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Stable high repetition rate, single-frequency Q-switched operation via feedback suppression of relaxation oscillation

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ABSTRACT

Stable, single-frequency, operation of a Q-switched laser requires initial establishment of a stable prelase, free from relaxation oscillation. Relying on natural decay of oscillation limits repetition rates and hence average power.

Using feedback suppression of relaxation oscillation, a Q-switched Nd:YAG laser has operated single-frequency reliably at repetition rates up to 25KHz, with 88% of available cw power extracted.

Q-switched lasers that can reliably produce high pulse-to-pulse amplitude stability are essential for many applications. For some applications single-frequency operation is also essential, e.g. for coherent laser radar, whereas in other applications, e.g. micro-machining, the spectral purity of single-frequency operation is not essential, but it does provide the means to achieve the required amplitude stability. For many nonlinear applications both amplitude stability and single-frequency operation are essential. A high pulse repetition frequency is also desirable for many of these applications, especially if a high average power is required.

Approaches to this requirement of high repetition-rate single-frequency Q-switched operation have included the use of microchip lasers[1] - or the use of a stable cw single-frequency source for injecting into a more powerful Q-switched slave oscillator. A drawback of the latter approach is the complexity of having two oscillators, which require to be mode-matched, while the microchip approach suffers from the drawback of limited power scalability. Another approach is to use what is effectively 'self-injection', i.e. allowing single-frequency operation to become established during a period of 'prelase' oscillation[2], prior to Q-switching. This approach used in conjunction with a unidirectional ring resonator (e.g. Ref. 3), provides a very simple, reliable and robust route to single-frequency operation, without the need for intracavity etalons, and is readily scalable to high powers.

In practice this technique has been limited to low PRFs (typically ≤1kHz) since the prelase usually begins with strong spiking behaviour followed by relaxation oscillations. These take a time of the order of a few fluorescence lifetimes to decay to the steady cw prelase required for reliable single-frequency operation and high pulse to pulse stability. At high PRFs, when the Q-switched pulse builds up from prelase spikes, large fluctuations in Q-switched pulse amplitude and excessive time jitter occur[3]. One can avoid these problems by allowing the relaxation oscillation to decay naturally, however this entails a significant penalty on average power since the maximum average power is approached only when the pulse repetition rate is greater than the inverse of the fluorescence lifetime. For earlier results on a Nd:YAG laser[3] (fluorescence lifetime 240μsec) the observed maximum stable operating frequency of 1kHz resulted in a factor of five penalty on average power compared to that available at 5kHz. We report here a solution to these conflicting requirements on repetition rate, provided by actively damping the prelase spiking via control of the Q-switch loss during the prelase. The prelase power is monitored and a simple PID (Proportional-Integral-Differential) control unit (see for example Ref. 4) then controls the loss of the Q-switch so as to hold the prelase at some adjustable preset power level. The spiking is thereby damped and the establishment of a unidirectional and single-frequency prelase occurs much sooner. Pulse to pulse amplitude fluctuation, and timing jitter are considerably reduced. With a Nd:YAG laser, reliable single frequency operation up to 25kHz has now been achieved in this way.

We have applied this technique to a Nd:YAG ring laser pumped by a 1.2W high brightness diode laser (Spectra Diode Labs SDL2362), with Q-switching provided by an acousto-optic (A-O) Q-switch (Fig.1). Unidirectional operation has been achieved via the A-O Q-switch itself[3,5]. Alternatively, a Faraday rotator device could have been used to induce unidirectional operation, with a separate Q-switch. However that arrangement is less satisfactory, requiring more optical components in the resonator and hence more background loss. The use of the A-O Q-switch has the advantage also that low voltage electronics are involved. The A-O Q-switch we have used was of lead molybdate, 16 mm long, with AR coated faces, driven by an 80MHz RF input. The main limitation of an A-O Q-switch is its response time, determined by the time delay for an acoustic wave to propagate from the transducer to the location of the laser beam. To minimise this delay the laser beam was arranged to pass as close as possible to the transducer. To control the prelase power we have monitored the power of the diffracted beam, which passes above the prism (shown as a dotted line in Fig.1). The detector is thereby protected from the high intensity of the Q-switched pulses, since by the time the pulse has developed, the diffracted beam is switched off. With a 15% transmission output coupler, a threshold was reached for 500mW of incident pump. For the maximum incident pump power of 1080mW, a cw output of 280mW was obtained, i.e. a slope efficiency of 48%.

For comparison we have Q-switched this laser using a standard prelase and the stabilised prelase. Fig. 2 shows the behaviour of the prelase intensity at a PRF of 5kHz. It can be seen that without prelase stabilization the Q-switched pulse builds up from one of the prelase spikes, which results in large amplitude fluctuations and time jitter of the Q-switched pulse. A comparison between performance with and without prelase stabilisation is shown in table 1. At lower repetition rates, $\sim$ 1kHz or less, pulse durations of $\sim$ 14ns and pulse energies of more than 50μJ were obtained. The average power is around a factor of five less than that available as cw output. Even at 1kHz the amplitude stability and timing jitter are significantly worse without stabilisation, and become progressively worse at higher repetition rates. In fact, without the active stabilisation scheme single-frequency output was only possible up to 15kHz and then only with very careful adjustment. The output became very unstable with amplitude variations down to zero and timing jitter of $\sim$ 90ns (i.e. much greater than the 35ns pulse length). By contrast, with the stabilisation circuit activated, reliable single-frequency operation was obtained, amplitude fluctuation remained below 2% and timing jitter below 2.5ns, up to a PRF of 25kHz. At this PRF the average power was 248mW, i.e. 88% of the cw power available.

The average power levels quoted refer in all cases to the power contained in the Q-switched pulses, and not including any power in the prelase. In general the output energy in the prelase is a very small fraction of the total output energy. The stabilisation is also beneficial in this respect in allowing a lower prelase level to be used reliably. The measurement of the prelase level was made by taking the diffracted beam onto a detector after passing through another A-O modulator, external to the laser resonator. The modulator was used as a gate, switching off the light to the detector at the time of the Q-switched pulse, so that only the prelase was monitored. In this way the prelase power emitted via the output coupler could be deduced, and these are the values quoted in table 1. As an example it can be seen that the energy content of the prelase, corresponding to the 5kHz PRF conditions in Fig. 2(b), is 0.5μJ (2.5mW average power at 5kHz PRF), and hence negligible compared to the 40μJ energy of the Q-switched pulse.

Since there are no frequency-selective elements in the resonator, the laser oscillates on the longitudinal mode nearest to the gain peak. As with any laser, oscillation on two adjacent modes can occur when the gain peak is close to the mid-point between them. By moving one of the resonator mirrors with a PZT, one could examine the range of mirror positions over which this two-mode operation could occur. At low repetition rates, up to 5kHz such two-mode operation would only occur with the gain peak very precisely centred between the two mode frequencies. At higher repetition rates, when less time is available for the prelase to allow frequency selection to occur, the range over which two-mode-operation occurs increases. At 10kHz two-mode-operation occurred over half of the scan range of the resonator mirror. For operation at higher repetition rates it would therefore be beneficial to include some extra frequency selection, in the form of an etalon, with adequate selection being readily available from a simple uncoated etalon. A small etalon tilt would be needed to avoid oscillation in the counter propagating direction.

In conclusion, we have demonstrated a simple technique for prelase stabilisation which allows reliable, stable single-frequency operation of a Q-switched laser at pulse repetition frequencies well in excess of the inverse fluorescence lifetime, up to 25kHz in the case of a Nd:YAG laser. This allows most of the available cw energy to be extracted as single-frequency Q-switched output. The same technique can be widely applied, for example to lasers operating in the 2μm region. The technique is readily compatible with scaling to higher powers, for example using a diode-bar-pumped laser. For example, using a novel scheme for shaping the beam from a diode-bar[6], end-pumped Nd:YAG lasers should give single-frequency Q-switched outputs of multiwatt average power, using a single 20W diode-bar. Via harmonic conversion one can then obtain highly stable, pulsed single-frequency sources in the visible and UV region with multiwatt average powers.

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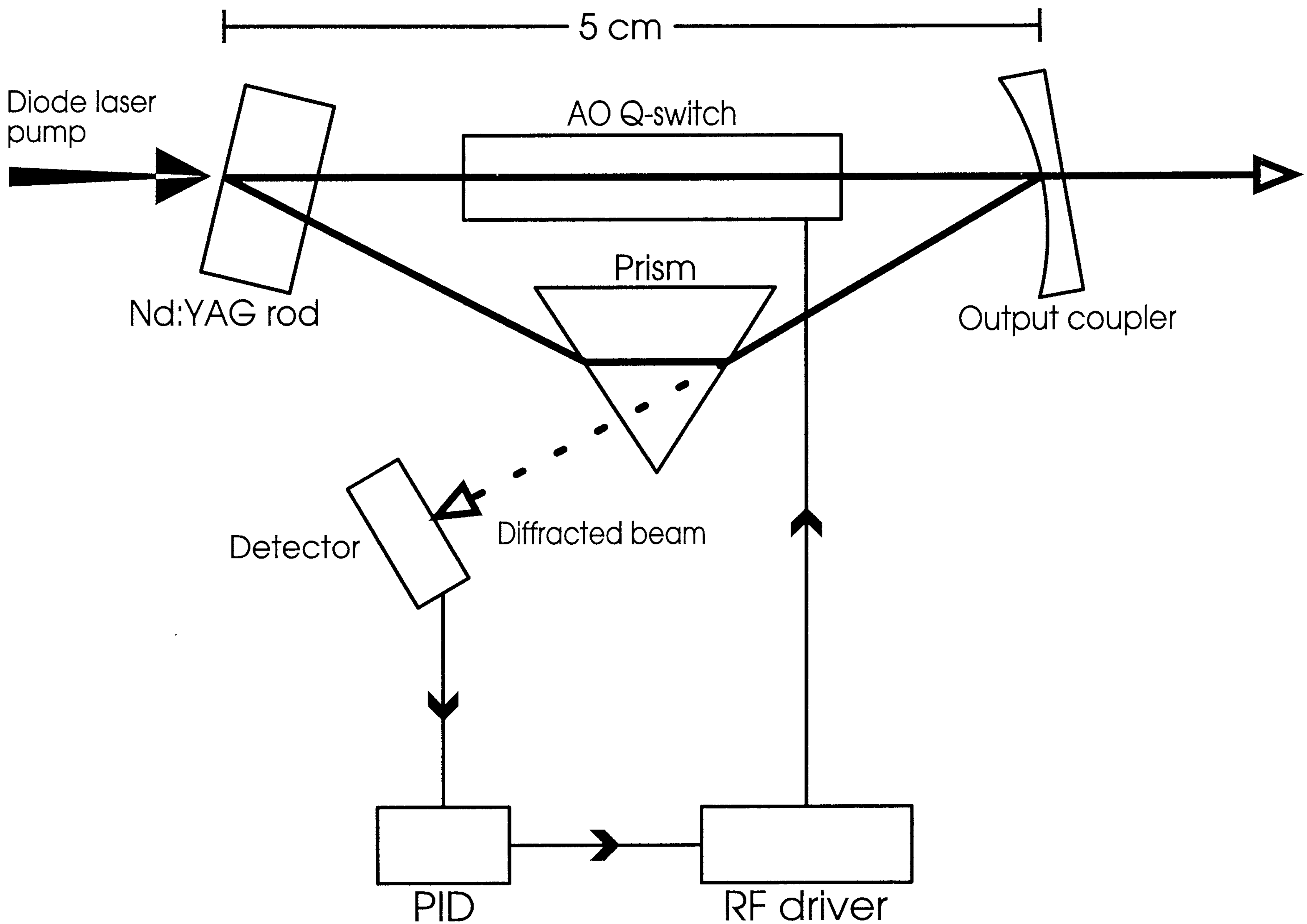
FIGURE CAPTIONS

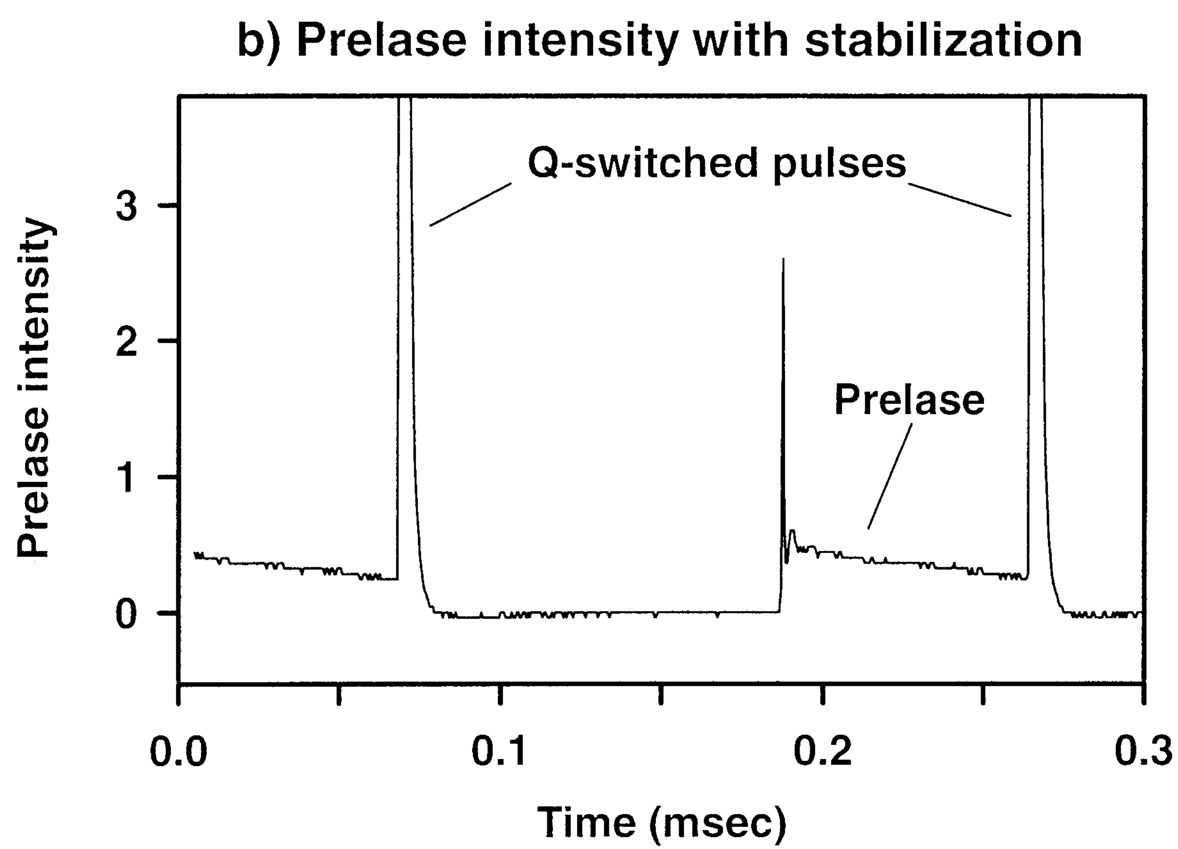
Fig. 1 Experimental setup for prelase power feedback control of a Nd:YAG ring laser. The diffracted beam (shown as a dotted line) passes over the prism to the detector.

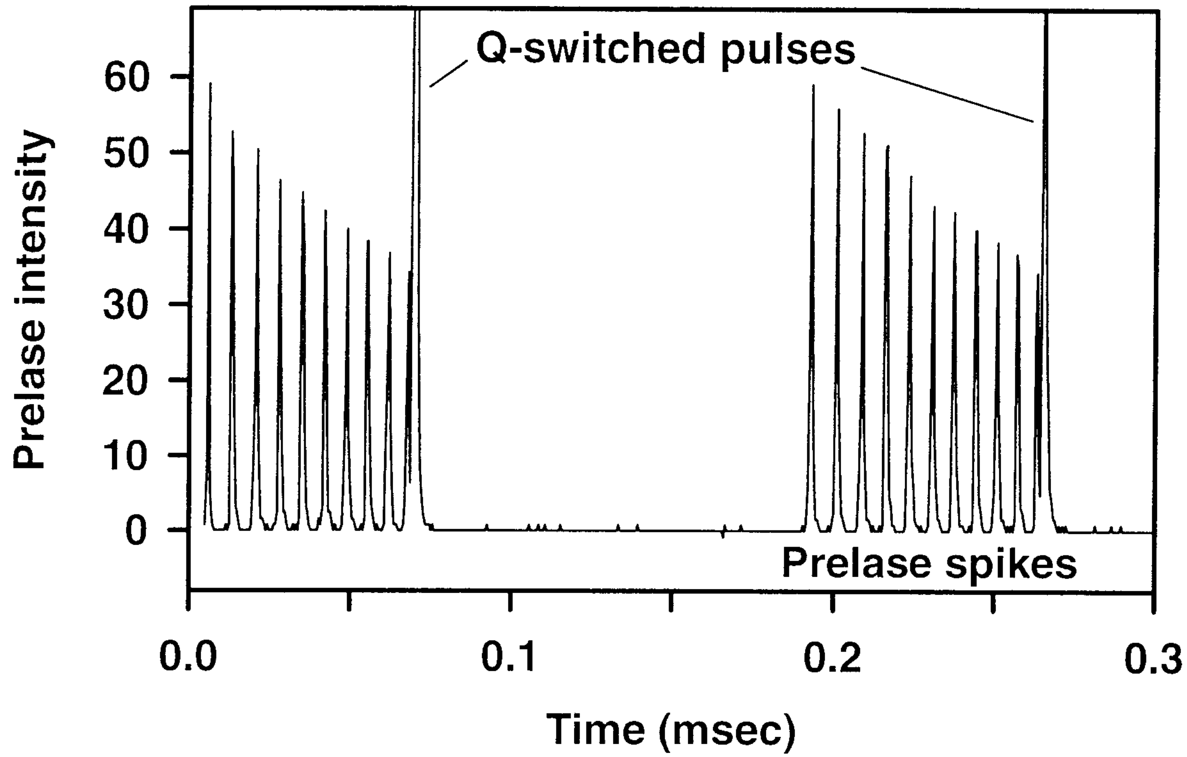
Fig. 2 Prelase intensity a) without active stabilization and b) with active stabilization. Note the fact that for b) the vertical scale (arbitrary units) is expanded by ~ 20 times compared with that for a).

TABLES

Tab. 1 Performance of the Q-switched ring laser with and without active prelase stabilization (stab = stabilized prelase, unstab = without stabilization)


5 cm
Diode laser pump
Nd:YAG rod
AO Q-switch
Prism
Output coupler
Diffracted beam
Detector
PID
RF driver


b) Prelase intensity with stabilization
Q-switched pulses
Prelase
Prelase intensity
3
2
1
0
0.0
0.1
0.2
0.3
Time (msec)



a) Prelase intensity without stabilization

Table 1.

PRF (kHz)	Mode of Operation	Time-Averaged Power (mW)	Time-Averaged Prelase Power (mW)	Pulse Width (ns)	Amplitude Jitter (%)	Timing Jitter (ns)
1	stab.	59	0.4	13.5	< 2	1.0
1	unstab.	57	6.8	14.5	8	4
5	stab.	201	2.5	16.5	< 2	1.5
5	unstab.	172	19.0	19.0	20	35
10	stab	233	7.1	24.5	< 2	1.5
10	unstab	224	19.0	24.0	50	40
15	stab.	247	11.4	33	< 2	2.0
15	unstab	227	27.2	35	100	90
25	stab	248	20.7	55	< 2	2.5