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THE CONSTRUCTION OF A PHOTODISSOCIATION ATOMIC IODINE LASER

THE UNIVERSITY OF ARIZONA

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THE CONSTRUCTION OF A
PHOTODISSOCIATION ATOMIC IODINE LASER

by

Michael Scott Soukup

A Thesis Submitted to the Faculty of the
COMMITTEE ON OPTICAL SCIENCES (GRADUATE)
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1983
STATEMENT BY AUTHOR

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Professor of Optical Sciences

Date: 1.15.83
ACKNOWLEDGMENTS

The author would like to thank Professor Fred A. Hopf for his very helpful guidance and advice on all aspects of this thesis. Special thanks go to fellow graduate student Till W. Liepmann for his technical assistance and support, without which this thesis could not have been completed, and to Norma Emptage for typing the thesis and ensuring that all University requirements were met.
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ABSTRACT

Photodissociation iodine lasers are currently of great interest because of their use in applications requiring high peak power pulses. This thesis describes in detail the iodine laser medium, specifically the chemical kinetics leading to the 1.315 micron lasing transition and the transition spectroscopy. Chemical quenching mechanisms and the influence of magnetic fields on the transition's hyperfine structure are examined. Next, the conversion of a flashlamp-pumped dye laser to a photolytic iodine laser is detailed, including descriptions of the equipment used, threshold energy estimates, flashlamp design, and power supply circuitry design. Lasing was achieved, but flashlamp firing problems developed. Possible sources of this problem are discussed. Finally, power supply and gas handling system improvements are suggested, and the potentials for Q-switching, mode-locking, and eliminating the flashlamp's magnetic field effects on the lasing transition are noted.
CHAPTER 1

INTRODUCTION

The photodissociation atomic iodine laser was first demonstrated by Kasper and Pimentel (1964, pp. 231-233) in 1964. They found a laser wavelength of 1.3 μm, corresponding with the magnetic dipole transition $^2P_{1/2} \rightarrow ^2P_{3/2}$ of atomic iodine at 1.315 μm to within experimental error, and they noted further the medium's extremely high stimulated emission gain (Kasper and Pimentel 1964, pp. 232-233).

Due to its capability to generate high peak powers, the iodine laser has since been the subject of much investigation as a potential thermonuclear fusion driver, along with Nd:glass and CO2 systems (Gross 1976, p. 311). Iodine lasers possess advantages of both gas lasers and solid-state lasers to include a very low nonlinear index of refraction, high damage threshold, high repetition rate of operation, relatively short wavelength, and the ability to be frequency upconverted to visible and near UV wavelengths (Gross 1976, pp. 311-316; Krupke and George 1976, p. 24; Palmer, Padrick, and Jones 1976, pp. 32-33). Several high power iodine lasers have already been built for fusion research: The Asterix III system at the Max Planck Institute for Quantum Optics in Garching, Germany; a 50J-5 nsec device at the Lebedev Physics Institute in the USSR; and a 20J-200 psec system at Sandia Laboratories in New Mexico (Witte et al. 1981, p. 1809; Basov et al. 1974, p. 524; Palmer, Padrick, and Jones 1976, pp. 33-35).
In addition to the photodissociation iodine laser, which operates in a pulsed mode, there is also a purely chemically driven iodine laser operating at the same wavelength, but producing a continuous wave (CW) output as well (Hays and Fisk 1981, pp. 1823-1827). It, too, is now a candidate for high power applications, and a prototype capable of producing at least 10 kW has been built at the Air Force Weapons Laboratory at Kirtland AFB, New Mexico.

Due to the high power applications of iodine lasers, it has become important to develop nonlinear optical materials and techniques at 1.315 µm. With this end in mind, the nonlinear optics (NLO) group at the Optical Sciences Center at the University of Arizona will soon begin work with phase conjugation and frequency doubling materials at the iodine laser wavelength. Preliminary testing will be done using a Q-switched Nd:YAG laser operating at 1.318 µm. Final testing needs to be accomplished at 1.315 µm, and herein lies the purpose in our building a small photodissociation iodine laser. Witte et al (1981, p. 1815) have done much work already in producing second, third, and fourth harmonic generations (SHG, THG, FHG, respectively) of the iodine laser's fundamental frequency using KDP and KD*P crystals. Because these crystals are so commonly used for frequency doubling, their results are summarized in Table 1 for future reference.

Before describing the construction of our iodine laser, it will first be necessary to discuss the iodine laser medium in some detail.
Table 1. Phase-Matching Angles and Energy Conversion Efficiencies for Various Harmonics of Iodine Laser Radiation at 1.315 \(\mu m\).

<table>
<thead>
<tr>
<th>Wavelength Generated</th>
<th>SHG 657.6 nm</th>
<th>THG 438.4 nm</th>
<th>FHG 328.8 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>KD*P</td>
<td>KDP</td>
<td>KD*P</td>
</tr>
<tr>
<td>Length of Crystal/mm</td>
<td>19</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Type of Phase-Matching</td>
<td>II</td>
<td>II</td>
<td>I</td>
</tr>
<tr>
<td>Phase-Matching Angle</td>
<td>51.3°</td>
<td>61.4°</td>
<td>44.3°</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>30%(^a)</td>
<td>16%(^a)</td>
<td>12%(^a)</td>
</tr>
<tr>
<td></td>
<td>70%(^d)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) At 1 GW/cm\(^2\)

\(^b\) At 1.5 GW/cm\(^2\); not corrected for coating transmission

\(^c\) At 1.5 GW/cm\(^2\); corrected for coating transmission

\(^d\) At 3 GW/cm\(^2\)

(From Witte et al. 1981, p. 1815.)
CHAPTER 2

THE IODINE LASER MEDIUM

Chemical Kinetics

The photodissociation iodine laser has been demonstrated using quite a number of compounds as the medium. The following is a listing of these substances (Davis et al. 1976, p. 339).

\[
\begin{align*}
\text{CH}_3\text{I} & \quad \text{C}_2\text{F}_5\text{I} & \quad \text{CF}_3(\text{C}_2\text{F}_5)\text{AsI} \\
\text{CF}_3\text{I} & \quad \text{i-C}_3\text{F}_7\text{I} & \quad \text{CF}_3(\text{C}_3\text{F}_7)\text{AsI} \\
\text{C}_2\text{H}_5\text{I} & \quad \text{n-C}_3\text{F}_7\text{I} & \quad (\text{C}_2\text{F}_5)_2\text{AsI} \\
i-\text{C}_3\text{H}_7\text{I} & \quad \text{CF}_3\text{CH}_2\text{I} & \quad (\text{C}_3\text{F}_7)_2\text{AsI} \\
n-\text{C}_3\text{H}_7\text{I} & \quad \text{CD}_3\text{I} & \quad \text{CF}_3(\text{C}_2\text{F}_5)\text{PI} \\
n-\text{C}_4\text{H}_9\text{I} & \quad (\text{CF}_3)\text{AsI} & \quad \text{CF}_3(\text{C}_3\text{F}_7)\text{PI} \\
i-\text{C}_4\text{H}_9\text{I} & \quad (\text{CF}_3)_2\text{PI} & \quad (\text{C}_2\text{F}_5)_2\text{PI} \\
(\text{CF}_3\text{F}_7)_2\text{PI} & \quad \text{CF}_3(\text{CH}_3)\text{PI} & \quad \text{CF}_3\text{PI}(\text{CN}) \\
\text{CF}_3(\text{CF}_2\text{Cl})(\text{CFH})\text{PI} & \quad \text{F}_3\text{PI} & \\
(\text{CF}_3)_2\text{SbI} & \quad \text{OPF}_2\text{I} & 
\end{align*}
\]

From the above list, one can see that nearly all these compounds are organic iodides, either alkyl or perfluoroalkyl iodides. Some of these are difficult to lase, while those containing phosphorous (P) or arsenic (As) are extremely poisonous and are therefore difficult to handle. The organic iodides all require photons in the ultraviolet (UV) to cause photolysis. Essentially, the compound absorbs a
UV photon, and then breaks apart into its original radical and either an excited iodine atom or a ground state iodine atom. The chemical reactions representing this are given by (Davis et al. 1976, p. 339)

\[
RI + hv \rightarrow R^* (P_{3/2})
\]

\[
RI + hv \rightarrow R + I^* (P_{1/2})
\]

where \( R \) represents the parent compound radical (CF\(_3\), C\(_2\)H\(_5\), etc.) and \( I^* \) represents the iodine in its excited state. The stimulated emission is represented by (Aldridge 1973, p. 180)

\[
I^* (P_{1/2}) + I^* (P_{3/2}) \rightarrow I (2p_{3/2}) + hv (\lambda = 1.315 \text{ um}).
\]

Just how many ground state iodine atoms are produced depends on what compound is photolyzed. Table 2 lists the fractional yields \( \rho^* \) obtainable from a variety of iodides. Here, \( \rho^* = I*/I^* + I \) in terms of the initial concentration of atoms produced immediately following photolysis. It can be seen that the perfluoroalkyl iodides are superior to the alkyl iodides in producing the greatest concentration of \( I^* \). CD\(_3\)I is also very good in this respect. For the best pumping efficiency, one would want to choose CD\(_3\)I, CF\(_3\)I, CH\(_3\)I, C\(_2\)F\(_5\)I, n-C\(_3\)F\(_7\)I, or i-C\(_3\)F\(_7\)I due to their high fractional yields of \( I^* \) produced.

Another factor to be considered in comparing different iodides is the photodissociative absorption band of each. It is important to know this because an experimenter must be able to efficiently as possible couple his pumping source to the medium's absorption band. The pumping sources are usually flashlamps, but can also be excimer lasers (Witte et al. 1981, p. 1814), electron beam pumped rare-gas
Table 2. Fractional Yields $p^*$ of Excited Iodine Atoms Following the Photolysis of Various Alkyl Iodides.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$p^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_3$I</td>
<td>0.92 ± 0.02</td>
</tr>
<tr>
<td>C$_2$H$_5$I</td>
<td>0.69 ± 0.05</td>
</tr>
<tr>
<td>n-C$_3$H$_7$I</td>
<td>0.67 ± 0.04</td>
</tr>
<tr>
<td>i-C$_3$H$_7$I</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>n-C$_4$H$_9$I</td>
<td>0.82 ± 0.04</td>
</tr>
<tr>
<td>s-C$_4$H$_9$I</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>i-C$_4$H$_9$I</td>
<td>0.69 ± 0.04</td>
</tr>
<tr>
<td>t-C$_4$H$_9$I</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>CD$_3$I</td>
<td>0.99</td>
</tr>
<tr>
<td>CF$_3$I</td>
<td>0.91 ± 0.03</td>
</tr>
<tr>
<td>C$_2$F$_5$I</td>
<td>&gt;0.98</td>
</tr>
<tr>
<td>n-C$_3$F$_7$I</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>i-C$_3$F$_7$I</td>
<td>0.90 ± 0.02</td>
</tr>
<tr>
<td>HI</td>
<td>0.10 ± 0.05</td>
</tr>
</tbody>
</table>

(From Davis et al., 1976, p. 339.)
halogens (Krupke and George 1976, p. 33). Absorption band parameters for the most useful iodide compounds are given in Table 3. The peak absorption coefficient, $a_{\text{PEAK}}$, are also given. Davis et al. (1976, p. 342) found that the absorption bands are approximately Gaussian. They further note that the coupling efficiency of the flashlamp to the absorption band is dependent on the medium's peak absorption coefficient and on the peak absorption wavelength, and that compounds which absorb at the longer wavelengths can be more efficiently pumped. Examining the table, one can see that $n$-C$_3$F$_7$I and $i$-C$_3$F$_7$I offer better pumping efficiency as their absorption bands extend to the longest wavelengths compared to the other iodides.

In the iodine laser the excited states are deactivated by collisional processes, as is the case in other gas lasers. Here, the primary deactivator is molecular iodine ($I_2$) (Gross 1976, p. 318). Belousova et al. (1974, pp. 254-257) stated that $I_2$ resulted only upon the start of pyrolysis and not before. However, Davis et al. (1976, p. 339) believe that $I_2$ is formed following photolysis and before pyrolysis, as well as with the onset of pyrolysis through two different reactions. The reaction following photolysis producing $I_2$ is

$$I + I + M \rightarrow I_2 + M.$$  

$M$ represents a third body necessary to stabilize the atoms in order for the reaction to occur. In a sealed system where the gas is not flowing $M$ is more and more likely to be the $I_2$ molecule itself as the buildup of $I_2$ continues. With the onset of pyrolysis, the reaction is (Belousova et al. 1974, p. 254)
Table 3. Parameters of Photodissociative Absorption Bands.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\lambda_{\text{PEAK}}$ (Å)</th>
<th>$\alpha_{\text{PEAK}}$ (cm$^{-1}$ torr$^{-1}$)</th>
<th>$\Delta\lambda$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD$_3$I</td>
<td>2555</td>
<td>3.7 x 10$^{-2}$</td>
<td>235</td>
</tr>
<tr>
<td>CF$_3$I</td>
<td>2665</td>
<td>1.9 x 10$^{-2}$</td>
<td>370</td>
</tr>
<tr>
<td>C$_2$F$_5$I</td>
<td>2665</td>
<td>2.3 x 10$^{-2}$</td>
<td>400</td>
</tr>
<tr>
<td>n-C$_3$F$_7$I</td>
<td>2705</td>
<td>2.5 x 10$^{-2}$</td>
<td>430</td>
</tr>
<tr>
<td>i-C$_3$F$_7$I</td>
<td>2735</td>
<td>2.2 x 10$^{-2}$</td>
<td>435</td>
</tr>
</tbody>
</table>

$\Delta\lambda$ is the full width of the absorption band between the wavelengths where $\alpha = \alpha_{\text{PEAK}}/2$. (From Davis et al., 1976, p. 342.)
RI + R + I
I + RI + R + I₂.

The quenching reaction is (Davis et al. 1976, p. 339)

I* + I₂ + I + I₂.

Another important quenching reaction that occurs is (Davis et al. 1976, p. 339)

I* + RI + I + RI.

Just how much this reaction affects the laser medium efficiency depends upon what R is.

As already mentioned, pyrolysis occurs in the medium. This means that not all the parent radicals and ground state iodine atoms are able to recombine back into the original iodide and be available for another pumping shot. Heat deposition into the medium from the flashlamp's UV output not used in photolysis eventually causes the thermal decomposition of the parent iodide molecules, causing the formation of more I₂ leading to more quenching of I*. For the same gas fill, the laser output power drops with each successive shot as pyrolysis increases its effect. This is illustrated in Figure 1 for a variety of iodides at constant pressures and pumping energy. Note that the greatest change in performance occurs after the first shot, with i-C₃F₇I showing the smallest change. Davis and his co-workers (1976, pp. 342-343) have stated that the larger the alkyl iodide molecule, the more stable it is against pyrolytic breakup. This is
Fig. 1. Laser output energy dependence of shot number at fixed pressures and pump energies.

(From Davis et al. 1976, p. 346.)
due to the molecule's greater number of degrees of freedom, and thus its greater heat capacity as compared to a smaller alkyl molecule. CF$_3$I, for example, is more subject to pyrolysis than i-C$_3$F$_7$I or n-C$_3$F$_7$I. Once the molecule is decomposed, it frequently can act as a quenching agent itself.

Pyrolysis can best be combatted by adding inert buffer gases to the laser medium. These buffer gases serve to increase the heat capacity of the mixture and to therefore reduce the decomposition of the parent molecules (Davis et al. 1976, p. 343; Gross 1976, p. 317). CO$_2$ is a good buffer gas.

Quenching processes and absorption coefficients help influence the pressure dependence of the laser energy output. Figure 2 shows this dependence for a number of alkyl iodides. Compounds with higher absorption coefficients generally exhibit peak energies at lower pressures than those with lower coefficients. This is due to the gases becoming optically thick as the pressure increases. Likewise, those iodides subject to high quenching rates also show optimum energies at lower pressures than do those subject to lower quenching rates (Davis et al. 1976, p. 342).

Spectroscopy of the Iodine Laser Transition

The photodissociation of the organic iodides produces excited iodine atoms in the $5^2P_{1/2}$ state. This is the lowest-lying electronic state of the halogen group. The laser transition occurs between this state than the $5^2P_{3/2}$ ground state. This transition involves a spin
Fig. 2. Pressure dependence of laser energy output for various alkyl iodides. (From Davis et al. 1976, p. 342.)
change and is therefore forbidden by selection rules. The upper level is thus a metastable state, and the transition wavelength of 1.315 \( \mu \text{m} \) is due to a magnetic dipole transition. The spontaneous lifetime of the transition, then, is fairly long. The transition's Einstein A factor has been experimentally determined numerous times. The most recent determination of A for the total spontaneous transition rate over all six hyperfine transitions (the hyperfine structure is discussed below) was made by Sandia Laboratories at Kitt Peak National Observatory (unpublished). A value of \( A_{\text{TOTAL}} = 7.8 \text{ sec} \) was found. For the hyperfine transition having the highest gain, the \( F = 3 + F = 4 \) transition, a value of \( A_{34} = 5.1 \text{ sec}^{-1} \) seems to be the most appropriate (Galanti, Thieme, and Witte, 1981, p. 1820).

The iodine atom nucleus has an atomic weight of 127 and the nuclear spin is \( I = \frac{5}{2} \). The nucleus has a magnetic moment associated with it, and this moment leads to a coupling between \( I \) and \( J \), the electron's total angular momentum. \( I \) and \( J \) therefore precess slowly about \( F \), the total angular momentum vector of both the electron and the nucleus. This gives rise to a small energy difference between states with different \( F \) numbers, and so hyperfine splitting in the states results. \( F \) can take values of

\[
F = J + I, J + I - 1, J + I - 2, \ldots, |J - I|.
\]

Thus, for the \( ^2P_{1/2} \) state, \( J = 1/2 \) and \( F = 3 \) and 2. For the \( ^2P_{3/2} \) state, \( J = 3/2 \) and \( F = 4, 3, 2, \) and 1. There are then a total of six hyperfine levels and six allowed hyperfine transitions.
Things become more complicated in an external magnetic field as each of the hyperfine levels is itself degenerate. In the field the nuclear spin of $5/2$ results in $2I + 1$ or six possible projections of the spin with respect to the field. In the $^2P_{1/2}$ state, for $F = 3$ the spin number $M_F$ takes on the values $-F$ through $+F$ or $-3, -2, -1, 0, 1, 2, 3$ for a total of seven degeneracies. For $F = 2, M_F = -2, -1, 0, 1, 2$ for a sum of five degeneracies. So, for the upper level, there are a total of twelve degeneracies. Proceeding similarly for the $^2P_{3/2}$ state, one finds a total of twenty-four degeneracies. The six hyperfine levels and their associated degeneracies are illustrated in Figure 3.

An external magnetic field, such as that produced by a flash-lamp, has a substantial effect on the laser's emission that is manifested in several ways. One way is a shift in frequency of the transition components. Davis et al. (1976, pp. 336-337) pumped an iodine laser using both a slow, low voltage (3 kV) flashlamp and a fast, high voltage (15 kV) flashlamp. Using the low voltage lamp, the peak current was 1124 A producing a transverse (to the lasing axis) magnetic field of 44 G two inches from the gas cell. The frequency shift of the $F = 3 \rightarrow F = 4$ (noted hereafter as 3-4) transition was found to be 103 MHz. This is small compared to the 1.8 GHz homogeneous linewidth of that transition at a medium pressure of 100 torr. So, no appreciable difference in the laser transitions is made using this lamp. However, using the fast, high voltage lamp did produce a significant shifting. The peak current here was about 15 kA, and a frequency shift of 1.4 GHz was found for the 3-4 transition.
Fig. 3. (top) Hyperfine structure of the iodine laser transition, where F are the quantum numbers and g the degeneracies (from Gross 1976, p. 323).

Fig. 4. (bottom) Relative intensities of the hyperfine transitions shown in Fig. 3 (from Gross 1976, p. 323).
Unfortunately, for the best pumping efficiency, we must use lamps at high voltages and large peak currents. This will be discussed in more detail later.

Another interesting effect caused by a flashlamp's magnetic field concerns the polarizations of the components of the transitions (Davis et al. 1976, p. 337). If the transition results in a $\Delta M_F$ of $\pm 1$, the radiation will be $\pi$-polarized. In a transverse field, the polarization will be parallel to the field. For a $\Delta M_F$ of 0, the radiation will be $\sigma$-polarized and will be perpendicular to a transverse field. If Brewster-angled windows are at each end of the photolysis tube (as they are on our laser), then, depending on their orientation, one of these polarizations will be transmitted and the other will not. This will lead to a less than maximum possible power output if the $\pi$-polarizations are not transmitted as there are more $\pi$ than $\sigma$ components. In our laser, the $\sigma$-components are preferentially transmitted.

The six hyperfine lines do not all have the same transition probabilities. Normally, in an oscillator, lasing occurs on the transition having the highest gain. In an iodine laser, the highest transition probabilities (gain) of the two hyperfine line groups are the 2-2 and the 3-4 transitions (Gross 1976, p. 322). The 3-4 transition has the overall highest gain and, at low pressures where there is no line overlap, it is usually the only one to lase, although occasionally the 2-2 transition will occur as well (Palmer, Padrick, and Jones 1976, p. 32). Figure 4 shows the relative intensities of
of the two hyperfine line groups. This is true, however, in zero magnetic field, but not necessarily so in an applied field.

With a nonzero field it is possible to alter the gain of a transition. In other words, by applying a magnetic field of some specific strength, one can suppress lasing on one transition while allowing other transitions to reach threshold and lase on that line. Experiments done by Hwang and Kasper (1972, pp. 511-514) showed that for a fixed pressure of CF$_3$I and C$_2$F$_5$I with no applied field, their laser emitted radiation from both the 3-4 and 2-2 transitions. The 2-2 line was weak and barely above threshold, while the 3-4 line was prominent. However, with a transverse field of 500 G, the 3-4 line was entirely absent, and all emission was from the 2-2 transition only. Another effect noted was that the beginning of laser emission was delayed compared to that of the zero field emission. What happens is that the magnetic field causes each of the hyperfine lines to split into its Zeeman components (degenerate levels). Thus, the energy of each transition line is, in a sense, diluted by this splitting. Now, as the field is increased the Zeeman components of the 3-4 transition separate to distances comparable to the line width. The contribution of each of the components to the gain at the central frequency of the profile falls faster than the components' contribution to the profile of the 2-2 transition. So, at some field strength, the gain of the 3-4 transition falls below that of the 2-2 transition by the field. In a field of 1100 G, both the 2-2 and 3-4 transitions appeared, and apparently so did the 3-3 line (they did not directly observe the
emission of this line). In an axial field of 500 G, Hwang and Kasper found that both the 3-4 and 2-2 lines appeared. As mentioned earlier, only π-polarized transitions occur in axial fields, and, for transverse fields, both σ- and π-polarized transitions can occur. The σ and π transitions have different line strengths in magnetic fields, so the relative gains of the lines will vary according to the direction of the field. So, in an axial field, the π transitions have similar gains on each of the two lines, and both will lase (Hwang and Kasper, 1972, p. 513). They also tried time-varying fields (such as that from a flashlamp) and observed the emission (Hwang and Kasper, 1972, p. 514). They found that lasing started on the 2-2 line, terminated, and then began on the 3-4 line, which continued to the end of emission. Sometimes, the 3-4 line would oscillate in a strong varying field.

Belousova et al. (1974, pp. 258-263) have also done work on the effects of a magnetic field on the emission. Their work was similar to that of Hwang and Kasper, and their results were much the same. They noted that in a transverse field in their laser, only σ-polarizations were emitted. They further found that the 3-4 line position did not shift at all in the magnetic field up to the field strength in which it terminated (about $H = 440$ Oe). However, the 2-2 line did shift appreciably at field strengths above 2000 Oe. Between 800 and 2000 Oe, the 3-3 transition was noticed along with the 2-2 line lased. Belousova et al. also varied the pressure of the medium. They discovered that as the pressure increased, the 2-2 line would appear only for higher applied transverse fields. In an axial field, they found only the
π-components (now circularly polarized in an axial field, not linearly as in a transverse field) from the 3–4 transition at lower field strengths. At 800 Oe the 2–1 transition appeared and was shifted enough with the 3–4 line for them to cross (Belousova et al., 1974, p. 260).

The iodine laser, as is true of most electronic-transition gas lasers, has transitions of rather low linewidths. For fusion applications, however, the laser should produce large linewidths so that very short pulses can be amplified and the energy storage of an amplifier can be increased greatly without the amplifier becoming superradiant. It may also be desirable to increase the energy storage of our small laser at some time in the future. This can be done in one of two ways: One way is to increase the linewidths by applying external magnetic fields as mentioned above, or by pressure broadening the lines by adding one of a variety of inert gases such as CO₂ or argon (Ar). Magnetic broadening was considered first (Gensel, Hohla, and Kompa, 1971, pp. 48–50), but it was later found that pressure broadening worked equally well, and was simpler to enact as well (Aldridge 1973, pp. 180–181).

The linewidth of a transition is

\[ \Delta \nu = kP_{\text{TOT}} \]

where \( k \) is a proportionality constant dependent upon which gas is used and \( P_{\text{TOT}} \) is the sum pressure of the medium and the buffer gases. For a number of transitions with overlapping lines, as in the case of the iodine laser, it is difficult to directly measure \( \Delta \nu \). It is better to measure the stimulated emission cross-section, \( \sigma_{\text{MAX}} \), than solve for the effective linewidth using the relation (Gross 1976, p. 324)
\[ \sigma_{\text{Max}}(\nu) = \frac{\lambda^2 f(\nu)}{4\pi^2 \Delta \nu} \]

where \( \lambda \) is the Einstein A factor, \( \lambda \) is the wavelength, \( f(\nu) \) is the normalized lineshape function, and \( \Delta \nu \) is the effective linewidth. One can see that \( \sigma_{\text{MAX}} \) is inversely proportional to \( \frac{1}{\Delta \nu} \).

Figure 5 shows the gain profiles of the pressure broadened transitions. As the effective linewidth increases, \( \sigma_{\text{MAX}} \) decreases (and the pumping threshold increases). The lines of each of the two groups of upper state hyperfine lines merge together first, and then these two profiles merge completely into a single profile above a linewidth of 12 GHz. The maximum of the profile is at the place of the 3-4 line.

This is where the laser will lase. It is possible (Gross 1976, pp. 356) to force oscillation on the 2-2 line at high pressures along with the 3-4 line by applying a magnetic field as discussed earlier. The specific gas used to pressure broaden the transitions will strongly influence how much pressure is needed to produce a given linewidth, and thus \( \sigma_{\text{MAX}} \). Figure 6 plots \( \sigma_{\text{MAX}} \) versus \( P_{\text{TOT}} \) for pure \( C_3F_7I \) and the diluent gases \( CO_2 \) and \( Ar \). \( CO_2 \) is the diluent of choice by the Garching group. Using this gas and a \( P_{\text{TOT}} = 760 \) torr, an effective linewidth of 17 GHz is achieved. \( Ar \) has been used by Sandia Labs (Palmer, Padrick, and Jones 1976, p. 32). One of the concerns about adding large quantities of a pressure broadener was the possibility of deactivating the excited iodine by collisions. As Gross (1976, p. 326) describes, deactivation measurements were performed for the gases in Figure 6. The maximum allowable diluent pressure was defined as the
Fig. 5. Gain profiles of the iodine transition hyperfine structure as a result of pressure broadening, where $\Delta \nu$ is the linewidth of the individual hyperfine lines (from Gross 1976, p. 325).
pressure where 10% of the inversion was collisionally deactivated by the added gas in 10 $\mu$sec. These pressures are indicated by the hatch markings in Figure 6.

The saturation energy density, $e_s$, can also be used to characterize the iodine laser medium. The saturation energy density is the energy per cm$^2$ that is required to pass a certain point in an amplifier in order to reduce the inversion at this point to $1/e$ (Gross 1976, p. 330). It is usually defined for a homogeneously broadened line of frequency $\nu$ and stimulated emission cross section $\sigma_{\text{HOMO}}$ by (Gross 1976, p. 330)

$$
e_s = \frac{h\nu}{\gamma \sigma_{\text{HOMO}}}
$$

Here, $\gamma = 1 + g_u/g_L$, where $g_u$ and $g_L$ are the numbers of degeneracies of the upper and lower levels of the transition, respectively.

However, the above equation must be modified because (1) the total linewidth is not homogeneous for all pulse lengths, (2) there is overlap between the pressure broadened hyperfine lines, and (3) because of the hyperfine structure of the iodine transition. A coefficient "a" is introduced so that (Gross 1976, p. 330)

$$
e_s = ah\nu/\gamma \sigma_{\text{MAX}} \quad \text{where} \quad \sigma_{\text{HOMO}} = \sigma_{\text{MAX}}/a.
$$

"a" is defined as the fraction of the total inversion that is reached by the incoming radiation of frequency $\nu$ (Gross 1976, p. 330), and is expressed as

$$
a = \left(\frac{g_{hf}}{g_{\text{TOT}}}\right)_{\text{UPPER}} \quad \text{(Gross 1976, p. 330)}
$$
Fig. 6. Effect of diluent pressure of various gases on the maximum stimulated emission cross section of the iodine laser transition (from Gross 1976, p. 327).
and \( g_{hf} \) is the degeneracy of the hyperfine line of frequency \( \nu \) and \( g_{TOT} (=12) \) is that of the entire upper level. For low pressures where \( \Delta \nu \leq 0.5 \) GHz, \( a = 7/12 \) for the 3-4 transition and \( a = 5/12 \) for the 2-2 transition. \( \gamma = 1 + 7/9 = 1.78 \) for the 3-4 lines and \( \gamma = 2 \) for the 2-2 line under the same condition. The hyperfine structure energy distribution influence disappears for high pressures (\( \Delta \nu >> 15 \) GHz) and long pulses (\( t_p \geq 100 \) nsec) and thus \( a = 1 \). At these conditions, \( \gamma = 1 + 12/24 = 1.5 \). For both transitions occurring simultaneously, \( a = 1 \) and \( \gamma = 1.5 \). For \( \Delta \nu = 5-8 \) GHz, the lower level is broadened because of fast interstate relaxation processes for pulse lengths greater than 100 psec. Here, \( \gamma = 1 + 7/24 = 1.29 \) for the 3-4 line and \( \gamma = 1 + 5/24 = 1.21 \) for the 2-2 line.
CHAPTER 3

IODINE LASER DESIGN AND CONSTRUCTION

Description of Apparatus

In constructing our iodine laser, we decided to convert a flash-lamp-pumped dye laser into a flashlamp-pumped iodine oscillator. We examined the option of using the dye laser to pump a quartz cell filled with some pressure of a perfluoroalkyl iodide, but we felt that this was more complex than a direct conversion. Also, it would have involved finding a dye that would lase in the iodide absorption bands, or by pumping an I₂ filling, lasing it, and using its output to pump the organic iodide.

The dye laser converted is an Electro-Photonics Ltd. system made in Northern Ireland in the early 1970s. This laser was intended to be used in picosecond experiments, and is capable of being passively mode-locked using suitable dyes placed inside the cavity.

The laser head consists of an elliptical cavity which is highly reflecting on the inside— it appears to be highly polished aluminum. At the top focal line is the quartz tube through which the dye is normally flowed. This tube is 17.8 cm long and is 0.6 cm in inside diameter. The tube being of quartz is fortunate because quartz transmits 93% of the radiation in the absorption bands of the perfluoroalkyl iodides. The dye cell is surrounded by a cladding cell, also of quartz, and is as long as the dye cell but is 1.0 cm in diameter. The
original purpose of this all is to provide more efficient optical matching of the flashlamp pump energy into the dye solution. The dyes are mixed usually in ethanol, and so pure ethanol is flowed through the cladding cell. Both tubes are held in place and sealed by metal end-plates and "O"-rings. The plate holding the dye cell also contains the quartz Brewster-angle windows. The inlet and outlet pipes for circulating both the dye and cladding liquid are brazed onto the plates.

At the conjugate focal line is the quartz flashlamp. Originally, the laser was fitted with an air flashlamp. It could be evacuated with a vacuum pump so that the voltage from the capacitor bank could be held off, thus preventing the lamp from firing prematurely. The lamp was mounted by metal endplates, one of which held the vacuum housing and the trigger spark plug, and the other holding the high-voltage cable from the capacitor bank. The lamp was triggered manually by a switch providing a 5V pulse which causes a 300 V line leading to a trigger transformer to induce a 30 kV transient in the windings of the secondary. This trigger voltage was then supplied to a modified automotive spark plug at the cathode end of the lamp, causing the capacitor bank to discharge through the lamp. As will be discussed later, the air flashlamp was discarded and replaced with a xenon filled lamp. The trigger electronics were retained (except, of course, for the sparkplug).

The elliptical cavity is parted in the middle. On one side, the two halves are hinged together, and on the other side are two fastening clips. Both the cells and the flashlamp are thus easily
accessible for inspection. The cavity is mounted on a one meter long aluminum baseplate. Two optical railings for the dielectric mirrors and their mounts are on the baseplate as well, along with the trigger transformer.

The power supply for the lamp is an in-house built unit. There are two Maxwell Laboratories 25 kV low inductance, rapid discharge capacitors, each of 5 μF capacitance. The high voltage supply for the capacitors is capable of a charging voltage from 1 to 20 kV at a current of 25 mA. The trigger electronics for the transformer are located with the HV supply. This power supply is designed to be of low inductance in order to provide a very fast flashlamp pulse. Organic dyes in a pulsed laser require intense and rapid pumping, and, for the best efficiency, so do the organic iodides.

Another unit is the dye circulating unit. This holds the pumps that circulate the dye and the cladding through the cells. It also contains the vacuum pump for pumping down the flashlamp.

Four dielectric mirrors for use at iodine wavelengths are on hand for use with an iodine laser. Each mirror is one inch in diameter. Two of them are flats, and the other two have 5 m radii of curvature. All four were tested on a Cary spectrophotometer and found to have reflectances of 99.7%.

**Modifications to the Dye Laser**

We first ran the laser as a dye laser so as to gain familiarity with how the system worked. The dye used was Rhodamine 6G. Resonator alignment was accomplished using a helium-neon laser. The device
lased very easily, but the lamp could not be fired until it was evacu-
ated down to a pressure of about $3 \times 10^{-2}$ torr—this typically would
take about 10 minutes. We found also that the repetition rate was
only about one pulse every 8-10 seconds. Beam quality was poor, even
with the alignment fine-tuned. The problem was probably due to turbu-
lence in the flowing dye and to thermal effects from the dye being
heated as it ran through the electric pumps. After about 400 shots, one
end of the flashlamp broke. This was probably caused by the repeated
high voltage pulses making the quartz brittle. Rather than attempting
to obtain another air flashlamp, we decided to modernize the laser by
utilizing a properly designed xenon flashlamp.

Very few modifications were needed to prepare the dye laser for
conversion to an iodine laser. First, the dye and cladding circulation
tubing was removed from their fittings at the laser head. The air
flashlamp, along with its' mounting plates and associated vacuum fit-
tings, were taken out the cavity. The final modification was to arrange
the mirror mounts and the elliptical cavity in a straight line con-
figuration. Previously, the mounts were on rails laterally displaced
from one another, with the cavity canted at the proper angle between
the mounts. This was due to the presence of the Brewster-angled windows,
and the fact that the refractive index of the dye inside the flow tube
is greater than is the index of the air outside. The collinear
arrangement of the cavity and the mirrors is dictated by the fact that
the index of the iodide gas is essentially the same as that of the air.
The Iodide Gas and the Gas Handling System

The iodide gas selected for use as a medium is CF$_3$I, or trifluoromethyl iodide, and it is one of the perfluoroalkyl iodides. The gas is supplied by PCR Research Chemicals Co. in 100g cylinders. After consulting Table 2, it can be seen that CF$_3$I does not yield as high a fraction of I* atoms as does n-C$_3$F$_7$I. CF$_3$I also is more subject to pyrolytic breakup than is n-C$_3$F$_7$I, for reasons discussed in Chapter 2. n-C$_3$F$_7$I is, indeed, a better iodide to use, and it is used almost exclusively in the high power systems for fusion research. However, CF$_3$I was selected because of its substantially lower price than n-C$_3$F$_7$I, and was more readily available at the time of purchase. CF$_3$I is, though, quite satisfactory for our small system.

Ideally, we wanted to have a closed gas handling system in which a high vacuum could be obtained in the dye cell and in which a specific pressure of CF$_3$I could be added. The same could then be used for a number of shots. However, due to time constraints, we were compelled to initially adopt a flow-through system. At one end of the cell is the CF$_3$I cylinder, connected by rubber tubing to the metal pipe brazed onto the mounting plate on that end. At the other end is a rubber tube leading to a differential pressure gauge that can measure a vacuum down to one torr. Connected to the gauge is the high vacuum pump from the original dye laser. A valve between the gauge and the pump allows control over the rate of evacuation in the system. The cell is first pumped down to remove as much air as possible. Then the valve is
closed just enough to maintain that vacuum. Then the CF$_3$I cylinder is
opened, and the flow is adjusted until the desired pressure of gas is
reached, as observed on the pressure gauge.

The obvious disadvantages of flowing the gas are (1) that much
gas is wasted since about ten seconds elapses between shots, and (2)
flowing the gas could cause turbulence in the medium, leading to poor
output beam quality.

The biological hazards of CF$_3$I are not known, so to be on the
safe side, the gas from the exhaust outlet on the pump is piped through
tubing to an exhaust hood which vents the gas outside the building.

Threshold Estimation

Before ordering a xenon flashlamp, it was important to have
some idea of what capacitor bank energy would just cause laser oscil­
lation in our device. The calculations below for finding this pump
energy yield only an approximate result as the efficiency factors may
not be accurate, nor the estimation of losses in the laser.

First, we needed to find an estimate of the inversion density
needed to reach threshold. Yariv (1976, p. 116) gives the following
equation for $N_t$, where the "t" represents threshold:

$$N_t = (N_2 - N_1) \left( \frac{8\pi n^2 t_{SPONT}}{g(\nu)\lambda^2} \left( \alpha - \frac{1}{k} \right) n r_1 r_2 \right).$$

$n$ is the refractive index of the medium, and for CF$_3$I, can be es­
sentially considered unity. $t_{SPONT}$ is the spontaneous lifetime of the
upper laser level, and is equal to $A^{-1}$, where $A$ is the Einstein
coefficient (spontaneous transition rate). Here, \( A = 5.1 \text{ sec}^{-1} \) for the 3–4 transition, so \( t_{\text{SPONT}} = 0.196 \text{ sec} \). \( g(v) \) is the transition lineshape function, and the linewidth \( \Delta \nu \) is approximately \( g(v) \). \( \lambda \) is the wavelength of the transition. \( \alpha \) represents the passive losses of the medium due to scattering and absorption. We will assume \( \alpha = 5\% \).

The length of the resonator cavity is \( l \), and for our laser, \( l = 47 \text{ cm} \). \( r_1 \) and \( r_2 \) are the dielectric mirror reflectivities. Now \( R_1 = r_1^2 \) and \( R_2 = r_2^2 \), where \( R_1 \) and \( R_2 \) are the reflectances. As stated earlier \( R_1 = 0.997 \) and \( R_2 = 0.997 \), and therefore \( r_1 r_2 = \sqrt{R_1 R_2} = 0.997 \). For low pressures, \( \Delta \nu = 0.5 \times 10^9 \text{ Hz} \) and so \( g(\nu_0) \approx 2 \times 10^{-9} \text{ sec} \) where \( \nu_0 \) represents the value of \( g(v) \) at the line center frequency. Substituting this value and the others given above into the threshold inversion density equation yields

\[
N_e = 7.1 \times 10^{15} \text{ cm}^{-3}
\]

Now, \( N_e h \nu_{\text{ABS}} \) represents the actual energy absorbed by the medium necessary to cause the threshold inversion. \( \nu_{\text{ABS}} \) is the average frequency of the pumping source that is absorbed by the medium. For \( \text{CF}_3\text{I} \), \( \lambda_{\text{abs}} \approx \lambda_{\text{PEAK}} = 267 \text{ nm} \) (from Table 3), so \( \nu_{\text{ABS}} \approx 1.12 \times 10^{15} \text{ Hz} \). \( h \) is Planck's constant and has the value \( 6.63 \times 10^{-34} \text{ J-sec} \). Multiplying these values gives an energy density of \( 5.27 \times 10^{-3} \text{ J/cm}^3 \). The dye cell has a volume of \( 5.03 \text{ cm}^3 \), so \( 0.027 \text{ J} \) is required to pump the medium to threshold. If we had a perfect pumping arrangement, this would be all that was necessary. However, only about \( 5\% \) of the lamp's
output is in the CF$_3$I absorption band. Garching's specially designed lamps emit about 9% in the band (Gross 1976, p. 361). We will use 5% in our calculations. Perhaps 20% of this is actually reflected by the cavity into the dye cell, and the lamp efficiency (optical output/electrical input) is assumed to be 50%.

Therefore, the capacitor bank energy should be

$$\frac{0.027 \text{ J}}{0.05 \times 0.20 \times 0.50} = 5.4 \text{ J.}$$

If the overall efficiency is even lower, say, 0.1%, then the capacitor energy needs to be 27 J.

Another way to calculate the threshold inversion density is to use the stimulated emission cross-section, $\sigma_{\text{MAX}}$. Siegman (1971, p. 403) gives the following expression for $N_t$:

$$N_t = \frac{2 \alpha + \frac{1}{\lambda} \ln \left( \frac{1}{r_1 r_2} \right)}{\sigma_{\text{MAX}}}.$$ 

At a pressure of 100 torr, CF$_3$I has $\sigma_{\text{MAX}} = 1.9 \times 10^{-18}$ cm$^2$ (Aldridge 1973, p. 181). Substituting this in and using the previously given values for $\alpha$, $\lambda$, and $r_1 r_2$ gives

$$N_t \geq 5.3 \times 10^{16} \text{ cm}^{-3}.$$ 

Proceeding as before, $N_t h \nu_{\text{abs}} = 0.039 \text{ J/cm}^2$ and multiplying by the cell volume gives 0.196 J. Using the same efficiency factors indicates a capacitor storage energy of 39.2 J (0.5% efficiency) and 196 J.
From Figure 2, one sees that CF$_3$I exhibits its' peak power output at a pressure of around 100 torr. We decided to perform the initial lasing attempts at pressures around 25 torr. Here, threshold is lower than at 100 torr (due to a larger $\sigma_{\text{MAX}}$).

**Flashlamp Design**

After doing these threshold calculations, the next step was to examine various criteria for a suitable flashlamp.

Typical xenon flashlamps used for pumping most solid-state lasers operate at a few kilovolts and at low current densities. These lamps have a spectral output primarily in the visible and infrared and very little in the absorption bands of the alkyl iodides. To increase the emissivity in the spectral region around 270 nm, it is necessary to operate the lamp at a high current density ($>20$ kA/cm$^2$). This will shift the lamp's output to shorter wavelengths. To achieve these high current densities the lamp must operate at high voltages (at least, say, 6 kV and preferably higher), low capacitances, and short discharge times (Gross 1976, pp. 359-361). To keep the discharge time short, one must have very low inductance in the circuit. Lowering the xenon fill pressure also helps improve the UV output. ILC Technology (Report R-ILC-74-10, 1974) did a study for Sandia Laboratories on the UV output of xenon lamps for use in pumping iodine lasers. For an input energy of 2 kJ per meter of arc length, a fill pressure of 30 torr provided an optimum UV output, and for an energy of 5 kJ/m, 60 torr proved optimum. Most xenon lamps usually use a fill of 350-450 torr. ILC also found that a simmer current of 0.03 A further improved UV output.
Their test lamps stored 8% of their energy in the 250 nm-300 nm spectral range. The lamps for the Garching fusion laser operate at 50 kV, are 100 cm long, and dissipate 50 kJ in 10 usec. These lamps have an efficiency of 9.03% in the medium absorption band (Gross 1976, pp. 361-362). Another way to enhance the UV radiation is to dope the lamps with zinc or cadmium (Palmer, Padrick, and Jones 1976, pp. 36-37). They state that the efficiency can thus be increased by a factor of 2 or 3. The problem with doping the lamps is that the lamp lifetime is seriously lessened (Krupke and George 1976, p. 22).

Regardless of how the UV efficiency is improved, it results in short lamp lifetimes. The high shock forces produced by fast, high current density pulses age the lamps quickly.

For our iodine laser, we desired a nominal flashlamp energy of 200 J from the capacitor bank. The pulse width is determined by the diameter of the dye cell. Gas dynamic shock waves that emanate from the inside surface of the cell after the pumping pulse will destroy the beam quality unless the pulse is fast enough. These shock waves are caused by the flash evaporation of I\textsubscript{2} that has been deposited on the cell inside surface from previous shots (Gross 1976, p. 341). The propagation speed of these waves in the medium is about 10^4 cm/sec. To prevent the shock wave from propagating further than 1/10 of the cell radius r, it will be necessary to pump and extract the laser in a time

\[ t_{\text{ex}}/r \leq 10 \text{ usec/cm}. \]
This defines the lamp maximum pulse duration to prevent the shock waves from affecting the beam (Gross 1976, p. 342). The dye cell has an inside radius of $r = 0.3$ cm, so $t_{ex} \leq 3 \mu\text{sec}$. This sets a lamp pulse width of about $3 \mu\text{sec}$ for our flashlamp.

After examining these basic requirements, we felt that the proper lamp should be a dye laser flashlamp as these lamps are designed for high current densities, high voltages, and fast risetimes. An ILC Technology "D"-series lamp was chosen after consulting their Technical Bulletin No. 5 on dye laser flashlamp design. Using this technical bulletin we made a preliminary lamp design before having the company begin fabrication.

First, a lamp lifetime of about 10,000 shots was desired, and using a graph in the bulletin of the ratio of energy input to lamp explosion input versus lamp life, we found an explosion energy of $E_{xp} = 588$ J for an energy input of 200 J and a life of 10,000 shots. Now,

$$E_{xp} = E_1 \frac{dT^{1/2}}{1/2}$$

where $l$ = the lamp arc length in cm, $d$ = the lamp bore diameter in cm, $T = (LC)^{1/2}$ ($L$ = inductance, $C$ = capacitance) and is about $1/3$ of the pulse width, and $E_1$ = the lamp explosion energy parameter (for "D"-series lamps, $E_1 = 4.0 \times 10^4$ J -cm$^{-2}$ -sec$^{-1/2}$). $T = \frac{1}{3} (3 \times 10^{-6}$ sec) = $1 \times 10^{-6}$ sec, and $l = 17.8$ cm for our laser. Solving for $d$ gives a lamp bore diameter of $8$ mm. The energy stored in a capacitor is given by

$$E_0 = \frac{1}{2} CV^2$$
where $V$ is the charging voltage. Letting $E_0 = 200$ J and using one of the available 5$\mu$F capacitors, the charging voltage needed is 8.95 kV. The required inductance is

$$L = \frac{T^2}{C}.$$ 

Again using $C = 5 \times 10^{-6}$ F and $T = 1 \times 10^{-6}$ sec gives an inductance of $L = 2 \times 10^{-7}$ henry. This is one parameter over which we had little control. The capacitors, cabling, spark gap, and even the configuration of the lamp connections all contribute to the total inductance. To minimize the inductance we kept all electrical cabling to the shortest length feasible. However, I am unable to measure the total circuit inductance. We decided, though, to use the above figure of $L$ in all the flashlamp design calculations as the ideal number. The peak current through the flashlamp is approximated by

$$I_{\text{peak}} \approx \frac{1}{2} V \left( \frac{C}{L} \right)^{1/2}.$$ 

Substituting in the appropriate values gives an $I_{\text{peak}} \approx 22.4$ kA. The lamp bore has a cross-sectional area of $0.503 \text{ cm}^2$, so the peak current density is approximately $44.5$ kA/cm$^2$.

At this point ILC Technology was contacted to discuss the manufacture of two flashlamps capable of handling these parameters. Their design called for a bore diameter of 8 mm also, but they suggested a xenon fill pressure of 50 torr instead of the usual 450 torr.
As discussed earlier, this would help increase the output into the CF$_3$I absorption band from the lamp. The preferred capacitance is given by

$$C = \left[ \frac{2E_0 a T^2}{K_o} \right]^{1/3}$$

where $a$ is the circuit damping factor and is equal to 0.8 for a critically damped pulse. $K_o$ is the lamp impedance parameter and can be found from

$$K_o = 1.28 \left[ \frac{P_{XE}^{0.2}}{450} \right] \left[ \frac{z}{d} \right]$$

where $P_{XE}$ is the xenon fill pressure in torr. For $P_{XE} = 50$ torr, $z = 17.8$ cm, and $d = 0.8$ cm gives $K_o = 18.4$ ohm - A$^{1/2}$. Using the $K_o$ value and $E_o = 200$ J, $T = 1 \times 10^{-6}$ sec, and $a = 0.8$ into the capacitance equation yields a result of $C = 11.3$ μF. This indicates that both 5μF capacitors (10μF total) should be used. Doing this requires a charging voltage of 5.3 kV and a circuit inductance of $1 \times 10^{-7}$ henry, which is a rather severe requirement. The peak current density will be about 63 kA/cm$^2$ which will help the lamp's UV output, but shorten the lifetime.

We resolved to try the first attempts at lasing using a 5μF capacitance, and then try a 10μF capacitance.

Two flashlamps meeting the above specifications were ordered, and upon their arrival, we had to make the mounts for holding the lamps at the line focus of the cavity. For this, two lucite blocks cut to an appropriate size were used. Each was centrally drilled, forming a hole
1.27 cm in diameter (the lamps are 1.195 cm in diameter). Mounting holes were drilled and tapped so that each block could be attached to the outside of the cavity. These holes were countersunk so that the mounting screws would not be responsible for causing arcing between them and the lamp connections. To prevent the lamp from sliding back and forth, a hole was drilled from a side of each block to the central hole containing the lamp. A small Teflon plug was inserted, followed by a screw. The screw was tightened, and the plug was forced against the lamp, thus holding it firmly in position.

**Flashlamp Circuit Design**

After installing one of the flashlamps, the next step was to determine the proper circuit needed for firing the lamp. It was obvious that the lamp would not be able to hold off the high voltages needed to charge the capacitor bank. In other words, the lamp would discharge prematurely once some particular voltage was reached if the lamp anode were connected directly to the capacitor. Some sort of hold-off switch was necessary between the capacitor and the lamp. Two choices of a switch were possible: We could use a thyratron or a triggered spark gap. We chose a spark gap, because thyratrons and their associated electronics are quite expensive. Also, using a thyratron represented "overkill" at the voltages and currents we would be using.

An EG&G GP-22B triggered spark gap was chosen. The specification sheet for this gap (EG&G Data Sheet G6000E-2, 1981) gave an operating voltage range of 5 kV to 15 kV and a static breakdown voltage
(SBV) of 19 kV. The minimum trigger voltage needed to fire the gap is 20 kV. The gap is capable of being triggered with either a trigger module or a trigger transformer. We chose to use the 30 kV trigger transformer and the firing circuit for it already described.

The gap consists of a ceramic body cylinder, brazed on each end to convex refractory metal electrodes. One electrode has an open area to accommodate the trigger electrode probe and insulating bushing. To achieve the SBV, an appropriate gas mixture is introduced into the gap at the appropriate pressure, and the gap is then sealed. The gap is able to change rapidly from a near-perfect insulator to a low-impedance conductor in response to voltage applied to the electrodes. After conduction is initiated by the trigger electrode the two main electrodes carry the load current. The GP-22B can handle a peak energy of 2500 J, 100 kA peak current, and 5 coulombs of total charge in one shot. Under these conditions the lifetime is very short, as the lifetime will be only 500-1000 coulombs of total charge. Electrode damage occurs through two factors: The first, and most significant factor, is the dissipation in the plasma sheaths, and is measured by the total number of coulombs per shot passed through the gap, or

\[ \int |i| \, dt. \]

This integral can be approximated by CV. For \( C = 5 \times 10^{-6} \) F and \( V = 9000 \) volts, \( CV = 45 \) millicoulombs per shot. Now, the GP-22B has a lifetime of 5000 - 20,000 total coulombs. At 45 millicoulombs per shot, the minimum expected lifetime is
\[
\frac{5000 \text{ COUL}}{45 \text{ MILLICOUL/SHOT}} = 111000 \text{ shots.}
\]

The second factor is resistive dissipation in the electrodes and plasma, and is roughly measured by

\[
\int i^2 dt.
\]

This effect is not as great as the first (EG&G Data Sheet G6000E-2, 1981).

The spark gap was mounted to two Lucite blocks for insulation. The circuit is illustrated in Figure 7. Here,

- \( R_1 \) = limiting resistor
- \( R_2 = 1 \) megohm
- \( R_3 = 8000 \) ohms
- \( C_1 \) = main discharge capacitor(s) (5\( \mu \)F or 10\( \mu \)F)
- \( C_2 = 500 \) pF at 30 kV
- \( C_3 = 0.5 \) F
- \( T_1 = 30 \) kV trigger transformer
- SCR = silicon controlled rectifier.

\( R_3 \) is a parallel load resistor that is used with gas discharge loads. It is used to provide a parallel electrical path to maintain a closed circuit if the flashlamp fails to fire. This will help to protect the various components from damage due to a surging back of the electrical energy. According to the EG&G Data Sheet, the \( R_3 \) resistance should be such that it allows a current of 1-5A to flow through the spark gap.
Figure 7. Flashlamp circuit diagram for the iodine laser.
Finding the proper resistance value merely involves Ohm's Law,

\[ V = IR. \]

For a current of 1A and \( V = 9 \text{ kV} \), \( R_3 = 9000 \text{ ohms} \). For a current of 5A, \( R_3 = 1800 \text{ ohms} \). \( R_3 \) must also be capable of absorbing the power from the capacitor bank of the lamp does not fire. Now,

\[ P = \frac{E_o}{t} \]

where \( P \) is the power and \( t \) is the time interval between pulses which in this case is 10 seconds. Thus, for \( E_o = 200 \text{ J} \), \( P = 20 \text{ watts} \). The only resistors conveniently obtained that are capable of handling at least this much power are two 16000 ohm, 100 watt resistors. By connecting these in parallel, the net resistance is

\[ R_{\text{NET}} = \frac{R_a R_b}{R_a + R_b} \]

where \( R_a = R_b = 16000 \text{ ohms} \). So, \( R_{\text{NET}} = 8000 \text{ ohms} \) and this value is between the 1800-9000 ohm range required. A current of about 1.13 A can pass through the gap. \( R_a \) and \( R_b \) were mounted on a wooden board using Lucite fittings, and wired in parallel to make up \( R_3 \).
CHAPTER 4

RESULTS

Once the flashlamp and its' circuitry were connected, attempts to achieve lasing were begun. The dielectric mirrors were placed in their mounts, and both mirrors had 5m radii of curvature, forming a stable resonator configuration. Alignment of the cavity was accomplished using a He-Ne laser. Next, the dye cell was evacuated down to 1 torr, and the CF\textsubscript{3}I cylinder was opened enough to provide a medium pressure of 25 torr. The vacuum control valve was closed only to the point of maintaining this pressure. In this way, the flow of CF\textsubscript{3}I could be somewhat reduced and minimize wattage. The capacitor (5\mu F) was charged to 8 kV for an electrical energy of 160 J. A Kodak IR phosphor card was used to detect lasing. Lasing was detected, but weakly. However, on subsequent shots, the lamp would often fire prematurely. Most frequently this would occur when a voltage of 6-7 kV was reached. 6 kV is the minimum voltage recommended for discharging the lamp, and the lamp frequently would not flash at all. This problem rapidly grew worse, until the capacitor would not hold its' charge beyond 6 kV. Obviously, this situation would have to be corrected before further experimentation could proceed.

In troubleshooting the circuit, the spark gap was checked first. We thought that perhaps the gas used to establish the SBV had leaked, and the gap was breaking down at much lower voltages. Removing the
gap from the circuit, we connected it to a D.C. high voltage source and slowly increased the voltage, noticing at what value the gap broke down. In this way, an SBV of 18 kV was found. We then suspected some fault in the spark gap triggering circuit, i.e., the transformer or its' associated electronics. We disconnected the lead from the transformer to the gap and changed the capacitor. Again, the capacitor would spontaneously discharge at around 6 kV. Next, the other 5μF capacitor was used, and the same phenomena still occurred. We then tried another high voltage supply to charge the capacitor. This made no difference. At this point, we used a 2μF capacitor, originally from another dye laser and the second high voltage supply. This capacitor is also discharged through the flashlamp by using a spark gap built onto the end of the capacitor. The circuit configuration is essentially the same as before. The transformer lead was connected to the gap, and all other necessary connections were made. This time, the lamp worked perfectly. We fired the lamp at voltages from 7 kV to 13 kV (this gap's SBV) with no premature, spontaneous firings. Using this capacitor, the flash energy is somewhat less than it would be using one of the 5μF capacitors, even though it can be safely used at higher voltages without breaking the lamp. It seems now that either the capacitors originally tried are deteriorated to the point where they cannot hold a high voltage, or there is some unknown defect in the EG&G spark gap.

Charging the 2 μF capacitor to 12 kV (an energy of 144J) we observed (with the phosphor screen) weak and intermittent lasing.
Attempts to observe the laser pulse on an oscilloscope via the beam impinging on a photo-diode detector failed. The slow repetition rate greatly hampered our ability in fine-tuning the alignment of the mirrors and also in positioning the detector in the beam.
CHAPTER 5

CONCLUSIONS

For this iodine laser to work optimally, at least two modifications should be made. First, the two 5μF capacitors or the spark gap, depending on which is at fault, need to be replaced to prevent the lamp from self-firing. Evidence seems to indicate that the capacitors are most likely the culprits. The second task is to utilize a closed gas handling system. This will allow the possible complications resulting from turbulence associated with flowing the gas to be alleviated. Also, the same gas can be used for a number of shots, thus allowing much better economic efficiency of the CF₃I. Of course, power output will drop with each succeeding shot if this method is adopted, unless a recycling unit is added to filter out I₂ and other impurities. If possible, a new power supply capable of a faster repetition rate of the lamp should be obtained.

Once the laser is working well, it will be possible to mode-lock and Q-switch it. This has been demonstrated many times (Ferrar 1968, pp. 381-383; Gensel, Hohla, and Kompa 1971, p. 49; Gross 1976, pp.354-358) and both passive and active methods can be employed. For passive mode-locking and Q-switching, the only saturable absorber previously available was I₂ vapor. Now, a more convenient saturable dye has been found to work at 1.3 μm. This is JUL-2 dye, and it is being used in iodine laser experiments at Garching (Witte et al. 1981, p.1811).
To negate the complications caused by the flashlamp's magnetic field, i.e. other hyperfine transitions lasing besides the 3-4 line, it should be possible to place oppositely two copper wires or strips parallel to the flashlamp for the return current to pass through. This should do a good job of greatly reducing the magnetic field effects on the iodine transition.
REFERENCES


