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Special Optical Fibres

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Introduction

Optical fibres are making ever-increasing inroads into areas traditionally satisfied by older, more established technologies. In particular, sensors which rely on the external modulation of the properties of an optical fibre (intrinsic sensors) are receiving much attention since they can be made extremely sensitive and can be used for distributed measurements. Distributed sensing provides some particularly exciting prospects for acoustic, magnetic and electric field monitoring. To date, however, the great majority of experimental and commercial fibre sensors employ telecommunications-grade fibres, largely as a result of their ready availability. Not only does this policy frequently lead to a design compromise, but in some cases makes the performance marginal or untenable as a result of excessive environmental sensitivity. Consequently, attention is now being given to the design of special sensor fibres with enhanced (or depressed) sensitivity to specific measurands.

There are few special fibres currently commercially available, with perhaps the best known being the highly-birefringent fibre[1], either in polarisation-maintaining[2] or polarising[3] form. These fibres are extensively used for polarisation control in fibre gyroscopes and other sensors, and are also under investigation for use in coherent communications systems[4]. The situation is improving, however, and a large number of new fibre designs tailored to specific applications have been reported. These include circularly-birefringent fibres[5,6] whose unusual propagation properties make them ideal for magnetic field sensing. Work is also underway on metal/glass composite fibres for the production of polarisers[7] and Kerr modulators[8].

Considerable scope exists for modifying the properties of silica fibres by incorporating dopants to enhance a given effect. Thus, although the acousto-optic, magneto-optic, non-linear and electro-optic coefficients are low in pure silica, they can be increased by adding various transition and rare-earth ions[9]. Work in this area has begun in several laboratories[10]. However, it should be noted that, in general, the greatest improvements in sensors, modulators and other devices can be obtained by abandoning silica altogether as a host material and employing compound glasses, calcogenide glasses or even polymers. The increased loss intrinsic to this approach is not normally a problem, since several orders of magnitude improvement in device sensitivity is obtainable and only a few metres of fibre are required.

Perhaps the most exciting recent development has been the demonstration of lasing action at wavelengths of 1.06, 1.08 and 1.536μm in single-mode fibres using Pr^{3+}, Nd^{3+} and Er^{3+} respectively[11-13]. The losses at the lasing wavelength in these fibres is so low that it has been possible to construct lasers up to 300m in length. Apart from the obvious application of the fibres as sources and amplifiers for communication and sensor systems, the availability of a multi-pass resonant active-device suggests a number of sensor possibilities. Both ring-resonator and Fabry-Perot laser devices have been built with a finesse of up to 300. Consequently, a sensitivity enhancement of the same order to acoustic radiation, for example, should be obtainable. In addition, the availability of low-loss rare-earth-doped fibres with controlled absorption and fluorescence characteristics provides further opportunities for distributed sensing using the variation of these parameters with temperature[14].

It is clear from the above that fibre fabrication technology is able to offer a number of attractive solutions to the unique problems presented by fibre sensors. A wide range of possibilities are available, including modified telecommunications fibres which are bend resistant, metal[15] and special polymer-coated[16] fibres, fibres with liquid cores[17] or claddings[18], spun low-birefringence fibres[19] and twin-core fibres[20]. As examples of the potential for special fibre designs, we will review here linearly and circularly-birefringent fibres, metal/glass composite fibres and rare-earth-doped fibres. In addition, recent developments in non-silica based "soft" glass fibres are reviewed.

Polarisation-Maintaining Fibres

Perhaps the best known of all special fibres is the highly-birefringent (hi-bi) polarisation-maintaining fibre, the two most common forms of which are shown in Figures 1(a) and (b). The birefringence is created by means of anisotropic thermal stress produced by the two regions of high-expansion glass disposed on either side of the core. The fibres are able to transmit linearly-polarised light because their very high intrinsic birefringence greatly exceeds that induced externally by bends, kinks and twists. Thus, whereas conventional fibres have an output polarisation state which is sensitive to environmental factors, in a hi-bi fibre it is possible to select and transmit one of the two orthogonally-polarised modes. In practice, however, some small power transfer occurs to the unwanted-polarisation and this is normally characterised by the h-parameter[21], the power transfer per metre of fibre length. The best fibre measured to date[22] has a power transfer (h-parameter) of 1.6×10^{-7}, corresponding to an output extinction ratio of -38dB after one kilometre. Note that this figure is dependent on the fibre configuration and packaging and will be worse in tight coils or badly-designed cables.

Recent theoretical work has shown[23] that the previous interpretation of the h-parameter was incorrect, since no account was taken of the fibre birefringence. From this, it can be shown that for significant mode coupling to occur, the correlation length of the applied perturbation must be comparable to the fibre beat length, typically a few mm. The currently observed levels of polarisation cross-talk cannot, therefore, be due to imperfections within the fibre. They are a consequence of uneven fibre coating and externally applied stresses and bends arising from winding onto a drum. This interpretation is supported by recent measurements on the effects of different fibre coatings[24].

The ultimate linear polarisation-holding ability of a hi-bi fibre is limited by Rayleigh scatter which continuously feeds a small amount of power into the unwanted polarisation, and by the fact that the fibre mode is not truly linearly-polarised, but exhibits field curvature. It therefore has both a major and a minor (orthogonally-polarised) field component[25]. The polarisation-holding limits are shown in Figure 2, where the polarisation crosstalk is plotted as a function of fibre length. It can be seen that for short fibre lengths the mode-field curvature limits the transmission of linearly-polarised light to an extinction ratio of about -40dB, whereas for a length of 100km the Rayleigh scattering limit is -30dB. For comparison, experimental results[22] for long lengths of PANDA fibre are also shown. We see that the current status of polarisation-holding ability is some 15dB worse than the theoretical limit, a result which is attributable to externally-induced mode coupling as outlined above.

Hi-bi fibres are necessary whenever polarisation colinearity is required between two interfering beams, as for example in interferometric sensors, or the fibre gyro. Unfortunately, however, current polarisation-maintaining fibres do not yield the required polarised-mode discrimination (>60dB) to ensure reciprocity in the fibre gyro, and further discrimination is required in the form of a polariser.

Polarising Fibres

The polarising fibre combines the polarisation-holding ability of a hi-bi fibre with a discriminatory loss for the unwanted polarisation[3]. Thus, power coupled into the latter is continuously attenuated down the length of the fibre and higher extinction ratios can be achieved. In effect, the fibre behaves like a distributed polariser.

The discriminatory loss mechanism is due to a difference in the guidance of the x- and y-polarised modes caused by the influence of stress-producing sectors on the fibre core. One mode is more susceptible to bends or microbends than the other and a wavelength window exists (Figure 3) in which the x-polarised mode is sufficiently well guided to give low-loss propagation (<5dB/km), while the y-polarised mode experiences greater than 50dB/km attenuation. The effect can also be exploited to produce high-performance polarisers in which the fibre is coiled with a radius carefully selected to give maximum polarisation discrimination. Such polarisers are of interest for use in the fibre gyro.

The effect on polarisation holding ability of having a continuous discriminatory loss of 50dB/km for the unwanted polarisation, as in a polarising fibre, is also indicated in Figure 2. The extinction ratio now becomes independent of fibre length and stabilises at a value of -60dB after a length of 200m as a result of balance between power feed and loss in the unwanted mode. The advantage of using polarising fibres to improve the output extinction ratio in long lengths can be clearly seen.

Circularly-Birefringent Fibres

Polarisation-maintaining fibres as described above are well known to preserve linear polarisation. It is less well known that by making a fibre highly-circularly birefringent, it can be made to preserve circular polarisation. Highly circularly-birefringent fibres have an important potential application as the sensing fibre in electric-current monitors[26] and magnetic-field detectors. In both cases the high circular-birefringence swamps the unwanted effects of linear birefringence caused by bending and packaging the fibre. Once these effects are eliminated, the full Faraday polarisation rotation can be readily detected.

As in a linearly-birefringent fibre, it is necessary to have a polarisation beat-length of the order of mms in order to preserve polarisation and a number of techniques have been proposed to achieve this. Circularly-birefringent fibres[27] have been fabricated based on the photoelastic effect, which is induced by twisting the fibre after the draw. This imparts an optical rotation per metre $\alpha = g\xi$, where ξ is the twist rate in rads/m, and g (≈ 0.07) is the stress-optic rotation coefficient. Therefore, fibres need sub-mm twists to obtain mm beat lengths. This is clearly impractical, since the fibre would break.

More recently, two practical fibre designs have been reported in which beat lengths as short as 3mm have been obtained. These are the so-called helical-core[5] and spun hi-bi[6] fibres. As a result of the high circular birefringence, such fibres can sense Faraday rotation while remaining insensitive to external perturbations caused by packaging.

Helical-core fibres

Highly circularly-birefringent fibres which use geometrical birefringence can be fabricated. The fibres are based on the optical rotation which occurs when light is constrained to follow a helical path. These fibres have achieved optical rotation lengths $L_R = 2\pi/\alpha$ as low as 6mm [28] a figure which is an order of magnitude better than ever previously reported.

When light follows an isotropic helical path (inset Figure 4), it experiences a rotation θ of the plane of polarisation per unit pitch P, given by

$$\theta = 2\pi(1 - P/S) \qquad (1)$$

where S is the arc length of the helix. Thus the dependence of the optical rotation length $L_R = P^3/2\pi^2Q^2$ can be plotted versus P for different values of core offset Q, as shown in Figure 4. The points plotted here represent experimentally-determined optical rotation lengths for a number of helical-core fibres and indicate good agreement with theory.

Helical-core fibres have been fabricated from composite rod and tube preforms, the helix being formed by spinning the preform during the fibre drawing process. A photograph of a helical-core fibre is shown in Figure 5 where the helical waveguiding region is clearly visible. One of the novel features of these fibres is that they maintain monomode operation at V-values of up to 25. This is due to the small radius of curvature of the core which induces severe discriminatory bend-loss for higher-order modes.

Spun hi-bi fibres

If a highly-birefringent Bow-Tie fibre is rapidly spun during the draw, a fibre with a large elliptical birefringence is produced[6]. The polarisation ellipticity (major:minor axis) of the eigenmodes is given by

$$\varepsilon = \tan(\tfrac{1}{2}\tan^{-1}(2L_p/L_t))$$

where L_p is the beat-length of the unspun fibre and L_t is the spin pitch. At high spin rates, ($L_p/L_t > 1$) the ellipticity approaches unity and the modes are therefore predominantly circularly polarised. In practice, it is necessary to choose a fibre with an unspun beat-length of less than about 3mm to obtain a sufficiently large elliptical birefringence (elliptical beat length, $L_p' < 10$mm).

The performance of these fibres in current sensing applications has been investigated[29] and a typical sensor coil containing 80 turns of fibre is shown in Figure 6. The response of this coil in a current sensor configuration is shown in Figure 7, where the device linearity can be seen to be excellent, up to a maximum measured current of 370A. In addition, a sensitivity of 100μA was obtained. By increasing the number of turns, and optimising the optical configuration, a sensitivity of a few microamps should be obtainable.

Composite Glass/Metal Fibre Polarisers

An alternative to the coiled fibre polariser described above is provided by the glass/metal fibre polariser shown schematically in Figure 8. The fibre contains a hollow D-section filled with metal in close proximity to the core. The effect of the metal is to introduce a large differential attenuation between the x- and y-polarised (pseudo TE and TM) modes. Spectral attenuation plots for a typical glass/metal polariser are shown in Figure 9. An extinction ratio in excess of 37dB, combined with an insertion loss of less than 1dB was obtained over a wide spectral window of 1300 to 1550nm. This measurement was limited by the measurement equipment used, and subsequent results indicate that extinction ratios in excess of 52dB can be obtained[7]. In particular, it should be noted that, since the attenuation ratio α_y/α_x is approximately constant, it is therefore theoretically possible to design a polariser with virtually unlimited extinction ratio, albeit at the expense of increased insertion loss. This is particularly important in many applications (particularly the fibre gyroscope) where the extinction ratio is critical, and an increased insertion loss can be tolerated.

Kerr Modulator Fibres

In addition to the glass/metal fibre polarisers described above, the ability to introduce metal-fitted sectors into a fibre leads to the Kerr-effect phase modulator fibre[8] shown schematically in Figure 10. Here, two electrodes consisting of an indium/gallium mixture are present, one on either side of the fibre core. By applying a voltage to these electrodes, a birefringent phase shift may be obtained between the two orthogonally-polarised modes of the fibre. In spite of the very low electro-optic Kerr effect in silica glass, the long interaction length possible in optical fibre allows the construction of efficient phase modulators.

A typical frequency response curve is shown in Figure 11. A $\pi/2$ phase-shift was obtained with an applied AC drive voltage of only 47V rms, an unprecedentedly low value for a Kerr modulator based on amorphous materials. Further improvements may be expected by the use of multi-component glasses (see below).

A further application of the twin side-pit fibre is as a pressure sensor[30]. Here, the holes are filled with the fluid whose pressure is to be monitored and any changes in the fluid pressure is translated into a change in the polarisation state at the output of the fibre. Response times as fast as 1msec have been reported[30].

Multi-Component Glass Fibres

Fibres fabricated from multi-component non-silica based glasses may find many applications in areas where the ultra-low losses of telecommunications fibre are not required. Such areas include fibre sensors and non-linear devices where the increased performance obtainable in non-silica glasses is more critical than the fibre loss, particularly since such devices may use only a few metres of fibre. By using rod-in-tube fabrication techniques, in combination with careful selection of glass properties, it should be possible to obtain single-mode fibres with many desirable properties. Indeed, the Verdet constant and non-linear coefficient $\chi^{(3)}$ can be an order of magnitude higher in soft glasses than in silica.

Examples of fibres produced in our laboratories are shown in Figure 12, from which it can be seen that many fibre designs are possible. Single-mode "soft glass" fibres which have been produced by the rod-in-tube technique have losses of < 400dB/km. Additionally, high-birefringence fibres have been produced with beat lengths of less than 7mm.

An area where "soft" glass fibres may prove highly attractive is for the generation of non-linear effects, since a small core diameter is associated with the large Δ available. This results in high power densities which, combined with high non-linear coefficients, should lead to considerably reduced thresholds for the generation of, for instance, Raman or Brillouin spectra[31].

Rare-Earth-Doped Fibres

Rare-earth doping of glasses is well known to enhance the magneto-optic, electro-optic and non-linear coefficients of the material. In addition, it provides temperature-sensitive absorption bands and fluorescence characteristics, as well as the possibility of constructing optical amplifiers and lasers. Until recently, however, it was thought that incorporation of these dopants would destroy the hard-won low-loss characteristics of telecommunications fibres and render them inoperable as distributed sensors and amplifiers.

Simple, reproducible fibre-fabrication techniques have now been developed[9,32,33] which d not significantly increase the fibre loss. These processes allow the uniform incorporation of low levels of rare-earth ions in the core of many types of optical fibres. The dopants used are not limited to the rare-earth elements, and could be applied to any dopant with a solid precursor material, for instance the transition metals.

Using these techniques, single-mode fibres have been fabricated containing various rare-earths (Nd, Er, Dy, Tb, Ce, Eu, Yb and Pr) with dopant levels of between 0.2ppm and 3000ppm. Remarkably, all exhibit windows in which losses are comparable with conventional fibres, despite the close proximity of very high-loss dopant absorption bands (see Figure 13). These low fibre losses, combined with the consistency of dopant incorporation along the fibre length, make the fibre suitable for use in distributed sensors, fibre lasers and non-linear devices.

Rare-earth-doped fibre sensors

Nd^{3+}-doped glass point-temperature sensors based on changes in absorption spectrum with temperature have been known for many years[34]. However, the application of this technique to distributed sensors required the development of low-loss rare-earth-doped fibre described above. In a distributed sensor of this type, the loss of a fibre at a wavelength on the edge of an absorption band is monitored by interrogating the local fibre absorption using optical time-domain reflectometry (OTDR). The typical temperature-dependence of absorption of a Nd^{3+}-doped fibre at a wavelength of 600nm is shown in Figure 14. Although the fibre contains only 5ppm Nd^{3+}, a linear change in absorption of 0.2%/^{o}C was found over the temperature range investigated. This represents a 10dB/km variation in fibre loss for a 100^{o}C temperature change. With this fibre, temperature distribution along the fibre could be determined with 2^{o}C accuracy and a spatial resolution of 15m [14].

Considerable improvements in performance can be obtained by using other rare-earth dopants at higher concentrations. This has been demonstrated by using a Ho^{3+}-doped fibre containing 1000ppm Ho^{3+} ions. In this way a sensitivity of better than 1^{o}C with a spatial resolution of 3.5m was obtained over the temperature range -200 to +100^{o}C [35].

Rare-Earth-Doped Fibre Filters

The very large, sharp absorption bands of rare-earth-doped fibres, combined with the low losses obtainable away from these absorptions, suggest that compact, low-insertion-loss wavelength filters with extremely high rejection can be fabricated. These find application in wavelength multiplexing and also in spectroscopy, where very high rejection of the exciting laser is required. As a demonstration of such a filter, a length of Ho^{3+}-doped fibre has been used to separate the anti-Stokes spontaneous Raman scattering from the pump wavelength in a short length of fibre[36]. The fibre used had a differential attenuation of $> 10^9$ between the pump laser wavelength (HeNe at 633nm) and the anti-Stokes Raman line at 616nm. The experimental arrangement used is shown in Figure 15. A 20m length of monomode fibre was used to generate forward-scattered anti-Stokes Raman, with a 7m length of Ho^{3+}-doped fibre used to filter the unwanted pump signal. The resulting Raman spectrum obtained is shown in Figure 16 in which the anti-Stokes scattering at 616nm and a weak emission at 684nm (corresponding to the 1183^{-1} Raman line in silica) are clearly visible. Some pump throughput is still visible, but greater rejection could be obtained, if required, by simply increasing the fibre length. This demonstrates the extremely high rejections obtainable in rare-earth-doped fibre filters.

Fibre Lasers

A class of active fibre devices compatible with single-mode optical fibre sensor systems is highly desirable to supplement the hybrid semiconductor-diode/optical-fibre technologies currently in use. As a first step towards this goal, lasing action in rare-earth-doped silica single-mode fibre lasers (SMFL) has been demonstrated. These possess a number of advantages over their bulk counterparts. By virtue of their small active areas, very-low thresholds and high gains can be achieved. Since the typical fibre diameter is 125μm, thermal effects which plague bulk-glass lasers are minimal. Silica, the host material, has good power-handling characteristics; moreover, it broadens the rare-earth transitions, enabling compact, tunable diode-pumped lasers at various wavelengths to be constructed. Such devices could be of considerable interest as light sources for sensors and measurements. Moreover, it is now possible to construct a wide range of active fibre devices and sensors which exploit the numerous fibre components available, such as 4-port couplers, ring-resonators, polarisers and filters. The very-low loss of the fibre permits the construction of long amplifiers and lasers (300m has been demonstrated) as well as non-linear devices and distributed active-sensors.

A typical fibre-laser configuration is shown in Figure 17. For Nd^{3+}-doped fibres, a lasing threshold as low as 100μW can be obtained using a semiconductor laser end-pump[12]. In an optimised cavity, an output exceeding 6mW at a wavelength of 1088nm has been observed, with a slope efficiency of 40%. Tuning of the output wavelength can be accomplished by substituting a grating for one of the mirrors[37] and a tuning range of 92nm (from 1065-1150nm) is possible. This is the most extensive tuning range yet obtained in a Nd: glass laser and compares favourably with that of a dye laser.

Erbium-doped fibre lasers operate between 1530nm and 1555nm, which coincides with the important minimum-loss window for optical communications. The fluorescence spectrum with a typical tuning curve for an Er^{3+}-doped fibre laser superimposed on it is shown in Figure 18. This corresponds to the $^4I_{13/2}$ - $^4I_{15/2}$ (ground-state) transition and, despite being a 3-level laser system, the Er^{3+}-doped fibre laser operates continuously[13] and has a threshold of only 4mW. To our knowledge this represents the lowest threshold 3-level glass laser yet reported. Optical bistability has also been observed in an Er^{3+}-doped fibre laser operating at 1.54μm[38]. This is based on the mechanism of saturable absorption and has many potential applications including optical memories, switching and amplification.

Q-switching of fibre lasers using an acousto-optic modulator or rotating chopper is also possible and peak powers of up to 250 watts have been observed in pulses ranging from 50ns to 1μs. In particular, it is possible to obtain 13W pulses from a diode-pumped Nd^{3+} fibre laser, a performance which will find many applications in fibre sensors.

Figure 19 compares the fluorescence spectrum of a Pr^{3+}-doped fibre with the laser turning curve. Pumping was by a CW Rh6G dye laser operating at 590nm and the output could be tuned from 1060nm to 1107nm[11]. Threshold for this dopant was 10mW and an output of several mW could be obtained. This was the first report of lasing action in Pr^{3+} ions in glass.

Recently, a number of optical fibre devices have been integrated into fibre lasers. These include fibre polarisers, to give single-polarisation operation of the laser[39], and fibre gratings to reduce the output linewidth[40]. In addition, a number of novel resonant configurations have been demonstrated which obviate the need for dielectric mirrors[41,42]. These demonstrate the possibilities of creating all-fibre systems containing no bulk optical components.

Fibre lasers represent a new class of active fibre devices which are fully compatible with existing fibre components. Their low threshold, tunability and high peak-power pulsed output provides a unique new all-fibre laser technology which will find application in fibre sensors. Immediate potential uses are as high-power source for fibre OTDR measurements and as a broadband emitter for the optical-fibre gyroscope.

Fibre Amplifiers

Optical amplifiers are of interest as wideband in-line repeaters for telecommunications and as signal regenerators for a variety of sensor applications. Much current research has concentrated on semiconductor laser amplifiers[43] which are difficult to splice to fibre systems. It is clear that an amplifier consisting of a special optical fibre compatible with telecommunications fibre would overcome this problem. An optical fibre amplifier based on an Er^{3+}-doped fibre which has a maximum gain at a wavelength of 1.536μm has been reported[44]. The gain characteristic at 140MHz modulation rate is shown in Figure 20 and from this it can be seen that a single-pass gain of 26dB is obtained, with a maximum output power of +13dB/m. The input equivalent noise power was measured at -45dBm in a 140MHz bandwidth. These preliminary results show that Er^{3+}-doped fibre amplifiers have excellent gain and noise characteristics which make them attractive as wideband optical repeaters.

Conclusions

Application of optical fibres are diversifying rapidly from their original base in telecommunications. This trend is expected to increase as more fibres designed specifically for sensor and device application becomes available. This is already apparent from the widespread adoption of highly-birefringent fibres in fibre sensors. Future developments are likely to be equally important.

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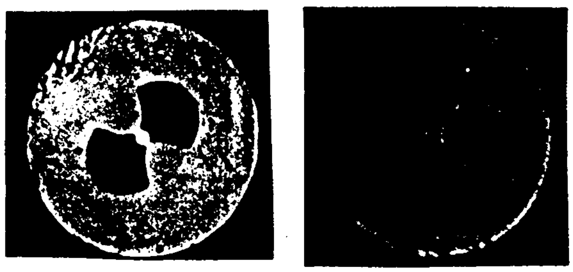

a. b.

Figure 1 "Bow-Tie" (a) and PANDA (b) polarisation-maintaining fibres.

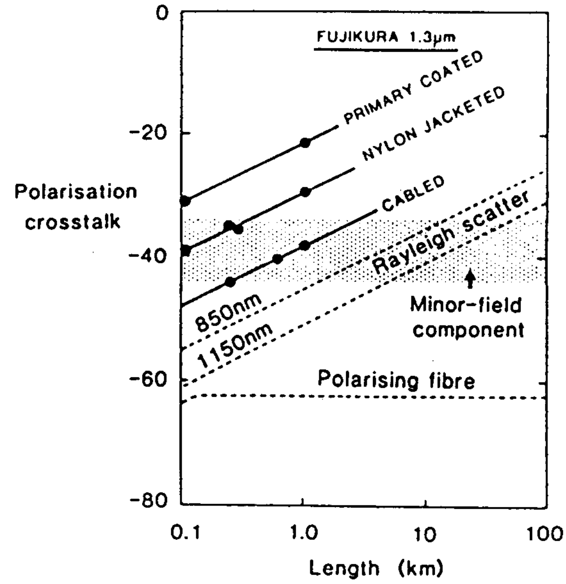

Figure 2 Fundamental limits to polarisation holding in highly-birefringent optical fibres.

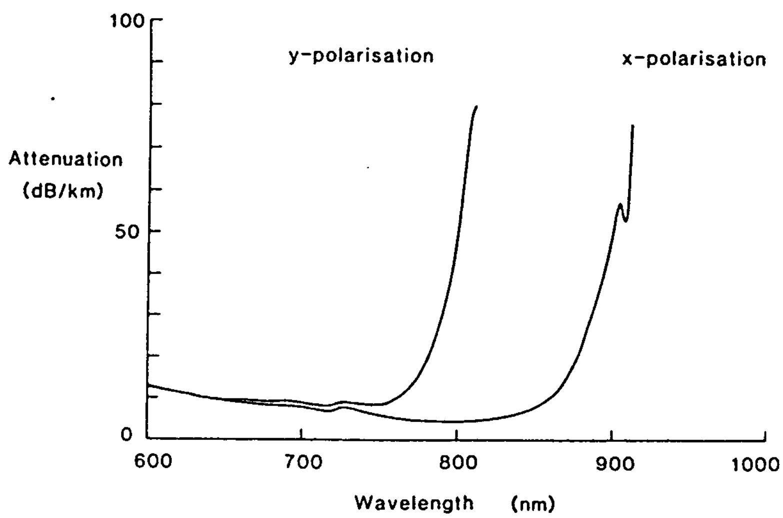

Figure 3 Wavelength response of polarising fibre.

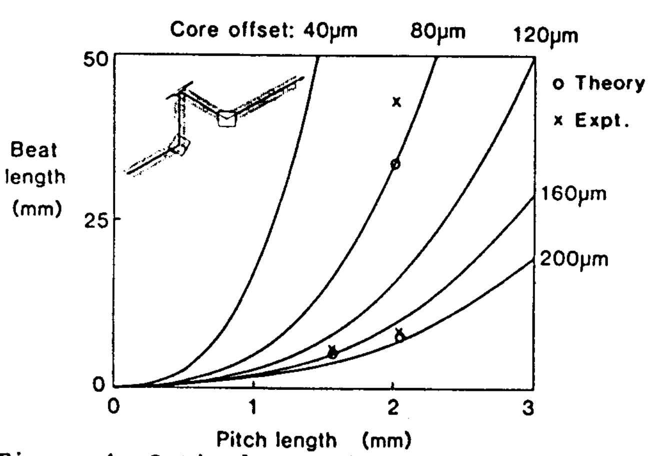

Figure 4 Optical rotation lengths obtained in circularly-birefringent helical-core fibres. Inset shows rotation of light following an isotropic helical path, as in these fibres.

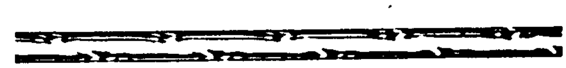

Figure 5 Helical-core circularly-birefringent fibre

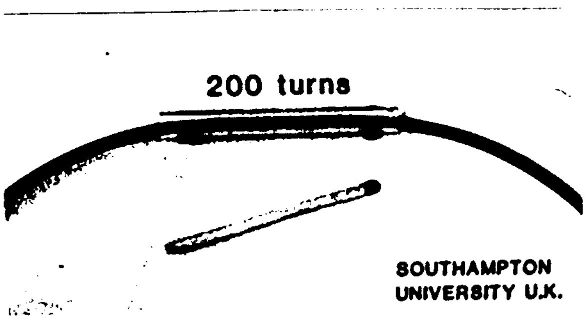

Figure 6 Typical current sensor coil fabricated from spun Bow-Tie fibre.

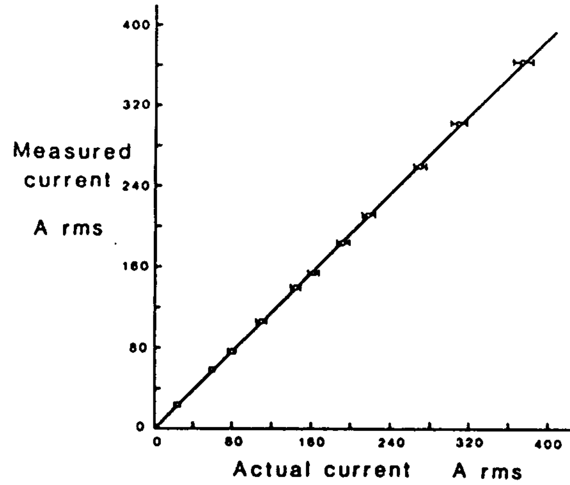

Figure 7 Response of coil in Figure 6.

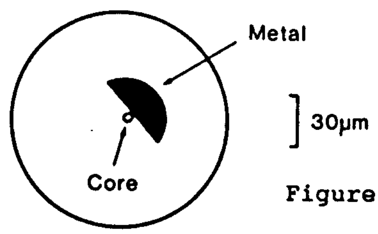

Figure 8 Schematic of composite metal/glass polariser

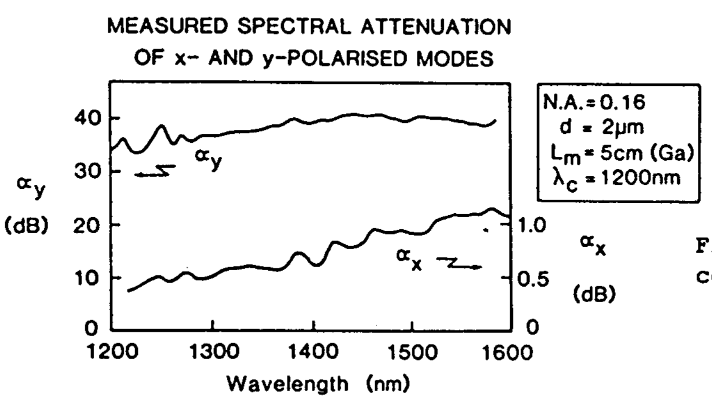

Figure 9 Extinction ratio of composite metal/glass polariser

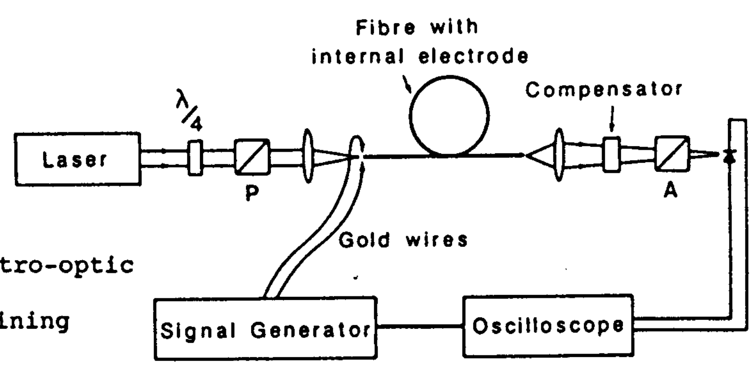

Figure 10 Schematic of electro-optic Kerr-effect fibre modulator constructed from fibre containing two metal-filled sectors.

POOLE

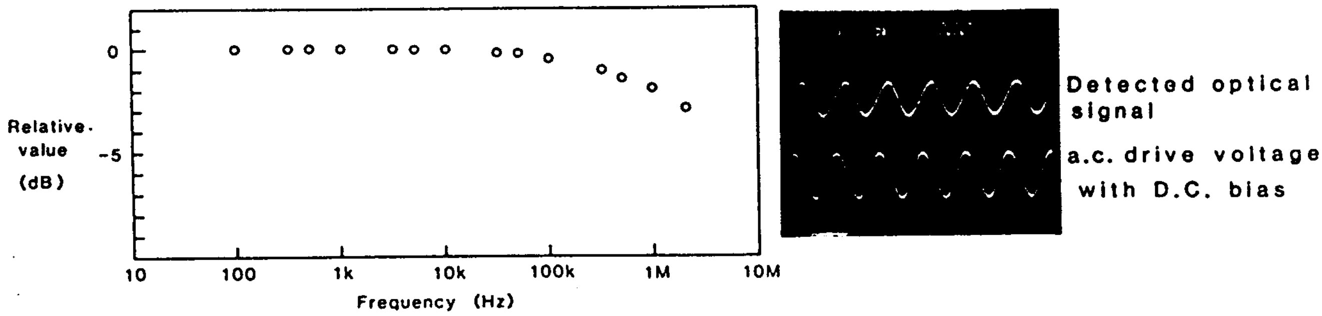

Figure 11 Frequency response of all-fibre Kerr modulator. Inset shows typical response waveforms when operated with a dc bias voltage

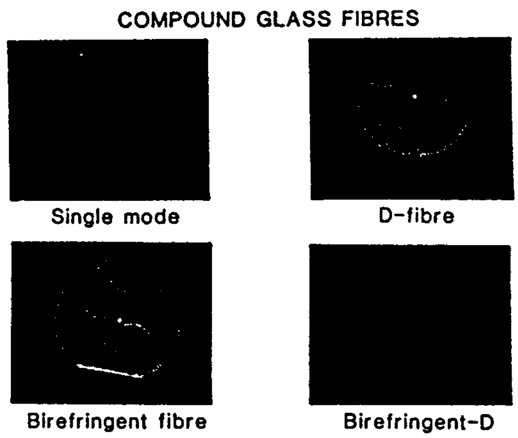

Figure 12 Examples of "soft-glass" monomode fibres produced at Southampton University.

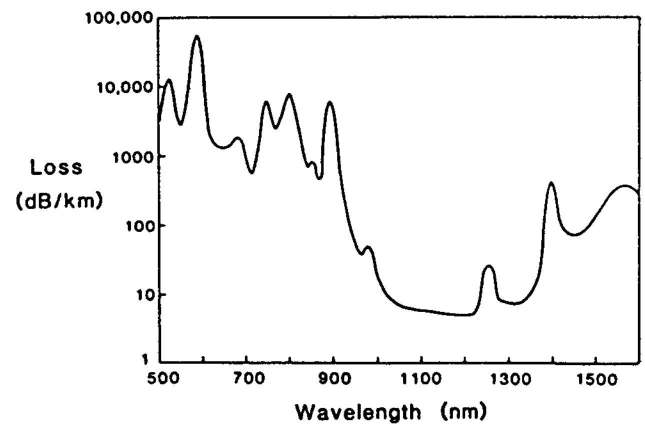

Figure 13 Absorption spectrum of fibre doped with 300ppm Nd^{3+} ions

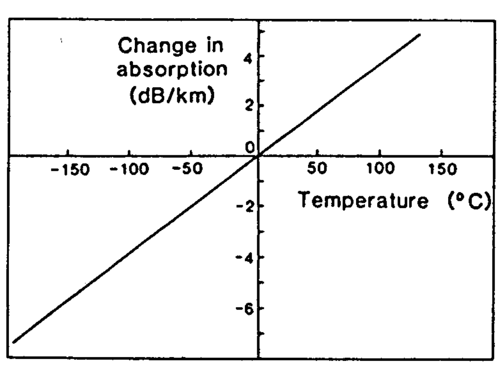

Figure 14 Temperature dependence of absorption of Nd^{3+}-doped fibre at 600nm.

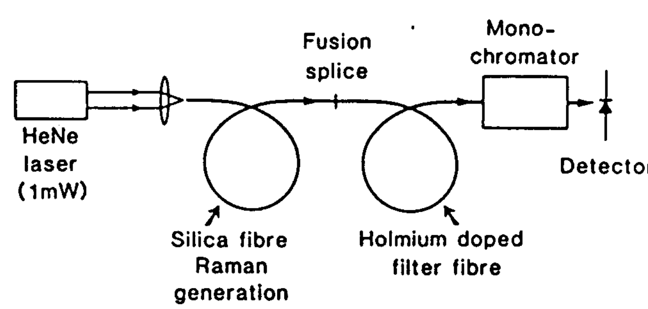

Figure 15 Experimental configuration for fibre filter. Doped fibre length was 7m.

POOLE

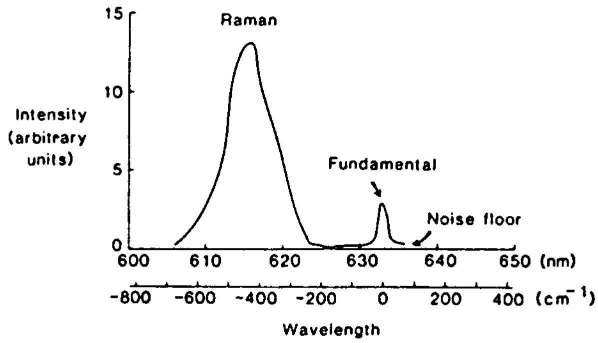

Figure 16 Transmission of fibre filter showing pump rejection and Raman transmission.

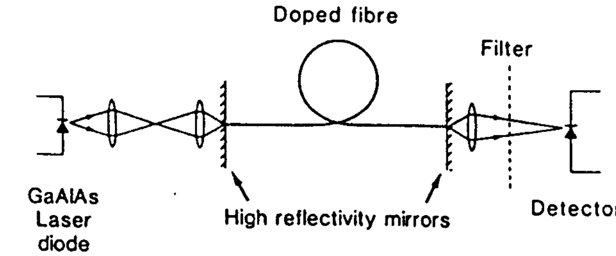

Figure 17 Fabry-Perot configuration for diode-pumped fibre laser

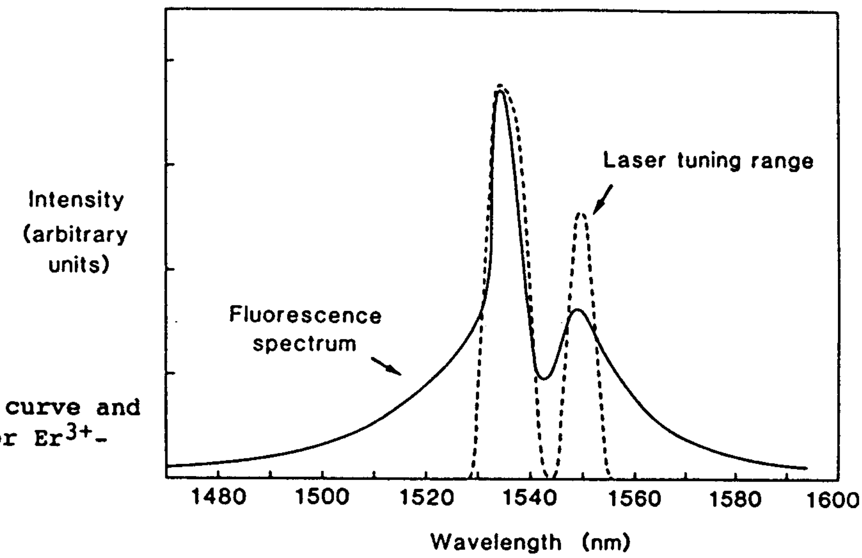

Figure 18 Laser tuning curve and fluorescence spectrum for Er^{3+}-doped fibre laser.

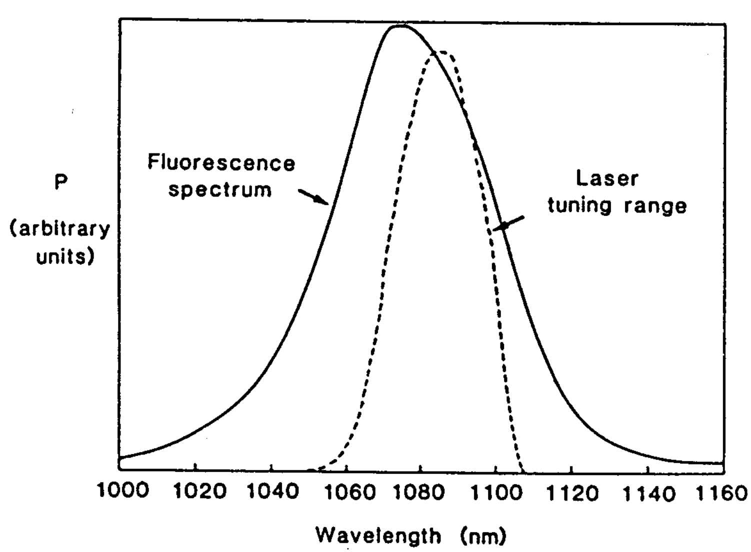

Figure 19 Laser tuning curve and fluorescence spectrum for Pr^{3+}-doped fibre laser.

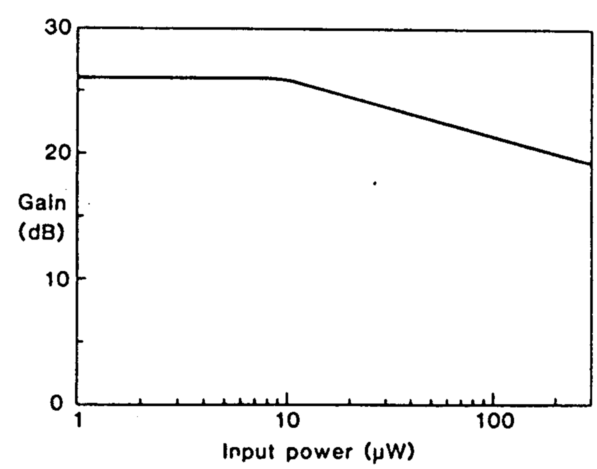

Figure 20 Gain characteristic of Er^{3+}-doped fibre amplifier operating at 1550nm with a modulation rate of 140MHz.

Poole