494

Invited Paper

POLARISATION EFFECTS IN FIBRE LASERS: Phenomena, Theory and Applications

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I. INTRODUCTION

Single-mode fibre lasers [1,2] play a important role in optical fibre communications and sensors. They exhibit a number of interesting phenomena, one of the most important being polarisation effects, which have not yet been properly evaluated.

Fibre lasers differ from conventional glass lasers by having a linearly-polarised pump source, a birefringent cavity and a longitudinal pumping system. These characteristics not only cause special output polarisation properties of fibre lasers, but they also provide an opportunity, for the first time, to investigate the relation between the polarisation states of the pumping light and the lasing light. More information of the microscopic system of rare-earth ions in a glass matrix can ,therefore, be obtained.

Technically, an understanding of the polarisation properties is essential for producing single-polarisation single-mode (SPSM) fibre lasers, and is necessary for a number of sensor and switching devices. Furthermore, polarisation-sensitive intra-cavity components such as fibre gratings, acousto-optic modulators, and crystals for frequency doubling are frequently employed, and their successful operation also requires a knowledge of the polarisation behaviour of fibre lasers.

The principal aims of this study are to characterize the basic factors governing polarisation effects in fibre lasers, to provide further information about the microscopic system of rare-earth ions in a glass matrix, to understand the influence of polarisation effects on the operation of fibre lasers, and to devise a theoretical model for interpreting their performance.

Based on the theoretical studies, a practical integral fibre polariser technique for making SPSM fibre lasers has been developed. A polarisation-switched fibre laser using a photon-injection technique has also been demonstrated.

II. PHENOMENA

Experimental investigation of various fibre lasers with a Fabry-Perot cavity shows that the polarisation effects can be characterised by three basic factors [3,4]:

(1) The fluorescence caused by spontaneous emission is depolarised independently of the polarisation of the pump light.

(2) Two orthogonal, phase-independent, polarisation eigenmodes may be excited in the 'single-mode' fibre cavity, which have different thresholds, slope efficiencies, relaxation oscillation frequencies and different spectra.

(3) The polarisation state of the output from an ordinary fibre laser depends on the orientation of the pump light polarisation, the pump power level and the dopant characteristics. The degree of polarisation (DOP) of laser output can be expressed as the following function:

$$DOP = f(P_{ab}, A)\cos(2\alpha) \qquad (1)$$

where the parameter A is the polarised cross-section ratio [5] defined as $A=\sigma_s/\sigma_p$, α is the angle the pump polarisation makes with the x-axis, P_{ab} is the total absorbed pump power.

III. THEORETICAL MODELLING

On the basis of the experimental observations of polarisation effects in fibre lasers described above, the following postulates can be made for modelling the effects:

– Each rare-earth ion in glass corresponds to a partially anisotropic oscillator;

– The orientations of these oscillators, and the associated transition dipole moments, are randomly distributed in space.

– The absorbing and emitting oscillators of the same rare-earth ion have the same orientation in space related to a system of coordinates which is rigidly fixed to the centre, independently of the non radiation transition.

The last condition follows from the experimental investigation of the dependence of the polarisation output from the fibre laser on the pump polarisation. This assumption is necessary, at least for those non-resonant transitions of rare-earth ions which are measured and discussed in this study.

With these fundamental conditions the concept of an effective pump power for each of the polarisation eigenmodes is introduced and may be expressed as follows

$$\begin{bmatrix} P_x \\ P_y \end{bmatrix} = P_{ab} \begin{bmatrix} \cos^2\alpha & \sin^2\alpha \\ \sin^2\alpha & \cos^2\alpha \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \tag{2}$$

where P_x and P_y are the effective absorbed pump power components for the x and y, polarisation eigenmodes, respectively, and

$$C_1 = (3+4A+8A^2)/(4+12A+14A^2) \tag{3a}$$

$$C_2 = (1+8A+6A^2)/(4+12A+14A^2) \tag{3b}$$

The effective absorbed pump power is defined as that fraction of the absorbed pump power which contributes to the corresponding polarisation mode.

The concept is now applied to existing laser theory, which is valid only for one individual lasing mode, in order to analyse the polarisation eigenmodes in a fibre laser. Thus the laser performance can be predicted, and it turns out that the model fits the experimental results very well. An accurate interpretation of the third character of polarisation effects, namely the $\cos(2\alpha)$ function form in eq.(1), is deduced, and a certain form of function $f(P_{ab},A)$ is then obtained as

$$f(P_{ab},A) = (C_1 - C_2) / (1 - P_{th}/P_{ab}) \tag{4}$$

where P_{th} is the absorbed power required to reach threshold.

The good agreement between the experimental measurements and the theoretical calculation indicates the reasonableness and feasibility of the modelling. Consequently, the fibre laser can now contribute to laser spectroscopy an opportunity of obtaining a microscopic parameter, namely the polarised cross-section ratio A, for some materials.

IV. SPSM FIBRE LASERS

The polarisation efficiency η can be defined as

$$\eta = P_x/P_{ab} \tag{5}$$

where the operating single polarisation mode has been assumed to be the x mode. Both the theory and the experiments show that it is far more efficient to use an intra-cavity polariser than to polarise the output light with an external polariser. Figure 1 theoretically compares the polarisation efficiency of Nd^{3+} and Er^{3+}-doped SPSM fibre lasers having intra-cavity polarisers with ordinary fibre lasers having a polariser located outside the cavity.The experimental results for a Nd^{3+}-fibre laser are also shown. It can clearly be seen that the SPSM fibre laser offers a much higher polarisation efficiency. This is because a high proportion of the total population inversion of excited ions has contributed to the operating polarisation, if the undesired polarisation component has been suppressed within the resonator.

To suppress the undesired polarisation mode, say the y-mode, a differential loss between the operating and the undesired modes is needed. The minimum additional loss for the y-mode L_y (in nepers) required for a given absorbed pump power is expressed by

$$L_y > 2KP_y - L + \ln R_2 \tag{6}$$

where L is the intrinsic cavity loss, which is identical for both x- and y-modes, R_2 is the reflectivity of the output mirror, K is the laser parameter related to pumping efficiency, saturation density and the cross-sectional area of the fibre cavity. Both L and K can be determined experimentally.[6]

Three kinds of in-line integral polariser have been developed for the construction of all-fibre SPSM fibre lasers. Instead of splicing a fibre polariser onto the fibre laser, integral fibre polarisers are fabricated from rare-earth-doped fibres themselves. A conventional rare-earth-doped optical fibre preform is made, after which a flat is ground onto the preform to form an optical interaction surface. The resultant D-shaped preform is then fused into a sleeving tube to form a composite preform. After drawing, the fibre contains longitudinal hollow sector (Figure 2a). When part of this hollow sector is filled with metal it acts as a polariser, since the polarisation component aligned in a direction normal to the metal surface is differentially absorbed. An alternative design is fabricated by drilling holes in a rare-earth-doped fibre preform, and then pulling into single-mode fibre (Figure 2b). Advantages of these techniques are: (1) minimal interfacial scattering, (2) accurate separation between the core and the metal surface, (3) choice of metal/glass interaction length, (4) automatic alignment of the birefringent axes with the interaction surface and (5) zero splicing loss. A third in-line polariser design is made by evaporating metal onto a side-polished fibre. The active fibre cladding is removed to expose the core (Figure 2c) using a novel fibre polishing technique [7], after which aluminium or silver is evaporated to form the polariser. A metal film of 0.2μm to 0.5μm thickness is typically used. This technique dramatically simplifies the fabrication procedure, since it uses a conventional fibre design and leaves the fibre ends unaffected., However, misalignment between the birefringent axis and the metal interaction surface can reduce laser performance.

In practice, the extinction ratio of the output from a SPSM fibre laser is limited by the superfluorescence of the unwanted polarised mode. Increasing L_y leads to a higher extinction ratio, at the expense of less output power. Figure 3 shows calculated curves of extinction ratio as a function of absorbed pump power for a LD-pumped SPSM laser using a Ga-filled D-shaped integral polariser.

A variety of Nd^{3+} and Er^{3+}-doped SPSM fibre lasers have been constructed using the integral fibre polariser technique. Some typical results are summarised in Table 1.The measured lasing characteristics of the LD-pumped, Nd^{3+}-doped, SPSM fibre laser using a metal-plated integral polariser listed in the right-hand column of Table 1 are shown in Figure 4. A continuous wave (CW) output power of 3mW, a 25dB extinction ratio and 37% slope efficiency have been obtained.

V. POLARISATION MODE COMPETITION

Both the x- and y- modes are always "trying" to stimulate the inverted population to build up their own lasing oscillation. Thus polarisation mode competition inevitably exists in a fibre laser. CW operation of an ordinary fibre laser is an equilibrium state of the polarisation mode competition, and can be analysed by the theoretical model of effective absorbed pump power. However, pulsed operation, as a transient process, breaks the equilibrium of polarisation mode competition.

Figure 5 shows how the relaxation oscillations of the y-mode extract the population inversion from the CW oscillation of the preliminary x-mode. The fibre laser reaches stationary equilibrium in the polarisation mode competition in four steps. First, the x-mode starts to lase as a result of higher effective pump power than the y-mode, as shown by the initial pulse train of relaxation oscillations. Secondly, CW operation of the x-mode becomes established, resulting in a single polarisation operation accompanied by the superfluorescence of the y-mode. Thirdly, the y-mode begin to lase with a relaxation of lower frequency than the x-mode. Finally, the y-mode reaches CW operation, and the polarisation mode competition reaches stationary equilibrium.

When the launching orientation of the pump polarisation α is near to 45^o, the polarisation mode competition leads to a "push-pull" procedure as shown in Figure 6. The push-pull phenomenon shows that after a stimulated pulse of a certain polarisation component, the other polarisation component will have greater population inversion. Such a polarisation competition in the time domain influences the pulsed operation of fibre lasers. It was discovered that when the pump beam is launched on the x- or y-axis, the first peak of a slow Q-switched pulse is the corresponding polarisation component and the orthogonal counterpart occurs at the second peak.

In the frequency domain, polarisation mode competition causes a special spectrum property. It has been found that each lasing line belongs to a certain polarisation component, either the x-mode or the y-mode. Figure 7 shows a typical polarisation-resolved spectrum. The x-mode (the upper picture) has occupied multiple-lines around the centre of the fluorescence spectrum, and the y-mode has, consequently, been pushed away to lase at another wavelength. This means that the polarisation mode competition has created a significant polarisation frequency splitting.

VI. PHOTON-INJECTION POLARISATION-SWITCHING

At relatively low pump levels, only one polarisation mode oscillates, and polarisation mode competition causes lasing action in this polarisation component to deplete the majority of the population inversion. As a result of the fact that two competing polarisation eigenmodes share the same gain medium, the operating polarisation mode can be switched to its orthogonal counterpart if a sufficient number of coherent photons having the correct polarisation are injected into the cavity.

A theoretical analysis shows that the threshold power P_o of the injected photons at lasing wavelength for switching to occur is given by

$$P_o > (P_x - P_y)\, \eta\, \xi\, (\nu_o / \nu_p) \qquad (7)$$

where η is the pumping efficiency factor, ν_o and ν_p are the lasing and pump frequencies, respectively. The parameter ξ is the solid angle ratio and can be expressed as

$$\xi = 1 - (n_{cl}/n_{co}) \qquad (8)$$

where n_{cl} and n_{co} are the refractive indices of the cladding and core, respectively. Physically, ξ is the fraction of the spontaneous emission which is captured by the fibre waveguide. An extremely low threshold is expected from eq.(7).

In order to demonstrate feasibility, we have fabricated the new switching device with a Nd^{3+}-doped fibre laser pumped by a laser diode. Either CW or pulsed linearly-polarised photons at the lasing wavelength were injected into the cavity of the fibre laser via an intra-cavity coupler, and low-threshold polarisation switching was observed in both cases.

A schematic of the experimental set-up is shown in Figure 8. A SPSM fibre laser provided the CW injection light. This light has exactly the same wavelength as the operating laser, since the active fibres and pumping sources are identical. The polarisation switching process can be clearly seen from Figure 9, where the upper trace is for the preliminary operating x-polarisation mode, whilst the lower is the y-polarisation mode trigged by the injected photons. In this case, the injected light was chopped by a mechanical chopper.

As expected from the theoretical analysis, the switching threshold for such a device is extremely low. Only 0.1μW of optical power is sufficient for CW switching of the laser. The on/off ratio of the switching is also high, since the lasing action can be totally extinguished (as seen in Figure 9), leaving only the fluorescence level. A ratio of 12:1 has been measured for CW switching, even when the fluorescence was detected over its full spectral bandwidth.

By using a tunable, pulsed dye-laser as photon-injection source, a switching time of 4μs was measured, and is limited by the photon lifetime in the cavity. A lower reflectivity of the output mirror will therefore give faster switching at the expense of a higher pump level and switching threshold. It was also found that the switching effect can tolerate a relatively large wavelength variation. No significant effect was observed when using pulsed, injected light with a tuning range of 10nm.

VII. CONCLUSIONS

Three basic factors governing the polarisation effects in fibre lasers are identified and characterised. A unified theoretical model, incorporating the electric dipole model for rare-earth ions in a glass matrix, is formulated. The concept of an effective pump power is introduced and can be applied to existing laser theory; thus laser performance characteristics can be predicted accurately.

In the engineering domain, an effective technique for making single-polarisation, single-mode fibre lasers has been developed involving the use of an integral fibre polariser. The latest progress in polarisation studies of fibre lasers has been photon-injection polarisation-switching. This all-optical switching device, offers the advantages of extremely low threshold, a high switching extinction ratio and simplicity of the device configuration. The potential applications of the device include optical logic, optical sensing and optical signal processing.

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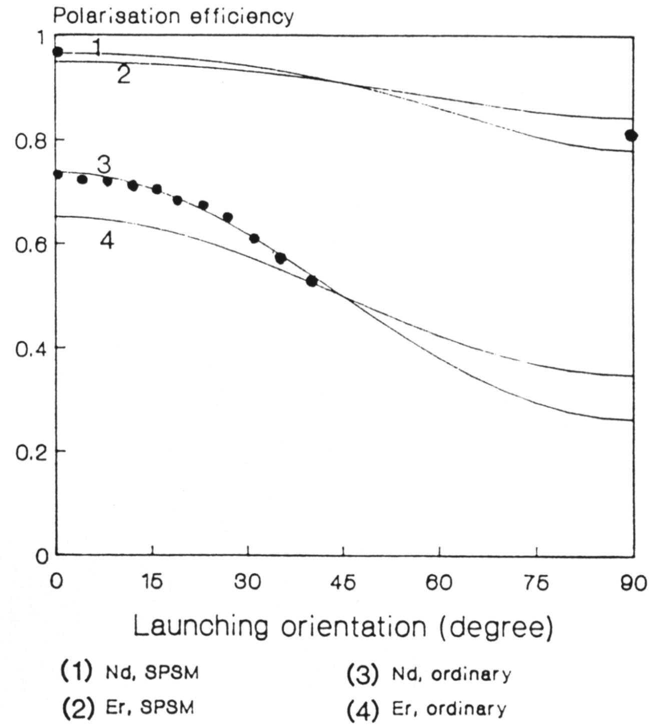
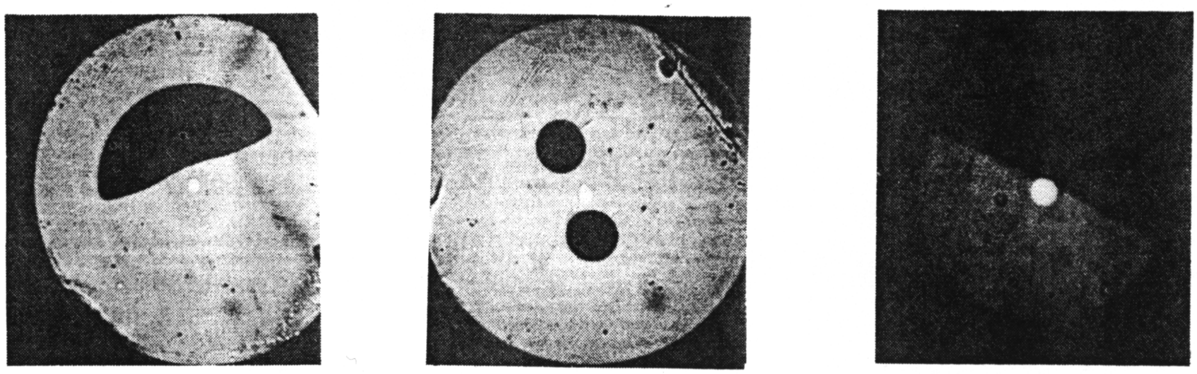
Fig.1 Polarisation efficiency as a function of launching orientation for two different configurations.





(a) D-shaped (b) Twin-hole (c) Metal-plated

Fig.2 Cross-sections of integral fibre polarisers.

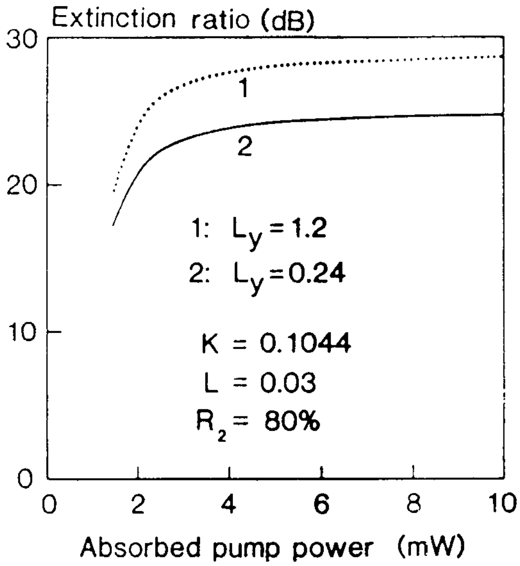


Fig.3 Theoretical curves of extinction ratio as a function of absorbed pump power for two sets of integral polariser parameters.

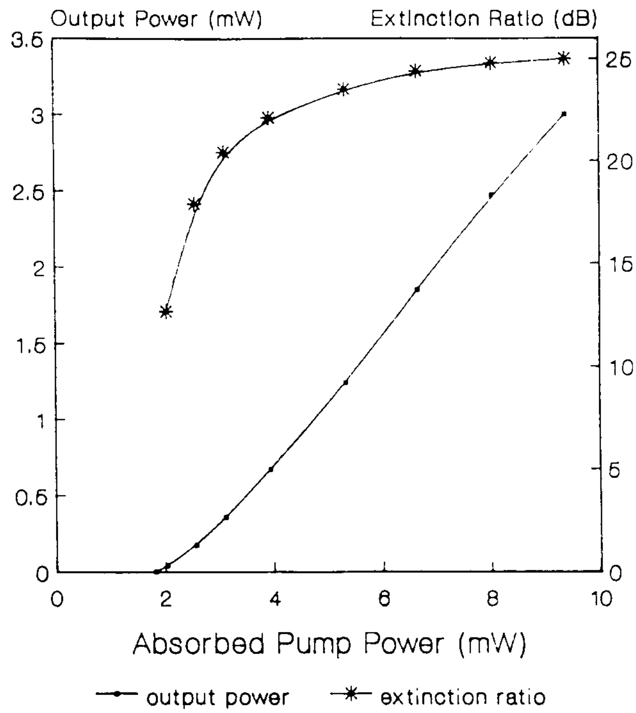


Fig.4 CW lasing characteristics of a LD-pumped SPSM Nd^{3+}-doped fibre laser.

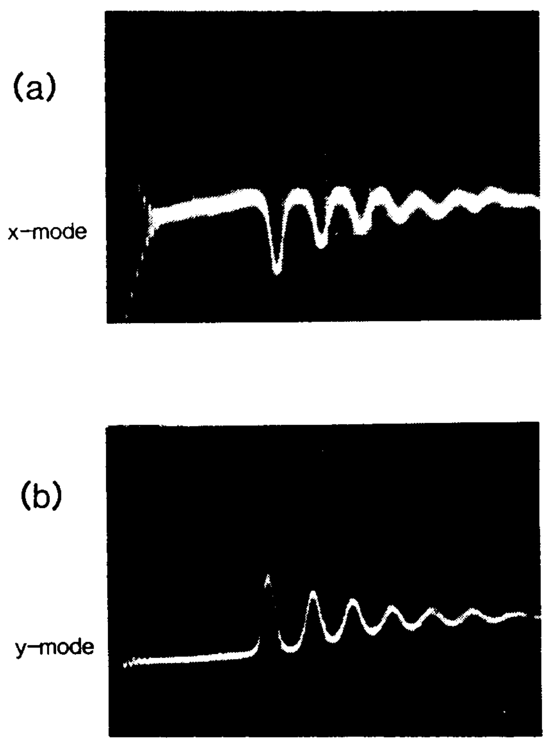


Fig.5 Polarisation-resolved relaxation oscillation showing polarisation mode competition in the time domain.

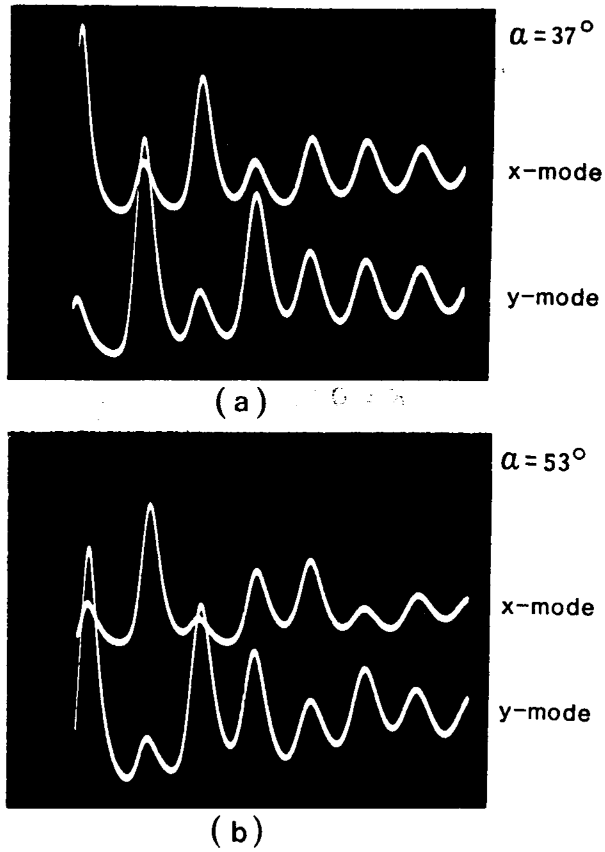


Fig.6 Polarisation-resolved relaxation oscillations showing "push-pull" patterns.

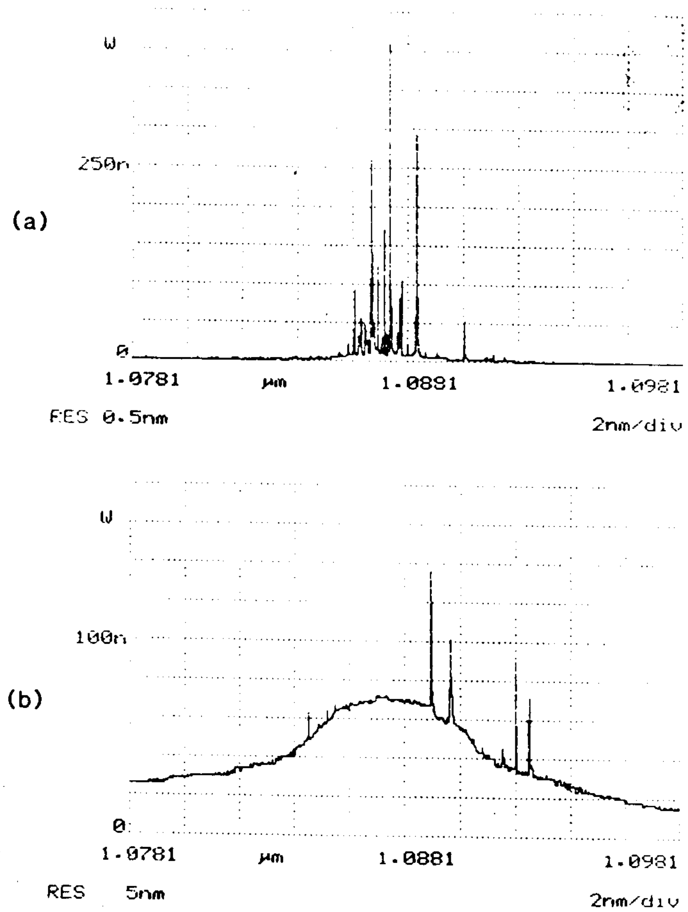


Fig.7 Polarisation-resolved spectra of a Nd^{3+}-doped fibre laser pumped on x-axis. (a) the x-mode, (b) the y-mode.

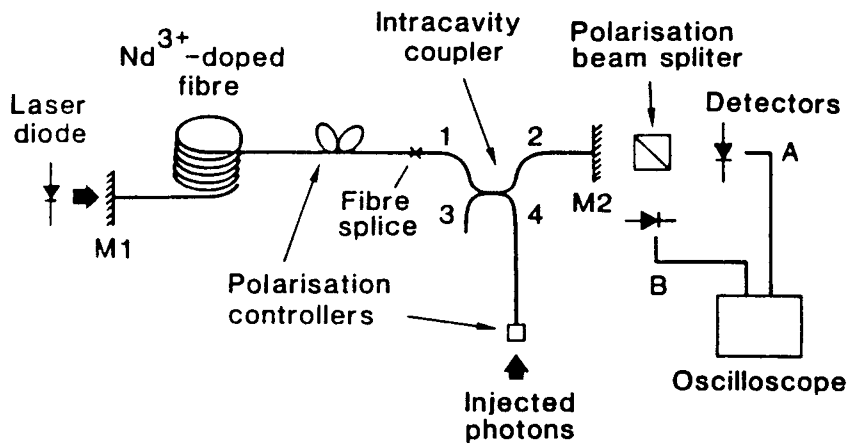


Fig.8 A schematic of the polarisation-switched fibre laser.

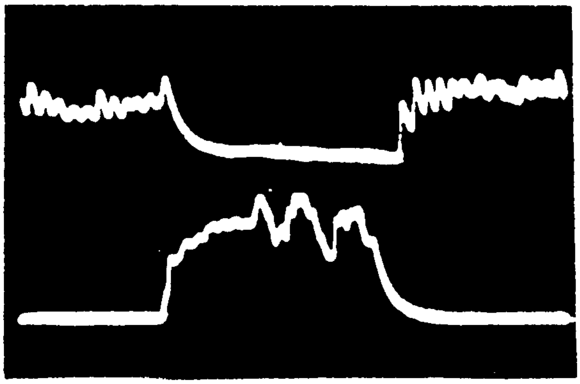


Fig.9 CW polarisation switching in a fibre laser. Upper trace: the x-mode; Lower trace: the y-mode.

		D-SHAPED	TWIN-HOLE	METAL-PLATED
POLA-RISER	metal type separation d/a metal length	Ga 3.8 35mm	Ga 2.5 7mm	Al 3.0 15mm
CAVITY	dopant fibre length R_2	Nd^{3+} 200cm 50%	Er^{3+} 140cm 80%	Nd^{3+} 26cm 80%
PUMP	source wavelength absorbed power	LD(Sony SLD 204V) 825nm 10mW	DCM Dye 650nm 50mW	LD 825nm 10mW
SPSM-LASER	output power extinc. ratio pulse width wavelength	(CW) (Q-switched) 2.1mW 3.9W 23dB 29dB 150ns 1088nm	(CW) 1.2mW 22dB 1536nm	(CW) 3mW 25dB 1080nm

Table 1 SPSM fibre lasers.