

STABILISATION OF SINGLE-LONGITUDINAL MODE OPERATION IN A Q-SWITCHED Nd:YAG LASER

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Detection of the reflected laser beam power from the mode-selecting etalon in a pre-ase-Q-switched laser provides an indicator of mode-frequency drifts. The detected signal can be used to control a piezo-mounted resonator mirror, thus correcting the drift and providing a means for maintaining single longitudinal mode operation on every shot.

In a recent paper [1] a method was described for ensuring single longitudinal mode (SLM) operation of a Q-switched Nd:YAG laser on every shot. The basis of the technique involved detection of any beating at a frequency of $c/2L$ between two adjacent longitudinal modes during the pre-ase period and suppression of the Q-switching until this beat signal had disappeared (see [2,3] for a discussion of pre-ase-Q-switching). While this technique worked successfully, it had the disadvantage that the RF detection circuitry was somewhat inflexible since it had to be tuned for a particular $c/2L$ frequency and, hence, a

particular resonator length. In this paper we report an alternative technique in which the gradual drift towards two-mode operation is detected and corrected before two-mode oscillation actually occurs. In addition, the scheme has greater flexibility since it works with any resonator length. We have tested this on a Q-switched Nd:YAG laser and confirmed that SLM operation can be reliably maintained.

The principle of this improved technique is indicated schematically in fig. 1. It is assumed that the pre-ase Q-switched laser has a transmission etalon as its dominant mode selector. The selected mode will,

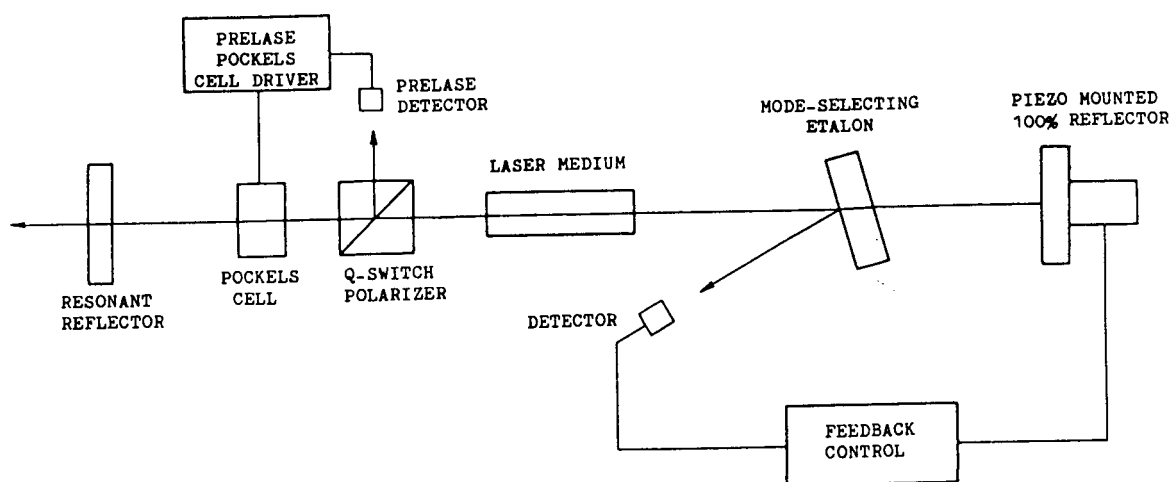


Fig. 1. Schematic diagram of the arrangement for control of the resonator length to ensure single longitudinal mode operation.

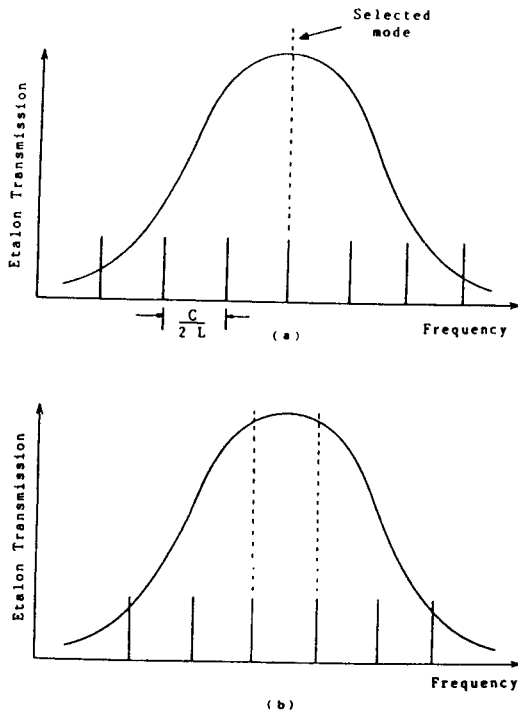


Fig. 2. (a): Optimum situation where the selected mode frequency coincides exactly with the transmission maximum of the etalon. (b) Worst situation where the two modes have the same net gain.

therefore, be the one whose frequency is closest to the transmission maximum of the etalon. This situation is depicted in fig. 2(a). As the resonator length drifts so the mode frequency will move away from the etalon maximum until eventually the situation shown in fig. 2(b) develops. Here the resonator modes are symmetrically situated on either side of the etalon maximum and two-mode oscillation will occur since both modes have the same net gain. In principle it is possible to detect that the mode frequency has drifted from the etalon maximum by observing the increased reflection of the laser beam from the etalon. A photodetector monitoring this reflected beam can thus provide an error signal to drive a piezoelectric-mounted resonator mirror so as to restore the mode frequency to the peak of the etalon transmission maximum. For this technique to work it is necessary to meet two main requirements:

(i) the change in reflectivity at the etalon should be sufficient to provide a usable error signal, and

(ii) resonator length drifts between successive shots should occur sufficiently slowly.

We have carried out tests with a Q-switched Nd:YAG laser which confirm that both of these requirements can be met. Some care is needed to satisfy requirement (i) and we discuss below the precautions taken to ensure this. Condition (ii) is readily met in practice. Our laser components were mounted upon an optical table and no attempts were made to temperature control the resonator length. Typically, the behaviour of the laser (operating at 5 Hz repetition rate without any resonator length control) was characterised by periods of SLM operation lasting around 2–3 min, separated by periods of two-mode operation lasting approximately 30 s.

In principle, for an ideal etalon with plane-wave illumination, the reflectivity should be zero when the mode frequency coincides exactly with the etalon transmission maximum. In practice, some residual reflection will occur and a variety of causes can contribute to this. Obvious candidates are unequal surface reflectivities and walk-off effects in the etalon due to both tilt and diffraction spread [4]. These are quantifiable effects and we make estimates of their likely contribution to the residual reflection. Care must also be taken to eliminate stray reflections so that they do not interfere with the weak reflected signal. Having taken precautions to eliminate or minimise spurious reflections, we found that under the conditions of our experiments the reflected intensity from the etalon increased by around 50% from its minimum value before the onset of two-mode operation occurred. This is a somewhat smaller increase than expected on the basis of the residual reflectivity that can be accounted for, suggesting the presence of other, less easily quantifiable contributions to the reflected signal. Nevertheless, the increase is sufficient to provide a reliable error signal.

First we estimate the residual reflectivity due to unequal reflectivities of the etalon surfaces. We note that the etalon finesse, and hence mode selectivity, is determined by $(R_1 R_2)^{1/2}$. Unequal reflectivities do not, therefore, degrade the selectivity; however, the peak transmission is reduced and in the case $R_1 = R - \delta, R_2 = R + \delta, (\delta \ll R)$ the etalon reflectivity at the peak of the transmission maximum can be shown to be $\delta^2/R(1 - R^2)$. Our etalon (1 cm thick, fused quartz) had coatings of nominally $R = 0.7$. Measure-

ment of the face reflectivities indicated that they were equal to within experimental accuracy (± 0.01), hence, taking the worst case reflectivities of 0.71 and 0.69 gives a maximum residual reflection of approximately 0.3%.

Next we consider the reflection loss resulting from the fact that the multiply reflected beams within the etalon do not overlap each other perfectly due to both tilt of the etalon and diffraction spread between successive reflections. An approximate expression for the single pass tilt loss (i.e. the residual reflection) is given by Leeb [5], namely $R(2t\theta/\mu W_0)^2/(1-R)^2$ where R is the reflectivity, θ the tilt angle, t the thickness, μ the refractive index and W_0 is the waist spot size. In ref. [6] it was shown that this approximate expression is in reasonable agreement with experimental measurements and with the more exact analysis of Arnaud et al. [4]. It can be seen that tilt loss is greatly reduced by reducing the etalon tilt. However, with a very small tilt angle, the risk of lasing from the etalon reflection increases. We have, therefore, adopted the scheme described in ref. [6] allowing use of the etalon at exact normal incidence, thus eliminating entirely the tilt walk-off loss and its associated reflection. Fig. 3 shows the arrangement used, with the etalon sandwiched between two $\lambda/4$ plates (orientated to cancel each others phase shift)

and these in turn sandwiched between two parallel polarisers. Thus any reflection from the etalon due to the laser beam arriving from the left is then rejected by the polariser 1. This is the reflected beam used to provide the error signal. The second polariser (2) serves to eliminate the etalon reflection due to the beam travelling from the right and ensures decoupling of the two reflections thus preventing unwanted etalon effects due to multiple reflections between etalon and total reflector. In practice, polariser 1 was not perfect and also coupled out a small fraction of the horizontally polarised beam travelling from right to left through the etalon. To eliminate this unwanted beam (which would otherwise appear as a residual reflection) a third polariser, orientated to transmit vertically polarised light, was used.

Even with the etalon at normal incidence there remains a residual reflection due to diffraction walk-off. From Arnaud et al. [4] it is seen that the single pass power reflection loss due to this is $\sim 2Rt^2\lambda^2/\pi^2\mu^2(1-R)^2W_0^4$ where W_0 is the waist spot size of the beam incident on the etalon. For our resonator this was calculated to be $\sim 0.05\%$.

It now remains to calculate the increase in etalon reflection that occurs when the resonator modes detune from the etalon transmission maximum (by $c/4L$) to the condition shown in fig. 2b, when two-

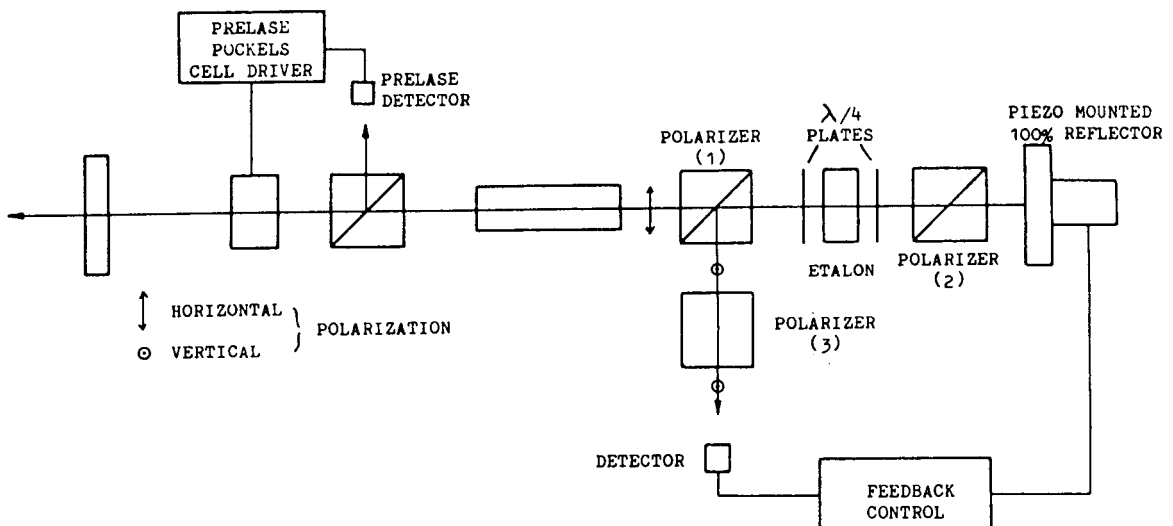


Fig. 3. Prelase Q-switched resonator with normal incidence etalon. The reflection from the etalon, having vertical polarization, is deflected by polarizer 1 onto the photodetector. Any horizontally polarized light deflected by polarizer 1 is eliminated by polarizer 3, which transmits vertically polarized light.

mode oscillation occurs. In fact, to make a more conservative estimate we shall calculate the reflectivity when the mode is detuned from the etalon maximum by $c/8L$. It is readily shown that the reflectivity is then $\pi^2 R t^2 \mu^2 / 4(1 - R)^2 L^2$, which for our resonator ($L(\text{optical}) = 0.9 \text{ m}$) gives $\sim 0.4\%$.

These estimates suggest that at worst an increase in etalon reflectivity from a minimum of around 0.35% ($0.05\% + 0.3\%$) to $\sim 0.75\%$ can be expected before two-mode operation sets in. The measured 50% increase in reflectivity is less than the estimated value implying the presence of additional residual reflection, possibly due to limitations imposed by etalon flatness and parallelism. These estimates indicate the feasibility of the proposed technique while also pointing to the importance, in view of the small reflectivity increase, of taking careful precautions to eliminate sources of spurious reflections and residual reflectivity.

We now give some more details on the resonator and the procedure taken to ensure and control SLM operation. The resonator was a conventional stable resonator with a 2 m radius of curvature concave total reflector separated by an optical length, $L = 0.9 \text{ m}$, from a plane resonant reflector (RR) output mirror. The Nd:YAG rod was located between $\lambda/4$ plates to eliminate spatial hole-burning effects in the laser rod [7,1] which could otherwise lead to a weaker secondary pulse on a different longitudinal mode. This would give confusing results if a slow detector were used to monitor the etalon reflection as the weaker secondary pulse would give a disproportionately large contribution to the etalon reflection. The total reflector was mounted on a piezo-electric element with provision to allow its position along the resonator axis to be scanned by $\sim 1 \mu\text{m}$, more than sufficient to sweep a mode frequency by $c/2L$. A circular aperture selected the TEM_{00} mode and the calculated waist size W_0 at the resonant reflector was 0.57 mm. The RR, of fused silica 6 mm thick, having a free spectral range of 0.56 cm^{-1} , had the purpose of providing coarse frequency narrowing. Oscillation on a single RR maximum, tuned to the centre of the Nd:YAG gain profile, was therefore required. This was achieved by temperature tuning the RR (without the transmission etalon in the resonator) and observing the frequency-doubled output of the laser with a Fabry-Perot interferometer. Simultaneous oscillation on two RR maxima could be easily resolved in this

way and the RR temperature was set to midway between the values at which the onset of this two-frequency oscillation occurred. The transmission etalon (1 cm thick, 0.34 cm^{-1} free spectral range, $R = 0.7$) was then introduced into the resonator together with its $\lambda/4$ plates and polarisers as shown in fig. 3. It was then aligned for exact normal incidence and the temperature set to bring its transmission maximum into coincidence with the resonant reflector reflection maximum. This was again observed using the frequency-doubled output of the laser, and it was seen that with the etalon maximum sufficiently detuned from the desired RR maximum, the laser oscillation would jump to a different RR maximum. The etalon temperature was set to midway between the values at which such jumps occurred. This completed the setting-up of the frequency selectors. A double check on correct setting-up was provided by scanning the voltage on the piezo-electric element while the laser was operating with the pre-lase Q-switch. A complete resonator length scan of $\sim 1 \mu\text{m}$ ensured that the laser passed from SLM through two-mode operation, to SLM on the adjacent longitudinal mode. The absence of any coarse frequency jump from one RR maximum to another confirmed that the laser oscillation was also confirmed to just one etalon maximum. This is an important check since the basis of this mode control technique is that oscillation is confined throughout to just one etalon reflectivity maximum.

With this setting-up procedure completed, the reflected signal from the etalon was observed with a fast photodetector and oscilloscope. At first it was found that random, uncontrolled jumps from SLM operation to two-mode operation were occurring. These were traced to air currents across the resonator and when beam tubes were incorporated, it was found that manual scans of the piezo-mounted mirror gave a reliable and repeatable behaviour, in which the minimum reflected signal corresponded to a smooth unmodulated SLM pulse. As the piezo-mounted mirror was translated this reflected signal (which showed only a few percent fluctuation from shot to shot, the same as the main laser output) increased smoothly by $\sim 50\%$ typically before eventually breaking into deeply modulated pulses characteristic of two-mode operation. Fig. 4 shows energy measurements taken over a total period of 4 min, at 5 Hz repetition rate,

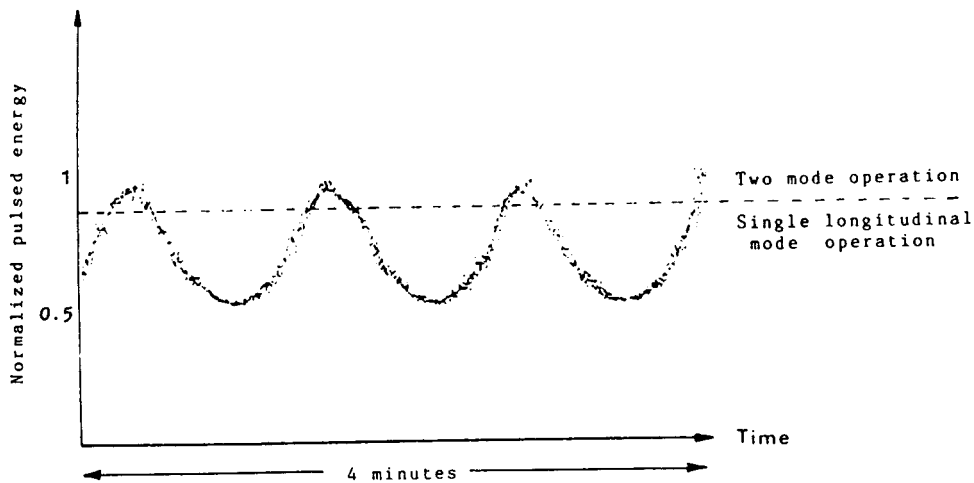


Fig. 4. Energy reflected from the etalon measured as a function of time. The signal is large (above the dotted line) when the laser oscillates on two modes, and lower (below the dotted line) when it oscillates on a single longitudinal mode.

of the signal reflected from the etalon when the piezo-electric voltage was held constant. A steady drift of resonator length was taking place, with a total drift of ~ 3 half wavelengths during the period. Two-mode operation occurred for $\sim 20\%$ of shots, confined to those intervals of time above the dotted line in fig. 4, where the reflected signal had increased by more than $\sim 50\%$ from its minimum value. As can be seen from fig. 4, the resonator length drifted quite slowly from shot to shot. This allowed manual control of the voltage to the piezo-electric element to maintain operation near the reflection minimum. With this simple manual control, SLM operation could be reliably maintained over long periods (up to half an hour at 5 Hz repetition rate was tested) without drifting into two-mode oscillation. The reliability and ease of manual control of this scheme suggest that a number of simple electronic feedback control schemes would be effective, based upon the principle of actively controlling the piezo-mounted mirror to minimize the etalon reflection. Any control technique will benefit from an increase in the fractional change of etalon reflectivity with mode detuning from the etalon maximum. It is therefore of some interest to establish the cause of the residual reflection from the etalon. A rough measurement of the power in the beam reflected from the etalon indicated a residual reflectivity of $\sim 0.6\%$. An estimate of this reflectivity

can also be made from the fact that the observed reflectivity increased by a factor of ~ 2 between its minimum and maximum (fig. 4). Since the reflectivity increase in going from minimum to maximum, due to detuning the mode frequency by $c/4L$ from the etalon transmission maximum is calculated to be $\sim 1.5\%$, this suggests a residual reflectivity of $\sim 1.5\%$. The two estimates of residual reflectivity do not show good agreement, and the origin of the discrepancy is not known. However, it is clear that the residual reflectivity is greater than can be accounted for on the basis of calculated diffraction walk-off or loss due to inequality of etalon surface reflectivities. We suggest that the most likely source of this loss is imperfect surface flatness of the etalon and a simple estimate given below suggests that this is a very demanding requirement. First we note that the technique requires the ability to detect a mode frequency shift of the order of $c/4L$ where L is the laser resonator optical length. We assume the optical path, μt , in the etalon varies by λ/q across the beam cross section. Suppose a mode frequency ν is exactly at the etalon transmission maximum in the region where the etalon thickness is μt , then

$$nc/2\mu t = \nu. \quad (1)$$

If the mode frequency shifts to $\nu - c/4L$ and is now in resonance with another part of the etalon, of thick-

ness $\mu t + \lambda/q$, then

$$nc/2\mu t(1 + \lambda/\mu tq) = \nu - c/4L. \quad (2)$$

So, from (1) and (2) we find $q = 4(L/\mu t)$ and therefore q must exceed this value if there is to be a significant change in the reflectivity of the etalon as the mode frequency shifts by $c/4L$. Typical values of L and μt imply a flatness requirement across the beam of hundredths of a wavelength. This is an exacting requirement. However, the etalon used in our experiment had a nominal flatness of only $\lambda/10$ in the visible and yet gave satisfactory performance. It should be noted, however, that this same etalon did not give satisfactory performance in a telescopic resonator configuration [2] where the beam size in the etalon was some three times larger, presumably as a result of larger thickness variations over the larger beam area.

Conclusion. A new technique for control of SLM operation in a Q-switched Nd:YAG laser has been demonstrated. The technique relies upon the detection of the weak reflected signal from the mode-selecting etalon and its increase as the mode frequency goes out of tune with the etalon resonance. Care

is needed to ensure the elimination of spurious reflection and to minimise the residual background reflection from the etalon. However, given this care, the technique provides a simple means for ensuring reliable single longitudinal mode operation on every shot of the laser.

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