistor circuits is the recover, or recharce, time. Again a current-bias technique will be assumed. Figure A-8 graphically illustrates the recovery.

Because Rl in Figure $A-6$ is many times RL in the currentbiased arrangement, Equation ( $\mathrm{A}-1$ ) represents the curve of capacitor recharge in Figure A-8.

$$
\begin{equation*}
V_{C E}=V_{C E(s a t)}+\left[V_{C C}-V_{C E}(s a t)\right]\left[1-e^{-t / R I C}\right] \tag{A-1}
\end{equation*}
$$

$B V_{C E R}$ is the final voltage, so Equation (A-1) simplifies to Equation (A-2)

$$
\begin{equation*}
e^{t / R I C}=\frac{V_{C C}-V_{C E}(s a t)}{V_{C C}-B V_{C E R}} \tag{A-2}
\end{equation*}
$$

Thus, recharge time becomes:

$$
t=\operatorname{RIC} \ln \frac{V_{C C}-V_{C E}(s a t)}{V_{C C}-B V_{C E R}}
$$

When operating in the current biased mode, the maximum repetition rate is the reciprocal of recharge time, or $1 / t$.
e. Specific Pockels Cell Driver Circuitry

The specific Pockels cell driver circuitry will now be discussed. As its name "Avalanche Transistor Pockels Cell Driver" implies, the driver circuitry relies upon the avalanche switch to generate the drive to the Pockels celi. The avalanche switch is


P3010

Figure A-8. Collector Waveforms for Current Biased Operation
selected because of the extremely short time interval required to collapse the impressed voltage across the transistor. Theoretically, the collector-emitter voltage collapses in less than 0.8 nsec .

Certain problem areas relating to transistor packaging technique -- lead inductance, inter-electrode stray capacitance, bonding lead resistance and miscellaneous other considerations - increase the voltage collapse time significantly. International Laser Systems has innovated a novel Pockels cell driver construction technique to overcome most of the problem areas and to enhance the voltage collapse. A later discussion will illustrate the technique utilized.

The selected Pockels cell requires $\lambda / 4$ voltage change to be effective. This voltaçe equates to approximately 3 kV . obviously, the avalanche transistor driver must either switch a $3-\mathrm{kV}$ voltage, or generate a $3-k V$ voltage.

One technique, currently in use at ILS, consists of several avalanche transistors operated in a series configuration to generate voltage switching in the kilovolt region. Several stages of transistor groups are operated in a Marx generator connection to build additive voltages as required by the application. This technique is viable for most applications; however, where switching speed is paramount in the design criterion, the added inductance and stray capacitance associated with this technique renders the approach unsatisfactory.

The only viable approach to achieve the speed requirement necessitates the avalanche transistors be operated in the series configuration to discharge the $\lambda / 4$ voltage of 3.25 kV . The selected collector-current bias mode is compatible with series connection of the transistors. A large value resistor establishes the biascurrent level and removes the requirement that the hich-voltage supply be closely regulated. Additionally, the low-bias current allows a small high-voltage supply to be chosen.

Schematic Dl018734 illustrates the Pockels cell driver in schematic format.

The operation of the series configured switch is essentially the same as previously described for a single avalanche device. Transistors Ol through Ql4 comprise the avalanche switch. Resistor Rl establishes the bias current level and establishes the Pockels cell quiescent voltage at $3500-\mathrm{Vdc}$. The $\mathrm{BV}_{\mathrm{CER}}$ composite



# FOGSTI FRAME 2 

|  |  | 11 |  |  |  | P4774 |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | int mimen | Nㅡㄴ | deemerito |  |  |  |  |  |
|  |  | 1. | rr |  |  |  |  |  |  |  |
|  |  |  | (3) |  |  | dar |  |  |  |  |
|  |  |  |  | - $x=1 \times 4$ | gricke |  |  |  |  |  |
|  |  |  |  |  |  |  | PCCKELS CELL DRIVERS |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | 0-738 |  | Nos |  |  | ceek timi no |  | NEV |
| \% | 0 | Mexthery | uniol | A-41 ${ }^{\text {0\% }}$ |  |  |  | 34860 | 1018734 |  |
| ma | nem |  | arion |  |  |  | xale |  | [metr |  |

for the 14 transistors selected equates to $3.5-\mathrm{kVdc}$ when biased at approximately $100 \mu \mathrm{~A}$. Only transistor ol4 is actively controlled by the event-initiate pulse.

Current flows in R7, and the base-emitter junction of transistor Ql4 when the pulse is applied. Collector current flows in Q14 and Ol4 enters avalanche conduction mode. The collector voltage of 014 falls to near-ground potential or $V_{C E}$ (sat). Under this condition, transistor 013 is voltage-stressed beyond $B V_{C F R}$ and the $I_{H O R}$ current is exceeded. Therefore, $Q 13$ enters avalanche conduction. Similarly, each successive stage enters avalanche conduction until Ql.also is in the avalanche conduction mode. This action causes the collector voltage of Ol to become a voltage level near zero $\mathrm{V}_{\mathrm{CE}}$ (sat) x l4; the Pockels cell voltage also is discharged through diodes $C R$, and $\mathrm{CR}_{2}$.

At first inspection, the ripple action appears to occur rather slowly; however, this is not the case at all. Because the devices are biased in the current mode, each device is operating at a collector current of approximately 100 A in the direction approach ing $I_{H O R}$. When the collector current of Ql4 increases as the result of the drive pulse, all 13 other transistors also experience an increase in collector current because they are series connected. Thus, all transistors enter avalanche conduction essentially simultaneously.

The load resistance of the discharge circuitry consists of the series resistance component of the Pockels cell, the lead inductance/resistance and the "on resistance" of the avalanche switch. Because all of these are small, the Pockels cell capacity "sees" the minimum resistance and discharges rapidiy. Typical indicated fall time from the $90 \%$ to $10 \%$ points is $\leq 4 \mathrm{nsec}$.

The input initiate command occurs through transformer TI. Diode $\mathrm{CR}_{8}$ is reverse biased during the initiate command; however, when the avalanche string collapses the base of 014 experiences a large negative spike pulse, which diode $\mathrm{CR}_{\mathrm{g}}$ suppresses.

The PTM driver is identical to the O-switch driver, with the exception that the transistors are selected to afford an output voltage excursion of $3,400 \mathrm{~V}$.

## APPENDIX B

GENERATION BREAKDOWN


| 4rat international Laser Systems, Inc. |  |  |  |  |  |  | CODE IDENT NO. $34860$ | generation BREAKDOWN | G8 $0 / 0 / 6815$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\stackrel{u}{z}$ |  | $\begin{aligned} & \text { INDE } \\ & 2] 3 / 45 \end{aligned}$ | $\begin{array}{\|l\|l\|} \hline \text { enture } \\ \hline 6 / 7\|8\| 9 \mid 0 / 1 / 2 \\ \hline \end{array}$ | $\begin{aligned} & \text { ary } \\ & \text { N/A } \end{aligned}$ | D | PART/ITEM NUMBER |  | Nomenclature | NEXT ASSY |  | EfFECTIVITY |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| 2 |  |  |  |  |  |  |  |  |  |  |  |
| 3 | , | 0 |  | 6 |  | B1015834-1 | BRACKET, | T, CORNER |  |  |  |
| 4 | 0 | ) |  | 1 |  | 81016887-1 | INSULATIN | NG SHT, AMPLIFIER |  |  |  |
| 5 | 1 | $\theta$ |  | 1 |  | B1016889-1 | INSULATIN | NG SHT, OSCILLATOR |  |  |  |
| 6 | 0 | - |  | 1 |  | B1016886\%1 | INSULATIN | NG SHT, Q SWITCH |  |  |  |
| 7 | 0 | 0 |  | 1 |  | C1015590-1 | DOUBLE P | POLARIEER ASSY |  |  |  |
| 8 |  | $\theta$ |  | 1 |  | C1015391-1 | PLATFDRM, | , DOUBLE POLARIEER |  |  |  |
| 9 |  | 0 |  | 1 |  | C1015387-9 | MOUNT, DOU | DOUBLE POLARIEER |  |  |  |
| 10 |  | X |  | 1 |  | C1015638-1. | WEDGED | POLARIEER |  |  |  |
| 11 |  |  |  | 1 |  | C1015640-1 | POLAEER | R, EXIT |  |  |  |
| 12 |  |  |  |  |  |  |  |  |  |  |  |
| 13 |  |  |  |  |  |  |  |  |  |  |  |
| 14 |  |  |  | 1 |  | A100845/-9 | ADIUSTER | R, POLARIEER |  |  |  |
| ${ }^{15}$ |  | , |  | 1 |  | C1015591-9 | WEDGED R | RISLEY PRISM ASSY |  |  |  |
| 16 |  | 0 |  | 1 |  | C1014649-1 | BASE, RISL | LEY PRISM MOUNT |  |  |  |
| 17 |  | 0 |  | 1 |  | C1014652-9 | MOUNT RISL | LEY PRISM CELL** 2 |  |  |  |
| 18 |  | X |  | 1 |  | C1014652-1 | MOUNT RISL | LEY PRISM CELL*/\#2 |  |  |  |
| 19 |  |  |  |  |  |  |  |  |  |  |  |
| 20 |  |  |  |  |  |  |  |  |  |  |  |
| 21 |  |  |  |  |  |  |  |  |  |  |  |
| 22 |  | X |  | 1 |  | C1014650-1 | $C E L \angle, P R /$ | ISM 71 |  |  |  |
| 23 |  | 0 |  | I |  | C1014651-1 | CELL, PRI | ISM\#2 |  |  |  |
| 24 |  | 0 |  | 1 |  | C1015636-1 | PRISM ${ }^{\text {\# }} 1$ |  |  |  |  |
| 25 |  | X |  | 1 |  | C1015637-1 | PRISM\#2 |  |  |  |  |
|  |  | K.CH | EEEK |  |  | $\angle A S E R$ RANG ASSEME | $\begin{aligned} & G E F / N D E R \\ & 3 \angle Y \end{aligned}$ |  | $\begin{aligned} & \text { SOB NO. } \\ & \text { b739 } \end{aligned}$ | $\left.\right\|_{\underset{Z}{2}} ^{\text {SHEET }}$ | ns |




ILS FORM Nก 2 an







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International Laser Systems, Inc.
1016815



CODE IDENT NO.
34860

## 3480

GENERATION BREAKDOWN

REV




## APPENDIX C

OPTICAL BED THERMAL ANALYSIS

## 1.

## BACKGROUND AND RESULTS

The thermal and g-load analysis presented in this appendix was performed on a preliminary design version of the Spaceborne optical bed. The bed configuration analyzed is shown in Figure C-l. The actual bed was shown previously in Figure 3-3. The latter bed has more Invar area for heat transfer to the surrounding environment. Thus, the temperature rise of the actual bed and the resulting distortions are $20 \%$ less than that of the bed analyzed. The actual optical bed is also more rigid structurally than that analyzed and distortions due to gravity are estimated to be approximately $10 \%$ less than those calculated for the preliminary bed design.

One basic result of the optical bed analysis was that the optical bed should be mounted vertically. This was implemented in the actual design via a kinematic mounting beneath the optical bed as shown previously in Figure 3-32. The actual mounting of the optical bed is more stable than the cases considered in the following analysis with respect to bed distortion by gravity. The kinematic mounting assumed in the analysis is fully equivalent to the actual kinematic mounting with respect to thermal distortion since, by definition, a kinematic mounting permits free thermal expansion in all three dimensions.

A second basic result of the analysis was the optical bed expansion in the direction parallel to the optical path. With reference to Figure $C-2$, this expansion corresponds to the net distance increase between nodes 34 and 44 or nodes 134 and 144. The analytical model assumes heat input into the bed from the noryl blocks on which the oscillator and amplifier pump cavities are mounted. As a worst case, the temperature of the noryl blocks were assumed to be $130^{\circ} \mathrm{F}$ due to heat from the pump cavities. Under this condition, with the bed initially at $70^{\circ} \mathrm{F}$, the average of the expansion between nodes 34 and 44 and nodes 134 and 144 was $5.88 \times 10^{-5}$ inches. The average rise in bed temperature was $5.5^{\circ} \mathrm{F}$. Thus the optical bed expanded $1.07 \times 10^{-5}$ inches per Farenheit degree increase in temperature. For the bed length of 10 inches along the laser optical paths, this expansion corresponds to an actual thermal coefficient of expansion of $1.07 \times 10^{-6} \mathrm{in} /$ in $/{ }^{\circ} \mathrm{F}$. Thus, the analysis, shows that the optical bed expands with temperature very nearly the same as the INVAR material with a coefficient of $0.9 \times 10^{-6}$ in/in/ ${ }^{\circ} \mathrm{F}$. This latter conclusion was the objective of the optical bed analysis. For vertical mounting,


Figure $C-1$. Optical Bed Configuration


Figure C-2. Bed Model Node Description
 those due to thermal distortion.
2. INTRODUCTION

A thermal structural math model of the Spaceborne Laser Rangefinder optical bed was constructed and four load cases were run with the ANSYS computer program (Engineering Analysis System). The cases considered were: 1) determine temperature distribution; 2) determine distortion due to temperature effects; 3) determine distortion due to weight-when horizontally mounted; 4) determine distortions due to weight when vertically mounted. The results obtained for each of these load cases are presented and discussed in this report.

## 3. MODEL DESCRIPTION

The math model is an assemblage of three dimensional isoparametric solid elements. Most of the elements are cubical but the elements representing the corner brackets have a triangular shape. Each element is identified by nodes at the corners of the geometric solid. It is at these corners (or nodes) that the temperatures and distortions are calculated. Figure C-I shows a sketch of the physical configuration and Figure $\mathrm{C}-2$ shows the model as defined by the node points. The nodes numbered from 1 to 77 are on the bottom of the 1.0 inch thick bed. Nodes 101 to 177 are on the top of the bed. These nodes are arranged such that node 1 is directly below node 101 etc. This system of numbering does not apply to the end plates nor to the Noryl plates. There are additional nodes in the printout which are not shown in Figure C-2. For example, directly behind node 78 is node 79. These additional nodes are of no interest to the reader but were necessary in formulating the problem. Note node 78 and 79 have essentially the same temperature and distortion. Table C-l is a list of the physical properties for Invar and Noryl used in the analysis. Node 43 is constrained such that there is no displacement in the $X, Y$ or $Z$ directions. Node 24 is constrained in the $X$ direction- and node 46 is constrained in the $Z$ direction. There are no constraints on rotation in any direction.

## 4. TEMPERATURE DISTRIBUTION

The temperature on the surface of the Noryl pads facing away from the Invar slab was assumed to be $130^{\circ} \mathrm{F}$. All exposed

## TABLE C-1. MATERIAL PROPERTIES

|  | INVAR | NORYL |
| :---: | :---: | :---: |
| Modulus of Elasticity (psi) | $20.5(10)^{+6}$ | $1.20(10)^{+6}$ |
| Expansion Coefficient (IN/IN/ ${ }^{\circ} \mathrm{F}$ ) | $.9(10)^{-6}$ | $1.2(10)^{-5}$ |
| Poisson's Ratio | . 27 | . 27 |
| Density (\#/IN ${ }^{3}$ ) | . 382 | . 0602 |
| Thermal Conductivity ( $\mathrm{BTU} / \mathrm{HR}-\mathrm{IN}-{ }^{\circ} \mathrm{F}$ ) | . 50417 | . 00769 |

surfaces both on the Noryl and Invar are assumed to exchange heat with a $68^{\circ} \mathrm{F}$ sink. The effective coefficient for heat transfer was assumed to be $1.0 \mathrm{BTU} / \mathrm{HR}-\mathrm{FT}{ }^{\circ}{ }^{\circ} \mathrm{F}$. This coefficient is representative of combined radiation and free convection for the temperature range considered. The resulting temperatures at each node are presented in Table C-2. Figure C-3 shows some of the temperature results in pictorial form. The maximum temperature is $78.89^{\circ} \mathrm{F}$ at the interface between the Noryl pad and the Invar (node 151) on the top face. The lowest temperature is 73.11 at node 80 which is located at the lower corner of the end bracket. The average temperature is about $75.5^{\circ} \mathrm{F}$ or $7.5^{\circ} \mathrm{F}$ above the $68^{\circ} \mathrm{F}$ sink.

The temperature distribution obtained from this run was used as input to determine the thermal distortions.

## 5. THERMAL DISTORTION

For the thermal distortion run the assumption is made that there is no distortion at $70^{\circ} \mathrm{F}$. The distortion at each node is then calculated for the change in temperature from $70^{\circ} \mathrm{F}$ to the temperatures calculated previously. No stresses were calculated because they are very low and the computer cost for calculating them is not justified. Table C-3 is the computer printout of the distortions. Figures $C-4$ and $C-5$ are plots of the thermal distortion greatly exaggerated. The maximum distortion in the Invar slab is 0.5809 (10) ${ }^{-4}$ at node 67.

The Noryl has a maximum distortion of 0.1063 (10) ${ }^{-3}$ at node 185. The thermal distortions are much greater than those from gravity (at one g). It is worthwhile to remember that this is a linear problem and that the results may be extrapolated. If the temperature difference between the source and the sink is increased each temperature will increase proportionally as will each distortion. Maximum thermal distortions are of the order of $5 \times 10^{-5}$ inches in the Invar and $10^{-3}$ inches in the Noryl. Since the average temperature is $5.5^{\circ} \mathrm{F}$ above the no distortion temperature of $70^{\circ} \mathrm{F}$ the thermal distortion is approximately $1 . \mathrm{x} 10^{-5} \mathrm{in} /{ }^{\circ} \mathrm{F}$.
6. GRAVITY EFFECTS (HORIZONTAL)

The horizontal configuration is defined as the $Z$ direction being down or as shown in Figures $C-1$ and $C-2$. A one "g" acceleration was applied in the $Z$ direction and the resulting distortions were calculated. The temperature is assumed to be $70^{\circ} \mathrm{F}$ for this run (no thermal distortions). Table $\mathrm{C}-3$ is the computer printout of
|Table C-2: TEMPERATURE DISTRIBUTION|



Figure C-3. Optical Bed Temperature Distribution



Figure C-4. End Plate Thermal Distortion


Figure C-5. Bed Plate Thermal Distortions
the resulting distortions. Figure $C-6$ is a highly exaggerated view of the distortion of the slab. The maximum Invar distortion is $0.1106(10)^{-4}$ inches at node 72. The maximum Noryl distortion is $0.104(10)-4$ inches at node 187.
7. GRAVITY EFFECTS (VERTICAL)

The vertical configuration is defined as the $-X$ direction down. A one " $g$ " acceleration in the X direction was applied and the resulting distortions were calculated. Thermal distortions were not considered. Table C-4 is the computer printout of the distortions. Figure $C-7$ is the exaggerated distortion plot of the end plate. The maximum distortion of the Invar slab is $0.186(i 0)^{-5}$ inches at node 72. The Noryl is 0.539 (10)-5 inches at node 192. The distortions in general an order of magnitude smaller than those obtained in the horizontal orientation.


Figure C-6. Bed Plate Gravity Distortion-Horizontal

# Table C－4． 

ACCELERATION IN $Z$

## .72 .227 .92 .25 .34 .46 .48 .46 .30 .17 .3 .90 .21 .31 .4 .4 .44 .31 0.1

$.5335785-07$ .137723 －06 $.223137 \mathrm{E}-06$ －2905115－06 $.314732 E-06$ $.339162 E-06$ ． $3596405-06$ $.309480 E-06$
$.583887 E-08$ $.517329 \%-03$ $.579570=-08$ $.8 \wedge 38995-08$
$.101928=-07$ ．827780玉゙ーC $.1039018-07$ $144529 E-07$
$.113153 \mathrm{E}-07$ 522562E－08 0. $.156762 \mathrm{t}-08$
 $.908185 E-03$ - － $3755585-07$ $-118313 \bar{z}-06$ － $1489192-05$ －$-258295 F-06$ － 301606 E－06 $-3246975-06$ -345955 E－06 $-.303784 E-66$
$-.754822 E-68$ －． $733034 E-07$ $-1957055-06$ $-.314734 E-06$
$-.3890855-06$ -+32637 F－06 －． $430896 E-00$ $-+316648 \mathrm{E}-06$
$-.1737115-06$ $-.215554 E-08$ $-.7437118-07$ － $2298995=06$ －－ 3 － 9526 트－06 －． 438560 ت－06 －． $476361 E=06$ $-.3054858-06$
$-.1704475-06$ $-244014 \mathrm{E}-07$ -.30027 CE－07 －207672E－07 ． .930216 E－08 $.8445185-08$ $-.4159345-09$ $.8774015-09$ $.4141365-67$ $.493824 E-07$ $-.2709448-07$ －． 360914 EENT

 $.2304 \pi 7 \mathrm{~F}-06$ .237096 － － 1302375 －- ถ $-1+7425 K-06$ ． $693.31 \mathrm{nt}-06$



UY

$$
0
$$

$$
-614595 E-07
$$

$$
-659161 E-07
$$

$$
\text { - } 3381985-05
$$

$$
\begin{array}{r}
.310190=-02 \\
-.334205 E-05 \\
-7077415-06
\end{array}
$$

$$
\begin{aligned}
& -.2977615-05 \\
& -.2421405-05
\end{aligned}
$$

$$
\begin{aligned}
& +172100 E-05 \\
& -.105
\end{aligned}
$$

$$
\begin{array}{r}
\text { - } 9950 n 4 E-06 \\
-A \cap 2453=
\end{array}
$$

$$
\begin{aligned}
& -203453=06 \\
& =281057=-07
\end{aligned}
$$

$$
-3819575-07
$$

$$
\begin{array}{r}
.77163 E-07 \\
-335974 E-05
\end{array}
$$

$$
-335606 E-05
$$

$$
\begin{aligned}
& -365172 E-05 \\
& -245168 E-05
\end{aligned}
$$

$$
\begin{aligned}
& =.245168 E-05 \\
& -17300 a E-05
\end{aligned}
$$

$$
\begin{array}{r}
+101190 E-05 \\
-10150
\end{array}
$$

$$
\begin{array}{r}
-+08599 \mathrm{E}-03 \\
-186024 \mathrm{E}-07
\end{array}
$$

$$
\begin{array}{r}
156024 E-07 \\
-110760 \mathrm{E}-06
\end{array}
$$

$$
-110760 E-06
$$

$$
\begin{aligned}
& -335639 E-05 \\
& -3773705-05
\end{aligned}
$$

$$
\begin{aligned}
& =.337239 E-05 \\
& -303985 E-05
\end{aligned}
$$

$$
-243945 E-05
$$

$$
-172404 E-05
$$

$$
\begin{array}{r}
\text { - } 100833 E-05 \\
-17 \rightarrow a n c z-08
\end{array}
$$

$$
\begin{array}{r}
-3229075-08 \\
.120315 E-06
\end{array}
$$

$$
.7229675-05
$$

$$
\begin{array}{r}
724174 E-05 \\
\hline
\end{array}
$$

$$
\begin{aligned}
& =10453 n F-04 \\
& -104664 E-04
\end{aligned}
$$

$$
730354 E-05
$$

$$
.7301525-05
$$

$$
=105603 E-04
$$

$$
\begin{array}{r}
-1055908-04 \\
.723439 \mathrm{~F}-05
\end{array}
$$

$$
\begin{array}{r}
723439 \mathrm{~F}-05 \\
.724 \times 71 \mathrm{~F}-05
\end{array}
$$

$$
\begin{array}{r}
.724 \times 71 E-05 \\
-.104 \% 2 E-n 4
\end{array}
$$

$$
\begin{aligned}
& -104911 E-04 \\
& -.10
\end{aligned}
$$

$$
\begin{array}{r}
-1041575=04 \\
-7224
\end{array}
$$

.7.353NE-05

$$
.72421 \mathrm{Nt}-05
$$

$$
=1057148-04
$$

$$
\begin{aligned}
& -105214 F-04 \\
& 770 \text { ank }
\end{aligned}
$$

$$
.739140 \mathrm{E}-05
$$

$$
.73 H 7 \mathrm{aNF}-04
$$

$$
\begin{aligned}
& =\ln 3211 E-04 \\
& 10301-04
\end{aligned}
$$

$$
-1037105-64
$$

$.7124165=65$

$$
\begin{aligned}
& -.334425 E-05 \\
& \text { - } 104143 \mathrm{E}-04 \\
& \begin{array}{l}
-3341248-075 \\
-.29749 \mathrm{E}-05
\end{array} \\
& -.7379 \times 3 \mathrm{~F}=05 \\
& \text {-. } 1605 \mathrm{HAF}-05 \\
& \text { - . } 95 \mathrm{n} 475 \mathrm{~F}-\mathrm{OH} \\
& -.371407 E-06 \\
& \begin{array}{r}
.370339 \mathrm{E}-07 \\
.148097 \mathrm{E}
\end{array} \\
& -.3348795-05 \\
& \rightarrow 33 \text { - } 3577 \mathrm{E}-05 \\
& \begin{array}{l}
-.300955 E-05 \\
-.239222 \mathrm{~F}-05
\end{array} \\
& -.167150 E-05 \\
& -938609 E-01 \\
& \begin{array}{r}
-.359533 E-06 \\
.543945 \mathrm{E}-07
\end{array} \\
& \text {. } 137141 \mathrm{E}=0 \mathrm{O} \\
& -3370285-05 \\
& \text { - } .334107 \mathrm{E}-05 \\
& -295911 \text { - }-05 \\
& -.236331 \text { ह-05 } \\
& \begin{array}{l}
-.165831 E=05 \\
-.956269 E-06
\end{array} \\
& -.362700 \mathrm{E}-\mathrm{CR} \\
& -.5729415-08 \\
& .984935 E-07 \\
& -334620 E-05 \\
& \begin{array}{r}
-.334625 E-05 \\
-.33354 E-05
\end{array} \\
& \begin{array}{l}
-333545-05 \\
-.3211625-05
\end{array} \\
& -248056=-105 \\
& -234219 \text { E-05 } \\
& \begin{array}{r}
-.166041 E-05 \\
-.949351 E-06
\end{array} \\
& -.3424275-\mathrm{C6} \\
& .5361635-07
\end{aligned}
$$

UZ

## $-307784 \mathrm{C}=05$ $.104320 \mathrm{~F}=05$ $.41017 \mathrm{RF}-05$ $-.7554 A M F=05$ $=.902619 \mathrm{E}-05$ $-.106730-04$ $-10673 \times 5-04$ $-103074=-04$ －． 83 AKAAE－05 $-.277994-05$ $.192047 \mathrm{E}-03$ － $214625 E-65$ －．743407E－05 －$\quad 979343=-05$ － $16005 \mathrm{c}=04$ $-.8143135-05$ $-.519147 E-05$ 0.1

 －． $403567 E-05$ －． $717995 \mathrm{E}-05$ $-.936084 E-05$$-.101902 \mathrm{E}=04$ $-.101902 \mathrm{E}-04$
$-.95745 \mathrm{E}-05$ $-761214 E-0 b$ $-+4 \times K 29 E-05$
$-147205 E-05$ ． 21291 KE－05 $.301139 E-05$
$-.690360 E-16$ $-.394206 E-05$
$-102327-05$ $=+192322 E-05$
$-.396726 E-05$ $-.973666 E-05$

$$
\begin{array}{r}
-905371 F-05 \\
-7 م 2647 \mathrm{E}-05
\end{array}
$$

$$
\begin{aligned}
& =.154041=-05 \\
& 0.399536 \overline{0}-05
\end{aligned}
$$ 0.

$.238308 E-05$
$.159622 E-05$ 0.
$-.405169 E-05$ $-.721274 E-05$ $-.943028 E-05$
$-.1033198-04$ $-10331 \mathrm{YE-04}$
$-.973604 \mathrm{E}-05$ $-.7814295-05$
$-4922142-05$ $-.171336 \mathrm{E}-05$ $.213819 E-05$ －． $409149 E-05$
$-.748352=-05$
$-.986169 E-05$ $-108425 E-04$
$-.1031905-04$ $-.3431255-05$
-.5540505
$-.5546565-05$
$.574129 E-06$
$.301565 E-05$
－ $412206 E-05$
$-760968 E-05$
$-.100438 E-04$ －． 110027 E－04
－ $10554 \mathrm{CE}-04$
-.8682 9aE－05
$-133889 E-05$
$.304257 E-05$ $.2110595-05$ －30002 4E－05 $-209885 E-05$
$.300770 E-05$ － $206418=-05$ $.2997021:-05$ $.207767 E-05$ $.304743 E-05$ － $2107 \mathrm{R} 3 \mathrm{E}-05$ $.20916 F F-05$ － 1 MbsA4－05 $.104117 F-05$ .1015 N JE－05 － $2707875=05$ $.11107 \mathrm{CE}-\mathrm{ns}$ － $2210727=04$ －llagntrons $\rightarrow$ フッチロ3： $.1460738-05$

NODE
100
$1 \infty$
108
＝．
$.59057 \mathrm{BF}-1 \mathrm{AB}$

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 －305395E－n5
 $-.755^{745 E-1) 5}$ $-.002148 \mathrm{BF}-05$ － 10 10～734f－T4 －． 103025 E － 44 －． $33 \times 34$ วF－75 $-.5279345-05$ $.1800735-05$ －270261E－05 －406700E－05 －．74s131E－05 $-.9751775-05$ －．10667つE゙－04 － .10 のgnnemy $-813938 E-05$ －． $515033 \mathrm{E}-55$
160743F－ns
 $-.396673 E-05$ $-.7193732-05$ $-.9357125-05$ －． $101915 \mathrm{E}-04$ $-.9574085-05$ $-.761595 E-05$ -.4 ． 752 （E -05 $-.132447 \mathrm{E}-05$ $-213663 E-05$ ．298567E－05 -.539215 E－06 $-394849 \mathrm{ET}-75$ $-.69248: 5-05$ $-.8965555-05$ －．973を14を゙ーロ5 －$+905029 \mathrm{~F}-05$ － －7C＝799E－05 $-369987 E-05$ $-4986435-06$ $.241211 E-05$ $.1577727-05$
 －．3979698－05 $-.722122=-05$ －． $9428.33 E-05$ -103336 － 04 $-973401 E-05$ $-.762147 E-05$ $-.493455 E-05$ $-1624042=05$ ． $219592 \mathrm{E}-65$
 －．74 ゴきたこー05 -.985737 －05 $-.105424 E$ ت0 04 － 103221 E－04 $-.842935 E-05$
$-.555563 E-05$ ． 574658 －06 $.304724 E-05$ -4119 － $05-05$ $-76109 \mathrm{EE}-65$ $-100415 E-04$
$-110529=-04$ －． 105 ． 105 E～04 －． 86 ais $5=05$ $-.5673435-05$ $.131847 E-05$ － $6771.16 \mathrm{~F}-05$ $-.391103 E-05$
$-.68425 \mathrm{~F}-05$ $-.877-5$ ？ 5 － 25 －． $983.30035-05$ － 89 ภnnor－07 $-.307344505$ $=.71343 \mathrm{~F}=05$
$-.0232745-n 5$ － 1 － 1 anpripmo －．©nloomi．－n5 －ann cunc－05 －n94m3F－n5
－3n9e7cF－05 －－ 249015 CmA
 $=.04 J 1+97:-04$




Figure C-7. End Plate Gravity Distortion-Vertical

## APPENDIX D

ELECTRONIC DESIGN REVISIONS

## Final System Modification

Various problems, arising from the radiation control loop concept adopted, necessitated re-evaluation of the overall system.

Specifically, the required event sequence necessary for proper system performance is as follows:

- The flashlamp imparts energy to the laser rod.
- Lase.action occurs, controlled by the active modelocker modulator, and is allowed to circulate between the inter-
- ferometer mirrors for a sufficient time interval to allow pulse narrowing. The lase action must be of extreme low level for this portion of the action.
- High "Q" is established•within the interferometer by the - "Q" switch, and the resonator energy builds rapidly.
- Pulse transmission switching occurs whenever the resonator energy is near the peak value, to provide a single pulse output.

Slight system modification is effected to allow deletion of the radiation control loop as originally conceived. Specifically, the "Q" switch bias voltage is adjusted to allow sufficient optical resonator gain to produce lase action at approximately $2 \%$ above lase threshold. The lase action is of the normal mode type and is controlled by the active modelocker modulator. Thus, this normal mode lase action is composed of a single short duration circulating photon packet of little energy, which is the "seed-pulse" when the high "Q" state is established.

The high "Q" switching action is initiated by the use of an energy detector, or threshold circuit. Whenever the low level "seedpulse" is of a specific energy content, the threshold circuit generates an output command to activate the "Q" switch driver. This signal is synchronized to the photon-packet position within the resonator in order to prevent pulse slicing.

Various energy sequence illustrations: are depicted. in Figure 3-5. It is to be noted that the revised süsteminconcept energy sequence is identical, to the oxtignt concept, in at respects.

In view of the fact that the remainder of the system is.". configured as originally conceived, no additional description is considered necessary.

The temporal jitter, for a shot to shot basis, is slightly degraded in the revised concept, since the normal mode gain is somewhat dependant upon optical noise. High level noise results in a reduced time for the "seed-pulse" energy to reach threshold. Conversely, low level noise requires more time for the energy to achieve threshold level. This build time variation results in jitter, from "shot-to-shot", which is in the microsecond region.

## 2. Revised Q-Switch Interface

Modification of the radiation control loop circuitry allows simplification of the Quswitch Interface circuitry.

As originally conceived, the radiation control voltage was introduced to the Pockels cell at the PTM drive side. Connection was via connector J6, as depicted in Figure 4-6.

Introduction of this control function, required diode CR3 in series with the PTM driver voltage input. Additionally, resistors R3 \& R4 were required to provide proper bias currents. The series diode and the stray-capacitance of the additional components degrade the fall time of the PTM driver.

The circuitry was revised to the simpler configuration as depicted in Figure D-1.

Indicated cell voltage transition was noted to be $\leq 6$ nanoseconds.


Figure D-1. Q-switch Interface Schematic (Revised)

## R.F. Power Amplifier (Booster)

The power output of the ENI wide-band amplifier was found to be inadequate to achieve the required modulation depth of the picosecond laser resonator energy. If picosecond pulses were to be reliably generated, more drive voltage was required to the ": active modelocker*modulator cell.
'The most expedient move to obtain more drive voltage is the addition of a power amplifier to enhance the output power level. Careful consideration of the available amplifier configurations, i.e. wide-band versus narrow-band and the amplifier class, "A, $B, C$, or D ", resulted in the selection of a narrow band class "C" circuit.

This choice resulted because:

- The resonator round trip frequency is fixed, and varies little with operating ambient temperature; thus, widebanding is of little advantage. Additionally, by nature, the helical-resonator is a narrow-band mechanism.
- The very nature of the helical-resonator provides an excellent narrow band filtering action; thus, the amplifier distortion and harmonic content are of little consequence.
- Wide-band amplifiers are inherently hard to stabilize from self oscillations.
- Narrow band, class "C" amplifiers exhibit good operating power gain and power conversion efficiency.

The booster power amplifier is depicted schematically in Figure D-2. This circuit is designed to operate in the burst mode. It utilizes a single power source of 28 V ac nominal; it is self biased as a class "C" amplifier; it posesses input/output impedances of approximately 50 ohms; and it is "tuned" in a straight-forward fashion.

Transformer $T 1$ is the input impedance matching transforming network. A ferrite bead transformer is utilized, since the power level is modest. Additionally, this network type requires no input tuning for obtaining match. The input impedance is $\simeq 50$ ohms, while the output to the transistor base is $\simeq 3.5$ ohms.


Figure D-2. R.F. (Booster) Power Amplifier

Transistor Q1 is the active gain device. A type 2N3950 is selected to afford the required power gain, and because the device is designed for operation at the 60 mHz frequency region. It is to. be noted that selection of devices designed to operate at a much increased frequency generally results in severe parasitic products, since the device gain is optimized for the increased frequency region, additionally, the dc stability becomes annoying to achieve, since the low frequency gain for the extended•frequency devices also is enhanced.

Diode, CRl prevents damage in event of reverse voltage polority application.

Inductor RFCl provides a dc voltage path to the collector of Ql, and serves to decouple the R.F. energy from the power source. Capacitor, C5, aids in isolation of the RF energy from the power source.

Capacitors, CI-4, and Inductor II comprise the matching network for the collector of Q1. In actuality, this network is of the " $\pi$ " section type, rather than the apparent "L" section illustrated. The collector output capacity forms the input capacitor for the network. Since this capacity is not a separate component, it is not illustrated.

Capacitors Cl-4 are chosen to afford an output match to 50 ohms impedance i.e. the input impedance of the helical-resonator).

Tuning of the output network is accomplished in the following manner:
a. Adjust $C 3$ and $C 4$ to minimum capacity.
b. Apply 28 V dc power.
c. Apply an input signal of the desired frequency ( $\simeq 60 \mathrm{mHz}$ ), and increase level until a perceptable increase in collector current is observed ( $\simeq 100 \mathrm{~m} \mathrm{~A} \mathrm{dc}$ ) in Ql.
d. "Tune" C1 and C2 for a "dip" or minimum collector current.
e. With the load connected, "tune" C3 and C4 for a broadening of the response in d. above, i.e. broad tuning null, and an increase in collector current.
f. Monitor the power to the load, and continue the loading, step e, for maximum output. As capacitors C3 and C4 are increased, the power output will rise to a point, then the power output will decrease as the capacitors are further increased. Proper tuning is the setting for maximum output. It is to be noted that interaction between step e. and step d. occurs. Each time step e. is accomplished, it is necessary to repeat step d. Also note that the collector current for the tuning operation is an approximate value.
9. Observe the power output, and increase the input drive level to a value which yields the desired output power. The input level will be $\leq 20$ watts peak-pulsed while the output will be $\simeq 80$ watts peak-pulsed.

This amplifier is designed for burst mode usage only. Continuous wave (cw) operation may be utilized provided the peak output power is less than 30 watts, and provided that the load match is predominantly resistive.

APPENDIX E
AMPLIFIER SUBSYSTEM
OPTICAL DRAWINGS


## NOTES:

UNLESS OTHERWISE SHECIFIED WANUFACTURE
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; DREALLEL TOVAL RECHIVUTE.
2. POLAREER WUST WTHETANO FIELDS OF UPTD $10 \mathrm{GW} / \mathrm{Cm}$, DEAN AT PULSE RATES NO 70 LOgOS. NODNAL AULSEWIDTH 1OODS. COATING MUST HEEC DUEABMITY TEST PEE MILC-6T5 AND MLS-心フOOB.

3 SURFALE QUALITY:(SCRATCH-DIG) $10-5$ ON POLNHED SUEFACES.


FOLDOUT FRAME 2

FOLDOIIT FRAME $/$

A


## NOTES：

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2 SURFACES A F $B$ SHOULD BE NOENAL
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A SURFACE ${ }^{\circ} D$ B8＇ $30^{\circ}$ IIMIN TO SUCFACE $C$ ：
4．SURFACE DUALITY：（SCBATCH－DN）10－5 ON SURFACES $A, B, G C$ ．
W POUSH GEINO ON $C, F, F F$ ．
6．ALL AOLLSHED SUEFALES SHALL BE FLAT TO WITHIN $1 / 4$ WIVILLENGTH OF SODICSILIGHT．
7．TRANUAITTING FACE（SCIRESGE DI AHCNT EE ANTI－REFLECTION COATED MITA MULTI－LAVEQ $V$－COAT SO THAT NORNIK QCFLECTHIV Q
$\% 067 \times 15 \leq 0.25 \%$.
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9．．．AAP COATING HAOST WITHSTAIID FIELDS OPTO TO GHICND AT IO PRS TOR WOMINAL PULSE DIOTH OF 10 PSEC
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2. SURFACES "A"AND "E" TO BE ANTI REFLECRON COMED FOR
mangaum rergovit with multinyeri v-coar as founows:

c. AL. COATNES TO WITHSTAND $10 \mathrm{GW} / \mathrm{cm}^{2} \mathrm{IN}$

A 100 picosecind pulse.

d. $0.25 \%$ NORMAL REFLECTANLE OR LESS AT
d. 1.054 micRon.
e. ALL COATINGS to wItristand $10 \mathrm{Gw} / \mathrm{cm}^{2} \mathrm{GT}$ CIASH MICRONS IN A 100 PICOSECOND DULSE

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2. 5 . 70 EACES A FB SHOULD BE NORMAL
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4 SURFACE QUAYTY: (SCEATCH DIGI O-S ON
SUEFACES A, $\sigma^{*}$
5. ROUGA GRIN ON G, G,F, NNO . WSO NELKFF
6. ALL PDLASHED SUELACES SHALL BE FLAT TO

7 TRANSAITTING FALE CSURFACE D) HUST BE
ANTT REFLCCTION COATED WITH HULTI-LAVEE
V-COATLED SO THAT NORABA EEFECTMITY

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NOTES:
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UNEES5 OTHERWNE SNECHFIED MANUFACTUEE
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    FEQ KS जPEC A/OO7727
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B. SURFALE O SHALL BE ALRMANENTLY WARKED FOE $\triangle D E N T I F I C A T I D N$ PUBPDSES.
9. AR COATING MIUST WITHSTAND FIELDS UF TO DO GWHGO AT 10 PPS FOR HOHNAAL NUSE HIDTH
 MIL-M-13503.

B

FOLDO: FRAME 1


[^0]:    Sponsor: NASA GODDARD SPACE FLIGHT CENTER, Greenbelt, MD 20771
    Contract Number: NAS5-22916
    Technical Officer: John J. Degnan

