Transient dynamics of a CW-pumped Nd:YAG laser

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We investigate the dynamics of a diode-pumped Nd:YAG laser at 1.06 µm under perturbation while operating in continuous-wave (CW) mode. We characterize the laser output and obtain a slope efficiency of 9% in single-mode operation. Various perturbations to the cavity are considered: optical chopping of the pump, noise-induced relaxation oscillations (RO), and perturbation by an acousto-optic modulator at both small and large amplitudes. With increasing perturbation, the laser undergoes a transition from linear response to spiking behavior and eventually Q-switching. The small-signal, linear RO response is used to estimate the upper-state lifetime of the Nd^{3+} ions in YAG to be 230 µs.

OCIS codes: (140.3580) Lasers, solid state; (14.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched

1. Introduction

Solid-state lasers—with a gain medium consisting of a dopant embedded in a crystalline or glass matrix—are a highly versatile class of lasers with particular importance for applications requiring fast pulses or high power, including nonlinear optics. Historically, one disadvantage of solid-state lasers was the lack of an efficient pump source; flash lamps are a popular choice but are typically low efficiency. The recent development of high power, high efficiency, and low cost diode lasers have made them a near-ideal pump source for solid-state lasers. [1]

One prominent choice of solid-state laser gain medium is neodymium-doped yttrium aluminum garnet (Nd:YAG), which can lase at 1064 nm. The Nd:YAG is a four-level laser system: a pump at 808 nm excites the Nd^{3+} ions to the $^4F_{5/2}$ state, where they undergo a rapid, non-radiative decay to the $^4F_{3/2}$ state, which has a lifetime of about 230 µs. The lasing transition at 1064 nm takes the ions from $^4F_{3/2}$ to $^4I_{11/2}$, normally forbidden by dipole selection rules but is enabled by lattice perturbations from the YAG crystal. This lower state (which has a very small thermal population) decays to the ground state with a lifetime of 30 ns. [1]

In contrast with gas lasers like the HeNe, the relatively long upper-state lifetime $\tau_2 = 230\,\mu s$ can be exploited to generate interesting transient effects allowed by laser rate equations. These effects range from linear relaxation oscillations (RO) for small-signal perturbations to spiking and Q-switching, whereby optical energy from the pump is stored in the gain medium and then quickly extracted in a short, intense pulse. [2]

In this report, we use a CW diode laser at 808 nm to pump a Nd:YAG rod in an open cavity, with the goal of investigating such laser dynamics under various perturbations. We describe the experimental setup and characterize the CW laser output in Section 2. In Section 3, we look at relaxation oscillations caused by noise and weak modulation of the cavity loss. Finally, in Section 4, we observe spiking and Q-switching by chopping the pump and fully modulating the cavity loss.

2. Description of laser

The pump is a 10 W Lightwave diode bar laser, liquid-cooled, tuned by a Thorlabs LDC 3065 current controller, and mounted on an optical rail and 3-axis stage. A series of lenses brings the pump beam to a focus onto a 20 mm Nd:YAG crystal rod ∼20 cm away, after which the pump diverges and scatters. The output facet of the rod is AR-coated for 1064 nm, while the input facet is HR at 1064 nm and AR-coated at 808 nm. Thus, the input facet forms one end of the laser resonator, which is completed by a 5 % output coupler approximately 29.7 cm away. Within the cavity is an iris, located 6.5 cm from the output coupler, and an acousto-optic modulator (AOM) (model not available) located 10 cm from the crystal.

The pump is characterized by measuring its output power as a function of current. Its behavior is extremely linear past its threshold of 8.03 A, with a slope of 0.624 W/A up to 18 mA. The Nd:YAG laser is aligned by translating the pump laser until its focus is centered on the crystal rod. Fine tuning of the alignment is performed by optimizing for the lowest possible lasing threshold, found to be $P_{\text{pump}} = 1.23$ W with iris open.

Fig. 1 summarizes the output characteristics of the Nd:YAG laser. Interestingly, with the iris fully open, the laser output does not exhibit linear behavior above threshold (inset, blue). We suspect this indicates mode-hopping of the laser as thermal lensing develops in the crystal, misaligning the cavity. By partially closing the iris (inset, red), we introduce spatially-dependent loss into the cavity and can prevent higher-order modes from lasing. The result is much more linear behavior, until about 5.3 W (output ∼240 mW), when saturation-like behavior is observed. The inset traces are taken using a photodetector (PD) after a pickoff, as the pump current is ramped at 1 Hz using an external signal generator.

We operate the laser with the iris partially closed (and fixed) for the remainder of the experiment. Fitting the hand-taken data (main plot) for this configuration to a line, we obtain a slope efficiency of 9 % (W output per W pump), and a lasing threshold at $P_{\text{th}} = 3.69$ W.

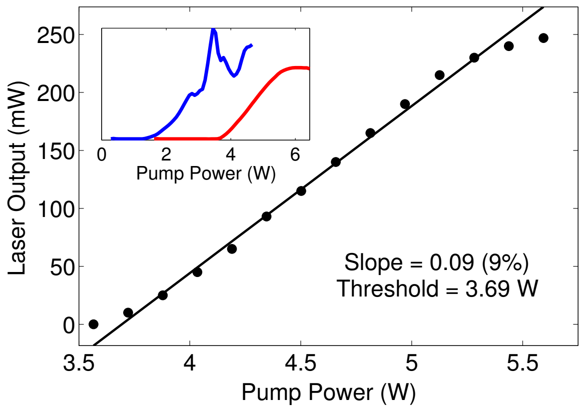

Fig. 1. Laser output as a function of pump power, with iris in cavity. Line shows a fit to the linear part of data. Inset: PD traces of the laser output with iris open (top, blue) and partially closed (bottom, red), as pump power is ramped (ordinate, arbitrary units).

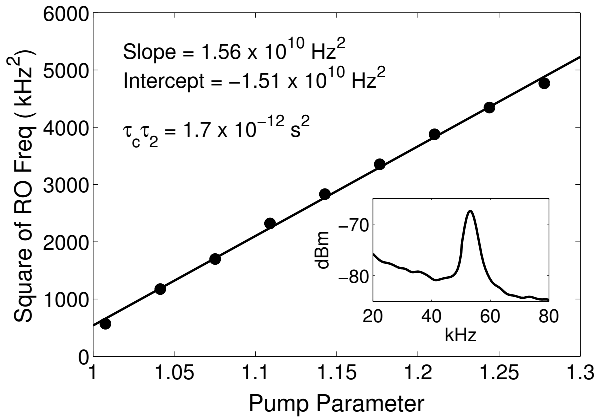

Fig. 2. Relaxation oscillations driven by noise, versus number of times above threshold. Line shows a fit to the data. Inset: A trace of the laser output noise spectrum as seen by an RF spectrum analyzer for $I_{\mathrm{pump}} = 14.8\,\mathrm{A}$, showing the RO peak.

3. Relaxation oscillations

Even under CW operation, the Nd:YAG laser, like many other solid state lasers, shows characteristic output fluctuations called relaxation oscillations. The large upper-state lifetime (compared to the photon cavity lifetime) creates a lag in the gain medium's response when the laser is perturbed, e.g., by noise. This lag translates to an oscillatory behavior as the upper state population over- and under-shoots the steady-state value.

For small perturbations, a linearized analysis of the laser rate equations as in [2] shows that when the upper-state lifetime τ_2 is much longer than the cavity decay time τ_c, the system response to a small perturbation is an exponentially damped sinusoid. The frequency of the sinusoidal response is

$$(2\pi) f_{\mathrm{RO}} = \sqrt{\tau_c \tau_2\,(r-1)}, \tag{1}$$

where $r = P_{\mathrm{pump}}/P_{\mathrm{th}}$ is the pump parameter (i.e., number of times above threshold).

One of the simplest perturbations to consider is technical noise in the system. By running the laser in CW mode and looking at the output using a fast PD, we can send the signal into an RF spectrum analyzer to find the characteristic RO peak for various values of the pump.

We use pump currents from 14 A to 15.6 A, corresponding to r from about 1 to 1.3. We send the PD output to an RF spectrum analyzer (RBW 3 kHz; VBW 30 Hz; 15× averaging), which gives traces like the one shown inset of Fig. 2. We take the peak to be the RO frequency for that pump power.

The main plot of Fig. 2 shows the relationship between pumping and the RO frequency found in this way: we see a very linear trend plotting f_{RO}^2 versus r. From Eq. 1, we expect the slope and intercept to be equal; this is in relatively good agreement with the fit, which yields slope and intercept of approximately $1.5 \times 10^4\,\mathrm{kHz}^2$. Dividing $(2\pi)^2$ by this value gives $\tau_c\tau_2 = 1.7\,\mu\mathrm{s}^2$.

To derive the upper-state lifetime τ_2, we need to know the cavity photon lifetime τ_c, which we can approximate using the cavity length $L = 29.3\,\mathrm{cm}$ and an appropriate estimate for the single-pass losses in the cavity. Taking 2.5 % from the output coupler and 10 % static losses in the AOM and iris combined, we estimate $a \approx 12.5\,\%$. Through an analysis as in [3], we have $\tau_c = (L/c)/\log(1-a)^{-1} \approx 7.3\,\mathrm{ns}$. Thus, we estimate $\tau_2 \approx 230\,\mu\mathrm{s}$, in agreement with accepted values. [1]

Alternatively, we can actively perturb the cavity using the AOM to modulate the loss. For a small-signal drive, the laser output responds linearly, and we expect that the magnitude of the response is maximal when the modulation frequency is near the RO frequency for a given pump power. The response amplitude as a function of modulation frequency therefore gives a "transfer function" for the laser response to perturbation.

We use a $30\,\mathrm{mV_{pp}}$ sinusoidal drive linearly swept at a rate of 3 Hz from 1 Hz to 110 kHz and measure the response using a fast PD and an oscilloscope. The envelope of the PD signal (e.g., after a low-pass filter) gives us the transfer function. For simplicity, however, we save the entire time trace of the PD signal and extract the envelope using computer post-processing.

An example of such a processed sweep is shown inset in Fig. 3 below. Interestingly, there is not one, but (at least) three peaks generally, at what appears to be a geometric progression of half-frequencies. While we are unable to explain these multiple peaks, examining their trend versus pump power (main plot) clearly indicates that the largest peak (and at the highest frequency) is the one corresponding to the RO frequency of interest.

Again, we see a very linear dependence of f_{RO}^2 on r, with a slope/intercept value of $1.5 \times 10^4\,\mathrm{kHz}^2$, in almost exact agreement with the noise-induced measurement. Thus, this alternative measurement again yields an estimate of the upper-state lifetime to be $\tau_2 = 230\,\mu\mathrm{s}$.

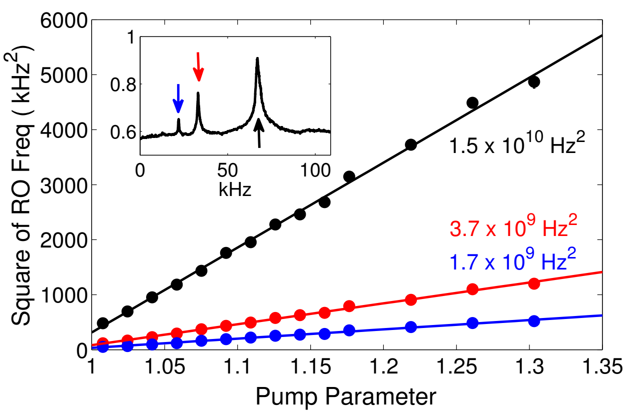

Fig. 3. Relaxation oscillations driven by an intracavity AOM, versus number of times above threshold. Lines show fits to the various peaks as indicated in the inset; the labels give the slope of the line (approximately equal in magnitude to the intercept for all three data sets). Inset: A sweep post-processed to extract the envelope as discussed in main text, taken at $I_{\text{pump}} = 14.8\,\text{A}$.

4. Spiking and Q-switching

To explore the consequences of the nonlinear laser rate equations as we move beyond the small-signal linear regime, we can simply turn up the AOM drive amplitude (for a fixed modulation frequency) and observe the output of the laser. This is shown through the series of traces in Fig. 4, taken at a pump current of 15 A ($r = 1.18$) and AOM frequency 58.2 kHz.

As expected, the laser output follows the modulation linearly at low drive amplitudes (50 mV_{pp}, upper-left), producing a quasi-sinusoidal intensity modulation matching the drive. But as the drive is turned up (150 mV_{pp}, upper-right), the output develops nonlinearities, starting with the appearance of pronounced peaks. As the drive amplitude is increased further (250 mV_{pp}, bottom-left), these peaks become increasingly "spiky" and stop tracking the modulation of the cavity loss, showing complicated nonlinear dynamics. Finally, as the drive power is made very large (750 mV_{pp}, bottom-right), the laser moves to a periodic, locked regime where power is output in a large spike, with a periodicity different from the modulation.

Traditionally, however, the phenomenon of spiking is associated with modulation of the pump: as pulsed flash-lamps pumped the gain medium, the laser output at the beginning of each flash was found to exhibit intense spiking behavior, before settling down near the end of the flash. [2] To reproduce this classic effect, we place a chopper wheel (frequency 350 Hz) directly after the pump output aperture to turn the pump on and off.

A trace showing this spiking phenomenon is shown in Fig. 5, taken at a pump current of 16.36 A ($r = 1.41$). The interval between successive spikes progressively decreases, so it is difficult to define a "spiking frequency". However, the first few are separated by $\sim$40 µs, corresponding to about 25 kHz at this pump power.

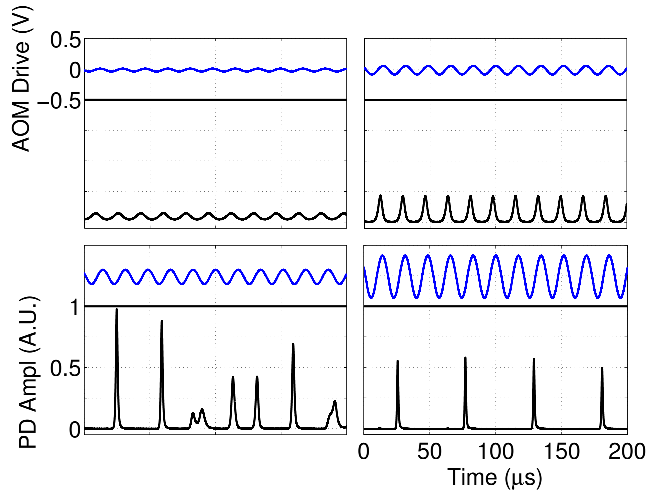

Fig. 4. Traces of laser output for increasing AOM (pk-pk) drive voltages of 50 mV, 150 mV, 250 mV, and 750 mV (upper trace, AOM drive; lower trace, PD). Note that in the last trace, the power going to the PD is cut by a factor of $\sim$5 relative to the others, to prevent saturation at the peak; PD amplitudes are comparable otherwise.

As discussed in [2], laser spiking behavior is caused by the lag between the population inversion N in the gain medium and the photon population n in the cavity. As the pump suddenly turns on, N builds for some time $\sim\tau_c$, but n only becomes large enough to burn up the inverted population after N greatly exceeds its threshold value. Then, even as N starts to decrease, n continues to increase, until N hits and falls below threshold. At this point n drops quickly down to zero since loss dominates gain, and the cycle repeats. The spiking transient eventually settles down to a steady-state value, perturbed only by relaxation oscillations due to noise as discussed in Sec. 3 above. This behavior is consistent with the observations made in Fig. 5.

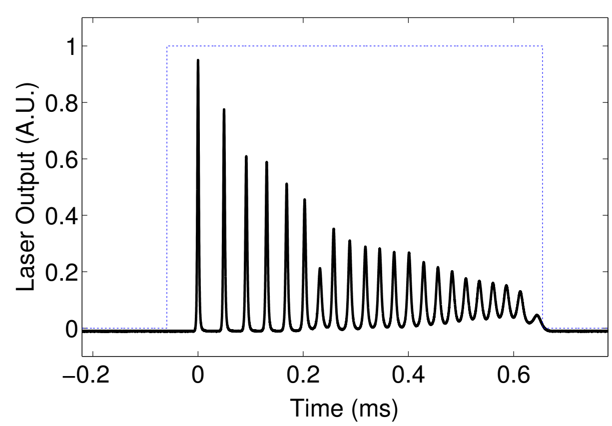

Fig. 5. Trace showing spiking behavior as the pump beam is chopped. The dashed square pulse is a back-inferred reference for the chopped pump, based on a known frequency of 350 Hz but presumed duty cycle of 25 %; unfortunately, we do not have an actual trace of the reference.

Finally, we pursue the operation of Q-switching, where the cavity loss is quickly switched between high (laser well below threshold) and low. Since the pump continues to produce population inversion in the crystal during periods of high loss, the sudden switch to a low loss cavity causes a giant pulse to develop in the cavity, extracting large amounts of optical power from the crystal in a short amount of time. The process by which this occurs is similar to the sort of dynamics described for laser spiking, and with the right switching rate, it is possible to obtain exactly one pulse per Q-switch. [2]

We perform Q-switching by driving the AOM with a $1\,\mathrm{V_{pp}}$ square wave, while the laser is pumped CW at a pump current of 16 A ($r = 1.35$). To explore the effect of the Q-switch rate on the pulses, we vary the AOM frequency between 500 Hz and 10 kHz and record the mean amplitudes of the pulses using an oscilloscope. We expect the maximal amplitude on the pulses to occur when the Q-switch rate is $\sim 1/\tau_2$, since above this rate, the Q-switch opens before maximal inversion occurs.

The results are summarized in Fig. 6. We see a peak near 4 kHz, corresponding to a Q-switching period of 250 µs, consistent with $\tau_2 = 230\,\mu\mathrm{s}$. As expected, the pulse amplitude decreases rapidly with increasing frequency. Interestingly, the pulse amplitude also slightly decreases when the Q-switch rate is below $1/\tau_2$ and furthermore even rises again (e.g., near 500 Hz).

From the inset, we also observe the shape of the Q-switched pulse in time. The pulse width is slightly less than 1 µs. The buildup time is about 2 µs, measured between the edge of the AOM signal reference and the start of the pulse as seen by the PD. From the analysis in [2], we expect the buildup time to be $25\tau_c/(r-1) \approx 0.5\,\mu\mathrm{s}$. Regarding this discrepancy, it is possible that the shape of the cavity loss differs significantly from the AOM reference signal, or that the cavity losses when the Q-switch is open differs from the static case (so that τ_c changes).

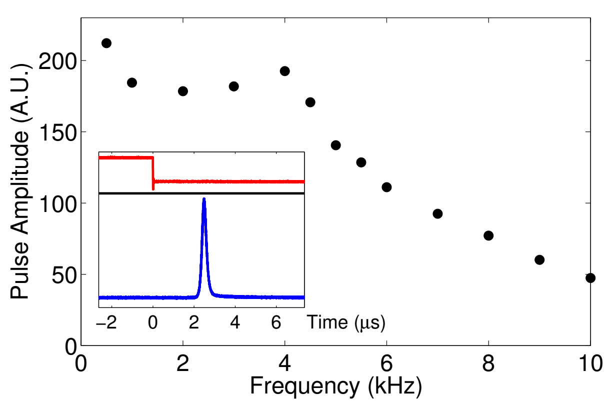

Fig. 6. Pulse amplitude as a function of Q-switching rate. Pulse amplitudes are calculated by the measure function of an oscilloscope. Inset: A PD trace of a Q-switched pulse (bottom, blue) alongside the AOM modulation signal (top, red), taken at 4 kHz Q-switch frequency (PD, arbitrary units; AOM signal, $0.92\,\mathrm{V_{pp}}$, -0.02 V offset).

5. Conclusions

A CW Nd:YAG laser at 1.06 µm is constructed, with a slope efficiency of 9 % in single-mode operation. The laser exhibits relaxation oscillations in the presence of small perturbations. The RO frequency as a function of pump power is measured using both a RF spectrum analyzer and by actively modulating the cavity with an AOM. These measurements yield an estimate for the upper-state lifetime of Nd^{3+} ions in YAG to be $\tau_2 = 230\,\mu\mathrm{s}$. With increasing perturbation, the laser exhibits nonlinear behavior, such as multiply-periodic peaks and spiking. Finally, Q-switching under a CW pump is attained when the intracavity loss is modulated with a square wave by an AOM; the pulse amplitude is found to decrease as the Q-switching frequency exceeds the natural decay rate $1/\tau_2$.

References

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