Q-switching in fibre lasers

Bill Barnes, Paul Morkel, Mark Farries, Laurence Reekie and David Payne

Optical fibre group
Southampton University
Southampton
SO9 5NH
England

ABSTRACT

The performance and charactersics of various Q-switched fibre lasers are examined. All results presented are for laser diode pumped systems, emphasizing the practicality of the Q-switched fibre laser. Operation at 0.94, 1.06, 1.09 and 1.57μm wavelengths are covered. The results presented show that Q-switching is currently limited by the performance of the modulator. Theoretical modelling of the process allows us to determine the required properties for a modulator and in addition to predict the expected performance of Q-switched fibre lasers under different conditions.

1. INTRODUCTION

Glasses doped with rare-earth ions have relatively long fluorescent lifetimes ($\sim 1ms$) and are thus good for energy storage. Q-switching allows the stored energy to be extracted as a succesion of high power pulses. This is a particular advantage of fibre lasers and is due to the high optical damage threshold of glass (often silica), when compared with semiconductor materials. Potential applications for Q-switched fibre lasers include non-linear switching, OTDR measurements, materials processing and range-finding. At present, Q-switching is effected by the insertion of bulk components into the laser cavity, however, schemes can be envisaged that rely on all fibre components. The present work is aimed at demonstrating that useful performance may be obtained from diode pumped fibre lasers, and at pointing out the problems involved in enhancing their performance.

In optimizing a Q-switched fibre laser many factors have to be considered. Several of these are worth bearing in mind whilst discussing the different methods of Q-switching.

Pump power	Higher power pulses will be obtainable by increasing the pump power.
Modulator loss	This must be low to ensure diode pumped operation.
Modulator efficiency	In general, fibre lasers are high gain systems so that the Q-switch must have a high extinction ratio in order to hold off CW lasing action.
Cavity length	Short cavities produce shorter, and, as a result, higher power pulses. The minimum practical length will be governed by the dopant level.

2. EXPERIMENTAL

In order to modulate the finesse of the cavity, bulk components are introduced; this requires the cavity to be *opened up*[1] and is achieved by using an intra-cavity lens, fig 1. Inevitably, this results in additional cavity loss: carefull selection of components may keep this below 1dB (round trip) ~~The usual methods of Q switching lasers~~ , namely mechanical, acousto-optic, electro-optic and saturable absorption, may be applied to fibre lasers. Of these the first two are the most common and we will now look at them in detail.

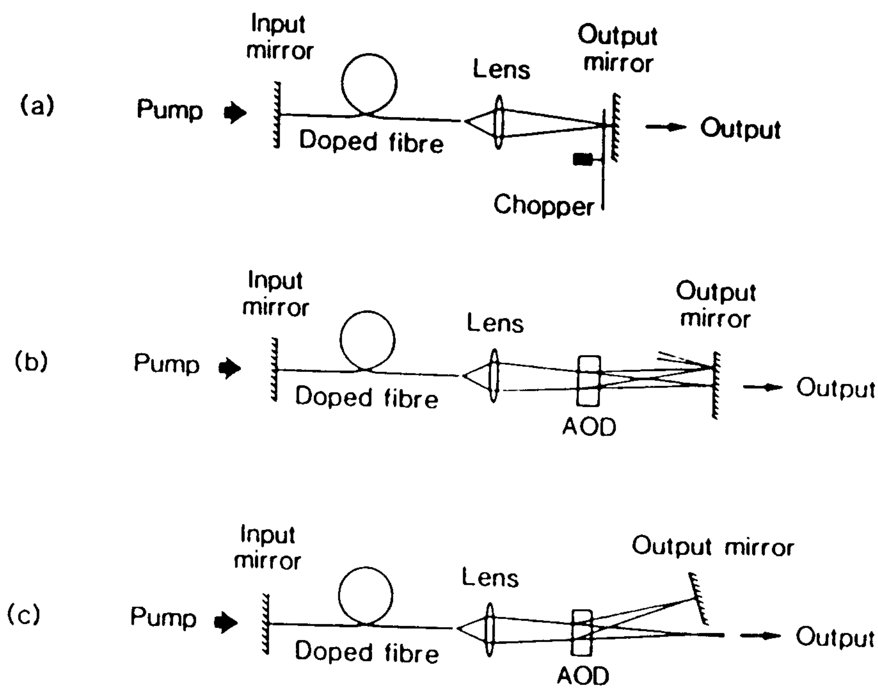

Fig 1. Experimental Q-switching configurations, a) mechanical, b) acousto-optic zero-order, c)acousto-optic first-order.

2.1) Mechanical.

Lasers may be Q-switched with a mechanical chopper. The chopper provides a very high extinction ratio (hold off) and has zero insertion loss in the high Q state. Unfortunately it has a slow switching time and poor pulse to pulse stability. The switching time is minimized by reducing the spot size on the chopper and/or increasing the speed and diameter of the chopper wheel, (the latter may adversly affect the lowest attainable repetition rate).

2.2) Acousto-optic.

More rapid modulation of the cavity finesse may be achieved by use of an acousto-optic deflector (AOD). In addition the mark to space ratio of the modulation may now be accurately controlled via the RF driver. Careful choice of the acousto-optic material together with anti-reflection coating may reduce the insertion loss of the modulator thus allowing low threshold operation of the laser. As we will see later, the greatest problem associated with the AOD is its' limited diffraction efficiency. The AOD may be used in one of two configurations, zero and first-order, discussed in more detail below and shown in fig 1.

2.2.a) ~~Zero order In this arrangement~~ the high Q state is achieved with the AOD off. The undeflected beam is then fed back to the fibre by the output coupler. Once a Q-switched pulse has been emitted the AOD is turned on, suppressing further laser action and allowing a significant population inversion to build up to provide the next pulse. The AOD has a diffraction efficiency less than 100% (typically 50%) so that some light is fed back from the output coupler even in the low Q state. Due to the high gain of many fibre lasers, this feedback may become sufficient to set off CW lasing; thus reducing the stored energy in the cavity and seriously effecting the Q-switched performance. One solution to this problem is first-order operation.

2.2.b) First-order As shown in fig 1, feed back is provided by positioning the output coupler so as to reflect the first-order diffracted beam back into the fibre. With the AOD off there is *no* deflection and there can be no CW lasing in the low Q state. The lack of CW lasing is bought at the expense of significantly increased intra-cavity loss. (In zero-order the loss is just the insertion loss of the AOD, perhaps $0.5dB$. In first order it is insertion loss $\times$ (diffraction efficiency)^2, perhaps $6dB$.)

So far little if any work has been carried out using electo-optic devices or saturable absorption.

3. RESULTS

For convenience the results are divided firstly by dopant type, and secondly by operating wavelength.

3.1 Nd^{3+} at $\sim 1\mu m$

This is the commonest Nd^{3+} transition and, being 4-level it has a very low pump power requirement on threshold. As a result, it can easily tolerate additional intracavity loss in the form of Q-switching components. Nd^{3+} doped SiO_2/GeO_2 fibres lase at $1.09\mu m$ and early results in first-order produced pulses of $\sim 13W$ peak power for a FWHM duration of $120ns$; the absorbed pump power was $15mW$ at $825nm$ for a $2.5m$ length of fibre. Use of a more efficient AOD in zero-order gave pulses of $\sim 21W$ and $53ns$; $8mW$ of pump power was absorbed in a $1m$ length of fibre. Before going on to examine ways of improving this it is worth looking at the functional dependance of both the peak power and pulse width on some of the device papmeters. (Results in this section were all obtained in zero-order.)

3.1.1) Fibre length

For a CW 4-level fibre laser, the optimum fibre length is one which absorbs all of the pump power; extra fibre is of little consequence provided it contributes minimal extra loss at the lasing wavelength. In a Q-switched laser there is the competing requirement of reducing the fibre length to decrease the cavity decay time. This *competition* is clearly seen in fig 2 where an optimum length is seen to exist, in this case ~ $1.5m$.

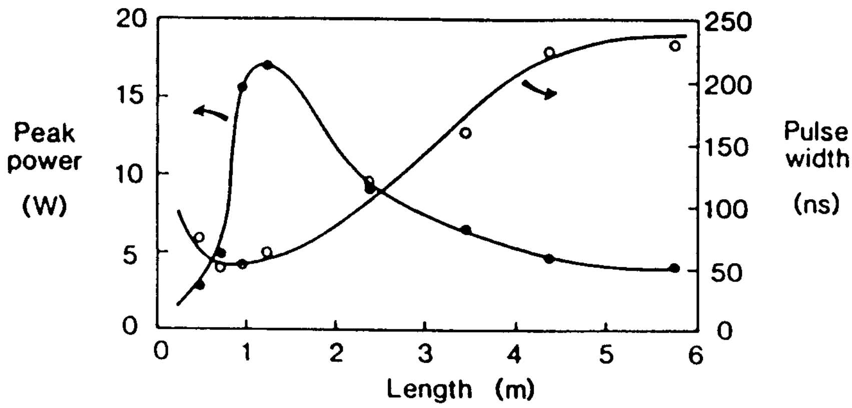

Fig 2. Peak power and pulse width as a function of fibre length. Cavity length = fibre length $+0.5m$. The rep rate was $1kHz$ and the launched pump power was $12mW$. Output coupling was $R = 30\%$ and Q-switching was carried out in first order.

3.1.2) Output coupling

Figure 3 shows the effect of output coupling. Optimum output coupling for the pump power used ($12mW$) was attained at $R = 40\%$. A mirror with too large a reflectivity does not couple out much power whilst a low reflectivity mirror does not allow the laser to get very far above threshold.

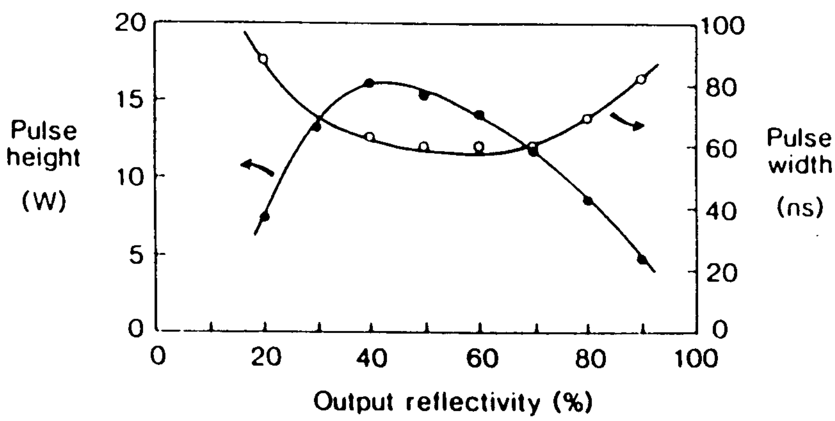

Fig 3. Peak power and pulse width as a function of output coupling. $0.8m$ of fibre was used, other conditions being as for fig 2.

3.1.3) Pump power

The effect of pump power is seen in fig 4. As expected, once above threshold the peak power increases linearly with pump power, along with a corresponding reduction in pulse duration. Further results indicate that the peak power saturates above $\sim 20mW$ of pump power as a result of CW lasing, brought about by a lack of hold off of the AOD. Thus, although increasing the pump power might be considered advantageous, this is not always so. Once there is a sufficient combination of gain and feedback for CW lasing to occur a further increase in pump power is of no benefit (see also section 3.3).

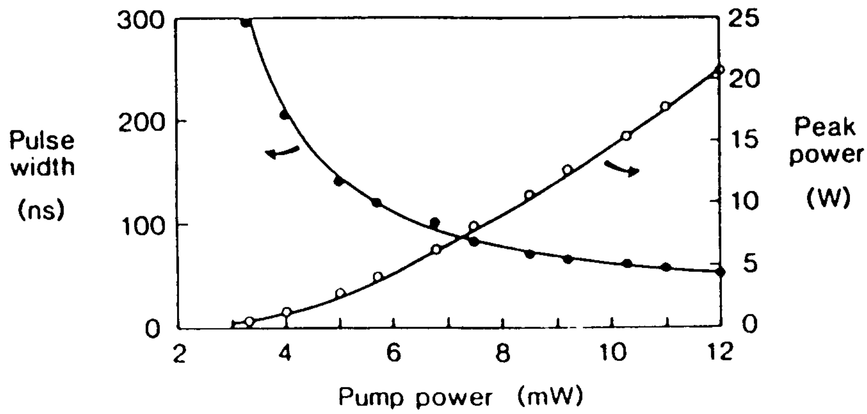

Fig 4. Dependence of peak power and pulse width on launched pump power. $1.22m$ of fibre was used, the rep rate was $400Hz$ and $R = 30\%$ was used as the output coupling.

3.1.4) Repetition rate

Figure 5 shows how the pulse energy and average power are effected by the repetition rate. The pulse energy starts to roll off much above $1kHz$ due to the finite recovery time of the Nd^{3+} sytem. Although the pulse energy falls, the average power of the laser rises untill nearly all of the equivalent CW power is recovered. Devices requiring high repetition rates will have to take this frequency dependance into carefull consideration.

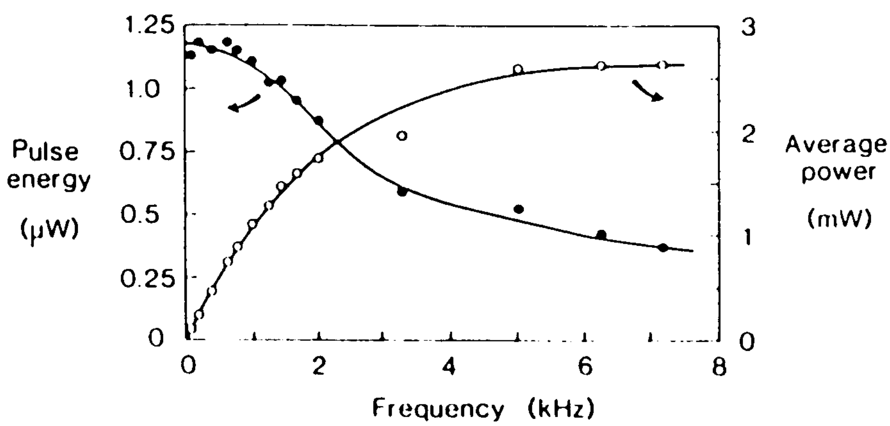

Fig 5. Pulse energy and average power as a function of repetition rate. $1.07m$ of fibre was

used, $R = 30\%$ and the launched pump power was $12mW$.

An interesting feature arises when we examine the shape of the Q- switched pulse. The intensity of the Q-switched pulse is modulated at the round trip frequency, fig 6. This effect was particularly noticable in long lasers where the round trip time was greater than the response time of the detector used. Further, the depth of modulation observed is limited by the response time of the detection system so that the peak power observed will be less than the real peak power. Similar behaviour has been observed before[5], although the mechanism in fibre lasers is not yet clear. The modulation may have important consequences when considering nonlinear optic and perhaps OTDR applications.

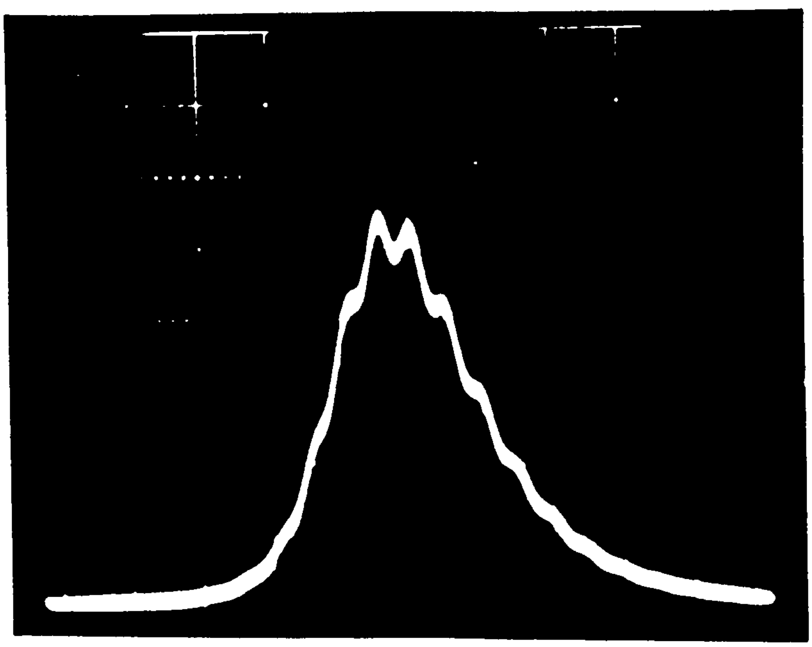

Fig 6. Experimental Q-switched pulse showing modulation at the round trip frequency.

In the results presented so far, peak power has been limited, at least in part by the cavity length. Improved performance thus requires a reduction in fibre length. This in turn necessitates an increase in dopant level and is ultimately limited by clustering and concentration quenching of the Nd^{3+} ions. Higher dopant levels (than those used for the above results) in silica fibres may be achieved by co-doping the fibre with Al_2O_3. For one such fibre, and for typical diode pump powers, the optimum length was reduced to $\sim 20cm$. As a result, consideration must now be given to reducing the length of the open part of the cavity. To this end the intra cavity lens was replaced with a grin rod, which, in addition, reduced the beam diameter and hence the turn on time of the AOD. The resulting pulse, obtained in zero-order, is shown in fig 7. The relavent experimental details are;- fibre length, $17cm$; cavity length, $37cm$; pump power, $17mW$; repetition rate, $800Hz$. The diffraction efficiency of the AOD was measured in the cavity to be

55%. The peak power of $110W$ represents a significant improvement over results obtained with lower dopant levels.

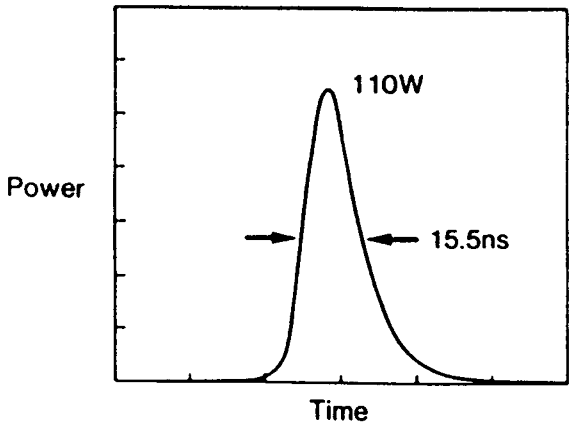

Fig 7. High power pulse from a diode-pumped Q-switched fibre laser. Output coupling $R = 50\%$.

An alternative to higher doped silica fibres is to make fibres by drawing down bulk laser glass. Initial diode pumped experiments have produced $26W$ for a duration of $12ns$ at a wavelength of $1.054\mu m$. Results reported here are all for single stripe diode-pump lasers. Multi-stripe arrays may also be used. By simultaneously mode-locking and Q-switching, pulses with a peak power in excess of $1kW$ have been produced[4],

3.2 Nd^{3+} at $0.94\mu m$

This wavelength results from the three level transition in Nd^{3+} and is of interest beacause of the enhanced sensitivity of silicon detectors at this wavelength when compared with $1.1\mu m$. In order to bleach the three level transition with diode pump powers, a fibre with a large numerical aperture was made ($NA = 0.24$). For this fibre and the maximum pump power available (from two polarization multiplexed diodes) the optimum length was found to be $\sim 1.5m$. Pulses with a peak power of $5.2W$ and a duration of $80ns$ were obtained. On increasing the repetition rate, the peak power fell to half its' maximum value at $\sim 3kHz$. No problems associated with hold off were found - presumably due to the improved diffraction efficiency of the AOD at this wavelength and the low gain available with diode pump powers.

3.3 Er^{3+} at $\sim 1.5\mu m$

Q-switching of erbium is particularly attractive for such applications as range-finding since such devices may be eye-safe. The very high gain available from erbium[6] means that the Q-switched output will eventualy be limited by amplified spontaneous emission (ASE), however, the anticipated output (see below) make it well worth persuing.

Two significant practical problems exist. Firstly, the hold off of an AOD at $1.5\mu m$ is poor since the diffraction efficiency falls as the wavelength rises. Thus the problem of CW lasing becomes even more important: it seems likely that an electro-optic Q-switch will be required. The second problem is the pump wavelength. A practical device requires a diode pump source. Although erbium has a pump band at the commonly used diode wavelength of ~ 810*nm* it is unfortunately affected by pump excited state absorption (ESA). This signifacntly degrades the performance of the laser[7]. Further, because the 1.5μm transition is 3-level, the fibre must be bleached by the pump source before lasing may occurr. This requires a high pump intensity within the core and, to date, only a co-doped $Er^{3+} - Yb^{3+}$ fibre, has been Q-switched using ~ 810*nm* diodes as the pump source[8].

This ability to achieve Q-switching is due to the higher numerical aperture (NA) produced by the 1.3 *wt*% of Yb^{3+} in the core; it is not intrinsic to the Yb^{3+}. The high NA allowed sufficient intensity to be reached in the core to bleach the fibre at diode pump powers. The length dependance of a Q-switched $Er^{3+} - Yb^{3+}$ fibre laser pumped with two laser diodes is shown in fig 8. Q-switching was carried out in zero-order and, once again, lack of sufficient hold off is evidenced by the unexpected behaviour around the *optimum* fibre length [8].

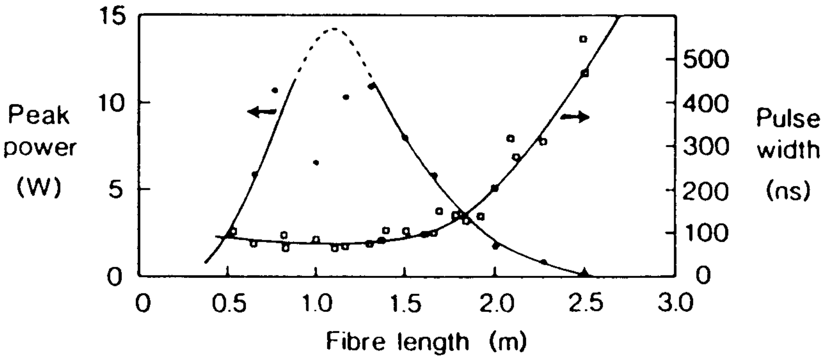

Fig 8. Q-switched performance of a $Er^{3+} - Yb^{3+}$ laser as a function of fibre length. The dashed curve represents the expected performance, see text.

With 980*nm* demonstrated as an efficient pump wavelength[7,9] (there is no ESA), and the arrival of 980*nm* laser diodes, it is worth considering the potential of an erbium fibre laser pumped with such a device. Using a simple rate equation approach (see for example ref 2) and taking account of such things as modal overlap, re-absorption etc.. [10,11] a simple numerical model was set up. In particular we wished to examine how the modulator' performance effected the output. For the following data 10*mW* of pump power was launched into the fibre, most of which was absorbed; other data required, eg fluorescent time constat, was taken from the literature.

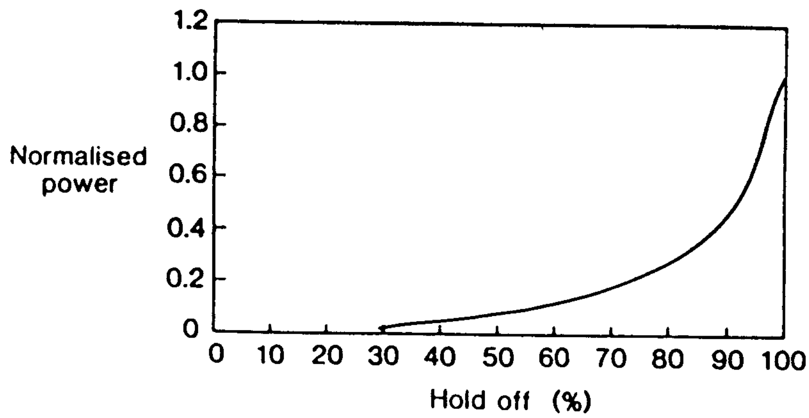

Fig 9. Performance (in terms of peak power) of a Q-switched Er^{3+} fibre laser pumped at 980nm as a function of modulator hold off.

Figure 9 shows how the Q-switched peak power is affected by hold-off in zero-order operation: a high degree of hold-off is clearly desirable. This figure clearly shows that an AOD will be of little use for zero-order Q-switching of erbium. In figure 10 peak power falls as the switching time of the modulator increases, showing that a modulator with a switching time of order 10ns is required (the result here applies to a 0.3m cavity). Results such as these allow us to specify the performance of a potential modulator

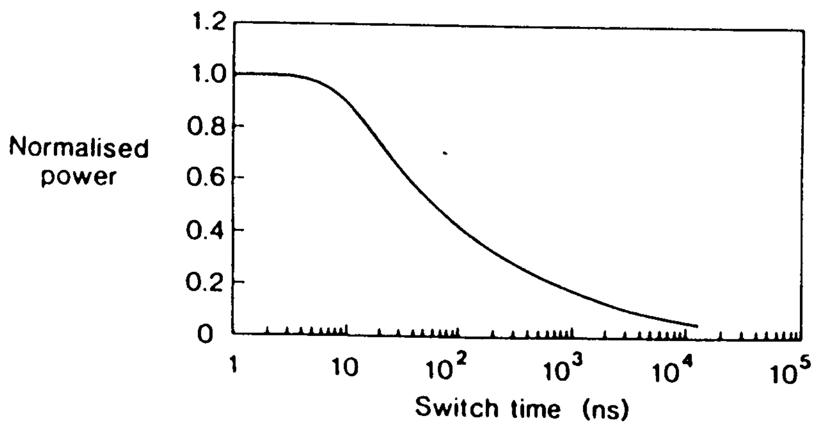

Fig 10. As fig 9 but now examining the effect of modulator switching time.

With this model, and assuming a Q-switched performance not limited by the modulator, we predict that output powers of 0.1 – 1kW should be available from a fibre laser pumped by a few tens of milliwatts at 980nm

4 CONCLUSIONS

Q-switched fibre lasers have outputs worthy of consideration for device applications. In particular they offer the prospect of small, diode pumped lasers emitting relatively high power pulses. Considerable work is now required in improving their performance. In particular, the cavity decay time must be reduced, principally by reduction in fibre length. As has been pointed out, this can only be achieved by increasing the dopant concentration. The maximum tolerable dopant concentration for each type of ion has still to be determined and further investigation, especially with regard to glass host material, is required. All fibre methods of performing the Q- switching have not been discussed here but are particularlly interesting from the device point of view: a practical Q-switched system would then be a true blend of fibre and laser technology. Calculations presented here have shown that the Er^{3+} laser in particular merits thorough investigation.

5 ACKNOWLEDGEMENTS

The authors wish to thank the many members of the Optical fibre group at Southampton, both past and present for their assistance. This work was funded in part by the Amoco Technolgy Company.

6 REFERENCES

1. R.J.Mears, L.Reekie, S.B.Poole and D.N.Payne, "Low threshold tunable CW and Q-switched fibre laser operating at 1.55μm", Electronics Letters, Vol 22, pp 159-160, 1986.

2. A. Yariv Optical Electronics, Holt- Saunders, New York, 1985.

3. L.Reekie, I.M.Jauncey and D.N.Payne, "Near optimum operation of a diode-laser pumped fibre laser", European Conference on Optical Communications, Technical Digest Vol 1, 105-108, Helsinki, 1987.

4. I.N.Duling, L.Goldberg and J.F.Weller, "High-power, mode-locked Nd: fibre laser pumped by an injection-locked diode array", Electronics Letters, Vol 24, 1333-1334, 1988.

5. H.W.Mocker and R.J.Collins, "Mode competition and self-locking effects in a Q-switched ruby laser", Applied Physics Letters, Vol 7, 270-273, 1965.

6. E.Desurvire, J.R.Simpson and P.C.Becker, "High-gain erbium-doped traveling=wave fiber amplifier", Optics Letters, Vol 12, 888-890, 1987.

7. W.L.Barnes, P.R.Morkel, L.Reekie and D.N.Payne, "High quantum efficiency Er^{3+} fibre lasers pumped at 980 nm", to be published in, Optics Letters, Sept 1989.

8. W.L.Barnes, S.B.Poole, J.E.Townsend, L.Reekie, D.J.Taylor and D.N.Payne, "Er^{3+} – Yb^{3+} and Er^{3+} doped fiber lasers", to be published in, Journal of Lightwave Technology, Vol 7, No 10, 1989.

9. R.I.Lamming, S.B.Poole and E.J.Tarbox, "Pump excited-state absorption in erbium-doped fibres", Optics Letters, Vol 13, 1084-1086, 1988.

10. C.J.Gaeta, M.J.F.Digonnet and H.J.Shaw, "Pulse charateristics of Q-switched fiber lasers", Journal of Lightwave Technology, Vol 5, 1645-1651, 1987.

11. W.P.Risk, "Modeling of longitudinally pumped solid-state lasers exhibiting reabsorption losses", Jornal of the Optical Society of America B, Vol 5, 1412-1423, 1988.