354

APPLICATIONS AND TECHNOLOGY OF SPECIAL OPTICAL FIBRES

D.N. Payne and S.B. Poole

University of Southampton Southampton Hampshire United Kingdom

INTRODUCTION

Telecommunications transmission using optical fibres can now be regarded as a mature technology. As a result, optical fibres are freely available at relatively low cost and this has led to an increasing interest in their use of fibres for other applications such as sensing, signal-processing and various fibre devices. There is also much interest in fibre-based switching using non-linear optical effects.

However, whilst the great majority of experimental and commercial applications currently employ telecommunications-grade fibres, this policy frequently leads to a design compromise, and in some cases makes the performance marginal or even untenable, owing to excessive environmental sensitivity. Consequently, attention is now being given to the design of sensor fibres with enhanced (or depressed) sensitivity to suit the particular application.

There are few special fibres currently commercially available. Perhaps the best known is the highly-birefringent fibre[1] both in polarisation-maintaining[2] and polarising[3] form. Such fibres are extensively employed for polarisation control in fibre gyroscopes and other sensors, and are also under investigation for use in coherent communications systems[4] and in non-linear switching. The pace of development is increasing, however, and a large number of other fibre designs tailored to specific applications have been reported. For example, the unusual propagation properties of circularly-birefringent fibres[5,6] make them very suitable 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 suitable dopants to enhance a given effect. Thus, the acousto-optic, magneto-optic, non-linear and electro-optic coefficients, which are small in pure silica, can be increased by adding various transition and rare-earth ions[9]. Several laboratories[10] are studying such effects. 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, infrared (Eg chalcogenide) glasses or even polymers. The increase in loss which may result from the use of alternative glasses is not normally a problem, since several orders of magnitude improvement in device sensitivity is attainable and only a few metres of fibre are usually required.

Perhaps the most exciting recent development has been the demonstration of lasing action at wavelengths of 0.652, 1.06, 1.08 and 1.536μm in single-mode fibres, by doping with Sm^{3+}, Pr^{3+}, Nd^{3+} and Er^{3+}, respectively[11,12,13,14]. The losses at the lasing wavelength in these fibres is so low that it has been possible to construct lasers up to 1400m 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 finesses of up to 300. Consequently, a sensitivity enhancement of the same order to acoustic radiation, for example, should be possible. In addition, the availability of low-loss rare-earth-doped fibres having controlled absorption and fluorescence characteristics provides further opportunities for distributed sensing by monitoring the variation of these parameters with temperature[15].

It is clear that fibre fabrication technology is now able to offer a number of attractive solutions to the unique problems presented by alternative fibre applications. A wide range of possibilities are available, including modified telecommunications fibres which are bend resistant, metal[16] and special polymer-coated[17] fibres, fibres with liquid cores[18] or claddings[19], spun low[20] and high[21] birefringence fibres and twin-core fibres[22].

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 outlined.

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 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[23], the power transfer per metre of fibre length. The best fibre measured to date[24] has a power transfer (h-parameter) of 1.6 x 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. Quoted figures for the h-parameter should be treated with caution as they are as much indicative of the fibre winding and packaging as they are of the intrinsic fibre properties.

Hi-bi fibres are useful whenever polarisation colinearity is required between two interfering beams, as for example in interferometric sensors, the fibre gyro or in heterodyne coherent detection. 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 2) 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.

COMPOSITE GLASS/METAL FIBRE POLARISERS

An alternative to the coiled fibre polariser described above is provided by the glass/metal fibre polariser[7] shown in Figure 3. 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.

The extinction ratio η and insertion loss α_x for a typical glass/metal polariser are plotted in Figure 4 as a function of fibre length. It can be seen that for lengths less than about 7cm, insertion loss remains below 1dB while the extinction ratio approaches 50dB, this being the limit of the measurement equipment. Subsequent measurements have shown extinction ratios exceeding 60dB over a wide spectral range. Calculations show that for the metal used (indium/gallium alloy), the ratio of extinction ratio to insertion loss should be about 100, which is indeed the case for the section of Figure 3 in which no measurement saturation occurred. This suggests that in applications such as the fibre gyro where an insertion loss of a few dB is tolerable, extremely high extinction ratios are possible by using sufficient metal length.

The metal section is introduced into the fibre either directly during fibre drawing or subsequently by pumping a liquid metal into the fibre.

KERR MODULATOR FIBRES

The ability to introduce metal-fitted sectors into a fibre has lead to the Kerr-effect phase modulator fibre[8] shown schematically in Figure 5. 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 fibres and the extremely high fields allows the construction of efficient phase modulators.

A typical frequency-response curve is shown in Figure 6. 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).

The availability of fibres containing integral metal electrodes has led to some exciting prospects for non-linear optical effects. It has been found possible to apply fields as high as 300V per micron across the core of the fibre shown in Figure 5. This extraordinarily high field (300MV/m) allows second-harmonic-generation to occur in the fibre by a mixing process between the optical and the d.c. field. In addition, a permanently-poled second-order non-linearity is found in the fibre after the voltage is removed. These effects indicate good prospects for fibre modulators, parametric oscillators and numerous other devices normally associated with the properties of crystals.

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 application as the sensing fibre in electric-current monitors[25] 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.

Optical fibre current sensors have several attractive advantages. They are compact, light weight and being electrically insulating, do not require the heavy ceramic insulation normally associated with high-voltage current sensors. They are also potentially highly sensitive provided the circular birefringence can be made sufficiently large to enable small multi-turn coils to be wound without destroying the circular polarisation properties of the fibre.

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 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 relatively immune 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[27]. These fibres have achieved optical rotation lengths $L_R = 2\pi/\alpha$ as low as 6mm, a figure which is an order of magnitude better than ever previously reported.

Helical-core fibres are fabricated from composite eccentric 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 7 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

Although helical-core circularly-birefringent fibres are well suited to current sensors, they are large in diameter (400μm) and cannot therefore be wound in small coils. An alternative solution to producing a circularly-birefringent fibre with a more suitable diameter is the spun hi-bi technique[6].

If a highly-birefringent bow-tie fibre is rapidly spun during the draw, the polarisation eigen modes become elliptically polarised and, provided the spin pitch is sufficiently large, the eigen modes are quasi circularly-polarised. The fibre can be regarded as possessing some of the polarisation-holding properties of the precursor linearly-birefringent fibre, together with the magnetic-field sensing capability of a circularly-birefringent fibre. However, since these two attributes are mutually exclusive, a compromise must be made. Spinning the fibre too rapidly results in a decrease in birefringence and therefore reduces the polarisation holding properties. Insufficient spin results in a fibre which lacks sensitivity to magnetic fields. This is clearly shown in Figure 8 where both the elliptical birefringence and the current sensitivity are plotted as functions of the ratio of the spin pitch to the unspun fibre beat-length, i.e. the beat-length that would be observed if the fibre had not been spun. From the Figure it can be seen that a suitable compromise is to make the spin pitch equal to the unspun beat length, at which point the current sensitivity is about 80% of that of a perfect circularly-birefringent fibre, while the beat-length is increased only by a factor of 4. Thus a typical Bow-Tie fibre having a 1mm beat length will exhibit an elliptical birefringence beat length of 4mm after spinning and this has been found sufficient to allow coils as small as 5mm in diameter to be wound[28] without reducing the current sensitivity, as shown in Figure 9.

The performance of these fibres in current sensing applications has been investigated[28] and a typical sensor coil containing 80 turns of fibre is shown in Figure 10. The response of this coil in a current-sensor configuration is shown in Figure 11. In addition, a sensitivity of 1mArms/$\text{Hz}^{0.5}$ was obtained and a temperature drift of 0.05%/°C. By increasing the number of turns, and optimising the optical configuration, a sensitivity of a few microamps should be obtainable.

MULTI-COMPONENT GLASS FIBRES

Fibres fabricated from multi-component 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 compund 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 is 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. In addition, the fibres can be highly dispersive and possess very large numerical apertures.

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[29].

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[9,10,30,31] which do 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, Sm 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[32]. 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 the absorption bands of a Ho^{3+}-doped fibre is shown in Figure 13. Although the fibre contains a low concentration of Ho^{3+} (1000 ppm), a linear change in absorption of 0.5dB/km°C was found over the temperature range investigated. With this fibre, temperature distribution along the fibre could be determined with 1°C accuracy and a spatial resolution of 3.5m over the temperature range -200°C to +100°C.

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, it is possible to achieve very-low thresholds and high gains. Since the typical fibre diameter is 125μm, thermal effects which plague bulk-glass lasers are greatly reduced. 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, telecommunications 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 (1400m has been demonstrated) amplifiers and lasers, as well as non-linear devices and distributed active sensors.

A typical fibre laser Fabry-Perot configuration is shown in Figure 14, together with some of the ions and transitions which have exhibited laser action. The fluorescence spectra of some common rare-earth dopants are shown in Figure 15. The well-known neodymium ion shows fluorescence at 940nm, 1088nm and 1300nm. Erbium exhibits fluorescence conveniently at 1540nm, while holmium (which has not yet lased in fibre) shows potential for a source in the 2μm region. The latter two rare-earths show particular promise as fibre amplifiers and sources for use in the third and fourth telecommunications windows.

Neodymium Fibre Lasers

The absorption spectrum of of a single-mode fibre doped with 30 ppm neodymium ions is shown in Figure 16. The loss at the lasing wavelength of 1.08μm is particularly low, while convenient pump bands exist around 800nm, the semiconductor laser diode wavelength.

In an optimised cavity and using a laser-diode pump injected longitudinally, 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[34] and a tuning range of 85nm (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.

Despite being a three-level laser system, neodymium-doped fibres have also exhibited laser action at 942nm when diode pumped. Several milliwatts of output power were obtained.

Q-switching of fibre lasers with an acousto-optic modulator or rotating chopper is also possible and peak powers in excess of 100 watts from a diode-pumped neodymium-fibre laser have been obtained. This is a particularly significant development, since at these power levels many non-linear optical effects become accessible. Thus the fibre laser provides a convenient and highly practical source for non-linear optical fibre devices such as switches and gates.

Erbium-Doped Fibre Lasers

Erbium-doped fibre lasers operate between 1530nm and 1555nm, i.e. within the important minimum-loss window for optical communications. The absorption spectrum is shown in Figure 17 and the fluorescence spectrum, with a typical tuning curve for an Er^{3+}-doped fibre laser superimposed on it, is shown in Figure 18. The transition is between the $^4I_{13/2}$ and $^4I_{15/2}$ (ground-state) levels and, despite being a three-level laser system, the Er^{3+}-doped fibre laser operates continuously[35] and has a threshold of only 1.6mW [36]. At the time of writing this represented the lowest threshold three-level glass laser ever reported. The recent demonstration of a diode-pumped Er^{3+} fibre laser[37] will lead to many practical applications of this device. Optical bistability has also been observed in an Er^{3+}-doped fibre laser operating at 1.54μm [38]. The mechanism is one of saturable absorption and has many potential applications including optical memories, switching and amplification.

Neodymium and erbium represent the two rare earths on which which current research is based. However, the low threshold capability and lack of thermal effects make fibre lasers an ideal medium in which to obtain lasing action from more unusual rare-earth dopants and it is highly probably that a number of new laser systems will emerge which have no bulk counterparts. Examples of the first two of these are the samarium laser operating at 652nm[11] and the praeseodymium laser at 1.06μm[12].

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. By this means single frequency operation with a linewidth of only 1MHz has been reported[40]. In addition, a number of novel resonant configurations are possible which obviate the need for dielectric mirrors[41,42]. Thus the way is open to the creation of 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 a 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 or power amplifiers 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 amplifier (shown schematically in Figure 19) is optically pumped, and a number of different pump sources, including Ar^{+} and dye lasers are available. With a dye-laser pump operating at 665nm, a maximum gain of 32dB has been obtained at modulation rates up to 400Mhz [44]. The input equivalent noise power was measured at -45dBm in a 140MHz bandwidth which compares favourably with state-of-the-art APD detectors at 1.54μm. A maximum output power of +13dBm has been achieved before the onset of saturation. These preliminary results show that Er^{3+}-doped fibre amplifiers have excellent gain and noise characteristics which make them attractive as wideband optical amplifiers and repeaters for multi-channel optical systems.

CONCLUSIONS

Applications 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 applications become available. It is clear from the examples given in this paper that there are considerable benefits to be gained by designing fibres specifically with a given application in mind. It is expected that the future will bring widespread adoption of so-called "designer" fibres in numerous telecommunications and non-telecommunications applications.

REFERENCES

1. Dyott, R.B., Cozens, J.R., Morris, D.G.: "Preservation of polarisation in optical fibre waveguides with elliptical cores", Electron. Lett., Vol. 15, pp. 380-382, 1979.
2. Birch, R.D., Payne, D.N., Varnham, M.P.: "Fabrication of polarisation-maintaining fibres using gas-phase etching", Electron. Lett., Vol. 18, pp. 1036-1038, 1982.
3. Varnham, M.P., Payne, D.N., Birch, R.D., Tarbox, E.J.: "Single-polarisation operation of highly-birefringent Bow-Tie optical fibres", Electron. Lett., Vol. 19, pp. 246-247, 1983.
4. Smith, D.W., Harmon, R.A., Hodgkinson, T.G.: "Polarisation stability requirements for coherent optical fibre trans- mission systems", British Telecom Tech. J., Vol. 1, 1983.
5. Varnham, M.P., Birch, R.D., Payne D.N.: "Helical-core circularly-birefringent fibres", Proc. IOOC/ECOC., pp. 135-138, 1985.
6. Li, L., Qian, J.-R., Payne, D.N.: "Current sensors using highly-birefringent Bow-Tie fibres", Electron. Lett., Vol. 22, pp. 129-130, 1986.
7. Li. L., Wylangowski, G., Payne, D.N., Birch, R.D.: "Broadband metal/glass single- mode fibre polarisers", Electron. Lett., Vol. 22, pp. 1020-1022, 1986.
8. Li. L., Birch, R.D., Payne, D.N.: "An all fibre electro-optic Kerr modulator", Proc. IEE Colloquium on "Advanced Fibre Waveguide Devices, London, May 1986.
9. Poole, S.B., Payne, D.N., Fermann, M.E.: "Fabrication of low-loss optical fibres containing rare-earth ions", Electron. Lett., Vol. 21, pp. 737-738, 1985.
10. Millar, C.A., Ainslie, B.J., Miller, I.D., Craig, S.P.: "Concentration and co-doping dependence of the $^4F_{3/2}$ to $^4I_{11/2}$ lasing behaviour of Nd^{3+} silica fibres", Proc. IOOC/OFC., Reno, Nevada, 1987, Paper WI4.
11. Farries, M.C., Morkel, P.R., Townsend, J.E.: "A samarium doped visible glass laser operating at 651nm", Proc. CLEO, Anaheim, California, Paper PD5, April 1988.
12. Reekie, L., Mears, R.J., Poole, S.B., Payne, D.N.: "A Pr^{3+}-doped single-mode fibre laser", IOP/IEE Symposium on "Advances in Solid State Lasers", London, 1986.
13. Mears, R.J., Reekie, L., Poole, S., Payne, D.N.: "Neodymium-doped silica single-mode fibre lasers", Electron. Lett., Vol. 21, pp. 738-740, 1985.
14. Mears, R.J., Reekie, L., Poole, S.B., Payne, D.N.: "Low threshold tunable CW and Q-switched fibre lasers operating at 1.55μm", Electron. Lett., Vol. 22, pp. 159-160, 1986.
15. Farries, M.C., Fermann, M.E., Laming, R.I., Poole, S.B., Payne, D.N., Leach, A.P.: "Distributed temperature sensor using Nd^{3+}-doped fibre", Electron. Lett., Vol. 22, pp. 418-419, 1986.
16. Dandridge, A., Tveten, A.B., Sigel, G.H., West, E.J., Giallorenzi, T.G.: "Optical fibre magnetic field sensors", Electron. Lett., Vol. 16, pp. 408-409, 1980.
17. Koo, K.P., Sigel, G.H.: "An electric field sensor utilising a piezo electric polyvinylidene fluoride (PVF2) film in a single-mode interferometer", IEEE J. Quantum Electron., Vol. QE-18, p. 670, 1982.
18. Hartog, A.H.: "A distributed temperature sensor based on liquid-core optical fibres", J. Lightwave Tech., Vol. LT-1, pp. 498-509, 1983.
19. Scheggi, A.M., Brenchi, M., Conforti, C., Falciai, R., Preti, G.P.: "Optical fiber thermometer for medical use", 1st Int. Conf. on Optical Fibre Sensors, London, 1983.
20. Barlow, A.J., Payne, D.N., Hadley, M.R., Mansfield, R.J.: "Production of single- mode fibres with negligible intrinsic birefringence and polarisation mode dispersion", Electron. Lett., Vol. 17, pp. 725-726, 1981.
21. Qian, J.-R., Li, L.: "Current sensors using highly birefringent Bow-Tie fibres" Proc. OFS, Tokyo, pp. 85-88, 1986.
22. Snitzer, E., et al.: In "Fibre optic rotation sensors", Springer Verlag, p. 406, 1982.
23. Rashleigh, S.C.: "Origins of polarisation in single-mode fibres", J. Lightwave Tech., Vol. LT-1, pp. 312-331, 1983.
24. Suganuma, H., Yokota, H., Myogadani, T.,: "Characteristics of low-loss low-crosstalk polarisation-maintaining fibres", Proc. OFC., Atlanta, p. 36, 1985.
25. Smith, A.M.: "Polarisation and magneto-optic properties of single-mode optical fibre", Appl. Opt., Vol. 17, p. 52, 1978.
26. Ulrich, R., Simon, A.: "Polarisation optics of twisted single-mode fibres", Appl. Opt., Vol. 18, p. 2241, 1979.
27. Birch, R.D.: "Fabrication and characterisation of circularly-birefringent helical fibres", Electron. Lett., Vol. 23, pp. 50-52, 1987.
28. Laming, R.I., Payne, D.N., Li, L.: "Sensitive miniature optical fibre current monitor with active temperature stabilisation", Fourth Int. Symp. on Optical and Optoelectronic Science, The Hague, March 1987.
29. Sudo, S., Hosaka, T., Itoh, H., Okamoto, K.: "High-ΔN small-core single-mode fibres for efficient non-linear optical effects", Electron. Lett., Vol. 22, pp. 833-835, 1986.
30. Poole, S.B., Payne, D.N., Mears, R.J., Fermann, M.E., Laming, R.I.: "Fabrication and characterisation of low-loss optical fibres

containing rare-earth ions", J. Lightwave Tech., Vol. LT-4, pp. 870-876, 1986.

31. Townsend, J.E., Poole, S.B., Payne, D.N.: "Solution-doping technique for the fabrication of rare-earth-doped optical fibres", Electron. Lett., Vol. 23, pp. 329-331, 1987.
32. Snitzer, E., Morey, W.W., Glenn, W.H.: "Fiber optic rare-earth temperature sensors", 1st Int. Conf. on Optical Fibre Sensors, London, pp. 79-81, 1983.
33. Farries, M.C., Fermann, M.E., Poole, S.B., Townsend, J.E.: "Distributed temperature sensor using Holmium-doped optical fibre", Proc. OFC., Reno, Paper WI5, 1987.
34. Reekie, L., Mears, R.J., Poole, S.B., Payne, D.N.: "Tunable single-mode fibre lasers", J. Lightwave Tech., Vol. LT-4, pp. 956-960, 1986.
35. Mears, R.J., Reekie, L., Poole, S.B., Payne, D.N.: "Low threshold tunable CW and Q-switched fibre lasers operating at 1.55μm", Electron. Lett., Vol. 22, pp. 159-160, 1986.
36. Jauncey, I.M., Reekie, L., Poole, S.B., Payne, D.N.: "Extended wavelength operation of an Er^{3+}-doped fibre laser pumped at 808nm", Proc. OFC 88, New Orleans, January 1988.
37. Reekie, L., Jauncey, I.M., Poole, S.B., Payne, D.N.: "Diode laser pumped operation of an Er^{3+}-doped single-mode fibre laser", Electron. Lett., Vol. 23, pp. 1076-1078, 1987.
38. Reekie, L., Mears, R.J., Poole, S.B., Payne, D.N.: "Optical bistability at 1.54μm in an Er3-doped fibre laser", Proc. CLEO., San Francisco, 1986.
39. Lin, J.T., Reekie, L., Li, L.: "Single polarisation operation of a Nd3-doped single-mode fibre laser", Proc. CLEO., Baltimore, 1987.
40. Jauncey, I.M., Reekie, L., Mears, R.J., Payne, D.N., Rowe, C.J., Read, D.C.J., Bennion, I., Edge, C.: "Narrow-linewidth fibre laser with integral fibre grating", Electron. Lett., Vol. 22, pp. 987-988, 1986.
41. Payne, D.N.: "Special fibres and their applications", Invited Paper at IOOC/OFC., Reno, Paper WI1, 1987.
42. Miller, I.D., Mortimore, D.B., Ainslie, B.J., Urqhart, W.P., Craig, S.P., Millar, C.A., Payne, D.B.: "A new type of all-fibre laser", Proc. OFC., Reno, Paper WI3, 1987.
43. O'Mahoney, M.J., Marshall, I.W., Devlin, W.J., Regnault, J.C.: "Low-reflectivity semiconductor laser amplifier with 20dB fibre to fibre gain at 1500nm", Electron. Lett., Vol. 21, pp. 501-502, 1985.
44. Mears, R.J., Reekie, L., Jauncey, I.M., Payne, D.N.: "High-gain rare-earth-doped fibre amplifier at 1.54μm", Proc. OFC., Reno, Paper WI2, 1987.

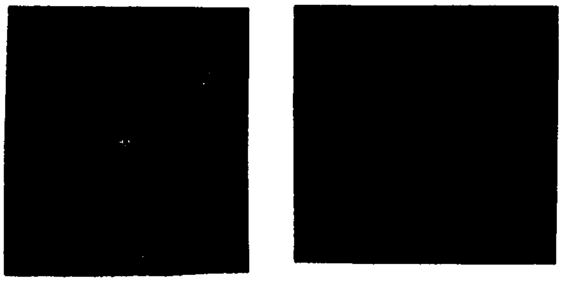

Fig. 1 (a) Bow Tie and (b) PANDA polarisation-preserving fibres.

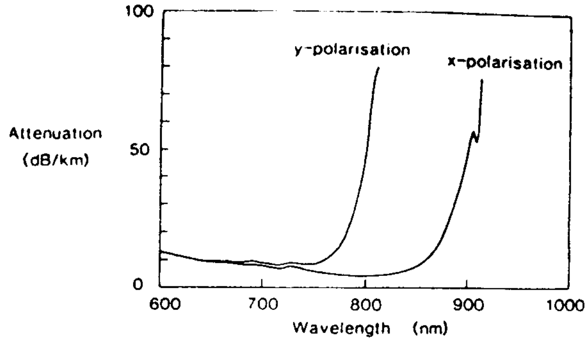

Fig. 2 Spectral attenuation plot of polarising fibre showing differential loss for two polarised modes.

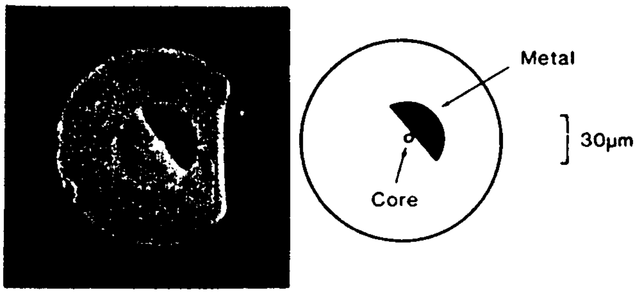

Fig. 3 Cross-section of composite glass/metal polarising fibre.

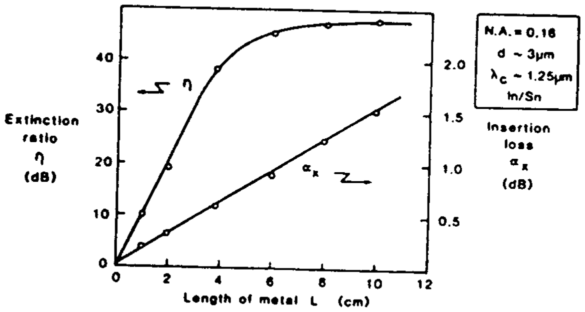

Fig. 4 Extinction ratio and insertion loss shown as a function of length for glass/metal polarising fibre.

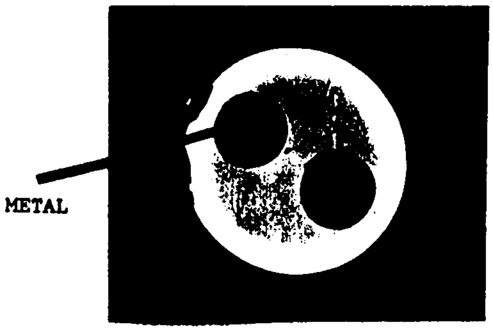

Fig. 5 Kerr modulator fibre containing two metal electrodes adjacent to the core.

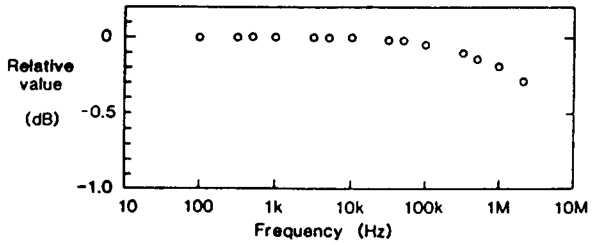

Fig. 6 Frequency response of glass/metal fibre Kerr modulator.

Fig. 7 Helical-core circularly-birefringent fibre for current sensors.

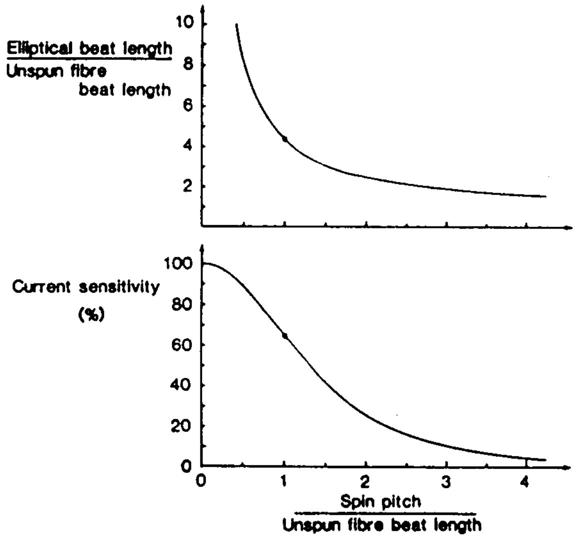

Fig. 8 Elliptical birefringence beat length and relative electrical current sensitivity as a function of spin pitch for a spun hi-bi fibre. Both beat length and spin pitch are normalised to the unspun precursor fibre beat length, typically 1mm for a Bow-Tie fibre.

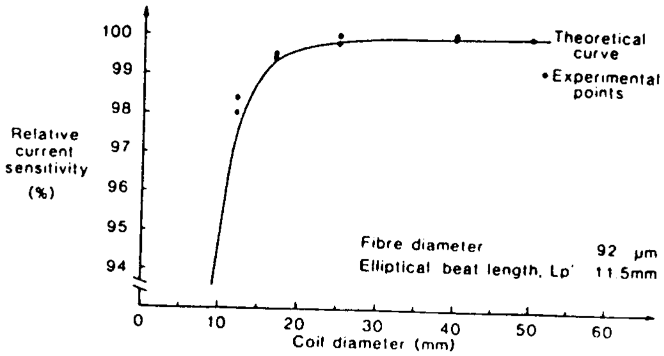

Fig. 9 Electrical-current sensitivity of a spun hi-bi fibre for various coil diameters.

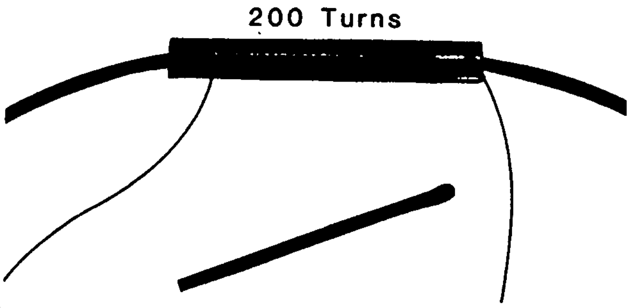

Fig. 10 Current-sensor coil composed of 200 turns of spun hi-bi fibre wound on 12mm diameter coil former.

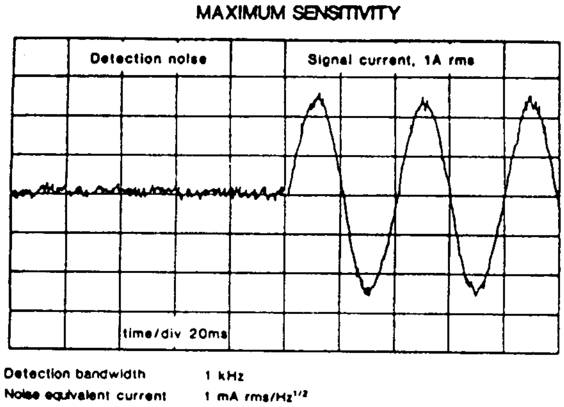

Fig. 11 Response of coil shown in Fig. 10 to 25Hz 1Amp current signal.

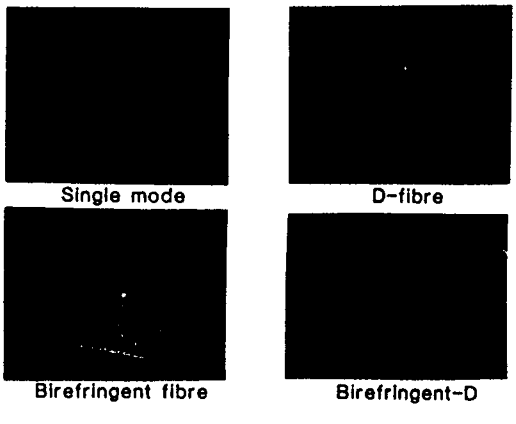
Single mode
D-fibre
Birefringent fibre
Birefringent-D

Fig. 12 Compound glass fibre cross-sections.

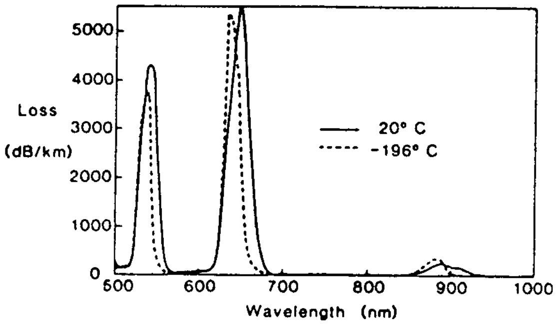

Fig. 13 Loss spectrum of holmium-doped fibre showing variations in absorption bands with temperature.

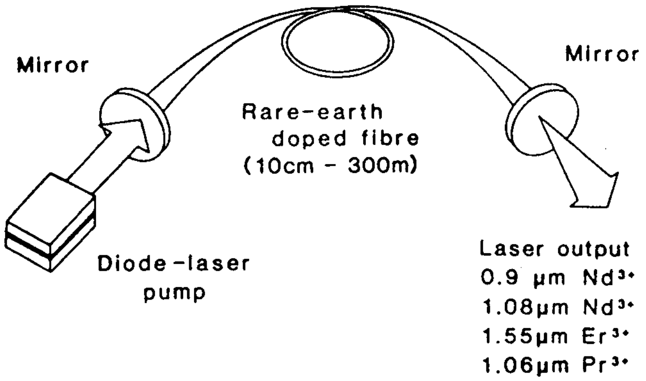

Fig. 14 Typical fibre laser Fabry-Perot configuration. The fibre length depends on dopant concentration.

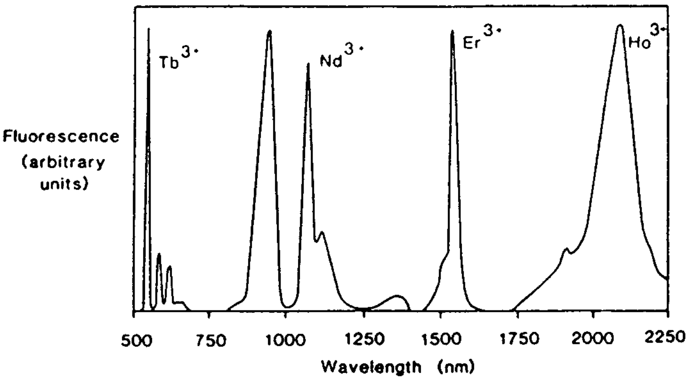

Fig. 15 Fluorescence spectra of some rare-earth ions in optical fibres.

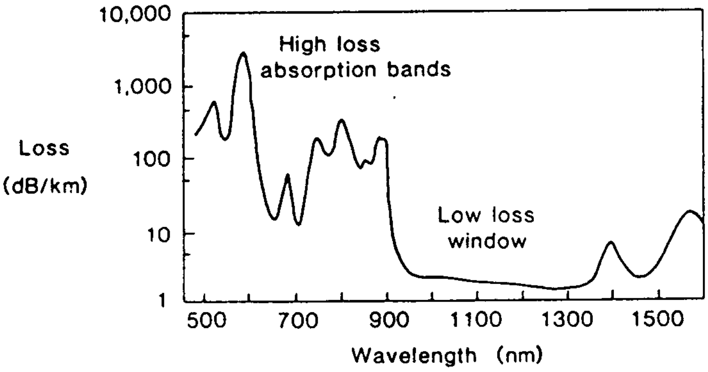

Fig. 16 Absorption spectrum of fibre containing 30ppm Nd^{3+} ions.

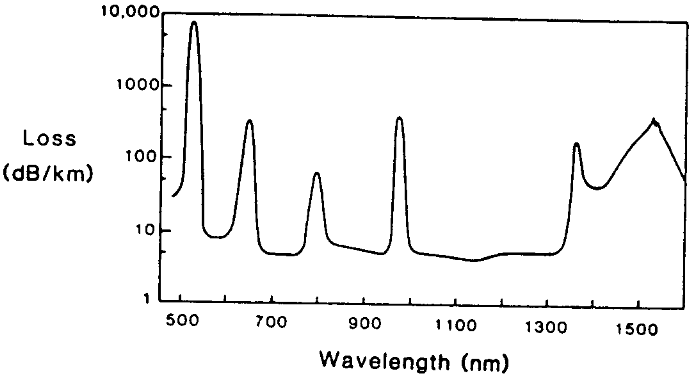

Fig. 17 Absorption spectrum of fibres containing Er^{3+} ions.

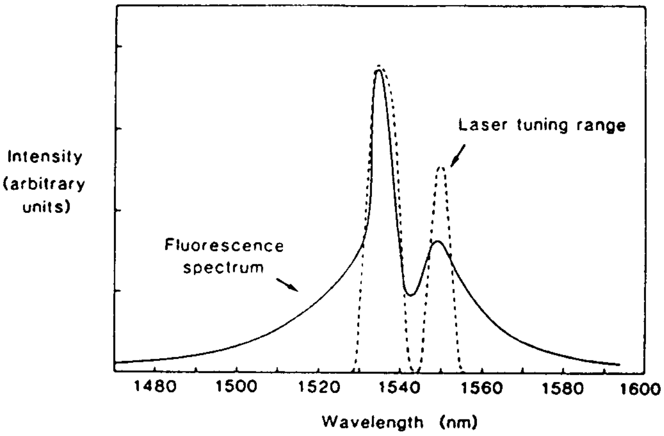

Fig. 18 Fluorescence spectrum and laser tuning range for fibre doped with Er^{3+} ions.

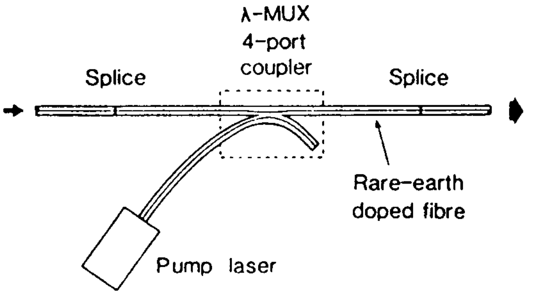

Fig. 19 In-line fibre amplifier based on Er^{3+}-doped fibre.