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Q-switching in a neodymium laser

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Abstract

We present a laboratory experiment for advanced undergraduate or graduate laser-related classes to study the performance of a neodymium laser. In the experiment, the student has to build the neodymium laser using an open cavity. After that, the cavity losses are modulated with an optical chopper located inside, so the Q-switching regime is achieved. Also a nonlinear crystal can be inserted in the cavity in order to have second harmonic generation. Finally, the relation between the transverse modes and the temporal emission in the Q-switching regime can be observed.

(Some figures may appear in colour only in the online journal)

1. Introduction

Q-switching is a technique used to obtain high power peak pulses of short duration (tens of nanoseconds, typically) [1, 2]. Although Q-switching is a technique to generate short pulses known since the 1960s, it continues to be necessary to develop simple experimental setups in order to teach its principles, since nowadays pulsed lasers by Q-switching are widely employed in many scientific fields and industrial applications.

For this purpose, we propose an experiment in which the student can observe some characteristic results of a Q-switched laser (temporal variations of the emission, typical pulse width and Q-switching with second harmonic generation).

The experiment is made with a neodymium-based laser pumped by a diode laser, since a great variety of neodymium crystals (mainly, Nd:YAG and Nd:YVO₄) and mirrors coated at their main laser wavelengths are commercially available at a quite low price. Moreover, potassium titanyl phosphate (KTP) crystals ready for frequency doubling are relatively cheap too.

As is well known, to achieve the Q -switching regime, it is necessary to switch in a fast enough way between high and low cavity losses. Although there are pulsed lasers whose switch is passive (based on some saturable absorber [1, 3], for instance), this scheme is not suitable for our purposes since it would be extremely difficult to observe the switching process. Therefore, active Q -switching (that is to say, with external control over the switch) is preferred.

In our setup, the Q -switching is achieved with an optical chopper inside the laser resonator (open cavity). We selected this kind of modulator because it is the most simple, cheap and intuitive, and also because students can see directly the switch of the cavity losses. When the blade covers the output mirror, the losses of the cavity are high, so the population inversion grows. When the output mirror is uncovered, the cavity Q -factor becomes high and the laser emits a short pulse.

This experiment can be set up in any laser or optics lab. The time the students spend in the laboratory can be planned by the instructor. If the students start from the very beginning, aligning each element, and make all the measurements, it can take several 2 h or 4 h sessions. If the instructor prepares the initial set up and lets the students make only a few measurements, one session can be sufficient.

2. Q -switching fundamentals

The Q -switching technique is based on the growth of population inversion to a level much higher than required in order to achieve continuous-wave laser operation. This particular growth is due to a continuous pump of the active medium while the feedback of the laser is suspended, because of the high losses in the cavity. The high population inversion obtained allows the medium to store much more energy than it usually does, and that energy is released in the form of an intense and short pulse when the laser cavity is restored to a low loss situation.

The Q -factor is a parameter that describes the quality of the cavity. It is defined as 2π times the ratio between the energy stored in the cavity and the total energy loss in one oscillation cycle.

So if the cavity has high losses (low Q -factor), all the energy pumped into the cavity is used to raise the population inversion, because of the impossibility of building-up an oscillation. At a certain time, the losses are switched to a low value (high Q -factor) and the energy stored is suddenly emitted. This process is shown in figure 1 in terms of the photon number inside the cavity and population inversion. The output power of the laser is directly related to photons inside the cavity. The number of photons inside the cavity starts to increase, causing the population inversion to decrease to a level lower than critical, N_c , which is the threshold for the laser to run in the continuous-wave mode. The peak of the pulse is reached when the population inversion matches its critical value.

Therefore, if the active medium stores a high amount of energy and this energy is suddenly released, the laser power will be emitted as a high power pulse of very short duration. In fact, the peak power of the Q -switched pulse is much higher than the steady state emission power, which is achieved in the continuous-wave mode after a transient regime.

The operation of a four-level laser can be theoretically studied. We can use the rate equations [1] and simulate the dynamics of a Q -switched laser. These equations rule the evolution of the number of photons in the cavity, ϕ , and the population inversion in the active medium, N :

$$\left(\frac{dN}{dt}\right) = R_p - B\phi N - \left(\frac{N}{\tau}\right), \quad \left(\frac{d\phi}{dt}\right) = V_a B(\phi + 1)N - \left(\frac{\phi}{\tau_c}\right), \quad (1)$$

where R_p is the pump rate, B is the stimulated transition rate per photon and per mode, V_a is the mode volume in the active medium, τ_c is the cavity photon lifetime and τ is the active

Figure 1. Behaviour of population inversion (solid red line) and photon number (dashed blue line) when the losses of the cavity (dotted green line) are switched. The photon number is initially very low and it grows slowly after the cavity is opened. Meanwhile, the population inversion keeps growing until the number of photons is high enough to make the population inversion decay fast.

medium upper level lifetime. For a diode laser as the pump source, these parameters can be obtained through

$$R_p = \eta_p \left(\frac{P_p}{h\nu_p} \right) \frac{1}{\pi w_p^2 l}, \quad B = \frac{\sigma c}{V}, \quad (2)$$

where P_p is the diode laser electrical power, ν_p is the pump frequency, w_p is the pump spot size (for simplicity, we assume $w_p \simeq w_0$, where w_0 is the spot size at the beam waist), l is the active medium length, σ is the stimulated emission cross section, V is the mode volume within the laser cavity and η_p is defined as

$$\eta_p = \eta_r \cdot \eta_t \cdot \eta_a, \quad (3)$$

where η_r is the diode radiative efficiency, η_t is the efficiency of the pump transfer system and $\eta_a = 1 - e^{-\alpha l}$ is the absorption efficiency, where α is the absorption coefficient under laser operating conditions.

If we want to use equations (1) to study a Q-switched laser, we need to make the losses of the cavity vary periodically between a high and a low value. The logarithmic cavity loss per pass γ is included in τ_c through

$$\tau_c = \frac{L_e}{\gamma \cdot c}, \quad (4)$$

where L_e is the optical length of the resonator, and $\gamma = \gamma_i + \left(\frac{\gamma_1 + \gamma_2}{2} \right)$ is a dimensionless parameter that represents the logarithmic cavity loss per pass through the logarithmic losses per pass due to the mirror transmission

$$\gamma_1 = -\text{Ln}(1 - T_1), \quad \gamma_2 = -\text{Ln}(1 - T_2),$$

with T_1 and T_2 the power transmissions of the mirrors, and the logarithmic internal loss per pass

$$\gamma_i = -\text{Ln}(1 - a - L_i),$$

where a is the fractional mirror losses and L_i the single-pass internal loss of the cavity.

Figure 2. Simulation of Q -switched Nd:YAG laser performance. The dynamics of the number of photons in the cavity (solid blue line) and the population inversion (dashed line) in the active medium can be observed.

The variation of the pulse width, τ_p , with the pumping power is also interesting for the experiment. This duration depends on the pump power and the cavity photon lifetime, τ_c , as [4]

$$\tau_p \approx \frac{r \cdot \eta_E}{r - 1 - \ln r} \times \tau_c, \quad (5)$$

where η_E is called the energy-utilization factor given by

$$\eta_E \equiv \frac{N_i - N_f}{N_i}, \quad (6)$$

and $r = N_i/N_c$ is the initial inversion ratio (r grows linearly with the pump power increase). N_i and N_f are the initial and final population inversion values, respectively, and $N_c = \frac{\alpha}{\sigma \cdot I}$ is the critical population inversion, which results from equation (1) for steady state conditions.

Therefore, the behaviour of the Nd:YAG laser can be studied both theoretically and experimentally. The experiment let the students observe how theory predicts the empirical results. They can simulate the behaviour of a laser if the losses are modulated, that is, a Q -switched laser. To obtain this, we must solve the rate equations (1) using a square periodic function for the losses of the cavity. We use the experimental parameters to calculate the constants (B , R_p , τ_c) and solve the rate equations (1). With N_i , N_f and N_c , we can obtain η_E and r by their definitions, so we have the variation of τ_p with the pump power.

Depending on the programming skills of the students, the simulation can be easily done on Mathematica (www.wolfram.com/mathematica/) or Maple (www.maplesoft.com) or using a numerical algorithm (Runge–Kutta, for example) in a more basic programming language (C or FORTRAN, for instance).

In figure 2, we can see the typical Q -switching laser emission, where two oscillation periods can be observed. In the simulation, which has been performed using Matlab (www.mathworks.com), a linear variation of the losses has been used to simulate the effect of an optical chopper, which is used in the experiment. The fall time of the losses from the high value (closed cavity) to the low value (open cavity) is about 20 μs .

We see that while the losses are high, the population inversion grows and the photon number remains very low. When the losses are switched, the photon number suddenly grows and the population inversion falls. When the population inversion falls to the critical value, N_c , the photon number reaches its peak value and starts to decrease. After the pulse is emitted, the laser achieves a transient regime and, after that, a steady state. When the cavity is closed, the laser power (proportional to the number of photons in the cavity) becomes negligible again.

Figure 3. Setup used with the Nd:YVO₄ laser. The coating of the input face of the active medium acts as rear mirror of the cavity.

3. Experimental setups

Before performing the Q-switching experiment, it is necessary to build the laser that will be used. This will be a solid state laser pumped by a diode laser. As we have two crystal samples (Nd:YVO₄ and Nd:YAG), our experiment is proposed for both crystals with different configurations to let the students test different cavity architectures.

First, a Nd:YVO₄ laser is built. The active medium is a crystal sample made of 1% neodymium-doped vanadate, bought from Casix (www.casix.com), with dimensions 3 mm × 3 mm × 1 mm. It has a coating on one of its bigger faces. This coating has high transmission for the 808 nm radiation pump wavelength, and high reflection for the 1064 nm and 532 nm wavelengths of the laser emission and its second harmonic, respectively.

The setup in this case is shown in figure 3. The pump source is a diode laser, with a half-wave plate to optimize the polarization according to the absorption of the active medium. Moreover, a converging lens is needed to focus the pump laser and concentrate the pump power inside the active medium. The smaller the spot, the higher the irradiance of the laser, so less pump power is needed to get the laser emission.

The pump power needed is about 3 or 4 W. In our case, the pump laser is used in the continuous-wave mode, and its wavelength can be tuned by varying the operation temperature. We will use a wavelength between 804 nm and 806 nm, because it is close to the wavelength that offers maximum absorption, which is 807.4 nm for Nd:YVO₄. We do not use a longer wavelength because the operation temperature necessary is too high and the diode laser life expectancy will be reduced.

In order to set up the cavity, we will use high reflection mirrors. The cavity is formed with the reflective coating of the input face of the active medium as the input mirror and a second mirror, made to have a reflection of 90% for 1064 nm and high transmission for 532 nm, which will be the output coupler of the cavity. This is a half-symmetric resonator; it is stable but a careful alignment is necessary. A band-pass filter, centred in 1064 nm, is located after the cavity, so the laser emission can be measured while the pump is rejected.

There is also an optical chopper inside the cavity. The optical chopper is used to modulate the cavity losses and hence have a Q-switched laser. An optical chopper can be made easily with a small motor and a homemade blade. The optical chopper we use has a 10 slot blade and a frequency of operation between 25 and 1000 Hz.

Figure 4. Setup used with the Nd:YAG laser.

We can measure the pump power and the laser output power with a power meter. The temporal measurements are obtained with a fast photodiode (risetime ~ 1 ns) connected to an oscilloscope (bandwidth 500 MHz).

We can also build a laser using our second crystal sample: Nd:YAG. This sample is an uncoated rod of 1% neodymium-doped YAG, with 3 mm of base diameter and 5 mm of height.

The pump laser is the same as in the Nd:YVO₄ setup, with similar values for power and wavelength. The maximum absorption for Nd:YAG laser crystals is achieved in a wavelength of 807.5 nm, so the diode laser is also suitable as a pump laser for this active medium.

In order to set up a cavity, as the sample has no reflective coatings, the setup used has to be different because two external mirrors are needed to form the cavity. This is shown in figure 4: an input mirror with an 808 nm high transmission and high reflection for 1064 nm and 532 nm, and a second mirror, the same that was used before, as output mirror. The radii of the mirrors, and their separation, will define the kind of resonator of the laser.

In our case, both mirrors have the same radius, and the distance between them is also equal to the radius, so this is a symmetric confocal resonator. It is stable and fairly insensitive to misalignments, and also the cavity modes have a small size so a combination of lower and higher order modes is necessary to extract all the energy from the cavity [4].

In this setup, we also use the converging lens to focus the pump laser, the band-pass filter and the optical chopper to achieve the *Q*-switching regime and the detectors to characterize the laser performance.

As the pump diode is a class 4 laser and the neodymium laser is a class 3b laser, it is necessary for the people who are doing the experiment to use adequate protective eyewear. The safety goggles must have a high optical density for the 808 nm radiation and high L-rating for 1064 and 532 nm. Furthermore, students must be careful while working with the optics since it can burn the skin, especially if the beam is focused. The teacher must pay attention to the safety issues in the lab and to the correct development of the experiment.

So, in brief, the experiment is made with a crystal sample, a pump source and an open cavity, made with two mirrors, that is used as a resonator. Thanks to this open cavity, an optical chopper can be easily located before the output mirror to achieve the *Q*-switching regime. This assembly is several times cheaper than commercial kits with the same purpose, and easy to set up.

The students can also characterize the crystal samples used in the experiment. The absorption spectrum of the samples sets the pump wavelength needed, and the upper level lifetime gives an idea of the capacity to store energy in the active medium, so we propose to make these two measures complementary information to the experiment.

Figure 5. Transmission spectrum of the Nd:YVO₄ sample. We can observe the pump absorption peak at 800 nm and the high reflection of the coating around 532 nm.

Figure 6. Transmission spectrum of the Nd:YAG sample. We can observe the pump absorption peak at 800 nm.

In order to know the absorption of the samples, we need a halogen lamp and a spectrometer. If we take a spectrum of the lamp and a spectrum of the lamp behind the sample, we can extract the dependence of the transmission of the sample with the wavelength. The results obtained for this spectrum are shown in figures 5 and 6 in terms of 1-transmission. We can see how the transmission falls in the region around 806 nm, our pump wavelength. Furthermore, in the Nd:YVO₄ case (figure 5), the coating produces high losses in the second harmonic wavelength (532 nm). The peaks of absorption obtained from this measurement are those expected for a neodymium-doped crystal [5].

For the fluorescence decay measure, a fast enough switchoff of the pump laser is necessary not to affect the lifetime. We can achieve this by placing the optical chopper in front of the active medium, so the pump laser will be modulated. We detect the transverse fluorescence with a fast photodiode. In figures 7 and 8, the fluorescence decays and the pump switchoff are shown, so we can observe that the switchoff is fast enough. The exponential decay obeys $N_u = N_{u0} \cdot e^{-\frac{t}{\tau}}$, so we can obtain the lifetime τ for each sample. In our case, the value obtained

Figure 7. Fluorescence exponential decay for the Nd:YVO₄ sample.

Figure 8. Fluorescence exponential decay for the Nd:YAG sample.

for the Nd:YVO₄ is 93 μs and for the Nd:YAG it is 232 μs . These results are in agreement with the fluorescence lifetimes that can be found in the literature, which are 100 μs and 240 μs , respectively [5].

4. Results

Once the laser is built and running, the operation regime can be changed from the continuous wave to the pulsed mode. The pulsed mode is achieved by introducing the optical chopper inside the cavity to modulate the losses, so the laser operates in the *Q*-switching regime.

When the blade is covering the output mirror, the cavity has high losses. At the moment the mirror is uncovered, the cavity losses become very low so all the energy stored in the active medium is released in one high peak power pulse of very short duration. This kind of technique is adequate for a teaching experiment, since the variation of losses in the cavity is observed directly.

In order to have a high pulse power peak, a fast switch of the losses is needed. We can get a fast switch of the cavity losses by having a small spot size in the optical chopper. We will

Figure 9. Temporal evolution of the Nd:YVO₄ laser emission in the Q-switching regime. Cavity open and close times are shown. We can also see relaxation oscillations after the main pulse. The pump power is 1.70 W and the wavelength of the pump is 806 nm.

Figure 10. Q-switched pulse emitted by the Nd:YVO₄ laser. The pump power is 1.81 W and the wavelength of the pump is 806 nm.

also make the switch faster by making the optical chopper run at a higher frequency. In our case, a switch of the losses of about 20 μ s of fall time is used when the lasers are operating in the Q-switching regime.

First, we use the Nd:YVO₄ laser. The experiment is made with a pump power $P_p = 1.70$ W and a pump wavelength $\lambda_p = 806$ nm. The optical chopper frequency is fixed at $f = 500$ Hz. The result obtained is shown in figure 9. We can see that at the moment the laser emission begins, the power obtained is very high. After a transition regime the emission becomes stable and the power is much lower than the peak power of the first pulse. This temporal evolution is characteristic of the Q-switching regime.

Once the temporal evolution of the emission is observed, the students can focus on the emitted pulses. If we zoom into the main pulse, we will be able to measure its duration. Typically, this duration is of the order of 100–200 ns. We show in figure 10 a typical Q-switched laser pulse. The pulse shown in figure 10 was obtained with the Nd:YVO₄ laser. The experiment parameters were $P_p = 1.81$ W, $\lambda_p = 806$ nm and an optical chopper frequency

Figure 11. Pulse width versus pumping rate in the Nd:YVO₄ laser.

Figure 12. Temporal evolution of the Nd:YAG laser emission in the *Q*-switching regime. The pump power is 3.77 W and the wavelength of the pump is 806 nm.

$f = 500$ Hz. The pulse has a FWHM (full width at half maximum) of 146 ns, which is a typical duration of *Q*-switched pulses [1].

If we vary the pump power we can observe how it affects the pulse width. As seen in equation (5), we expect the FWHM of the pulse to decrease as the pump power increases, because of the rise of the initial inversion ratio, r , with the pump power.

We show the result obtained for the Nd:YVO₄ laser in figure 11, where we can see the expected decrease of the FWHM of the pulse.

We can repeat the experiment for the Nd:YAG laser. In this case, the experiment parameters were $P_p = 3.77$ W, $\lambda_p = 806$ nm and the optical chopper frequency $f = 524$ Hz. The result obtained with this laser is different, as shown in figure 12. We can see a first high peak power pulse again, characteristic of the *Q*-switching regime. But, contrary to the previous case, the next pulses have power not much lower. This is because of the cavity of the Nd:YAG laser. It is a symmetric confocal resonator, which has a small average size of the cavity modes. This means that the TEM₀₀ mode will not be able to extract all the energy from a large-diameter active medium. In this case, the laser will oscillate in a combination of the different modes.

As the resonator is highly multimode, when operating in the Q-switching regime each mode of the cavity will release the energy stored at different times. This is what we can see in figure 12, where each mode causes a secondary pulse after the main one.

The students, varying the alignment of the cavity mirrors, can observe these different propagation modes of the Nd:YAG laser. This study belongs to a more advanced level and it is described in section 6.

We can also observe how the FWHM of the pulse varies with the pump power in the Nd:YAG laser. In this case, the pulses obtained have a shape and duration similar to the pulses measured in the Nd:YVO₄ laser, and the dependence of the FWHM with the pump power shows the same behaviour when the pump power is varied.

In both cases, the theoretical model, using the experimental parameters, with pump waist $w_p = 0.25$ mm predicts the experimental results. Figure 11 shows an acceptable concordance between theory and experiment.

5. Q-switching and second harmonic generation

Once we have the neodymium laser running, we can use a nonlinear crystal to obtain the second harmonic of its fundamental emission. In neodymium-doped lasers, the second harmonic emission falls within the visible spectrum, so it is interesting for students because of the possibility of observing the laser emission directly. However, we must stress that the students must wear protective goggles, even at 532 nm.

Second harmonic generation is a second order process and requires relatively high irradiance to have a good conversion efficiency. Phase matching and good beam quality are also necessary.

We use the Nd:YAG for this experiment. The setup used is the same that was previously shown, but in this case a nonlinear crystal is added after the active medium. This crystal is KTP with dimensions 5 mm × 3 mm × 3 mm. As the nonlinear crystal is located inside the cavity, we deal with intracavity second harmonic generation.

After a careful alignment, the temporal shape of the second harmonic emission can be obtained and its FWHM can be measured. As the power of the second-harmonic wave grows with the square of the fundamental wave power, we expect the duration of the second harmonic pulse to be smaller than the fundamental emission pulse.

In figure 13, we see the measured pulse. The conditions of the experiment were $P_p = 2.94$ W, $\lambda_p = 806$ nm and the optical chopper frequency $f = 644$ Hz. The FWHM of the pulse is 54 ns, which agrees with the expected shorter duration compared to the fundamental pulse.

6. Fundamental transverse modes

One of the advantages of using a symmetric confocal resonator is that the students can observe how the alignment of the cavity affects the transverse modes of the laser. We show in figure 14 the transverse modes of the fundamental emission of the Nd:YAG laser.

In order to observe these modes, slight changes in the input and output mirror are necessary, so the cavity alignment will be different and thus the transverse mode too. For taking these measures we use a CCD camera with infrared detection (Dataray camera, WinCamD UCD23 UV model; www.dataray.com).

Also spatial and temporal profiles of the emission can be studied. To measure this, we used the second harmonic emission of the Nd:YAG because it is easier to observe the peak of the Q-switching pulse without the spiking effect.

Figure 13. Q -switched pulse emitted by second harmonic generation in the Nd:YAG laser. The pump power is 2.94 W and the wavelength of the pump is 806 nm.

Figure 14. Transverse modes obtained for different alignments of the Nd:YAG resonator.

The setup used to take these measures is the same as when the second harmonic generation pulse was measured. However, to observe the transverse mode of the second harmonic, we need a CCD camera for the visible spectrum (we used a Ueye camera, UI-1440-C model; www.ids-imaging.com).

The obtained results are shown in figure 15. When a fundamental transverse mode is achieved, only one peak is emitted, corresponding to a typical Q -switching emission (as

Figure 15. Transverse modes observed in the second harmonic of the Nd:YAG laser. We show the image of the modes and the corresponding temporal profile. The temporal profile is shown in arbitrary units of power versus time in microseconds.

shown in figure 9). Nevertheless, if the beam is a combination of transverse modes, the temporal profile shows more peaks (as shown in figure 12). This behaviour has been recently studied in a different system with similar results [6].

7. Summary

We have presented a simple experiment, aimed at students in laser-related classes (graduate or undergraduate), to build a solid state laser and study its emission in the *Q*-switching regime.

The laser setup is very simple, and the power needed for pumping is not very high so it is also a cheap setup for any optics lab, where it can be built easily. In our experiment, the emission process of two different lasers is studied. The students can extend the experiment to different cavities and active media not mentioned in this paper.

This experiment has been applied in a laser-related masters degree. In the future, it will be applied in advanced optics classes as part of a physics degree.

The typical duration of *Q*-switched laser pulses has been measured, and how it depends on the pump power. Both experiments give the expected results. The students can check it performing an easy simulation of a *Q*-switching four-level laser.

Also a nonlinear crystal can be used to generate the second harmonic and study the *Q*-switching pulses obtained in this case.

Finally, a relationship between the spatial and temporal profile of the emission has been observed.

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