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"NOVEL OPTICAL FIBRES FOR SENSING APPLICATIONS"

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INVITED PAPER

Novel optical fibres for sensing applications

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Abstract. Optical fibres have some degree of sensitivity to a wide range of external parameters. On the other hand the effects are usually small and are minimised as far as possible in fibres designed for telecommunications. Furthermore it is often difficult to differentiate between a number of small responses that may occur simultaneously. Considerable advantages can be gained by appropriate selection of core and cladding materials and by novel fibre structures and designs.

Thus, by spinning the preform during fibre drawing a high degree of circular birefringence can be introduced whilst the linear birefringence becomes negligible. Such fibres can behave as sensors of magnetic fields and electric currents. By introducing a high degree of linear birefringence fibre gyroscopes capable of measuring angular rotation become possible. The introduction of rare-earth materials into the core produces absorption bands with steep edges that have a strong wavelength sensitivity to changes in temperature. This produces the basis for distributed sensors that cover a wide range of temperatures.

A variety of novel types of optical fibres are presently being explored for potential application to sensors and transducers.

1. Introduction

Optical fibres have been developed to a high degree of sophistication for applications in long-distance transmission. Silica-based fibres have attenuations close to the theoretical minimum at wavelengths of 0.85, 1.3 and 1.55 μm, while the bandwidth of single-mode fibres can, for all practical purposes, be made almost infinite at wavelengths greater than 1.3 μm. Attention is now being given to the design of new types of fibre for application as active and passive fibre components, as sensors and in other new types of optical circuit element.

Optical fibres have some degree of sensitivity to a wide range of external parameters. On the other hand the effects are usually small and are minimised as far as possible in fibres designed for telecommunications. Furthermore, it is often difficult to differentiate between a number of small responses that may occur simultaneously. Considerable advantages can be gained by appropriate selection of core and cladding materials and by novel fibre structures and designs.

Many possible configurations may be applied to sensors and transducers. For example, a small numerical aperture gives rise to enhanced radiation loss at bends and microbends so that such fibres can be made to respond to changes in pressure and displacement. This is an example of a class of fibre sensor in which the measurand controls, in some way, the optical power transmitted by the fibre. In another class of fibre sensor it is the propagation time or phase that is modified, giving rise to a whole array of interferometric devices generally having a high sensitivity but small dynamic range. An interesting example is the fibre gyroscope.

Other types of sensor produce a modification of the mode distribution in a multimode fibre, the state of polarisation, the degree of coupling between two fibres and so on. In some applications the fibre simply acts as a light transmission medium to guide light safely and conveniently to the sensing region.

The present paper, however, covers the fabrication of fibres having novel design features and materials. It is intended to be tutorial rather than definitive and illustrates some of the wide range of options available to the designers of fibre sensors.

The fundamental HE_{11} mode, the only mode possible in single-mode fibres, is linearly polarised. Fibres can thus be made to exhibit almost zero birefringence, or high degrees of linear, circular and elliptical birefringence. Each of these can be used in sensor applications with varying degrees of success. It is also possible to make composite glass/metal fibres in order to exploit the optical Kerr effect or to produce highly effective polarisers. Doping the core with rare-earth ions can give a useful degree of thermal sensitivity over a wide temperature range as well as giving rise to a new type of fibre laser and optical amplifier. Examples of each of these sensing fibres are considered here.

2. Fibres with negligible birefringence

Research into 'funny fibres' for sensor applications began at Southampton in 1979 with an attempt to make a single-mode fibre having a sufficiently low birefringence for the measurement of magnetic fields and electric currents through the Faraday effect. The detection of magnetic fields in this way requires the fibre to have very low inherent linear birefringence in order to observe the small field-induced polarisation rotation. This is particularly the case in the fibre current sensor where several turns of the fibre are wrapped around a current-carrying conductor. The angle through which the plane of polarisation is rotated is proportional to the integral of the magnetic field in the axial direction along the fibre. The approach taken was to reduce non-circularity by improved fabrication methods and to minimise asymmetric stress by forming the core and cladding from materials having equal thermal expansion coefficients (Norman *et al* 1979). The task was by no means an easy one, since calculations indicated that even for a relative index difference as low as 3.4×10^{-3} the noncircularity must be no greater than 0.06% in order to achieve a retardance of 3° m^{-1}.

This approach was partially successful and retardances as low as 2.6° m^{-1} were achieved, some three orders of magnitude smaller than in a typical fibre. A length of such fibre coiled around a current-carrying busbar in Fawley Power Station operated by the CEGB over a period of two years gave results in agreement with conventional ammeters. However, the fabrication process was difficult, so that the yield was not high and the usable lengths were limited to about 100 m.

Another possibility is to average out the linear birefringence in a fibre by twisting it. Unfortunately the fibre breaks before the effect becomes useful, i.e. at beat lengths (see § 3) of about 0.1 m, and in any case strongly twisted fibres are not easy to handle. However, it has been demonstrated that fibres with almost zero internal birefringence can be made by rotating the preform of a conventional fibre about its longitudinal axis

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(Barlow *et al* 1981) during fibre drawing. Spinning rates of several thousand revolutions per minute are possible, with the result that any azimuthal inhomogeneities rotate along the length of the fibre with a very short pitch length. Linearly polarised light is unable to follow this rapid rotation of the birefringence axes, so that the core appears to be circularly symmetric as far as the propagating mode is concerned. The inherent linear birefringence, and polarisation mode dispersion, can be reduced to a very low level in this way. External effects, such as bends, pressure, etc, can re-introduce birefringence that is not affected by the spun core, so that spun fibres can be used as sensors. They are particularly useful for the measurement of magnetic fields and electric currents if the externally induced birefringence is kept small.

3. Linearly birefringent fibres

In many applications the state of polarisation of the modes in a fibre must be strictly controlled. For example, a stable state of linear polarisation is necessary in fibres for interferometric sensors, in coherent transmission and for coupling to integrated optical circuits. The state of polarisation in ordinary single-mode fibres is indeterminate. In theory, if a fibre is perfectly constructed so that it is circularly symmetric and laid in a straight line then linearly polarised light launched at the input will maintain this state along the whole length of the fibre to the output. In practice, however, such ideal conditions are not possible. Fibres cannot be made as perfect cylindrical structures so that both intrinsic imperfections, as well as external factors such as bends, stress and changes of temperature, produce optical azimuthal inhomogeneities. Linearly polarised input light may be decomposed into linearly polarised, orthogonal, components having different phase velocities. Thus, uncontrolled coupling between the two orthogonal components and random variations in the relative phase velocity, cause the state of polarisation to vary along the length of the fibre in an unpredictable way.

In order to stabilise the linear polarisation state it is necessary to reduce the amount of coupling between the two mode components and this can be done by introducing strong linear birefringence into the fibre.

One method of doing so (Dyott *et al* 1979) is to make the core non-circular in shape so that the refractive-index distributions in the two principal directions are different. Such form-birefringent fibres are available, but the refractive-index difference between core and cladding must be large, which in turn means that in order to maintain single-mode propagation the core diameter must be very small. This gives rise to problems of fabrication and jointing of the fibre.

On the other hand, coupling to the non-circular active emission spot of a semiconductor laser is eased and a simple butt connection to a laser diode can have a loss (Dyott 1983) of only 1.9 dB. The transmission loss of this type of fibre has been reduced to 9 dB km^{-1} at 0.85 μm and 2.5 dB km^{-1} at 1.3 μm.

A more common method of producing linear birefringence is by introducing an asymmetric stress over the core of the fibre. The core and cladding remain circular but non-circularly symmetric sectors of very different expansion coefficient are introduced into the substrate region of the fibre. Several methods have been suggested but the one producing the largest birefringence is the 'bow-tie' structure (Varnham *et al* 1983a) in which the shape of the stress-producing sectors has been optimised to produce the maximum degree of birefringence.

The fibres are fabricated by a modification of the MCVD process. After the normal buffer layer has been deposited on the inside of the deposition tube, to prevent the diffusion of water into the core and cladding regions, a layer of stress-producing material (for example borosilicate glass) is deposited. The tube rotation is then stopped and some of the stress-producing glass is etched away on opposite sides of the preform tube. The tube is again rotated and layers of cladding, followed by core, glass are deposited in the usual way. The deposited tube is then collapsed into a solid rod preform. During the collapse process the cusp-like regions of the stress-producing glass in the tube assume the 'bow-tie' shape. It is possible to produce a high degree of stress in the preform, even up to the breakdown level of glass thus causing the preform to shatter. Assuming that shattering has not occurred the preform rod is then drawn into a fibre. The cross section of a bow-tie fibre is shown in figure 1. During the cooling from the drawing temperature of approximately 2000 °C to room temperature a high degree of asymmetric stress is once again introduced, due to the different thermal expansion coefficients of the borosilicate sectors and the silica substrate. The fibre, as distinct from the preform, is mechanically strong and is no more likely to break than a conventional fibre. On the contrary, the compressive stress at the fibre surface tends, if anything, to increase the strength and reduce stress corrosion.

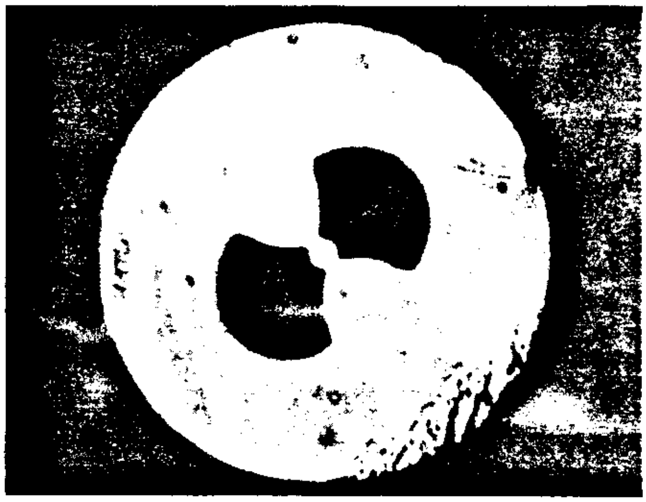

Figure 1. Cross section of a bow-tie fibre showing central core and cladding regions and (dark) stress-producing sectors.

The degree of birefringence can be easily assessed by observing the light scattered sideways from the fibre when the input (from a helium–neon laser for example) is linearly polarised at an angle of 45° to the principal transverse axes. Because of their different phase constants, the two propagating polarisation modes run in and out of phase at a rate determined by the birefringence, thus producing a periodic variation in the transmitted polarisation state from linear to circular and back again. The radially scattered intensity therefore fluctuates with the same periodicity.

If the phase constants of the two polarisation modes are β_1 and β_2 then the 'beat length' L measured in this way is given by

$$L = \frac{2\pi}{\beta_1 - \beta_2} = \frac{\lambda}{B}$$

where λ is the optical wavelength and B is the normalised birefringence, which is related to the refractive indices by

$$B = n_1 - n_2 = (\lambda/2\pi)(\beta_1 - \beta_2).$$

Beat lengths as low as 0.55 mm ($B = 10^{-5}$) have been measured.

In order to obtain maximum birefringence the stress-producing sectors should be as close to the core as possible. However, too close a proximity may cause an increased attenuation by interaction with the evanescent field in the cladding. Nevertheless under production conditions (York VSOP Ltd: private communication) beat lengths of 0.7 mm and transmission losses of less than 0.2 dB km^{-1} have been obtained.

3.1. *Polarisation-maintaining fibres*

A fibre exhibiting a high degree of linear birefringence can operate in two quite distinct ways. In the first of these the two orthogonal modes have a low transmission loss and propagate with roughly equal attenuation. If an equal amount of light is launched into each of the modes then, as described above, the state of polarisation changes periodically along the length of the fibre from linear, to circular, to linear and so on. On the other hand, if only one of the modes is launched, then the light remains linearly polarised along the entire length of the fibre because the large difference in the phase constants of the modes greatly reduces the coupling between them that might be caused by bends, microbends, kinks, twists and so on. In the presence of strong external distortion some of the original polarisation couples into the orthogonal mode and continues to propagate in that mode to the output. The intensity of light in the coupled mode can then provide a measure of the external parameter. Thus the characteristic of a polarisation-maintaining fibre is that the attenuations of the two polarisation modes are equal but the phase constants are very different.

3.2. *Polarising fibres*

Another method of operating a linearly birefringent fibre is to introduce attenuation preferentially into one of the modes. Light launched into the low-loss mode will continue in that mode to the end of the fibre. Any light coupled into the orthogonal, i.e. high-loss, mode is attenuated and the output remains linearly polarised despite the mode coupling. Such a fibre is termed a 'polarising' fibre because, for any state of input polarisation, only linearly polarised light emerges.

A preferential loss may be introduced into one mode by winding the fibre into a coil. Because of the different refractive-index distributions in the two principal transverse planes, the bending loss edges of the two modes are at different wavelengths, so that there is a wavelength region where the attenuation of the two modes is very different. The steepness of the bending edges, their positions and their separation, can be changed by the fabrication conditions, the radius of bend and by microbends (Varnham *et al* 1983b). The wavelength region in which polarising action occurs can also be controlled. Extinction ratios of 60 dB have been obtained, together with extremely wide wavelength windows.

Another method, in which a flat metal surface is inserted close to the core, is described in § 6.

4. Circularly birefringent fibres

Fibres exhibiting a high degree of circular birefringence can find application in the monitoring of electric current and magnetic fields. As distinct from spun fibres they are relatively unaffected by internal or external perturbations.

Probably the simplest method of producing circular birefringence is by twisting a conventional optical fibre about its longitudinal axis. It is then found that the propagation constants of modes polarised in the left- and right-hand circular directions are different. However, this method is quite limited since, as indicated earlier, the fibre will break at beat lengths shorter than about 0.1 m.

A much more effective method is to produce a fibre in which the core does not lie along the longitudinal fibre axis but follows a helical path about it. Such fibres have been developed and fabricated at Southampton (Varnham *et al* 1986) by inserting a normal MCVD preform, containing core and cladding, into a hole drilled off-axis in a silica rod. Whilst the silica rod containing the off-set core/cladding preform is drawn into fibre it is rotated about its longitudinal axis. The core of the resulting fibre is in the form of a tight helix with a quite short pitch length. The degree of circular birefringence is more than an order of magnitude greater than is possible by twisting the fibre and beat lengths down to 5 mm (corresponding to a modal birefringence of $B = 1.3 \times 10^{-4}$) and less have been produced.

An interesting consequence of this method of fabrication is that the bend loss of the second- and higher-order modes is greatly increased compared with that of the fundamental mode so that the fibre can be operated at high normalised frequencies, e.g. $V = 25$, whilst effectively maintaining single-mode operation. The core diameter can thus be much larger than normal.

The helical-core fibre is stable and its birefringence is relatively uninfluenced by external effects. It is therefore robust, in polarisation terms, and can be looped around a conductor for current measurement with ease. Since the rotation of the plane of polarisation is proportional to the line integral of the magnetic field the position of the coil is of no consequence and it can be close to the conductor or some distance from it. Clearly the measurement is unaffected by stray magnetic fields, including those created by nearby currents that are not enclosed by the coil. However, the fibre has a larger diameter (~0.5 mm) than normal, because the degree of circular birefringence increases rapidly with helix diameter, and is therefore stiff, restricting applications to coils of 0.3 m radius or more. The mode axis is set at an angle to the fibre axis so that launching is more difficult than with a conventional fibre. Furthermore the small Verdet constant of silica causes the sensitivity to be low and only large currents can be measured. Nevertheless it is well suited to measurements on power lines.

5. Elliptically birefringent fibres

An elliptically birefringent fibre can be fabricated by spinning a fibre having high linear birefringence (e.g. a bow-tie fibre) during drawing. This results in a fibre with a permanent frozen-in rotation of the birefringent axes. The polarisation eigenmodes of such a fibre are elliptically polarised, the elliptical birefringence being dependent on the linear birefringence of the unspun fibre and the rate of twist. The beat length L'_p between the elliptically polarised modes of the spun fibre is given in terms of the beat length L_p of the unspun fibre by (Li *et al* 1986a)

$$L'_p = L_p L_t / [(4L_p^2 + L_t^2)^{1/2} - 2L_p]$$

where L_t is the spin pitch.

The beat length L'_p is a measure of the resistance to external perturbations, and should normally be less than 10 mm. The elliptical-mode beat length is shown in figure 2 as a function of

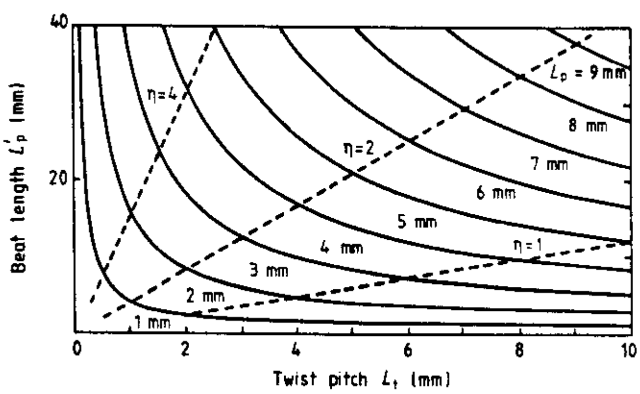

Figure 2. Calculated resultant elliptically polarised beat length L'_p as a function of spin pitch L_t for various values of unspun fibre beat length L_p.

the spin pitch L_t for various values of unspun beat length L_p. Curves for values of the ratio $2L_p/L_t$ from one to four are also shown, and it can be seen that, provided the spin pitch is not less than the unspun beat length, an acceptable increase in fibre beat length of four times results from the spinning process. A bow-tie fibre thus remains highly (elliptically) birefringent. The ellipticity (minor/major axis) of the eigenmodes is given by

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

At high spin rates ($2L_p/L_t > 2$) the ellipticity approaches unity, and the modes are therefore predominantly circularly polarised. There is little quenching of the Faraday effect. The sensitivity (Faraday rotation angle $< 20°$) differs little from the perfect isotropic fibre ($2L_p/L_t = \infty$) for values of $2L_p/L_t$ greater than about two, corresponding to a resultant elliptical beat length $L'_p = 4.24\,L_p$. Thus to ensure a sufficiently large elliptical birefringence ($L'_p < 10$ mm) the unspun beat length L_p must be less than about 3 mm.

Elliptically birefringent fibres have been designed and fabricated by spinning bow-tie fibres. The initial linearly birefringent beat lengths of the fibres ranged from 1.8 mm to 3 mm (at 633 mm) and the spin pitches from 0.9 mm to 7.7 mm. Fibres were wound into coils with diameters of 3.3 and 5.5 mm around a current-carrying conductor. The number of turns on the coils were (i) 100, (ii) 140 and (iii) 60. The coil leads were about 1 m long. Currents were measured by detecting the rotation angle (at 633 nm) of the output state of polarisation.

Currents of less than 10 mA at frequencies up to 2 MHz have been determined using fibre coil (i) and a 13-turn wire coil of 0.2 m diameter. The system was dominated by laser amplitude noise, which was not compensated by the usual method. Nevertheless, a noise equivalent current of 450 μA Hz$^{-1/2}$ was observed for a current input at a frequency of 30 kHz.

Since the linear birefringence of a bow-tie fibre is temperature sensitive, some form of temperature compensation is needed in a practical device to reduce the instability of the output polarisation state. This was achieved by bifilar winding two identical fibres with opposite spin directions. The fibres were spliced together with their principal axes orthogonal, to interchange the fast and slow axes. The temperature-compensated fibre coil (coil (ii)) was found to have considerably reduced temperature sensitivity, and normal laboratory temperature fluctuations were no longer a problem.

Spun bow-tie fibres thus exhibit high elliptical birefringence, which permits the measurements of Faraday rotation while retaining resistance to perturbations due to packaging. Coils of up to 140 turns with diameters down to 33 mm have measured currents from 10 mA to 400 A. The new fibre has considerable potential for sensitive current monitors employing small-diameter multiturn coils, as well as in more conventional current measuring applications.

6. Evanescent-field devices

In some kinds of sensor it is necessary to make direct access to the propagating optical field in and near the core. Examples embrace Raman spectroscopy, chemical and biological sensing, and resonant absorption. There are several methods of exposing the evanescent field near the core. One is to grind away and polish off the cladding, which is tedious and difficult. Another is to taper the fibre, thus causing field expansion beyond the reduced cladding, which is also difficult and produces a fragile fibre. A preferable technique is to create a longitudinal, precise, aperture inside the fibre and at a controlled distance from the core. It is possible to produce such a cavity, into which suitable liquids or gases can be made to flow, with extremely smooth surfaces that are probably optically flat.

The technique is based on a fibre fabrication process that, while allowing continuous access to the core optical field, also provides an extremely smooth, low-scatter surface at which interactions can be obtained. One application has been to metal/glass fibre polarisers in which a metal is incorporated directly into the fibre close to the core, as shown in figure 3. The result is a high-performance metal/glass fibre polariser, produced in continuous lengths, and having an extinction ratio that can be selected by cutting to a given length.

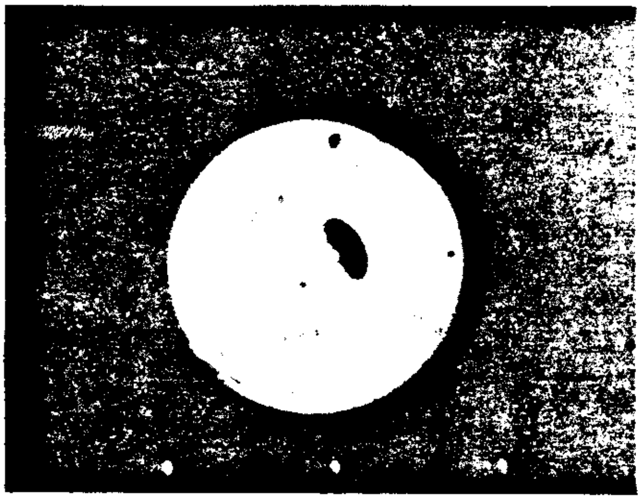

Figure 3. Cross section of a metal/glass composite fibre polariser.

The metal/glass fibre (Li *et al* 1986b) polarisers were made as follows. A fibre containing a hollow section (figure 3) was fabricated by grinding and polishing a flat onto the side of a preform. The preform was then sleeved with a close-fitting tube and drawn into a fibre. The acrylate-coated fibre had an NA of ~0.16, a cut-off wavelength of ~1.25 μm and the distance between the core and hollow section was ~3 μm. The fibre was then bonded to a stainless steel syringe containing a tin (48%)/indium (52%) alloy (melting point (MP) ~120 °C). The syringe and the fibre were heated to ~130 °C and a gas pressure of ~0.4 MPa was introduced above the metal through a stainless steel tube. Filling a two metre length took about one minute. The resultant composite metal/glass fibre could be handled, cleaved and spliced in a similar manner to a conventional fibre. The extinction ratio of a 0.48 m length of polariser fibre is greater than 50 dB over a wide spectral window from 1300 to 1600 nm.

Both the extinction ratio and insertion loss are proportional to the length and it is theoretically possible to design a polariser with a virtually unlimited extinction ratio at the expense of increased insertion loss. This is important since in many applications, particularly the fibre gyroscope, extinction ratio is critical while an insertion loss of 1 or 2 dB is acceptable. The fibre polariser reported here allows this choice to be made by simply cutting the fibre to the required length. Moreover, the fibre can be designed to provide a given extinction ratio for lengths of a few centimetres to several metres by adjusting the core/metal separation.

As indicated above, other liquids and gases can be introduced into the cavity for sensor applications. By providing longitudinal metal sectors symmetrically placed on either side of the core (Li and Payne 1987) even a moderate voltage can produce a strong electric field across the core. Modulation of the propagating wave can then occur via the optical Kerr effect. The device could be applied to the measurement of voltage or, more usefully, as a modulator. In the latter mode a bandwidth of

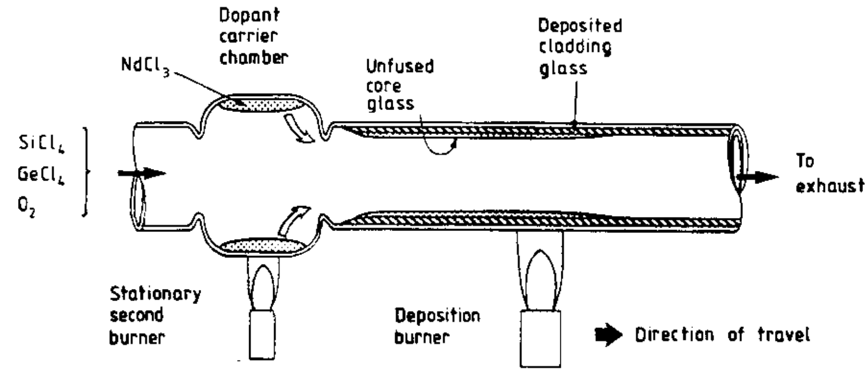

Figure 4. Modified deposition tube for rare-earth dopant incorporation in single-mode optical fibres.

several megahertz has been reported for a few tens of volts applied.

7. Fibres doped with rare-earths

In order to maintain low transmission losses in the near-infrared wavelength region it is necessary to reduce all but the essential glass constituents of optical fibres to an absolute minimum. On the other hand, optical fibres also have attractive potential applications as sensors and signal-processing devices if the appropriate fibre properties can be introduced, or enhanced, without appreciably increasing the attenuation at the low-loss wavelengths. In the methods discussed so far in this paper the purity of both core and cladding is maintained and the propagating wave is modulated by externally applied forces such as mechanical strain, electric field, magnetic field, change of temperature and so on. Another method of modifying the fibre properties is by introducing small quantities of suitable materials into the core or cladding.

At Southampton a study has been made of possible techniques for introducing rare-earth ions into the light-guiding regions of the fibre. Possible developments could be

(i) Fibre laser and amplifiers.

(ii) Distributed temperature sensor based on (*a*) absorption and (*b*) fluorescence.

(iii) Increased Verdet constant.

(iv) Increased Kerr effect and non-linear optical coefficients.

We have devised a method of doping fibres through a modification of the MCVD technique. A major advantage of conventional MCVD fabrication is that it enables the appropriate material halides to be used as starting materials and these can be obtained in very pure form and are liquid at room temperature. The problems to be overcome in extending this technique to the rare-earth halides is that they are solid at room temperature, they have a high melting point and thus a low vapour pressure, and they occur in hydrated form.

One of the methods adopted to overcome these difficulties (Poole *et al* 1985) is illustrated in figure 4. Prior to deposition, a conventional deposition tube is modified and the required dopant, for example $NdCl_3 . 6H_2O$ (99.9% pure, MP = 758 °C) is introduced into a special dopant chamber that is added at the upstream end. The dopant is dried by heating the chamber under a chlorine atmosphere and, at the same time, the anhydrous crystals are fused to the chamber wall. The inside of the deposition tube is then cleaned to remove any dopant that may have been deposited there during the drying process, following which the cladding glass is deposited in the usual way. During the core deposition the dopant chamber is heated to about 1000 °C to produce a small quantity of $NdCl_3$ vapour, which is carried downstream by the reactant flow where it is oxidised and incorporated into the core. The temperature for core deposition is kept lower than usual so that the core components are initially unfused. Further drying is carried out by heating in a chlorine atmosphere, after which the core is fused into a clear non-porous layer. Subsequent collapse of the deposited tube into a solid rod preform, and drawing of the preform into fibre, then follows the normal MCVD procedures.

Initial results have been very successful. A number of dopants, such as neodymium, erbium, ytterbium, terbium and praseodymium, have been incorporated into fibres, giving absorption bands of very high loss (greater than 3000 dB km^{-1}) at visible and near-infrared wavelengths, whilst maintaining the characteristic low loss (less than 2 dB km^{-1}) in the region of 1.3 μm. Further research is proceeding in the study of doping, and co-doping, of other rare-earth and transition metals. Measurements by optical time-domain reflectometry indicate that the dopant is incorporated uniformly along the length of the fibre. The technique is simple, reproducible and can provide multicomponent or single-component doping of a wide range of materials into the core or cladding of both multimode and single-mode optical fibres. The doping level can be varied over a wide range, up to about 1% by weight, without significantly affecting the low-loss characteristics in the wavelength region 0.95–1.4 μm. Such fibres can produce distributed sensors as well as fibre lasers, amplifiers and active components in optical communication systems.

Table 1. Parameters of optical fibres.

Numerical aperture $\mathrm{NA} = \sin\theta_m = (n_1^2 - n_2^2)^{1/2} \simeq n_1(2\Delta)^{1/2}$
where

θ_m = maximum acceptance angle in air

n_1, n_2 = refractive indices of core and cladding, respectively

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \simeq \frac{n_1 - n_2}{n_1}$$

Difference in propagation times of axial and extreme rays in:
(*a*) step-index multimode fibre

$$(\Delta t)_s = \frac{n_1 L}{c}\left(\frac{n_1 - n_2}{n_1}\right) \simeq \frac{n_1 L}{c}\Delta$$

(*b*) parabolic-index multimode fibre

$$(\Delta t)_m \simeq \frac{n_1 L}{c}\frac{\Delta^2}{8}$$

where

L = fibre length
$c = 3 \times 10^8$ m s^{-1}.

In a measurement of the sensitivity of a neodymium-doped fibre as a temperature sensor the change of absorption edge was measured to be 5 dB km^{-1} for a 50 °C change in temperature.

However, the sensitivity to temperature of a silica fibre doped with holmium is an order of magnitude greater than that of one doped with other rare earths. The sensitivity of the absorption to temperature is thought to be due to a satellite band on the long wavelength side of the main absorption bands. Thermal population at this energy level causes the attenuation to increase rapidly with temperature.

There are large changes in the fibre attenuation with temperature at wavelengths of 555, 670 and 910 nm. In the wavelength range 665–685 nm the attenuation change is greater than 2% per degree centigrade. Distributed measurements have been made with a tunable dye laser and an optical time-domain reflectometer. The dopant concentration in the fibre is optimised to provide a long sensitive fibre length and a high temperature sensitivity. The distributed attenuation obtained from the backscatter signal is shown in figure 5. A low loss of 10 dB km^{-1} is measured at −196 °C, which enables a long fibre length to be used. A 5 m section of fibre at 20 °C produces a significant attenuation of 100 dB km^{-1}. The large change may be easily detected with a simple OTDR. A further section of fibre in a variable temperature environment shows the resolution of the sensor to small temperature changes far down the fibre.

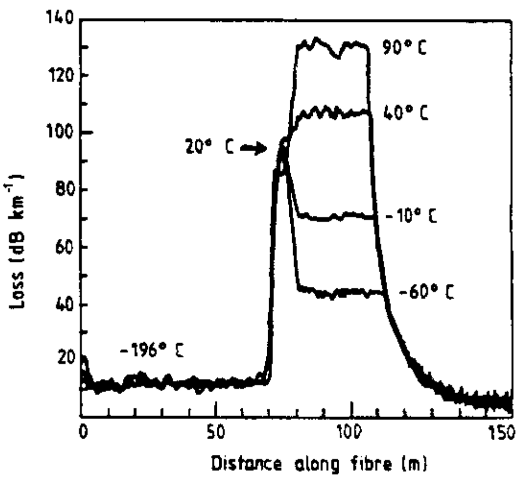

Figure 5. Distribution of temperature and associated attenuation along an optical fibre having a core doped with holmium.

The temperature resolution is of the order of 1 °C and the spatial resolution is 3.5 m. This sensor is particularly sensitive at low temperatures beyond the range of other distributed temperature sensors. A particularly useful wavelength is 940 nm at which suitable semiconductor lasers are available. By tuning the laser wavelength it has been shown possible to vary the range and sensitivity of the sensor.

8. Conclusions

A wide variety of new optical fibre materials and structures are possible that may lead to many different types of sensor application. The examples outlined in this paper are intended to be illustrative and not definitive. The design of novel fibre structures and sensors is in its infancy and much research remains to be done. The over-riding requirements are, as always, for high performance at low cost and only the future can tell whether, and in what systems, these targets can be met.

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