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HIGH POWER, SINGLE FREQUENCY OPERATION OF A Q-SWITCHED TEM$_{00}$ MODE NdYAG LASER

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An actively Q-switched NdYAG laser, using a telescopic resonator configuration has produced single longitudinal mode, TEM$_{00}$ outputs of 100 mJ with output pulses free from any observable mode-beating.

A telescopic resonator configuration has recently been described [1,2] in which reliable operation of a Q-switched NdYAG laser with TEM$_{00}$ energies of ~100 mJ was achieved. We have now applied to this laser a technique of active Q-switching which allows selection of a single longitudinal mode. Single frequency TEM$_{00}$ outputs of ~100 mJ are obtained and the ripple-free output pulses show excellent amplitude stability. These results demonstrate the advantage the stable telescopic resonator holds over unstable resonator configurations, since frequency selection is more difficult in unstable resonators (see [3]) and more complex techniques involving injection from a stable single mode master oscillator have had to be adopted [4]. In our laser no attempts were made at temperature stabilisation of the overall resonator length, but despite this it was found that single frequency operation can persist for several hundred shots at 10 Hz repetition rate. With simple stabilisation techniques it is expected that single frequency operation with ripple-free output pulses could be maintained indefinitely.

The layout of the laser resonator is shown in fig. 1. The details of the telescopic resonator design have been given in [1,2] and the active Q-switching technique which we briefly summarise here was first described in [5,6]. The technique consists of initially setting the Pockels cell voltage to such a level that the laser is just able to reach oscillation threshold. The laser oscillation is monitored by a detector (see fig. 1, the monitored output consisting of light reflected off the polariser after being slightly depolarised by passing through the laser rod). The laser pulse grows slowly, taking very many cavity transits to reach a preset level

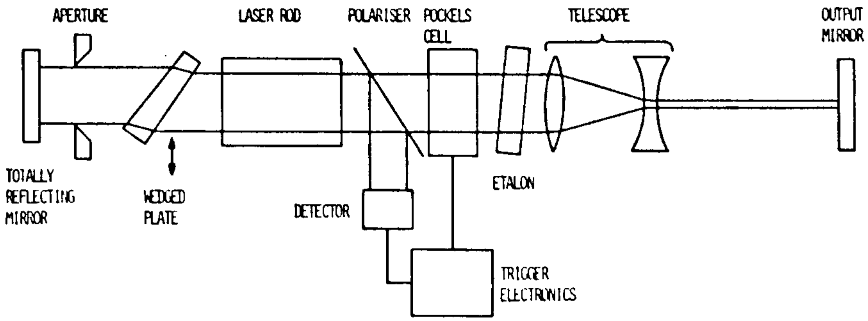

Fig. 1. Schematic layout of TEM$_{00}$ mode telescopic resonator which single mode Q-switching.

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at which the output from the detector is used to trigger the Pockels cell open. As a result of these many transits a very large cumulative degree of mode-selection, enough for selection of a single mode, can be obtained from a selector such as a resonant reflector or tilted intracavity etalon even though these provide only a small selectivity per transit. When the Pockels cell is switched fully open this mode-selected radiation is amplified to the full Q-switched pulse energy.

Clearly it is the suppression of modes adjacent to the selected mode that presents the greatest problem and we adopt here as our criterion of "single-mode operation" the requirement that the displayed output pulse of the laser using a fast detector and oscilloscope (~1 ns response) must show no observable ripple due to beating between adjacent modes. This proves to be a very stringent requirement as the following example will show, but it does reflect the practical requirement for many experiments in which a high power pulse of very well defined intensity is needed. Consider the situation where a pulse contains just two oscillating modes with a ratio of their powers given by N (where $N > 1$), and let k be the difference in power between peak and trough of the modulation, normalised with respect to the mean power (see fig. 2). Then it can be shown that for $k \ll 1$, the relationship $k = 4N^{-1/2}$ applies. Typically one requires $k < 10^{-2}$ if beating is to be unobservable, hence the mode selection must ensure that one mode dominates its adjacent modes by a factor $N > 1.6 \times 10^5$. In [5], equations were derived for the power ratio P_m/P_n for two adjacent longitudinal modes after q round trips of a resonator containing either a resonant reflector (RR) or a transmission etalon (TE). In calculating the intensity ratio it was assumed in [5] that the selected mode is at a reflectivity maximum of the RR or a transmission maximum of the TE. The results are

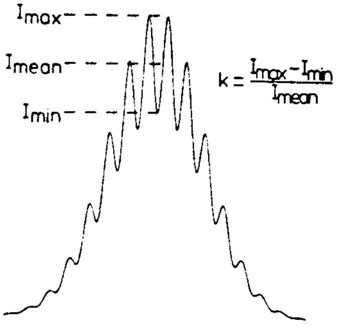

Fig. 2. Intensity I as a function of time showing beating between two modes having an intensity ration N. The normalised depth of modulation k is given by $k = 4N^{-1/2}$

$$\left(\frac{P_m}{P_n}\right)_{\mathrm{TE}} = \left[1 + \frac{8\pi^2\mu^2 l^2 R}{L^2(1-R)^2}\right]^q, \qquad (1)$$

$$\left(\frac{P_m}{P_n}\right)_{\mathrm{RR}} = \left[1 + \frac{\pi^2\mu^2 l^2 (1-R)^2}{L^2(1+R)^2}\right]^q, \qquad (2)$$

where, in each case the mode selector has surfaces of reflectivity R separated by a medium of thickness l and refractive index μ. L is the overall optical length of the laser resonator. It is clear from (1) and (2) that it is advantageous to make L small since this increases the expression in brackets i.e. enhances the mode selectivity. In addition a smaller L implies a larger number of transits q before the preset intensity is reached ‡. On the other hand, the telescopic resonator design favours a long resonator [1,2]. Despite these conflicting requirements, our results have shown that the conditions for single mode operation can in practice be met quite readily.

The value of L used for most of these experiments was 1.3 m, this being the length originally adopted in our telescopic resonator design [1,2] and the value of q was roughly estimated as 1000 [5]. If we consider the use of a tilted solid etalon of thickness $l = 10$ mm, refractive index 1.45, and reflectivity 60% it is found from (1) that $P_m/P_n = 5 \times 10^{15}$, which is clearly a large enough ratio to satisfy our criterion of single mode operation. Similarly, if we consider an uncoated resonant reflector of thickness 5 cm, and refractive index 1.45 (hence $R = 0.0337$), then (2) indicates that $P_m/P_n \approx 3 \times 10^{11}$. We have indeed found experimentally that single mode operation can be obtained with either a tilted etalon or a resonant reflector having the parameters indicated above and figs. 3a and 3b show multiple exposures of ~250 shots (at 12 Hz) and 50 mJ and 100 mJ output respectively, using the resonant reflector. After some tens of seconds, i.e. several hundred shots, the laser

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‡ This fact is perhaps not obvious at first sight, but it must be remembered that the net round-trip gain is itself growing during the pulse growth.

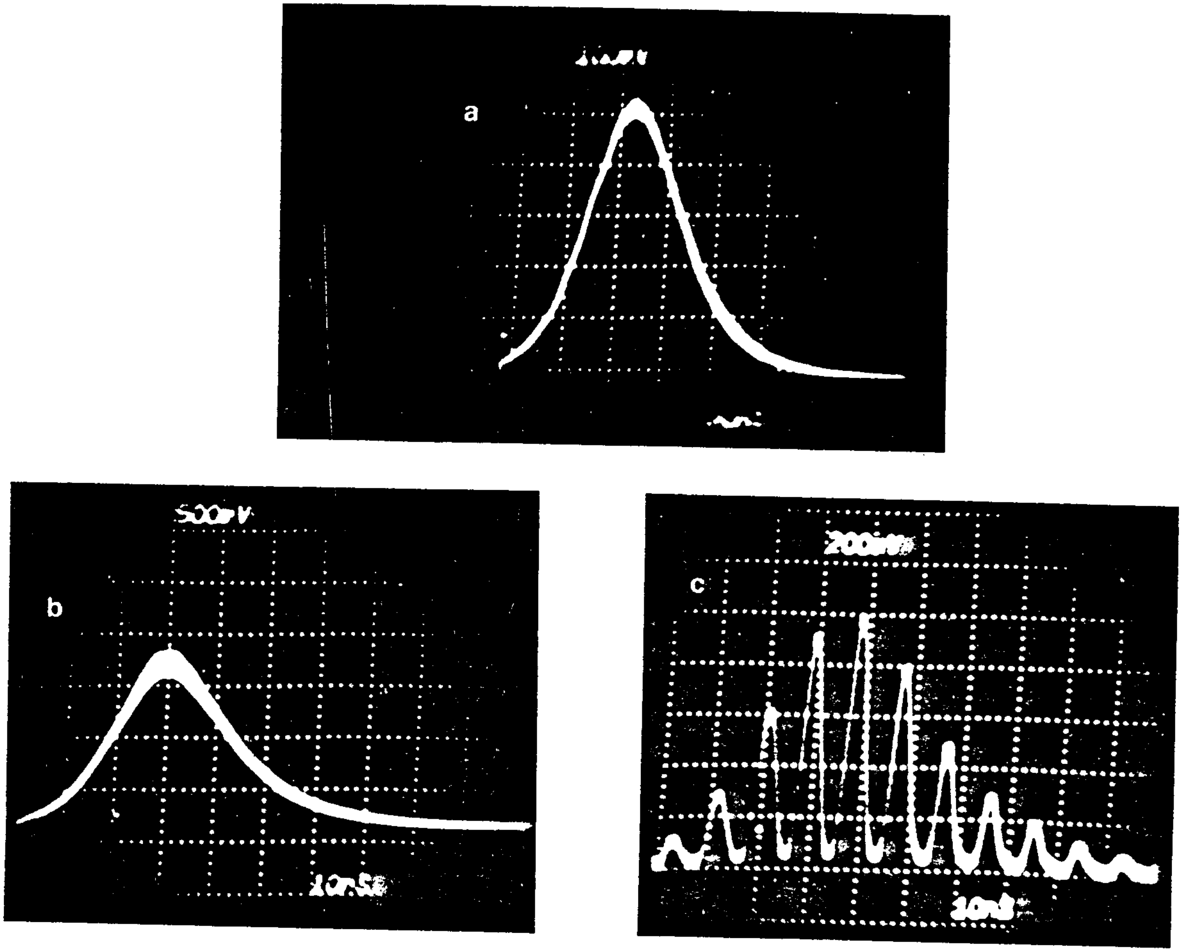

Fig. 3 (a). A multiple exposure of 250 output pulses (12Hz repetition rate) at 50mJ pulse energy in a TEM_{00} mode (20ns/division). (b). As (a) but at 100 mJ pulse energy (10ns/division). (c). A typical pulse showing beating between two modes after the resonator length has drifted. The beat-free pulse of (a) is restored by translating a wedged plate across the resonator axis.

drifts into two-mode operation (due to a drift of the overall optical length of the resonator) and fig. 3c shows a typical output pulse under those conditions. Single mode operation is restored very simply by translating an intracavity wedged plate across the beam, thus tuning the resonator length, until beat-free pulses are again observed. The simplicity of this operation, and the length of time before adjustments are required (~1 min) suggests that a simple feed-back scheme should permit essentially beat-free pulses to be maintained indefinitely.

The single mode Q switching technique described here relies for its success on the cumulatively large mode selection that results when a small degree of frequency discrimination is experienced for many round trips. The required frequency selection can then be provided by a single device and this offers the advantage that the degree of mode selection can both be calculated and controlled with ease. On the other hand it does mean that care must be taken to avoid any spurious, unwanted frequency selection, since even quite small effects can end up by modifying or even dominating the intended frequency selection. Examples of this are etalon effects from the laser rod faces and from the various surfaces in the Pockels cell. Our Pockels has wedged windows and a wedged crystal to avoid such effects. Similarly, a laser rod with wedged faces can be used. In our case the rod had parallel faces, so these were misaligned by ~30 min from the beam axis. It has been noted [7] that alignment of the rod faces parallel to the resonator mirror can give a very large degree of mode selection, enough to achieve single mode using conventional Q-switching. We have also observed this behaviour, but the realibility was poor and the effect was therefore deliberately suppressed by tilting the laser rod. With these precautions taken the dominant cause of mode selection was then provided by the resonant reflector or tilted etalon.

When considering whether to use a transmission etalon or resonant reflector it appears at first sight that the tilted etalon has two advantages. Firstly (1) suggests that provided R is made large enough then l can be made quite small. Thus oscillation on adjacent resonances of the etalon would be suppressed since with one resonance arranged to coincide with the peak of the gain curve, the adjacent resonances would fall well outside the gain-narrowed line. One must however use (1) with caution, since it assumes the theoretical finesse corresponding to a situation with plane waves incident on the etalon. In practice the walk-off loss of a finite size beam within a tilted etalon leads to a degradation of its finesse [8,9] and hence a smaller selectivity than (1) suggests. The magnitude of this effect is not easy to quantify, although rough estimates have been derived [10,11]. The walk-off loss can be kept to a minimum by using the etalon as close to normal incidence as possible while avoiding laser oscillation due to the etalon reflection. Despite this precaution we found that the high reflectivity etalon ($R = 60\%$, $l = 10$ mm) still showed a significant insertion loss and an increased pumping level was therefore required to restore the output to the 100 mJ level. To tune the etalon transmission into coincidence with the gain curve one can either adjust the angle of tilt or change its temperature. The resonant reflector does not suffer from problems of beam walk-off. It is however necessary to use a larger l to get sufficient selection between adjacent modes and this in turn means that some additional selection is required to suppress oscillation on adjacent resonances of the reflector. With the 5 cm RR used in our experiments it is found that an uncoated silica plate of 6 mm thickness, used as a tilted transmission etalon, is quite enough to achieve this suppression, as can be confirmed using (1) with L interpreted as the optical thickness of the resonant reflector. This transmission etalon was tilted to ensure that its transmission maximum coincided with the resonance of the reflector. Operated in this way we found that it was not necessary to temperature tune the resonant reflector to coincide with the gain maximum of the laser medium. An advantage of this RR mode selection scheme is that the tilted, low reflectivity etalon was found to exhibit only a small insertion loss. Eqs. (1) and (2) both assume that the mode to be selected is situated at the peak of the selector's frequency response. This can be achieved by fine-tuning the angle of the tilted etalon or tuning the temperature of the resonant reflector, or (and this has proved the most convenient) by tuning the resonator length by means of the wedged plate.

A number of further precautions have contributed to the realibility of single mode operation. Mechanical stability is clearly important and all components have therefore been firmly bolted down to a good quality optical table (NRC). The laser rod has been positioned as close as possible to the resonator mirror, thus exploiting the spatial hole-burning behaviour to discourage growth of adjacent modes when the dominant mode has saturated the gain [12]. Before taking this precaution the laser rod has been situated close to the centre of the resonator and the main laser pulse was seen to be followed by a weaker secondary pulse (up to ~15% of the main pulse energy). With the rod placed near the mirror this secondary pulse was no longer observed. Finally, we found that the krytron switching circuit which opened the Pockels cell produced a considerable amplitude of voltage spiking, which in turn led to amplitude modulation of the output pulse. This could easily be misinterpreted as mode beating. By cleaning up the voltage step to the Pockels cell this effect was removed and completely smooth pulses were then obtained as shown in fig. 3.

In conclusion, we have shown that the telescopic resonator, whose capability of producing large TEM_{00} mode volume has already been demonstrated, can also be operated so as to give reliable single longitudinal mode output.

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Note added

Park and Byer [13] have recently reported the application of a Q-switching technique, which they refer to as electronic linewidth narrowing ("ELN"), to an unstable resonator Nd : YAG laser. Apart from the fact that their Q-switch is triggered open during the second rather than the first prepulse, their ELN technique is identical to that reported in the present paper and first reported by Hanna et al. in 1972 [5,6]. The two-step-Q-switching technique referred to by Park and Byer is incorrectly referenced. It was first reported by Hanna et al. in 1971 [14], but was quickly abandoned in favour of the simpler technique of our ref. [5]. It should also be noted that the application of "ELN" to an unstable resonator NdYAG laser, with a discussion of the special problems posed by unstable resonators was previously reported by Hanna and Laycock in 1979 [3].

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