FIBRES FOR SENSORS

D.N. Payne

Department of Electronics, The University, Southampton, UK.

Introduction

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. Despite this, little attention has been given to the design of special sensor fibres with enhanced (or depressed) sensitivity to specific measurands. The position is somewhat better with respect to fibres designed to eliminate sensor polarisation problems (e.g. polarisation-maintaining fibres), but even here further work is required to provide the performance demanded.

The purpose of this paper is to review the fibres which have emerged for use in optical sensors and to indicate possible future developments. The constraints on sensor performance imposed by the use of telecommunications fibre will be indicated, and an idea of the improvements attainable by the design of special fibre structures, or the use of different materials, will be given.

Sensor Fibres

Modified telecommunications fibres: Perhaps the most obvious sensor fibre, and one which is classified as such by several manufacturers, is that in which the fibre parameters have been adjusted to suit it for sensor service. Thus fibres with a high core index-difference Δ can be bent tightly or coiled into a small volume without sustaining large losses; fibres with a small diameter (80μm) are used to obtain a greater number of turns in a given space[1] or to reduce the bend-induced birefringence; single-mode fibres with acceptable loss can be supplied for operation at 400nm

It is perhaps not generally realised that conventional fibre technology can be extended to yield fibres which may at first sight appear outrageous, particularly if relatively short lengths (100m) are required. In this case, loss is not a problem and compound glasses can be used. For example, fibres with a diameter of 20μm which can be wound into a coil of a few mm radius are possible. Conversely, very large diameter fibres (1mm) with a single-mode spot size of 30-40μm could be employed in applications where well-controlled gentle bends prevail, as in the fibre ring-resonator. Fibres with very accurately specified bending-birefringence have already been made[2]. Finally, very high optical power densities to exploit non-linear optical effects are attainable in high Δ, small core, single-mode fibres.

Coated Fibres: Interferometric fibre sensors rely for their operation on the change in optical path length produced by the measurand. The fibre optical length is invariably modified mechanically, either directly by application of a force or acoustic wave, or indirectly by the application of a piezo-electric[3] or magneto-strictive coating[4]. The path change is detected interferometrically, usually in a Mach-Zender configuration, to give a strain, acoustic, electric- or magnetic-field sensor respectively. Fibre coatings can also be used, for example, to provide insensitivity to acoustic fields in the reference arm of an interferometer[5].

Further uses of fibre coatings require the coating material to have an optical function, as for example in the fibre PH monitor[6]. Here absorption changes in a chemically-sensitive polymeric optical cladding are detected through the cladding penetration of the core evanescent field.

Fibre coating technology is well advanced in the telecommunications field and the development of coatings specific to sensor applications deserves more attention. It is expected that a wide range of new fibre coatings will emerge in the future.

Liquid-Core Fibres: An important class of intrinsic fibre sensors is that in which the measurand affects the optical properties of the fibre core or cladding, for example their absorption, scatter or refractive index. These changes can be detected by backscatter measurements to give a truly distributed sensor, sensitive along the entire fibre length.

Although the optical properties of glasses vary with temperature and pressure, liquids vary much more rapidly and are therefore more attractive candidate fibre materials. A composite fibre with a glass cladding and liquid core has been used successfully as a distributed temperature sensor with a 0-200°C range[7]. The fibre is shown in Fig. 1. The sensor exploits the change in Rayleigh scattering with temperature within the liquid which forms the core. Another version[8] utilises the relatively large reduction in refractive index of the liquid core with rising temperature. At a certain temperature the core index equals that of the cladding and guidance is destroyed, so that the fibre is able to detect the presence of a hot spot. A variation on the latter is the use of a liquid cladding for an otherwise unclad glass-core[9]. Again, the variation in relative index, and thus the fibre throughput, is used to detect temperature changes.

Although liquid-core fibres have been successfully used in fibre sensors (and some sensitivity has been found in silica fibres[7]), a more desirable approach is to develop solid-core fibres which exhibit similar sensitivity to that found in liquids. This should be realised in the future by the use of composite polymer/glass fibres or special glass compositions.

Twisted and Spun Fibres: The detection of magnetic fields in fibres by the Faraday effect requires the fibre to have very low linear birefringence in order to observe the small field-induced polarisation rotation. This is particularly so for the fibre current monitor[10] where a few turns of fibre are wrapped around a current-carrying conductor to sample the surrounding magnetic field and hence determine the current, using Ampere's Law. For this application special fibres (spun fibres) have been developed in which the birefringence has been virtualy eliminated by a process of spinning the fibre during the draw to periodically interchange the fast and slow axes of birefringence. These fibres (Fig. 2) were probably the first designed specifically for a sensor application. They have been successfully used in a number of current measuring devices, particularly those designed to measure very large currents such as found in plasma research.

Commercial exploitation of the fibre current monitor in the power distribution industry has been limited by the problem of the birefringence reappearing when the fibre is wound and packaged into a practical coil. Provided the intrinsic fibre birefringence is initially sufficiently low (as in a spun fibre), twisting the fibre to induce circular birefringence[11] can be used as a remedy for this bend and pressure-induced linear birefringence. Unfortunately, the twist rate is limited by fibre fracture and to date for many applications it has not proved possible to apply sufficient twist to totally eliminate linear birefringence effects.

The problem could be overcome by the development of special fibres using glasses which exhibit a larger Verdet constant, thus giving a greater Faraday rotation, or fibres which naturally exhibit a large circular birefringence. Work in both these areas is underway.

Twin-Core Fibres: A novel extension of the well-known Mach-Zender interferometric sensor is to incorporate both the signal and the reference arms into the same fibre by using two separate cores[12]. Several versions of this idea are possible. When the cores are sufficiently separated they act independently and behave as an interferometer of a length equal to that of the fibre. If both cores are equal the interferometer is balanced and this obviates the need to accurately match the length of signal and reference arms. If the cores are dissimilar, a given path length difference exists per unit length of fibre and this can be exploited in various multiplexing schemes. In both cases, the fibre output is very sensitive to bends and pressure, and in the case of dissimilar cores, to temperature.

In another version the cores are closely spaced and coupling between them occurs continuously. Again the output is sensitive to bends and pressure which affect not only the core optical lengths, but also their coupling.

In a highly-birefringent fibre, the two polarisation states propagate virtually independently and can be selected with a polariser. The fibre can therefore be regarded as similar in concept to the twin-core fibre, only the two modes travel in the same core. Polarimetric sensors of this type are twin mode, rather than twin core, and are regarded by many as a more convenient implementation of the idea.

Polarisation-Maintaining Fibres: Perhaps the best known of all fibres designed for sensor work is the highly-birefringent (hi-bi) polarisation-maintaining fibre, the two most common forms[14] of which are shown in Figs. 3(a) and (b). The birefringence is induced 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 value of 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[15], the power transfer per metre of fibre length. The best fibre measured to date[15] is the Bow-Tie fibre[13] shown in Fig. 3(a), which has a power transfer (h-parameter) of 5×10^{-6} m^{-1}, corresponding to an output extinction ratio of -23dB after one km. Note that this figure will be dependent on the fibre configuration and packaging and will be worse in tight coils or badly-designed cables.

The use of hi-bi fibres is 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 discrimation (>60dB) to ensure reciprocity in the fibre gyro, and further discrimination is required in the form of a polariser.

Polarising Fibres: A recent development is the polarising fibre[16] which combines the polarisation-holding ability of a hi-bi fibre with a discriminatory loss for the unwanted polarisation. 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 two polarised modes. One mode is more susceptible to bends or microbends than the other and a polarising wavelength window exists in which one mode is sufficiently well guided to give low-loss propagation (<5dB/km), while the other experiences greater than 50dB/km attenuation[16]. 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[17]. Such polarisers are of interest for use in the fibre gyro.

The ultimate linear polarisation-holding ability of a hi-bi fibre is limited by Rayleigh scatter[18] 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[19], but exhibits field curvature. It therefore has both a major and a minor (orthogonally-polarised) field component. The polarisation-holding limits are shown in Fig. 4, 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 -35dB, whereas for a length of 100km the Rayleigh scattering limit is -30dB. For comparison, experimental results[20] 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 of which is attributable to intrinsic and externally-induced mode coupling. Fig. 4 also illustrates the effect of having a continuous discriminatory loss of 50dB/km for the unwanted polarisation, as in a polarising fibre. 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 a 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.

As well as transmission of polarised light, hi-bi fibres can themselves be used as intrinsic sensors. The birefringence changes both with longitudinal strain[22] and temperature[23] and this suggests a number of possible polarimetric sensors. As pointed out earlier, polarimetric sensors have the advantage of containing both the signal and reference arm of an interferometer within the same fibre and are therefore rather simpler to construct.

The performance of polarisation-maintaining and polarising fibres is essentially limited by the level of stress-induced birefringence which can be incorporated into the core before fracture occurs. Higher birefringence for a similar stress level could be achieved by using compound glasses with a much larger stress-optic coefficient than silica. It may thus be possible to increase the birefringence an order of magnitude above current levels, so permitting the construction of a number of interesting devices and sensors. Stress guides[24] in which the mode confinement is purely a result of the stress-induced index change would also become a reality, giving high performance polarising fibres with a large wavelength window and high extinction ratio.

Discussion

A number of fibres dedicated to sensor applications have been developed, although few have at present an optimal performance. It would appear that there are considerable opportunities for improvement once it is realised that telecommunictions-based fibre technology is not necessarily the most appropriate for sensor fibre fabrication. In particular, the removal of the low-loss constraint allows a wide range of new materials and fibre structures to be contemplated. In Table 1 some of the more speculative ideas for future developments are outlined, together with suggested fibre construction and uses. The table is not intended to be exhaustive and could indeed be considerably extended. As new materials and fibre construction techniques emerge, a large number of possible new sensor applications will be possible, indicating exciting prospects for the future.

References

1. R. Ulrich, p. 17, First Int. Conf. on Opt.Fibre Sensors, London, 1983.
2. G.W. Day et al., J. Lightwave Tech., LT-2, p. 56, 1984.
3. K.P. Koo, IEEE J. Quantum Electron., QE-18, p. 670, 1982.
4. A. Dandridge et al., Electron. Lett., 16, p. 408, 1980.
5. N. Lagakos et al., Optics Lett., 7, p. 460, 1982.
6. R. Reid and J. Cramp, European Patent 61884A.
7. A.H. Hartog, J. Lightwave Tech., LT-1, p. 498, 1983.
8. J.J. Geddes and G.B. Hocker, UK Patent No. GB 2037448A.
9. A.M. Scheggi et al., p. 13, First Int. Conf. on Opt. Fibre Sensors, London, 1983.
10. A.M. Smith, Appl. Opt., 17, p. 52, 1978.
11. R. Ulrich and A. Simon, Appl. Opt., 18, p. 2241, 1979.
12. E. Snitzer et al, p. 406, Fibre-Optic Rotation Sensors, Springer-Verlag, 1982.
13. R.D. Birch et al., Electron. Lett., 18, p. 1036, 1982.
14. Y. Sasaki et al, Paper THCC6, OFC '82, Phoenix, 1982.
15. S.C. Rashleigh, J. Lightwave Tech., LT-1, p. 312, 1983.
16. M.P. Varnham et al, Electron. Lett., 19, p. 246, 1983.
17. M.P. Varnham et al, Optics Lett., July 1984.
18. E. Brinkmeyer and W. Eickhoff, Electron. Lett., 19, p. 996, 1983.
19. M.P. Varnham et al., Electron. Lett., 20, p. 55, 1984.
20. Y. Sasaki et al., Electron. Lett., 19, p. 792, 1983.
21. S.C. Rashleigh, Paper 4.1, First Int. Conf. on Optical Fibre Sensors, London, 1983.
22. M.P. Varnham et al., Electron. Lett., 19, p. 699, 1983.
23. A. Ourmazd et al., Appl. Opt., 22, p. 2374, 1983.
24. R.D. Birch et al., 19, p. 866, 1983.
25. E. Snitzer et al., p. 79, First Int. Conf. on Opt. Fibre Sensors, London, 1983.

Fibre	Construction	Application
Magnetic field sensitive	High Verdet constant glass	Current monitor Magnetometers Isolators
Circularly-birefringent	High levels of torsion	Current monitor Magnetometers
Very high linear birefringence	Glass with large stress-optic coefficient	Polarising fibres Polarisation-maintaining fibres
Stress guides	High stress levels Glass with large stress optic coefficient	Polarisers Gyro Interferometers
Pressure sensitive	Glass with large stress-optic coefficient	Acoustic detectors Hydrophones Pressure monitors
Selectively absorbing	Doping with absorbing ions[25]	Temperature sensors
Controlled scatter	Liquid core, polymeric, compound-glass	Distributed temperature sensor
Temperature - stable optical length	Glasses with low dn/dt, negative expansion coefficient cladding and coatings	Gyro Interferometric sensors
IR Transmitting	IR materials	Remote Pyrometry IR Spectroscopy

Table 1 Possible Sensor-Fibre Developments

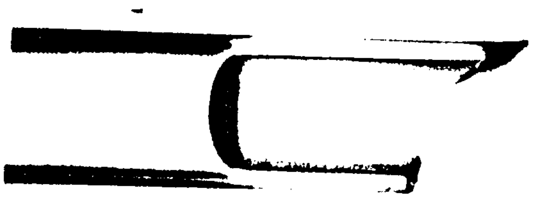


Fig. 1 Liquid-core fibre

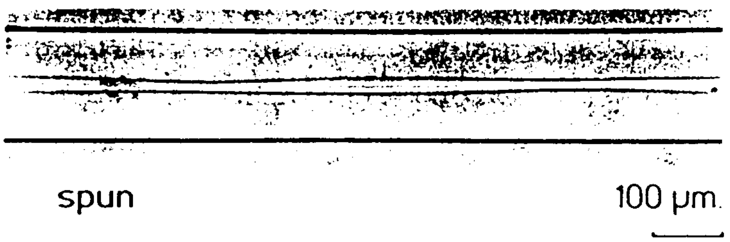
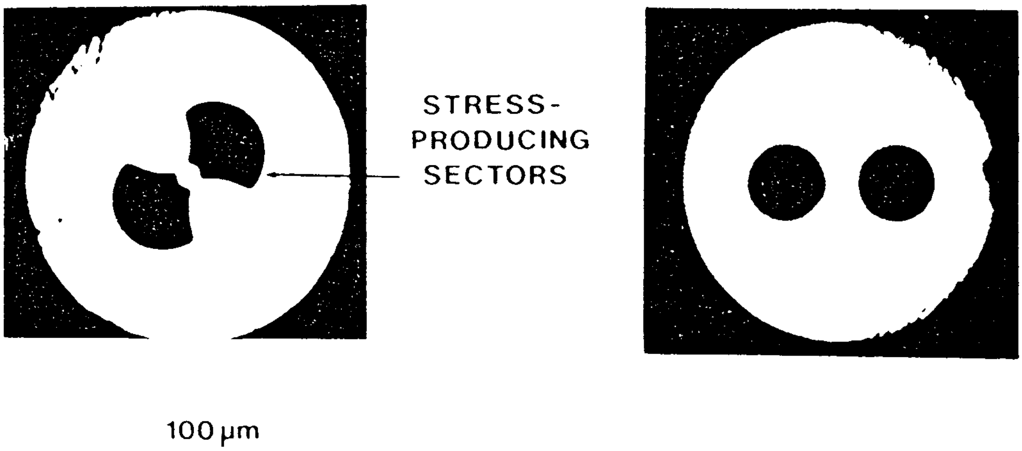


Fig. 2 Low-birefringence spun fibre



(a) (b)

Fig. 3 Polarisation-maintaining fibres. (a) Bow-Tie (b) PANDA

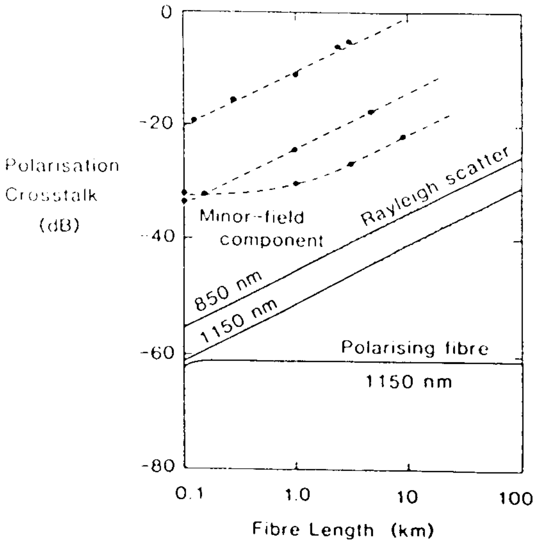


Fig. 4 Fundamental limits to polarisation crosstalk