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Q-switched fibre-lasers.

8.1

Introduction

This chapter is aimed at providing a detailed description of the techniques involved in Q-switching fibre lasers. In view of the potential of these sources, particular emphasis is placed on diode-pumped operation. In addition, the present status of this type of laser is reviewed, current limitations discussed and possible future progress outlined.

There are many applications where it is preferable to operate lasers in a pulsed mode. For example, as sources for distributed sensing and for range finding. Diode lasers, although convenient and compact, are inherently poor at this due to the low damage thresholds of semiconductor materials. Glass on the other hand can withstand high optical intensities (typically x 10^3) without damage. A compromise is thus to pump a fibre-laser with a laser diode. In this way a compact, all solid-state device can still be made. Direct modulation of the fibre-laser in the form of Q- switching allows significant peak powers and short duration pulses to be generated.

8.2

The technique of Q-switching enables intense, short duration pulses of energy to be obtained from a lasing system. Q-switching works in the following way. The high finesse or 'Q' of the laser cavity is in some way lowered whilst the fibre is being pumped. During this time oscillation is inhibited and the inversion, and therefore gain, are driven to high valves whilst energy is stored. Once the inversion has reached its maximum value the Q of the cavity is rapidly restored to its high value. The gain is suddenly well above threshold and a rapid build-up of lasing photons within the cavity takes place. The population inversion is thus quickly exhausted so that lasing occurs only over a short period of time - a Q-switched pulse is emitted

Methods of modulating the Q of the fibre-laser cavity are examined individually in the following sections. To date these have largely consisted of "opening" the cavity and inserting some kind of bulk modulator. It would however be preferable to keep the cavity closed by using an integrated optic or all fibre device. Such schemes are now under evaluation and are also discussed.

8.2.1 Methods of Q-switching

8.2.1a Mechanical Q-switching

A mechanical chopper is the simplest Q-switching device. The required experimental configuration is shown in figure 8.1a. The introduction of bulk elements into the fibre-laser means that a lens is required to maintain the optical continuity of the cavity. The lens may be placed so as to focus or collimate light on the output coupler. The focussing configuration, as depicted in fig 8.1a, is found to be more stable due to the reduced allignment tolerance on the output coupler. Mechanical Q-switching provides a very high extinction ratio, ie. a large difference in cavity loss between low and high Q states. Its limitations are the slow switching time and poor pulse to pulse stability. Switching times may be reduced to about 1μs by using a fast chopper and a small diameter beam.

The simplicity of the mechanical Q-switching scheme and the high, wavelength independent extinction ratio make it a usefull device for demonstrating Q-switching action in new fibre lasers [1].

8.2.1b Electro-optic Q-switching

Very little Q-switching has been carried out in fibre lasers using electro-optic modulators. Although such devices offer fast modulation times and reasonable extinction ratios, the high drive voltage requirement means that they are not in general suited to practical applications. Bulk electro-optic modulators have however been used to mode-lock fibre lasers and this is discussed in chapter 9.

8.2.1c Acousto-optic Q-switching

Use of an acousto-optic modulator (AOM) to switch the cavity finesse has been the preffered method of Q-switching in fibre lasers [2]. They offer the advantage of short switching times and electronic control of both the repetition rate and mark to space ratio
(ie, the ratio of modulator on to off time). Their main disadvantages are a limited diffraction efficiency, resulting in either high insertion loss, or low extinction ratio, depending on the configuration used. The AOM may be used in one of two configurations, zero and first order, discussed in more detail below and shown in figures 8.1.b and c. Results obtained by acousto-optic Q-switching are discussed in section 8.2.3.

8.2.1c(1) Zero-order

In this arrangment the high Q state is achieved with the AOM off, as shown in fig 8.1.b. The undeflected beam is then fed back into the fibre by the output coupler. Once a Q-switched pulse has been emitted the AOM is turned on, supressing further laser action and allowing a significant population inversion to build up to provide the next pulse. When sufficient energy has been stored the AOM is turned off and the next Q switched pulse emitted.

AOM's exhibit a diffraction efficiency significantly lower than 100% (typically 50%) so that some light is feed back from the output coupler even in the low Q state. Due to the high gain of many fibre lasers, this feed back may become sufficient to set off CW lasing. The pump power must therefore be kept low enough to avoid CW lasing, thus effectively putting an upper limit on the maximum energy and peak power of the Q-switched pulses. One solution to this problem is first-order operation of the AOM.

8.2.1c(11) First-order

As shown in figure 8.1c, feed back in this arrangement is provided by positioning the output coupler so as to reflect the first-order diffracted beam back into the fibre. With the AOM in the off state, there is no diffraction and there can be no laser oscillation in the low Q state. Suppression of CW oscillation is bought at the expense of significantly increased insertion loss. In the zero-order configuration the loss was due just to the transmission loss of the modulator, of order 0.5dB. In the first-order configuration the loss is given by (transmission loss) x (diffraction efficiency)^2, of order 6dB. This significantly raises the threshold for Q-switched operation so that more pump power is required in this configuration.

First-order operation offers another advantage; the AOM is on only for a small percentage of the time. This reduces problems associated with thermal effects in the accusto-optic material which have been noted under zero-order operation.

8.2.1c(iii) Modulator design and material

Although acusto-optic Q-switching is currently the most popular approach it suffers from several limitations, namely higher transmission loss and limited diffraction efficiency. This arises in part from the fact that commerically available modulators are used, rather than modulators designed specifically for fibre-lasers.

An important factor to bear in mind is that for a given modulator drive power the diffraction efficiency falls off as ${}^{1}/\lambda^{2}$, where λ is the optical wavelength. As the drive power is limited by a number of practical considerations, in particular thermal effects, it is therefore necessary to find materials offering high acousto-optic figures of merit for use at longer optical wavelengths. This may well result in a compromise between transmission loss and switching time. There is also a compromise to be made between diffraction efficiency and switching time. Current results suggest that diffraction efficiency is the more important although this will be covered in more detail in section 8.2.4. Clearly the transmission loss of the material should be kept as low as possible at the lasing wavelength.

Suitable materials for AOM's fall into two basic catagories; glass and crystalline. Generally, when compared with crystals, glasses have the advantage of lower cost, higher homogeneity and higher damage threshold. However, their main disadvantage is that of lower refractive index (and hence lower acoustic figure of merit - since this depends on the sixth power of the refractive index) resulting in lower diffraction efficiency. Materials currently in use are lead molybdate, a crystal, and silica and soft flint glasses.

Accousto-optic design considerations dictate that in order to obtain high diffraction efficiency and short switching times it is necessary to match the acoustic and optical beam divergences at the point of interaction. The large optical beam divergencies usually found in fibre-laser cavities makes this matching difficult to achieve in practice although novel transducer designs might help. It is also important to remember that the laser cavity should be kept as short as possible (see sec 8.2.2.a(1)). At the present time the modulator is beginning to occupy a significant fraction of the cavity. Materials that allow a short device to be made without sacrificing other parameters are therefore of interest.

Before leaving this section it is worth pointing out a problem that is common in fibre lasers that are Q-switched using bulk components. Eventualy, as the pump power is raised, reflections from the fibre end and/or the intracavity lens may become sufficient to cause CW oscillation. The high gain of fibre lasers means that this can be an important problem. With care it is possible to overcome these problems, for example, reflections from the end of the fibre can be suppressed by polishing at a small angle. It would be preferable to use all fibre devices instead where such problems would not arise, these will be discussed in section 8.2.1.f.

8.2.1d Passive Q-switching : saturable absorbers

Passive loss modulation is an attractive route to Q-switching because of the inherent simplicity in the method, the modulator of fig 1 is replaced by a saturable absorber. Q-switching is effected in the following way. The saturable absorber consists of a two level system whose energy gap corresponds to that of the lasing transition of the fibre laser. Initially the loss of the absorber is high. Then, as the optical power in the cavity builds up, the loss in the absorber starts to bleach out. The absorber rapidly approaches a state in which it presents no loss, it has been saturated. Lasing is now possible and emission takes place. However, the recovery time of the dye is very fast so that absorption rapidly sets in again. Consequently only a short pulse of light is emitted: the process then repeats.

Some work has already been carried out using a solid dye as the saturable absorber: the dye was placed between the fibre end and the output coupler [3]. In fact the laser was found to operate both mode locked and Q-switched, providing 9W pulses of 8ns duration within the Q-switched envelope. The limitation in peak power arose from the slow response time of the dye used. It should also be possible to allow the evanescent field in the fibre to "see" a saturable absorber, thus avoiding the problem of opening up the cavity. This could be done by polishing down the cladding of the fibre until the surface was close to the core [4] and then immersing the whole section in a dye solution.

8.2.1e Integrated optics

Use of an integrated optic switch has the advantage of maintaining the light within a guided wave form. The completed laser should thus be less susceptible to environmental disturbances. Integrated optic devices do however suffer from several disadvantages. They have a high coupling loss to fibre because of modal mismatch and high fresnel losses at the modulator-air interface. In general they also have a non-negligable propogation loss. Despite these problems, the advantages of maintaining the optical field in guided mode form

make this type of device attractive. In the only demonstration of an integrated Q-switched Nd^{3+} fibre-laser made to date [5], a switched directional coupler was used as the modulator. High insertion losses (9dB) were experienced, as is typical when combining planar and fibre optics. Nevertheless, Q-switching was demonstrated and well characterised. In the on-state the modulator adds 10dB to the round trip loss of the laser. Pulses of 1.6W peak power and 100ns duration were obtained (0.16μJ). Integrated optic modulators may now be used as efficient Q-switches and offer the usual integrated optic advantages, on chip design, potential mass production, easy extension to more complex designs etc... The problem of high insertion loss has still to be overcome to allow diode pumped operation.

We also note that it is possible to gain switch fibre lasers by modulating the pump source. Although short (40ns) duration pulses were obtained, peak powers were low (<1W) owing to the high repetition rates [6].

8.2.1f In-fibre modulation

An elegant alternative to the above schemes would be some kind of in-fibre modulator. No such devices exist at present, the main problem being the large deflection angle required to remove light from the core of the fibre. (The capture fraction of the fibre is significantly greater than that of a bulk laser). For this reason in-fibre devices are more suited to the mode-locking application, where a change in phase rather than amplitude is required. It is possible to cause modulation in other ways, for example the fibre laser may be operated in single polarization mode and a polarization switch used to modulate the cavity finesse. Alternatively a modal switch might be employed. If the latter were used in a slightly multimode fibre and followed by a mode filter this could also form a modulator.

8.2.2. Laser design considerations and experimental results.

In this section we present experimental results that show how the performance of Q-switched fibre lasers are affected by the various adjustable microscopic parameters, eg. fibre length. Optimization of a given Q-switched fibre laser is a compromise between many competing mechanisms. Careful laser design can lead to significant improvements in output as shown below. Q-switched fibre-lasers may be divided into those based on three and four level lasing transitons. This is conveniently done by examining the two commonest rare-earth doped fibre types, neodymium (4-level) and erbium (3-level).

8.2.2aQ-switched Nd^{3+}-doped fibre lasers at ~ 1.1μm

The 1.06μm line is the most common of the Nd^{3+} transitions and, being a 4-level transition it has a very low pump power requirement on threshold. It may thus tolerate additonal intracavity loss in the form of Q-switching components. All results presented in this section were obtained with an acusto-optic modulator working in zero-order configuration (see fig 1b) and used 810nm laser diodes as pump sources. By making use of analytical theories [7] and/or simple physical arguments it is easy to show that high peak power and short duration pulses are obtained for lasers pumped as far above threshold as possible, and for short cavity decay times. (Clearly, the more pump power absorbed, the more energy is available for each pulse. Futher, pulse width is largely controlled by cavity decay time, ie. the effective lifetime of a photon in the laser cavity). These two requirements are somewhat contrdictoray as a lossy cavity enables short cavity decay times but increases the laser threshold. A detailed examination of the effect of device parameters now follows.

8.2.2a(1) Effect of the fibre-length.

Strictly we should discuss cavity length, at present however cavity length is dominated by the fibre. For a c.w. 4-level laser the optimum fibre length is such that most of the pump power (say >90%) is

absorbed. Increasing the fibre length beyond this optimum value is of little consequence as it contributes minimal additional loss at the lasing wavelength. However, in a Q-switched fibre laser one must contend with the competeing requirement of reducing the fibre length to reduce the cavity decay time. This competition is seen in figure 8.2 where peak power and pulse duration are plotted as a function of fibre length. It is clear that an optimum length exists, in this case about 1.5m. For too short a fibre length there is insufficient pump absorption and hence reduced gain. Too long a length produces long duration pulses with a consequent reduction in peak power.

8.2.2a(ii) Effect of the output coupler transmission.

Figure 8.3 shows the effect of output coupling on peak power and pulse width. A mirror with too large a reflectivity does not couple out much of the intracavity power and also increases the cavity decasy time. Conversly a low reflectivity mirror reduces the cavity decay time. Further, it increases the threshold and does not allow the laser to operate as far above threshold. Consequently, as seen in figure 8.3, an optimum value for the output coupling exists. For the conditions pertaining to the data of figure 8.3, R=40% was found to be optimum. This is a typical result and compares with R~80% for optimum coupling in the CW case. The difference arises from the increased intra-cavity loss in the Q-switched configuration.

8.2.2a(iii) Effect of the pump power.

The effect of pump power on Q-switched pulses is shown in figure 8.4. As expected, once above threshold the peak power increases linarly with pump power, along with a corresponding reduction in pulse width. More recent results indicate that the peak power saturates for pump powers much above 20mW. This saturation is due to the occurence of CW lasing arising from insufficient hold-off of the AOM, as discussed in section 8.2.1C(1) [8].

8.2.2a(IV) Effect of the repetition-rate

Figure 8.5 shows how the pulse energy and average power are affected by the repetition rate. The pulse energy starts to roll off much above 1kHz due to the finite recovery time of the Nd^{3+} system. This recovery time is governed by the spontaneous life time of the metastable level. For Nd^{3+} in glass this is about $450\mu s$ so that degradation of pulse energy for repetition rates above about 2kHz is expected, as observed in fig 8.5. Devices requiring high repetition rates will need to have this frequency dependence taken into carefull consideration.

Although the pulse energy falls off at higher repetition rates, the average power of the laser rises asymptotically until nearly all of the equivalent CW power is recovered.

8.2.2a(v) Fibre-design

Optimization of the geometrical design of fibres for Q-switching has been examined in detail by Gaeta et al [7]. They concluded that the most important consideration was the overlap of the dopant distribution with both the pump and lasing optical fields - a subject dealt with in chapter 4. (No consideration of the interplay between modulator and fibre geometry was made).

In the results outlined above the Q-switched output has been limited at least in part by the cavity length. This in turn necessitates an increase in doping level so that sufficient pump power can be absorbed in the shorter length. Increasing the doping level is ultimately limited by dustering and concentration quenching, as discussed in chapter 2. Such effects significantly reduce the efficiency of fibre lasers and must be overcome if improved performance is to be achieved.

One method of increasing the maximum usefull doping level is to include Al_2O_3 in the fibre core. Making this change alone it has been possible to go from pulses of 21W and 53ns to 110W and 16ns. An alternative to increasing the doping level of MCVD type fibres is to make fibres by drawing down bulk laser glass. Only about 1cm of fibre is then required [9] so that the modulator part of the cavity will dominate the laser length.

An interesting feature arises when we examine the shape of the Q- switched pulse. We find that the intensity of the pulse is modulated at the round trip frequency, as seen in fig 8.6. The modulation arises from the difference in optical power on the two sides of the modulator before it is opened. This difference in power is retained during lasing so that spikes at the round trip frequency appear in the output. The modulation depth observed is limited were by the response time of the detector so that the observed peak power is likely to be lower than the real peak power. Similar effects have also been seen in the Q-switched Sm^{3+} fibre laser, operating near 640nm [1]. As discussed later, detailed numerical modelling allows this behaviour to be predicted. The modulation may have important consequences in such applications as non-linear optics, and sensors.

8.2.3 Three level fibre lasers

Most of the functional dependances of 3-level Q-switched fibre lasers show trends similar to the 4-level devices described above. The length dependence is however more critical because of excess loss at the lasing wavelength will result if any of the fibre is left unpumped. Bearing this in mind we will now look at the performance of various three level Q-switched fibre lasers.

8.2.3a Q-switched Nd^{3+} fibre lasers at 0.94μm

This wavelength is of interest because of the enhanced sensitivity of silicon detectors at this wavelength, compared to 1.1μm. In order to bleach a 3-level transition with diode pump powers it is important to work with a fibre of high numerical aperture, thus keeping the intensity in the core high. Diode-pumped Q-switched operation has been achieved[10] with a fibre of NA=0.24. The doping level in the fibre was 1200ppm of Nd^{3+} and a length of 160cm was used. Q-switching was carried out in zero-order and 80ns pulses of 5W were obtained. As with the 1.1μm operation, peak power fell by 50% when the repetition rate was raised to 3kHz. No problems associated with lack of hold - off were found, presumably due to the increased diffraction efficiency of the AOM at this shorter wavelength.

8.2.3b Q-switched Er^{3+} fibre lasers at 1.5μm

Q-switching in erbium is particularly attractive for such applications as range finding since these devices may be eye-safe. However, three significant practical problems exist with this type of fibre laser. Firstly, the hold-off (or extinction ratio) of acousto-optic modulators at 1.5μm is poor since the diffraction efficiency falls as the wavelength rises. Second, the problem of CW lasing resulting from stray reflections etc. is critical due to the very high gain of erbium doped fibres. The third concern is the pump wavelength. Excited state absorption at 800nm reduces the efficiency of diode pumped operation on this absorption band - although it is possible. Because of the application of erbium doped fibres in optical amplifiers, diodes are now becoming available for other pump bands that do not suffer from ESA, 980nm and 1480nm.

The only Q-switched fibre laser demonstrated to date has in fact been based on an Er^{3+} - Yb^{3+} doped fibre[8]. The Yb^{3+} co-dopant in this instance merely serves to provide a high NA for the fibre. The length dependence of the output from this fribre laser is shown in figure 8.7. Q-switching was carried out using the zero order configuration so that the diode pump source was sufficient to reach threshold. Lack of sufficient hold off is evidenced by the unexpected behaviour around the 'optimum' fibre length. CW oscillation set in and reduced the maximum possible peak power.

8.2.4 Modelling and future predictions

Modelling of Q-switched operation in fibre lasers should allow optimization to be carried out without recourse to a full series of experiments covering a large range of the available parameters. The details of an analytical model have been well covered by Gaeta et al. Several simplifying assumptions were made in this model, namely that there was no pump saturation, that there was negligable spontaneous emission and that the pump energy decayed exponentialy along the fibre. Further, it was assumed that the Q-switch had infinite loss in the low Q state, that it had an infintely short switching time, and that the fibre occupied the entire cavity. In spite of these simplifications such a model allows many of the important parametric dependances of the Q-switched fibre laser to be studied. The authors modelled both peak power and pulse width as well as pulse energy as a function of core radius and cavity loss for a four-level laser. They predicted that pulses of several nanoseconds duration and several hundred Watts peak power could be obtained, a prediction that has since been vindicated [11].

Using a similar model, we consider the potential output from a 980nm diode pumped Er^{3+} Q-switched fibre laser. Assuming 10mw pump power and zero-order operation we can examine laser output as a function of modulator performance. Figure 8.8

shows how the Q-switched peak power is affected by modulator hold-off; a high degree of hold off is clearly desirable. Figure 8.8 shows that an 'off the shelf' AOM will be far from ideal as a modulator for this laser. In figure 8.9 peak power falls as the switching time of the modulator increases. For the 0.3m cavity considered a switching time of 10ns is required (a typical AOM is 100μs). Results such as these allow us to specify the performance of a potential modulator. With this model, and, assuming no limiatations due to the modulator (ie infinite hold off and zero switching time), we predict output powers in the range 100-1000W at 1.5μm should be available from a Q-switched fibre laser pumped by a few tens of milliwatts at 980nm. The analytical approach as described in ref [7] and outlined above has limitations due to the inbuilt assumptions mentioned. By retaining all of the terms of significance (for the populations of the various energy levels <u>and</u> the optical fields) the rate equations that must be solved take on a transcendental form. This means that the cavity (fibre, Q-switch and passive space) must be broken up into segments and the rate equations applied numerically. This approach is important in order to match experimental and theoretical results where the inclusion of pump saturation, even in four-level systems is found to be important. The effect of spontaneous emission is also important due to the high capture fraction (ie solid angle for which light emitted in the core is retained as guided light) of the fibre-laser - this is the source of noise from which the Q-switched pulse starts.

We note that such a numerical model is well able to predict the intensity modualtion observed in section 8.2.2. For those interested in such a model, a clear exposition is given in ref [12]).

8.2.5 Tunability

The broad fluorescence linewidth of rare-earth transitions in glass gives rise to considerable tuning ranges, eg 60-70nm for neodymium at ~1.1μm, for cw fibre-lasers. (Tuning is covered extensively in chapter 6). The addition of Q-switching components to the cavity raises the laser threshold, thus increasing the pump power required for a given tuning range. Nonetheless tunable Q-switched operation is possible and may be eleqantly obtained with one device, the accoust-optic modulator. In ref [13] only tuning was carried out. The laser was operated in the first order configuration and by changing the drive frequency to the AOM the wavelength that is fed back into the laser may be altered. Tuning over 19nm was accomplished in this way with Er^{3+} being used as the active ion.

8.2.6 Limitations on performance.

We have already discussed how the length of the lasing cavity, and in particular the doped fibre, must be reduced in order to produce shorter duration pulses. We have also discussed accusto-optic modulator design, the need for high diffraction efficiencies etc... Similar criteria apply to the use of other types of modulator, a high degree of hold-off (large extinction ratio) is critical to all. At present insertion loss is only a problem with the integrated optic switch, a problem that is already being adressed for other reasons.

With high power pulses in the fibre laser cavity the optical intensity can be considerable. We have therefore to be concerned with both optical damage and nonlinear optical interactions. It seems unlikely that problems will be encountered with the laser mirrors used as coatings have already been produced for Q-switched miniature YAG lasers that can cope with 0.5MW pulses [14]. Potentialy the greater problem is damage to the modulator material. Surface optical damage within the cavity could obviously be avoided by integrated optic or all-fibre modulators.

The principle non-linear interaction that may occur is stimulated Raman generation. We can apply a simple theory to predict the value of the (intra-cavity) peak power at which the power of the first Stokes shifted band is 10% of that at the lasing wavelength [15]. The critical parameter is the product of the peak power and the fibre length, thus

$$P \,.\, L_{crit} = \frac{80 \,.\, A}{\gamma_R} \tag{8.1}$$

where A is the core area and γ_R is the Raman gain coefficient.

Substituting typical values for a single-mode silica fibre

($A = 6 \times 10^{-12}$ m^2, $\gamma_R = 1.5 \times 10^{-13}$ m/W [16]) we find,

$$P.L_{crit} = 3000 \tag{8.2}$$

Range finding applications may require a pulse of say 1kW for which the critical length is 3m. Clearly fibre length could become important from the point of view of stimulated Raman. To some extent this is automaticaly taken care of by the requirement of short fibre lengths to reduce cavity decay times. It is likely to be of more significance when considering delivery of the output of a Q-switched fibre-laser.

Another nonlinear process that could result in limiting the peak power is stimulated Brillouin scattering. The anologous formula to that for stimulated Raman scattering is [15],

$$P.L_{crit} = \frac{100.A}{\gamma_B} \qquad 8.3$$

In this case the stimulated Brillouin gain coefficient is 3×10^{-11} m/W so that,

$$P.L_{crit} = 20 \qquad 8.4$$

This would appear to imply that stimulated Brilloin scattering is more important than Raman and indeed, should be limiting the performance of current Q-switched fibre lasers. However, this is not so because the power length product applies to the power within the Brillouin gain bandwidth, say 50 MHz. Typically the fibre laser may have a bandwidth of at least 10 GHz so that the critical power length product is nearer 4000 than 20 and is thus comparable with the limit imposed by stimulated Raman scattering.

Optical damage, ie damage to the ends of the fibre due the high intensities is less of a problem. We have been able to launch pulses of 10 kW peak power and 0.1 ns duration from a Nd:YAG laser into our fibres, the exact limit being dependant on the quality of the fibre end surface.

8.2.7 Summary

Q-switching is now a well established technique for fibre lasers. Experimental results obtained so far show that nearly all of the equivalent CW power of a fibre laser may be obtained in the form of Q-switched output. Q-switched pulses suitable for sensor applications have already been produced from diode pumped Q-switched fibre-lasers.

The main difference between Q-switching in fibre lasers and other miniature lasers is the high single pass gain often encountered in the fibre geometry. As a result modulators for Q-switching must have a very high extinction ratio, indeed this is one of the major limiting factors in increasing the output of Q-switched fibre-laser. Further improvements will be obtained when shorter fibre lengths can be used. Shorter fibre lengths will in turn require higher doping levels than can at present be acieved and these problems are now being addressed.

Whilst many practical problems still exist calculations show that significant improvements should be possible and these are now actively being sought.

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Figure Captions

Fig. 8.1 Experimental Q-switching geometries

a) Mechanical; b) Accousto-optic zero-order;

c) Accusto-optic first-order.

Fig. 8.2 Q-switched performance as a function of fibre length.

Fig. 8.3 Q-switched performance as a function of output coupling.

Fig. 8.4 Q-switched performance as a function of pump power.

Fig. 8.5 Pulse energy and average power as a function of repetition rate.

Fig. 8.6 Experimental Q-switched pulse showing distinctive modulation.

Fig. 8.7 Q-switched performance of Er^{3+} - Yb^{3+} fibre laser as a function of fibre length.

Fig. 8.8 Normalized peak power as a function of modulator hold off.

Fig. 8.9 Normalized peak power as a function of modulator switching time.

References

1 "Properties of the Samarium fibre-laser", M.C. Farries, P.R. Morkel and J.E. Townsend, Proc. SPIE, Vol. 1171, p271-280, 1989.

2 "Low threshold tunable CW and Q-switched fibre-laser operating at 1.5μm", R.J. Mears, L. Reekie, S.B. Poole adn D.N. Payne, Electronics Letters, 22, p159-160, 1986.

3 "All solid state passively Q-switched mode-locked Nd^{-} doped fiber-laser", L.A. Zenteno, H. Po and N.M. Cho, Optics Letters, 19, p115-117, 1990.

4 "Optical fibre polishing with a motor driven polishing wheel", C.D. Hussey and J.D. Minelly, Electronics Letters, 24, p805-807, 1988.

5 "Integrated-optical Q-switch/mode locker for a Nd^{3+} fiber laser", G. Geister and R. Ulrich, Applied Physics Letters, 56, p509-511, 1990.

6 "Gain switching of a Nd^{3+} doped fiber laser", L.A. Zenteno, E. Snitzer, H. Po, R. Tumminelli and F. Hakimi, Optics Letters, 14, p871-873, 1989.

7 "Pulse characateristics of Q-switched fibre lasers", C.J. Gaeta, M.J.F. Digonnet and H.J. Shaw, Journal of Lightwave Technology, 5, p1645-1651, 1987.

8 "Er^{3+}-Yb^{3+} and Er^{3+} doped fibre lasers", W.L. Barnes, S.B. Poole, J.E. Townsend, L. Reekie, D.J. Taylor and D.N. Payne, Journal of Lightwave Technology, 7, p1461-1465.

9 "Application - specific optical fibres manhufactured from multicomponent glasses", E.R. Taylor, D.J. Taylor, L. Li, M. Tachibana, J.E. Townsend, J. Wang, P.J. Wells, L. Reekie, P.R. Morkel and D.N. Payne in "Optical fibre materials and processing", Eds. J.W. Fleming, G.H. Siegel, S. Takahashi and P.W. France, Pub. Materials Research Society, p321-329, 1990.

10 "CW, tunable and Q-switched operation at 939nm of a diiode-laser pumped Nd^{3+} doped fibre laser", L. Reekie, I.M. Jauncey, S.B. Poole and D.N. Payne, CLEO Technical Proceedings, Paper THM46, 1988.

11 "Q-switched and single polarization diode pumped Nd^{3+} doped fibre lasers", W.L. Barnes, J.T. Lin, L. Reekie, D.J. Taylor, I.M. Jauncey, S.B. Poole and D.N. Payne, IEE Colloqium on "All fibre devices", June 1988, LONDON.

12 "Diode-pumped active fibre devices", I.M. Jauncey , PhD Thesis, Southampton University, UK, 1989.

13 "Electronically tunable, 1.55μm erbium-doped fibre laser", P.F. Wysocki, M.J.F. Digonnet and B.Y. Kim, Optics Letters, 15, p273-275, 1990.

14 "High-peak-power operation of a diode-pumped Q-switched Nd:YAG laser", D.C. Gerstenberger, A Probshofl and R.W. Wallace, Optics Letters, 15, p124-126, 1990.

15 "Optical power handling capacity of low loss optical fibres as determined by stimulated Raman and stimulated Brillouin scattering, R.G. Smith, Applied Optics, 11, p2489-2494.

16 "Raman Gain in glass optical waveguides", Applied Physics Letters, 22, p276-278, 1973.

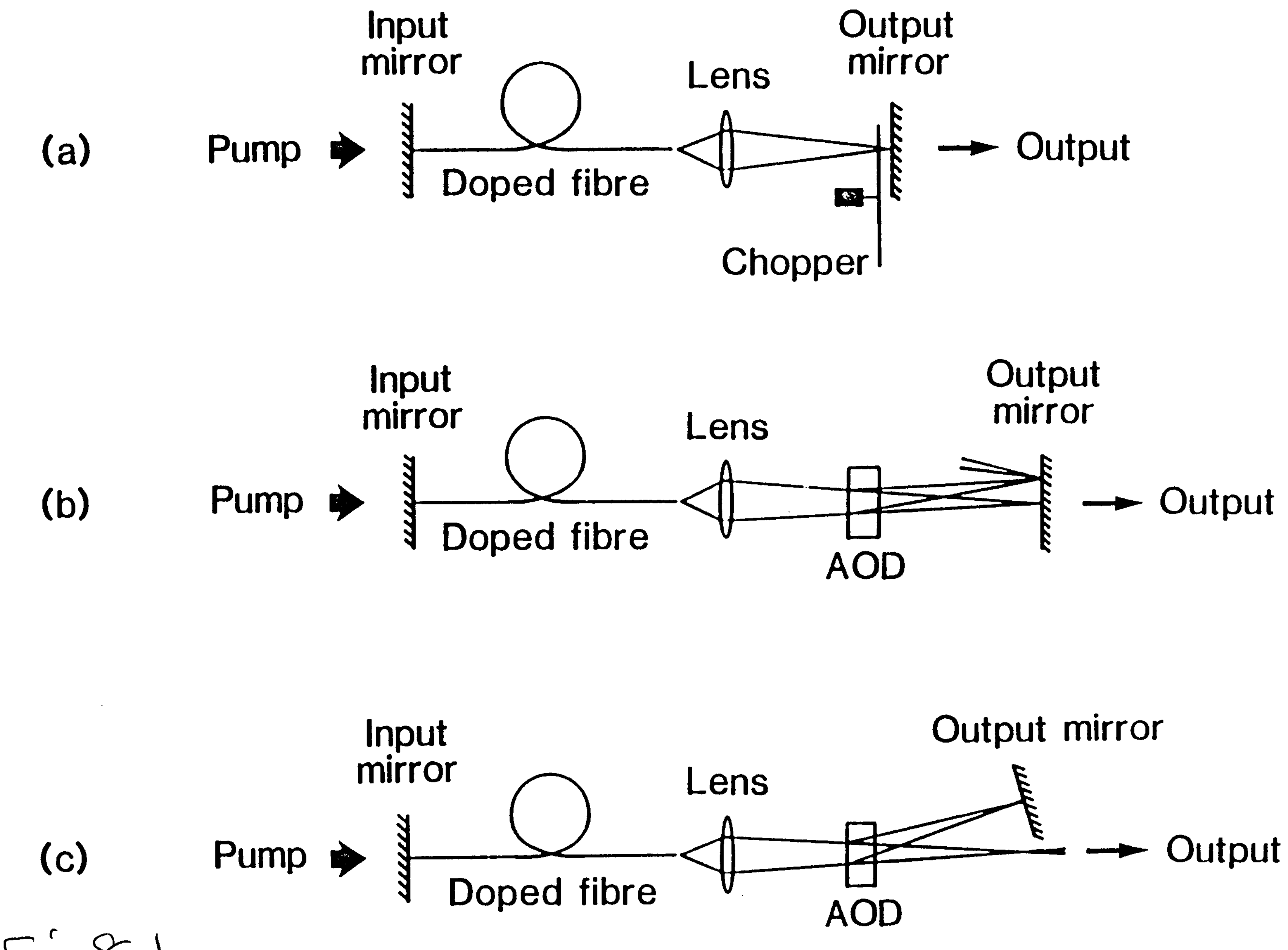
(a)
Pump
Input mirror
Doped fibre
Lens
Output mirror
Chopper
Output
(b)
Pump
Input mirror
Doped fibre
Lens
AOD
Output mirror
Output
(c)
Pump
Input mirror
Doped fibre
Lens
AOD
Output mirror
Output

Fig 8·1

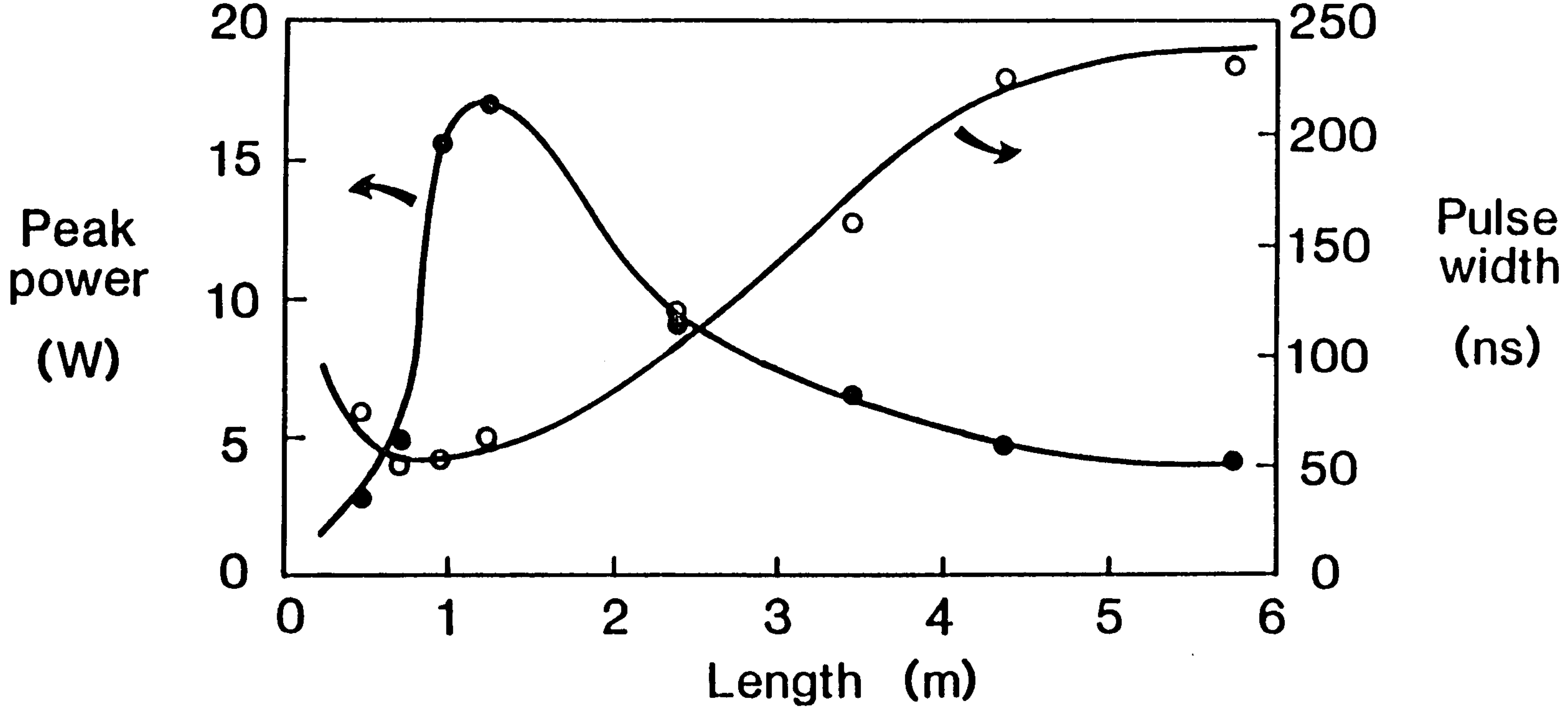
Peak power (W)
20
15
10
5
0
0
1
2
3
4
5
6
Length (m)
250
200
150
100
50
0
Pulse width (ns)

Fig 8.2

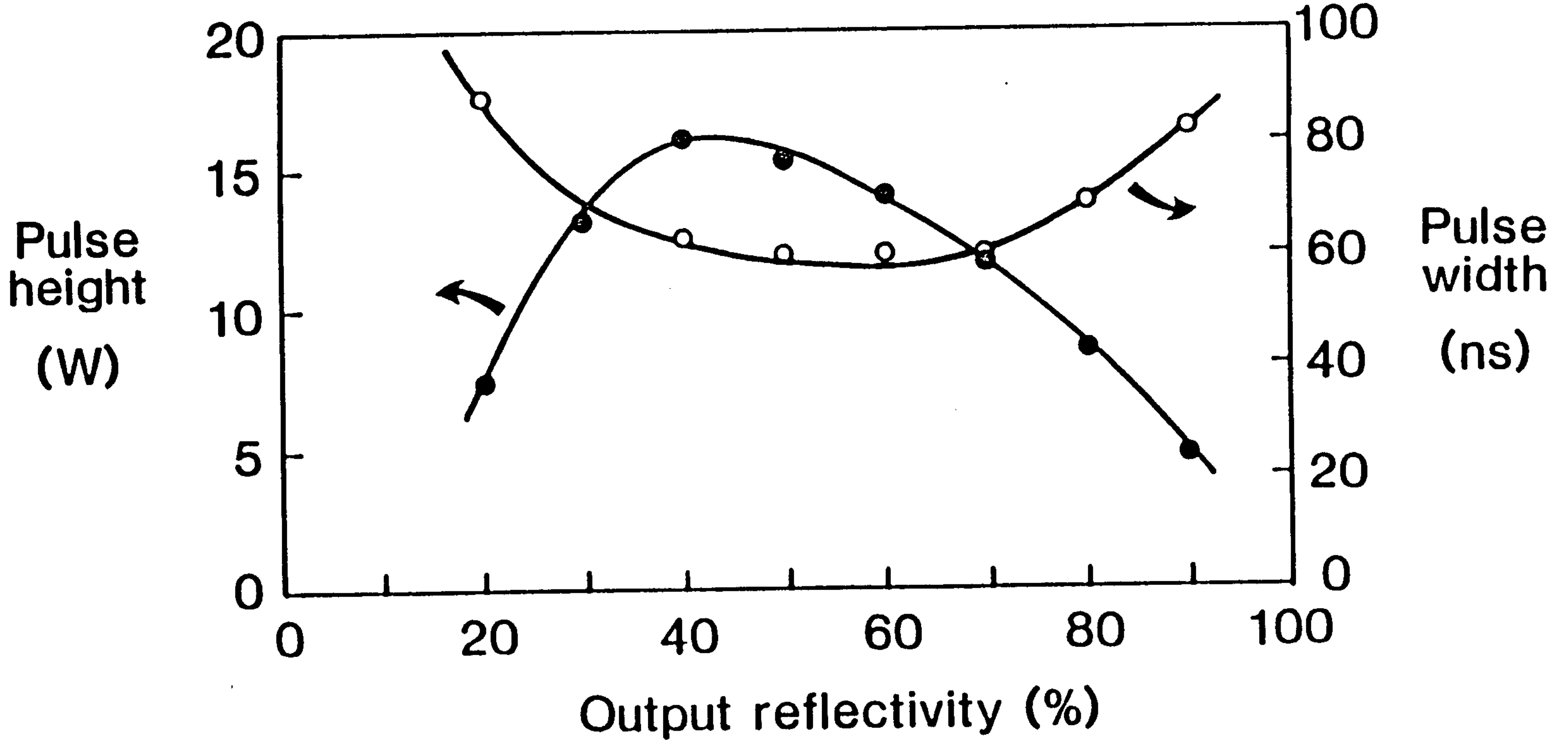
20
15
10
5
0
Pulse
height
(W)
100
80
60
40
20
0
Pulse
width
(ns)
0
20
40
60
80
100
Output reflectivity (%)

Fig 8.3

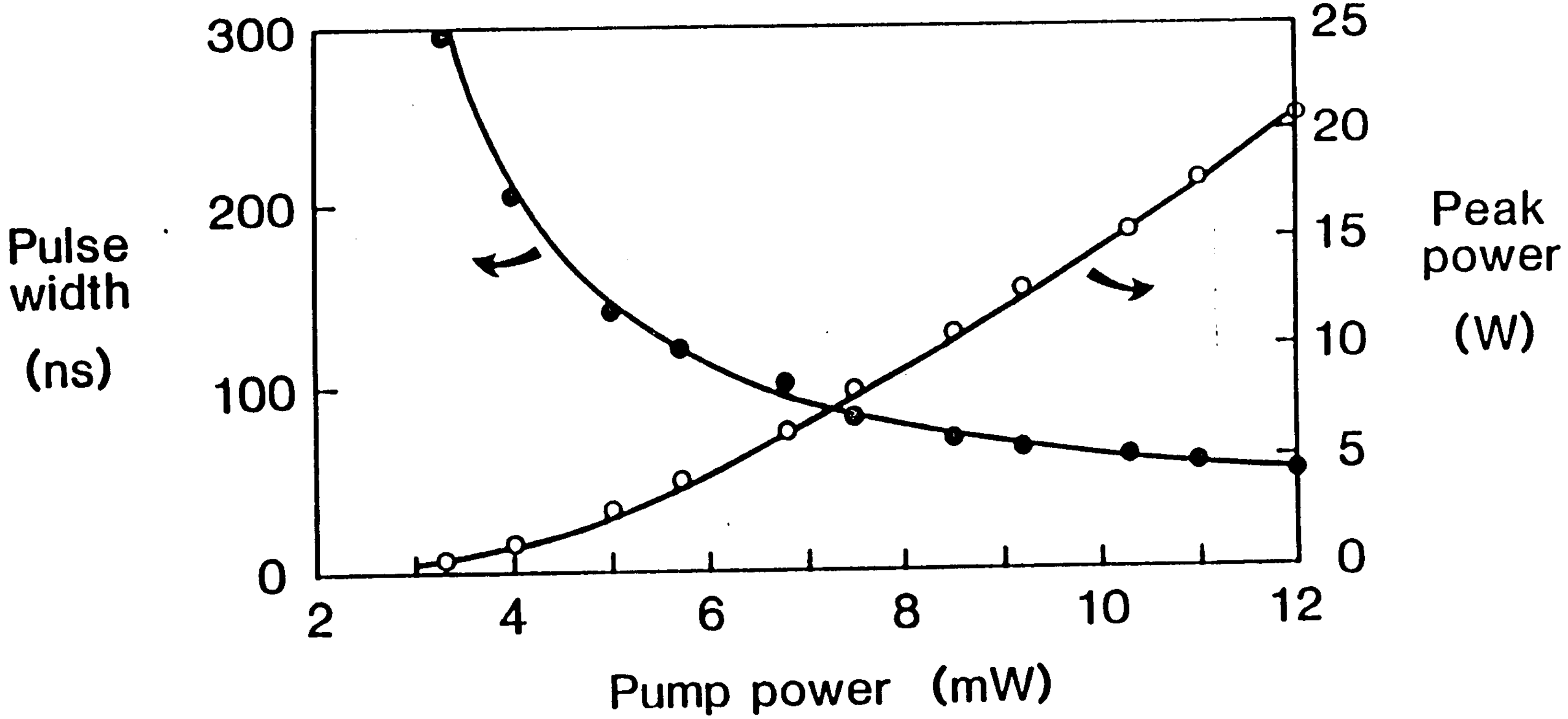
300
200
100
0
Pulse
width
(ns)
25
20
15
10
5
0
Peak
power
(W)
2
4
6
8
10
12
Pump power (mW)

Fig 8.4

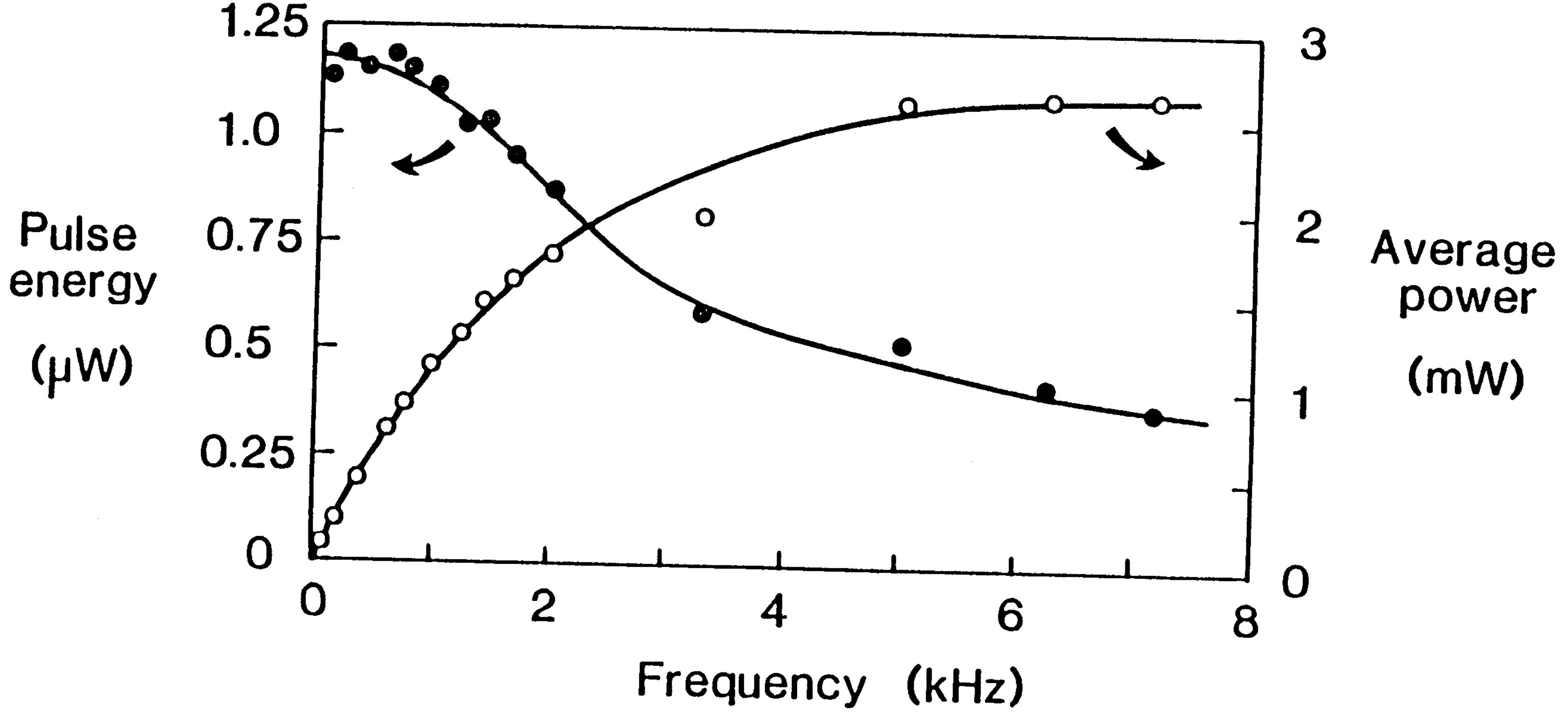
1.25
1.0
0.75
0.5
0.25
0
Pulse energy (μW)
3
2
1
0
Average power (mW)
0
2
4
6
8
Frequency (kHz)

Fig 8.5

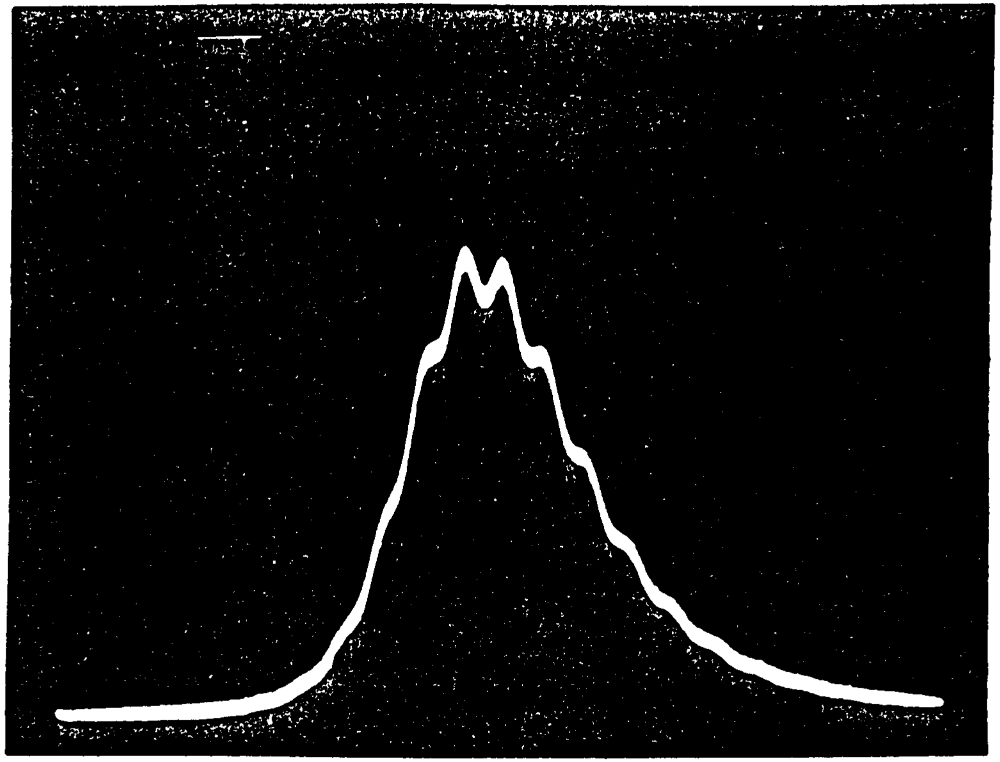

Fig 8.6

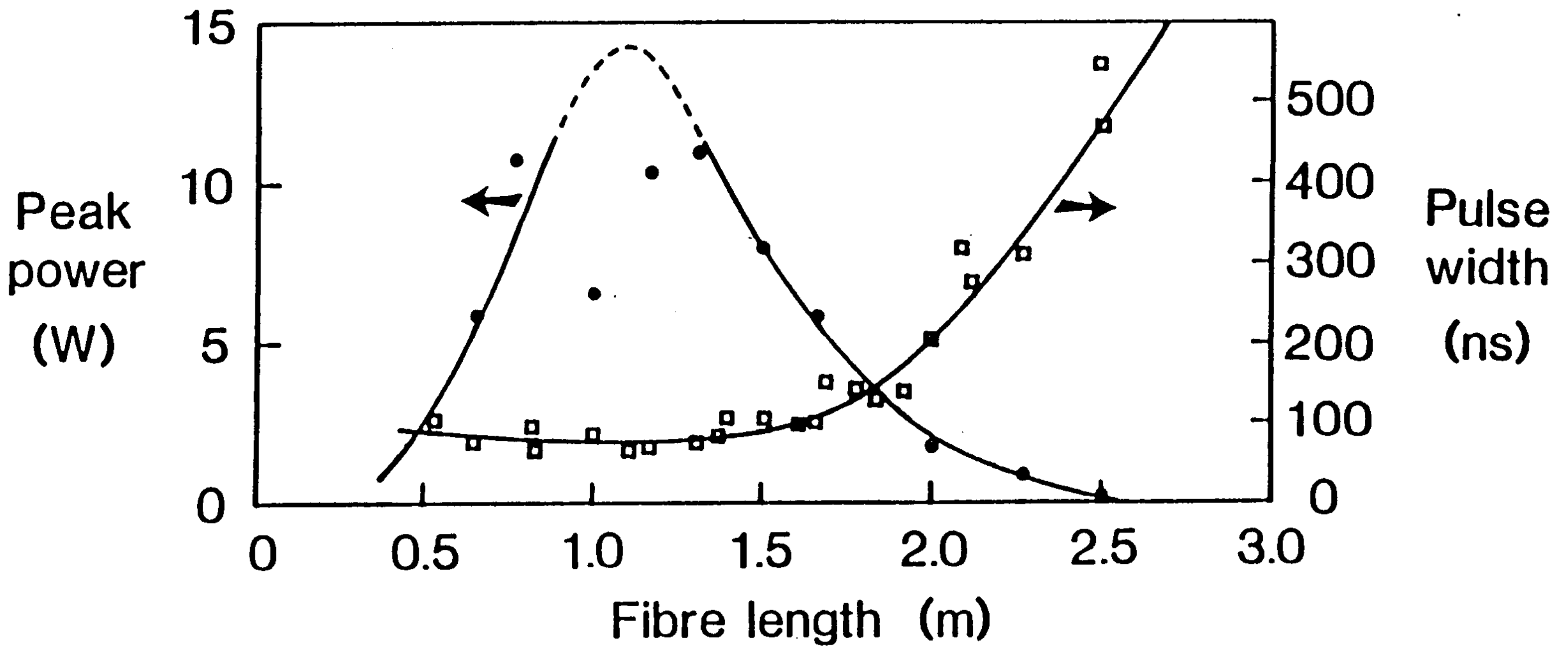
15
10
5
0
Peak
power
(W)
500
400
300
200
100
0
Pulse
width
(ns)
0
0.5
1.0
1.5
2.0
2.5
3.0
Fibre length (m)

Fig 8·7

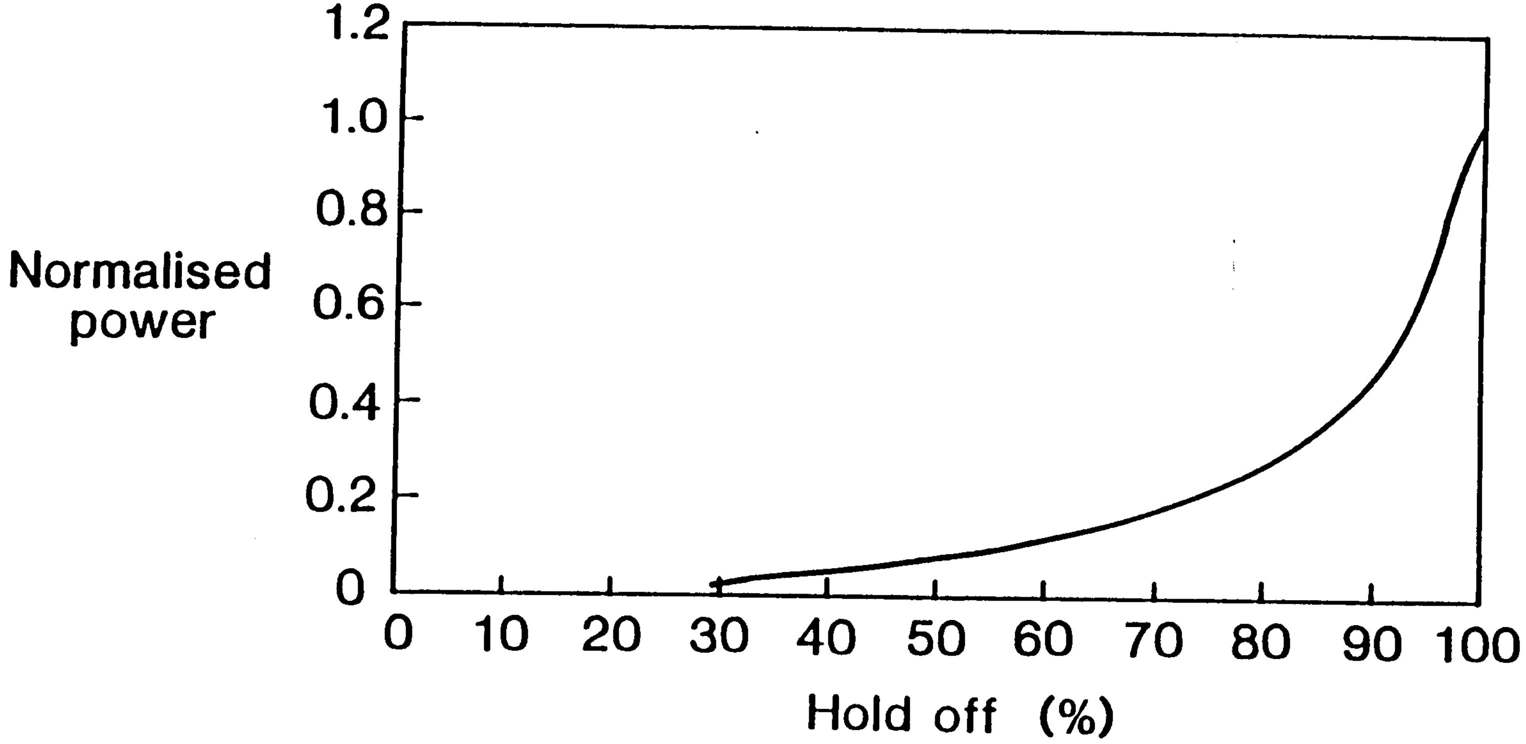
Normalised power
1.2
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
Hold off (%)

Fig 8.8

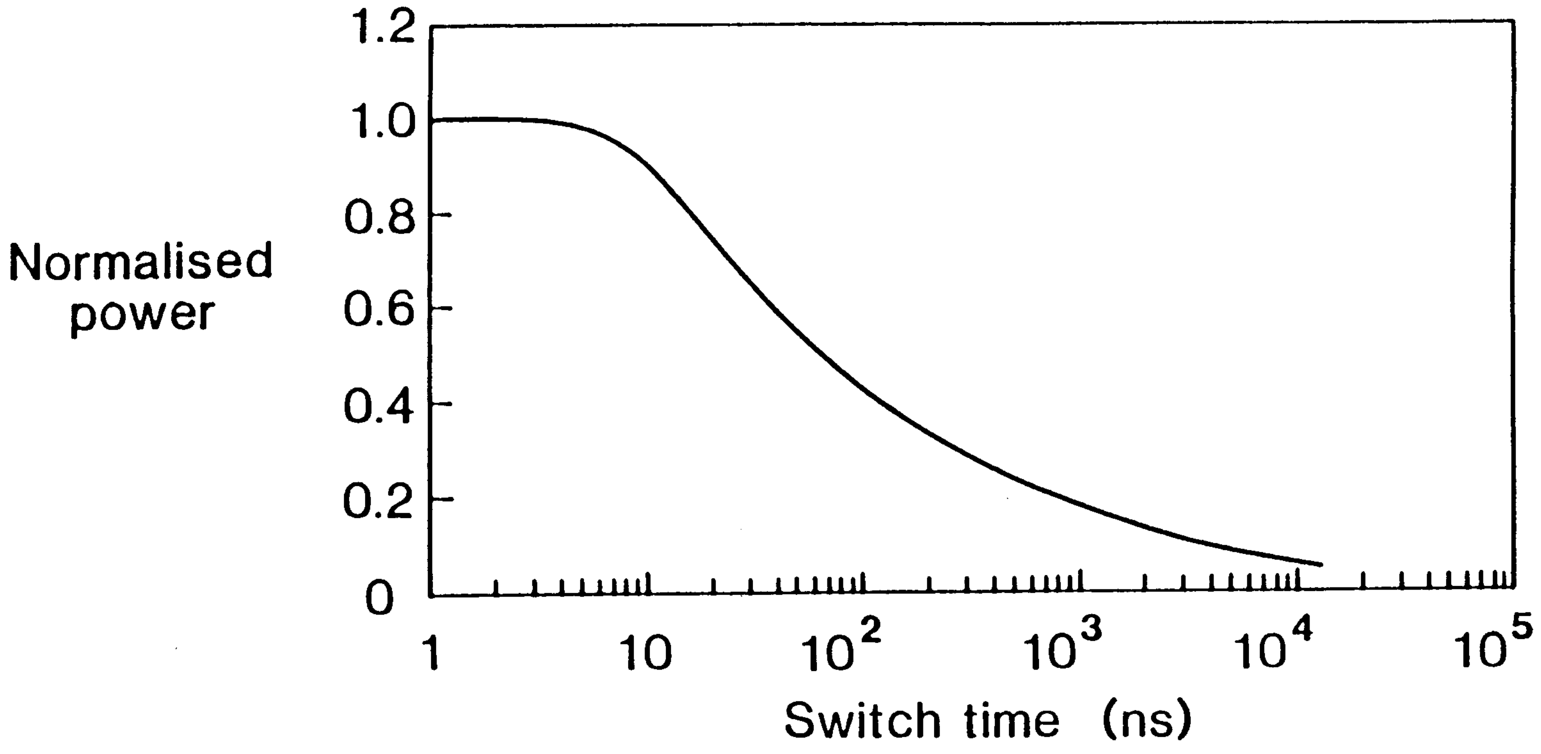
Normalised
power
1.2
1.0
0.8
0.6
0.4
0.2
0
1
10
10^2
10^3
10^4
10^5
Switch time (ns)

Fig 8.9