Flash Lamp Pumped Quanta Ray
Nd:YAG Laser Experiment

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Abstract—Since the advent of Nd:YAG as a gain medium for laser oscillators and optical amplifiers, its long upper state lifetime and high damage threshold have been advantageously exploited for the generation of high-energy Q-switched pulses. In this paper we present experimental results of a “prototype” \(^1\) flash lamp pumped Q-switched laser with built-in single pass amplifier. Large peak power pulses could be generated and were used to ionize a gas mixture consisting of nitrogen, oxygen, argon, neon, and helium among others. For some parameters, quantitative agreement between experimental results and theoretically predicted values could not be achieved to a satisfactory degree.

Keywords—Nd:YAG, Spiking, Q-switching, Quanta-Ray.

I. INTRODUCTION

The generation of short coherent high-energy optical pulses has been subject to many years of research [1] and will most likely stay a current research topic for many more years to come. Applications for these pulses can be found in diverse fields such as nonlinear optics [2] (e.g. SHG, THG, etc.), medicine (e.g. spot welding of blood vessels, laser hair removal, etc.), and energy generation (e.g. inertial confinement fusion (ICF)) to list only a few.

There are several techniques that allow the creation of short, high peak power laser pulses. We can distinguish between methods capable of generating ultrashort pulses in the femtosecond domain ([3], [4]) and methods for the generation of nanosecond long pulses. Obviously, the notion of what constitutes an ultrashort pulse changes over time as new methods are being invented to generate even shorter pulses. Let me mention just a few of the more popular methods for the generation of ultrafast pulses.

- additive pulse modelocking (APM)
- colliding pulse mode locking (CPM)
- Kerr-lens mode locking (KLM) [5]
- extra cavity optical pulse compression [6]

For an in depth description of modelocking see [7].

To generate so-called “giant” pulses in the nanosecond regime, one can use one of the following methods.

- cavity dumping
- Q-switching
- large-amplitude pump modulation (spiking)

In this article, we present experimental data taken with a Q-switched Nd:YAG laser with built-in single pass amplifier (Spectra-Physics QUANTA-RAY). We attempted to characterize this device and compare its parameters with theoretically predicted values.

\(^1\)This word was added to make this experiment sound more cutting edge. Turning on a well behaved commercial laser just doesn’t have a nice ring to it.
ference will start to decrease, but the photon number will keep growing until the upper laser level is depleted. Once $N_{\text{th}}$ is reached, there are no more photons that could be added to the circulating photons and the photon number will start to decrease due to absorption. At the moment where most of the photons have been absorbed, the population difference will rise once again, since the pump source is still supplying energy. It is easy to see that this cycle repeats until steady state is reached due to the fact that in each cycle, a growing number of photons remains inside the cavity mode. Therefore, the initial conditions for this cycle change from pulse to pulse until steady state is reached.

This process just described is called relaxation oscillation (or spiking) and is present in every laser system at pump turn on if $\tau_s \gg \tau_e$. If a repetitive pulsed pump is being used, it can be easily observed using a fast photodetector as shown in Fig. 1. This method of generating pulsed output pulses can be modified to extract a single pulse by appropriately choosing the pulse length of the pump source. If we can turn off the pump after the first pulse has reached its maximum, no further pulses can be generated. This is already very similar to Q-switching, which we will examine next.

If we could somehow prevent the photon number from building up while the gain medium is being pumped, we could easily exceed the population difference’s threshold value and therefore store more energy in the upper laser level. This, of course, is only efficient as long as we do not exceed the upper state lifetime of the gain medium, since spontaneous emission will then start equilibrating the population difference. At this point every additional energy supplied by the pump will be wasted in spontaneously emitted photons. Before this happens we have to let stimulated emission take over, so we can extract the stored energy as a coherent laser pulse.

The question is, how to influence the build-up of radiation by stimulated emission during the pump period? If we increase the round-trip losses inside the cavity beyond the small signal gain of the gain medium, laser oscillation cannot start. Doing so, we change the quality of the resonator, hence the “Q” in Q-switching. This spoiling of the cavity’s Q can be achieved by introducing a fast switchable loss element, such as an acousto-optic modulator (AOM) or electro-optic modulator (EOM), into the cavity. Other methods exist, such as rotating prisms or output couplers.

III. Experimental Results Using The Quanta-Ray Q-switched Laser

The laser used in this experiment was a Q-switched Nd:YAG laser (Spectra-Physics Quanta-Ray) with built-in single pass power amplifier. The pump energy for the master oscillator and the power amplifier could be adjusted separately, which allowed us to examine the gain of the amplifier at various pumping levels. A qualitative picture of a Q-switched pulse generated by this laser was already shown in Fig. 1. We will now examine the behavior of this laser in more detail.

A. It’s All About The Right Timing…

First, we measured the master oscillator’s output power as a function of Q-switch delay with the amplifier not being pumped at all. The results for two different pump energies are shown in Fig. 2. Let us try to understand what this graph tells us and why it makes sense. The Q-switch delay is defined with respect to the triggering of the pump pulse exciting the gain medium. It should be obvious after our previous discussion that a long delay between the pump and the switching of the cavity Q$^3$ will cause a decrease in the population difference caused by spontaneous emission. The energy lost will not be available for the generation of the coherent pulse, thus decreasing the output pulse’s energy. Too short a delay will result in a reduction of the output energy as well, since the population difference didn’t have enough time to reach its maximum value.

For continuity reason, it is easy to see that there must be an optimal delay between the pump pulse and the switching of the loss element that maximizes the output energy. Fig. 2 clearly shows the existence of this maximum and the overall trend as discussed above.

B. Rise And Shine

Besides the output pulse’s energy, another very important parameter is the temporal width of the pulse, since this, together with the total energy per pulse, determines its peak power. Looking at Fig. 1 we can clearly see that the pulse shape, thus its width, varies if we change the energy per pump pulse. Why is this the case? Without writing down the coupled differential equations describing the dynamic behavior of the population difference and

\[2\text{What this means will be explained below.}\]

\[3\text{This is done by eliminating the artificial loss introduced by either an AOM or EOM as discussed above.}\]
the photon number, we would like to give a more or less intuitive explanation for this behavior.

It is certainly true that the rate of change of the photon number must be driven by the initial population inversion at the time of the Q-switching. It is also clear that the population difference will increase if we are pumping more energy into the gain medium as long as we don’t change the time over which this happens. We can therefore conclude that the change in photon number and the pump energy of the oscillator are positively correlated. To normalize the pump energy, we introduce a parameter $r = E_{\text{pump}}/E_{\text{thr}}$, which represents how many times the pump energy exceeds the threshold value for oscillation.

A large $r$ will therefore cause an increase in the rate of change of the photon number, which can be translated into a faster rise and build-up time of the pulse as shown in Fig. 3. The definitions for the rise time $\tau_r$ and the build-up time $\tau_d$ are depicted in the inset in Fig. 3.

The rise time will therefore decrease with increasing pump energy. This is not true for the fall time of the pulse. Since we cannot drive the population inversion down, we have to wait for the circulating photons to empty the upper laser level. In the limit, we would expect a fall time of a few cavity lifetimes $^4$ ($\tau_c \approx 5$ ns). The lower right graph in Fig. 1, though, shows a fall time of a few hundred nanoseconds. The reason for this might be saturation of the photodetector or some kind of “afterglow” effect caused by the absorbing target hit by the high-energy pulse. In any case, this apparent discrepancy should not be taken to seriously, since other researchers have been successful in measuring the true pulse shape void this type of error.

$^4$The quoted value is taken from the specification sheet of the laser. In our measurements we measured the cavity lifetime to be about 0.36 ns. The reason for this discrepancy is unclear to the authors.

C. Pump Up The Volume

As mentioned earlier in this article, the Q-switched laser investigated offers a built-in single pass flash lamp pumped power amplifier. This amplifier enables us to generate pulses with energies in excess of 1 J with durations of a few nanoseconds. Assuming a 10 ns long pulse, this would result in a peak power of about 100 MW. Focusing this pulse to a 1 mm$^2$ spot size produces an intensity of 100 TW/m$^2$, a number of truly exorbitant dimensions. This enormous intensity is certainly the key for inertial confinement fusion.

Fig. 4 shows the absolute energy gain experienced by the Q-switched pulses after passing through the amplifier. It clearly shows the amplifier’s tendency toward saturation as the input power increases, which is equal to an increase in power extraction efficiency. The theoretical plot shown agrees well with the experimental data for high-energy input pulses $^5$

IV. Conclusions

In this article, we developed a qualitative picture that explains the basics about relaxation oscillation and Q-switching and presented experimental results to show the agreement between theory and experiment. Future measurements have to be performed to explain some of the quantitative discrepancies observed. A more precise knowledge about the oscillator’s parameters will be necessary to facilitate meaningful theoretical predictions.

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$^5$The discrepancy of the experimental data and the theory can be explained by the fact that the formula leading to the theoretical plot is only valid in the high-energy limit to start with.
REFERENCES


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