Laser Diode CW Pumped Nd:YAG Laser

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Abstract—Efficient pumping of solid state lasers has been made possible by the advent of high-power laser diode arrays. These arrays can be used for direct band pumping, minimizing the amount of quantum defect in the laser system. In this paper we demonstrate the basic principles of this new technique by pumping a Nd:YAG crystal using a high-power laser diode operating at 810 nm. Comparison with the underlying theory will show excellent agreement of the general trends observed. Q-switched operation as well as observation of relaxation oscillations will tie the results presented in this paper to the ones described in “Flash Lamp Pumped Quanta Ray Nd:YAG Laser Experiment”, published earlier.

Keywords—Nd:YAG, Diode Pumping, Q-switching, Last Report of the Quarter.

I. INTRODUCTION

WAY BACK in the early days, the only method to achieve population inversion in a solid state gain medium like ruby was to hit the crystal as hard as possible using a flash lamp. This way, the first laser ever was operated. Unlike in gas lasers, where electric discharges (glow discharge in helium-neon, arc discharge in argon) cause the inversion, for the longest time no other method could be thought of to get the job done in solid state lasers. It is immediately obvious that flash lamp pumped lasers suffer from a number of severe disadvantages. A few of these are

- inefficient conversion from electrical to optical power
- inefficient pumping of the gain medium
- thermal loading of the gain medium
- no CW operation possible
- short lifetime of the flash lamp

Yet, flash lamps are still being used to pump solid state and dye lasers. This is due to the fact that flash lamps are fairly inexpensive and are capable of delivering a large amount of optical power in a short timespan. This feature makes them useful in pulsed laser systems, such as Q-switched lasers (described earlier).

As the processing techniques for the production of laser diodes become more and more refined, these devices seem to be the obvious replacement for flash lamp based pump sources. Since the wavelength of operation of a diode laser can be selected within certain bounds by choosing the appropriate combination of semiconductor materials, it is possible to engineer these devices according to the needs of various solid state laser gain media. This allows us to efficiently pump the gain medium without waisting a large amount of energy by heating the crystal.

A single diode laser can certainly not deliver enough power to pump a multiwatt solid state laser due to its small cavity volume. A solution to this problem is easily found by stacking multiple diode lasers into an array. Nowadays, these arrays are capable of producing more than 100 W of cw optical power. In the experiment described in this article, we used a 15 W laser diode array operating at 810 nm to pump a 7.5 mm long 1% doped Nd:YAG rod. The diode’s output power as a function of driving current is shown in Fig. 1.

II. EXPERIMENTAL SETUP

For the design of the resonator, we chose to use an L-shaped folded cavity configuration, with a flat dichroic folding mirror. This allowed for collinear pumping of the gain medium, therefore maximizing the spatial overlap between the pump and the cavity mode inside the crystal. A lens system was used to focus the diode’s light through the dichroic mirror into the Nd:YAG rod. To complete the resonator, we chose a hemispherical mirror configuration consisting of a 1 m curvature and a flat dielectric mirror. The flat mirror, being the output coupler (OC), had a power transmission of 2.5%, while the curved mirror was a high reflector (HR) with a reflectivity exceeding 99%. The gain medium was placed close to the folding mirror, 25 cm away from the HR and 41 cm away from the OC, to allow for efficient pumping.
After the cavity and the pump had been aligned well enough\(^1\) the laser started oscillating at the expected center wavelength of 1064 nm.

### III. First Principle Measurements

As a first experiment, we measured the signal power at 1064 nm as a function of the laser diode’s pump power at 810 nm. We expected to see next to no output power below a certain pump power and a linear increase in power after crossing this threshold value (similar to the behavior of laser diodes). This expectation was nicely confirmed as shown in Fig. 2. Using linear regression, the threshold value was determined to be 6.14 W. The differential efficiency, which is defined as the amount of increase in signal power per unit increase in pump power above threshold, was measured to be 6.4%. This is not too bad, even though larger values have been reported elsewhere. One can certainly improve the slope efficiency by optimizing the mode overlap between the pump and the fundamental cavity mode inside the gain medium while increasing the reflectivity of the OC. All in all, we are confident that we will be able to achieve an electrical to optical conversion efficiency of a few percent in the near future.

### IV. Relaxation Oscillations

As described in “Flash Lamp Pumped Quanta Ray Nd:YAG Laser Experiment”, fluctuations in pump power or mechanical vibrations changing the cavity Q will lead to relaxation oscillations. These oscillations are due to the finite response time of the coupled system consisting of the photon number and inversion population as described by the rate equations.

Using a Ge photodiode placed behind the HR, we could observe these oscillations using an RF spectrum analyzer. The peak in the spectrum could easily be spotted, even without disturbing the cavity manually. A small signal analysis of the dynamic rate equations predicts the following dependence of the oscillation frequency $\omega_s$ on the pumping ratio $r$, the upper-state lifetime $\tau_2$, and the cavity decay time $\tau_c$:

$$\omega_s = \sqrt{\frac{r - 1}{\tau_2 \tau_c}}$$  \hspace{1cm} (1)

This suggests that the square of the relaxation oscillation frequency should depend linearly on the pumping ratio $r$. This could be verified experimentally as shown in Fig. 3. Assuming $\tau_2 = 230 \mu s$, and knowing the cavity round-trip time $t_{RT} \approx 2L/c$, we should have been able to verify the losses inside the cavity. Running the numbers, we calculated a value that was at least an order of magnitude too small, knowing that the OC had a 2.5% transmission. Additional losses inside the cavity (e.g. scatter losses inside the crystal, reflections on the crystal surfaces) are likely to be present and should have increased the overall losses. A likely suspect is the pumping ratio. Since our alignment of the pump with respect to the cavity mode was certainly sub-optimal, the calculated threshold value of 6.14 W could easily be wrong. Decreasing the threshold value will increase the pumping ratios, therefore increasing the calculated losses, which can be seen from Eqn. 1.

### V. Q-switched Operation

Since the upper state lifetime $\tau_2$ for Nd:YAG is much larger than the cavity decay time $\tau_c$ in our experimental setup, Q-switched operation of the laser seemed feasible. The underlying principles of the Q-switching process have been explained elsewhere. An acousto-optic modulator (AOM) was placed inside the cavity and driven by a fast switchable high voltage source following a similar scheme to the one employed in the commercial QUANTA RAY Laser from SPECTRA-PHYSICS examined in a different experiment. In the commercial laser, an electro-optic

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\(^1\) Two groups – and Karel Urbanek – worked on that before the laser decided to oscillate.
modulator (EOM) served as the variable loss element inside the resonator. The advantage of using an EOM instead of an AOM are its larger bandwidth and improved dynamic range, resulting in the ability to store more energy inside the gain medium without a premature breakdown into oscillation. For our purposes, the AOM was more than good enough, since we only wanted to conduct a proof of principle.

We connected the AOM driver’s monitor output to the same oscilloscope as the photodiode which was placed behind the HR mirror and triggered on its trailing edge. A representative trace is shown in Fig. 4. We can clearly see the typical features of Q-switched pulses predicted by the theory. The leading edge exhibits a fast rise-time while the trailing edge of the pulse decays more slowly due to the finite cavity lifetime.

A more quantitative investigation of the Q-switched operation was also performed, measuring the pulsewidth $\tau_p$ as well as the build-up time $\tau_d$ of the pulse as a function of pump power. Recalling the following theoretical relations for these two quantities, we can see that the data shown in Fig. 5 follows the predicted trend quite nicely.

$$\tau_d \approx \frac{25}{r - 1} \tau_c \quad \text{and} \quad \tau_p \approx \frac{r}{r - 1} \tau_c$$

It should not be left unsaid that due to difficulties in exactly measuring the build-up time and the above mentioned uncertainties regarding the correct determination of the pump threshold, the data shown in Fig. 5 don’t agree perfectly with the theoretically predicted values. Yet, it shows the right trend, which is as well for this part of the experiment.

Once again, we would like to point out, that our investigations of this new laser diode pumping scheme haven’t been perfected and that general trends are all we wanted to prove at this point.

VI. Conclusions

In this article, we qualitatively proved a new pumping scheme for solid state lasers. This scheme used a high-power laser diode array as the pump source for a Nd:YAG laser oscillator. We have shown that diode pumped solid state lasers (DPSS) have major advantages over their flash lamp pumped counterparts and will therefore most probably be found more frequently in the near future. A commercialization of this new type of solid state laser system is likely to occur within the next few years.

We have also measured the relaxation oscillation of the gain medium as well as shown Q-switched operation using an intracavity AOM. The results were in good agreement with theoretical predications and future measurements are likely to produce even closer absolute agreement. A more careful alignment of the pump source inside the gain medium will help to increase the differential efficiency as well as help to determine the correct pump threshold.

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