A Flashlamp-Pumped, Q-Switched Cr: Nd: GSGG Laser

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Abstract—A long-pulse Cr: Nd: GSGG laser was operated at almost 2 J output energy and almost 5 percent efficiency, using an uncooled pump cavity. An Nd: YAG rod in the same pump cavity produced 3.75 percent efficiency. Using a water-cooled pump cavity of standard design, the thermal focusing of Cr: Nd: GSGG was found to be almost six times that of Nd: YAG for the same flashlamp input energy. The thermal birefringence of the GSGG was also observed to be significantly higher than that of YAG. The performance of a Q-switched Cr: Nd: GSGG laser was characterized and compared to the predictions of a mathematical model for the laser. This yielded an estimate of $4.2 \times 10^{-19} \text{cm}^2$ for the peak stimulated emission cross section of Nd$^{3+}$ in GSGG. Using the same technique for Nd: YAG yielded a value of $9 \times 10^{-19} \text{cm}^2$.

I. INTRODUCTION

In many applications of the neodymium laser its energy efficiency is important because this impacts its size and weight, and can affect its reliability. In some lasers the efficiency can determine whether liquid cooling, or a less cumbersome cooling technique is required. So considerable effort has been expended toward improving the energy efficiency of neodymium lasers, particularly the Nd: YAG laser. Codoping of Nd: YAG with Cr$^{3+}$ to increase the energy efficiency of a laser using this material has been accomplished with some success for CW-pumped lasers. However, the measured Cr$^{3+} \rightarrow$ Nd$^{3+}$ transfer time of 6.2 ms [1] prevents the Cr$^{3+}$ from being an effective sensitizer for Nd: YAG pulse-pumped lasers.

Recently, a new neodymium laser host material has emerged which is more effectively sensitized by Cr$^{3+}$: gadolinium scandium gallium garnet (GSGG). It has been shown to be a more efficient laser material than Nd: YAG when pulse-pumped [2] and has also been efficiently CW-pumped with a krypton laser [3]. The Cr$^{3+} \rightarrow$ Nd$^{3+}$ transfer time has been measured to be 17 $\mu$s [3]. The objectives of the work to be reported here were twofold.

1) To maximize the efficiency of a flashlamp-pumped Cr: Nd: GSGG laser.

2) To fully characterize the material for its use in a flashlamp-pumped, Q-switched laser.

II. EXPERIMENTAL APPARATUS

The laser testing was accomplished using two pump cavities and several resonator configurations. Fig. 1 shows a cross section of the pump cavity which was used to obtain high-efficiency laser operation. It consists of coaxial Pyrex tubes, between which BaSO$_4$ powder is packed. The end plates are of aluminum with BaSO$_4$ on the inner surfaces. The pump cavity is 2.5 in long and the center-to-center spacing of the lamp and rod is 0.4 in. There is no provision for cooling with this cavity, so that laser tests were done using a pulse repetition frequency (PRF) of 2 Hz, and operating the laser only for short time periods. The pulse forming network (PFN) used with the high-efficiency laser had a capacitance of 95 $\mu$F and an inductance of 25 $\mu$H, for a current pulsewidth of about 150 $\mu$s.

With the exception of the high-efficiency long-pulse laser tests, all experiments were done using a silver-plated pump cavity of standard design which was cooled using deionized water. This allowed operation at high PRF's, and for long periods of time.

The $Q$-switching experiments were carried out using a resonator whose optical schematic is shown in Fig. 2. The polarizer splits the beam into orthogonal polarizations, which counterpropagate around the ring at the prism end of the resonator. A half-wave voltage pulse applied to the LiNbO$_3$ Pockels cell (about 6 kV for our cell) opens the $Q$-switch. The output beam from this resonator is unpolarized.

III. RESULTS AND ANALYSIS

A. Laser Rod Characterization

Table I summarizes the specifications and results of passive tests on the two Cr: Nd: GSGG rods, obtained from Union Carbide. The dopant concentrations were com-
Fig. 2. Optical schematic of the resonator used in the Q-switched laser experiments.

**TABLE I**
Cr: Nd: GSGG LASER ROD SPECIFICATIONS AND PASSIVE TEST RESULTS

<table>
<thead>
<tr>
<th>Rod Size</th>
<th>0.250 x 3.00 INCHES</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOPANT CONCENTRATIONS</td>
<td>Nd 1.56 ATOMIC %</td>
</tr>
<tr>
<td>[CALCULATED]</td>
<td>Cr 1.18 ATOMIC %</td>
</tr>
<tr>
<td>INSERTION LOSS</td>
<td>4.5%</td>
</tr>
<tr>
<td>[1554 nm]</td>
<td></td>
</tr>
<tr>
<td>OPTICAL QUALITY</td>
<td>BETTER THAN % FRINGE FOR ROD LENGTH</td>
</tr>
<tr>
<td>Nd FLUORESCENCE LIFETIME</td>
<td>256 MICROSECONDS</td>
</tr>
<tr>
<td>Cr-Nd TRANSFER TIME</td>
<td>~15 MICROSECONDS</td>
</tr>
</tbody>
</table>

The last four entries in the table were determined from measurements performed on one of the rods at the Lawrence Livermore National Laboratory. Only one rod was available at the time of this testing, but subsequent laser testing indicates that the two rods are essentially identical from a laser performance viewpoint. About half of the 4.5 percent insertion loss is caused by reflection losses at the rod ends due to an error in the wavelength centering of the antireflection coatings. The Nd fluorescence lifetime and transfer time were determined from measurements performed on a small crystal from the laser rod boule, to eliminate the effects of radiation trapping. The transfer time determination was made from relatively crude data, so that the entry in the table is given as approximate.

**B. Long-Pulse Laser**

Fig. 3 shows the performance of the high-efficiency long-pulse laser, for both a GSGG and a YAG laser rod. The resonator used is shown in the inset. The reflectivities used for the coupling mirrors (50 percent for GSGG, 60 percent for YAG) were approximately optimum for the two lasers. The 5 mm-bore, 1500 torr Xe flashlamp, with Ce-doped quartz envelope, was found to provide the maximum laser output energy at flashlamp input energies above about 12 J compared to lower pressure lamps with Ti-doped envelopes.

Fig. 4 shows the laser's efficiency versus PFN stored energy: that of the GSGG laser is near 5 percent, while that for the YAG laser is about 3.75 percent. The YAG rod used in this laser was selected from three or four that were available, and is believed to be a better performer than an "average" YAG rod selected at random.

**C. Wavelength**

The lasing wavelength of Cr : Nd : GSGG was measured for a long-pulse laser operating at a PRF of 10 Hz, using a Jarrell-Ash 0.5 m monochromator. The detection system used a Hamamatsu R928 photomultiplier and a Keithley model 602 electrometer, whose output was displayed on a chart recorder. The second-order spectrum of a neon pen lamp was recorded simultaneously with the laser's output and served as a wavelength reference. The measured lasing wavelength is 10611.8 ± 0.1 Å.

**D. Thermal Focusing and Birefringence**

The thermal focusing strength of the GSGG rod, defined as the reciprocal of its focal length, is shown in Fig. 5 as a function of the average input power to the flashlamp (or, more precisely, the energy stored on the PFN capac-
itor times the PRF). The common technique of using a HeNe laser to measure the rod’s thermal focal length could not be used because the rod is opaque to this wavelength. There is also the question with this technique of whether the focal length is the same at the HeNe and laser wavelengths. The focal length was determined by measuring the beam divergence of the laser shown as an inset in Fig. 5, and using an ABCD ray-matrix calculation for the resonator to find the value of rod focal length which was compatible with it. To vary the average input power to the flashlamp, the PFN stored energy was kept constant at 14.5 J and the PRF was varied. The straight line through the data points in Fig. 5 is a least-squares fit to the data and has the equation

$$\frac{1}{f_{\text{rod}}(\text{cm})} = 0.0235 P_{\text{in}} (\text{kw}) + \text{constant}. \quad (1)$$

The constant in (1) is small, in keeping with the fact that the focusing power should vanish for the unpumped rod.

Fig. 6 shows the results of the same measurements repeated for a Nd:YAG laser rod. In this case the least-squares fit to the data is given by

$$\frac{1}{f_{\text{rod}}(\text{cm})} = 0.00398 P_{\text{in}} (\text{kw}) + \text{constant}. \quad (2)$$

The relative focusing powers of the two rods is given by

$$\frac{1}{f_{\text{rod}}(\text{GSGG})} = 0.0235 \quad \frac{1}{f_{\text{rod}}(\text{YAG})} = 0.00398 \quad 5.9. \quad (3)$$

It is not surprising that the thermal focusing of GSGG is stronger than that of YAG because the broad red, and particularly blue, pump bands of Cr [2], [3] lead to a higher thermal loading in GSGG. The smaller thermal conductivity (about two-thirds that of YAG) also contributes to an increased thermal focusing strength.

The thermally induced birefringence of GSGG was studied using the laser shown as well as an inset in Fig. 7. The laser’s output energy per pulse, as the S-polarized energy reflected from the polarizer, were observed as a function of average flashlamp input power. The PFN stored energy was kept constant and the PRF was varied. A couple of things are noteworthy in this figure. First, there is a precipitous drop in the output energy at small flashlamp input powers (<100 W). Second, there is an oscillatory character to the output energy which is not present in the data for Nd:YAG. The Nd:YAG data show a gentle, monotonically decreasing output energy, as shown in Fig. 8. This oscillatory character is apparently due to the varying spatial overlap between the resonator’s mode structure and the rod’s birefringence loss. At high average input powers the laser’s output beam, when observed with an IR viewer, resembles a spider-web, with somewhat irregular circles of high intensity separated by regions of lower intensity.

The polarizer output energy shown in Fig. 7 supports this view of the oscillatory character. Note that the sum of the laser and polarizer output energies is not constant with lamp input power, but is also oscillatory, particularly below 400 W input. This would be expected when the birefringence loss is perturbing the laser’s mode structure.

E. Q-Switching

The performance of the Q-switched laser is shown in Fig. 9. These data were taken at a PRF of 10 Hz, using the resonator shown in Fig. 2. Since the laser is unpolarized, birefringence characteristics of the laser rod do not affect the laser performance. The maximum efficiency of about 1.5 percent is limited by the relatively poor pump cavity (silver plating) and the optical loss of the Q-switch.
It is interesting to attempt to fit the laser data using a mathematical model for the laser Q-switching dynamics, in order to arrive at an estimate of the peak stimulated emission cross section \( \sigma \) for Nd in GSGG. The results of the analysis are shown in Fig. 9. It can be seen that a \( \sigma \) of \( 4.2 \times 10^{-19} \) cm\(^2\) fits the data very well, and that the fit to the data is fairly sensitive to the assumed value of the cross section: changing it by about 20 percent leads to a poor fit to the data. The mathematical model and the assumptions made in the analysis will be described next.

In the theory of Dishington [4], the output energy from a Q-switched laser is written as

\[
E_0 = E_i U \frac{(-1/2) \ln R}{L - (1/2) \ln R} \tag{4}
\]

where \( R \) is the reflectivity of the output mirror, \( L \) is the single pass loss coefficient of the resonator, \( E_i \) is the energy stored in the \( ^4F_{3/2} \) manifold (i.e., the total inversion in the rod multiplied by the laser photon energy), and \( U \) is a utilization factor which is the fraction of the inverted ions which produce stimulated emission. \( U \) is a function only of the ratio of the peak population inversion to the inversion at threshold. Besides \( E_i, L, \) and \( R \), which are parameters explicit in (4), this inversion ratio depends on \( A/k_i \sigma \), where \( A \) is the cross-sectional area of the beam in the rod, and \( k_i \) is the fraction of the inverted ions which reside in the upper laser level. The fraction \( k_i \) can be computed from the splitting of the \( ^4F_{3/2} \) manifold. An absorption measurement performed on a laser rod at room temperature yielded a value for the splitting of 60 cm\(^{-1}\), as shown in Fig. 10. An examination of the Nd:GSGG energy level structure indicates that the lasing transition probably originates from the upper level in this manifold [5]. The factor \( k_i \) is then computed to be 0.43 at 320 K (the laser rod operates slightly above room temperature).

With the exception of \( E_i \) and \( \sigma \), all of the remaining parameters in (4) are measurable. To compensate for edge losses, \( A \) was taken to be 90 percent of the rod’s geometrical cross-sectional area. \( R \) was measured to be 53.7 percent. \( L \) was measured using the Findlay–Clay technique [6] to be 14.3 percent. With only \( E_i \) and \( \sigma \) remaining to be determined, the following approach was taken for fitting the experimental laser output energy data: first a value of \( \sigma \) was assumed, and the value of \( E_i \), which produced agreement between theory and experiment at 80 mJ energy output, was found by trial and error. Finally, to generate the rest of the theoretical curve for a given value of \( \sigma, E_i \) was assumed to scale linearly with the PFN stored energy.

Because of the assumptions made in the above analysis (besides the explicit ones, the basic theory itself applies to a beam of uniform intensity propagating in the laser rod, which is not precisely the case in practice), it is difficult to assign a meaningful uncertainty to the above estimate of the cross section for Nd:GSGG. It is probably more revealing to repeat the above set of experiments and the analysis for a Nd: YAG laser rod and compare the values of the measured cross sections. The results for a Nd: YAG laser rod are shown in Fig. 11. Note that a cross section of \( 9 \times 10^{-19} \) cm\(^2\) provides a good fit to the data. There have been a number of experimental determinations of this parameter [7]–[12] and the reported values have ranged from \( 2.7 \times 10^{-19} \) to \( 8.8 \times 10^{-19} \) cm\(^2\). Thus, the Q-switched laser data indicate that \( \sigma \) for Nd:GSGG is about one-half that for Nd: YAG. The analyses also indicate that, for a fixed flashlamp input energy, the stored energy achieved in Cr: Nd: GSGG is about 1.85 times that for Nd: YAG.

**IV. Summary**

In summary, the Cr: Nd: GSGG laser rods tested were of excellent optical quality. The lasing wavelength was measured to be 10611.8 \pm 0.1 \AA. A long-pulse laser efficiency (laser output energy divided by PFN stored en-
ergy) of almost 5 percent was achieved, compared to 3.75 percent for a Nd: YAG laser rod in the same pump cavity. No attempt was made to optimize the Cr and Nd concentration in GSGG for maximum laser efficiency. The thermal focusing strength for GSGG is almost six times that of YAG for the same flashlamp input energy, and also exhibits a significantly higher thermal birefringence. An estimate of the peak cross section for stimulated emission yielded the value of $4.2 \times 10^{-19}$ cm$^2$; using the same technique to estimate the cross section for Nd: YAG yielded $9 \times 10^{-19}$ cm$^2$.

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REFERENCES

5. M. Shinn, Lawrence Livermore Laboratory, private communication.