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# STABLE SINGLE-MODE OPERATION OF A Q-SWITCHED LASER BY A SIMPLE RESONATOR LENGTH CONTROL TECHNIQUE

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A simple extension to the technique of "pre-lase" Q-switching ensures that a $TEM_{00}$ mode, Q-switched NdYAG laser produces single longitudinal mode oscillation on *every* shot.

The technique of "pre-lase Q-switching" [1,2, and references therein] is being adopted increasingly for selection of a single longitudinal mode (SLM) in Q-switched solid state lasers. The technique involves deliberately leaving the Q-switch shutter slightly open to allow the laser oscillation to grow at a low intensity level over very many resonator transits (the "pre-lase" growth). This permits selection of a single mode and after this has been achieved the Q-switch is fully opended to allow growth to full intensity. A very large degree of mode selection can be achieved in this way and it is easy to ensure that the majority of pulses are single mode (e.g. 80–90% of pulses free from discernible mode-beating [2]). However this technique alone is not sufficient to ensure SLM operation on *every* laser shot since any uncontrolled drifts of resonator length (and hence of mode frequency) will lead occasionally to the situation where two resonator modes have nearly equal net gain. Thermal stabilisation of the resonator length is a costly and elaborate way of overcoming this problem. In this paper we report the use of a modified version of the prelase Q-switch technique which, without the need for thermal stabilisation of the resonator, ensures SLM output on *every* laser shot.

The modification involves monitoring the prelase oscillation (which takes the form of a train of relaxation oscillation pulses) to see whether mode-beating is present. If the first pulse in this train shows beats the Q-switch is not opened on that pulse and the next pulse is examined in the same way and so on. Eventually a beat-free pulse will appear and the Q-switch is then opened to allow this pulse to grow to full intensity. The explanation for this eventual appearance of a beat-free pulse lies in the fact that the optical resonator length is swept as a result of heat generated in the laser rod by the pumping process. Thus if two modes have nearly equal gain on the first prelase pulse, as a result for example of their frequencies being symmetrically situated on either side of an intracavity Fabry–Perot transmission peak, then in later pulses the frequencies may be sufficiently swept so that one mode is closer to the peak and thus dominates its neighbours. For this technique to work successfully one clearly requires a sufficiently large sweep of frequencies and a sufficiently narrow transmisstion peak from the Fabry–Perot. For a NdYAG laser we have found that these conditions can be met and thus one has an automatic means of adjusting the resonator to an appropriate length during the pumping pulse. Kuizenga [3] has reported using this resonator length sweep to ensure SLM operation in a NdYAG laser having a very long prelase period. In his quasi-cw situation a simple observation of output power increase or decrease was used as an indicator of resonator length. The approach we describe in this paper requires a more sophisticated monitoring procedure during the prelase but on the other hand does not require the provision of a special flashlamp discharge circuit for very long prelase operation. It can therefore be applied in a straightforward way to existing laser systems without the need for any additional modification either to the laser power supply or resonator.

To gain a quantitative appreciation of how this new technique works we first calculate the range of resonator lengths over which two modes have net gains sufficiently close that SLM operation is not achieved. In practice one aims to provide enough mode-selection to ensure that this range is only a small fraction of the complete range of resonator lengths. This calculation indicates the magnitude of resonator length change required to move from two-mode oscillation to SLM oscillation. We than go on to estimate the sort of length change that occurs in typical operating conditions for a NdYAG laser and show that it is sufficient to ensure the appearance of a beat-free pulse during a few tens of microseconds of pumping.

We shall represent the action of the mode selector (which in practice will be a resonant reflector, tilted etalon or combination of these) by a mirror having a frequency-dependent reflectivity $R$. By a suitable choice of free spectral range and control of temperature and/or angle of tilt one can arrange that there is one dominant reflection maximum within the gain profile of the laser. We therefore consider the mode selection behaviour only for those longitudinal modes falling within this dominant maximum. This is shown schematically in fig. 1. Fig. 1(a) represents the ideal situation where one mode coincides with the peak of the maximum and hence receives the greatest possible discrimination in its favour. Fig. 1(b) shows the worst case situation with two adjacent modes having exactly the same gain and fig. 1(c) shows a situation between these two extremes where the dominant mode (mode $n$) is detuned by an amount $\delta\nu(<c/4L)$ from the maximum. The ratio of the powers $P_n/P_{n+1}$, of the modes $n$ and $n+1$, after $q$ round trips of prelase is thus [4],

$$P_n/P_{n+1} = (R_1/R_2)^q \ . \qquad (1)$$

Generally the reflectivities $R_1, R_2$ satisfy the inequality $1-R_1, 1-R_2 \ll 1$ and also the frequency behaviour of the normalised reflectivity can be approximated by a quadratic dependence on detuning from the maximum, i.e. $R \approx 1 - a(\delta\nu)^2$; hence equation (1) can be approximated to

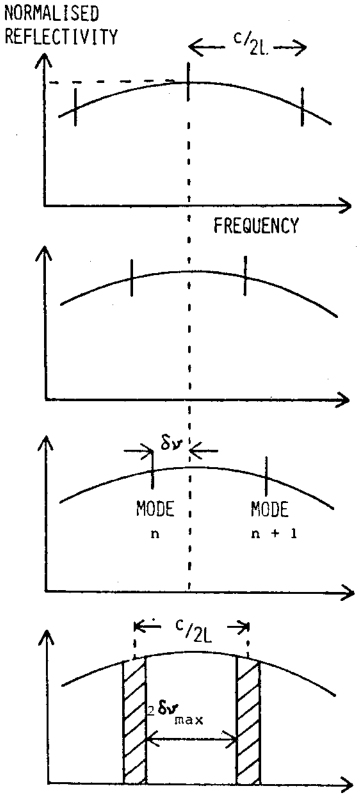


Fig. 1. The frequency selectivity of the mode selector is represented by a frequency dependent reflectivity. The mode frequencies are represented by vertical strokes, separated in frequency by $c/2L$. (a) The ideal situation providing maximum selectivity. (b) The worst situation where two adjacent modes have exactly the same reflectivity. (c) A general situation in which the dominant mode ($n$) is displaced by $\delta\nu(<c/4L)$ from the reflectivity maximum. (d) The hatched region represents the range of mode frequencies for which two mode oscillation occurs. Outside the hatched region single mode operation occurs.

$$P_n/P_{n+1} = [1 + a(c/2L)(c/2L - 2\delta\nu)]^q \ . \qquad (2)$$

Once the criterion of single-mode operation has been adopted, viz. that $P_n/P_{n+1}$ exceed some particular ratio $N$, eq. (2) can then be used to determine the maximum detuning, $\delta\nu_{max}$, before the SLM criterion is violated, i.e. two-mode operation occurs. This gives

$$\frac{\delta\nu_{max}}{c/2L} = \tfrac{1}{2} + (1 - N^{1/q})\frac{2L^2}{ac^2} \approx \tfrac{1}{2} - \frac{\ln N}{q}\left(\frac{2L^2}{ac^2}\right) \qquad (3)$$

In fig. 1(d) the range of mode frequencies for which two-mode operation would occur is indicated by the hatched regions. If one mode falls in one hatched region, the adjacent mode (spaced by $c/2L$) falls in the other hatched region. The width of each hatched region is $c/2L - 2\delta\nu_{max}$. Thus if a prelase oscillation pulse shows two-mode operation it only requires a resonator length sweep of at most $(\lambda/2)(1 - 4\delta\nu_{max}L/c)$ to shift the frequency out of the hatched region and thus ensure SLM in subsequent prelase pulses. Clearly it is desirable to make the hatched region in fig. 1(d) as narrow as possible i.e. $\delta\nu_{max}$ must approach $c/4L$. From (3) it can be seen that this requires the absolute magnitude of the quantity $2(1 - N^{1/q})L^2/ac^2$ to be made as small as possible, e.g. by using a short resonator (small $L$), a large degree of mode selectivity (large $a$) or a long prelase (large $q$).

We now illustrate these points using as a numerical example those parameters corresponding to a particular NdYAG resonator we have used in this work. The resonator was essentially the same as that described in [2]. This was a telescopic resonator in which the role of the telescope was to provide a large $TEM_{00}$ mode volume in the laser rod, but this Q-switch technique is equally applicable to more conventional resonators. The resonator differed from that in [2] in the following respects; the rod diameter was 6 mm; the telescope magnification was X3; $\lambda/4$ plates were placed either side of the rod to eliminate spatial hole-burning [5]. The resontaor optical length was 1.2 m and the output mirror a 6 mm thick uncoated resonant reflector (RR). This was held in an oven at an appropriate temperature to bring a reflection maximum to the centre of the gain profile. The selection between adjacent modes was provided by a 1 cm thick intracavity etalon (fused silica) with faces of 74% reflectivity, and tilted to match its transmission maximum to the RR reflection maximum. Besides providing a damage resistent output mirror the RR served to suppress oscillation on adjacent transmission maxima of the tilted etalon. The etalon parameters imply a value for $a$ given by $a(c/2L)^2 = 0.126$ [2], although in practice the etalon finesse is somewhat degraded from its value implied here as a result of tilt-induced walk-off losses. $N$ was taken to be $10^5$, this large value being necessary to ensure that any mode beating gives an intensity modulation of less than 1% [2]. These values inserted in (3), with an estimated $q = 1000$, yield $\delta\nu_{max}/(c/2L) = 0.45$. Thus a resonator length change of only 0.05 $\lambda$ would be necessary to pass from the condition for two-mode operation to the condition for SLM. We note in passing that if the resonator length drifts from shot to shot in a random fashion (over a range exceeding $\lambda/2$) then for our earlier prelase Q-switching technique, where switching is effected on the first prelase pulse, the fraction of pulses which are SLM will be $(4L/c)\delta\nu_{max}$. For the resonator parameters given above this would imply a proportion of SLM pulses of 90% when averaged over a large number of shots. We have made a rough check on the statistics of SLM operation under such prelase Q-switching conditions. In this case we provided a slow scan of resonator length by means of a wedged plate translated across the resonator [2], driven by a piezoelectric stack. The Q-switched pulse was observed on a oscilloscope and it was seen that a sequence of shots with SLM operation was followed by a (shorter) sequence of shots with two-mode operation. By timing the duration of these sequences with a stop-watch we estimated that ~80% of pulses were SLM. The simple analysis given here, while limited by the accuracy of the estimate for $q$, does appear to give a useful quantitative guide to the conditions required for SML operation. We also note that this measurements technique gives a convenient and direct way of checking quantitatively on the effectiveness of a mode selector.

An estimate is now made of the resonator length sweep that actually occurs in practice. This requires a knowledge of the heat energy, $E$, deposited in the laser rod (length $l$, radius $r$, specific gravity $\rho$, specific heat $\sigma$, refractive index $\mu$) during the flashlamp pulse of duration $\tau$. The rate of change of resonator length is then

$$[d\mu/dT + (\mu - 1)l^{-1}dl/dT]E/(\tau\rho\sigma\pi r^2) .$$

The energy $E$ is a fraction $\eta$ of the energy $E_l$ emitted by the flashlamp, i.e. $E = \eta E_l$. The fraction $\eta$, and hence $E$, can be determined from an observation of the steady state focal length $F_R$ induced in the laser rod by repetitive pulsing of the flashlamp at frequency $f$. Roughly this is given by [5]

$$F_R = \frac{2K\pi r^2}{E_l\eta f(d\mu/dT)} . \tag{4}$$

In practice we have found $F_R$ for the particular laser system we used, to be given by

$$F_R = \frac{2.0 \times 10^3}{E_l f} . \tag{5}$$

From (4) and (5) it is thus found that $\eta \sim 0.05$ and using this figure we calculate a resonator sweep rate of 2 nm/$\mu$s for a 140 $\mu$s flashlamp pulse (FWHM) of energy $E_l = 32$ J, these being the normal operating conditions. Thus we see from this rough estimate that in a time of 30 $\mu$s, which is sufficient time for 4 or 5 prelase pulses to occur, the resonator sweep is ~0.06 $\mu$m. On the basis of our estimate above, this length sweep should be sufficient to sweep the mode frequencies from two-mode operating conditions to SLM conditions. In practice we have found that it is necessary to allow up to four or five prelase pulses (total time span of ~30 $\mu$s) to guarantee that there was always a beat-free prelase pulse. The number of prelase pulses is adjusted simply via the flashlamp energy or the Pockels cell voltage in the partially open condition. The numerical example considered here underlines the importance of introducing sufficient mode selection, i.e. making the hatched region of fig. 1(d) sufficiently narrow that one can guarantee the ability to sweep the mode frequencies clear of the hatched region in a time which is a small fraction of the pumping pulse.

We now briefly describe the modified prelase detection and trigger electronics shown in block form in fig. 2. A fuller description will be given in a further publication [7]. The laser beam incident on the photodetector is that rejected by the intracavity polariser, hence the detector receives a strong signal during the prelase operation but is protected from the full Q-switched pulse intensity [1]. The photodetector output is split into two signals ($S_1$ and $S_2$) and $S_1$ is taken, as in the original prelase scheme, to the Pockels cell trigger circuit, but passing now by way of a gate. The signal $S_2$ is used to inhibit opening of the gate, and hence inhibit triggering of the Pockels cell, if a modulation at frequency $c/2L$ is present on signal $S_2$ To achieve this the signal $S_2$ is filtered (passing the $c/2L$ component), then rectified and amplified before being presented to the gate. The sensitivity, i.e. the depth of modulation at which triggering is inhibited, can be controlled by varying the gain of the amplifier stage. By opening the switch S the signal $S_2$ can be blocked from the gate, thus reducing the function of the circuit to that of the original prelase Q-switching scheme and a direct comparison can therefore be made between the original and modified schemes.

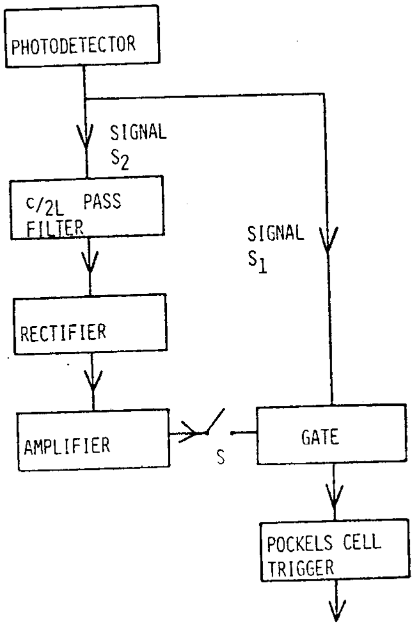


Fig. 2. Block diagram of prelase detection and trigger electronics. With the switch S closed the gate prevents the Pockels cell from being triggered open when $c/2L$ intensity modulation is present on the prelase pulse.

Operating the laser with the switch S open it was found that, at a Q-switched $TEM_{00}$ output level of 50 mJ, and 10 Hz pulse repetition rate, SLM operation with clean beat-free pulses would occur for a period of ~1 min before drifting into two-mode operation for a few seconds and then drifting again into SLM and so on. The two-mode operation was characterised by a sinusoidal intensity modulation at frequency $c/2L$, whose depth fluctuated from shot to shot, with many pulses showing modulation down to the base-line. With the switch S closed, the Q-switched pulses (which remained at the same 50 mJ level) were all free from discernible modulation. By monitoring the signal $S_1$ one could observe directly which prelase pulse the Q-switch opened on. On some shots, opening occurred on the fourth or fifth prelase pulse. If the pump energy and Pockels cell voltage were adjusted to give fewer than 4 or 5 prelase pulses (spanning ~30 $\mu$s) it was found that on occasional shots no Q-switched output occurred. This indicated that to guarantee the appearance of a heat-free pulse a sweep time of 30 $\mu$s had to be provided for. The

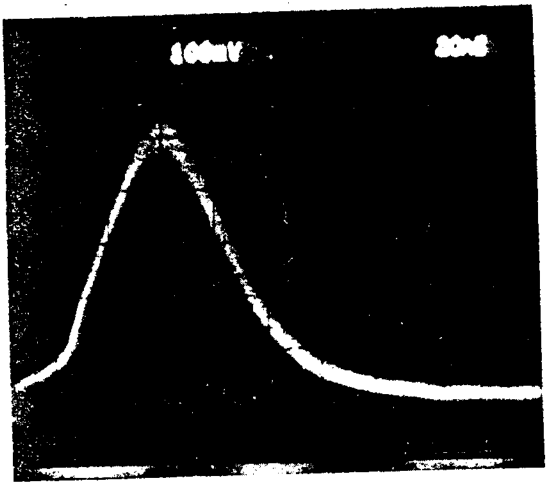

Fig. 3. 200 superimposed consecutive pulses at 50 mJ, $TEM_{00}$ output.

required sweep time can be reduced by providing additional mode selectivity. Fig. 3 shows a typical sequence of ~200 shots at the 50 mJ output level. Operation with clean, repeatable SLM pulses, and with no shots missed, as in fig. 3, can now be maintained indefinitely in this laser. It should be noted that although triggering of the Pockels cell now no longer necessarily occurs on the first prelase pulse, this does not introduce extra amplitude fluctuation of the Q-switched pulse since each prelase pulse occurs when the same gain and hence stored energy is present in the rod. It should also be noted that although the Q-switched pulse timing necessarily has a larger jitter with respect to the initiation of the flash lamp pulse (up to 30 $\mu$s in this laser), one can use a reference pulse from the Pockels cell trigger circuit in fig. 2, to ensure synchronisation of other equipment to the Q-switched pulse. Finally it should be noted that long term frequency stability of the laser is determined by the stability of the dominant mode-selector, i.e. in this case the tilted etalon, whereas the effect of resonator length sweep is to introduce at most a frequency instability of $c/4L$, i.e. in this laser, 0.002 $cm^{-1}$.

In this letter we have reported a simple modification to the detection/trigger electronics of a prelase Q-switched NdYAG laser such that this laser now shows single longitudinal mode operation on every laser shot. No thermal stabilisation of the resonator is required. In fact the laser will continue to operate SLM even with air draughts through the resonator R, and even starting from cold, i.e. without allowing warm-up time. The same technique would be readily applicable to other solid state lasers, such as ruby, Nd : glass. Where the thermal coefficient of the laser medium is less than for NdYAG (e.g. Nd : YLF) it may be necessary to deliberately introduce a resonator length sweep (e.g. via a second Pockels cell) or it may be sufficient merely to achieve greater mode selection. This could be done by using a much shorter resonator than ours, whose length was determined by the simultaneous requirement of a large $TEM_{00}$ energy [8]. Another possibility is to exploit a technique [9] which allows a transmission etalon to be used without tilt. In this case a much thicker etalon can then be used. In conclusion we have demonstrated a technique applicable to any Q-switched laser, which allows completely reliable operation of a single longitudinal mode. This is likely to be of considerable value in very many applications of high power lasers.

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