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Single longitudinal mode selection of high power actively Q-switched lasers

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A Pockels cell Q-switch has been operated in a manner analogous to a saturable absorber by initially keeping the cell partly open for the first 1000 or so double passes and then opening it completely at a pre-set resonator power. This then allows simple and reliable selection of a single longitudinal mode. A detailed discussion is given of the design considerations which lead to the correct choice of mode-selecting device. With three different devices, a TEM_{00} mode Nd:$CaWO_4$ laser has produced 400 kW pulses in a single longitudinal mode with a shot-to-shot frequency stability of $\sim$ 0.01 cm^{-1}.

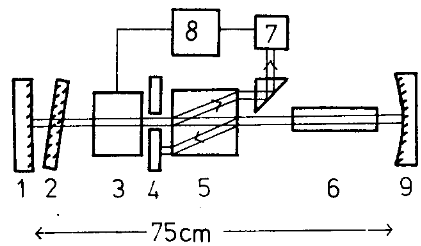
1. Introduction

In a previous publication [1] a technique has been described for producing high power in a single longitudinal mode by deliberately lengthening the build-up time of the giant pulse. This was achieved with a Pockels cell Q-switch which was opened in two stages. In the first stage a small net gain was produced which allowed a slow build-up, during which a high degree of mode-selection was obtained from a resonant reflector. In the second stage the Pockels cell was completely opened to allow the single mode selected during the first stage to grow to full power.

An improvement on this technique has been recently made [2] in which the switching of the Pockels cell is carried out in a manner which is more closely analogous to the bleaching behaviour of a saturable absorber. This leads to even longer build-up times and then, as with a saturable absorber Q-switch, sufficient mode-selection can be obtained from a simple intra-cavity etalon used in transmission or an uncoated etalon in reflection to allow reliable single longitudinal mode operation at megawatt powers. This technique is discussed more fully here with emphasis given to the design considerations which lead to the choice of particular mode selectors. Experimental results from a Nd:$CaWO_4$ laser are used by way of illustration but the treatment is quite general and can be applied in an obvious way to other lasers such as Nd:YAG or ruby. The technique is especially valuable with lasers for which there are no suitable saturable absorbers.

2. Experimental arrangement

Only an abbreviated description of the experimental arrangement for the Q-switching technique is given here since it has already been described elsewhere [2]. The arrangement of components in the laser resonator is shown in Fig. 1. All experiments have been carried out with a TEM_{00} transverse mode selected by a circular aperture. It has then been possible to use a 25 mm long block of calcite as a polarizer. Only the ordinary polarization can resonate since the extraordinary polarization suffers double-refraction



Laser resonator arrangement: (1) Plane reflector with anti-reflection coated back surface; (2) Tilted etalon mode selector; (3) Pockels cell; (4) Transverse mode-selection aperture; (5) Calcite block polarizer; (6) Nd:$CaWO_4$ laser rod; (7) Silicon photodiode; (8) Trigger electronics for Pockels cell; (9) High reflectivity concave mirror.

walk-off which is sufficient to remove it from the cavity where it is monitored by a silicon photodiode. Initially the Pockels cell is only partially open and it therefore presents a loss which is analogous to the low-level absorption loss of a saturable absorber. Due to pumping, the net gain increases until it exceeds unity and build-up of the giant pulse then starts. This build-up is monitored by the photodiode and its signal is used to trigger the Pockels cell to open completely when a preset signal level is reached. This is analogous to the bleaching of a saturable absorber at a particular intensity. Thus a long build-up time is achieved by an "active" Q-switch used in a way which is very closely analogous to a "passive" saturable absorber Q-switch.

3. Mode-selection

3.1. General considerations

Sooy [3] has discussed the enhanced mode-selection that results from a slow build-up of the giant pulse. Specific reference is made to saturable absorber Q-switching but the analysis is equally applicable to the behaviour of the pulse generated by our Q-switch. There are two essential results from this analysis. First, the growth with time t of the power P_n in mode n is given by

$$P_n(t) = P_{0n} \exp \{k_n(t - t_n)^2\} \tag{1}$$

where P_{0n} is the noise power in the mode at the start of build-up, t_n is the time at which the net gain for mode n reaches unity, k_n is equal to $(1/2T)\,dg_n/dt$ where T is the round-trip time for the resonator and $\exp\{g_n\}$ is the round-trip power gain within the laser rod. Secondly, the ratio of the powers P_m, P_n in modes m and n respectively after q double passes of build-up, is given to a good approximation by

$$\frac{P_n}{P_m} = \left(\frac{1 - L_n}{1 - L_m}\right)^q (1 - L_n)^{q(g_m/g_n - 1)} \tag{2}$$

where L_m, L_n are the losses per double pass for modes m and n. Apart from a difference of notation this equation is the same as Equation 10 of Sooy [3] with the final exponential term of that equation omitted since it is, as Sooy points out, usually negligible. The importance of a large value of q, i.e. a long build-up, is evident from Equation 2. Equation 2 also shows clearly the effect of the two different mode-selection mechanisms, the first term corresponding to loss discrimination and the second term to gain discrimination. The latter leads to a relatively coarse mode-selection, the linewidth due to gain-narrowing alone being typically one or two orders of magnitude less than the fluorescence linewidth. Once the extent of gain-narrowing is known, an etalon mode-selector (i.e. a loss-discriminator) can be chosen to provide the finer mode-selection. The choice of etalon must satisfy the conditions that its free spectral range be somewhat wider than the gain-narrowed linewidth (to confine oscillation to one etalon maximum) and that its finesse be sufficiently high, i.e. $L_n - L_m$ be sufficiently large, for the loss discrimination to select a single mode.

The criterion for "single-mode oscillation" is taken to be that the dominant mode should be at least ten times greater in power at the peak of the pulse than any other mode. We therefore calculate first the frequency shift $\delta\nu$ from line centre for which the spectral power density is reduced by gain-narrowing to one tenth that at line centre. For a Lorentzian line, and assuming $2\delta\nu/\Delta\nu \ll 1$, where $\Delta\nu$ is the FWHM of the fluorescence line, it can be shown that

$$\frac{g_n - g_m}{g_n} \simeq \left(\frac{2\delta\nu}{\Delta\nu}\right)^2 \tag{3}$$

where mode n is close to line centre and mode m is shifted by $\delta\nu$ from line centre. $\delta\nu$ must therefore satisfy

$$(1 - L_n)^{-q(2\delta\nu/\Delta\nu)^2} = 10 \; . \tag{4}$$

But, since at threshold

$$(1 - L_n) = e^{-g_{n0}} \tag{5}$$

(where g_{n0} is the value of g_n at threshold), Equation 4 can be rewritten as

$$\frac{\delta\nu}{\Delta\nu} = \tfrac{1}{2}\left(\frac{\log_e 10}{g_n\, q}\right)^{\frac{1}{2}} \tag{6}$$

Thus it is necessary to know g_{n0} and q in order to calculate the gain-narrowing $\delta\nu/\Delta\nu$. Methods for estimating g_{n0} and q are given in the section on experimental results, the values obtained with our laser being $g_{n0} \simeq 2.3$ and $q \simeq 1000$. This leads to a predicted value of 0.32 cm^{-1} for $\delta\nu$ since $\Delta\nu$ is 20 cm^{-1} for Nd:$CaWO_4$. For our laser this has implied the choice of a mode-selector having a free spectral range greater than 0.32 cm^{-1} and sufficient loss discrimination such that $[(1 - L_n)/(1 - L_m)]^{1000} > 10$ where modes m and n are adjacent modes separated in frequency by 0.0067 cm^{-1} corresponding to a 75 cm optical path between resonator mirrors.

One such device is a resonant reflector. Many workers have reported the use of a multiple plate resonant reflector to obtain single frequency oscillation from a ruby laser

Q-switched by a saturable absorber (see e.g. [4]). The design of resonant reflectors has been discussed by Watts [5]. The attractive feature of a properly designed multiple plate resonant reflector is that it provides both a high reflectivity and high degree of frequency selectivity. The particular resonant reflector we have used consists of two identical 2.5 mm plates of Schott BK7 glass, optically contacted to a fused quartz spacer of 25 mm. A discussion of this design has been given in [1]. It amply satisfies the conditions given above since its free spectral range is 1.3 cm^{-1} and $[(1 - L_n)/(1 - L_m)] \simeq 1.009$ which implies that $[(1 - L_n)/(1 - L_m)]^{1000} > 10^3$. Experimentally it has been found, using the present Q-switching technique, to give single longitudinal mode oscillation with excellent reliability. In fact with the longer build-up time now available this resonant reflector gives a greater degree of mode-selection than is strictly necessary and it has been found possible to use instead the simpler single plate devices. Bjorkholm and Stolen [6] have reported single mode output from a passively Q-switched ruby laser with a single sapphire or glass flat as output mirror and a number of authors have reported mode-selection using intra-cavity etalons [7-9]. In the analysis that follows we examine the suitability of such single plate devices for selecting a single mode.

3.2. Selectivity of single-plate etalon

Consider a parallel-sided etalon of thickness t, refractive index μ and having surfaces with reflectivities R_1, R_2 such that $R_1 R_2 = R^2$. Neglecting losses other than reflection losses the transmission T for light of wavelength λ is given by

$$T = \frac{1}{1 + \dfrac{4R}{(1 - R)^2} \sin^2(\delta/2)} \tag{7}$$

where $\delta = 4\pi\mu t \cos\theta/\lambda$ and θ is the internal angle of refraction in the etalon. We suppose that mode n has a wavelength such that $\delta = 2p\pi$ (p is an integer), then $T = 1$ for mode n, i.e. $L_n = 0$. This condition can be achieved by varying the angle of tilt of the etalon and hence varying δ. For an adjacent mode m, $\delta = 2p\pi + \Delta$ and $\sin^2 \delta/2$ will be small ($\simeq \Delta^2/4$). It can then be shown that for a double pass through the etalon the following relationship holds:

$$\frac{1 - L_n}{1 - L_m} \simeq 1 + \frac{2R\Delta^2}{(1 - R)^2} \tag{8}$$

$$\simeq 1 + \frac{8\pi^2 \mu^2 t^2 R}{L^2(1 - R)^2} \tag{9}$$

where L is the optical length of the laser resonator.

A similar analysis for a reflecting etalon shows that for one cavity round trip (i.e. one reflection from the etalon),

$$\frac{1 - L_n}{1 - L_m} \simeq 1 + \frac{\pi^2 \mu^2 t^2}{L^2} \left(\frac{1 - R}{1 + R}\right)^2 . \tag{10}$$

In this case it has been assumed that mode n has a wavelength which corresponds to a maximum reflectivity and mode m is an adjacent mode (i.e. m = n ± 1). Comparison of Equations 9 and 10 reveals that for a transmission etalon the mode selectivity increases with increasing R, whereas for a reflecting etalon the converse is true. This means in practice that the reflecting etalon is a useful mode selector only with high gain lasers which can tolerate the low reflectivity. Another feature which makes the reflection etalon less convenient is that tuning to ensure that mode n is at a maximum of reflectivity must be achieved by temperature variation since tilting is not possible.

The condition for suppression of the adjacent mode by 10 dB is

$$\left(\frac{1 - L_n}{1 - L_m}\right)^q > 10 \tag{11}$$

and using the fact that $(1 - L_n)/(1 - L_m) \simeq 1$ this condition can be written with the help of Equation 9 as

$$q \frac{8\pi^2\mu^2t^2R}{L^2(1 - R)^2} > \log_e 10 \tag{12}$$

for the transmission etalon.

For the reflection etalon the corresponding condition is

$$q \frac{\pi^2\mu^2t^2}{L^2}\left(\frac{1 - R}{1 + R}\right)^2 > \log_e 10\,. \tag{13}$$

Also if the etalon free spectral range ($1/2\mu t$ cm^{-1}) is chosen to be just equal to the gain-narrowed linewidth $\delta\nu$ given by Equation 6, the condition for single mode operation becomes

$$\frac{q\, g_{n0}^{\frac{1}{2}}R^{\frac{1}{2}}}{L(1 - R)} > \frac{(\log_e 10)\Delta\nu}{2\pi\sqrt{2}} \tag{14}$$

for the transmission etalon
and

$$\frac{q\, g_{n0}^{\frac{1}{2}}}{L}\left(\frac{1 - R}{1 + R}\right) > \frac{(\log_e 10)\Delta\nu}{\pi} \tag{15}$$

for the reflection etalon. $\Delta\nu$ is expressed in cm^{-1} in these equations.

From these equations one can see the rather obvious results that single mode operation is easier to obtain for small $\Delta\nu$, small cavity length, and a large number of passes q. For our laser, having $\Delta\nu = 20$ cm^{-1}, $g_{n0} = 2.3$, $L = 75$ cm and $q = 1000$, Equations 14 and 15 imply that for a transmission etalon to give single mode oscillation, R must be greater than 0.06 whereas for a reflection etalon R must be less than 0.16. As a reflecting etalon we have used an uncoated 1 cm thick plate of Schott BK7 glass and for such an etalon Equation 10 gives

$$\frac{1 - L_n}{1 - L_m} = 1.0031 \text{ and}$$

hence

$$\frac{1 - L_n{}^{1000}}{1 - L_m} \simeq 20$$

As a transmission etalon we have used a 6 mm thick plate of Schott BK7 glass coated with a single layer of ZnS on each face, giving a reflectivity of 0.3. Equation 9 gives $[(1 - L_n)/(1 - L_m)] = 1.007$ and $[(1 - L_n)/(1 - L_m)]^{1000} \simeq 10^3$ for such an etalon. In our experiments both etalons have been found to give single mode operation reliably.

4. Experimental

In this section we describe first the measurements taken to arrive at estimates for g_{n0} and q, these being necessary to calculate the gain-narrowed linewidth from Equation 6 and thus the required etalon reflectivity from either Equations 14 or 15.

The gain coefficient g_{n0} can be estimated in two ways, allowing a cross-check to be made. First one can measure the threshold with the Pockels cell held permanently open. The laser rod gain is then equal to the losses, so that if the losses are known, the gain at this pump level can be found. Since Nd:$CaWO_4$ is a four-level laser the gain at any pump level can then be calculated. An alternative method [10], which can also be applied to a three-level laser, is to observe the time delay of the appearance of the giant pulse after fast Q-switching, i.e. when the Pockels cell is completely opened without any prior build-up of laser power. If this time delay is τ, the number s of double-passes during build-up is given by $s = \tau/T$. The relation between the final peak power P and the initial noise power P_0 is given to a good approximation by

$$P/P_0 = (1 - L)^s e^{sg} \tag{16}$$

All quantities in this equation can be measured or calculated, hence g can be calculated. When g is known, dg/dt can be calculated and hence k in Equation 1. In our case for example dg/dt is given approximately by g/t_1, where t_1 is the pump duration. This is a good approximation since Q-switching occurs near the end of the pump pulse and the pump pulse is a square pulse of duration shorter than the fluorescence life-time of the laser material. Equation 1 can then be used to calculate the build-up time (and hence q) since k is known and the peak power can be measured. For illustration some experimental figures appropriate to our laser will now be given.

With the two-plate resonator reflector the round-trip cavity loss was estimated to be 0.7. P was measured under fast Q-switching conditions to be 400 kW for a flash-lamp input energy of 53J. P_0 was calculated to be 4×10^{-8} W for a TEM_{00} mode of 1 cm^{-1} bandwidth and τ was measured to be 140 ns (i.e. $s = 28$). From this data and using Equation 16, g was calculated to be 2.2. When the Pockels cell voltage was kept at zero the threshold was found to be 26.5J and the round trip gain in the laser rod under these conditions was therefore $\exp\{g\} = (1 - 0.7)^{-1}$. At 53J pump energy the gain coefficient g would therefore be 2.4. These two values for g agree well and the average value of 2.3 is used in subsequent calculations. Thus since $t_1 \simeq 200$ μs, then $dg/dt \simeq 1.15 \times 10^4$ s^{-1}. Using this value of dg/dt and $P/P_0 = 10^{12}$ in Equation 1 gives a build-up time of $\simeq 5$ μs or $q \simeq 1000$ for a 75 cm cavity. This value of P/P_0 corresponds to $P = 200$ W (this being the level at which the photodiode would trigger the Pockels cell) and $P_0 = 2 \times 10^{-10}$ W corresponding to the noise power in a TEM_{00} mode of 0.005 cm^{-1} bandwidth. The precise value chosen for P_0 has little effect on the calculated value of q.

The method used to monitor the spectral output of the laser has been described previously in [1]. The output of the laser was frequency doubled in a KDP crystal and then passed into a defocused confocal Fabry-Perot interferometer having a finesse > 20 and a free spectral range of 0.1 cm^{-1} [11]. The mode spacing was 0.0067 cm^{-1} so the interferometer was capable of resolving adjacent modes. Experiments have been performed using the three mode-selecting devices described above; two-plate resonant reflector, single plate reflector (uncoated) and coated intra-cavity etalon. The intra-cavity etalon was found to be very convenient since visual observation of Fabry-Perot fringes while operating the laser at 10 pps made it particularly simple to angle tune the etalon so as to get single longitudinal mode operation. Single mode operation has been maintained with all three devices with excellent reliability. The TEM_{00} output power was 400 kW peak at 10 pps, with a shot-to-shot frequency stability of the order of 0.01 cm^{-1}. Shot-to-shot variations in the output of the flash tube have the effect of varying $(dg_n)/dt$ and hence of q and therefore the degree of mode-selection. However, the three mode selectors used have each had more than adequate selectivity to ensure that such variations have not led to any observable degradation of the mode-selection.

It has even been possible to obtain single mode operation without any mode-selectors in the cavity but the reliability is less good. This is a result previously reported only for ruby lasers Q-switched by saturable absorbers [6, 12]. The explanation for this is not clear at present since there does not appear to be sufficient mode selection from the various anti-reflection coated surfaces within the resonator to account for this degree of mode selection.

Despite this possibility of dispensing with mode selectors it has generally been found worthwhile to add some mode-selection for better stability and reliability.

5. Conclusion

An active Q-switching technique has been described which allows single longitudinal mode operation in high power Q-switched lasers. The advantages of this technique over saturable absorber Q-switches are many. It may be used with lasers for which saturable absorbers are not available (Nd:YAG 1.32 μm and Ho:YAG 2.1 μm, for example). For neodymium lasers operating at 1.06 μm the available saturable absorbers have shown serious chemical instability. In addition, at repetition rates in excess of 1 pps, it becomes necessary to flow the absorber to avoid severe thermal distortion. Problems such as these may now be avoided using the technique described here whilst keeping the desirable mode-selecting properties of the saturable absorbers.

A detailed discussion has been given of the criteria by which a mode-selector should be chosen. Various mode-selecting devices have been used, the simplest from the fabrication point of view being a single plate of glass used as a reflector. This type of mode-selector has been shown to have a greater selectivity the lower the reflectivity of its surfaces. For typical pulsed Nd:$CaWO_4$, Nd:YAG and ruby lasers the selectivity of this device is adequate for single mode operation provided that one uses either the technique we have discussed or a passive Q-switch. These lasers generally have a sufficient gain under pulsed conditions to permit oscillation with such a low reflectivity mirror. For higher reflectivity and a higher mode-selectivity it is possible to use a two- or even three-plate resonant reflector.

An etalon used in transmission has a better frequency selectivity the higher the reflectivity of its surfaces. With a single layer dielectric coating on each face such a device has a much greater selectivity than the same uncoated etalon used in reflection. Too great a reflectivity must be avoided however since the light intensity within the etalon is increased and the risk of damage to the coatings is then greater. For the etalon we used there is a three-fold increase of light intensity inside the etalon but no signs of damage were observed. Since such an etalon has essentially zero insertion loss it may be used with lasers which have insufficient gain to oscillate with an uncoated etalon as mirror. Tuning of the transmission etalon is particularly simple since it is merely necessary to vary its angle of tilt whereas the reflectivity mode selection must be temperature tuned. Using this technique single axial mode operation has been obtained from a Nd:$CaWO_4$ laser with excellent reliability at TEM_{00} powers of 400 kW and 10 pps with a frequency stability of the order of 0.01 cm^{-1}. This suggests many applications particularly in multiple-exposure holography (see e.g. [13]) and in non-linear optics [14].

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