PROGRESS REPORT

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TITLE OF RESEARCH: Development of Mid-Infrared Solid State Lasers for Spaceborne Lidar

NASA GRANT NUMBER: NAG-1-877

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Summary

This semiannual progress report covers work performed during the period from April 13, 1988 to October 13, 1988 under NASA grant number NAG-1-877 entitled "Development of mid-infrared solid state lasers for spaceborne lidar". We have designed a flashlamp-pumped Cr\textsuperscript{3+}:GSAG laser of pulsed laser energy greater than 200 mJ and of pulse width of 1 ms FWHM to simulate a high power laser diode in pumping mid-infrared laser crystals such as Tm\textsuperscript{3+}, Er\textsuperscript{3+} and/or Ho\textsuperscript{3+}-ion doped YAG, YLF or other host materials. This Cr\textsuperscript{3+}:GSAG laser will be used to determine optimum conditions for laser diode pumped mid-infrared lasers, maximum energy extraction limit with longitudinal pumping, thermal damage limit, and other problems related to high power laser diode pumping. We have completed a modification of an existing flashlamp-pumped and liquid-nitrogen-cooled rare earth laser system for 60 J electrical input energy and 500 µs pulse width, and have carried out preliminary experiments with a Ho\textsuperscript{3+}:Er\textsuperscript{3+}:Tm\textsuperscript{3+}:YAG crystal to test the system performance. This flashlamp-pumped rare earth laser system will be used to determine optimum Tm\textsuperscript{3+}-ion concentration in Ho\textsuperscript{3+}:Cr\textsuperscript{3+}:Tm\textsuperscript{3+}:YAG crystal in the remaining research period.
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I. Flashlamp Pumped Cr:GSAG Laser for Rare Earth Laser Pumping

1. Introduction

During this report period we have designed a flashlamp pumped Cr:GSAG laser to simulate a high power laser diode in pumping rare earth ion (such as Tm$^{3+}$, Er$^{3+}$ and Ho$^{3+}$) doped crystals and to study various problems involved with high power laser diode pumping. The diode-pumped solid state laser system has been known as a very promising technology for the spaceborne lidar (light detection and ranging) and windshear lidar applications because of its long system lifetime, reliability, high efficiency, low thermal loading, compactness and low-voltage operation. However, the current technology on the laser diode is not mature especially in high power or high energy applications and its price per unit output power is very high. The reported highest cw laser output from a single array diode is 38 W [Ref.1]. The highest quasi-cw laser output from a one-dimensional bar is 134 W for a pulse width of 150 μs and repetition rate of 40 Hz and that from a two-dimensional stacked bar is 800 W (corresponding power density of 2 kW/cm$^2$) for the same pulse width and repetition. The flashlamp pumped Cr:GSAG laser can be built with a relatively low cost and can deliver high laser output energies of 200 mJ – 1 J. The corresponding average laser pulse powers are 100 W – 2 kW for 0.2 – 2 ms pulses. In addition, since the wavelength of most currently well-developed laser diodes is located near 800 nm, the Cr:GSAG laser wavelength matches well to the diode wavelength and can be precisely tuned to the absorption peak of the rare earth ions. Since the absorption lines of the Tm$^{3+}$ and Er$^{3+}$-ions match well with the diode laser wavelength and efficient energy transfer from the Tm$^{3+}$ and Er$^{3+}$ ions to Ho$^{3+}$ ions has been already utilized in low
power laser operation with laser diode pumping as listed in Table 1 [Refs.2-7], high power laser operation of rare earth crystals, such as Ho$^{3+}$:Tm$^{3+}$:YAG, Ho$^{3+}$:Er$^{3+}$:Tm$^{3+}$:YAG, Er:YAG and Er:YLF, at various wavelengths of 2.1$\mu$m, 2.3$\mu$m and 2.9$\mu$m may be expected with high power laser diode pumping. The flashlamp pumped Cr:GSAG laser will be used not only to simulate high power laser diode pumps but also to determine an optimum combination of the host and rare earth ions, threshold, slope efficiency, operating temperature and output coupler's reflectance for the efficient rare earth lasers. Furthermore, William E. Krupke predicted that the solid state lasers pumped longitudinally with laser diodes are limited to a maximum deliverable output of 10 W [Ref.8]. The Cr:GSAG laser will be useful in determination of the upper limit of the rare earth laser output with a longitudinal pumping at a wavelength which corresponds to diode laser wavelength and absorption peak of the rare earth ions.

In the following sections we will describe the characteristics of the flashlamp pumped Cr:GSAG laser and its system design.

2. Flashlamp Pumped Cr:GSAG Laser

Fig.1 shows the absorption and fluorescence spectra of the Cr:GSAG crystal. The fluorescence spectrum covers well the laser diode wavelength range which is around 780 nm to 850 nm. Previously other research groups [Refs.9,10] have demonstrated tunable laser operation of the crystal in the wavelength range from 765 nm to 800 nm and obtained the maximum laser output of 200 mJ at 780 nm with a pulse width of 150 $\mu$s. It is our primary objective to develop a long-pulsed high energy Cr:GSAG laser of adjustable pulsed laser energy of 200 mJ to 1 J and pulse width of 0.2 ms to 1 ms at the wavelength of 790 nm.

Typical pulse forming network (PFN) with a single RLC circuit
is shown in Fig.2. According to the Refs.11-13, the design parameters can be calculated using the following relations:

\[ C = \left( \frac{2 E_0 \alpha^4 T^2}{K_0^{-1/2}} \right)^{1/3} \]

\[ K_0 = 1.28 \frac{l_f}{D} (p/x)^{1/5} \]

\[ L = \frac{T^2}{C} \]

\[ V_0 = \left( \frac{2 E_0}{C} \right)^{1/2} \]

\[ E_x = K_e T^{1/2} \]

\[ \tau_{\text{life}} = \left( \frac{E_0}{E_x} \right)^{8.5} \]

\[ I = \left( \frac{V}{K_0} \right)^2 \]

\[ A = \pi \left( \frac{D}{2} \right)^2 \]

\[ T_B = \left[ \left\{ 9450 \times \left( \frac{D}{100} \right)^{0.03} \left( \frac{I}{A} \right)^{0.01} \right\}^6 + \left( 93 \times \left( \frac{D}{100} \right)^{0.27} \left( \frac{I}{A} \right)^{0.34} \right)^6 \right]^{1/6} \]

\[ \lambda_p = 2.898 \times 10^6 / T_B \]

\[ Z_o = \left( \frac{L}{C} \right)^{1/2} \]

\[ R_t = \rho \left( \frac{l_f}{A} \right) \]

\[ I_p = V / (Z_o + R_t) \]

where \( C \) is the capacitance of the charging capacitor in Farad, \( E_0 \) is electrical energy stored in capacitor in Joule, \( \alpha \) is damping factor (=0.8 for critical damping), \( T \) is circuit time constant (= \( T_0 / 3 \)), \( T_0 \) is current pulse width measured at 1/3 of peak in second, \( K_0 \) is impedance parameter of flashlamp in \( \Omega \) (amp)^{0.5}, \( l_f \) is arc length of the flashlamp in cm, \( D \) is flashlamp bore diameter in cm, \( p \) is gas fill pressure in flashlamp in Torr, \( x \) is a constant (= 450 for Xe-gas, and 805 for Kr-gas), \( L \) is inductance in Henry, \( V_0 \) is initial capacitor voltage in volt, \( E_x \) is explosion energy in Joule, \( K_e \) is explosion energy constant of the given flashlamp, \( \tau_{\text{life}} \) is flashlamp lifetime in shot number, \( V \) and \( I \) are instantaneous flashlamp discharge voltage and current in volt and ampere, respectively, \( A \) is flashlamp bore cross section in \( \text{cm}^2 \). \( T_B \) is
blackbody temperature in °K, \( \lambda_p \) is the wavelength at the peak of the blackbody spectrum in nm, \( Z_0 \) is the impedance of the LC circuit in ohm, \( R_t \) is flashlamp resistance, \( \rho \) is flashlamp resistivity in \( \Omega \cdot \text{cm} \) (0.02 for pulse width between 100 \( \mu \text{s} \) and 1 ms pulses), and \( I_p \) is the peak current on the discharge circuit. The result of the calculated parameters for ILC model 4F3 flashlamp \([D = 0.4 \text{ cm}, l_f = 7.62 \text{ cm}, \ K_0 = 25 \text{ \Omega(amp)}^{0.5}, K_o = 7.5 \times 10^4 \text{ Watts(sec)}^{0.5}, \text{Max } I_p = 500 \text{ A } ]\) is shown on Table 2. As long as the pulse width is kept long, the lifetime of the flashlamp can be extended even at high input energies.

In order to have long square-wave pulses, pulse forming network with multiple LC series sections has been designed. Design parameters for the multisection PFN circuit can be calculated according to Ref.14 using the same relations and parameters as above unless otherwise specified below:

\[
\begin{align*}
V &= 2 \left[ K_0^2 \frac{E_0}{T_0} \right]^{1/3} \\
C &= \left[ \frac{E_0 T^2}{K_0^4} \right]^{1/3} / 2 \\
L &= \left[ \frac{T_0^4 K_0^4}{E_0} \right]^{1/3} / 2 \\
C_0 &= C / n \\
L_0 &= L / n \\
\tau_{\text{rise}} &= \left[ L_0 C_0 \right]^{1/2} \\
Z_0 &= \left[ \frac{L}{C} \right]^{1/2} \\
I &= \frac{V}{2Z_0} \\
I_p &= \frac{V}{(Z_0 + R_t)}
\end{align*}
\]

where \( n \) is the number of the LC sections, \( C \) is capacitance of total charging capacitors, \( L \) is total inductance, \( C_0 \) and \( L_0 \) are each sectional capacitance and inductance, respectively, and \( \tau_{\text{rise}} \) is risetime of the square wave pulse. Typical pulse forming network with 3 LC sections is shown in Fig.3 and the calculated parameters for the PFN circuit with the same ILC model 4L3
flashlamp are listed on Table 3. The computer programs used in a HP9845B computer for the above calculations are found in the Appendix. The 3 LC section PFN designed for 300 J input energy and 1 ms pulse width with $C_0 = 150 \mu F$ and $L = 185 \mu H$ is being assembled for a preliminary setup in present time, and will be scaled up to higher energy and longer pulse width later.

The experimental arrangement to be used for the rare earth laser system with the flashlamp pumped Cr:GSAG laser pumping is shown in Fig. 4. The Cr:GSAG laser will be tuned with an internal prism to the absorption line of rare earth ions near typical diode laser wavelength which is around 790 nm, and then will be focused by a lens to the rare earth ion doped crystal through the highly reflective mirror for the rare earth laser. Narrow line pumping of the rare earth lasers with the Cr:GSAG laser will be useful to study the energy transfer processes and their effect on laser performance, and will enable simulation of high power diode laser pumping. Q-switching experiment will be also performed to study the efficiency of energy transfer mechanisms for short pulse DIAL and Doppler Lidar operation.

II. Flashlamp-Pumped Rare Earth Laser System

1. Introduction

Recently, codoping Cr$^{3+}$-ions in rare earth ion doped crystals has been demonstrated by many research groups as an effective way to improve efficiency of flashlamp pumped laser systems. Diode-pumped rare earth lasers are promising candidates for the space-borne lidar system in the mid-infrared spectral region. However, we see from the situation of the current technology that the flashlamp pumped laser systems have still several practical advantages over the diode-pumped lasers, although the latter have an order of magnitude higher efficiency and more easily obtain room temperature operation. The major advantages are that the
flashlamp systems are well developed and easily accessible. Especially in high laser energy (or power) applications the technology for the flashlamp pumped laser system is well developed compared to that for the diode lasers and capable to deliver a high laser energy (or power) at a relatively low cost. Thus, understanding of the mechanisms of the energy transfer processes between the chromium ions and rare earth ions such as Tm$^{3+}$, Ho$^{3+}$ and Er$^{3+}$ is very important to determine optimum doping concentrations and a proper host material, and to increase the laser efficiency. During this report period we have prepared for the flashlamp pumped and liquid nitrogen cooled rare earth laser system, which is shown in Fig.5, to study the laser characteristics of three Ho$^{3+}$:Cr$^{3+}$:Tm$^{3+}$:YAG crystals provided by Coherent Laser Technology Company and to determined the optimum Tm$^{3+}$ concentration in the Ho$^{3+}$:Cr$^{3+}$:Tm$^{3+}$:YAG crystals.

2. Flashlamp Pumped Rare Earth Laser Experiment

Fig.5 shows the typical energy transfer processes among Ho$^{3+}$, Cr$^{3+}$ and Tm$^{3+}$ ions the YAG crystal. The broad $^4T_1$ and $^4T_2$ states of the Cr$^{3+}$-ions provide an efficient absorption of the flashlamp light and energy transfer takes place from the $^4T_1$ state of the Cr$^{3+}$-ion to the $^3H_4$ state of the Tm$^{3+}$-ion and from the $^4T_1$ state to the $^3H_4$ through a cascade transition to the $^4T_2$ state. Then, when the Tm$^{3+}$ ions in the $^3H_4$ state make transitions to the $^3F_4$ state, the transition energy is used to excite another Tm$^{3+}$-ion from the ground state to the $^3F_4$ state. This, so called cross-relaxation phenomenon, will provide two excited Tm$^{3+}$ ions for one single pump photon by increasing the quantum efficiency to 2. Then the excited Tm$^{3+}$ ions transfer to the $^5I_7$ state of the Ho$^{3+}$ ions and the 2.1 μm laser transition takes place between the $^5I_7$ and $^5I_8$ states of the Ho$^{3+}$ ions. Since the crystals provided by Coherent Laser Technology Company have different Tm$^{3+}$-ion concentrations with fixed Cr$^{3+}$ and
Tm$^{3+}$-ion concentrations, the normal mode and Q-switched laser study on those crystals at various operating temperatures as well as the spectroscopic study will provide information on the energy transfer processes among those three ions and enable us to determine optimum Tm$^{3+}$-ion concentration in the Ho$^{3+}$:Cr$^{3+}$:Tm$^{3+}$:YAG crystal for the best flashlamp pumped and Q-switched 2.1$\mu$m laser performance.

In order to test the system performance we have taken normal mode laser operation of a Ho$^{3+}$:Er$^{3+}$:Tm$^{3+}$:YAG crystal under flashlamp pumping at various operating temperatures and with various output mirror reflectivities. The crystal had a doping concentration of 0.02 Ho$^{3+}$, 0.40 Er$^{3+}$ and 0.06 Tm$^{3+}$, and its dimension was 5 mm in diameter and 90 mm in length. A single LC section pulse forming network of $C=146.5$ $\mu$F and $L=184$ $\mu$H was used to generate discharge pulses with current pulse width of 500 $\mu$s (= $T_o$) at the capacitor charging voltage of 909 volts (= $V_o$) at which the corresponding electrical input energy was 60 $J$ (= $E_o$). The normal mode laser output energy as a function of the electrical input energy were measured at various operating temperatures with a 95% and 98% reflective output mirrors, respectively, as shown in Figs.7 and 8. As the operating temperature was decreased, the slope efficiency was increased and the threshold energy was decreased. The various electrical input energies were obtained by changing the charging voltage. Fig.9 shows the normal mode laser output of the same crystal obtained with various output mirror reflectivities as a function of the electrical input energy at the operating temperature of 170 oK. The normal mode laser output measurement was taken without the Q-switch crystal and polarizer in the experimental setup shown in Fig.5, and the resonator length was 91 cm.

Finally, the normal mode laser output was measured with a 2.17 mm thick ZnSe plate placed at the Brewster angle (= 67.8°) in the normal mode laser resonator to measure the optical loss caused
by the ZnSe polarizer. Figs.10 and 11 show the difference of the normal mode laser output between without and with ZnSe plate in the resonator. Optical loss in the ZnSe plate could be estimated by observing the variation of the slope efficiency with mirror reflectivity. The slope efficiency $\sigma_s$ is assumed to vary with the output mirror reflectivity $R_m$ according to Ref.16 as

$$\sigma_s = \sigma_{sm} \ln(R_m)/\ln(R_m RL)$$

where $R_L$ is a fictitious mirror reflectivity representing the losses in the system and $\sigma_{sm}$ is the maximum slope efficiency obtainable from the material. $R_L$ is related to the losses $L$ in the system as $R_L = 1 - L$. The above equation can be rewritten as

$$1/\sigma_s = (- \ln R_L/\sigma_{sm}) (- 1/\ln R_m) + (1/\sigma_{sm})$$

The inverse slope efficiency is plotted as a function of $-1/\ln R_m$ in Fig.12 using the data shown in Figs.10 and 11. From the slopes and y-intercepts of the two lines, each corresponding to results obtained with and without ZnSe plate in the resonator, respectively, we obtain $R_L = \exp(-20.868/64.681) = 0.72425$ for the case of the ZnSe plate placed in the resonator and $R_L = \exp(-16.953/78.465) = 0.80569$. Thus, the loss coefficient of the ZnSe plate is calculated as $\alpha = L_{\text{with}} - L_{\text{without}} = (1 - R_L \text{ with}) - (1 - R_L \text{ without}) = 0.081$ (or $0.081/0.217 \text{ cm} = 0.375 \text{ cm}^{-1}$). This means that the ZnSe plate causes only 8% loss of the laser efficiency.
## Table 2. Calculated Parameters for Single-LC-Section Pulse Forming Network.

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<td>8858</td>
<td>327.2</td>
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<tr>
<td>1000</td>
<td>4.53E-04</td>
<td>2.45E-04</td>
<td>1328.2</td>
<td>1369.3</td>
<td>34.9E-03</td>
<td>8851</td>
<td>327.4</td>
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</tr>
</tbody>
</table>
III. Conclusion

We have calculated pulse forming network parameters for long square-wave typed flashlamp pulse generation and have prepared for construction of a flashlamp-pumped Cr$^{3+}$:GSAG laser of pulsed laser greater than 200 mJ and of pulse width of 1 ms FWHM. This Cr:GSAG laser will be used to pump 2 - 3 μm lasers using mid-infrared laser crystals such as Tm$^{3+}$, Er$^{3+}$ and/or Ho$^{3+}$-ion doped YAG, YLF or other host materials. We have also completed a modification of an existing flashlamp-pumped and liquid-nitrogen-cooled rare earth laser system for 60 J electrical input energy and 500 μs pulse width to determine optimum Tm$^{3+}$-ion concentration in Ho$^{3+}$:Cr$^{3+}$:Tm$^{3+}$:YAG crystal, and have carried out preliminary experiments with a Ho$^{3+}$:Er$^{3+}$:Tm$^{3+}$:YAG crystal to test the system performance. The slope efficiency of the Ho$^{3+}$:Er$^{3+}$:Tm$^{3+}$:YAG laser increased as the operating temperature decreased and the highest slope efficiency obtained with a 60% reflective mirror was 0.88%. The optical loss coefficient of a 2.17 mm thick ZnSe plate placed at the Brewster angle in the laser resonator as a polarizer was measured to be 0.0814.
<table>
<thead>
<tr>
<th>Material</th>
<th>Ion Concentration</th>
<th>Laser λ (µm)</th>
<th>Diode Power</th>
<th>Laser Output</th>
<th>Threshold</th>
<th>Slope Efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm,Ho:YLF</td>
<td>1.5% Tm</td>
<td>2.31 (Tm)</td>
<td>21 mW</td>
<td>5.5 mW</td>
<td>10.5 mW</td>
<td>42%</td>
<td>ref. 2</td>
</tr>
<tr>
<td></td>
<td>0.2% Ho</td>
<td>2.08 (Ho) @ 791 nm</td>
<td></td>
<td></td>
<td>3.1 mW</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>Tm,Ho:YAG</td>
<td>5.7% Tm</td>
<td>2.1 μm</td>
<td>100 mW</td>
<td>2.7 mW</td>
<td>3.8 mW</td>
<td>17%</td>
<td>ref. 3</td>
</tr>
<tr>
<td></td>
<td>0.36% Ho</td>
<td></td>
<td></td>
<td></td>
<td>absorbed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr,Tm,Ho:YAG</td>
<td>2.5 x 10^20 cm^-3 Cr</td>
<td>2.1 μm</td>
<td>1.2 mW</td>
<td>4.4 mW</td>
<td>absorbed</td>
<td>19%</td>
<td>ref. 4</td>
</tr>
<tr>
<td></td>
<td>8 x 10^20 cm^-3 Tm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 x 10^19 cm^-3 Ho</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Er,Tm,Ho:YLF (at T=770K)</td>
<td>1 at wt % Ho</td>
<td>2.06 μm @ 784 nm</td>
<td>200 mW</td>
<td>20 mW</td>
<td>5 mW</td>
<td>20% (Conversion efficiency)</td>
<td>ref. 5</td>
</tr>
<tr>
<td></td>
<td>50 % Er</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12% Tm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Er,Tm,Ho:YAG (at T=770K)</td>
<td>60 % Er</td>
<td>2.1 μm @ 785.5 nm</td>
<td>100 mW</td>
<td>5.6 mW</td>
<td>40 mW</td>
<td>19%</td>
<td>ref. 6</td>
</tr>
<tr>
<td></td>
<td>3% Tm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2% Ho</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Er:YLF</td>
<td>8% Er</td>
<td>2.8 μm</td>
<td>200 mW</td>
<td></td>
<td></td>
<td>147 mW</td>
<td>ref. 7</td>
</tr>
</tbody>
</table>

* * with respect to absorbed pump power.
Table 3. Calculated Parameters for Multi-LC-Section Pulse Forming Network.

<table>
<thead>
<tr>
<th>INPUT ENERGY</th>
<th>PULSE WIDTH</th>
<th>TOTAL CAPAC.</th>
<th>TOTAL INDUCT.</th>
<th>VOLT.</th>
<th>SECTION CAPAC.</th>
<th>SECTION INDUCT.</th>
<th>RISE TIME</th>
<th>PEAK CURRENT</th>
<th>BLKBODY TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>200 J</td>
<td>1.06E-04</td>
<td>9.41E-05</td>
<td>1372</td>
<td>3.54E-05</td>
<td>3.14E-05</td>
<td>33</td>
<td>637</td>
<td>8732</td>
</tr>
<tr>
<td>200</td>
<td>200 200</td>
<td>1.34E-04</td>
<td>7.47E-05</td>
<td>1728</td>
<td>4.46E-05</td>
<td>2.49E-05</td>
<td>33</td>
<td>882</td>
<td>8773</td>
</tr>
<tr>
<td>300</td>
<td>200 300</td>
<td>1.53E-04</td>
<td>6.52E-05</td>
<td>1978</td>
<td>5.11E-05</td>
<td>2.17E-05</td>
<td>33</td>
<td>1060</td>
<td>8797</td>
</tr>
<tr>
<td>400</td>
<td>200 400</td>
<td>1.69E-04</td>
<td>5.93E-05</td>
<td>2177</td>
<td>5.62E-05</td>
<td>1.98E-05</td>
<td>33</td>
<td>1206</td>
<td>8813</td>
</tr>
<tr>
<td>500</td>
<td>200 500</td>
<td>1.82E-04</td>
<td>5.50E-05</td>
<td>2345</td>
<td>6.06E-05</td>
<td>1.83E-05</td>
<td>33</td>
<td>1330</td>
<td>8827</td>
</tr>
</tbody>
</table>

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References


8. William F. Krupke, "Semiconductor laser-diode-pumped solid-


11. ILC Technology Company Technical Bulletins (1 & 2) and Catalog on Flashlamps, 399 Java Dr., Sunnyvale, CA 94089, (1980).


15. Michael D. Williams, by private communication.

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(0.02 Ho, 0.40 Er, 0.06 Tm), 5 mm x 90 mm rod, C=146.5 μF, L=184μH, Flashlamp pulse width (FWHM) = 300 μs.
Figure 8. Normal mode laser output energy of Ho:Er:Tm:YAG crystal as a function of electrical input energy at various operating temperatures with a 98% reflective output mirror.

(0.02 Ho, 0.40 Er, 0.06 Tm), 5 mm x 90 mm rod, C=146.5 μF, L=184 μH, Flashlamp pulse width (FWHM) = 300 μs.
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Ho:Er:Tm:YAG (0.02 Ho, 0.40 Er, 0.06 Tm), 5 mm x 90 mm rod, T=170 K, with a 10 MCC HR mirror, 146.5μF, 184μH, and pulse width of 300μs FWHM. Laser beam angle on the plate = 67.8 degree (Brewster angle).
Figure 11. Loss coefficient measurement of ZnSe plate in a Ho:Er:Tm:YAG laser resonator with output mirrors of reflectivities of 80% and 98%.

Ho:Er:Tm:YAG (0.02 Ho, 0.40 Er, 0.06 Tm), 5 mm x 90 mm rod, T=170 K, with a 10 MCC Hr mirror, 146.5µF, 184µH, and pulse width of 300 µs FWHM. Laser beam angle on the plate = 67.8 degree (Brewster angle).
Figure 12. Inverse slope efficiency versus $-1/\ln R_m$ with and without ZnSe plate in a flashlamp-pumped Ho:Er:Tm:YAG Laser.
Appendix

Computer Programs for Pulse Forming Network Parameter Calculation
Computer Program for Multi-LC-Section Pulse Forming Network Design

```
10    PRINT "-----------------------------------------------"
20    PRINT "                                      "
30    PRINT "MULTISECTION PULSE FORMING NETWORKS "
40    PRINT "                                      "
50    PRINT "-----------------------------------------------"

60    PRINT USING 330;"INPUT ","PULSE "
    PRINT USING 330;"E "," WIDTH "
    PRINT USING 330;"CAPACI. "," INDUCT. ", "
70    PRINT USING 330;"ENERGY "," TIME "
75    PRINT USING 330;"CURRENT "
80    PRINT USING 330;"TEMP. "
90    S=7.62 ! ARC LENGTH ( cm )
100   D=.4 ! BORE DIAMETER ( cm )
110   FOR E=100 TO 500 STEP 100
120   I=0
130   PRINT "-----------------------------------------------"

140   FOR To=200 TO 2000 STEP 200
150   ! E INPUT ENERGY
160   ! To PULSE DURATION
170   T=To*10^(-6) ! PULSE DURATION ( sec )
180   Vo=2*(Ko^-2*E/T)^(1/3) ! SUPPLY VOLTAGE
190   C=.5*(E*T^2/Ko^-4)^(1/3) ! TOTAL CAPACITANCE
200   L=.5*(T^4*Ko^-4/E)^(1/3) ! INDUCTANCE
210   Lo=L/3 ! SECTION INDUCTANCE
220   Co=C/3 ! SECTION CAPACITANCE
230   Rt=50*(Lo*Co)/10^(-6) ! RISE TIME
240   Zo=50*(L/C) ! IMPEDANCE PARAMETER
250   K0=.5*Vo*Zo^(1/2) ! IMPEDANCE PARAMETER
260   Ip=Vo/(Zo+.02*S/(3.14*(D/2)^2)) ! PEAK CURRENT
270   Ca=3.14*(D/2)^2 ! CROSS SECTION
280   T=(9450*(D/100)^0.9*3*(Ia/Ca)^0.1)^6+(93*(D/100)^2.27*(Ia/Ca)^3.4)^6^(1/6)
290   ! TEMPERATURE
300   IF I=0 THEN PRINT USING 340;E,To,C,L,Vo,Co,Lo,Rt,Ip,T
310   IF I>0 THEN PRINT USING 350;To,C,L,Vo,Co,Lo,Rt,Ip,T
320   IMAGE 6A,2X,6A,1X,7A,2X,7A,2X,7A,3X,7A,2X,5A,1X,6A,1X,7A
330   IMAGE 4D,2X,2D,2X,1D.DDE,2X,1D.DDE,2X,4D,2X,1D.DDE,2X,1D.DDE,2X,4D,2X,5D,3D,6D
340   IMAGE 6X,2D,2X,1D.DDE,2X,1D.DDE,2X,4D,2X,1D.DDE,2X,1D.DDE,2X,4D,2X,5D,3X,6D
350   IMAGE 6X,6D,2X,1D.DDE,2X,1D.DDE,2X,4D,2X,1D.DDE,2X,1D.DDE,2X,4D,2X,5D,3X,6D
360   I=1
370   NEXT To
380   NEXT E
390   PRINT "-----------------------------------------------"
400   END
```

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Computer Program for Single-LC-Section Pulse Forming Network Design

10 PRINT "----------------------------------------"
20 PRINT "FLASHLAMP PULSE FORMING NETWORK"
30 PRINT "----------------------------------------"
40 PRINT "----------------------------------------"
50 PRINT "----------------------------------------"

60 PRINT USING 350;"PULSE "," PULSE ","CAPACIT. ","INDUCT. "," VOLT ","EXPLO.
70 PRINT USING 350;"LIFE ","BLKBDY. "," PEAK "," PEAK "," ENERGY ","WAVELEN. ","CURRENT"
80 PRINT USING 350;"I ","usec ","F ","H ","V ","J
90 FOR Eo=100 TO 500 STEP 100
100 I1=0
110 PRINT "----------------------------------------"
120 FOR To=100 TO 1000 STEP 100
130 T=To/3 !TIME CONSTANT
140 Ko=25 !IMPEDEANCE PARAMETER
150 Ke=7.5E4 !EXPLOSION ENERGY CONSTANT
160 A=.8 !CRITICAL DAMPING
170 C=(2*Eo*A^4*(T*10^(-6))^2+Ko^(-4))^(-1/3) !CAPACITANCE (F)
180 L=(T*10^(-6))^2/C !INDUCTANCE (H)
190 V=(2*Eo/C)^(-1/2) !VOLTAGE (V)
200 Ex=Ko*(T*10^(-6))^(-1/2) !EXPLOSION ENERGY
210 I=V^2/Ko^2 !CURRENT
220 Life=(Eo/Ex)^(-8.5)^10^6 !LIFE OF FLASH
230 Zo=50*(C/L) !IMPEDANCE
240 Re=.02 !FLASH RESISTIVITY FOR 100us<t<1ms
250 Le=7.3E2 !ARC LENGTH(cm)
260 Bo=.4 !BORE DIAMETER(cm)
270 Rt=Re*Le/(3.14*(Bo/2)^2) !FLASH RESISTANCE
280 Ip=V/(2o+Rt) !PEAK CURRENT
290 Ca=3.14*(Bo/2)^2 !CROSS SECTION (cm^2)
300 Do=Bo/100 !BORE DIAMETER (m)
310 Te=((9450*D-0.03*(I/Ca)^.01)^6+(93*D-.27*(I/Ca)^.34)^6)^(-1/6) !TEMPERATURE
320 Wm=2.898E6/Te !PEAK WAVELENGTH (nm)
330 IF I1=0 THEN PRINT USING 360;Eo,To,C,L,V,Ex,Life,Te,Wm,Ip
340 IF I1<0 THEN PRINT USING 370;To,C,L,V,Ex,Life,Te,Wm,Ip
350 IMAGE 6A,1X,6A,2X,7A,2X,7A,2X,5A,3X,6A,1X,6A,2X,7A,1X,8A,1X,7A
360 IMAGE 6D,1X,4D,2X,1D.DDE,2X,1D.DDE,2X,4D.D,2X,2D.D,2X,4D.D,2X,4D.D,2X,4D.D,2X,4D.D,2X
370 IMAGE 7X,4D,2X,1D.DDE,2X,1D.DDE,2X,4D.D,1X,4D.D,2X,2D.D,2X,4D.D,1X,4D.D,2X,2D.D,2X
380 I1=1
390 NEXT To
400 NEXT Eo
410 PRINT "----------------------------------------"  
420 PRINT "----------------------------------------"  
430 END